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As the sun disappears behind an approaching deck of clouds, the air above the snow-covered landscape slowly cools. As the air temperature lowers, the relative humidity increases, and the air gradually approaches saturation.

CHAPTER 4

Atmospheric Moisture

Sometimes it rains and still fails to moisten the desert—the falling water evaporates halfway down between cloud and earth. Then you see curtains of blue rain dangling out of reach in the sky while the living things wither below for want of water. Torture by tantalizing, hope without fulfillment. And the clouds disperse and dissipate into nothingness. . . . The sun climbed noon-high, the heat grew thick and heavy on our brains, the dust clouded our eyes and mixed with our sweat. My canteen is nearly empty and I'm afraid to drink what little water is left—there may never be any more. I'd like to cave in for a while, crawl under yonder cottonwood and die peacefully in the shade, drinking dust.

Edward Abbey, *Desert Solitaire—A Season in the Wilderness*

CONTENTS

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We know from Chapter 1 that, in our atmosphere, the concentration of the invisible gas water vapor is normally less than a few percent of all the atmospheric molecules. Yet water vapor is exceedingly important, for it transforms into cloud particles—particles that grow in size and fall to the earth as precipitation. The term *humidity* is used to describe the amount of water vapor in the air. To most of us, a moist day suggests high humidity. However, there is usually more water vapor in the hot, "dry" air of the Sahara Desert than in the cold, "damp" polar air in New England, which raises an interesting question: Does the desert air have a higher humidity? As we will see later in this chapter, the answer to this question is both yes and no, depending on the type of humidity we mean.

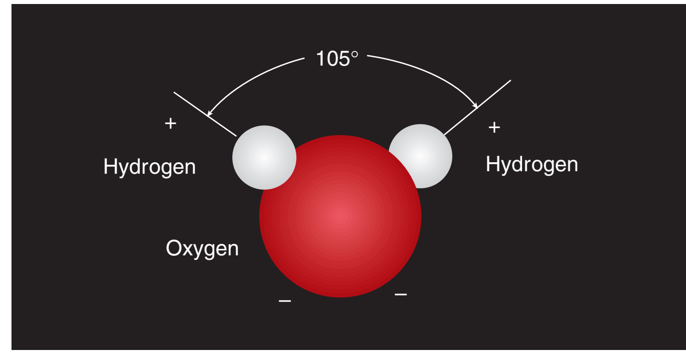
So that we may better understand the concept of humidity, we will begin this chapter by examining water vapor in the atmosphere. Then, we will look at different ways to express humidity. At the end of the chapter, we will investigate various ways to measure humidity.

Water in the Atmosphere

In the lower atmosphere, water is everywhere. As a gas, water vapor molecules move about quite freely, mixing well with neighboring atoms and molecules. As a liquid, the water molecules are closer together, and so they constantly jostle and bump each other. In the solid state (ice), the molecules arrange themselves into an orderly pattern, with each molecule more or less locked into a rigid position, able to vibrate, but not able to move about freely. Water vapor, an invisible gas, becomes visible only when many molecules join together to form tiny cloud droplets or ice particles. In this process—known as a *change of state* or, simply, a *phase change*—water only changes its disguise, it does not change its identity.

THE MANY PHASES OF WATER To obtain a slightly different picture of water in the atmosphere, suppose we catch a falling snowflake in the palm of a glove. If we could magnify that tiny crystal of ice about a billion times, we would see H_2O molecules in the shape of tiny heads that resemble Mickey Mouse (see • Fig. 4.1). The bulk of the "head" of the molecule is the oxygen atom. The "mouth" is a region of excess negative charge. The "ears" are partially exposed protons of the hydrogen atom, which are regions of excess positive charge.

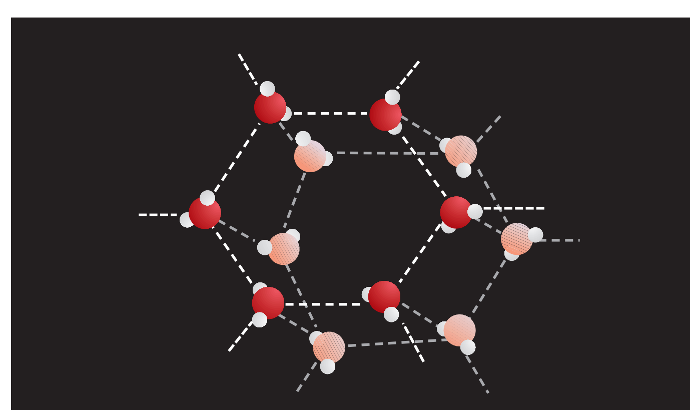
When we look at many molecules (see • Fig. 4.2), we can see that they are locked into specific positions and arranged as a six-sided (hexagonal) crystal form we call *ice.* Recall that the molecules are unable to move about freely, but they do vibrate. As we observe the ice crystal in freezing air, we see an occasional molecule gain enough energy to break away from its neighbors and enter into the air above. The molecule changes from an ice molecule directly into a vapor molecule without passing through the liquid state. This ice-to-vapor phase change is called **sublimation.** If a water vapor molecule should attach itself to the ice crystal, the vapor-to-ice phase change is called **deposition.**



• FIGURE 4.1
The water molecule.

If we apply warmth to the ice crystal, its molecules would vibrate faster. In fact, some of the molecules would actually vibrate out of their rigid crystal pattern into a disorderly condition—the ice melts. Suppose enough snow crystals melt to partially fill the beaker in • Fig. 4.3a.

If we were able to magnify the surface water in the beaker as we did with the ice crystal, we would see water molecules fairly close together, jiggling, bouncing, and moving about. We would also see that the molecules are not all moving at the same speed—some are moving much faster than others. At the surface, molecules with enough speed (and traveling in the right direction) would occasionally break away from the liquid surface and enter into the air above. These molecules, changing from the *liquid state into the vapor state* are **evaporating.** While some water molecules are leaving the liquid, others are returning. Those returning are **condensing** as they are changing from a *vapor state to a liquid state.*



• FIGURE 4.2
The partially exposed hydrogen atom of one molecule is attracted to the negative oxygen atom of another molecule. Because the hydrogen atoms of each water molecule are separated by an angle of 105°, the joining of many billions of molecules produces a hexagonal-shaped ice crystal. In the atmosphere, many ice crystals may join together to form a snowflake.

When a cover is placed over the beaker (see Fig. 4.3b), after a while the total number of molecules escaping from the liquid (evaporating) would be balanced by the number returning (condensing). When this condition exists, the air is said to be **saturated** with water vapor. For every molecule that evaporates, one must condense, and no net loss of liquid or vapor molecules results.

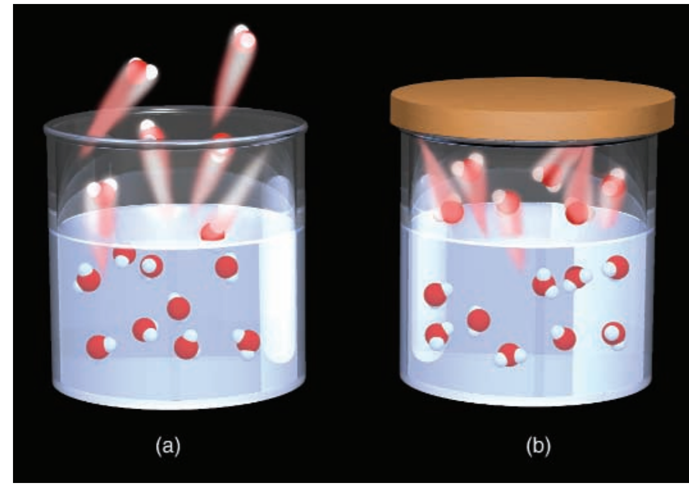
If we remove the cover and blow across the top of the water, some of the vapor molecules already in the air above would be blown away, creating a difference between the actual number of vapor molecules and the total number required for *saturation.* This would help prevent saturation from occurring and would allow for a greater amount of evaporation. Wind, therefore, enhances evaporation.

The temperature of the water also influences evaporation. All else being equal, warm water will evaporate more readily than cool water. The reason for this phenomenon is that, when heated, the water molecules will speed up. At higher temperatures, a greater fraction of the molecules have sufficient speed to break through the surface tension of the water and zip off into the air above. Consequently, the warmer the water, the greater the rate of evaporation.

If we could examine the air above the water in Fig. 4.3, we would observe the water vapor molecules freely darting about and bumping into each other as well as neighboring molecules of oxygen and nitrogen. When these gas molecules collide, they tend to bounce off one another, constantly changing in speed and direction. However, the speed lost by one molecule is gained by another, and so the average speed of all the molecules does not change. Consequently, the temperature of the air does not change. Mixed in with all of the air molecules are microscopic bits of dust, smoke, salt, and other particles called *condensation nuclei* (so-called because water vapor condenses on them). In the warm air above the water, fast-moving vapor molecules strike the nuclei with such impact that they simply bounce away (see • Figure 4.4a). However, if the air is chilled (Fig. 4.4b), the molecules move more slowly and are more apt to stick and condense to the nuclei. When many billions of these vapor molecules condense onto the nuclei, tiny liquid cloud droplets form.

We can see then that condensation is more likely to happen as the air cools and the speed of the vapor molecules decreases. As the air temperature increases, condensation is less likely because most of the molecules have sufficient speed (sufficient energy) to remain as a vapor. As we will see in this and other chapters, *condensation occurs primarily when the air is cooled.*

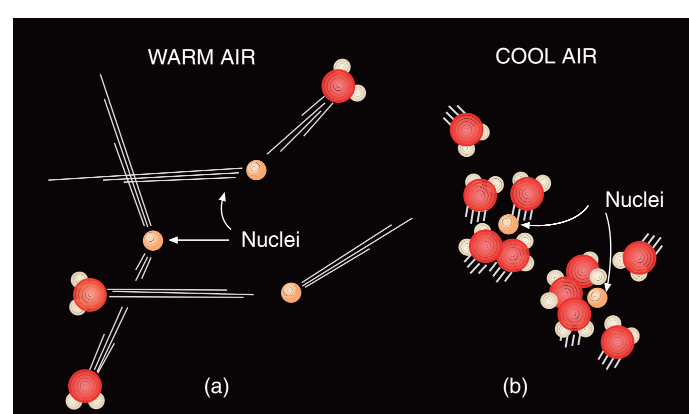
Even though condensation is more likely to occur when the air cools, it is important to note that no matter how cold the air becomes, there will always be a few molecules with sufficient speed (sufficient energy) to remain as a vapor. It should be apparent, then, that with the same number of water vapor molecules in the air, saturation is more likely to occur in cool air than in warm air. This idea often leads to the statement that "warm air can hold more water vapor molecules before becoming saturated than can cold air" or, simply, "warm air has a



• FIGURE 4.3
(a) Water molecules at the surface of the water are evaporating (changing from liquid into vapor) and condensing (changing from vapor into liquid). Since more molecules are evaporating than condensing, net evaporation is occurring.
(b) When the number of water molecules escaping from the liquid (evaporating) balances those returning (condensing), the air above the liquid is saturated with water vapor. (For clarity, only water molecules are illustrated.)

WEATHER WATCH

Possibly the highest reported temperature a human has experienced (and lived to tell about it) occurred in a dry sauna with an air temperature of 127°C (260°F). Even though a roast would cook at this temperature, the person survived the ordeal for about 45 minutes because rapidly evaporating perspiration formed a protective layer of cool air around the individual's body.



• FIGURE 4.4
Condensation is more likely to occur as the air cools. (a) In the warm air, fast-moving H_2O vapor molecules tend to bounce away after colliding with nuclei. (b) In the cool air, slow-moving vapor molecules are more likely to join together on nuclei. The condensing of many billions of water molecules produces tiny liquid water droplets.

greater capacity for water vapor than does cold air." At this point, it is important to realize that although these statements are correct, the use of such words as "hold" and "capacity" are misleading when describing water vapor content, as air does not really "hold" water vapor in the sense of making "room" for it. (As we will see later, another way of explaining why cooling produces condensation is that the saturation vapor pressure decreases with lower temperatures.)

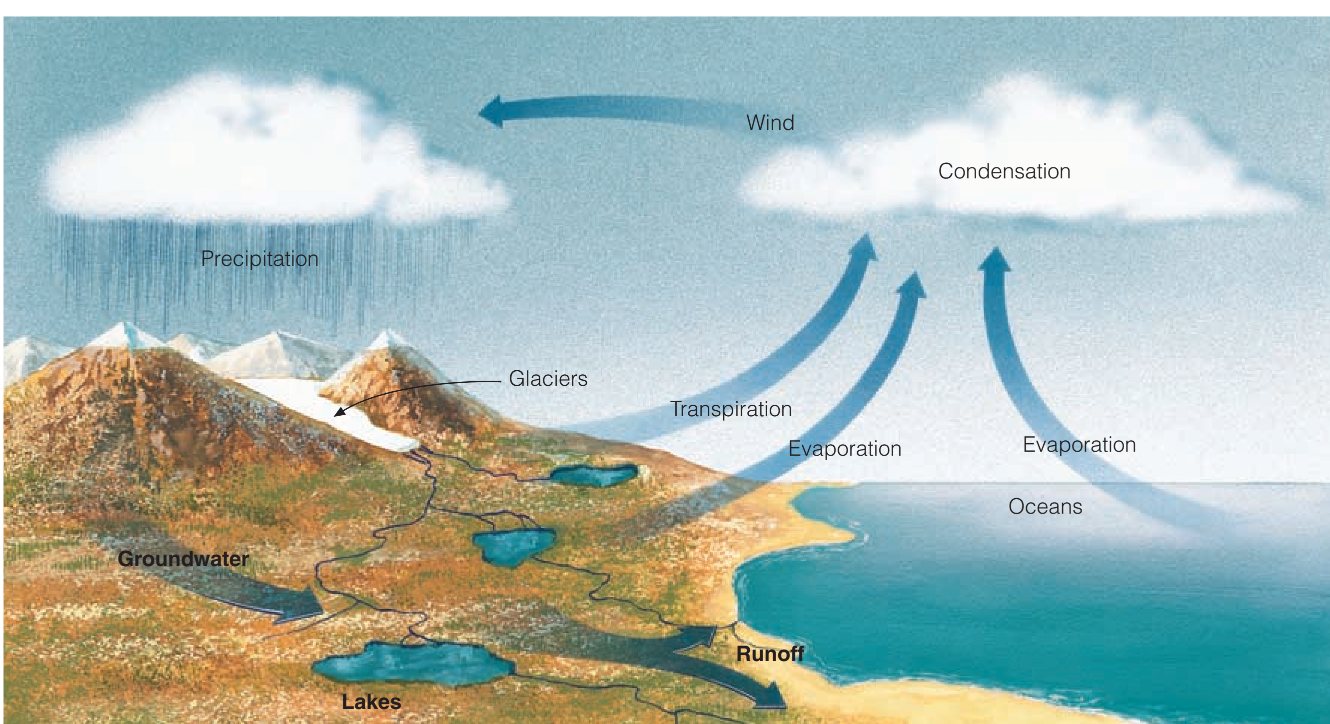
CIRCULATION OF WATER IN THE ATMOSPHERE Within the atmosphere, an unending circulation of water begins as energy from the sun evaporates enormous quantities of water from the oceans. Winds transport the moist air to other regions, where it condenses into clouds. Under certain conditions, the liquid (or solid) cloud particles may grow in size and fall to the surface as **precipitation—**rain, snow, or hail.* If the precipitation falls into an ocean, the water is ready to begin its cycle again. If, on the other hand, the precipitation falls on a continent, a great deal of the water returns to the ocean in a complex journey. This cycle of moving and transforming water molecules from liquid to vapor and back to liquid again is called the **hydrologic** (water) **cycle.** In the form with which we are most concerned, water molecules travel from ocean to atmosphere to land and then back to the ocean.

•Figure 4.5 illustrates the complexities of the hydrologic cycle. For example, before falling rain ever reaches the ground, a portion of it evaporates back into the air. Some of the precipitation may be intercepted by vegetation, where it evaporates or drips to the ground long after a storm has ended. Once on the surface, a portion of the water soaks into the ground by percolating downward through small openings in the soil and rock, forming groundwater that can be tapped by wells. What does not soak in collects in puddles of standing water or runs off into streams and rivers, which find their way back to the ocean. Even the underground water moves slowly and eventually surfaces, only to evaporate or be carried seaward by rivers.

Over land, a considerable amount of vapor is added to the atmosphere through evaporation from the soil, lakes, and streams. Even plants give up moisture by a process called *transpiration.* The water absorbed by a plant's root system moves upward through the stem and emerges from the plant through numerous small openings on the underside of the leaf. In all, evaporation and transpiration from continental areas amount to only about 15 percent of the nearly 1.5 billion billion gallons of water that annually evaporate into the atmosphere; the remaining 85 percent evaporates from the oceans. If all of this vapor were to suddenly condense and fall as rain, it would be enough to cover the entire globe with 2.5 centimeters, or 1 inch of water.* The total mass of water vapor stored in the atmosphere at any moment adds up to only a little over a week's supply of the world's precipitation. Since this amount varies only slightly from day to day, the hydrologic cycle is exceedingly efficient in circulating water in the atmosphere.

*Precipitation is any form of water that falls from a cloud and reaches the ground.

*If the water vapor in a column of air condenses and falls to the earth as rain, the depth of the rain on the surface is called *precipitable water.*



•FIGURE 4.5
The hydrologic cycle.

Absolute Humidity

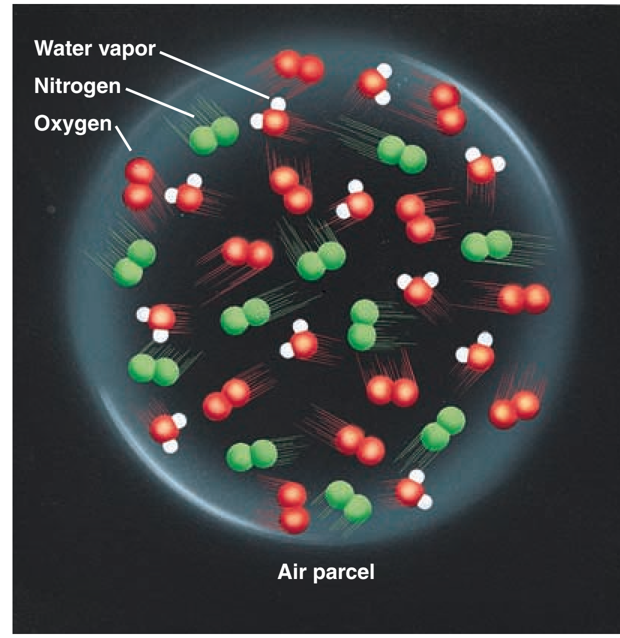
Humidity refers to any one of a number of ways of specifying the amount of water vapor in the air. Since there are several ways to express atmospheric water vapor content, there are several meanings for the concept of humidity.

Suppose we enclose a volume of air in an imaginary thin elastic container—a *parcel*—about the size of a large balloon, as illustrated in • Fig. 4.6. With a chemical drying agent, we can extract the water vapor from the air, weigh it, and obtain its mass. If we then compare the vapor's mass with the volume of air in the parcel, we would have determined the **absolute humidity** of the air—that is, the mass of water vapor in a given volume of air:

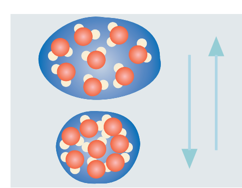
$$\text{Absolute humidity} = \frac{\text{mass of water vapor}}{\text{volume of air}}.$$

Absolute humidity represents the *water vapor density* (mass/volume) in the parcel and, normally, is expressed as grams of water vapor in a cubic meter of air. For example, if the water vapor in 1 cubic meter of air weighs 25 grams, the absolute humidity of the air is 25 grams per cubic meter (25 g/m^3).

We learned in Chapter 2 that a rising or descending parcel of air will experience a change in its volume because of the changes in surrounding air pressure. Consequently, when a volume of air fluctuates, the absolute humidity changes—even though the air's vapor content has remained constant (see • Fig. 4.7). For this reason, the absolute humidity is not commonly used in atmospheric studies.

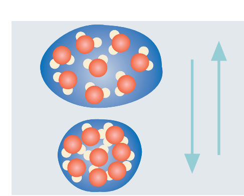


• FIGURE 4.6
The water vapor content (humidity) inside this air parcel can be expressed in a number of ways.



	Parcel Size	Mass of H_2O Vapor	Absolute Humidity
	2 m^3	10 g	5 g/m^3
	1 m^3	10 g	10 g/m^3

• FIGURE 4.7
With the same amount of water vapor in a parcel of air, an increase in volume decreases absolute humidity, whereas a decrease in volume increases absolute humidity.



	Mass of Parcel	Mass of H_2O Vapor	Specific Humidity
	1 kg	1 g	1 g/kg
	1 kg	1 g	1 g/kg

• FIGURE 4.8
The specific humidity does not change as air rises and descends.

Specific Humidity and Mixing Ratio

Humidity, however, can be expressed in ways that are not influenced by changes in air volume. When the mass of the water vapor in the air parcel in Fig. 4.6 is compared with the mass of all the air in the parcel (including vapor), the result is called the **specific humidity;** thus

$$\text{Specific humidity} = \frac{\text{mass of water vapor}}{\text{total mass of air}}.$$

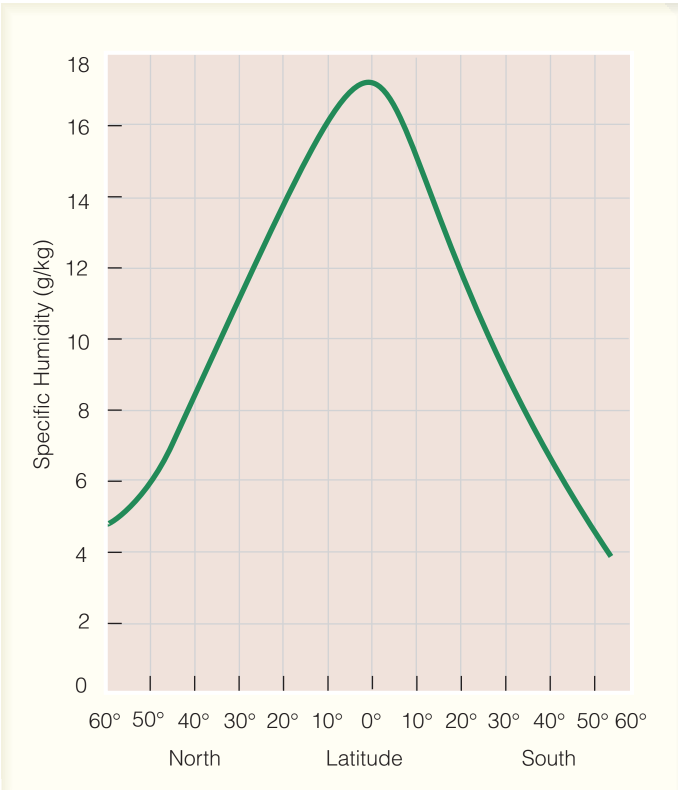
Another convenient way to express humidity is to compare the mass of the water vapor in the parcel to the mass of the remaining dry air. Humidity expressed in this manner is called the **mixing ratio:**

$$\text{Mixing ratio} = \frac{\text{mass of water vapor}}{\text{mass of dry air}}.$$

Both specific humidity and mixing ratio are expressed as grams of water vapor per kilogram of air (g/kg).

The specific humidity and mixing ratio of an air parcel remain constant *as long as water vapor is not added to or removed from the parcel.* This happens because the total number of molecules (and, hence, the mass of the parcel) remains constant, even as the parcel expands or contracts (see • Fig. 4.8). Since changes in parcel size do not affect specific humidity and mixing ratio, these two concepts are used extensively in the study of the atmosphere.

• Figure 4.9 shows how specific humidity varies with latitude. The average specific humidity is highest in the warm,



• FIGURE 4.9
The average specific humidity for each latitude. The highest average values are observed in the tropics and the lowest values in polar regions.

muggy tropics. As we move away from the tropics, it decreases, reaching its lowest average value in the polar latitudes. Although the major deserts of the world are located near latitude 30°, Fig. 4.9 shows that, at this latitude, the average air contains nearly twice the water vapor that the air at latitude 50°N contains. Hence, the air of a desert is certainly not "dry," nor is the water vapor content very low. Since the hot, desert air of the Sahara often contains more water vapor than the cold, polar air farther north, we can say that *summertime Sahara air has a higher specific humidity.* (We will see later in what sense we consider desert air to be "dry.")

Vapor Pressure

The air's moisture content may also be described by measuring the pressure exerted by the water vapor in the air. Suppose the air parcel in Fig. 4.6, p. 89, is near sea level. The total pressure inside the parcel is due to the collision of all the molecules against the inside surface of the parcel. In other words, the total pressure inside the parcel is equal to the sum of the pressures of the individual gases. (This phenomenon is known as *Dalton's law of partial pressure.*) If the total pressure inside the parcel is 1000 millibars (mb),* and the gases inside include nitrogen (78 percent), oxygen (21 percent), and water vapor (1 percent), then the partial pressure exerted by nitrogen would be 780 mb and by oxygen, 210 mb. The partial pressure of water vapor, called the **actual vapor pressure,** would be only 10 mb (1 percent of 1000).† It is evident, then, that because the number of water vapor molecules in any volume of air is small compared to the total number of air molecules in the volume, the actual vapor pressure is normally a small fraction of the total air pressure.

Everything else being equal, the more air molecules in a parcel, the greater the total air pressure. When you blow up a balloon, you increase its pressure by putting in more air. Similarly, an increase in the number of water vapor molecules will increase the total vapor pressure. Hence, the actual vapor pressure is a fairly good measure of the total amount of water vapor in the air: *High actual vapor pressure indicates large numbers of water vapor molecules, whereas low actual vapor pressure indicates comparatively small numbers of vapor molecules.*‡

In summer across North America, the highest vapor pressures are observed along the humid Gulf Coast, whereas the lowest values are experienced over the drier Great Basin, especially Nevada. In winter, the highest average vapor pressures are again observed along the Gulf Coast with lowest values over the northern Great Plains into Canada.

Actual vapor pressure indicates the air's total water vapor content, whereas **saturation vapor pressure** describes how much water vapor is necessary to make the air saturated at any given temperature. Put another way, *saturation vapor pressure is the pressure that the water vapor molecules would exert if the air were saturated with vapor at a given temperature.*

We can obtain a better picture of the concept of saturation vapor pressure by imagining molecules evaporating from a water surface. (Look back at Fig. 4.3a, p. 87.) Recall that when the air is saturated, the number of molecules escaping from the water's surface equals the number returning. Since the number of "fast-moving" molecules increases as the temperature increases, the number of water molecules escaping per second increases also. In order to maintain equilibrium, this situation causes an increase in the number of water vapor molecules in the air above the liquid. Consequently, at higher air temperatures, it takes more water vapor to saturate the air. And more vapor molecules exert a greater pressure. *Saturation vapor pressure, then, depends primarily on the air temperature.* From the graph in • Fig. 4.10, we can see that at 10°C, the saturation vapor pressure is about 12 mb, whereas at 30°C it is about 42 mb.

*You may recall from Chapter 1 that the millibar is the unit of pressure most commonly found on surface weather maps, and that it expresses atmospheric pressure as a force over a given area.

†When we use the percentages of various gases in a volume of air, Dalton's law only gives us an approximation of the actual vapor pressure. The point here is that, near the earth's surface, the actual vapor pressure is often close to 10 mb.

‡Remember that actual vapor pressure is only an approximation of the total vapor content. A change in total air pressure will affect the actual vapor pressure even though the total amount of water vapor in the air remains the same.

The insert in Fig. 4.10 shows that, when both water and ice exist at the same temperature below freezing, *the saturation vapor pressure just above the water is greater than the saturation vapor pressure over the ice.* In other words, at any temperature below freezing, it takes more vapor molecules to saturate air directly above water than it does to saturate air directly above ice. This situation occurs because it is harder for molecules to escape an ice surface than a water surface. Consequently, fewer molecules escape the ice surface at a given temperature, requiring fewer in the vapor phase to maintain equilibrium. Likewise, salts in solution bind water molecules, reducing the number escaping. These concepts are important and (as we will see in Chapter 7) play a role in the process of rain formation.

So far, we've described the amount of moisture actually in the air. If we want to report the moisture content of the air around us, we have several options:

1. *Absolute humidity* tells us the *mass* of water vapor in a fixed volume of air, or the *water vapor density.*
2. *Specific humidity* measures the *mass* of water vapor in a fixed *total mass* of air, and the *mixing ratio* describes the mass of water vapor in a fixed mass of the remaining dry air.
3. The *actual vapor pressure* of air expresses the amount of water vapor in terms of the amount of *pressure* that the water vapor molecules exert.
4. The *saturation vapor pressure* is the pressure that the water vapor molecules would exert if the air were saturated with vapor at a given temperature.

Each of these measures has its uses but, as we will see, the concepts of vapor pressure and saturation vapor pressure are critical to an understanding of the sections that follow. (Before looking at the most commonly used moisture variable—relative humidity—you may wish to read the Focus section on vapor pressure and boiling, p. 92.)

Relative Humidity

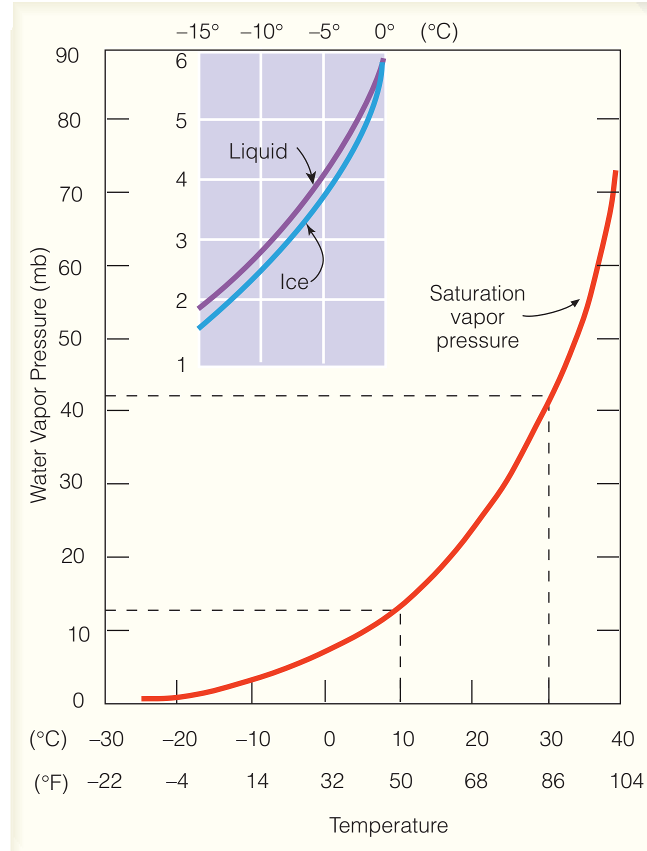
While relative humidity is the most common way of describing atmospheric moisture, it is also, unfortunately, the most misunderstood. The concept of relative humidity may at first seem confusing because it does not indicate the actual amount of water vapor in the air. Instead, it tells us how close the air is to being saturated. The **relative humidity** (RH) *is the ratio of the amount of water vapor actually in the air to the maximum amount of water vapor required for saturation at that particular temperature (and pressure).* It is the *ratio* of the air's water vapor *content* to its *capacity;* thus

$$\text{RH} = \frac{\text{water vapor content}}{\text{water vapor capacity}}.$$

We can think of the actual vapor pressure as a measure of the air's actual water vapor content, and the saturation vapor pressure as a measure of air's total capacity for water vapor. Hence, the relative humidity can be expressed as

$$\text{RH} = \frac{\text{actual vapor pressure}}{\text{saturation vapor pressure}} \times 100 \text{ percent.*}$$

Relative humidity is given as a percent. Air with a 50 percent relative humidity actually contains one-half the amount required for saturation. Air with a 100 percent relative humidity is said to be *saturated* because it is filled to capacity with water vapor. Air with a relative humidity greater than 100 percent



ACTIVE ● FIGURE 4.10
Saturation vapor pressure increases with increasing temperature. At a temperature of 10°C, the saturation vapor pressure is about 12 mb, whereas at 30°C it is about 42 mb. The insert illustrates that the saturation vapor pressure over water is greater than the saturation vapor pressure over ice.

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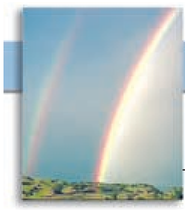
*Relative humidity may also be expressed as

$$\text{RH} = \frac{\text{actual mixing ratio}}{\text{saturation mixing ratio}} \times 100 \text{ percent,}$$

where the actual mixing ratio is the mixing ratio of the air and the saturation mixing ratio is the mixing ratio of saturated air at that particular temperature.

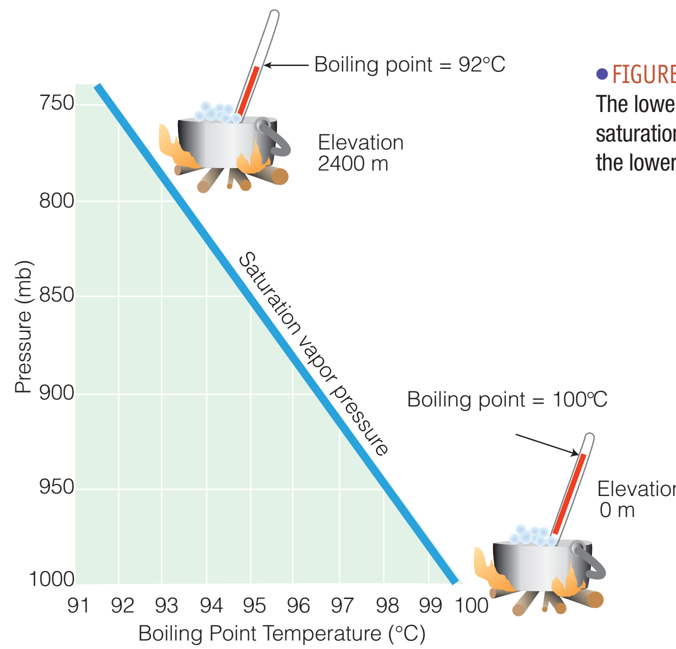


FOCUS ON
A SPECIAL TOPIC

Vapor Pressure and Boiling—The Higher You Go, the Longer Cooking Takes

If you camp in the mountains, you may have noticed that, the higher you camp, the longer it takes vegetables to cook in boiling water. To understand this observation, we need to examine the relationship between vapor pressure and boiling. As water boils, bubbles of vapor rise to the top of the liquid and escape. For this to occur, the saturation vapor pressure exerted by the bubbles must equal the pressure of the atmosphere; otherwise, the bubbles would collapse. Boiling, therefore, occurs when the saturation vapor pressure of the escaping bubbles is equal to the total atmospheric pressure.

Because the saturation vapor pressure is directly related to the temperature of the liquid, higher water temperatures produce higher vapor pressures. Hence, any change in atmospheric pressure will change the temperature at which water boils: An increase in air pressure raises the boiling point, while a decrease in air pressure lowers it. Notice in Fig. 1 that, to make pure water boil at sea level, the water must be heated to a temperature of 100°C (212°F). At Denver, Colorado, which is situated about 1500 m (5000 ft) above sea level, the air pressure is near 850 millibars, and water boils at 95°C (203°F).



● FIGURE 1
The lower the air pressure, the lower the saturation vapor pressure and, hence, the lower the boiling point temperature.

Once water starts to boil, its temperature remains constant, even if you continue to heat it. This happens because energy supplied to the water is used to convert the liquid to a gas (steam). Now we can see why vegetables take longer to cook in the mountains. To be thoroughly cooked, they must boil for a longer time because the boiling water is cooler than at lower levels. In New York City, which is near sea level, it takes about five minutes to hard boil an egg. An egg boiled for five minutes in the "mile high city" of Denver, Colorado, turns out to be runny.

is said to be **supersaturated.** Since relative humidity is used so much in the everyday world, let's examine it more closely.

A change in relative humidity can be brought about in two primary ways:

1. by changing the air's water vapor content
2. by changing the air temperature

In ● Fig. 4.11a, we can see that an increase in the water vapor content of the air (with no change in air temperature) increases the air's relative humidity. The reason for this increase resides in the fact that, as more water vapor molecules are added to the air, there is a greater likelihood that some of the vapor molecules will stick together and condense. Condensation takes place in saturated air. Therefore, as more and more water vapor molecules are added to the air, the air gradually approaches saturation, and the relative humidity of the air increases.* Conversely, removing water vapor from the air decreases the likelihood of saturation, which lowers the air's relative humidity. In summary, with no change in air temperature, adding water vapor to the air increases the relative humidity; removing water vapor from the air lowers the relative humidity.

Figure 4.11b illustrates that, as the air temperature increases (with no change in water vapor content), the relative humidity decreases. This decrease in relative humidity occurs because in the warmer air the water vapor molecules are zipping about at such high speeds they are unlikely to join together and condense. The higher the temperature, the faster the molecular speed, the less likelihood of saturation, and the lower the relative

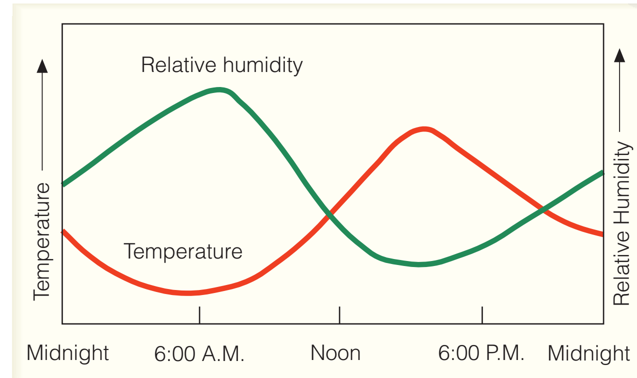
*We can also see in Fig. 4.11a that as the total number of vapor molecules increase (at a constant temperature), the actual vapor pressure increases and approaches the saturation vapor pressure at 20°C. This situation results in an increase in the relative humidity as the air approaches saturation.

humidity.* As the air temperature lowers, the vapor molecules move more slowly, condensation becomes more likely as the air approaches saturation, and the relative humidity increases. In summary, with no change in water vapor content, an increase in air temperature lowers the relative humidity, while a decrease in air temperature raises the relative humidity.

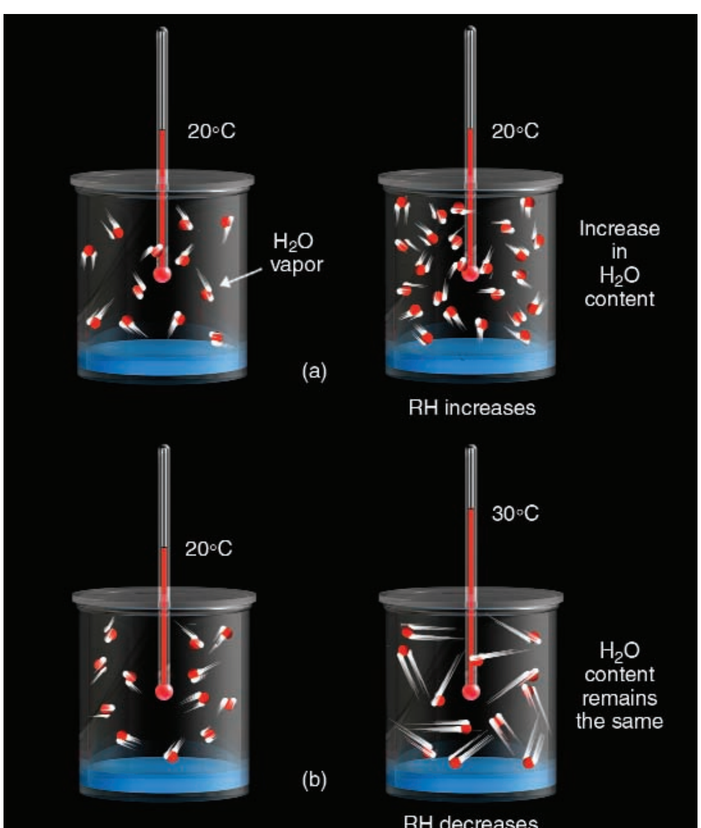
In many places, the air's total vapor content varies only slightly during an entire day, and so it is the changing air temperature that primarily regulates the daily variation in relative humidity (see •Fig. 4.12). As the air cools during the night, the relative humidity increases. Normally, the highest relative humidity occurs in the early morning, during the coolest part of the day. As the air warms during the day, the relative humidity decreases, with the lowest values usually occurring during the warmest part of the afternoon.

These changes in relative humidity are important in determining the amount of evaporation from vegetation and wet surfaces. If you water your lawn on a hot afternoon, when the relative humidity is low, much of the water will evaporate quickly from the lawn, instead of soaking into the ground. Watering the same lawn in the evening, when the relative humidity is higher, will cut down the evaporation and increase the effectiveness of the watering.

*Another way to look at this concept is to realize that, as the air temperature increases, the air's saturation vapor pressure also increases. As the saturation vapor pressure increases, with no change in water vapor content, the air moves farther away from saturation, and the relative humidity decreases.



•FIGURE 4.12
When the air is cool (morning), the relative humidity is high. When the air is warm (afternoon), the relative humidity is low. These conditions exist in clear weather when the air is calm or of constant wind speed.



•FIGURE 4.11
(a) At the same air temperature, an increase in the water vapor content of the air increases the relative humidity as the air approaches saturation. (b) With the same water vapor content, an increase in air temperature causes a decrease in relative humidity as the air moves farther away from being saturated.

RELATIVE HUMIDITY AND DEW POINT Suppose it is early morning and the outside air is saturated. The air temperature is 10°C (50°F) and the relative humidity is 100 percent. We know from the previous section that relative humidity can be expressed as

$$RH = \frac{\text{actual vapor pressure}}{\text{saturation vapor pressure}} \times 100 \text{ percent.}$$

Looking back at Fig. 4.10, p. 91, we can see that air with a temperature of 10°C has a saturation vapor pressure of 12 mb. Since the air is saturated and the relative humidity is 100 percent, the actual vapor pressure *must* be the same as the saturation vapor pressure (12 mb), since

$$RH = \frac{12 \text{ mb}}{12 \text{ mb}} \times 100\% = 100 \text{ percent.}$$

Suppose during the day the air warms to 30°C (86°F), with no change in water vapor content (or air pressure). Because there is no change in water vapor content, the actual vapor pressure must be the same (12 mb) as it was in the early morning when the air was saturated. The saturation vapor pressure, however, has increased because the air temperature has increased. From Fig. 4.10, note that air with a temperature of 30°C has a saturation vapor pressure of 42 mb. The relative humidity of this unsaturated, warmer air is now much lower, as

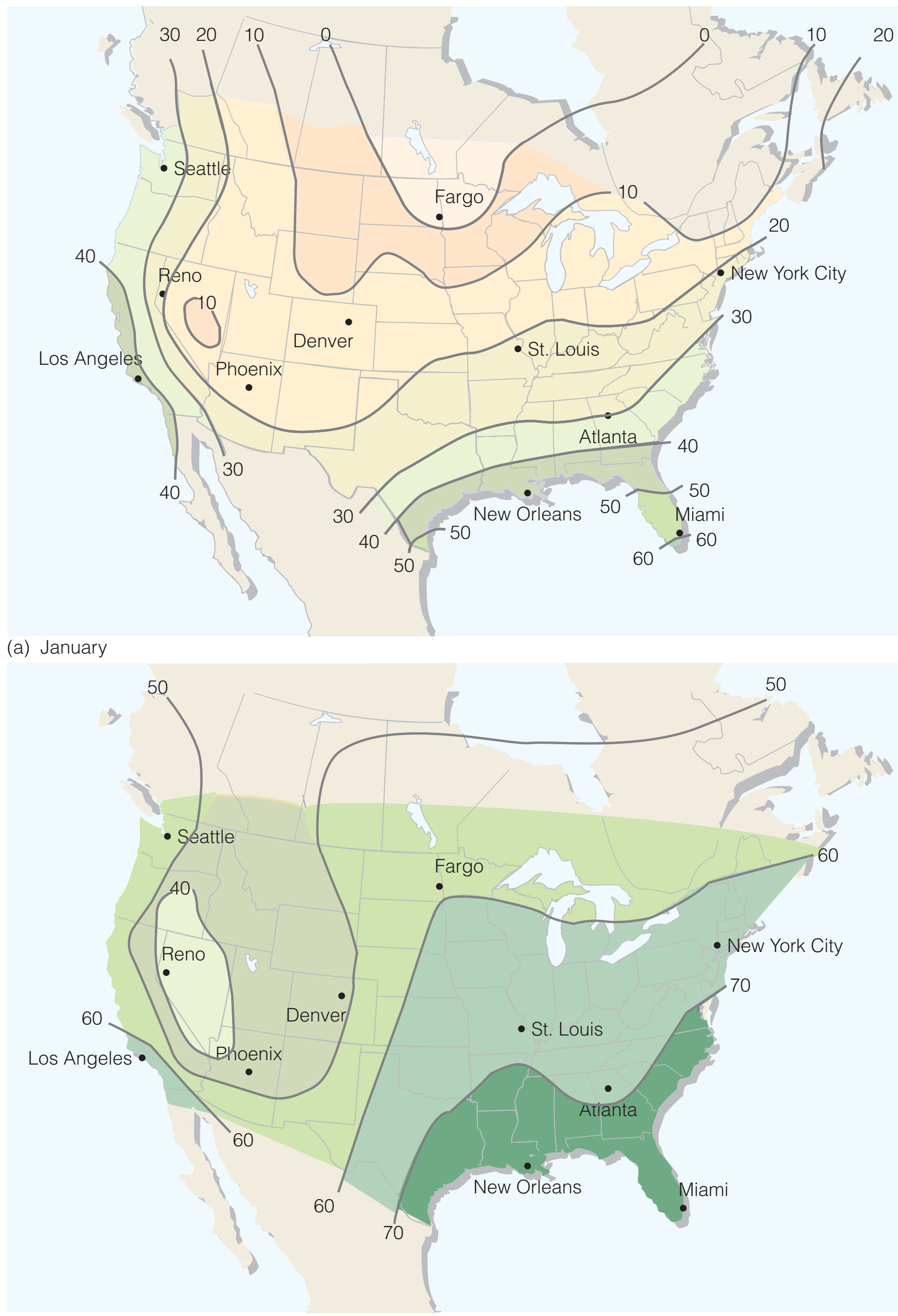
$$RH = \frac{12 \text{ mb}}{412 \text{ mb}} \times 100\% = 29 \text{ percent.}$$

To what temperature must the outside air, with a temperature of 30°C, be cooled so that it is once again saturated? The answer, of course, is 10°C. For this amount of water vapor in the air, 10°C is called the **dew-point temperature** or, simply, the **dew point.** It represents *the temperature to which air would have* *to be cooled (with no change in air pressure or moisture content) for saturation to occur.* The dew point is determined with respect to a flat surface of water. When the dew point is determined with respect to a flat surface of ice, it is called the **frost point.**

The dew point is an important measurement used to predict the formation of dew, frost, fog, and even the minimum temperature. When used with an empirical formula (see Chapter 6), the dew point can help determine the height of the base of a cumulus cloud. Since atmospheric pressure varies only slightly at the earth's surface, *the dew point is a good indicator of the air's actual water vapor content. High dew points indicate high water vapor content; low dew points, low water vapor content.* Addition of water vapor to the air increases the dew point; removing water vapor lowers it.

● Figure 4.13a shows the average dew-point temperatures across the United States for January. Notice that the dew points

● FIGURE 4.13
Average surface dew-point temperatures (°F) for (a) January and for (b) July.



WEATHER WATCH

On a hot, muggy summer day in the eastern half of the United States, it is common to hear someone complain that "the air temperature today is 90 degrees and the relative humidity is 90 percent." Although this weather situation is remotely possible, it is highly unlikely, as a temperature of 90°F and a relative humidity of 90 percent can occur only if the dew-point temperature is incredibly high—nearly 87°F.

are highest (the greatest amount of water vapor in the air) over the Gulf Coast states and lowest over the interior. Compare New Orleans with Fargo. Cold, dry winds from northern Canada flow relentlessly into the Center Plains during the winter, keeping this area dry. But warm, moist air from the Gulf of Mexico helps maintain a higher dew-point temperature in the southern states.

Figure 4.13b is a similar diagram showing the average dew-point temperatures for July. Again, the highest dew points are observed along the Gulf Coast, with some areas experiencing average dew-point temperatures near 75°F. Note, too, that the dew points over the eastern and central portion of the country are much higher in July, meaning that the July air contains between 3 and 6 times more water vapor than the January air. The reason for the high dew points is that this region is almost constantly receiving humid air from the warm Gulf of Mexico. The lowest dew point, and hence the driest air, is found in the West, with Nevada experiencing the lowest values—a region surrounded by mountains that effectively shields it from significant amounts of moisture moving in from the southwest and northwest.

The difference between air temperature and dew point can indicate whether the relative humidity is low or high. When the air temperature and dew point are far apart, the relative humidity is low; when they are close to the same value, the relative humidity is high. When the air temperature and dew point are equal, the air is *saturated* and the relative humidity is 100 percent. Even though the relative humidity may be 100 percent, the air, under certain conditions, may be considered "dry."

Observe, for example, in ● Fig. 4.14a that, because the air temperature and dew point are the same in the polar air, the air is saturated and the relative humidity is 100 percent. On the other hand, the desert air (Fig. 4.14b), with a large separation between air temperature and dew point, has a much lower relative humidity—21 percent.* However, since dew point is a

*The relative humidity can be computed from Fig. 4.10, p. 91. The desert air with an air temperature of 35°C has a saturation vapor pressure of about 56 mb. A dew-point temperature of 10°C gives the desert air an actual vapor pressure of about 12 mb. These values produce a relative humidity of 12/56 × 100, or 21 percent.

(a) POLAR AIR: Air temperature –2°C (28°F)
Dew point –2°C (28°F)
Relative humidity 100 percent

(b) DESERT AIR: Air temperature 35°C (95°F)
Dew point 10°C (50°F)
Relative humidity 21 percent

● FIGURE 4.14
The polar air has the higher relative humidity, whereas the desert air, with the higher dew point, contains more water vapor.

measure of the amount of water vapor in the air, the desert air (with a higher dew point) must contain *more* water vapor. So even though the polar air has a higher relative humidity, the desert air that contains more water vapor has a higher water vapor density, or *absolute humidity,* and a higher specific humidity and mixing ratio as well.

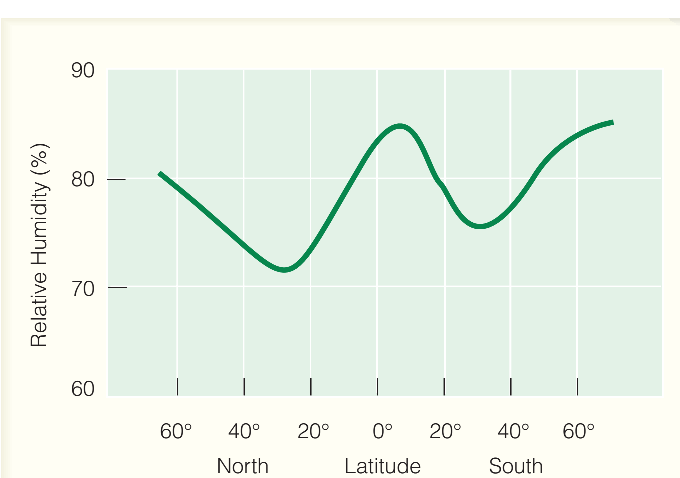
Now we can see why polar air is often described as being "dry" when the relative humidity is high (often close to 100 percent). In cold, polar air, the dew point and air temperature are normally close together. But the low dew-point temperature means that there is little water vapor in the air. Consequently, the air is said to be "dry" even though the relative humidity is high.

BRIEF REVIEW

Up to this point we have looked at the different ways of describing humidity. Before going on, here is a review of some of the important concepts and facts we have covered:

- **Relative humidity does not tell us how much water vapor is actually in the air; rather, it tells us how close the air is to being saturated.**
- **Relative humidity can change when the air's water-vapor content changes, or when the air temperature changes.**
- **With a constant amount of water vapor, cooling the air raises the relative humidity and warming the air lowers it.**
- **The dew-point temperature is a good indicator of the air's water-vapor content: High dew points indicate high water-vapor content; and low dew points, low water-vapor content.**
- **Dry air can have a high relative humidity. In polar air, when the dew-point temperature is low, the air is considered dry. But if the air temperature is close to the dew point, the relative humidity is high.**

Meteorology Now™ Click "Moisture Graph" to test the relationship between temperature, dew point, vapor pressure, and relative humidity.



● FIGURE 4.15
Relative humidity averaged for latitudes north and south of the equator.

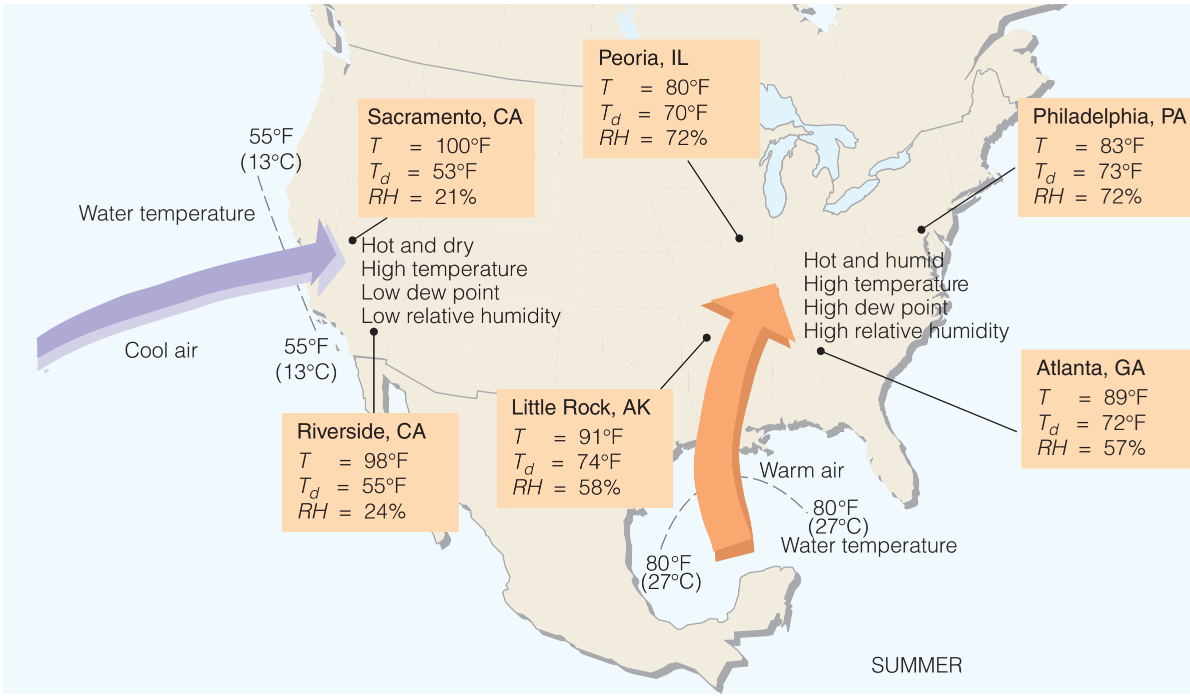
COMPARING HUMIDITIES ● Figure 4.15 shows how the average relative humidity varies from the equator to the poles. High relative humidities are normally found in the tropics and near the poles, where there is little separation between air temperature and dew point. The average relative humidity is low near latitude 30°—a latitude where we find the deserts of the world girdling the globe.

Of course, not all locations near 30°N are deserts. Take, for example, humid New Orleans, Louisiana. During July, the air in New Orleans with an average dew-point temperature of 22°C (72°F) contains a great deal of water vapor—nearly 50 percent more than does the air along the southern California coast. Since both locations are adjacent to large bodies of water, why is New Orleans more humid?

● Figure 4.16 shows a summertime situation where air from the Pacific Ocean is moving into southern California and air from the Gulf of Mexico is moving into the southeastern states. Notice that the Pacific water is much cooler than the Gulf water. Westerly winds, blowing across the Pacific, cool to just about the same temperature as the water. Likewise, air over the warmer Gulf reaches a temperature near that of the water below it. Over the water, at both locations, the air is nearly saturated with water vapor. This means that the dew-point temperature of the air over the cooler Pacific Ocean is much lower than the dew-point temperature over the warmer Gulf. Consequently, the air from the Gulf of Mexico contains a great deal more water vapor than the Pacific air.

As the air moves inland, away from the source of moisture, the air temperature in both cases increases. But the amount of water vapor in the air (and, hence, the dew-point temperature) hardly changes. Therefore, as the humid air moves into the southeastern states, high air temperatures along with high dew-point temperatures produce high relative humidities, often greater than 75 percent during the hottest part of the day. On the other hand, over the southwestern part of the nation, high air temperatures and low dew-point temperatures produce low relative humidities, often less than 25 percent during the hottest part of the afternoon. Much of this inland area over the southwest is a desert. However, keep in mind that although considered "dry," this area, with a dew-point temperature above freezing, still contains more water vapor than does the cold, arctic air in polar regions. (For more information on the computation of relative humidity and dew point, read the Focus section on p. 98.)

RELATIVE HUMIDITY IN THE HOME Question: How does the relative humidity of the winter air in your home compare with that in the Sahara Desert? Some homes actually have a lower relative humidity than the desert, and the inhabitants are usually unaware of it. Remember that cold polar air contains only a little water vapor. Even when saturated, air with a temperature and dew point of −15°C (5°F) has an actual vapor pressure of only 1.9 mb. When this air is brought indoors and heated to 20°C (68°F), its saturation vapor pressure increases to 23.4 mb—about 12 times what it was outside. Notice in ● Fig. 4.17 that the relative humidity of the heated air inside the



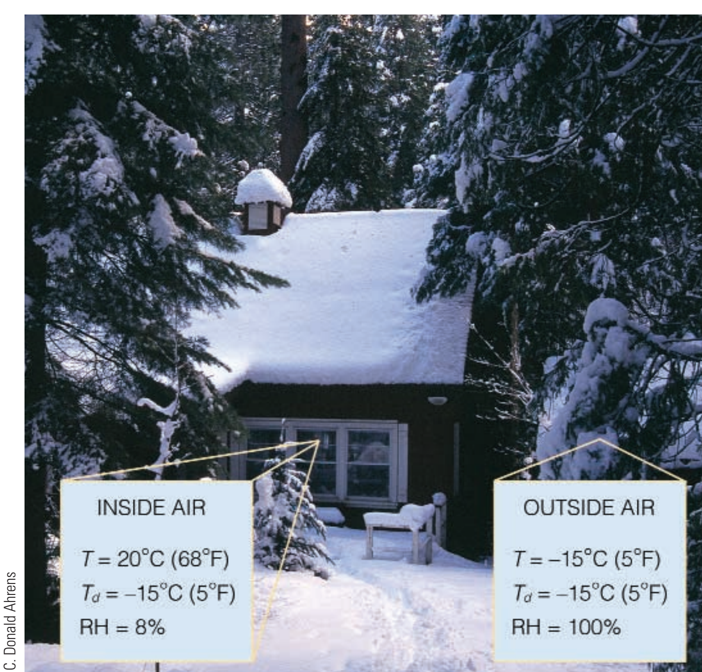
● FIGURE 4.16
Air from the Pacific Ocean is hot and dry over land, whereas air from the Gulf of Mexico is hot and muggy over land. For each city, T represents the air temperature, T_d the dew point, and RH the relative humidity. (All data represent conditions during a July afternoon at 3 P.M. local time.)

house drops to 8 percent.* This relative humidity is lower than what you would normally experience in a desert during the hottest time of the day!

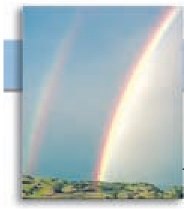
Very low relative humidities in a house can have an adverse effect on things living inside. For example, house plants have a difficult time surviving because the moisture from their leaves and the soil evaporates rapidly. Hence, house plants usually need watering more frequently in winter than in summer. People suffer, too, when the relative humidity is quite low. The rapid evaporation of moisture from exposed flesh causes skin to crack, dry, flake, or itch. These low humidities also irritate the mucous membranes in the nose and throat, producing an "itchy" throat. Similarly, dry nasal passages permit inhaled bacteria to incubate, causing persistent infections. The remedy for most of these problems is simply to increase the relative humidity. But how?

The relative humidity in a home can be increased just by heating water and allowing it to evaporate into the air. The added water vapor raises the relative humidity to a more comfortable level. In modern homes, a humidifier, installed near the furnace, adds moisture to the air at a rate of about one gallon per room per day. The air, with its increased water vapor, is circulated throughout the home by a forced air heating system. In this way, all rooms get their fair share of moisture—not just the room where the vapor is added.

*$RH = \frac{1.9 \text{ mb}}{23.4 \text{ mb}} \times 100\% = 8\%$.



● FIGURE 4.17
When outside air with a dew point of –15°C (5°F) is brought indoors and heated to a temperature of 20°C (68°F) (without adding water vapor to the air), the relative humidity drops to 8 percent, placing adverse stress on plants, animals, and humans living inside. (T represents temperature; T_d, dew point; and RH, relative humidity.)



FOCUS ON
A SPECIAL TOPIC

Computing Relative Humidity and Dew Point

•TABLE 1

Saturation Vapor Pressure Over Water for Various Air Temperatures

AIR TEMPERATURE (°C)	(°F)	SATURATION VAPOR PRESSURE (MB)	AIR TEMPERATURE (°C)	(°F)	SATURATION VAPOR PRESSURE (MB)
−18	(0)	1.5	18	(65)	21.0
−15	(5)	1.9	21	(70)	25.0
−12	(10)	2.4	24	(75)	29.6
−9	(15)	3.0	27	(80)	35.0
−7	(20)	3.7	29	(85)	41.0
−4	(25)	4.6	32	(90)	48.1
−1	(30)	5.6	35	(95)	56.2
2	(35)	6.9	38	(100)	65.6
4	(40)	8.4	41	(105)	76.2
7	(45)	10.2	43	(110)	87.8
10	(50)	12.3	46	(115)	101.4
13	(55)	14.8	49	(120)	116.8
16	(60)	17.7	52	(125)	134.2

Suppose we want to compute the air's relative humidity and dew point from Table 1. Earlier, we learned that relative humidity may be expressed as the actual vapor pressure divided by the saturation vapor pressure times 100 percent. If the actual vapor pressure is designated by the letter *e,* and the saturation vapor pressure by e_s, then the expression for relative humidity becomes

$$\text{RH} = \frac{e}{e_s} \times 100\%.^*$$

Let's look at a practical example of using vapor pressure to measure relative humidity and obtain dew point. Suppose the air temperature in a room is 27°C (80°F). Because the saturation vapor pressure (e_s) is dependent on the temperature of the air, to obtain e_s from Table 1 we simply read the value adjacent to the air temperature much like we did in Fig. 4.10. Hence, air with a temperature of 27°C has a saturation vapor pressure of 35 mb.

Now, suppose that the air in the room is cooled suddenly with no change in moisture content. At successively lower temperatures, the saturation vapor pressure decreases. As the lowering saturation vapor pressure (e_s) approaches the actual vapor pressure (e), the relative humidity increases. With an actual vapor pressure of 25 mb, 100 percent relative humidity will be reached at a temperature of 21°C (70°F). This temperature (21°C) must then be the *dew-point temperature* of the air. If, then, we know the actual vapor pressure in a room, we can determine the dew point by using Table 1 to locate the temperature at which air will be saturated with that amount of vapor. Similarly, if we are told that the dew point in the room has some value, we can look up that temperature in Table 1 and find the actual vapor pressure.

In essence, we can use Table 1 to obtain the saturation vapor pressure (e_s) and the actual vapor pressure (e) if the air temperature and dew point of the air are known. With this information we can calculate relative humidity. For example, what is the relative humidity of air with a temperature of 29°C and a dew point of 18°C? Answer: At 29°C, Table 1 shows $e_s = 41$ mb. For a dew point of 18°C, the actual vapor pressure (e) is 21 mb; therefore, the relative humidity is

$$\text{RH} = \frac{e}{e_s} = \frac{21}{41} \times 100\% = 51\%.$$

If we know the air temperature is 27ºC and the relative humidity is 60 percent, what is the dew-point temperature of the air? From Table 1, an air temperature of 27ºC produces a saturation vapor pressure *(e_s)* of 35 mb. To obtain the actual vapor pressure *(e),* we simply plug the numbers into the formula

$$\text{RH} = \frac{e}{e_s} \times 100\%; \; 60\% = \frac{e}{35}$$

$$e = 21 \text{ mb}$$

As we saw in the previous example, an actual vapor pressure of 21 mb yields a dew-point temperature of 18ºC.

*Relative humidity may also be expressed as RH $= w/w_s \times 100\%$, where w is the actual mixing ratio and w_s is the saturation mixing ratio. Relative humidity computations using mixing ratio and adiabatic charts are given in Chapter 6.

To lower the air's moisture content, as well as the air temperature, many homes are air conditioned. Outside air cools as it passes through a system of cold coils located in the air conditioning unit. The cooling increases the air's relative humidity, and the air reaches saturation. The water vapor condenses into liquid water, which is carried away. The cooler, dehumidified air is now forced into the home.

In hot regions, where the relative humidity is low, *evaporative cooling systems* can be used to cool the air. These systems operate by having a fan blow hot, dry outside air across pads that are saturated with water. Evaporation cools the air, which is forced into the home, bringing some relief from the hot weather.

Evaporative coolers, also known as "swamp coolers," work best when the relative humidity is low and the air is warm. They do not work well in hot, muggy weather because a high relative humidity greatly reduces the rate of evaporation. Besides, swamp coolers add water vapor to the air—something that is not needed when the air is already uncomfortably humid. That is why swamp coolers may be found on homes in Arizona, but not on homes in Alabama.

RELATIVE HUMIDITY AND HUMAN DISCOMFORT On a hot, muggy day when the relative humidity is high, it is common to hear someone exclaim (often in exasperation), "It's not so much the heat, it's the humidity." Actually, this statement is valid. In warm weather, the main source of body cooling is through evaporation of perspiration. Recall from Chapter 2 that evaporation is a cooling process, so when the air temperature is high and the relative humidity low, perspiration on the skin evaporates quickly, often making us feel that the air temperature is lower than it really is. However, when both the air temperature and relative humidity are high and the air is nearly saturated with water vapor, body moisture does not readily evaporate; instead, it collects on the skin as beads of perspiration. Less evaporation means less cooling, and so we usually feel warmer than we did with a similar air temperature, but a lower relative humidity.

A good measure of how cool the skin can become is the **wet-bulb temperature**—the lowest temperature that can be reached by evaporating water into the air. On a hot day when the wet-bulb temperature is low, rapid evaporation (and, hence, cooling) takes place at the skin's surface. As the wet-bulb temperature approaches the air temperature, less cooling occurs, and the skin temperature may begin to rise. When the wet-bulb temperature exceeds the skin's temperature, no net evaporation occurs, and the body temperature can rise quite rapidly. Fortunately, most of the time, the wet-bulb temperature is considerably below the temperature of the skin.

When the weather is hot and muggy, a number of heat-related problems may occur. For example, in hot weather when the human body temperature rises, the *hypothalamus* gland (a gland in the brain that regulates body temperature) activates the body's heat-regulating mechanism, and over ten million sweat glands wet the body with as much as two liters of liquid per hour. As this perspiration evaporates, rapid loss of water and salt can result in a chemical imbalance that may lead to painful *heat cramps.* Excessive water loss through perspiring coupled with an increasing body temperature may result in *heat exhaustion*—fatigue, headache, nausea, and even fainting. If one's body temperature rises above about 41°C (106°F), **heatstroke** can occur, resulting in complete failure of the circulatory functions. If the body temperature continues to rise, death may result. In fact, each year across North America, hundreds of people die from heat-related maladies. Even strong, healthy individuals can succumb to heatstroke, as did the Minnesota Vikings' all-pro offensive lineman, Korey Stringer, who collapsed after practice on July 31, 2001, and died 15 hours later. Before Korey fainted, temperatures on the practice field were in the 90s (°F) with the relative humidity above 55 percent.

WEATHER WATCH

Tragically, many hundreds of people died of heat-related maladies during the great Chicago heat wave of July, 1995. On July 13, the afternoon air temperature reached 104°F. With a dew-point temperature of 76°F and a relative humidity near 40 percent, the apparent temperature soared to 119°F. In a van, with the windows rolled up, two small toddlers fell asleep and an hour later were found dead of heat exhaustion. Estimates are that, on a day like this one, temperatures inside a closed vehicle could approach 190°F within half an hour.

In an effort to draw attention to this serious weather-related health hazard, an index called the **heat index (HI)** is used by the National Weather Service. The index combines air temperature with relative humidity to determine an **apparent temperature**—what the air temperature "feels like" to the average person for various combinations of air temperature and relative humidity. For example, in ● Fig. 4.18, an air temperature of 100°F and a relative humidity of 60 percent produce an apparent temperature of a little over 132°F. Heatstroke or sunstroke is imminent when the index reaches this level. However, as we can see from the preceding paragraph, heatstroke related deaths can occur when the heat index value is considerably lower than 130°F (see ● Table 4.1).

During hot, humid weather some people remark about how "heavy" or how dense the air feels. Is hot, humid air really more dense than hot, dry air? If you are interested in the answer, read the Focus section on p. 101.

MEASURING HUMIDITY One common instrument used to obtain dew point and relative humidity is a **psychrometer,** which consists of two liquid-in-glass thermometers mounted side by side and attached to a piece of metal that has either a handle or chain at one end (see ● Fig. 4.19). The thermometers are exactly alike except that one has a piece of cloth (wick) covering the bulb. The wick-covered thermometer—called the *wet bulb*—is dipped in clean (usually distilled) water, while the other thermometer is kept dry. Both thermometers are ventilated for a few minutes, either by whirling the instrument

• FIGURE 4.18
Air temperature (°F) and relative humidity are combined to determine an apparent temperature or heat index (HI). An air temperature of 95°F with a relative humidity of 55 percent produces an apparent temperature (HI) of 110°F.

Heat Index (or apparent temperature)

Air Temperature (°F) \ Relative Humidity (%)	0	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100
140	125																				
135	120	128																			
130	117	122	131																		
125	111	116	123	131	141																
120	107	111	116	123	130	139	148														
115	103	107	111	115	120	127	135	143	151												
110	99	102	105	108	112	117	123	130	137	143	150										
105	95	97	100	102	105	109	113	118	123	129	135	142	149								
100	91	93	95	97	99	101	104	107	110	115	120	126	132	138	144						
95	87	88	90	91	93	94	96	98	101	104	107	110	114	119	124	130	136				
90	83	84	85	86	87	88	90	91	93	95	96	98	100	102	106	109	113	117	122		
85	78	79	80	81	82	83	84	85	86	87	88	89	90	91	93	95	97	99	102	105	108
80	73	74	75	76	77	77	78	79	79	80	81	81	82	83	85	86	86	87	88	89	91
75	69	69	70	71	72	72	73	73	74	74	75	75	76	76	77	77	78	78	79	79	80
70	64	64	65	65	66	66	67	67	68	68	69	69	70	70	70	70	71	71	71	71	72

• TABLE 4.1
The Heat Index (HI)

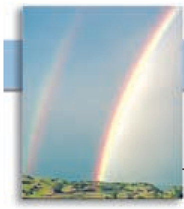
CATEGORY	APPARENT TEMPERATURE (°F)	HEAT SYNDROME
I	130° or higher	Heatstroke or sunstroke *imminent*
II	105°–130°	Sunstroke, heat cramps, or heat exhaustion *likely,* heatstroke *possible* with prolonged exposure and physical activity
III	90°–105°	Sunstroke, heat cramps, and heat exhaustion *possible* with prolonged exposure and physical activity
IV	80°–90°	Fatigue *possible* with prolonged exposure and physical activity

• FIGURE 4.19
The sling psychrometer.

(sling psychrometer), or by drawing air past it with an electric fan *(aspirated psychrometer).* Water evaporates from the wick and the thermometer cools. The drier the air, the greater the amount of evaporation and cooling. After a few minutes, the wick-covered thermometer will cool to the lowest value possible. Recall from an earlier section that this is the *wet-bulb temperature*—the lowest temperature that can be attained by evaporating water into the air.

The dry thermometer (commonly called the *dry bulb*) gives the current air temperature, or *dry-bulb temperature.* The temperature difference between the dry bulb and the wet bulb is known as the *wet-bulb depression.* A large depression indicates that a great deal of water can evaporate into the air and that the relative humidity is low. A small depression indicates that little evaporation of water vapor is possible, so the air is close to saturation and the relative humidity is high. If there is no depression, the dry bulb, the wet bulb, and the dew point are the same; the air is saturated and the relative humidity is 100 percent. (Tables used to compute relative humidity and dew point are given at the back of the book in Appendix D.)

Instruments that measure humidity are commonly called **hygrometers.** One type—called the **hair hygrometer**—is constructed on the principle that the length of human hair increases by 2.5 percent as the relative humidity increases from 0 to 100 percent. This instrument uses human (or horse) hair to measure relative humidity. A number of strands of hair (with oils removed) are attached to a system of levers. A small change in hair length is magnified by a linkage system and transmitted to a dial (see • Fig. 4.20) calibrated to show relative humidity, which can then be read directly or recorded on a chart. (Often, the chart is attached to a clock-driven rotating drum that gives a continuous record of relative humidity.) Because the hair



FOCUS ON
A SPECIAL TOPIC

Is Humid Air “Heavier” Than Dry Air?

• TABLE 2

GAS	WEIGHT		NUMBER OF ATOMS		MOLECULAR WEIGHT		PERCENT BY VOLUME
Oxygen	16	×	2	=	32	×	21% ≈ 7
Nitrogen	14	×	2	=	28	×	78% ≈ 22
					Molecular weight of dry air ≈ 29		

Does a volume of hot, humid air weigh more than a similar size volume of hot, dry air? The answer is no! At the same temperature and at the same level, humid air weighs *less* than dry air. (Keep in mind that we are referring strictly to water vapor—a gas—and not suspended liquid droplets.) To understand why, we must first see what determines the weight of atoms and molecules.

Almost all of the weight of an atom is concentrated in its nucleus, where the protons and neutrons are found. Neutrons weigh nearly the same as protons. To get some idea of how heavy an atom is, we simply add up the number of protons and neutrons in the nucleus. (Electrons are so light that we ignore them in comparing weights.) The larger this total, the heavier the atom. Now, we can compare one atom’s weight with another’s. For example, hydrogen, the lightest known atom, has only 1 proton in its center (no neutrons). Thus, it has an *atomic weight* of 1. Nitrogen, with 7 protons and 7 neutrons in its nucleus, has an atomic weight of 14. Oxygen, with 8 protons and 8 neutrons, weighs in at 16.

A molecule’s weight is the sum of the atomic weights of its atoms. For example, molecular oxygen, with two oxygen atoms (O_2), has a molecular weight of 32. The most abundant atmospheric gas, molecular nitrogen (N_2), has a molecular weight of 28.

When we determine the weight of air, we are dealing with the weight of a mixture. As you might expect, a mixture’s weight is a little more complex. We cannot just add the weights of all its atoms and molecules because the mixture might contain more of one kind than another. Air, for example, has far more nitrogen (78 percent) than oxygen (21 percent). We allow for this by multiplying the molecule’s weight by its share in the mixture. Since dry air is essentially composed of N_2 and O_2 (99 percent), we ignore the other parts of air for the rough average shown in Table 2.

The symbol ≈ means “is approximately equal to.” Therefore, dry air has a molecular weight of about 29. How does this compare with humid air?

Water vapor is composed of two atoms of hydrogen and one atom of oxygen (H_2O). It is an invisible gas, just as oxygen and nitrogen are invisible. It has a molecular weight; its two atoms of hydrogen (each with atomic weight of 1) and one atom of oxygen (atomic weight 16) give water vapor a molecular weight of 18. Obviously, air, at nearly 29, weighs appreciably more than water vapor.

Suppose we take a given volume of completely dry air and weigh it, then take exactly the same amount of water vapor at the same temperature and weigh it. We will find that the dry air weighs slightly more. If we replace dry air molecules one for one with water vapor molecules, the total number of molecules remains the same, but the total weight of the drier air decreases. Since density is mass per unit volume, *hot, humid air at the surface is less dense (lighter) than hot dry air.*

This fact can have an important influence on our weather. The lighter the air becomes, the more likely it is to rise. All other factors being equal, hot, humid (less dense) air will rise more readily than hot, dry (more dense) air. It is of course the water vapor in the rising air that changes into liquid cloud droplets and ice crystals, which, in turn, grow large enough to fall to the earth as precipitation.

Of lesser importance to weather but of greater importance to sports is the fact that a baseball will “carry” farther in less-dense air. Consequently, without the influence of wind, a ball will travel slightly farther on a hot, humid day than it will on a hot, dry day. So when the sports announcer proclaims “the air today is heavy because of the high humidity” remember that this statement is not true and, in fact, a 404-foot home run on this humid day might simply be a 400-foot out on a very dry day.

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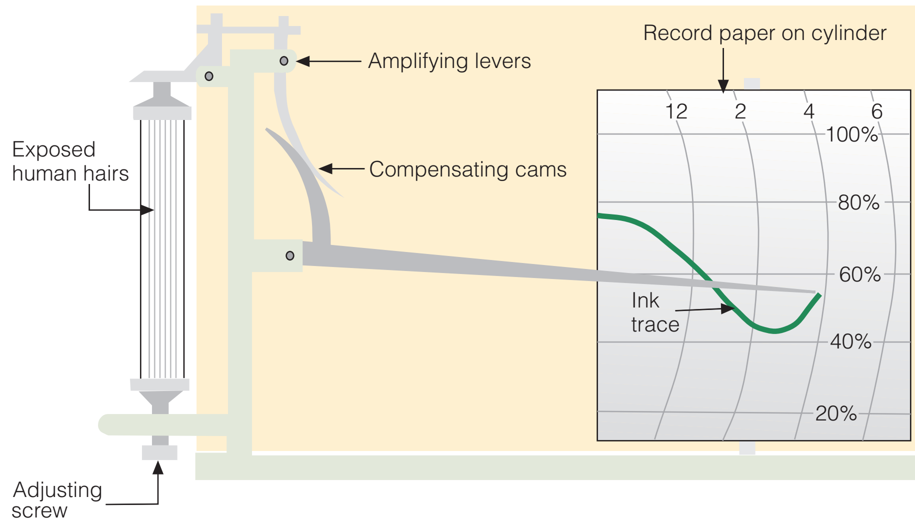
• FIGURE 2
A hot, humid summer day in Maryland. Is the air more dense or less dense than on a day when the air temperature is the same, but the air is much less humid?



● FIGURE 4.20
The hair hygrometer measures relative humidity by amplifying and measuring changes in the length of human (or horse) hair.

WEATHER WATCH

In hot, muggy weather, people with naturally curly hair often experience the "frizzies" as their hair increases in length. People with long, straight hair often experience a bad hair day as their hair goes "limp" in the hot, humid weather.

hygrometer is not as accurate as the psychrometer (especially at very high and very low relative humidities and very low temperatures), it requires frequent calibration, principally in areas that experience large daily variations in relative humidity.

The *electrical hygrometer* is another instrument that measures humidity. It consists of a flat plate coated with a film of carbon. An electric current is sent across the plate. As water vapor is absorbed, the electrical resistance of the carbon coating changes. These changes are translated into relative humidity. This instrument is commonly used in the radiosonde, which gathers atmospheric data at various levels above the earth. Still another instrument—the *infrared hygrometer*—measures atmospheric humidity by measuring the amount of infrared energy absorbed by water vapor in a sample of air. The *dew-point hygrometer* measures the dew-point temperature by cooling the surface of a mirror until condensation (dew) forms. This sensor is the type that measures dew-point temperature in the hundreds of fully automated weather stations—Automated Surface Observing System (ASOS)—that exist throughout the United States. Finally, the *dew cell* determines the amount of water vapor in the air by measuring the air's actual vapor pressure.

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Summary

This chapter examines water vapor in the atmosphere. It begins by looking at the different phases of water and how water circulates throughout our atmosphere. It then looks at the many ways of describing the amount of water vapor in the air. Here we learn that there are many ways of describing humidity. The absolute humidity represents the density of water vapor in a given volume of air. Specific humidity measures the mass of water vapor in a fixed mass of air, while the mixing ratio expresses humidity as the mass of water vapor in the fixed mass of remaining dry air. The actual vapor pressure indicates the air's total water vapor content by expressing the amount of water vapor in terms of the amount of pressure that the water vapor molecules exert. The saturation vapor pressure describes how much water vapor the air could hold at any given temperature in terms of how much pressure the water vapor molecules would exert if the air were saturated at that temperature. A good indicator of the air's actual water vapor content is the dew point—the temperature to which air would have to be cooled (at constant pressure) for saturation to occur.

Relative humidity is a measure of how close the air is to being saturated. Air with a high relative humidity does not necessarily contain a great deal of water vapor; it is simply close to being saturated. With a constant water-vapor content, cooling the air causes the relative humidity to increase, while warming the air causes the relative humidity to decrease. When the air temperature and dew point are close together, the relative humidity is high, and, when they are far apart, the relative humidity is low. High relative humidity in hot weather makes us feel hotter than it really is by retarding the evaporation of perspiration. Although relative humidity can be confusing (because it can change with either air temperature or moisture content), it is nevertheless the most widely used way of describing the air's moisture content.

The chapter concludes by examining the various instruments that measure humidity, such as the psychrometer and hair hygrometer.

Key Terms

The following terms are listed in the order they appear in the text. Define each. Doing so will aid you in reviewing the material covered in this chapter.

Questions for Review

1. Basically, how do the three states of water differ?
2. What are the primary factors that influence evaporation?
3. Explain why condensation occurs primarily when the air is cooled.
4. How are evaporation and condensation related to saturated air above a flat water surface?
5. How does condensation differ from precipitation?
6. Why are specific humidity and mixing ratio more commonly used in representing atmospheric moisture than absolute humidity? What is the only way to change the specific humidity or mixing ratio of an air parcel?
7. In a volume of air, how does the actual vapor pressure differ from the saturation vapor pressure? When are they the same?
8. What does saturation vapor pressure primarily depend upon?
9. Explain why it takes longer to cook vegetables in the mountains than at sea level.
10. (a) What does the relative humidity represent?
    (b) When the relative humidity is given, why is it also important to know the air temperature?
    (c) Explain two ways the relative humidity may be changed.
11. Explain why, during a summer day, the relative humidity will change as shown in Fig. 4.12, p. 93.
12. Why do hot and humid summer days usually feel hotter than hot and dry summer days?
13. Why is the wet-bulb temperature a good measure of how cool human skin can become?
14. Explain why the air on a hot humid day is less dense than on a hot dry day.
15. (a) What is the dew-point temperature?
    (b) How is the difference between dew point and air temperature related to the relative humidity?
16. Why is cold polar air described as "dry" when the relative humidity of that air is very high?
17. How can a region have a high specific humidity and a low relative humidity? Give an example.
18. Why is the air from the Gulf of Mexico so much more humid than air from the Pacific Ocean at the same latitude?
19. How are the dew-point temperature and wet-bulb temperature different? Can they ever read the same? Explain.
20. When outside air is brought indoors on a cold winter day, the relative humidity of the heated air inside often drops below 25 percent. Explain why this situation occurs.
21. Describe how a sling psychrometer works. What does it measure? Does it give you dew point and relative humidity? Explain.
22. Why are human hairs often used in a hair hygrometer?

Questions for Thought

1. Would you expect water in a glass to evaporate more quickly on a windy, warm, dry summer day or on a calm, cold, dry winter day? Explain.
2. How can frozen clothes "dry" outside in subfreezing weather? What exactly is taking place?
3. Explain how and why each of the following will change as a parcel of air with an unchanging amount of water vapor rises, expands, and cools: (a) absolute humidity; (b) relative humidity; (c) actual vapor pressure; and (d) saturation vapor pressure.
4. Where in the United States would you go to experience the *least* variation in dew point (actual moisture content) from January to July?
5. After completing a grueling semester of meteorological course work, you call your travel agent to arrange a much-needed summer vacation. When your agent suggests a trip to the desert, you decline because of a concern that the dry air will make your skin feel uncomfortable. The travel agent assures you that almost daily "desert relative humidities are above 90 percent." Could the agent be correct? Explain.
6. On a clear, calm morning, water condenses on the ground in a thick layer of dew. As the water slowly evaporates into

the air, you measure a slow increase in dew point. Explain why.

7. Two cities have exactly the same amount of water vapor in the air. The 6:00 A.M. relative humidity in one city is 93 percent, while the 3:00 P.M. relative humidity in the other city is 28 percent. Explain how this can come about.
8. Suppose the dew point of cold outside air is the same as the dew point of warm air indoors. If the door is opened, and cold air replaces some of the warm inside air, would the new relative humidity indoors be (a) lower than before, (b) higher than before, or (c) the same as before? Explain your answer.
9. On a warm, muggy day, the air is described as "close." What are several plausible explanations for this expression?
10. Outside, on a very warm day, you swing a sling psychrometer for about a minute and read a dry-bulb temperature of 38°C and a wet-bulb temperature of 24°C. After swinging the instrument again, the dry bulb is still 38°C, but the wet bulb is now 26°C. Explain how this could happen.
11. Why are evaporative coolers used in Arizona, Nevada, and California but not in Florida, Georgia, or Indiana?
12. Devise a way of determining elevation above sea level if all you have is a thermometer and a pot of water.
13. A large family lives in northern Minnesota. This family gets together for a huge dinner three times a year: on Thanksgiving, on Christmas, and on the March solstice. The Thanksgiving and Christmas dinners consist of turkey, ham, mashed potatoes, and lots of boiled vegetables. The solstice dinner is pizza. The air temperature inside the home is about the same for all three meals (70°F), yet everyone remarks about how "warm, cozy, and comfortable" the air feels during the Thanksgiving and Christmas dinners, and how "cool" the inside air feels during the solstice meal. Explain to the family members why they might feel "warmer" inside the house during Thanksgiving and Christmas, and "cooler" during the March solstice. (The answer has nothing to do with the amount or type of food consumed.)

Problems and Exercises

1. On a bitter cold, snowy morning, the air temperature and dew point of the outside air are both −7°C. If this air is brought indoors and warmed to 21°C, with no change in vapor content, what is the relative humidity of the air inside the home? (Hint: See Table 1, p. 98 and the formula on the same page.)
2. (a) With the aid of Fig. 4.13b, p. 94, determine the average July dew points in St. Louis, Missouri; New Orleans, Louisiana; and Los Angeles, California.
   (b) If the high temperature on a particular summer day in all three cities is 32°C (90°F), then calculate the afternoon relative humidity at each of the three cities. (Hint: Either Fig. 4.10, p. 91, or Table 1, p. 98, will be helpful.)
3. Suppose with the aid of a sling psychrometer you obtain an air temperature of 30°C and a wet-bulb temperature of 25°C. What is (a) the wet-bulb depression, (b) the dew point, and (c) the relative humidity of the air? (Use the tables in Appendix D at the back of the book.)
4. If the air temperature is 35°C and the dew point is 21°C, determine the relative humidity using (a) Table 1, p. 98; (b) Fig. 4.10, p. 91; and (c) Tables D.1 and D.2 in Appendix D.
5. Suppose the average vapor pressure in Nevada is about 8 mb.
   (a) Use Table 1, p. 98, to determine the average dew point of this air.
   (b) Much of the state is above an elevation of 1500 m (5000 ft). At 1500 m, the normal pressure is about 12.5 percent less than at sea level. If the air over Nevada were brought down to sea level, without any change in vapor content, what would be the new vapor pressure of the air?
6. In Yellowstone National Park, there are numerous ponds of boiling water. If Yellowstone is about 2200 m (7200 ft) above sea level (where the air pressure is normally about 775 mb), what is the normal boiling point of water in Yellowstone? (Hint: See Fig. 1, p. 92.)
7. Three cities have the following temperature (T) and dew point (T_d) during a July afternoon:
   Atlanta, Georgia, $T = 90°F$; $T_d = 75°F$
   Baltimore, Maryland, $T = 80°F$; $T_d = 70°F$
   Norman, Oklahoma, $T = 70°F$; $T_d = 65°F$
   (a) Which city appears to have the highest relative humidity?
   (b) Which city appears to have the lowest relative humidity?
   (c) Which city has the *most* water vapor in the air?
   (d) Which city has the *least* water vapor in the air?
   (e) For each city use Table 1 on p. 98 and the information on the same page to calculate the relative humidity for each city.
   (f) Using both the relative humidity calculated in (e) and the air temperature, determine the heat index for each city using Fig. 4.18 on p. 100.

Questions for Exploration

At MeteorologyNow™, go to Meteorology Interactive, select **Atmospheric Moisture and Stability** and click on **Moisture Graph.**

1. Using the current temperature and dew point in your location, investigate the vapor pressure, saturation vapor pressure, and relative humidity. (a) What is the amount of vapor pressure the atmosphere could hold at this temperature? (b) How much vapor pressure actually exists at the moment? (c) What is the relative humidity?
2. If your temperature rises 5°C without the addition of any more water vapor (i.e., the dew-point temperature remains constant) what will be the resulting relative humidity?
3. At MeteorologyNow™, go to Meteorology Interactive, select **Atmospheric Moisture and Stability** and click on **Moisture Graph** to answer the following questions:
   (a) If the temperature is 30°C, what must the dew-point temperature be to obtain a relative humidity of 90 percent?
   (b) If the dew-point temperature in part (a) decreases to 20°C, what is the resulting relative humidity?
   (c) At what temperature does a 20°C dew-point temperature result in 90 percent relative humidity?