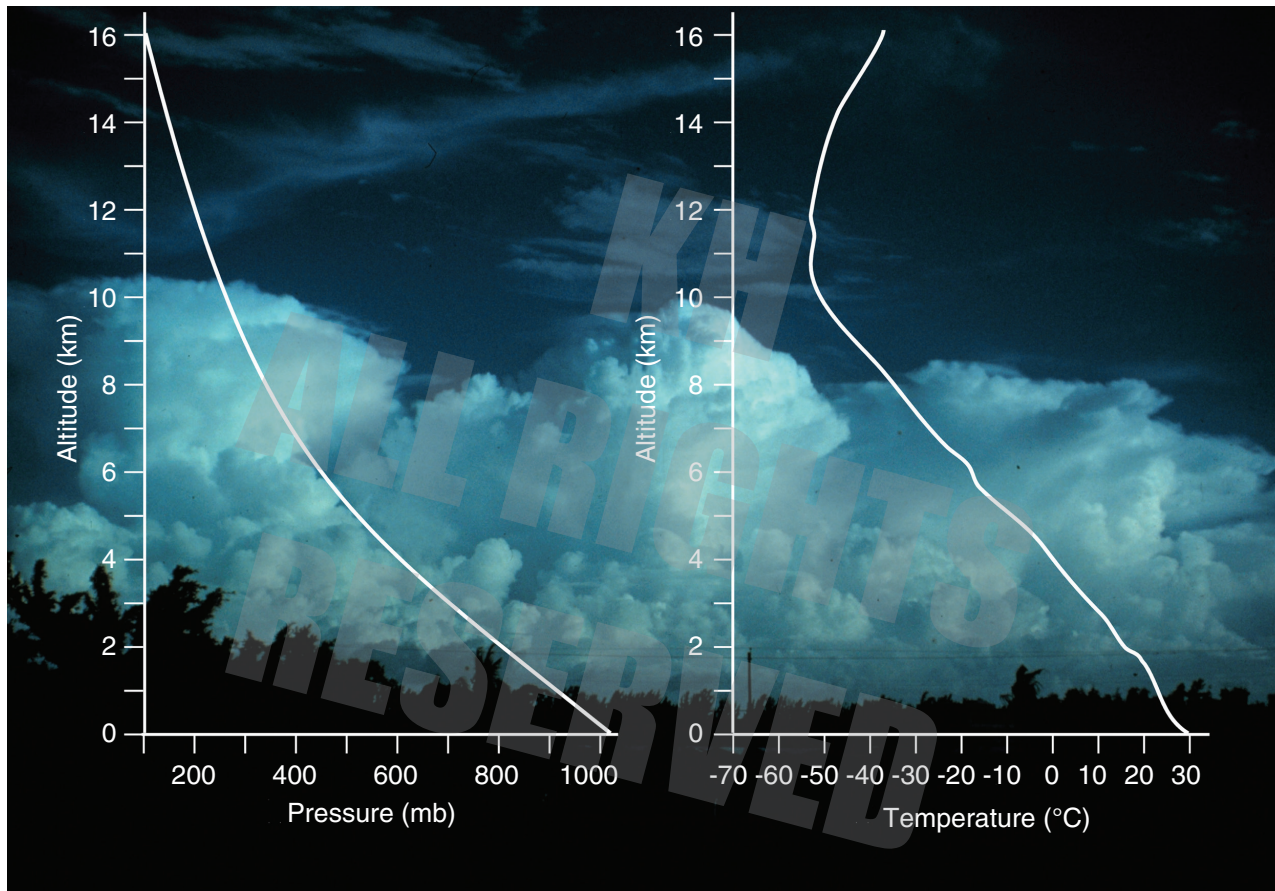


Chapter 1

Properties of the Atmosphere



Courtesy of NOAA.

Idealized change in pressure and temperature with altitude in the environment of an approaching thunderstorm.

Key Words

absolute zero	cirrostratus	dewpoint temperature	heating degree-day
aerosol	cirrus	evaporation	hurricane
altocumulus	cloud droplet	extratropical cyclone	ice nuclei
altostratus	condensation	Fahrenheit scale	ice pellet
anemometer	cooling degree-day	freezing	Kelvin scale
barometer	cumulonimbus	general circulation	latent heat
Celsius scale	cumulus	graupel	mean sea-level
centigrade scale	density	hail	mean sea-level pressure
cirrocumulus	deposition	haze droplets	melting

mesosphere	relative humidity	subtropical jet stream	tropopause
millibar	saturation	supercooled	tropopause fold
nimbostratus	saturation vapor pressure	supercooled water	troposphere
nimbus	sea-level pressure	temperature	vapor pressure
ozone	snow	thermistor	water vapor
phase change	snowflake	thermometer	wind
polar jet stream	stratosphere	thermosphere	wind barb
pressure	stratus	thunderstorm	
raindrop	sublimation	tornado	

Learning Objectives

After studying this chapter, you should be able to:

1. interpret the different temperature scales, and convert between them,
2. describe how temperature changes as one rises above the Earth's surface,
3. explain why atmospheric temperature varies across the Earth and in the vertical,
4. identify different units of pressure and understand how pressure varies with altitude,
5. explain the meaning of sea-level pressure,
6. identify what types of particles compose clouds,
7. differentiate between vapor pressure and saturation vapor pressure,
8. demonstrate an understanding of relative humidity,
9. explain the release and consumption of latent heat during phase changes using everyday examples of boiling water or freezing water into ice, and
10. interpret wind speed and direction using wind barbs.

The atmosphere is a thin layer of air extending from the earth's surface to a height of a few hundred kilometers. Ninety percent of the atmosphere's mass, and all of its weather, is confined to a layer extending from the ground and to a height of about 12 km (7.5 miles). The layer of the atmosphere where weather occurs is indeed a thin layer—about five times the length of San Francisco's Golden Gate Bridge. At highway speeds, it would only take 7 minutes to drive through this layer (if roads went straight up!).

The atmosphere is composed of different types of molecules. If we exclude water

vapor, the atmosphere primarily is made up of two gases: nitrogen (78%) and oxygen (21%). Other gases, which include carbon dioxide, ozone, hydrocarbons, and argon, make up the remaining percentage. The component of the atmosphere most important to weather is water, which can be present as a gas (**water vapor**), a liquid (**haze droplets**, **cloud droplets**, and **raindrops**), or a solid (**snow**, **ice pellets**, and **hail**). The atmosphere also contains large numbers of invisible tiny particles called **aerosols**.

We describe the atmosphere in terms of its properties. These include basic properties, such

as temperature, pressure, moisture content, wind speed, and direction, and other observable properties, such as visibility, cloud cover, and precipitation rate. These properties are measured and reported continuously worldwide by a network of instrumentation that has become increasingly complex with advances in technology. Meteorologists depict the measurements on weather maps to condense and more easily interpret the enormous quantity of weather data. In this chapter, we examine the basic properties of the atmosphere.

Temperature

We all have an intuitive feeling for temperature because our bodies feel hot and cold sensations. What is **temperature**? From a scientific viewpoint, temperature is a measure of the average speed that molecules move in a substance. In a solid, molecules vibrate in place, faster for higher temperatures and slower for lower temperatures. In a liquid, molecules remain in contact with one another, but move freely about; again, they vibrate faster for higher temperatures and slower for lower temperatures. In the air, individual molecules move around rapidly (hundreds of kilometers per hour!) in random directions continuously bouncing off each other. The faster the average speed of the molecules, the higher the temperature will be. When substances with different temperatures come in contact, energy associated with the vibration or movement of the molecules will be transferred from the substance with a higher temperature to the substance with a lower temperature. The average speed of the molecules will increase in the colder substance and decrease in the warmer substance. When energy transfer no longer occurs, the substances are at the same temperature.

A **thermometer**, or an electronic device called a **thermistor**, measures temperature. In the United States, temperature is commonly measured using the **Fahrenheit scale**, devised by Gabriel Daniel Fahrenheit (1686–1736). The range 0°F to 100°F spans the common

temperatures experienced outdoors—0°F being a very cold day in winter and 100°F being a very hot day in summer. Of course, air temperatures can be much colder; in the continental United States, wintertime extremes fall below –20°F and temperatures in the Antarctic fall below –100°F.

A second scale, called the **centigrade scale**, or **Celsius scale** after its developer Anders Celsius (1701–1744), is used in all countries except the United States. The Celsius scale is based on the boiling point of water and the melting point of ice. Celsius devised a scale such that the boiling point of water (at sea-level pressure) was 100°C (212°F) and the melting point of ice was 0°C (32°F).

Recall that temperature is related to the energy of motion of molecules. Imagine a situation where we continually remove energy from a substance. Eventually, the molecules will slow down to a point where they are essentially not moving and no more energy can be extracted. William Thomson (1824–1907), who later received the title Lord Kelvin, first devised a temperature scale where zero was set at this minimum energy state. **Absolute zero**, or zero on the **Kelvin scale**, occurs at –459.67°F (–273.15°C). Figure 1.1 compares the Kelvin, Celsius, and Fahrenheit temperature scales, shows some common and extreme values observed at different locations on the earth, and provides a table and simple formulas to convert between the three scales. In the United States, the Fahrenheit scale is used for surface temperatures, the Celsius scale for upper atmospheric temperatures, and the Kelvin scale for scientific applications. In other parts of the world, the Celsius scale is used for surface temperatures as well as upper atmospheric temperatures. In this book, we will use both Fahrenheit and Celsius temperatures.

Temperature varies every day as the sun rises and sets, and from season to season as the sun moves higher or lower in the sky. These temperature variations drive the weather, which we will see later.

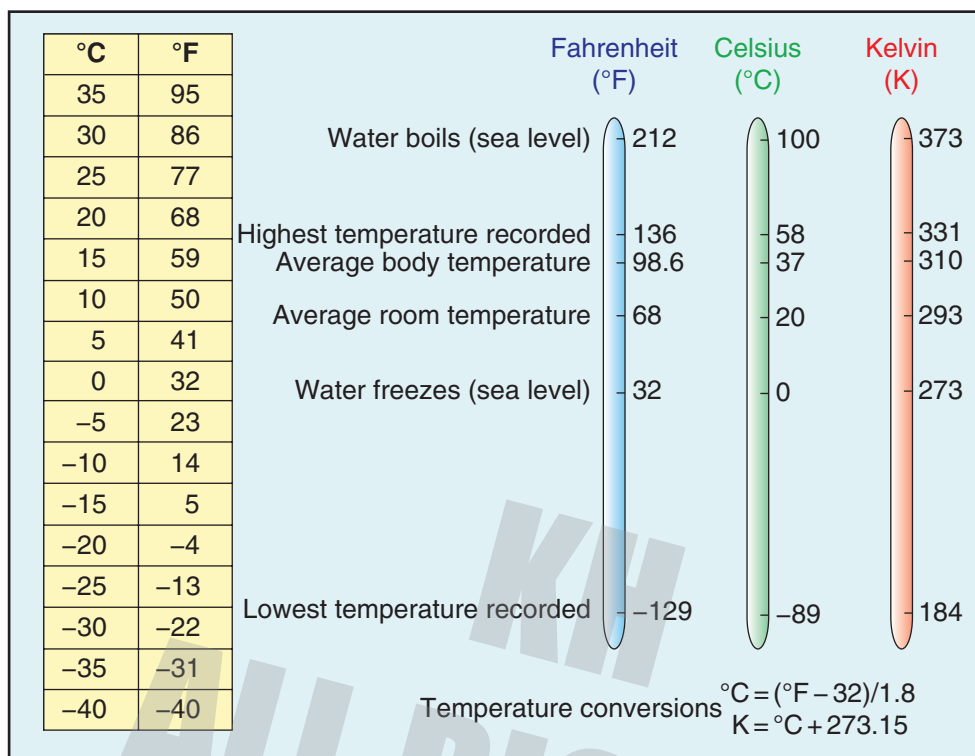


Figure 1.1 Examples of common and extreme temperatures observed on Earth as expressed on the Fahrenheit, Celsius, and Kelvin temperature scales. Formulas to convert between scales and a table of common Celsius temperatures and their Fahrenheit counterparts are also shown.



FUN FACT

Degree-days—A Measure of Energy Consumption

The energy required to heat or cool buildings is largely determined by outdoor air temperature. To estimate energy consumption for heating and cooling, power companies use a concept called a **heating degree-day** and a **cooling degree-day**. A degree-day is a unit and should not be confused with a calendar day. There can be more than one degree-day in a 24-hour period. Heating degree-days are defined as 65 minus the average of a day's high and low air temperature. For example, if a city's high was 40°F and low was 20°F, the number of heating degree-days for that day would be $65 - (40+20)/2 = 35$. If the average of the day's high and low temperatures exceeds 65, it is assumed that heating is not required and the city has no heating degree-days for that day. Cooling degree-days are the average

of a day's high and low Fahrenheit temperature minus 65. For example, if the city's high was 80°F and low was 60°F, the number of cooling degree days would be $(80+60)/2 - 65 = 5$. If the average temperature is below 65, the cooling degree-days for that day would be zero. The number of degree-days is summed up over all days in a heating season (typically, October–April) or a cooling season (typically, May–September) to obtain the season's total energy requirement.

The oceans have a moderating influence on temperature—the seasonal change of temperature over the oceans is much smaller than that over the interior continent. As a result, the energy required to heat and cool homes is much greater in the continental interior compared to the coasts. This is particularly true on the West Coast, where air arriving at the coast has more moderate temperatures than that over land. The difference between

continued

coasts and the interior continent is evident in the seasonal totals of heating and cooling degree-days. For example, in Omaha, Nebraska, the average annual number of heating degree-days (6300) is more than double that of San Francisco, California (3016). The average number of cooling degree-days in Omaha (1072) is over seven times that of San Francisco (145). The East Coast does not differ

as much from the interior because air arriving at the East Coast often flows off the continent. Nevertheless, the values of heating and cooling degree-days at Atlantic City, New Jersey (4728 and 824, respectively) are still well below those of Omaha. As a result, people in Omaha spend a lot more for energy to heat and cool their homes than people who reside on the coasts.

Temperature normally decreases rapidly upward away from the earth's surface. At the altitude where commercial jets fly, about 10–12 km (6–7 miles), temperatures are typically between -40°C (-40°F) and -50°C (-58°F). Figure 1.2 shows an average vertical profile of temperature from the earth's surface to space. Temperature decreases with height from the surface to an altitude of about 12 km (7 miles). Then something remarkable happens—above about 12 km, the temperature increases with height. The temperature begins to decrease again only above an altitude of about 50 km (31 miles). Temperature increases once again near the fringes of outer space.

Examine Figure 1.2 closely. Notice that the atmosphere can be divided into four layers based on the changing temperature. The layer of air in the lower atmosphere where temperature decreases with height is called the **troposphere**. For practical purposes, all weather that develops on Earth occurs in the troposphere. The layer of air above the troposphere where temperature increases with height is called the **stratosphere**. The boundary between these two layers is called the **tropopause**. Temperature increases with height in the stratosphere because of the absorption of ultraviolet radiation by **ozone** in that layer. The stratosphere has a very important effect on the earth's weather. While storms can grow vertically in the troposphere, they cannot penetrate far, if at all, into the stratosphere. We will examine the reasons why storms are limited to the troposphere when we study atmospheric stability in Chapter 6.

The tropopause can be thought of as a lid on the earth's weather. In essence, the tropopause prevents vertical air currents (typically associated with clouds and storms) from moving into the stratosphere. As shown in Figure 1.3, the tropopause slopes downward from the tropics to the poles. In the tropical regions, the tropopause occurs at an altitude from about 16 to 18 km (~10–11 miles). In the middle latitudes, the tropopause is typically at an altitude of 11–13 km (~7–8 miles); whereas at polar latitudes, the tropopause is found at altitudes as low as 8 km (~4–5 miles). Because the tropopause is higher in the tropics, tropical storms grow to greater heights than storms that form in middle latitudes and polar regions.

Two jet streams, the **subtropical jet stream** and the **polar jet stream**, circle the globe at latitudes of about 25° and 50° . These rivers of fast-moving air in the upper troposphere are critical to the development of the earth's weather systems. Just north of each of these jet streams, air from the stratosphere often descends in a narrow zone, leading to “folds” in the tropopause as depicted on Figure 1.3. A **tropopause fold** is one way in which air in the stratosphere mixes with air in the troposphere. We will learn more about jet streams and their importance to hazardous weather in Chapters 7 and 8.

The two additional layers of the atmosphere located at higher altitudes (see Figure 1.2) are the **mesosphere** (where temperature again decreases with height) and the **thermosphere** (where temperature increases with height). Although the mesosphere and thermosphere

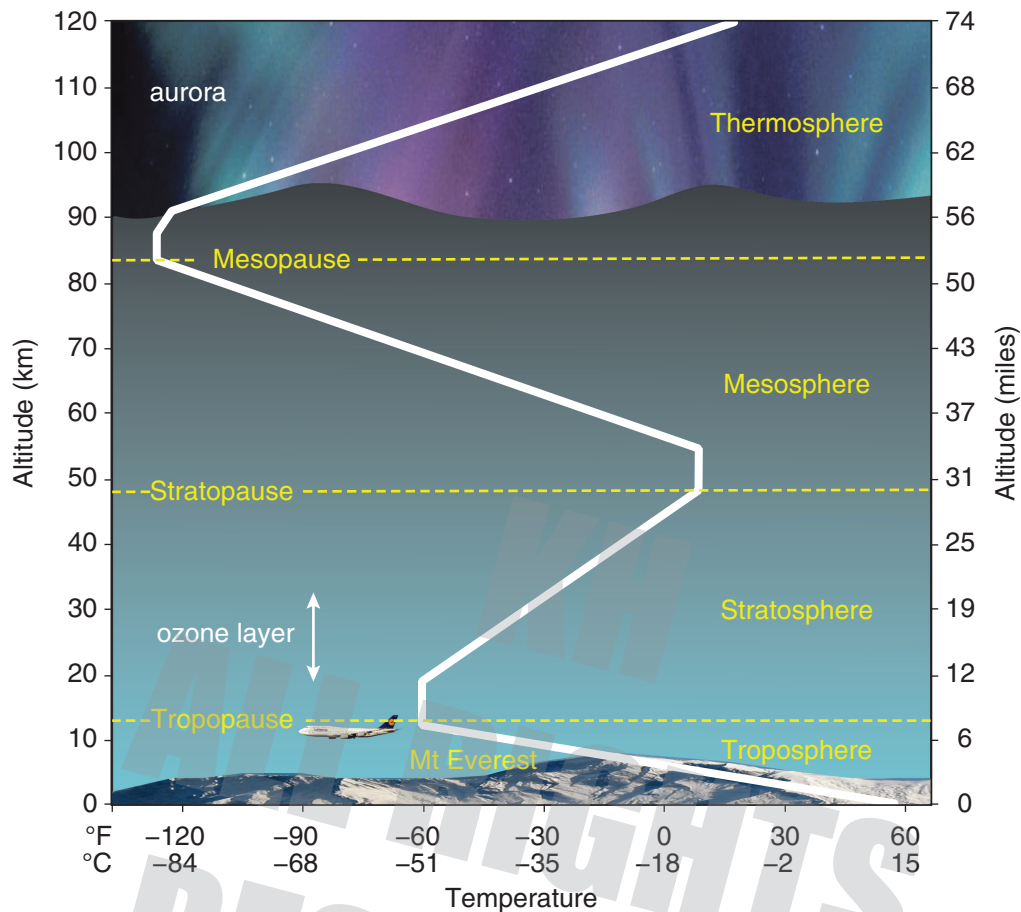


Figure 1.2 The global, annual average vertical variation of atmospheric temperature with altitude.

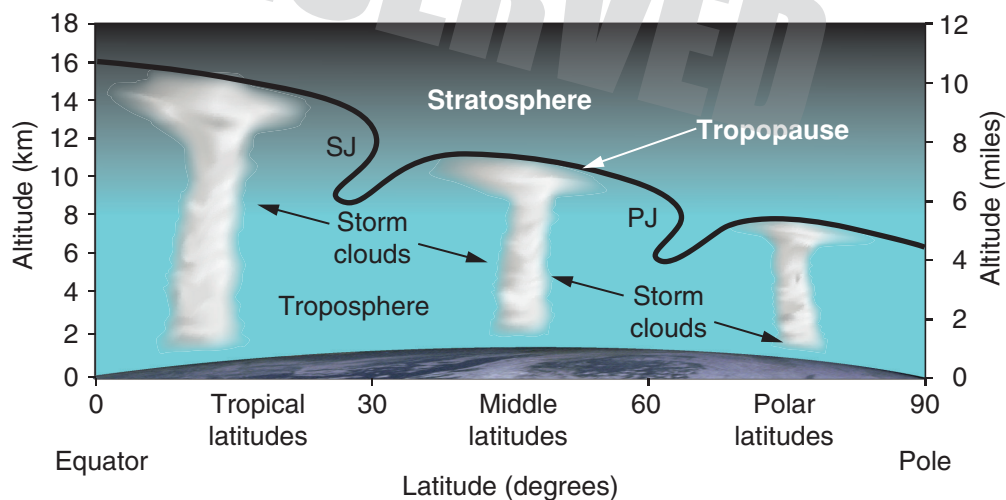


Figure 1.3 The annual average depth of the troposphere between the equator and the pole. The depth of storm clouds is limited to the height of the tropopause. The tropopause is located at higher altitudes in the tropics and lower altitudes in the polar regions. The labels SJ and PJ denote the positions of the subtropical jet stream and the polar jet stream, respectively. Stratospheric air sometimes descends on the poleward side of these jet streams leading to folds in the tropopause.

have no significant impact on Earth's weather, molecules within these layers intercept high-energy solar particles and radiation. These are the layers in which brilliant auroras occur over the polar latitudes (Figure 1.2).



Check Your Understanding 1.1

1. How is temperature defined? What temperature units are used in meteorology in the United States?
2. How does the magnitude of air temperature change with height in the troposphere and the stratosphere?
3. What is the tropopause?
4. How does the altitude of the tropopause influence the height of clouds in the troposphere?

Pressure

Atmospheric **pressure** is the force applied by air on a unit area of surface. To understand pressure, think of a wall with air on one side. Each air molecule that strikes the wall will impart a force on the wall. If we divide the wall into unit areas (e.g., square centimeters, square inches),

then the force applied per unit area will be the force applied by all of the molecules that strike the wall over a unit area.

A way of thinking about pressure, one that we will use extensively in this book, is to consider the “weight” of a column of the atmosphere above a unit area of surface. Let's suppose we choose a square inch of the earth's surface at sea level. How much does a column of air weigh above the square inch if we extend our imaginary column from sea level all the way to the top of the atmosphere, as shown for New York City in Figure 1.4? The answer will depend on when we choose to make the measurement; on average, we will find that at sea level the air in the column weighs 14.7 lb. The pressure applied on that square inch of surface is 14.7 lb/in². This value is called “average **sea-level pressure**.” This fact leads us to our first very important concept about pressure: *Pressure is equivalent to the weight of a column of air above a unit area.* Let's look at some examples.

Returning to Figure 1.4, we see a profile of the topography across the United States, with a few locations identified along with

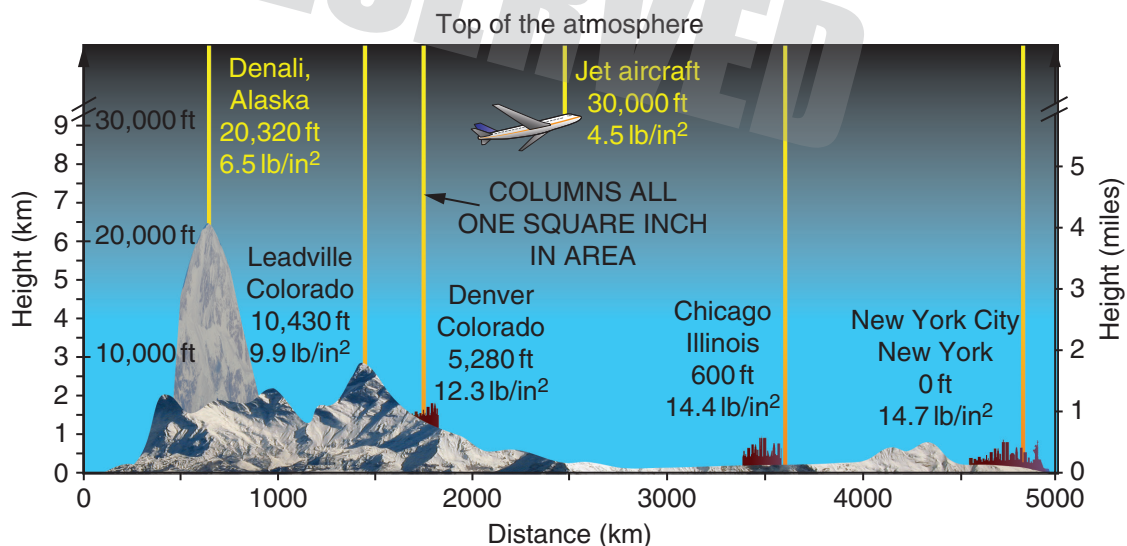


Figure 1.4 Columns of air of horizontal dimensions one square inch extending from the surface to the top of the atmosphere over locations at different elevations across the United States. The amount of air and average weight of the air in each column differs, with locations at the highest elevations having the least air in the columns, and consequently, the lowest surface pressure.

their elevation. The higher the elevation at a particular location, the lower the atmospheric pressure that location will experience. As we noted, above one square inch in New York City, which is at sea level, a column of atmosphere weighs 14.7 lb. and the pressure in New York is 14.7 lb/in². Chicago is about 600 ft above sea level. Chicago is a little closer to the top of the atmosphere than New York and, therefore, has fewer air molecules in its column. The air column, on average, weighs 14.4 lb, and the pressure in Chicago is 14.4 lb/in². Denver is 5280 ft above sea level, and the pressure there is 12.3 lb/in². At Leadville, Colorado, which is 10,430 ft above sea level, the pressure is 9.9 lb/in². In Alaska, at the top of Denali (formerly Mt. McKinley, 20,320 ft), the pressure is 6.5 lb/in². At 30,000 ft, the altitude that commercial aircraft fly, the air pressure is only 4.5 lb/in². At this altitude, you would have to take three breaths to receive the same amount of oxygen that one breath would supply at sea level. The English unit of lb/in² is rarely used in meteorology. Equivalent metric units are dynes/centimeter² and newtons/meter². The latter unit is called a Pascal. Meteorologists use a special unit called a **millibar**, which we will abbreviate *mb*. A millibar is equivalent to 1000 dynes/cm² or to a hectopascal (100 Pascals).

Average atmospheric pressure at sea level is 1013.25 mb. This pressure is also called **mean sea-level pressure** (MSLP). Pressure decreases rapidly as you move away from the earth's surface, as shown in Figure 1.5. Pressure decreases to about half its surface value (500 mb) approximately 5.5 km (18,000 ft) above sea level because about half of the air molecules are above this level and half below. The pressure at the tropopause, approximately 10 km (6 miles) above sea level, is about 250 mb, a quarter of its surface value. Atmospheric **density**, the amount of mass in a unit volume, also decreases with height, as indicated by the dots on the right side of Figure 1.5.

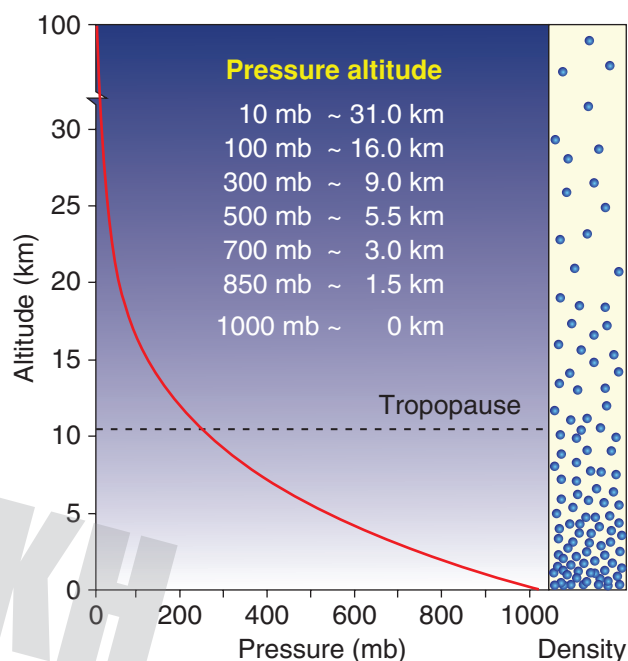


Figure 1.5 Average variation of pressure with altitude in the atmosphere. The dot pattern on the right side of the figure represents the air's density, which decreases with height.



FUN FACT

Dangerous Weather Is Always Nearby

The weather forecast for today is for a temperature of -46°C (-50°F) and 100 knot winds. The lack of oxygen in the air will likely cause suffocation in 2–3 minutes. Does this sound like a miserable day? On many days, this is an accurate forecast for a location only 10 km (6 miles) from your home. Getting there won't be easy—you have to go straight up. The next time you take a commercial airline flight, think of these conditions—they are right outside the window!

Pressure is measured with an instrument called a **barometer**. One of the simplest barometers is a mercury barometer, named so because it uses the liquid metal mercury. Figure 1.6 shows a mercury barometer. The dish at the bottom is open so that air can push down on the surface of the mercury. A vacuum exists in the upright

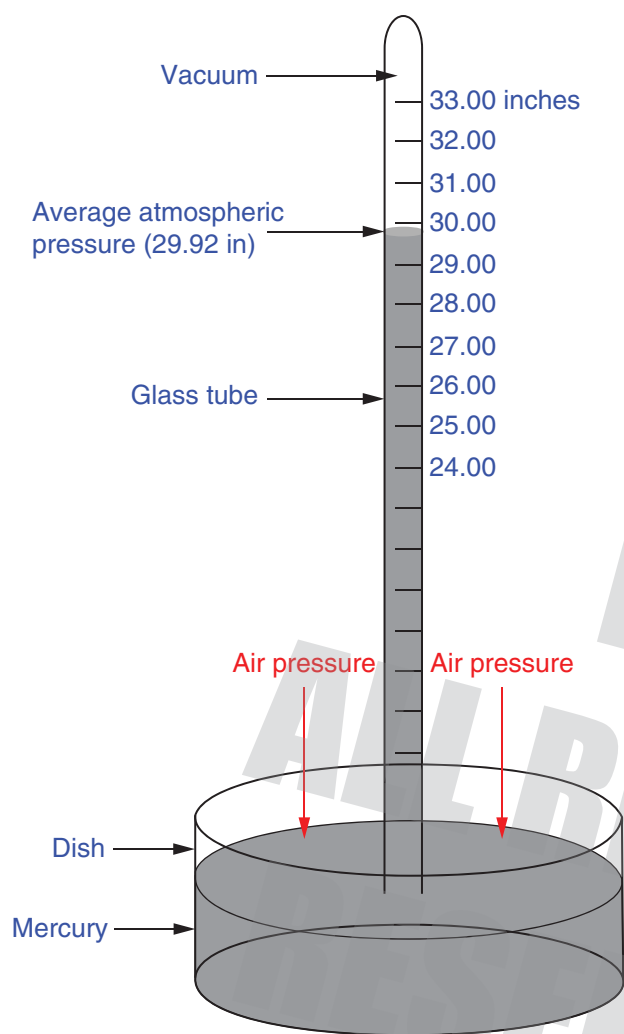


Figure 1.6 A mercury barometer. The height of the mercury column is proportional to atmospheric pressure. Units of pressure are inches of mercury in the figure.

tube. Air applying pressure on the surface of the mercury pushes the mercury up into the tube. The higher the pressure, the stronger the air's push and the higher the column of mercury rises. As atmospheric pressure fluctuates from day to day, the height of the column changes. When the pressure equals the mean sea-level pressure (1013.25 mb), the column height is exactly 29.92 in. Meteorologists, particularly those reporting in the media, sometimes use the pressure measurement "inches of mercury." Table 1.1 shows some common and extreme values of sea-level pressure observed on Earth in different pressure units. Although mercury barometers are not in common use today, pressure is often reported in the media using these units. Pressure measurements are made worldwide every hour.

A challenge with depicting pressure measurements on a weather chart is that pressure varies slowly in the horizontal but very rapidly with altitude. As a result, a map of station pressures (the actual measured pressures) will look much like a map of the topography. For example, the pressure in Denver, Colorado, would always be lower than the pressure in San Francisco, California, because Denver is much higher in elevation. To observe the *horizontal* distribution of pressure, meteorologists have to convert station pressure to a common altitude. Normally, this altitude is chosen as average sea level, or **mean sea level**. Once this conversion is made, meteorologists can then see how pressure varies

Table 1.1 Range of Sea-Level Pressures Observed on Earth

	Inches of Mercury (in Hg)	Pounds per Square Inch (lb/in ²)	Millibars (mb)
Highest recorded sea-level pressure (2001*)	32.06	15.8	1086
Strong high-pressure system	30.86	15.2	1045
Mean sea-level pressure	29.92	14.7	1013
Deep low-pressure system	28.94	14.2	980
Lowest recorded sea-level pressure (1979#)	25.69	12.6	870

Note: *Tosontsengel, Khövsgöl Province, Mongolia

#Super Typhoon Tip, Western Pacific

over a region. Surface maps depicting pressure distributions use mean sea level pressure.



Check Your Understanding 1.2

1. How is atmospheric pressure defined?
2. In what units are atmospheric pressure reported?
3. What is the numeric value of mean sea-level pressure in millibars?
4. Describe how a mercury barometer measures atmospheric pressure.

Moisture

When we view a photograph of the Earth, such as the Apollo 17 photograph in Figure 1.7A, the most striking features are the Earth's clouds. Earth's storms appear as elegant swirls of clouds that curl upon themselves in ever-tighter spirals. The organized cloud systems we see from space are composed of smaller clouds, each of which is created by an updraft of air, such as the thunderstorm that appears in Figure 1.7B. These clouds, in turn, are composed of individual water droplets and ice crystals, such as those in Figure 1.7C. When we look at clouds from space, we are really seeing countless numbers of tiny water droplets and ice crystals.

Moisture Variables

Clouds form from **water vapor**. Water vapor is an invisible gas composed of individual water molecules. In the atmosphere, water vapor is mixed with other gases, such as nitrogen and oxygen. Recall that pressure is the force applied by air molecules striking a unit area. Some of the molecules in the air are water vapor molecules. The force per unit area applied by only the water vapor molecules is the **vapor pressure**. The vapor pressure is a measure of the absolute amount of moisture in the air. The vapor pressure at normal atmospheric temperatures ranges from near 0 mb in a dry cold atmosphere to about 60 mb in a humid tropical atmosphere. Figures 1.8A and B show the average variation of vapor pressure across the

United States in January and July. Note the low value of vapor pressure in the summer in the western desert areas and the high values along the Gulf Coast. Note also that, in winter, the atmosphere in north-central areas of the United States contains only about a quarter of the moisture that the deserts do in summer. How can this be?

Imagine that we continually add water vapor into a small volume of the atmosphere

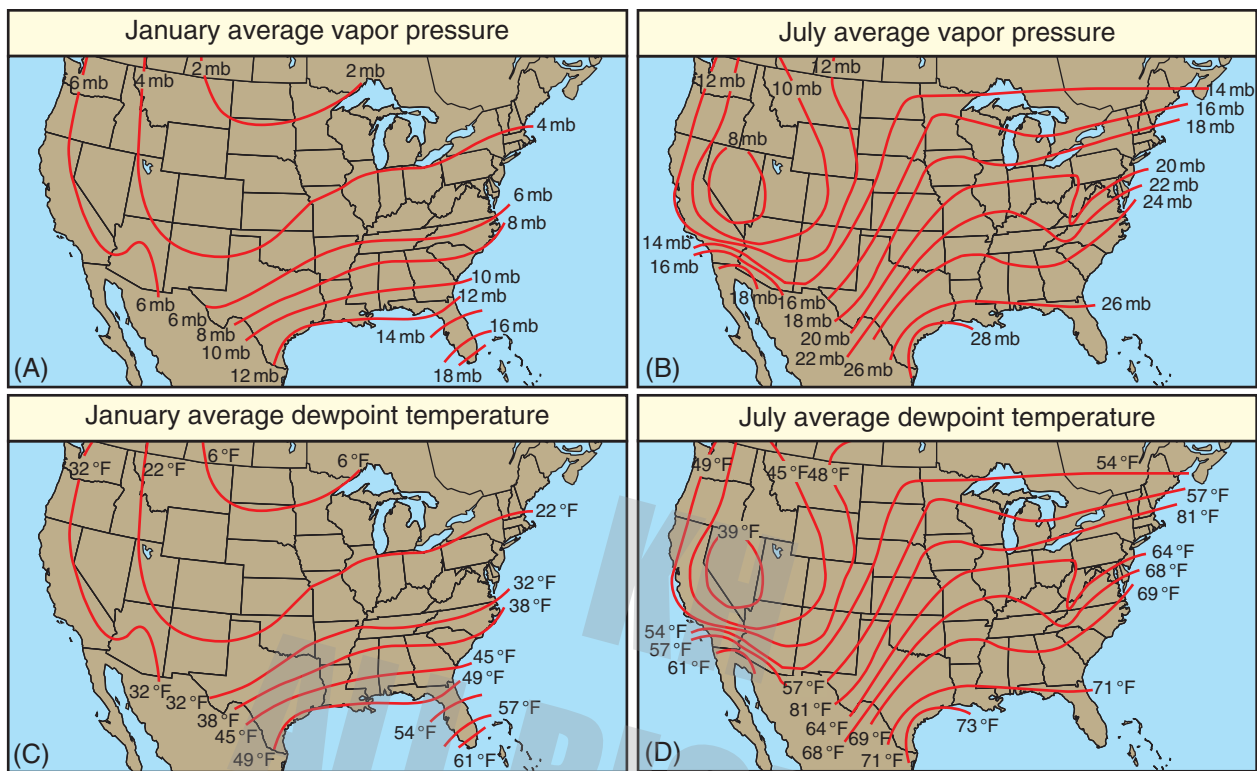


Figure 1.8 Average vapor pressure (mb) across the United States in (A) January and (B) July. Average dewpoint temperature (°F) in (C) January and (D) July. Note the correspondence between panels A and C and panels B and D, illustrating that vapor pressure and dewpoint temperature are both measures of the absolute amount of moisture in the air.

(you can do this experiment by taking a hot shower in the bathroom with the door closed). What will happen? After some time, a cloud or fog will form. The atmosphere reaches **saturation** when the invisible vapor condenses into visible cloud droplets. When the atmosphere cannot contain any more water vapor without condensing into cloud droplets, we say that the atmosphere is saturated. The vapor pressure at which the atmosphere becomes saturated is called the **saturation vapor pressure** (SVP). The atmosphere's capacity for water vapor, and therefore its SVP, depends on temperature. Think of the motion of individual air molecules and water molecules. At higher temperatures, the molecules move faster. It is harder for individual water molecules to coagulate into droplets when they are moving faster and enduring more and stronger collisions with their neighboring molecules.

The relationship between the SVP and temperature is shown in Figure 1.9. We can see from the table and the graph that the atmosphere has little capacity for moisture when the temperatures are very cold. The atmosphere can contain 84 times as many water vapor molecules at 30°C than it can at -30°C.

Humans are very sensitive to the amount of moisture in the air because our bodies use evaporation of perspiration to cool. When air is near saturation, our bodies cool inefficiently because perspiration (water) has difficulty evaporating. This is why summer temperatures near the humid Gulf of Mexico coast can seem suffocating, whereas the same temperatures in the dry western United States feel pleasantly warm.

Since humans are sensitive to how close air is to saturation, meteorologists frequently use a quantity called the **relative humidity** to describe the atmospheric moisture. The relative humidity,

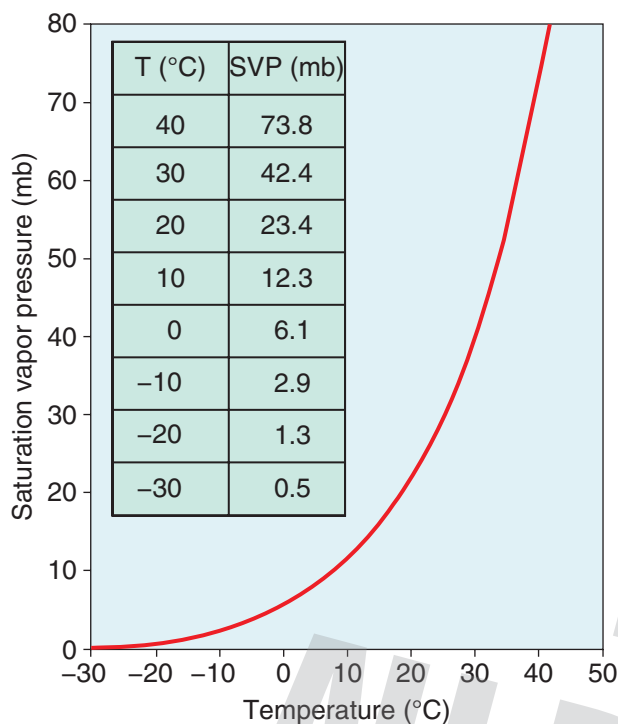


Figure 1.9 Relationship between saturation vapor pressure (mb) and temperature (°C). Saturation vapor pressure (SVP) for specific temperatures are shown in inset table.

the amount of water vapor in the atmosphere relative to the atmosphere's capacity for moisture at a given temperature, is defined as:

$$\text{Relative humidity} = \left(\frac{\text{vapor pressure}}{\text{saturation vapor pressure}} \right) \times 100\%.$$

The relative humidity depends on two quantities, the absolute amount of moisture in the air (the vapor pressure) and the amount of moisture the air can contain when it is saturated (the SVP). The air temperature determines the SVP, as we saw in Figure 1.9. When air is saturated, the relative humidity equals 100%.

We can visualize relative humidity by examining Figure 1.10, which shows four beakers. The capacity of each beaker represents temperature. The larger beakers can contain more water, just like warmer air can contain more water vapor. The amount of water in the beaker, relative to its capacity, determines the relative humidity. The smallest beaker in Figure 1.10 is nearly full, representing a high relative humidity. By contrast, the largest beaker is mostly empty, representing a low relative humidity.

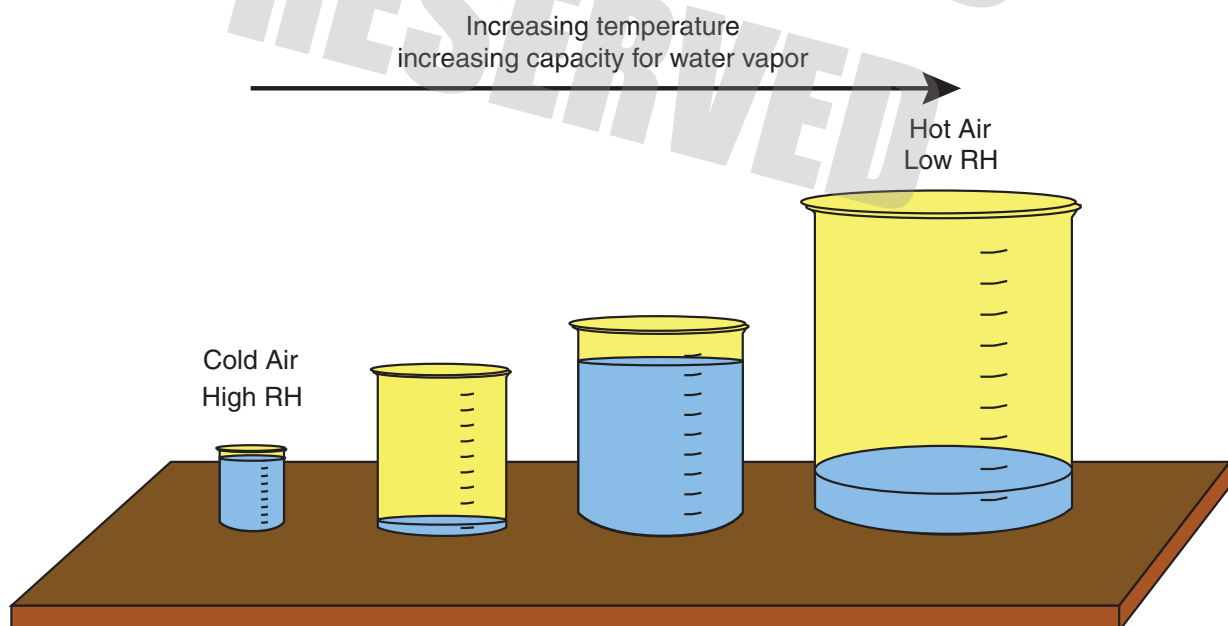


Figure 1.10 The four beakers represent the atmosphere's capacity for water vapor at progressively warmer temperatures. The amount of water in the beakers represents the actual amount of water vapor in the air. Full beakers represent high relative humidity and empty beakers represent low relative humidity.

even though there may be more water in the largest beaker than in the smallest.

Let us imagine a location where the atmosphere's vapor pressure was constant for an entire day. What would happen as the atmosphere is heated during the day and cooled during the night? Figure 1.11 shows the evolution of the temperature and relative humidity over a 24-hour period. As air temperature decreases, the relative humidity goes up and vice versa. In this case, the change in the relative humidity is due solely to the change in the SVP, which varies with the temperature. The amount of water vapor in the air remains essentially constant, and therefore, the vapor pressure is constant as well.

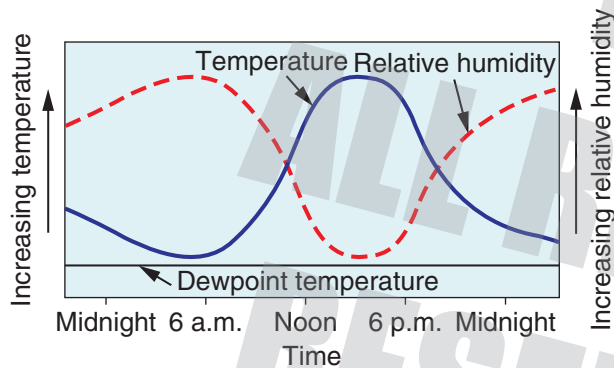


Figure 1.11 Daily variation of temperature, dewpoint temperature, and relative humidity on a day when the moisture content of the air (the vapor pressure) does not vary.

To understand how relative humidity can vary with temperature, let's return to the question concerning why the summer atmosphere in the deserts of the southwestern United States contains more moisture than the winter atmosphere in the north-central plains of the United States, yet the atmosphere in the desert feels dry and the winter atmosphere can feel moist. Suppose that the vapor pressure (the actual moisture content) is 8 mb in the desert and 2 mb in the north-central plains. Let's further suppose that the summertime temperature in the desert is 95°F (35°C) and the winter temperature is 32°F (0°C) in the north-central plains. Based on Figure 1.9, the SVP in the desert would be about 60 mb and in the north-central plains only about 6 mb. The relative humidity would be $8 \text{ mb} / 60 \text{ mb} \times 100 = 13\%$ in the desert and $2 \text{ mb} / 6 \text{ mb} \times 100 = 33\%$ in north-central plains. Hence, the air over the north-central plains has a higher relative humidity and is closer to saturation. This situation is equivalent to the left and right beakers in Figure 1.10. To our bodies, the atmosphere over the north-central plains would feel moist compared to the desert atmosphere, even though the desert atmosphere contains four times as much water vapor. The relative humidity is a measure of the moisture content of the atmosphere relative to its capacity for water vapor, which is determined by the temperature.



FUN FACT

Extreme Indoor Relative Humidity in Winter

In winter, cold air from outside enters our homes and is heated to a comfortable temperature. Although the amount of water vapor in the air (the vapor pressure) remains the same, the relative humidity of the air changes dramatically as it is heated. This is because the capacity of the indoor atmosphere for water vapor increases as the air is warmed. For example, consider a bitter-cold, foggy winter day when the outside temperature is -20°C (-4°F) and the relative humidity is 100%.

From the chart in Figure 1.9, the SVP would be 1.3 mb. Because the air is saturated, the vapor pressure would also be 1.3 mb. Let's assume that the air enters a house and is heated to 20°C (68°F). Now the SVP is 23.4 mb. The amount of moisture in the air does not change, so the vapor pressure remains 1.3 mb. The relative humidity of the indoor air becomes $1.3 \text{ mb} / 23.4 \text{ mb} \times 100\% = 6\%$. Values of relative humidity this low cause physical discomfort for many people. Humidifiers must be used to combat respiratory problems and cracked skin caused by the dry indoor air of winter.

While vapor pressure is a good way to describe the actual amount of moisture in the air, it is very difficult to measure. Instead, meteorologists rely on other variables to determine the absolute (as opposed to relative) amount of water vapor in the air. The most common variable used, and the one reported on surface weather maps, is the **dew-point temperature**. The dewpoint temperature is the lowest temperature to which air can be cooled at constant pressure before saturation occurs. To determine the dewpoint temperature, air is cooled until saturation occurs (and dew forms, hence the name) without changing the pressure. Although the dewpoint temperature is a temperature, *it is a measure of moisture content*. This concept is illustrated in Figures 1.8C and D, which show the average variation of dewpoint temperature across the United States in January and July. Note the direct correspondence to the vapor pressure in Figures 1.8A and B.

The relative humidity can be roughly estimated by comparing the dewpoint temperature and the actual temperature. For example, suppose that the dewpoint temperature is 69°F and the temperature is 70°F. This means that air only has to cool 1°F for saturation to occur. Thus, the relative humidity must be high (the air is close to saturation). In contrast, suppose the dewpoint is 40°F. Now the air at 70°F would have to cool 30°F to reach saturation. This means that the air is quite dry, and its relative humidity is low. Returning to Figure 1.11, we see that as air cools and heats, the dewpoint temperature is constant although the relative humidity changes. By comparing the dewpoint temperature and the air temperature, we can qualitatively estimate the relative humidity. When the dewpoint and the temperature are nearly the same, the relative humidity is high. When they are far apart, the relative humidity is low. The dewpoint can never exceed the air temperature for very long. As soon as it does, a cloud of liquid droplets immediately forms and the relative humidity returns to 100%.

Phase Changes and Clouds

Water is unique in that it is the only constituent of the atmosphere that exists naturally in all three phases. Air contains water vapor, and clouds in the air are composed of liquid and ice particles. **Phase changes**, from water to vapor (**evaporation**), vapor to water (**condensation**), ice to water (**melting**), water to ice (**freezing**), vapor to ice (**deposition**), and ice to vapor (**sublimation**), occur all the time in the atmosphere as water and ice clouds form and dissipate. Figure 1.12 shows all the phase changes that can occur in the atmosphere.

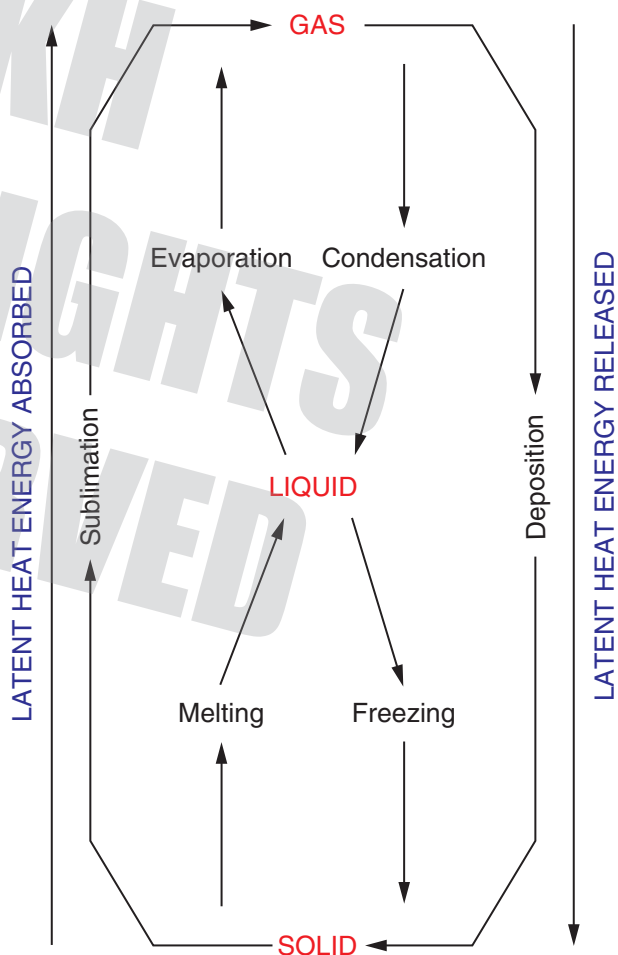


Figure 1.12 Phase changes of water. Energy is released into the atmosphere when water vapor becomes a liquid through condensation or ice through deposition, or when water becomes ice by freezing. Energy is absorbed from the atmosphere when ice melts or sublimates, or when water evaporates.

Phase changes of water are critical to the development of storms. The primary reason is that energy is either required or liberated during phase changes. To understand this idea, consider a simple thought experiment. Take a full, large pot of water out of the refrigerator (let the temperature of the water be 0°C), and put it on the stove on a cherry-red burner. How long does it take for the pot of water to begin to boil? Typically, it will boil in under 10 minutes. How long does it take the full pot of water to undergo the phase change and turn from liquid water in the pot to water vapor in the air? Depending on the pot size, it might take hours. Think of all the energy that goes into converting the water in the pot into vapor in the air. Where does all that energy go? The energy goes to accelerating the molecules to high speeds characteristic of vapor and to breaking the strong bonds that link individual water molecules to each other. The energy is called **latent heat** because it is the hidden heat required for a phase change.

Let's continue our thought experiment. Imagine now that, by some miracle, all of the vapor molecules fly back into the pot and become liquid again. What happens to all the energy they had? The energy actually would reappear as heat (and probably explode the kitchen off the house!). This experiment may seem silly, but it occurs in the atmosphere all the time. Water is evaporated off the oceans, lakes, and other water sources as solar energy heats the water. When clouds form, the water vapor condenses to liquid. At that time, all the latent heat required to evaporate the water reappears as heat and warms the air in which the cloud is forming. Heat is also required for other phase changes, such as melting of ice, and released during the reverse process, the freezing of water. Latent heat release is vital to the creation of thunderstorms. We will examine the role of latent heat in storm formation in Chapter 6.

Clouds are composed of ice particles, water droplets, or a mixture of both. Some water droplets in clouds can be liquid but have temperatures well below 0°C . How can this happen?

For water to freeze, microscopic impurities that have molecular crystalline structure similar to ice must be present in the water. These impurities, called **ice nuclei**, are always present in large water bodies (such as the ice cubes in a refrigerator) but are not necessarily present or active in all the tiny droplets that compose clouds. Drops that do not freeze when they are colder than 0°C are **supercooled**. In many clouds, ice nuclei only become active when the temperature cools below 5°F – 14°F (from -15°C to -10°C), so supercooled clouds are most common when the cloud-top temperatures are warmer than 5°F (-15°C). **Supercooled water** is important in the formation of aircraft icing and freezing rain. When ice particles falling through clouds encounter supercooled droplets, the droplets freeze instantly to the ice upon contact. If enough droplets are collected this way, an ice particle can grow to an appreciable size and becomes a small (<3 – 4 mm), soft ball of ice called **graupel**. Continued collection of supercooled water will lead to further growth and the formation of hail. Ice crystals can also collect other ice crystals and become **snowflakes**. At temperatures above freezing, the snow, graupel, and hail melt to form raindrops.

Clouds are classified by their shape and altitude, and whether they produce precipitation. Clouds are called **cumulus** if they are associated with strong updrafts and are towering, with cauliflower-like lobes. In general, the horizontal and vertical dimensions of these clouds are comparable. If they grow to thunderstorms and produce precipitation, they are called **cumulonimbus** ("nimbus" is the Latin word for rain). Clouds that are layered and widespread are **stratus** clouds. The width of these clouds is much greater than the depth. If precipitation falls from these clouds, they are called **nimbostratus**. High, wispy clouds are **cirrus** clouds. This terminology originated with a pharmacist named Luke Howard in 1803. He identified four broad categories: cumulus (clouds with vertical development), stratus (layer clouds), cirrus (high, fibrous clouds), and **nimbus** (precipitating clouds). High

(>6 km [4 miles]) clouds are called **cirrostratus** if they are layered and **cirrocumulus** if they are puffy. Middle clouds (~2–6 km [1–4 miles]) with similar shapes are called **altostratus** and **altocumulus**.



Check Your Understanding 1.3

1. What does it mean when we say air is saturated?
2. What is the relative humidity?
3. What is the dewpoint temperature?
4. What is value of the relative humidity if the dewpoint temperature equals the air temperature?
5. What is latent heat?

Wind

Wind is simply the horizontal movement of air. To specify the wind, we must refer to two quantities: the wind direction and its speed. Official measurements of wind at surface stations are made at an elevation of 10 m (~33 ft), which is called the anemometer height. An **anemometer** is a device to measure wind speed. Wind direction is measured using north-east-south-west coordinates and is expressed in degrees (Figure 1.13A). *The wind direction, by convention, is the direction from which the wind is blowing.* The easy way to remember this rule is to think of a north wind. When a north wind is blowing, the day is likely to be cold, since a north wind is blowing *from the north*, bringing cold air southward. A south wind is blowing *from the south*, bringing warm air northward. The wind direction can also be expressed in degrees. A north wind is from 0 degrees, an east wind from 90 degrees, a south wind from 180 degrees, and a west wind from 270 degrees. Meteorologists typically measure wind speed in knots. The exact conversion between knots and miles/hour is 1 knot = 1.15 mph. In metric units, winds are normally measured in meters/second (1 knot = 0.51 m/s).

Meteorologists depict wind speed and direction at a station using a **wind barb** (see Figure 1.13B). Wind barbs are made up of a staff (wind direction)

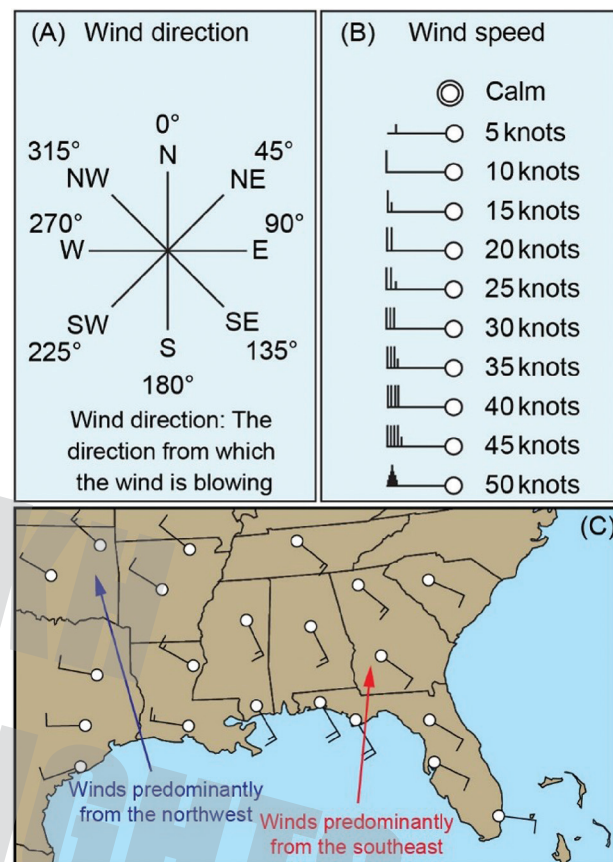


Figure 1.13 Conventions for plotting wind direction and wind speed. Wind direction is measured in degrees from north using the coordinate system in panel A. In panel B, wind direction is indicated by a staff that points toward the station in the direction the wind is blowing. Barbs on the end of the staff indicate the wind speed, with a half-barb representing 5 knots, a whole barb 10 knots, and a pennant 50 knots. Panel C shows examples of winds plotted in several cities in southeastern United States.

and short lines or flags (wind speed). The coordinate system used for wind direction, shown in Figure 1.13A, conventionally has north as up, south as down, east to the right, and west to the left. Using this coordinate system, if you move from the tail to the head of the staff, you are moving in the direction the wind is blowing. The marking on the end of the staff, called a barb, indicates the wind speed. A half barb is 5 knots; a whole barb is 10 knots; and a pennant is 50 knots. Combinations of these three are used for other wind speeds. The map of the southeastern United States in Figure 1.13C depicts the wind direction and speed in several cities. Cities

on the eastern side of the map generally have winds from the south or southeast from 10 to 20 knots, whereas cities on the western side have winds from the west or northwest from 10 to 15 knots.

Wind circulations in the atmosphere occur on many scales. Winds continually orbit around Earth in the **general circulation**, the large-scale pattern of prevailing winds and pressures. Embedded within the general circulation in the mid-latitudes are **extratropical cyclones**. These large storms, with diameters up to 3000 km (~1800 miles), can cover an area as large as about a third of the continental United States and are responsible for many types of severe weather. In the tropics, **hurricanes** are much smaller (~300 km [~180 miles] diameter) but

capable of terrible destruction as they move onto shore. **Thunderstorms** occur on an even smaller scale (~30 km [18 miles] or less), and **tornadoes** spawned by thunderstorms rarely are larger than 0.5 km (0.3 miles) in diameter. We will study all of these wind circulations as we examine specific weather phenomena in later chapters.



Check Your Understanding 1.4

1. Define wind.
2. What is the convention for reporting wind direction?
3. In what units can wind speeds be reported?
4. What do wind barbs represent on a weather map?

TEST YOUR UNDERSTANDING

1. Over what altitude range does most of the earth's weather occur?
2. In molecular terms, what is the difference between a solid, a liquid, and a gas?
3. Name four basic properties of the atmosphere used in describing weather.
4. Describe how temperature is used to define layers of the atmosphere.
5. Sketch the vertical temperature profile of the entire atmosphere. The x -axis should be temperature and the y -axis altitude. Label the four layers of the atmosphere and the tropopause.
6. Why does air temperature typically increase with height in the stratosphere?
7. How does the height of the tropopause change as you move from the equator to the poles? What implication does this have on the depth of storms at different latitudes?
8. What is a typical pressure in a strong high-pressure system and a deep low-pressure system? (Report your answer in mb.)
9. As you move upward away from Earth's surface, does the pressure increase, decrease, or remain constant? Explain your answer.
10. If a map shows station pressures (the actual pressure measured by an observer) across the contiguous United States, where would the lowest pressure values be found?
11. Why are maps of station pressure not very useful for meteorologists?
12. What is meant by "mean sea-level pressure"?
13. Why do your ears pop when you ride up an elevator in a skyscraper?
14. Define vapor pressure, saturation vapor pressure, and saturation.
15. What atmospheric variable determines the maximum amount of moisture that can be present in air?
16. Which two variables describe the absolute amount of moisture in the air?
17. Examine the middle beakers in Figure 1.10. Which represents a higher air temperature? Which represents an atmosphere with the higher relative humidity?

continued

18. How does relative humidity typically change over the course of a day?
19. State two ways that the relative humidity of air can be increased.
20. Qualitatively, what is the relative humidity if the dewpoint temperature and the air temperature differ substantially? What if the air temperature and the dewpoint temperature are close in value?
21. Latent heat is released to the air during which phase changes? During which phase changes is latent heat removed from the air?
22. Identify several storm types that represent different scales of wind circulations.
23. Name the four primary cloud categories.
24. You are standing in New York City and an east wind is blowing. Is this wind coming from the ocean to the east or the land to the west?

TEST YOUR PROBLEM-SOLVING SKILLS

1. On a very hot day, you decide to relax with a friend and enjoy a fruity cup of mango juice. You have ice in the cup and also a thermometer-swizzle stick. As the mango juice cup cools (because of the ice), moisture suddenly starts condensing on the outside of the cup. The mango juice cup temperature is 20°C when this happens. The air temperature is 30°C.
 - (a) What is the dewpoint temperature?
 - (b) Estimate the vapor pressure in the atmosphere. (Hint: use Figure 1.9.)
 - (c) Estimate the relative humidity in percent.
 - (d) Why did moisture condense on the outside of the cup?
2. Four cities report the following temperatures and dewpoint temperatures:

City	Temperature (°F)	Dewpoint Temperature (°F)
Newark, New Jersey	59	59
Tucson, Arizona	86	50
Miami, Florida	77	68
St. Louis, Missouri	77	59

 - (a) Which city has the highest vapor pressure?
 - (b) Which city has the lowest vapor pressure?
 - (c) Which city has the highest saturation vapor pressure?
 - (d) Estimate the relative humidity of each of the four cities. (Hint: use Figure 1.9.)
3. You and your friend decide to go on a weekend road trip to the nearby mountains. In your car is a barometer that reads 1003 mb as you leave home. Later, you arrive in the mountains and make the long, winding drive up to Summit Lodge, a motel known for its great view of the valley below. You notice that the barometer reads 960 mb. Your friend says, “That’s an extremely low pressure, which means a strong storm must be coming. We better head back home right now.” How would you reason with your friend to save the weekend?
4. Occasionally during the summer in the agricultural regions of the Midwest, the dewpoint temperature climbs to the low 80s.

continued

On one particular July day, the dewpoint temperature in Des Moines, Iowa, was 85°F.

- (a) Estimate the vapor pressure (mb) at the time the dewpoint was recorded.
- (b) How does this amount of moisture compare to the average amount in the air in Iowa during July? What about during January?
- (c) If the actual air temperature was 90°F, what was the relative humidity?
- (d) Automobile air conditioners running in these conditions were dripping liquid water. Those same air conditioners running in September produced no liquid water. How do you explain the difference?

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