18 Air Pressure and Wind

FOCUS ON CONCEPTS

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

18.1 Define *air pressure* and describe the instruments used to measure this weather element.

18.2 Discuss the three forces that act on the atmosphere to either create or alter winds.

18.3 Contrast the weather associated with low-pressure centers (cyclones) and high-pressure centers (anticyclones).

18.4 Summarize Earth's idealized global circulation. Describe how continents and seasonal temperature changes complicate the idealized pattern.

18.5 List three types of local winds and describe their formation.

18.6 Describe the instruments used to measure wind. Explain how wind direction is expressed using compass directions.

18.7 Describe the Southern Oscillation and its relationship to El Niño and La Niña. List the climate impacts to North America of El Niño and La Niña.

18.8 Discuss the major factors that influence the global distribution of precipitation.

Horizontal differences in air pressure created the winds that are propelling these sailboats. (Photo by UpperCut Images/Alamy)

Of the various elements of weather and climate, changes in air pressure are the least noticeable. When listening to a weather report, we are generally interested in moisture conditions (humidity and precipitation), temperature, and perhaps wind. Rarely do people wonder about air pressure. Although the hour-to-hour and day-to-day variations in air pressure are generally not noticed by people, they are very important in producing changes in our weather. Variations in air pressure from place to place cause the movement of air we call wind and are a significant factor in weather forecasting. As we will see, air pressure is closely tied to the other elements of weather in a cause-and-effect relationship.

18.1 UNDERSTANDING AIR PRESSURE

Define *air pressure* and describe the instruments used to measure this weather element.

In Chapter 16 we noted that **air pressure** is simply the pressure exerted by the weight of air above. Average air pressure at sea level is about 1 kilogram per square centimeter, or 14.7 pounds per square inch. Specifically, a column of air 1 square inch in cross section, measured from sea level to the top of the atmosphere, would weigh about 14.7 pounds (**FIGURE 18.1**). This is roughly the same pressure that is produced by a 1-square-inch column of water 10 meters (33 feet) in height. With some simple arithmetic, you can calculate that the air pressure exerted on the top of a small (50 centimeter-by-100 centimeter [20 inch-by-40 inch]) school desk exceeds 5000 kilograms (11,000 pounds), or about the weight of a 50-passenger school bus. Why doesn't the desk collapse under the weight of the ocean of air above? Simply, air pressure is exerted in all directions—down, up, and sideways. Thus, the air pressure pushing down on the desk exactly balances the air pressure pushing up on the desk.

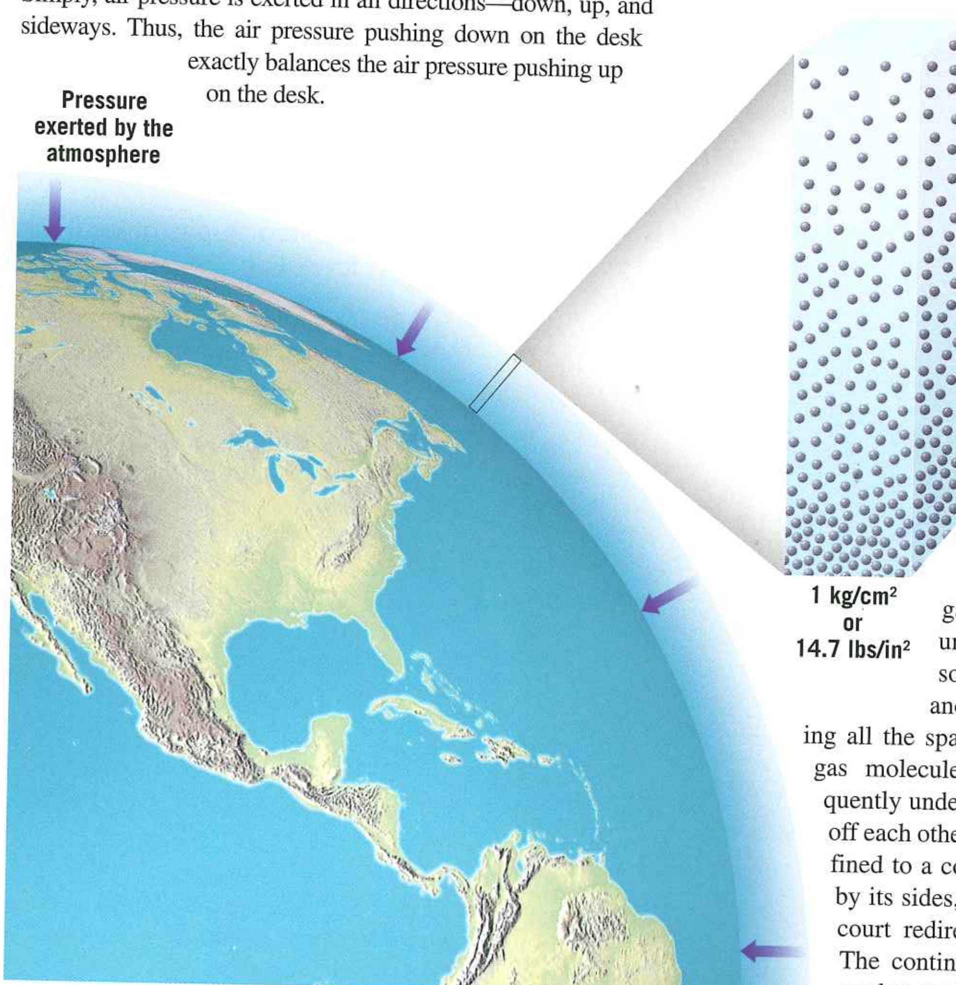
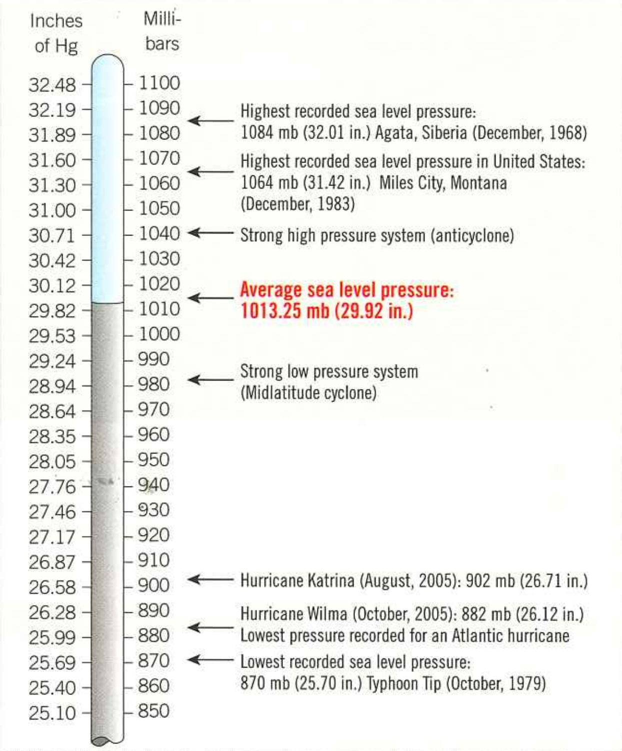


FIGURE 18.1 Sea-Level Pressure Air pressure can be thought of as the weight of the atmosphere above. A column of air 1-square inch in cross section extending from sea level to the top of the atmosphere would weigh about 14.7 pounds.

Visualizing Air Pressure

Imagine a tall aquarium that has the same dimensions as the small desk mentioned in the preceding paragraph. When this aquarium is filled to a height of 10 meters (33 feet), the water pressure at the bottom equals 1 atmosphere (14.7 pounds per square inch). Now, imagine what will happen if this aquarium is placed on top of our student desk so that all the force is directed downward. Compare this to what results when the desk is placed inside the aquarium and allowed to sink to the bottom. In the latter example, the desk survives because the water pressure is exerted in all directions, not just downward, as in our earlier example. The desk, like your body, is "built" to withstand the pressure of 1 atmosphere. It is important to note that although we do not generally notice the pressure exerted by the ocean of air around us, except when ascending or descending in an elevator or airplane, it is nonetheless substantial. The pressurized suits that astronauts use on space walks are designed to duplicate the atmospheric pressure experienced at Earth's surface. Without these protective suits to keep body fluids from boiling away, astronauts would perish in minutes.

The concept of air pressure can also be understood if we examine the behavior of gas molecules. Gas molecules, unlike molecules of the liquid and solid phases, are not bound to one another but freely move about, filling all the space available to them. When two gas molecules collide, which happens frequently under normal conditions, they bounce off each other like elastic balls. If a gas is confined to a container, this motion is restricted by its sides, much as the walls of a handball court redirect the motion of the handball. The continuous bombardment of gas molecules against the sides of the container



SmartFigure 18.2 Inches and Millibars A comparison of two units commonly used to express air pressure

exerts an outward push that we call air pressure. Although the atmosphere is without walls, it is confined from below by Earth's surface and effectively from above because the force of gravity prevents its escape. Here, we can define *air pressure* as the force exerted against a surface by the continuous collision of gas molecules.

Measuring Air Pressure

When meteorologists measure atmospheric pressure, they use a unit called the *millibar.* Standard sea-level pressure is 1013.2 millibars. Although the millibar has been the unit of measure on all U.S. weather maps since January 1940, the media use "inches of mercury" to describe atmospheric pressure. In the United States, the National Weather Service converts millibar values to inches of mercury for public and aviation use (**FIGURE 18.2**).

Inches of mercury is easy to understand. The use of mercury for measuring air pressure dates from 1643, when Torricelli, a student of the famous Italian scientist Galileo, invented the **mercury barometer**. Torricelli correctly described the atmosphere as a vast ocean of air that exerts pressure on us and all objects about us. To measure this force, he filled a glass tube, which was closed at one end, with mercury. The tube was then inverted into a dish of mercury (**FIGURE 18.3**). Torricelli found that the mercury flowed out of the tube until the weight of the column was balanced by the pressure that the atmosphere exerted on the surface of the mercury in the dish. In other words, the weight of mercury in the column equaled the weight of the same diameter column of air that extended from the ground to the top of the atmosphere.

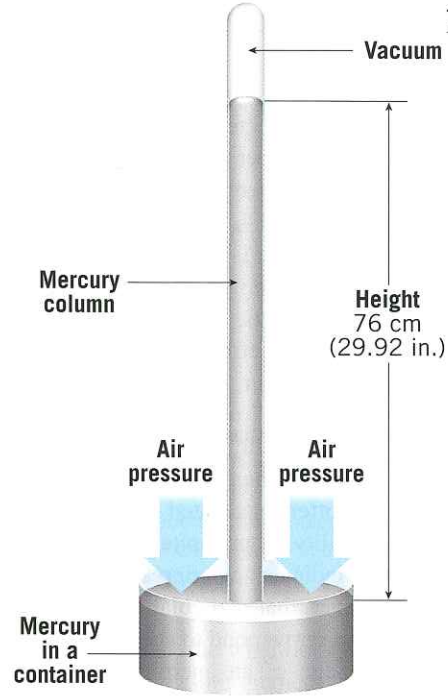


FIGURE 18.3 Simple Mercury Barometer The weight of the column of mercury is balanced by the pressure exerted on the dish of mercury by the air above. If the pressure drops, the column of mercury falls; if the pressure increases, the column rises.

When air pressure increases, the mercury in the tube rises. Conversely, when air pressure decreases, so does the height of the mercury column. With some refinements, the mercury barometer invented by Torricelli is still the standard pressure-measuring instrument used today. Standard atmospheric pressure at sea level equals 29.92 inches of mercury.

The need for a smaller and more portable instrument for measuring air pressure led to the development of the **aneroid barometer** (*aneroid* means "without liquid"). Instead of having a mercury column held up by air pressure, an aneroid barometer uses a partially evacuated metal chamber (**FIGURE 18.4**). The chamber is extremely sensitive to variations in air pressure

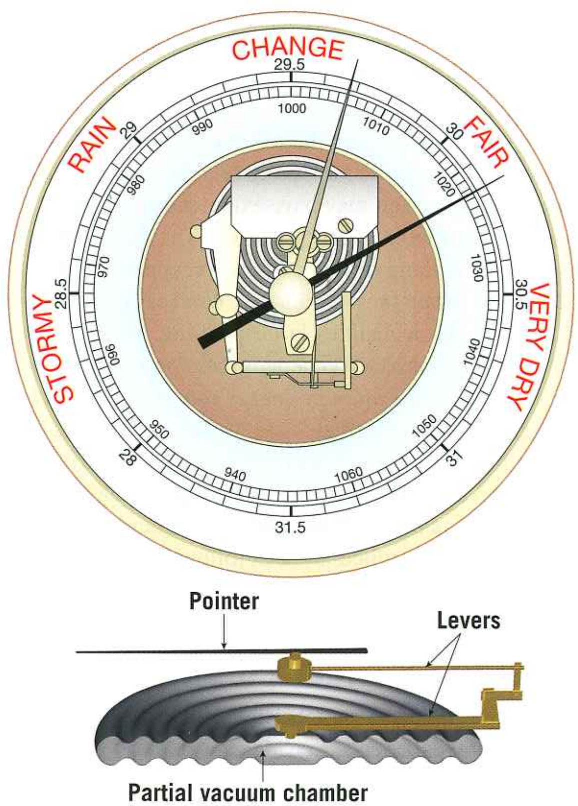


FIGURE 18.4 Aneroid Barometer The black pointer shows the current air pressure. When the barometer is read, the observer moves the other pointer to coincide with the current air pressure. Later, when the barometer is checked, the observer can see whether the air pressure has been rising, falling, or has remained steady. The bottom diagram is a cross section. An aneroid barometer has a partially evacuated chamber that changes shape, compressing as air pressure increases and expanding as pressure decreases.

and changes shape, compressing as the pressure increases and expanding as the pressure decreases. A series of levers transmit the movements of the chamber to a pointer on a dial that is calibrated to read in inches of mercury and/or millibars.

As shown in Figure 18.4, the face of an aneroid barometer intended for home use is inscribed with words such as *fair*, *change*, *rain*, and *stormy*. Notice that "fair" corresponds with high-pressure readings, whereas "rain" is associated with low pressures. Barometric readings, however, may not always indicate the weather. The dial may point to "fair" on a rainy day or to "rain" on a fair day. To "predict" the local weather, the change in air pressure over the past few hours is more important than the current pressure reading. Falling pressure is often associated with increasing cloudiness and the possibility of precipitation, whereas rising air pressure generally indicates clearing conditions. It is useful to remember, however, that particular barometer readings or trends do not always correspond to specific types of weather.

Another advantage of an aneroid barometer is that it can easily be connected to a recording mechanism. The resulting instrument is a **barograph**, which provides a continuous record of pressure changes with the passage of time (**FIGURE 18.5**). Another important adaptation of the aneroid barometer is its use to indicate altitude for aircraft, mountain climbers, and mapmakers.

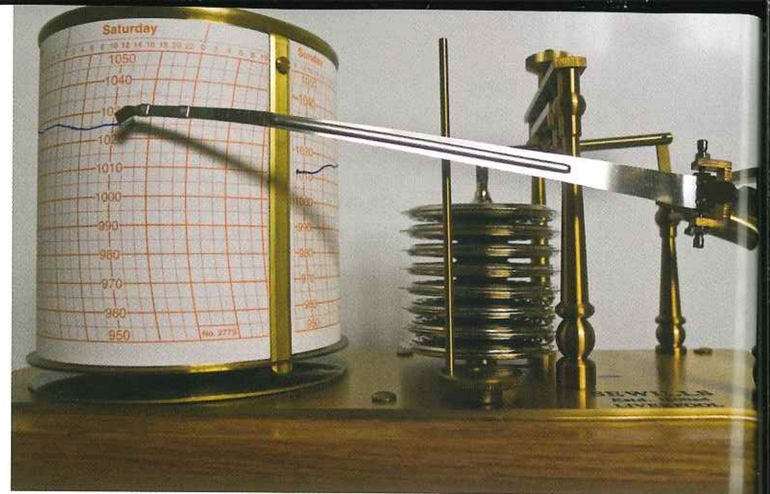


FIGURE 18.5 Aneroid Barograph This instrument makes a continuous record of air pressure. The cylinder with the graph is a clock that turns once per day or once per week. (Photo courtesy of Stuart Aylmer/Alamy)

18.1 CONCEPT CHECKS

1. Describe air pressure in your own words.
2. What is standard sea-level pressure in millibars, in inches, and in pounds per square inch?
3. Describe the operating principles of the mercury barometer and the aneroid barometer.
4. List two advantages of the aneroid barometer.

18.2 FACTORS AFFECTING WIND

Discuss the three forces that act on the atmosphere to either create or alter winds.

In Chapter 17, we examined the upward movement of air and its role in cloud formation. As important as vertical motion is, far more air moves horizontally, the phenomenon we call **wind**. What causes wind?

Simply stated, wind is the result of horizontal differences in air pressure. *Air flows from areas of higher pressure to areas of lower pressure.* You may have experienced this when opening something that is vacuum packed. The noise you hear is caused by air rushing from the higher pressure outside the can or jar to the lower pressure inside. Wind is nature's attempt to balance such inequalities in air pressure. Because unequal heating of Earth's surface generates these pressure differences, *solar radiation is the ultimate energy source for most wind.*

If Earth did not rotate, and if there were no friction between moving air and Earth's surface, air would flow in a straight line from areas of higher pressure to areas of lower pressure. But because Earth does rotate and friction does exist, wind is controlled by the following combination of forces: pressure gradient force, Coriolis effect, and friction.

Pressure Gradient Force

If an object experiences an unbalanced force in one direction, it will accelerate (experience a change in velocity). The force that generates winds results from horizontal pressure differences. When air is subjected to greater pressure on one side than on another, the imbalance produces a force that is directed from the region of higher pressure toward the area of lower pressure. Thus, pressure differences cause the wind to blow, and the greater these differences, the greater the wind speed.

Variations in air pressure over Earth's surface are determined from barometric readings taken at hundreds of weather stations. These pressure measurements are shown on surface weather maps using **isobars** (*iso* = equal, *bar* = pressure), or lines connecting places of equal air pressure (**FIGURE 18.6**). The *spacing* of the isobars indicates the amount of pressure change occurring over a given distance and is called the **pressure gradient force**. Pressure gradient is analogous to gravity acting on a ball rolling down a hill. A steep pressure gradient, like a steep hill, causes greater acceleration of a parcel of air than does a weak pressure gradient (a gentle hill). Thus, the relationship between wind speed and the pressure gradient is straightforward: *Closely spaced isobars indicate a steep pressure gradient and strong winds; widely spaced isobars indicate a weak pressure gradient and light winds*. Figure 18.6 illustrates the relationship between the spacing of isobars and wind speed. Note also that the pressure gradient force is always directed at *right angles* to the isobars.

In order to draw isobars on a weather map to show air pressure patterns, meteorologists must compensate for the *elevation* of each station. Otherwise, all high-elevation locations, such as Denver, Colorado, would always be mapped as having low pressure. This compensation is accomplished by converting all pressure measurements to sea-level equivalents.

FIGURE 18.7 is a surface weather map that shows isobars (representing corrected sea-level air pressure) and winds. Wind *direction* is shown as wind arrow shafts, and *speed* is shown as wind bars (see the accompanying key). Isobars, used to depict pressure patterns, are rarely straight or evenly spaced on surface maps. Consequently, wind generated by the pressure gradient force typically changes speed and direction as it flows.

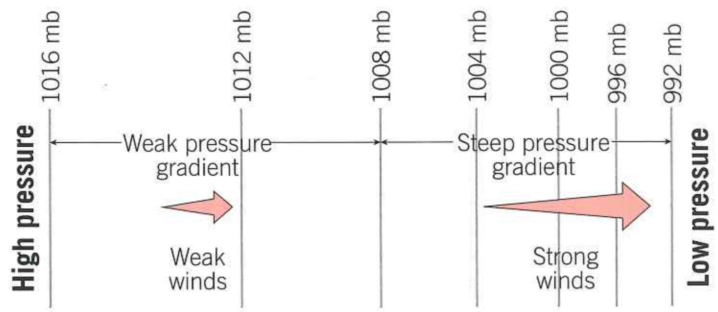


FIGURE 18.6 Isobars Show the Pressure Gradient Isobars are lines connecting places of equal air pressure. The spacing of isobars indicates the amount of pressure change occurring over a given distance—called the pressure gradient. Closely spaced isobars indicate a strong pressure gradient and high wind speeds, whereas widely spaced isobars indicate a weak pressure gradient and low wind speeds.

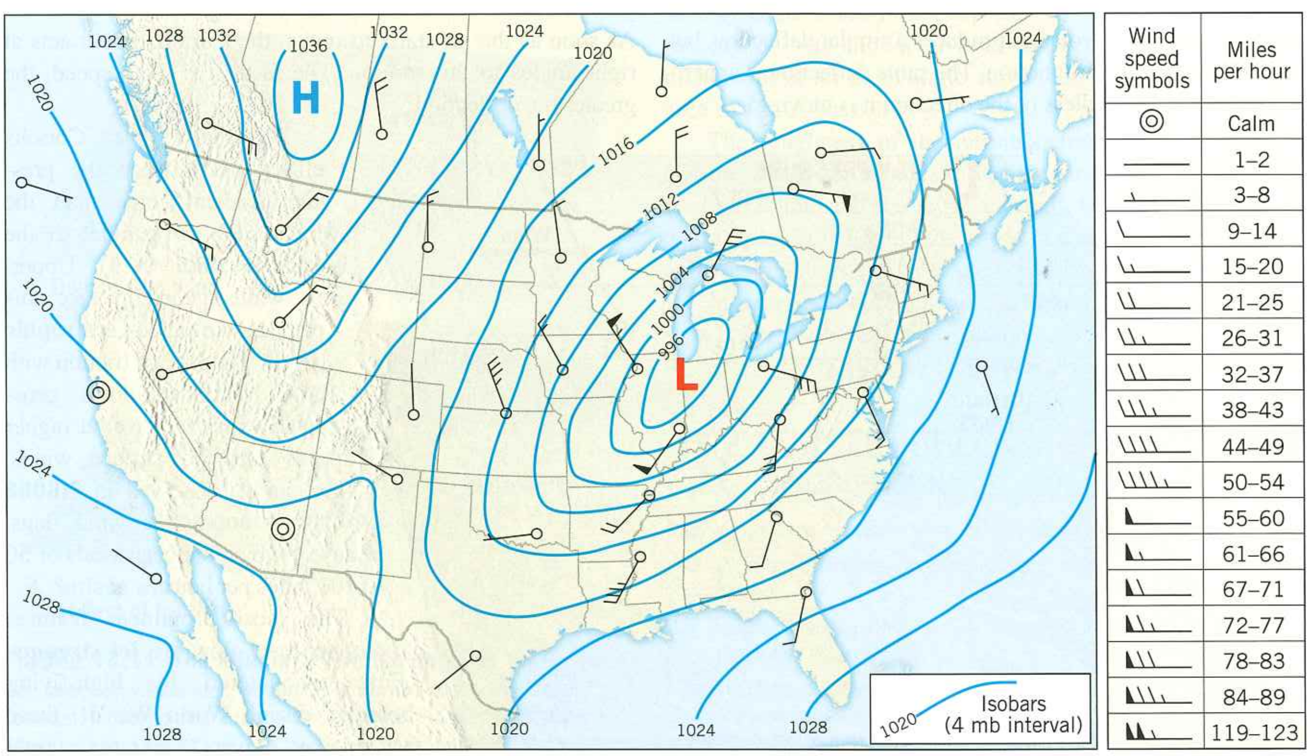
The area of somewhat circular closed isobars in eastern North America represented by the red letter *L* is a *low-pressure system*. In western Canada, a *high-pressure system*, denoted by the blue letter *H*, can also be seen. We will discuss *highs* and *lows* in the next section.

In summary, the *horizontal pressure gradient is the driving force of wind*. The magnitude of the pressure gradient force is shown by the spacing of isobars. The direction of force is always from areas of higher pressure toward areas of lower pressure and at right angles to the isobars.

Coriolis Effect

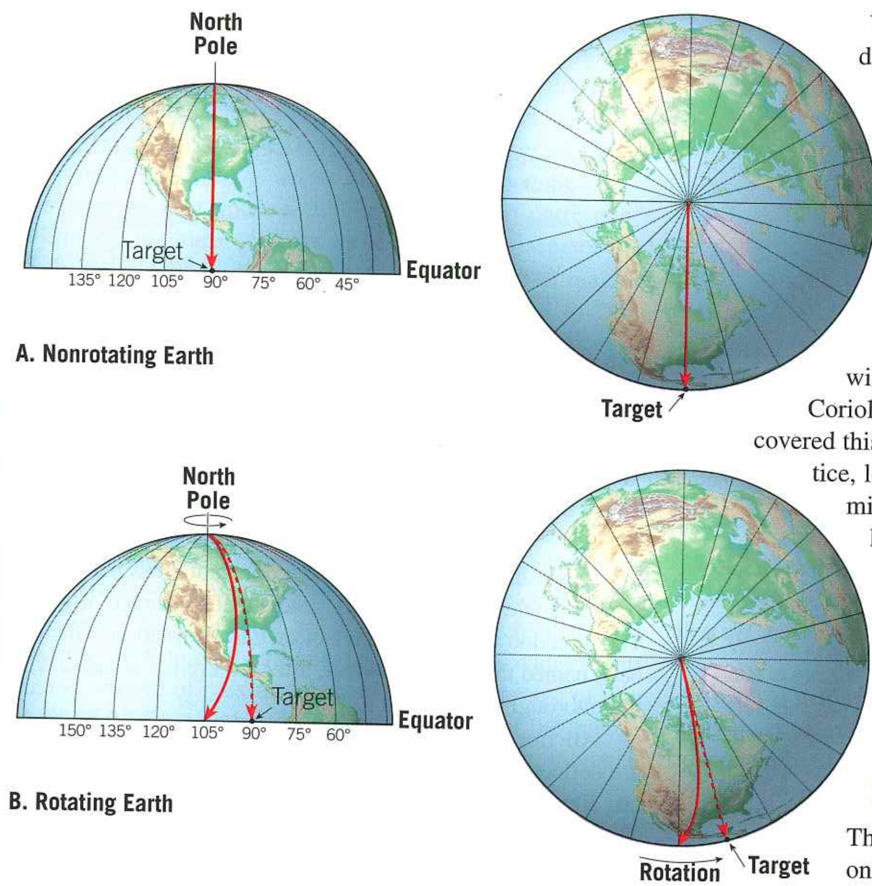
Figure 18.7 shows the typical air movements associated with high- and low-pressure systems. As expected, the air moves out of the regions of higher pressure and into the regions of lower pressure. However, the wind does not cross the isobars at right angles as the pressure gradient force directs it to do. The direction deviates as a result of Earth's rotation. This has been named the **Coriolis effect**, after the French scientist who first thoroughly described it.

All free-moving objects or fluids, including the wind, are deflected to the *right* of their path of motion in the Northern Hemisphere and to the *left* in the Southern Hemisphere. The reason for this deflection can be illustrated by imagining the path of a rocket launched from the North Pole toward a target located on the equator (**FIGURE 18.8**). If the rocket took an hour to reach its target, during its flight, Earth would have rotated 15 degrees to the east. To someone standing on Earth, it would look as if the rocket had veered off its path and hit Earth 15 degrees west of its target. The true path of



SmartFigure 18.7 Isobars on a Weather Map Isobars are used to show the distribution of pressure on daily weather maps. Isobars are seldom straight but usually form broad curves. Concentric isobars indicate cells of high and low pressure. The "wind flags" indicate the expected airflow surrounding pressure cells and are plotted as "flying" with the wind (that is, the wind blows toward the station circle). Notice on this map that the isobars are more closely spaced and the wind speed is faster around the low-pressure center than around the high.

SmartFigure 18.8 Coriolis Effect The Coriolis effect, illustrated using the 1-hour flight of a rocket traveling from the North Pole to a location on the equator. **A.** On a nonrotating Earth, the rocket would travel straight to its target. **B.** However, Earth rotates 15 degrees each hour. Thus, although the rocket travels in a straight line, when we plot the path of the rocket on Earth's surface, it follows a curved path that veers to the right of the target.



the rocket is straight and would appear so to someone out in space looking at Earth. It is Earth turning under the rocket that gives it its *apparent* deflection.

Note that the rocket is deflected to the right of its path of motion because of the counterclockwise rotation of the Northern Hemisphere. In the Southern Hemisphere, the effect is reversed. Clockwise rotation produces a similar deflection, but to the *left* of the path of motion. The same deflection is experienced by wind regardless of the direction it is moving.

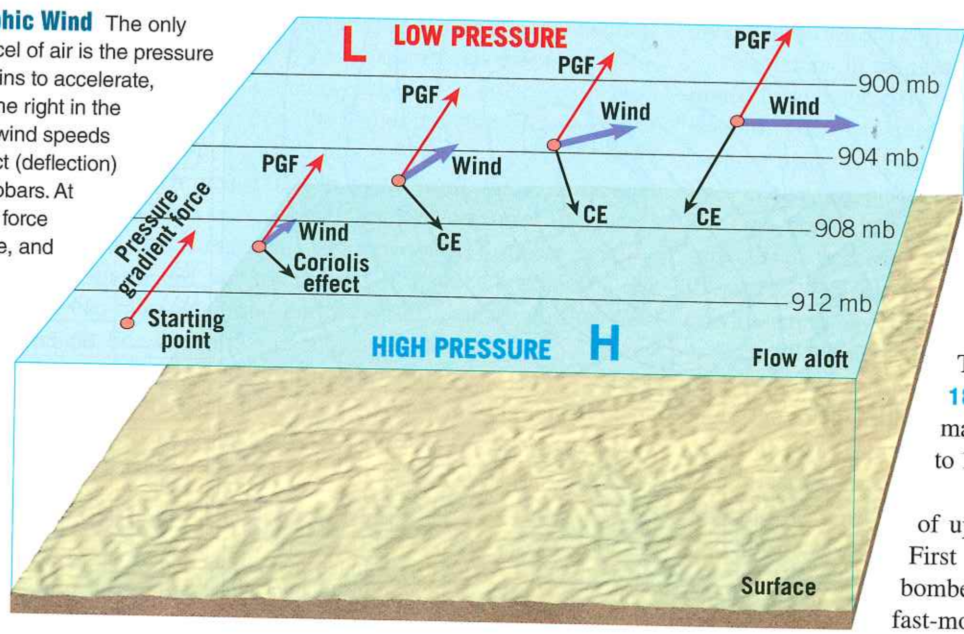
We attribute the apparent shift in wind direction to the Coriolis effect. This deflection (1) is always directed at right angles to the direction of airflow; (2) affects only wind direction, not wind speed; (3) is affected by wind speed (the stronger the wind, the greater the deflection); and (4) is strongest at the poles and weakens equatorward, becoming nonexistent at the equator.

Note that any free-moving object will experience a deflection caused by the Coriolis effect. The U.S. Navy dramatically discovered this fact in World War II. During target practice, long-range guns on battleships continually missed their targets by as much as several hundred yards until ballistic corrections were made for the changing position of a seemingly stationary target. Over a short distance, however, the Coriolis effect is relatively small.

Friction with Earth's Surface

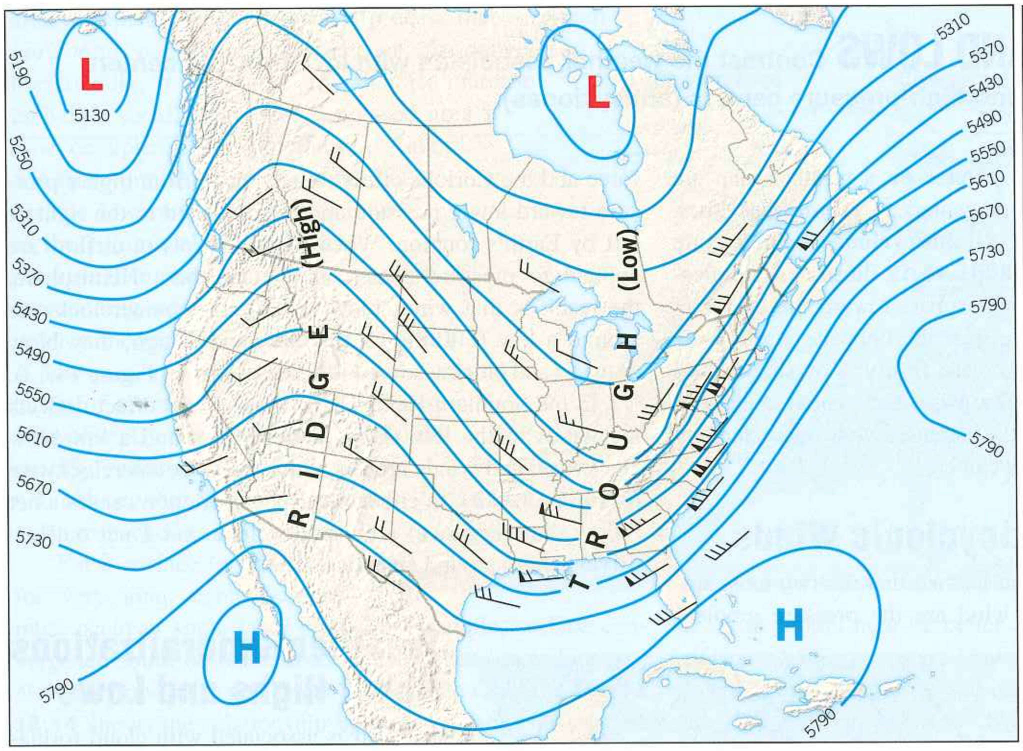
The effect of friction on wind is important only within a few kilometers of Earth's surface. Friction acts to slow air movement and, as a consequence, alters wind direction. To illustrate friction's effect on wind direction, let us look at a situation in which friction has no role. Above the friction layer, the pressure gradient force and Coriolis effect work together to direct the flow of air. Under these conditions, the pressure gradient force causes air to start moving across the isobars. As soon as the air starts to move, the Coriolis effect acts at right angles to this motion. The faster the wind speed, the greater the deflection.

IGURE 18.9 The Geostrophic Wind The only rce acting on a stationary parcel of air is the pressure radient force. Once the air begins to accelerate, e Coriolis effect deflects it to the right in the orthern Hemisphere. Greater wind speeds esult in a stronger Coriolis effect (deflection) ntil the flow is parallel to the isobars. At is point, the pressure gradient force nd Coriolis effect are in balance, and e flow is called a *geostrophic ind*. It is important to note at in the "real" atmosphere, rflow is continually adjusting r variations in the pressure ld. As a result, the ljustment to geostrophic uilibrium is much more egular than shown.



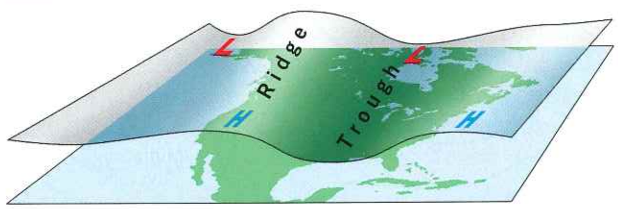
Eventually, the Coriolis effect will balance the pressure gradient force, and the wind will blow parallel to the isobars (**FIGURE 18.9**). Upper-air winds generally take this path and are called **geostrophic winds**. The lack of friction with Earth's surface allows geostrophic winds to travel at higher speeds than do surface winds. This can be observed in **FIGURE 18.10** by noting the wind flags, many of which indicate winds of 50 to 100 miles per hour.

The most prominent features of upper-level flow are **jet streams**. First encountered by high-flying bombers during World War II, these fast-moving "rivers" of air travel



Wind speed symbols	Miles per hour
◎	Calm
	1–2
	3–8
	9–14
	15–20
	21–25
	26–31
	32–37
	38–43
	44–49
	50–54
	55–60
	61–66
	67–71
	72–77
	78–83
	84–89
	119–123

Upper-level weather chart



Representation of upper-level chart

FIGURE 18.10 Upper-Air Weather Chart This simplified weather chart shows the direction and speed of the upper-air winds. Note from the flags that the airflow is almost parallel to the contours. Like most other upper-air charts, this one shows variations in the height (in meters) at which a selected pressure (500 millibars) is found instead of showing variations in pressure at a fixed height, like surface maps. Do not let this confuse you because there is a simple relationship between height contours and pressure. Places experiencing 500-millibar pressure at higher altitudes (toward the south on this map) are experiencing higher pressures than are places where the height contours indicate lower altitudes. Thus, *higher-elevation* contours indicate *higher* surface pressures, and *lower-elevation* contours indicate *lower* surface pressures.

between 120 and 240 kilometers (75 and 150 miles) per hour in a west-to-east direction. One such stream is situated over the polar front, which is the zone separating cool polar air from warm subtropical air.

Below 600 meters (2000 feet), friction complicates the airflow just described. Recall that the Coriolis effect is proportional to wind speed. Friction lowers the wind speed, so it reduces the Coriolis effect. Because the pressure gradient force is not affected by wind speed, it wins the tug of war shown in **FIGURE 18.11**. The result is a movement of air at an angle across the isobars, toward the area of lower pressure.

The roughness of the terrain determines the angle of airflow across the isobars. Over the smooth ocean surface, friction is low, and the angle is small. Over rugged terrain, where friction is higher, the angle that air makes as it flows across the isobars can be as great as 45 degrees.

In summary, upper airflow is nearly parallel to the isobars, whereas the effect of friction causes the surface winds to move more slowly and cross the isobars at an angle.

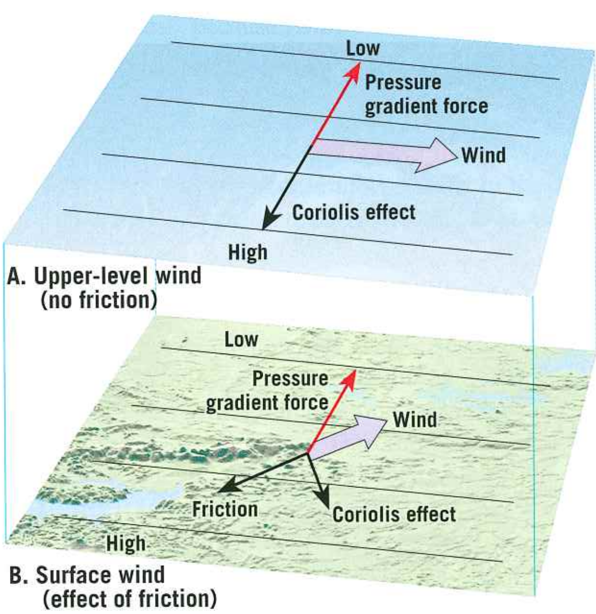


FIGURE 18.11 The Effects of Friction on Wind Friction has little effect on winds aloft, so airflow is parallel to the isobars. In contrast, friction slows surface winds, which weakens the Coriolis effect, causing winds to cross the isobars and move toward the lower pressure.

18.2 CONCEPT CHECKS

1. List three factors that combine to direct horizontal airflow (wind).
2. What force is responsible for generating wind?
3. Write a generalization relating the spacing of isobars to wind speed.
4. Briefly describe how the Coriolis effect influences air movement.
5. Unlike winds aloft, which blow nearly parallel to the isobars, surface winds generally cross the isobars. Explain what causes this difference.

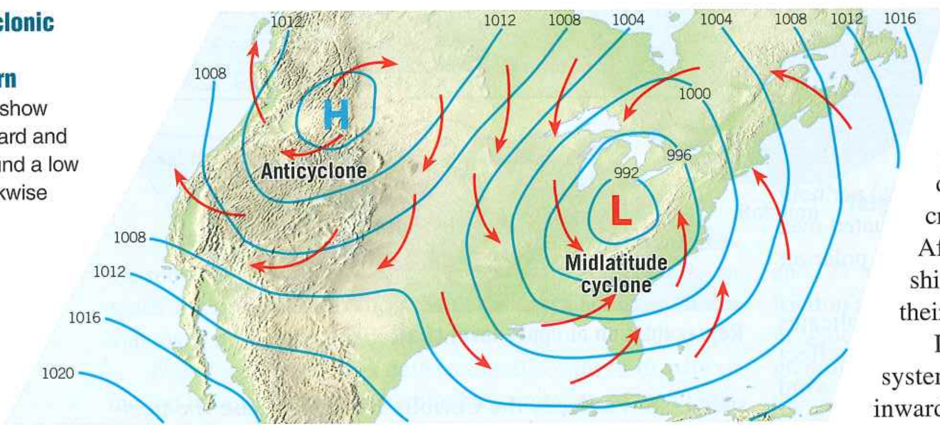
18.3 HIGHS AND LOWS Contrast the weather associated with low-pressure centers (cyclones) and high-pressure centers (anticyclones).

Among the most common features on a weather map are areas designated as pressure centers. **Cyclones,** or **lows,** are centers of low pressure, and **anticyclones,** or **highs,** are high-pressure centers. As **FIGURE 18.12** illustrates, the pressure decreases from the outer isobars toward the center in a cyclone. In an anticyclone, just the opposite is the case: The values of the isobars increase from the outside toward the center. Knowing just a few basic facts about centers of high and low pressure greatly increases your understanding of current and forthcoming weather.

Cyclonic and Anticyclonic Winds

In the preceding section, you learned that the two most significant factors that affect wind are the pressure gradient force and the Coriolis effect. Winds move from higher pressure toward lower pressure and are deflected to the right or left by Earth's rotation. When these controls of airflow are applied to pressure centers in the Northern Hemisphere, the result is that winds blow inward and counterclockwise around a low (**FIGURE 18.13A**). Around a high, they blow outward and clockwise (see left side of map in Figure 18.12).

In the Southern Hemisphere, the Coriolis effect deflects the winds to the left; therefore, winds around a low blow clockwise, and winds around a high move counterclockwise (**FIGURE 18.13B**). In either hemisphere, friction causes a net inflow (**convergence**) around a cyclone and a net outflow (**divergence**) around an anticyclone.



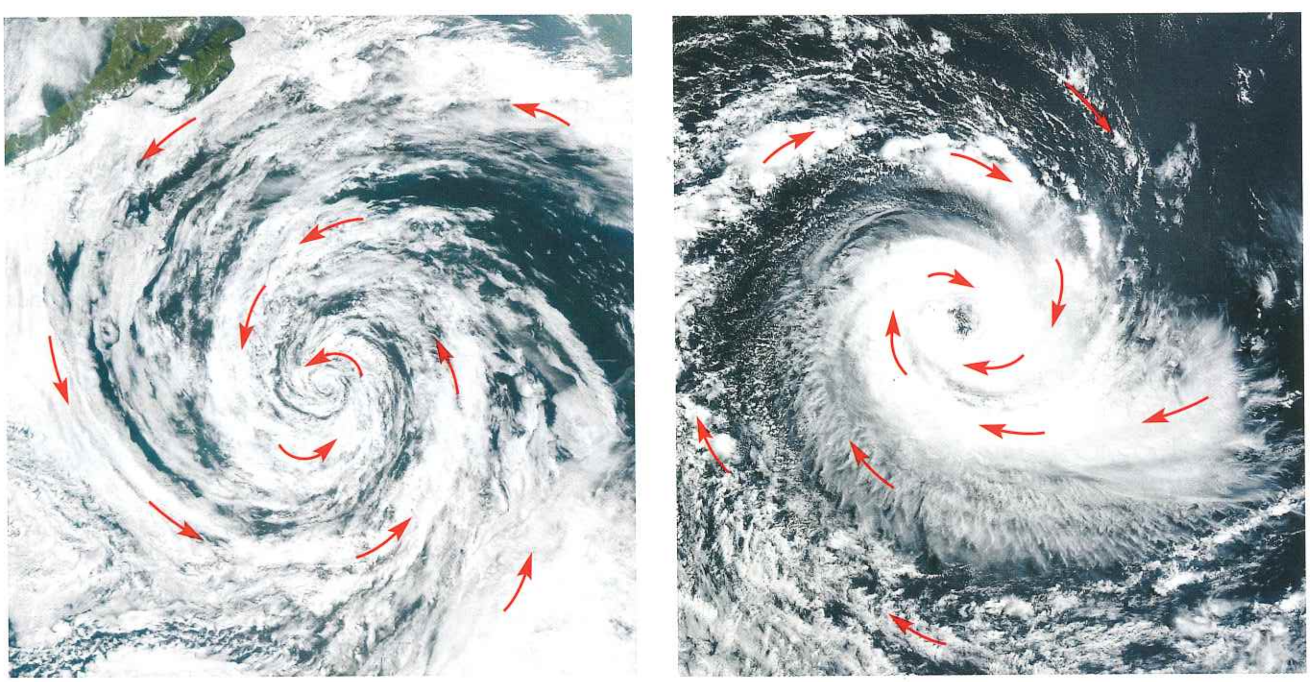
RE 18.12 Cyclonic Anticyclonic ls in the Northern isphere Arrows show inds blowing inward and terclockwise around a low outward and clockwise nd a high.

Weather Generalizations About Highs and Lows

Rising air is associated with cloud formation and precipitation, whereas subsidence produces clear skies. In this section we will discuss how the movement of air can itself create pressure change and generate winds. After doing so, we will examine the relationship between horizontal and vertical flow, and their effects on weather.

Let us first consider a surface low-pressure system where the air is spiraling inward. The net inward transport of air causes a shrinking of the

URE 18.13 Cyclonic ulation in the hern and Southern ispheres The cloud rns in these images / us to "see" the lation pattern in the r atmosphere. (NASA es)



A. This satellite image shows a large low-pressure center in the Gulf of Alaska. The cloud pattern clearly shows an inward and counterclockwise spiral.

B. This satellite image shows a strong cyclonic storm in the South Atlantic near the coast of Brazil. The cloud pattern shows an inward and clockwise circulation.

area occupied by the air mass, a process that is termed *horizontal convergence.* Whenever air converges horizontally, it must pile up—that is, increase in height to allow for the decreased area it now occupies. This generates a "taller" and therefore heavier air column. Yet a surface low can exist only as long as the column of air exerts less pressure than that occurring in surrounding regions. We seem to have encountered a paradox: A low-pressure center causes a net accumulation of air, which increases its pressure. Consequently, a surface cyclone should quickly eradicate itself in a manner not unlike what happens when a vacuum-packed can is opened.

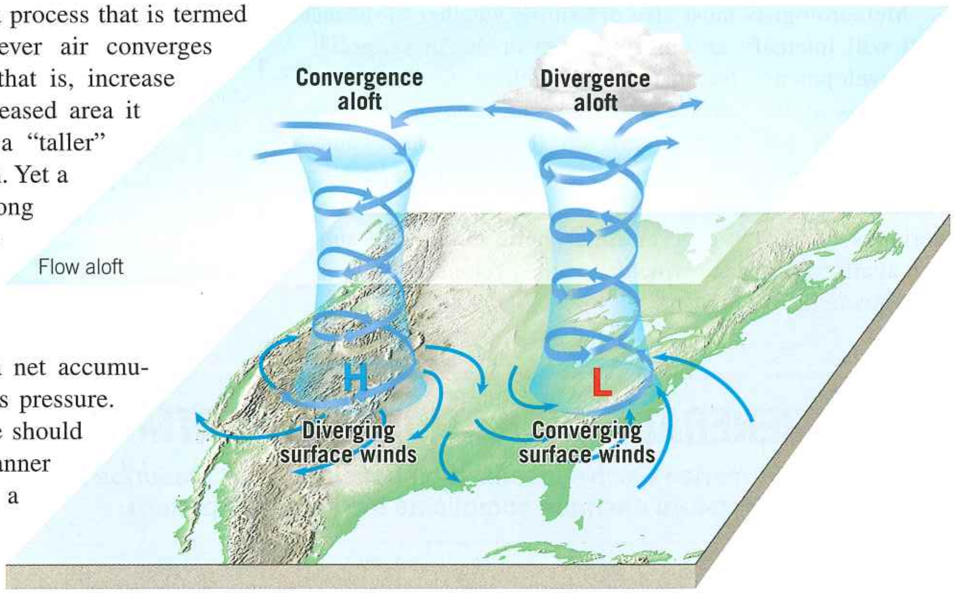


FIGURE 18.14 Airflow Associated with Surface Cyclones (L) and Anticyclones (H) A low, or cyclone, has converging surface winds and rising air, resulting in cloudy conditions. A high, or anticyclone, has diverging surface winds and descending air, which leads to clear skies and fair weather.

For a surface low to exist for very long, compensation must occur at some layer aloft. For example, surface convergence could be maintained if divergence (spreading out) aloft occurred at a rate equal to the inflow below. **FIGURE 18.14** shows the relationship between surface convergence and divergence aloft that is needed to maintain a low-pressure center.

Divergence aloft may even exceed surface convergence, thereby resulting in intensified surface inflow and accelerated vertical motion. Thus, divergence aloft can intensify storm centers as well as maintain them. On the other hand, inadequate divergence aloft permits surface flow to "fill" and weaken the accompanying cyclone.

Note that surface convergence about a cyclone causes a net upward movement. The rate of this vertical movement is slow, generally less than 1 kilometer (0.6 mile) per day. Nevertheless, because rising air often results in cloud formation and precipitation, a low-pressure center is generally related to unstable conditions and stormy weather (**FIGURE 18.15A**).

As often as not, it is divergence aloft that creates a surface low. Spreading out aloft initiates upflow in the atmosphere directly below, eventually working its way to the surface, where inflow is encouraged.

Like their cyclonic counterparts, anticyclones must be maintained from above. Outflow near the surface is accompanied by convergence aloft and general subsidence of the air column (see Figure 13.14). Because descending air is compressed and warmed, cloud formation and precipitation are unlikely in an anticyclone. Thus, fair weather can usually be expected with the approach of a high-pressure center (**FIGURE 18.15B**).

For reasons that should now be obvious, it has been common practice to print on household barometers the words "stormy" at the low-pressure end and "fair" on the high-pressure end. By noting whether the pressure is rising, falling, or steady, we have a good indication of what the forthcoming weather will be. Such a determination, called the **pressure,** or **barometric, tendency**, is a useful aid in short-range weather prediction.

You should now be better able to understand why television weather reporters emphasize the positions and projected paths of cyclones and anticyclones. The "villain" on these weather programs is always the low-pressure center, which produces "bad" weather in any season. Lows move in roughly a west-to-east direction across the United States and require a few days to more than a week for the journey. Because their paths can be somewhat erratic, accurate prediction of their migration is difficult, although essential, for short-range forecasting.

(A)

(B)

FIGURE 18.15 Weather Generalizations Related to Pressure Centers **A.** A rainy day in London. Low-pressure systems are frequently associated with cloudy conditions and precipitation. (Photo by Lourens Smak/Alamy) **B.** Clear skies and "fair" weather may be expected when an area is under the influence of high pressure. (Photo by Prisma Bildagentur AG/Alamy)

Meteorologists must also determine whether the flow aloft will intensify an embryo storm or act to suppress its development. Because of the close tie between conditions at the surface and those aloft, a great deal of emphasis has been placed on the importance and understanding of the total atmospheric circulation, particularly in the midlatitudes. We will now examine the workings of Earth's general atmospheric circulation and then again consider the structure of the cyclone in light of this knowledge.

18.3 CONCEPT CHECKS

1. Prepare a diagram with isobars and wind arrows that shows the winds associated with surface cyclones and anticyclones in both the Northern and Southern Hemispheres.
2. For a surface low-pressure center to exist for an extended period, what condition must exist aloft?
3. What general weather conditions are to be expected when the pressure tendency is rising? When the pressure tendency is falling?

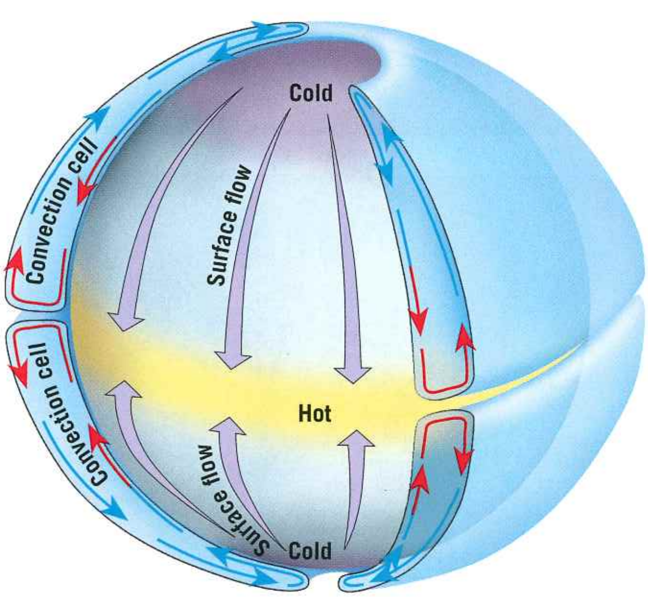
18.4 GENERAL CIRCULATION OF THE ATMOSPHERE

Summarize Earth's idealized global circulation. Describe how continents and seasonal temperature changes complicate the idealized pattern.

The underlying cause of wind is unequal heating of Earth's surface. In tropical regions, more solar radiation is received than is radiated back to space. In polar regions, the opposite is true: Less solar energy is received than is lost. Attempting to balance these differences, the atmosphere acts as a giant heat-transfer system, moving warm air poleward and cool air equatorward. On a smaller scale, but for the same reason, ocean currents also contribute to this global heat transfer. The general circulation is complex, and a great deal has yet to be explained. We can, however, develop a general understanding by first considering the circulation that would occur on a nonrotating Earth having a uniform surface. We will then modify this system to fit observed patterns.

Circulation on a Nonrotating Earth

On a hypothetical nonrotating planet with a smooth surface of either all land or all water, two large thermally produced cells would form (**FIGURE 18.16**). The heated equatorial air would rise until it reached the tropopause, which acts like a lid and deflects the air poleward. Eventually, this upper-level airflow would reach the poles, sink, spread out in all directions at the surface, and move back toward the equator. Once there, it would be reheated and start its journey over again. This hypothetical circulation system has upper-level air flowing poleward and surface air flowing equatorward.



URE 18.16 Global culation on a rotating Earth A ple convection system is duced by unequal heating he atmosphere.

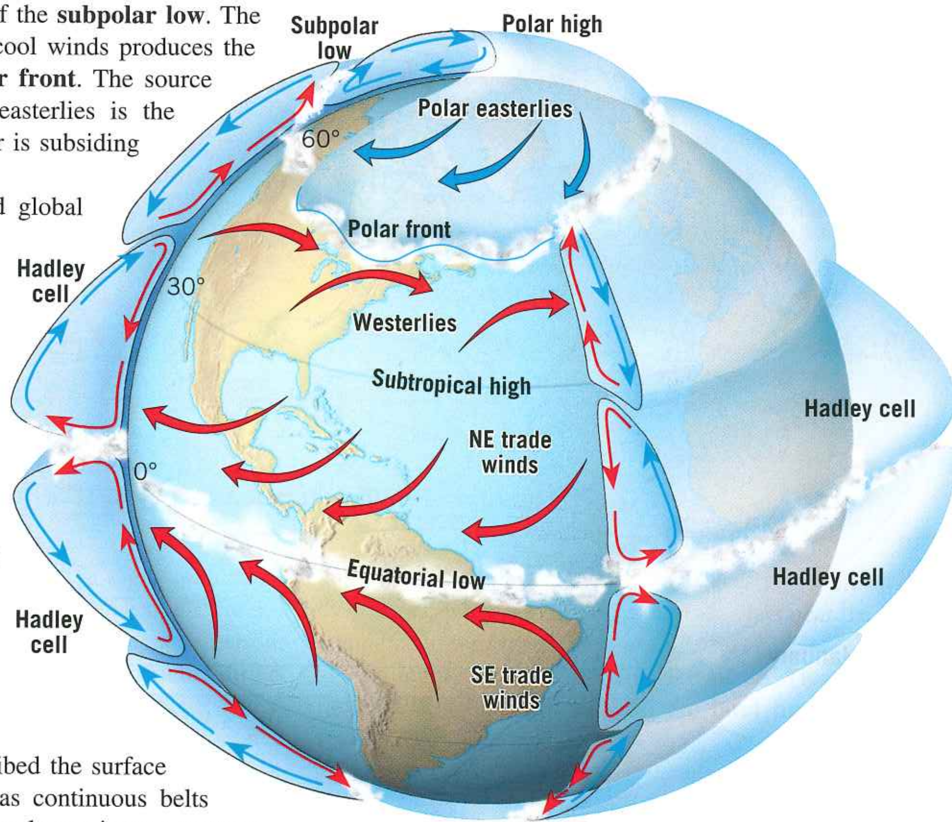
If we add the effect of rotation, this simple convection system will break down into smaller cells. **FIGURE 18.17** illustrates the three pairs of cells proposed to carry on the task of heat redistribution on a rotating planet. The polar and tropical cells retain the characteristics of the thermally generated convection described earlier. The nature of the midlatitude circulation is more complex and will be discussed in more detail in a later section.

Idealized Global Circulation

Near the equator, the rising air is associated with the pressure zone known as the **equatorial low**. This region of ascending moist, hot air is marked by abundant precipitation. Because this region of low pressure is a zone where winds converge, it is also referred to as the **intertropical convergence zone (ITCZ)**. As the upper-level flow from the equatorial low reaches 20° to 30° latitude, north or south, it sinks back toward the surface. This subsidence and associated adiabatic heating produce hot, arid conditions. The center of this zone of subsiding dry air is the **subtropical high**, which encircles the globe near 30° latitude, north and south (see Figure 18.17). The great deserts of Australia, Arabia, and Africa exist because of the stable, dry condition caused by the subtropical highs.

At the surface, airflow is outward from the center of the subtropical high. Some of the air travels equatorward and is deflected by the Coriolis effect, producing the reliable **trade winds**. The remainder travels poleward and is also deflected, generating the prevailing **westerlies** of the midlatitudes. As the westerlies move poleward, they encounter the cool polar easterlies** in the region of the **subpolar low**. The interaction of these warm and cool winds produces the stormy belt known as the **polar front**. The source region for the variable polar easterlies is the **polar high**. Here, cold polar air is subsiding and spreading equatorward.

In summary, this simplified global circulation is dominated by four pressure zones. The subtropical and polar highs are areas of dry subsiding air that flows outward at the surface, producing the prevailing winds. The low-pressure zones of the equatorial and subpolar regions are associated with inward and upward airflow accompanied by clouds and precipitation.



SmartFigure 18.17 Idealized Global Circulation Proposed for the Three-Cell Circulation Model of a Rotating Earth

Influence of Continents

Up to this point, we have described the surface pressure and associated winds as continuous belts around Earth. However, the only truly continuous pressure belt is the subpolar low in the Southern Hemisphere, where the ocean is uninterrupted by landmasses. At other latitudes, particularly in the Northern Hemisphere, where landmasses break up the ocean surface, large seasonal temperature differences disrupt the pattern. **FIGURE 18.18** shows the resulting pressure and wind patterns for January and July. The circulation over the oceans is dominated by semipermanent cells of high pressure in the subtropics and cells of low pressure over the subpolar regions. The subtropical highs are responsible for the trade winds and westerlies, as mentioned earlier.

The large landmasses, on the other hand, particularly Asia, become cold in the winter and develop a seasonal high-pressure system from which surface flow is directed off the land (see Figure 18.18). In the summer, the opposite occurs: The landmasses are heated and develop a low-pressure cell, which permits air to flow onto the land. These seasonal changes in wind direction are known as the **monsoons**. During warm months, areas such as India experience a flow of warm, water-laden air from the Indian Ocean, which produces the rainy summer monsoon. The winter monsoon is dominated by dry continental air. A similar situation exists, but to a lesser extent, over North America.

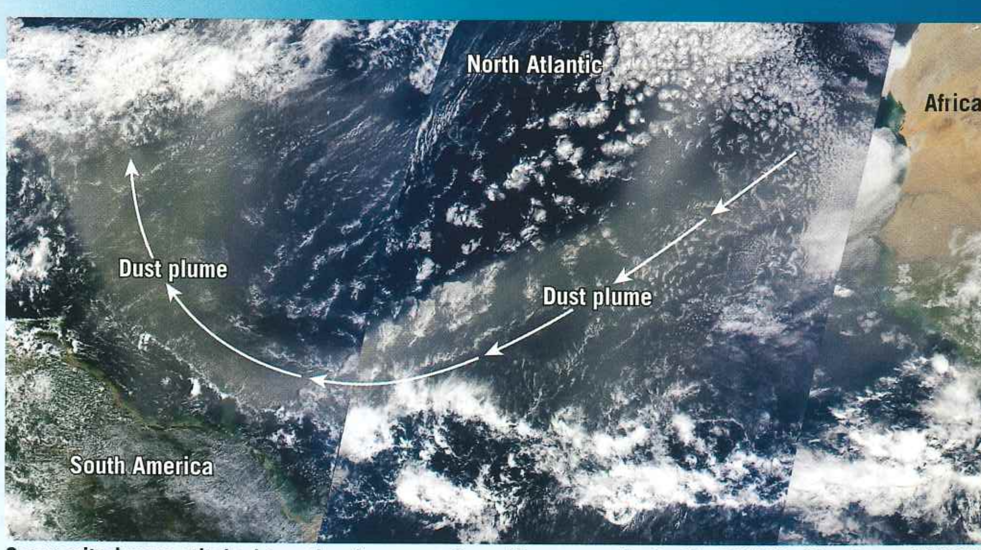
In summary, the general circulation is produced by semipermanent cells of high and low pressure over the

EYE ON EARTH

This image shows a January dust storm in Africa that produced a dust plume that reached all the way to the northeast coast of South America. It has been estimated that plumes such as this transport about 40 million tons of dust from the Sahara Desert to the Amazon basin each year. The minerals carried by these dust plumes help to replenish nutrients in rain forest soils that are continually being washed out of the soils by heavy tropical rains.

QUESTION 1 *Notice that the dust plume is following a curved path. Does the atmospheric circulation carrying this dust plume exhibit a clockwise or counterclockwise rotation?*

QUESTION 2 *What global pressure system was responsible for transporting this dust from Africa to South America? Referring to Figure 18.18 might be helpful.*



Composite image stitched together from a series of images collected by MODIS. (Courtesy of NASA)

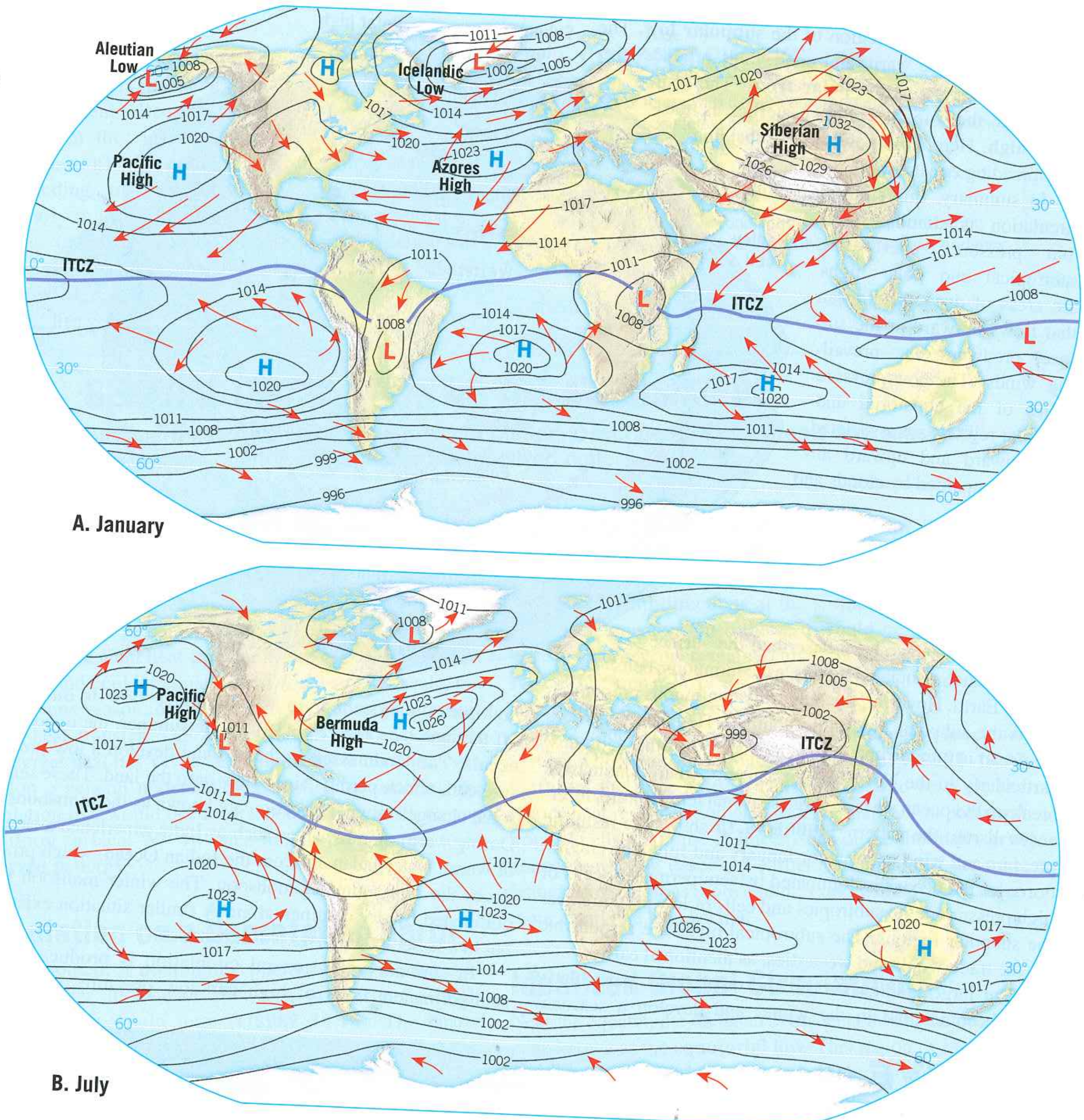


FIGURE 18.18 Average Surface Air Pressure These maps show the average surface air pressure, in millibars, for **A.** January and **B.** July, with associated winds.

oceans and is complicated by seasonal pressure changes over land.

The Westerlies

The circulation in the midlatitudes, the zone of the westerlies, is complex and does not fit the convection system proposed for the tropics. Between 30° and 60° latitude, the general west-to-east flow is interrupted by the migration of cyclones and anticyclones. In the Northern Hemisphere, these cells move from west to east around the globe, creating an anticyclonic (clockwise) flow or a cyclonic (counterclockwise) flow in their area of influence. A close correlation exists between the paths taken by these surface pressure systems and the position of the upper-level airflow, indicating that the upper air steers the movement of cyclonic and anticyclonic systems.

Among the most obvious features of the flow aloft are the seasonal changes. The steep temperature gradient across the middle latitudes in the winter months corresponds to a stronger flow aloft. In addition, the polar jet stream fluctuates seasonally such that its average position migrates southward with the approach of winter and northward as summer nears. By midwinter, the jet core may penetrate as far south as central Florida.

Because the paths of low-pressure centers are guided by the flow aloft, we can expect the southern tier of states to experience more of their stormy weather in the winter season. During the hot summer months, the storm track is across the northern states, and some cyclones never leave Canada. The northerly storm track associated with summer also applies to Pacific storms, which move toward Alaska during the warm months, thus producing an extended dry season for much of the West coast. The number of cyclones generated is seasonal as well, with the largest number occurring in the cooler months, when the temperature gradients are greatest. This fact is in agreement with the role of cyclonic storms in the distribution of heat across the midlatitudes.

18.4 CONCEPT CHECKS

1 Referring to the idealized model of atmospheric circulation, in which belt of prevailing winds is most of the United States?
2 The trade winds diverge from which pressure belt?
3 Which prevailing wind belts converge in the stormy region known as the polar front?
4 Which pressure belt is associated with the equator?
5 Explain the seasonal change in winds associated with India. What term is applied to this seasonal wind shift?

18.5 LOCAL WINDS

List three types of local winds and describe their formation.

Now that we have examined Earth's large-scale circulation, let us turn briefly to winds that influence much smaller areas. Remember that all winds are produced for the same reason: pressure differences that arise because of temperature differences caused by unequal heating of Earth's surface. **Local winds** are small-scale winds produced by a locally generated pressure gradient. Those described here are caused either by topographic effects or by variations in surface composition in the immediate area.

Land and Sea Breezes

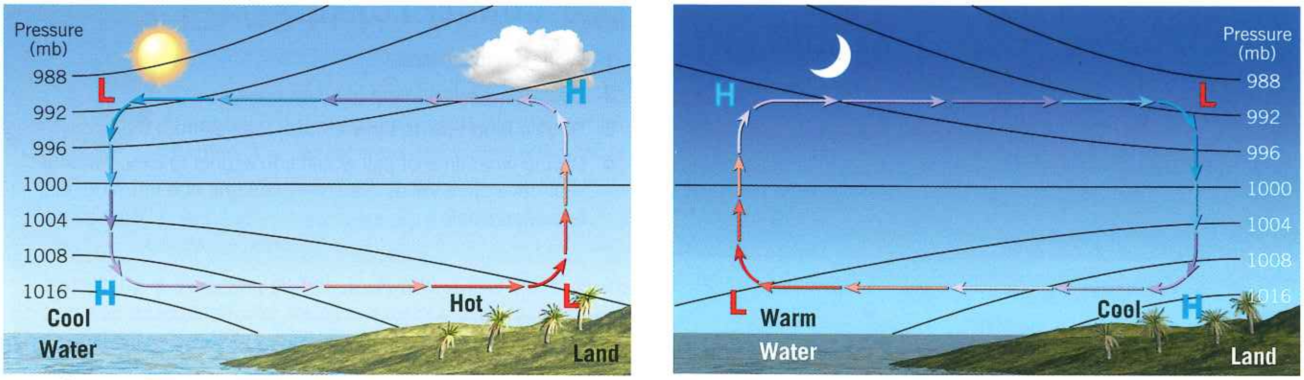
In coastal areas during the warm summer months, the land is heated more intensely during the daylight hours than is the adjacent body of water. As a result, the air above the land surface heats, expands, and rises, creating an area of lower pressure. A **sea breeze** then develops because cooler air over the water (higher pressure) moves toward the warmer land (lower pressure) (**FIGURE 18.19A**). The sea breeze begins to develop shortly before noon and generally reaches its greatest intensity during the mid- to late afternoon. These relatively cool winds can be a significant moderating influence on afternoon temperatures in coastal areas. Small-scale sea breezes can also develop along the shores of large lakes. People who live in a city near the Great Lakes, such as Chicago, recognize this lake effect, especially in the summer. They are reminded daily by weather reports of the cooler temperatures near the lake as compared to warmer outlying areas.

At night, the reverse may take place. The land cools more rapidly than the sea, and the **land breeze** develops (**FIGURE 18.19B**).

Mountain and Valley Breezes

A daily wind similar to land and sea breezes occurs in many mountainous regions. During daylight hours, the air along the slopes of the mountains is heated more intensely than the air at the same elevation over the valley floor. Because this warmer air is less dense, it glides up along the slope and generates a **valley breeze** (**FIGURE 18.20A**). The occurrence of these daytime upslope breezes can often be identified by the cumulus clouds that develop on adjacent mountain peaks.

After sunset, the pattern may reverse. Rapid radiation cooling along the mountain slopes produces a layer of cooler air next to the ground. Because cool air is denser than warm air, it drains downslope into the valley. This movement of air is called a **mountain breeze** (**FIGURE 18.20B**). The same type of cool air drainage can occur in places that have very modest slopes. The result is that the coldest pockets of air are usually found in the lowest spots.



A. During daylight hours, cooler and denser air over the water moves onto the land, generating a sea breeze.

B. At night the land cools more rapidly than the sea, generating an offshore flow called a land breeze.

SmartFigure 18.19 Sea and Land Breezes

FIGURE 18.20 Valley and Mountain Breezes

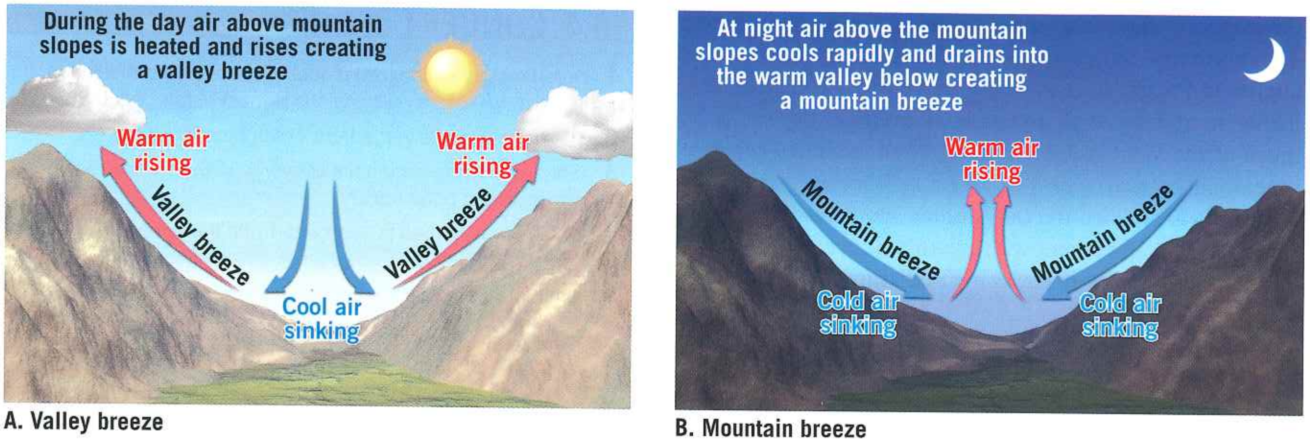


FIGURE 18.21 Santa Ana Winds Wildfires fanned by Santa Ana winds raged in southern California in October 2003. These fires scorched more than 740,000 acres and destroyed more than 3000 homes. The inset shows an idealized high-pressure center composed of cool, dry air that drives Santa Ana winds. Adiabatic heating causes the air temperature to increase and the relative humidity to decrease. (NASA)

Like many other winds, mountain and valley breezes have seasonal preferences. Although valley breezes are most common during the warm season, when solar heating is most intense, mountain breezes tend to be more dominant in the cold season.

Chinook and Santa Ana Winds

Warm, dry winds sometimes move down the east slopes of the Rockies, where they are called **chinooks**. Such winds are often created when a strong pressure gradient develops in a mountainous region. As the air descends the leeward slopes of the mountains, it is heated adiabatically (by compression). Because condensation may have occurred as the air ascended the windward side, releasing latent heat, the air descending the leeward slope will be warmer and drier than it was at a similar elevation on the windward side. Although the temperature of these winds is generally less than 10°C (50°F), which is not particularly warm, the winds occur mostly in the winter and spring, when the affected areas may be experiencing below-freezing temperatures. Thus, by comparison, these dry, warm winds often bring a drastic change. When the ground has a snow cover, these winds are known to melt it in short order.

A chinooklike wind that occurs in southern California is the **Santa Ana**. This hot, desiccating wind greatly increases the threat of fire in this already dry area (**FIGURE 18.21**).

18.5 CONCEPT CHECKS

1. What is a local wind?
2. Describe the formation of a sea breeze.
3. Does a land breeze blow toward or away from the shore?
4. During what time of day would you expect to experience a well-developed valley breeze—midnight, late morning, or late afternoon?

18.6 MEASURING WIND

Describe the instruments used to measure wind. Explain how wind direction is expressed using compass directions.

Two basic wind measurements, direction and speed, are particularly significant to weather observers. One simple device for determining both measurements is a *wind sock*, which is a common sight at small airports and landing strips (**FIGURE 18.22A**). The cone-shaped bag is open at both ends and is free to change position with shifts in wind direction. The degree to which the sock is inflated is an indication of wind speed.

Winds are always labeled by the direction from which they blow. A north wind blows *from* the north *toward* the south, an east wind *from* the east *toward* the west. The instrument most commonly used to determine wind direction is the **wind vane** (**FIGURE 18.22B**, upper right). This instrument, a common sight on many buildings, always points *into* the wind. The wind direction is often shown on a dial that is connected to the wind vane. The dial indicates wind direction, either by points of the compass (N, NE, E, SE, etc.) or by a scale of 0 to 360 degrees. On the latter scale, 0 degrees and 360 degrees are both north, 90 degrees is east, 180 degrees is south, and 270 degrees is west.

Wind speed is commonly measured using a **cup anemometer** (see Figure 18.22B, upper left). The wind speed is read from a dial much like the speedometer of an automobile. Places where winds are steady and speeds are relatively high are potential sites for tapping wind energy.

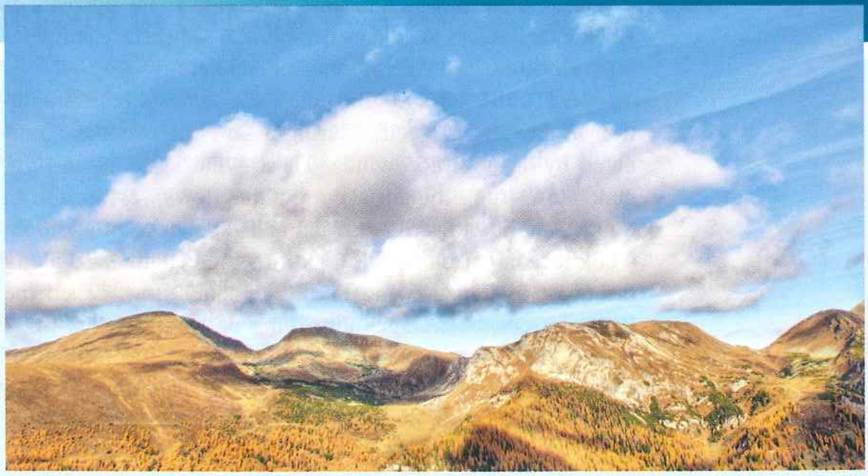
When the wind consistently blows more often from one direction than from any other, it is called a **prevailing wind**. You may be familiar with the prevailing westerlies that dominate the circulation in the midlatitudes. In the United States, for example, these winds consistently move the "weather"

A.

B.

FIGURE 18.22 Measuring the Wind The two basic wind measurements are speed and direction. (Photo A by Lourens Smak/Alamy Images; photo B by Belfort Instrument Company)

EYE ON EARTH



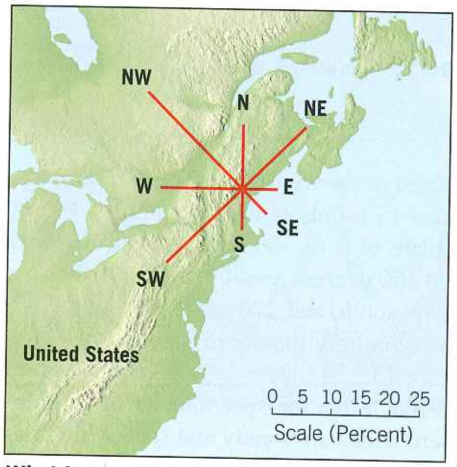
This mountain area was cloud free as this summer day began. By afternoon these clouds had formed. The clouds were associated with a local wind. (Photo by Herbert Koeppel/Alamy Images)

QUESTION 1 *With which local wind are the clouds in this photo most likely associated?*

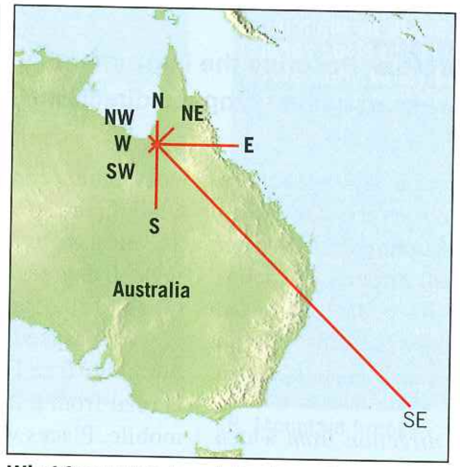
QUESTION 2 *Describe the process that created the local wind that was associated with the formation of these clouds.*

QUESTION 3 *Would you expect clouds such as these to form at night?*

FIGURE 18.23 Wind Roses These graphs show the percentage of time winds come from various directions.



Wind frequency for winter in the northeastern United States.



Wind frequency for winter in northeastern Australia. Note the reliability of the southeast trade winds in Australia as compared to the westerlies in the northeastern United States.

from west to east across the continent. Embedded within this general eastward flow are cells of high and low pressure, with their characteristic clockwise and counterclockwise flow. As a result, the winds associated with the westerlies, as measured at the surface, often vary considerably from day to day and from place to place. By contrast, the direction of airflow associated with the belt of trade winds is much more consistent, as can be seen in **FIGURE 18.23**.

By knowing the locations of cyclones and anticyclones in relation to where you are, you can predict the changes in wind direction that will occur as a pressure center moves past. Because changes in wind direction often bring changes in temperature and moisture conditions, the ability to predict the winds can be very useful. In the Midwest, for example, a north wind may bring cool, dry air from Canada, whereas a south wind may bring warm, humid air from the Gulf of Mexico. Sir Francis Bacon summed it up nicely when he wrote, "Every wind has its weather."

18.6 CONCEPT CHECKS

1. What are the two basic wind measurements? What instruments are used to make these measurements?
2. *From* what direction does a northeast wind blow? *Toward* what direction does a south wind blow?

18.7 EL NIÑO AND LA NIÑA AND THE SOUTHERN OSCILLATION

Describe the Southern Oscillation and its relationship to El Niño and La Niña. List the climate impacts to North America of El Niño and La Niña.

El Niño was first recognized by fishermen from Ecuador and Peru, who noted a gradual warming of waters in the eastern Pacific in December or January. Because the warming usually occurred near the Christmas season, the event was named El Niño—"little boy," or "Christ child," in Spanish. These periods of abnormal warming happen at irregular intervals of 2 to 7 years and usually persist for spans of 9 months to 2 years. **La Niña**, which means "little girl," is the opposite of El Niño and refers to colder-than-normal sea-surface temperatures along the coastline of Ecuador and Peru.

As **FIGURE 18.24A** illustrates, the atmospheric circulation in the central Pacific during a La Niña event is dominated by strong trade winds. These wind systems, in turn, generate a strong equatorial current that flows westward from South America toward Australia and Indonesia. In addition, a cold ocean current is observed flowing equatorward along the coast of Ecuador and Peru. The latter flow, called the Peru Current, encourages upwelling of cold, nutrient-filled waters that serve as the primary food source for millions of small feeder fish, particularly anchovies. Therefore, fishing is particularly good during the periods of strong upwelling. Every few years, however, the circulation associated with La Niña is replaced by an El Niño event (**FIGURE 18.24B**).

Impact of El Niño

El Niño is noted for its potentially catastrophic impact on the weather and economies of Peru, Chile, and Australia, among other countries. As shown in Figure 18.24B, during an El Niño, strong equatorial countercurrents amass large quantities of warm water that block the upwelling of colder, nutrient-filled water along the west coast of South America. As a result, the anchovies, which support the population of game fish, starve, devastating the fishing industry. At the same time, some inland areas of Peru and Chile that are normally arid receive above-average rainfall, which can cause major flooding. These climatic fluctuations have been known for years, but they were considered local phenomena.

Scientists now recognize that El Niño is part of the global atmospheric circulation pattern that affects the weather at great distances from Peru. One of the most severe El Niño events on record occurred in 1997–1998 and was responsible

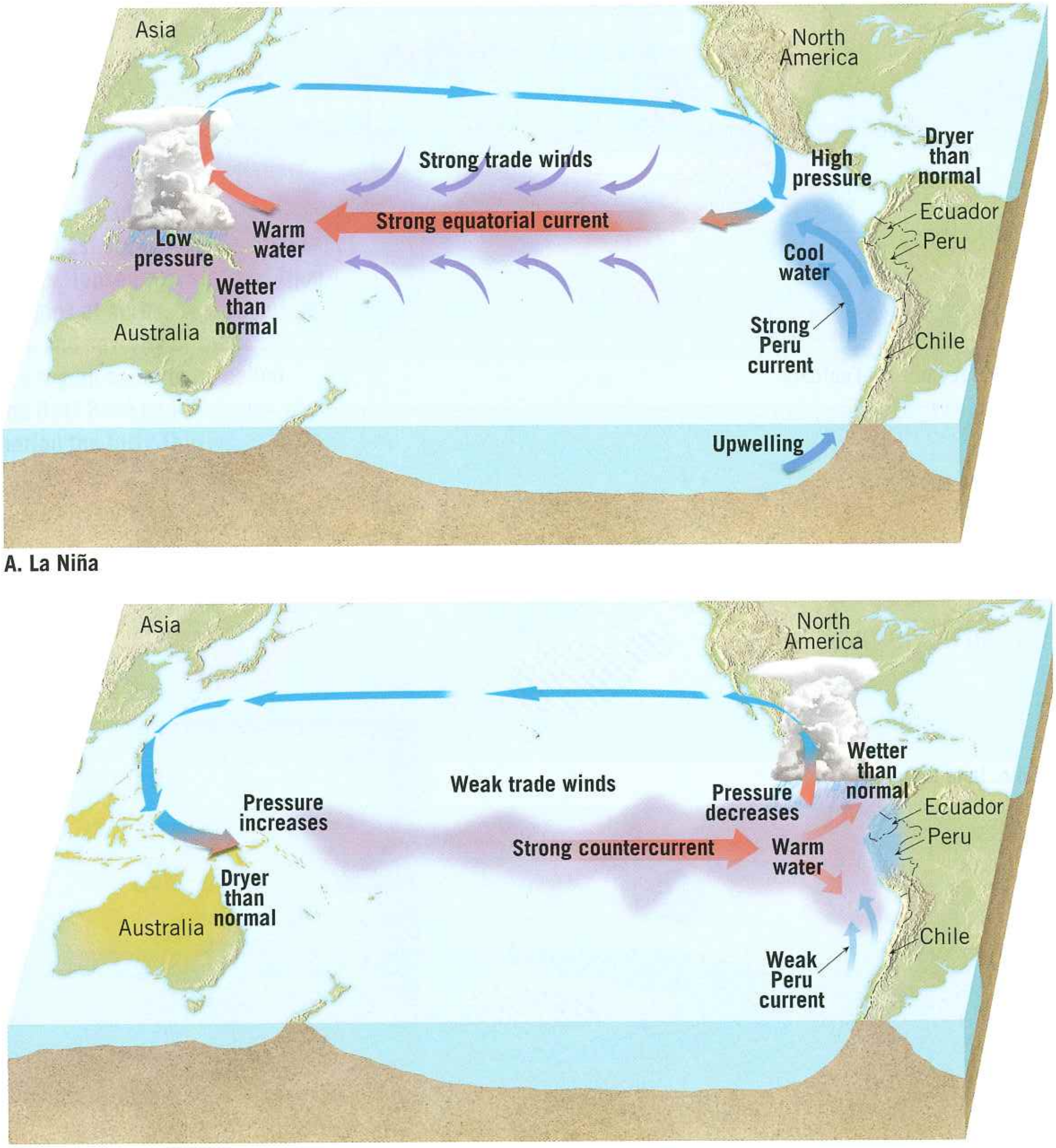


FIGURE 18.24 The Relationship Between El Niño, La Niña, and the Southern Oscillation

A. During a La Niña event, strong trade winds drive the equatorial currents toward the west. At the same time, the strong Peru Current causes upwelling of cold water along the west coast of South America. **B.** When the Southern Oscillation occurs, the pressure over the eastern and western Pacific flip-flops. This causes the trade winds to diminish, leading to an eastward movement of warm water along the equator and the beginning of an El Niño. As a result, the surface waters of the central and eastern Pacific warm, with far-reaching consequences for weather patterns.

for a variety of weather extremes in many parts of the world. During this episode, ferocious winter storms struck the California coast, causing unprecedented beach erosion, landslides, and floods. In the southern United States, heavy rains also brought floods to Texas and the Gulf states.

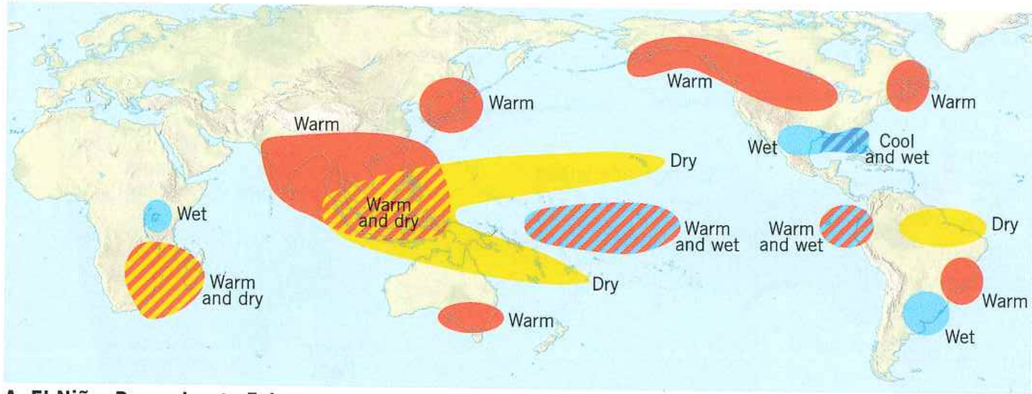
Although the effects of El Niño are somewhat variable, some locales appear to be affected more consistently. In particular, during the winter, warmer-than-normal conditions prevail in the north-central United States and parts of Canada (**FIGURE 18.25A**). In addition, significantly wetter winters are experienced in the southwestern United States and northwestern Mexico, while the southeastern United States experiences wetter and cooler conditions. In the western Pacific, drought conditions are observed in parts of Indonesia, Australia, and the Philippines (see Figure 18.25A). One major benefit of El Niño is a lower-than-average number of Atlantic hurricanes. El Niño is credited with suppressing hurricanes during the 2009 hurricane season, the least active in 12 years.

Impact of La Niña

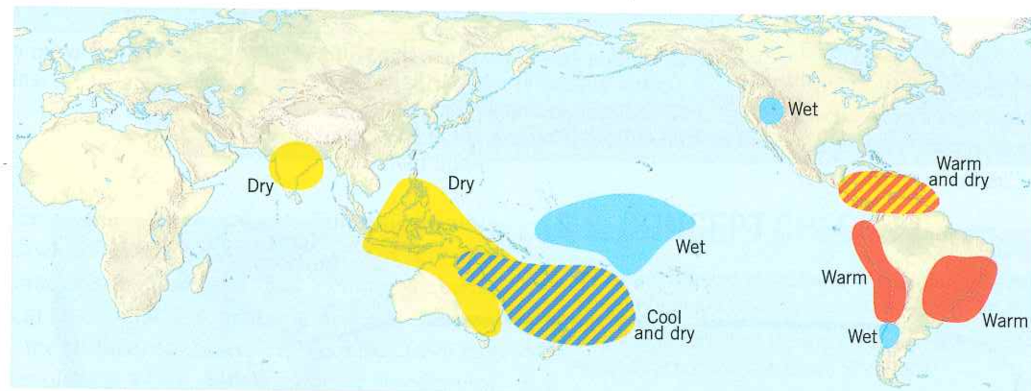
La Niña was once thought to be the normal conditions that occur between two El Niño events, but meteorologists now consider La Niña an important atmospheric phenomenon in its own right. Researchers have come to recognize that when surface temperatures in the eastern Pacific are *colder than average*, a La Niña event is triggered and exhibits a distinctive set of weather patterns (see Figure 18.24A).

Typical La Niña winter weather includes cooler and wetter conditions over the northwestern United States and especially cold winter temperatures in the Northern Plains states (**FIGURE 18.25C**). In addition, unusually warm conditions occur in the Southwest and Southeast. In the western Pacific,

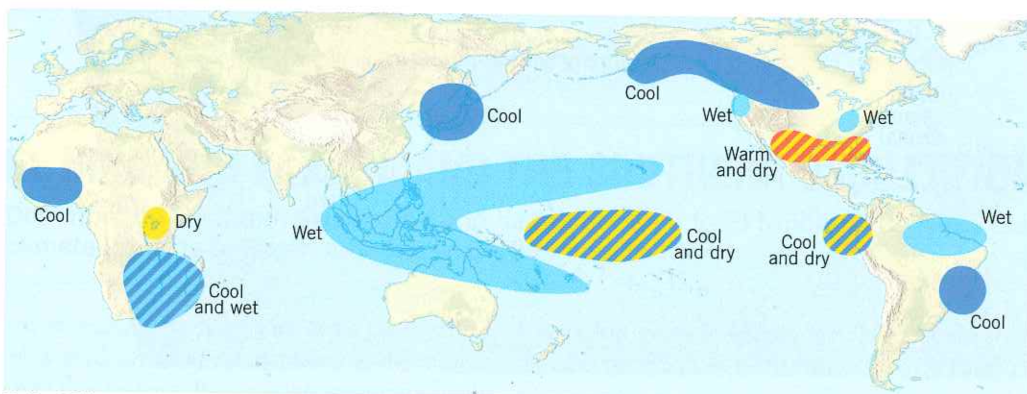
FIGURE 18.25 Climatic Impacts of El Niño and La Niña El Niño has the most significant impact on the climate of North America during the winter. In addition, El Niño affects the areas around the tropical Pacific in both winter and summer. Likewise, La Niña has its most significant impact on North America in the winter but influences other areas during all seasons.



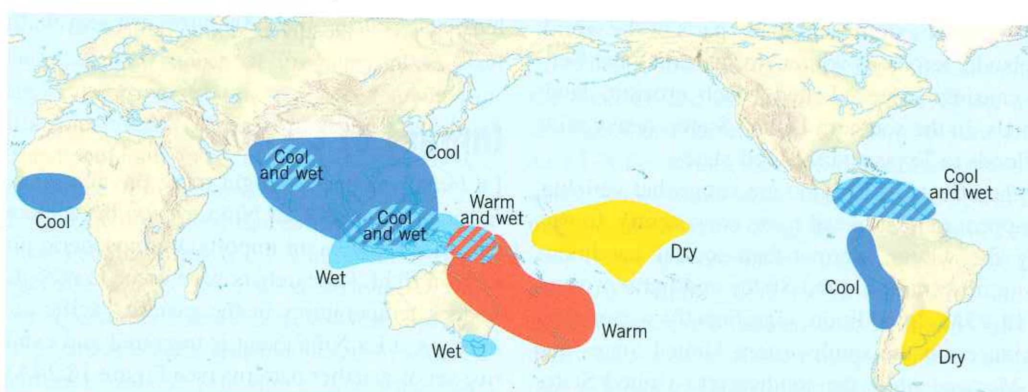
A. El Niño: December to February



B. El Niño: June to August



C. La Niña: December to February

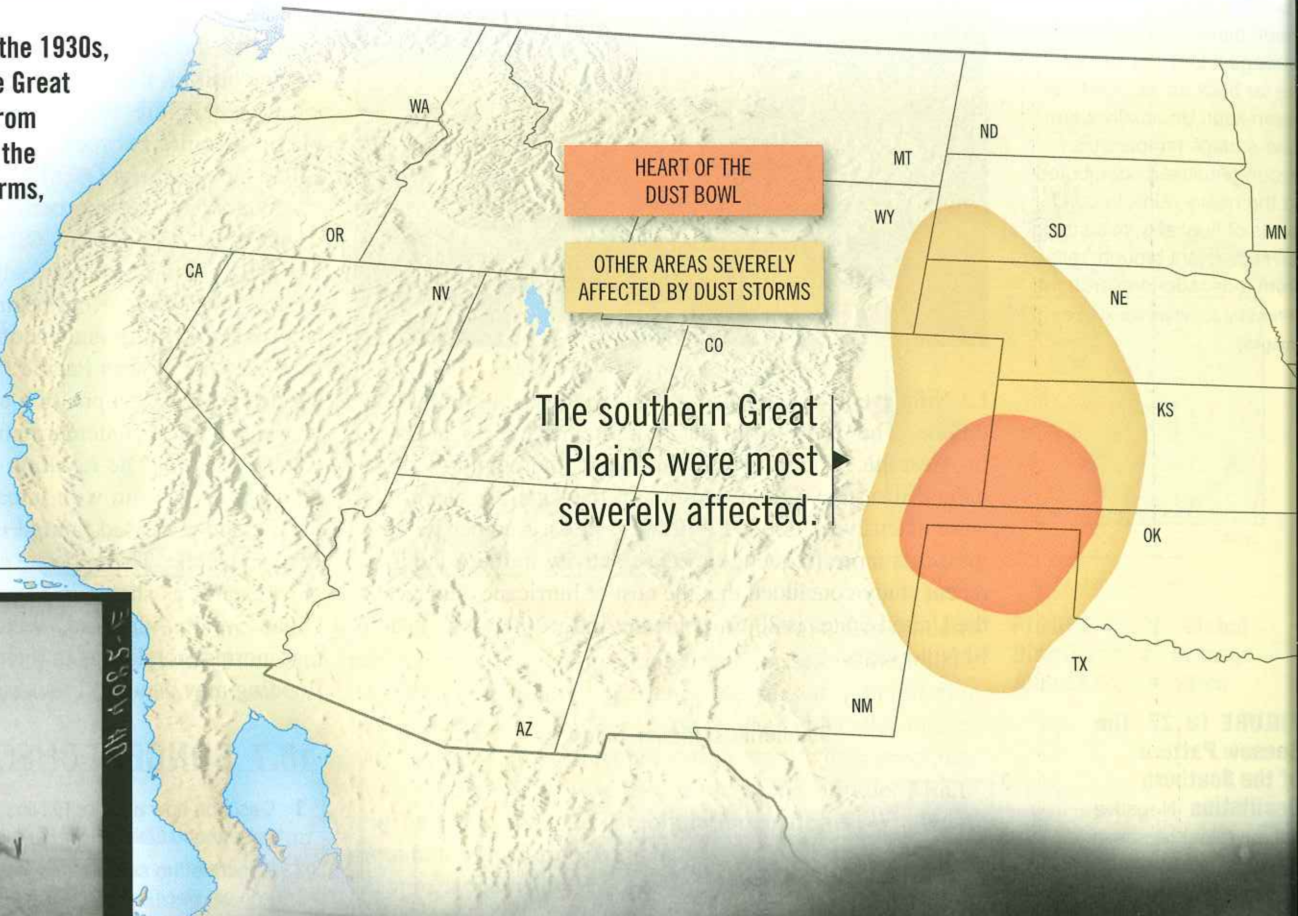


D. La Niña: June to August

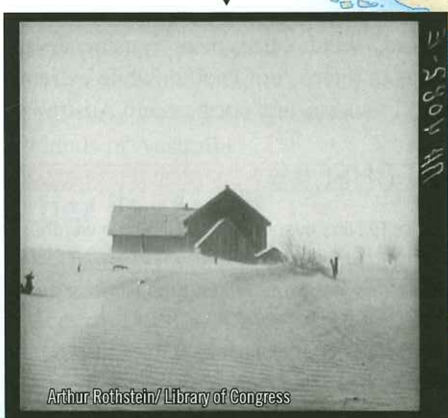
GEOGRAPHICS

The 1930s Dust Bowl
An Environmental Disaster

During a span of dry years in the 1930s, large dust storms plagued the Great Plains. Topsoil was stripped from millions of acres. Because of the size and severity of these storms, the region came to be called the Dust Bowl and the time period the Dirty Thirties.



In places, dust drifted like snow, covering farm buildings, fences, and fields. Crop failure and economic hardship resulted in many farms being abandoned.

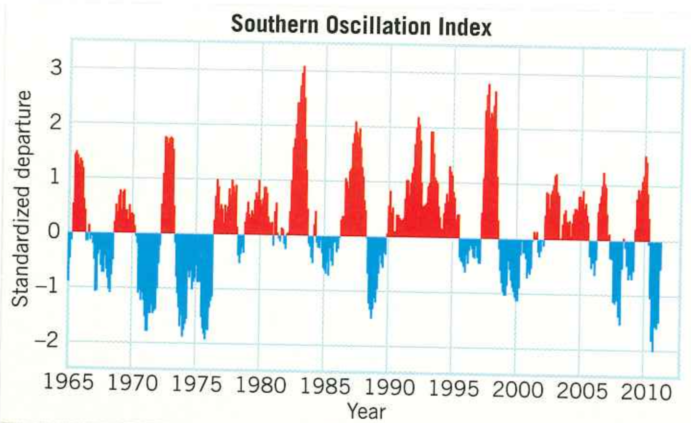

Arthur Rothstein/ Library of Congress

Dust blackens the sky near Elkhart, Kansas, on May 21, 1937. The transformation of semiarid grasslands into farms during an unusually wet period set the stage for this disastrous period of soil erosion. When drought struck, the unprotected soils were vulnerable to the wind.

Library of Congress

FIGURE 18.26 Queensland Floods A ocal resident rows through flood waters that turned this street in Rockhampton into a river. The Queensland floods of 2010–2011 have been attributed to one of the strongest La Niña events as far back as records have been kept. Unusually warm sea-surface temperatures around Australia contributed o the heavy rains. In other parts of Australia, this strong La Niña event brought relief rom a decade-long drought. Photo by Jonathan Wood/Getty mages)

La Niña events are associated with wetter-than-normal conditions. The 2010–2011 La Niña contributed to a deluge in Australia, which resulted in one of the country's worst natural disasters: Large portions of the state of Queensland were extensively flooded (**FIGURE 18.26**). Another La Niña impact is more frequent hurricane activity in the Atlantic. A recent study concluded that the cost of hurricane damages in the United States is 20 times greater in La Niña years than in El Niño years.



IGURE 18.27 The eesaw Pattern f the Southern scillation Negative alues (blue) represent e cold La Niña hase, whereas ositive values (red) present the warm Niño phase. The aph was created analyzing six riables, including a-surface mperatures and sea-vel pressures.

Southern Oscillation

Major El Niño and La Niña events are intimately related to the large-scale atmospheric circulation. Each time an El Niño occurs, the barometric pressure drops over large portions of the eastern Pacific and rises in the western Pacific (see Figure 18.24B). Then, as a major El Niño event comes to an end, the pressure difference between these two regions swings back in the opposite direction, triggering a La Niña event (see Figure 18.24A). This seesaw pattern of atmospheric pressure between the eastern and western Pacific is called the **Southern Oscillation** (**FIGURE 18.27**).

Winds are the link between the pressure change associated with the Southern Oscillation and the ocean warming and cooling associated with El Niño and La Niña. The start of an El Niño event begins with a rise in surface pressure over Australia and Indonesia and a decrease in pressure over the eastern Pacific (see Figure 18.24B). During a strong El Niño, this pressure change causes the trade winds to weaken and countercurrents to develop and move warm water eastward. The resulting change in atmospheric circulation takes the rain with it, causing drought in the western Pacific and increased rainfall in the normally dry regions of Peru and Chile. The opposite circulation develops during La Niña events, as shown in Figure 18.24A. When a strong La Niña develops, the trade winds strengthen, causing dryer-than-normal conditions in the eastern Pacific, while extreme flooding may occur in Indonesia and northeastern Australia.

18.7 CONCEPT CHECKS

1. Describe how a major El Niño event tends to affect the weather in Peru and Chile as compared to Indonesia and Australia.
2. Describe the sea-surface temperatures on both sides of the tropical Pacific during a La Niña event.
3. How does a major La Niña event influence the hurricane season in the Atlantic Ocean?
4. Briefly describe the Southern Oscillation and how it is related to El Niño and La Niña.
5. Describe how an El Niño event might affect the climate in North America during the winter. Describe the same for a La Niña event.

18.8 GLOBAL DISTRIBUTION OF PRECIPITATION

Discuss the major factors that influence the global distribution of precipitation.

A casual glance at **FIGURE 18.28** shows a relatively complex pattern for the distribution of precipitation. Although the map appears to be complicated, the general features of the map can be explained by applying our knowledge of global winds and pressure systems.

The Influence of Pressure and Wind Belts

In general, regions influenced by high pressure, with its associated subsidence and diverging winds, experience relatively dry conditions. On the other hand, regions under the influence of low pressure and its converging winds and ascending air receive ample precipitation. This pattern is illustrated by noting that the tropical regions dominated by the equatorial low are the rainiest regions on Earth. It is here that we find the rain forests of the Amazon basin in South America and the Congo basin in Africa. The warm, humid trade winds converge to yield abundant rainfall throughout the year. By contrast, areas dominated by the subtropical high-pressure cells clearly receive much smaller amounts of precipitation. These are the regions of

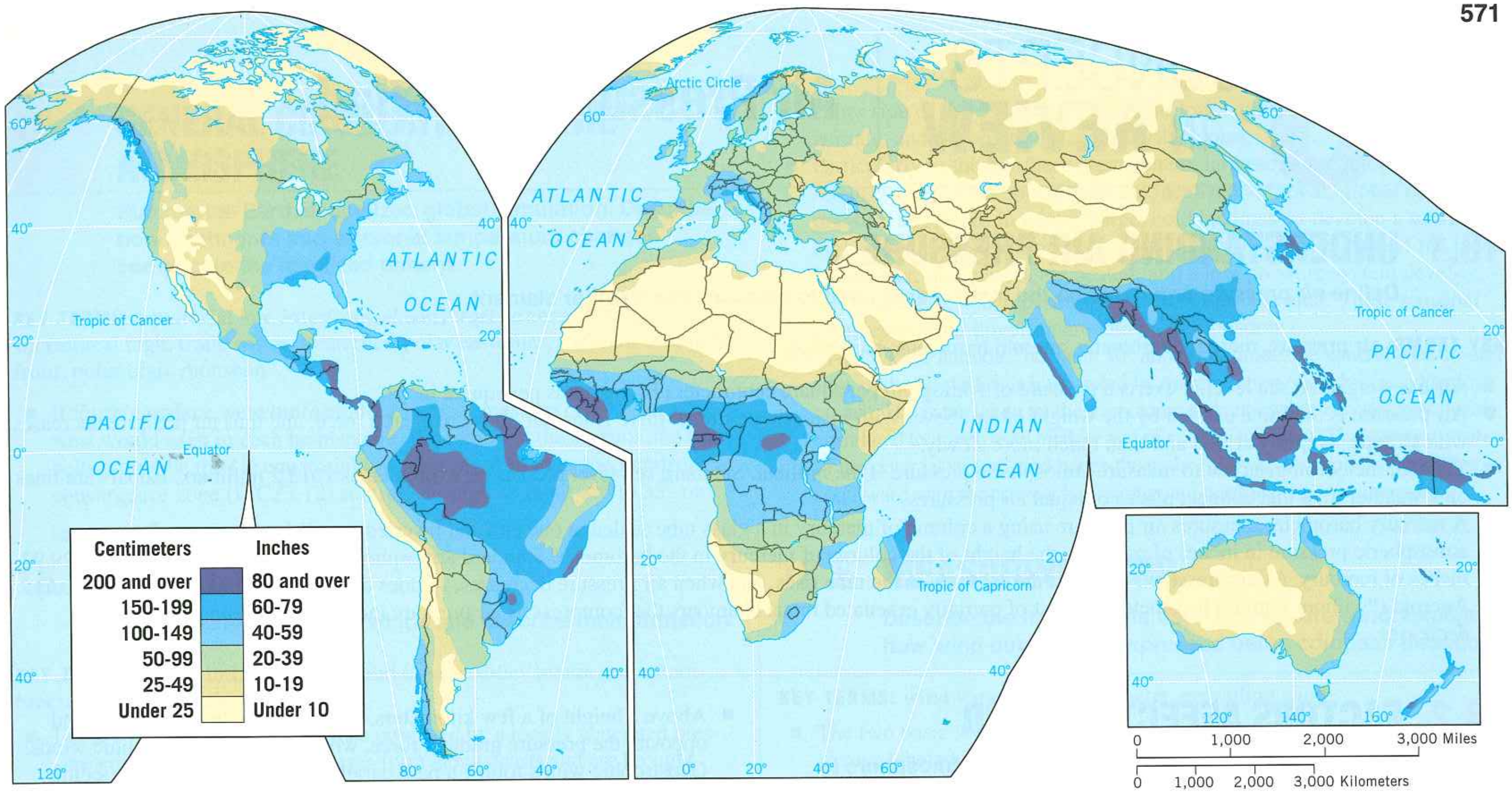


FIGURE 18.28 Global Distribution of Average Annual Precipitation

extensive subtropical deserts. In the Northern Hemisphere, the largest desert is the Sahara. Examples in the Southern Hemisphere include the Kalahari in southern Africa and the dry lands of Australia.

Other Factors

If Earth's pressure and wind belts were the only factors controlling precipitation distribution, the pattern shown in Figure 18.28 would be simpler. The inherent nature of the air is also an important factor in determining precipitation potential. Because cold air has a low capacity for moisture compared with warm air, we would expect a latitudinal variation in precipitation, with low latitudes receiving the greatest amounts of precipitation and high latitudes receiving the smallest amounts. Figure 18.28 indeed shows heavy rainfall in equatorial regions and meager precipitation in high-latitude areas. Recall that the dry region in the warm subtropics is explained by the presence of the subtropical high.

The distribution of land and water also complicates the precipitation pattern. Large landmasses in the middle latitudes commonly experience decreased precipitation toward their interiors. For example, central North America and central Eurasia receive considerably less precipitation than do coastal regions at the same latitude. Mountain barriers also alter precipitation patterns. Windward mountain slopes receive abundant precipitation, whereas leeward slopes and adjacent lowlands are often deficient in moisture.

18.8 CONCEPT CHECKS

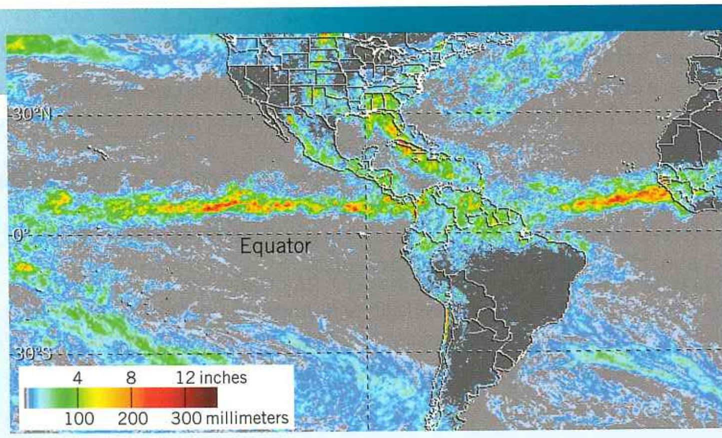
1. With which global pressure belt are the rain forests of Africa's Congo basin associated? Which pressure system is linked to the Sahara Desert?
2. What factors, in addition to the distribution of wind and pressure, influence the global distribution of precipitation?

EYE ON EARTH

This satellite image was produced with data from the *Tropical Rainfall Measuring Mission* (*TRMM*). Notice the band of heavy rainfall shown in reds and yellows that extends east–west across the image.

QUESTION 1 *With which pressure zone is this band of rainy weather associated?*

QUESTION 2 *Is it more likely that this image was acquired in July or January? Explain.*



18 CONCEPTS IN REVIEW Air Pressure and Wind

18.1 UNDERSTANDING AIR PRESSURE

Define *air pressure* and describe the instruments used to measure this weather element.

KEY TERMS: air pressure, mercury barometer, aneroid barometer, barograph

- Air has weight: At sea level, it exerts a pressure of 1 kilogram per square centimeter (14.7 pounds per square inch).
- Air pressure is the force exerted by the weight of air above. With increasing altitude, there is less air above to exert a force, and thus air pressure decreases with altitude—rapidly at first and then much more slowly.
- The unit meteorologists use to measure atmospheric pressure is the millibar. Standard sea-level pressure is expressed as 1013.2 millibars. Isobars are lines on a weather map that connect places of equal air pressures.
- A mercury barometer measures air pressure using a column of mercury in a glass tube sealed at one end and inverted in a dish of mercury. It measures atmospheric pressure in inches of mercury, the height of the column of mercury in the barometer. Standard atmospheric pressure at sea level equals 29.92 inches of mercury. As air pressure increases, the mercury in the tube rises, and when air pressure decreases, so does the height of the column of mercury.
- Aneroid ("without liquid") barometers consist of partially evacuated metal chambers that compress as air pressure increases and expand as pressure decreases.

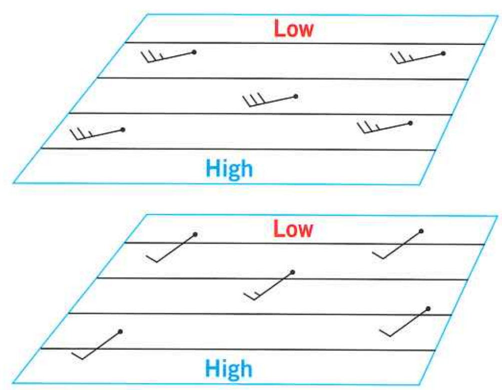
18.2 FACTORS AFFECTING WIND

Discuss the three factors that act on the atmosphere to either create or alter winds.

KEY TERMS: wind, isobar, pressure gradient force, Coriolis effect, geostrophic wind, jet stream

- Wind is controlled by a combination of (1) the pressure gradient force, (2) the Coriolis effect, and (3) friction. The pressure gradient force is the primary driving force of wind that results from pressure differences that are depicted by the spacing of isobars on a map. Closely spaced isobars indicate a steep pressure gradient and strong winds; widely spaced isobars indicate a weak pressure gradient and light winds.
- The Coriolis effect produces deviation in the path of wind due to Earth's rotation (to the right in the Northern Hemisphere and to the left in the Southern Hemisphere). Friction, which significantly influences airflow near Earth's surface, is negligible above a height of a few kilometers.
- Above a height of a few kilometers, the Coriolis effect is equal to and opposite the pressure gradient force, which results in geostrophic winds. Geostrophic winds follow a path parallel to the isobars, with velocities proportional to the pressure gradient force.

Q These diagrams show surface winds at two locations. All factors in both situations are identical except that one surface is land and the other is water. Which diagram represents winds over the land? Explain your choice.

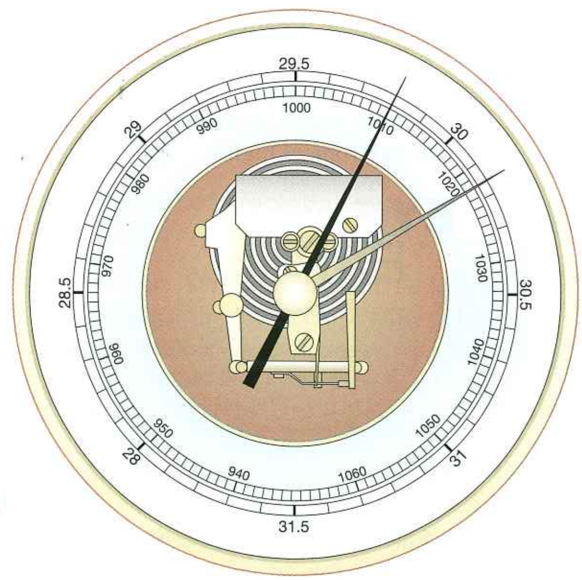


18.3 HIGHS AND LOWS

Contrast the weather associated with low-pressure centers (cyclones) and high-pressure centers (anticyclones).

KEY TERMS: cyclone (low), anticyclone (high), convergence, divergence, pressure (barometric) tendency

- The two types of pressure centers are (1) cyclones, or lows (centers of low pressure), and (2) anticyclones, or highs (high-pressure centers). In the Northern Hemisphere, winds around a low (cyclone) are counterclockwise and inward. Around a high (anticyclone), they are clockwise and outward. In the Southern Hemisphere, the Coriolis effect causes winds to be clockwise around a low and counterclockwise around a high.
- Because air rises and cools adiabatically in a low-pressure center, cloudy conditions and precipitation are often associated with their passage. In a high-pressure center, descending air is compressed and warmed; therefore, cloud formation and precipitation are unlikely in an anticyclone, and "fair" weather is usually expected.



Q Assume that you are an observer checking this aneroid barometer several hours after it was last checked. What is the pressure tendency? How did you figure this out? What does the tendency shown on the barometer indicate about forthcoming weather?

18.4 GENERAL CIRCULATION OF THE ATMOSPHERE

Summarize Earth's idealized global circulation. Describe how continents and seasonal temperature changes complicate the idealized pattern.

KEY TERMS: equatorial low, intertropical convergence zone (ITCZ), subtropical high, trade winds, westerlies, polar easterlies, subpolar low, polar front, polar high, monsoon

- If Earth's surface were uniform, four belts of pressure oriented east to west would exist in each hemisphere. Beginning at the equator, the four belts would be the (1) equatorial low, also referred to as the intertropical convergence zone (ITCZ), (2) subtropical high at about 25° to 35° on either side of the equator, (3) subpolar low, situated at about 50° to 60° latitude, and (4) polar high, near Earth's poles.
- Particularly in the Northern Hemisphere, large seasonal temperature differences over continents disrupt the idealized, or zonal, global patterns of pressure and wind. In winter, large, cold landmasses develop a seasonal high-pressure system from which surface airflow is directed off the land. In summer, landmasses are heated, and a low-pressure system develops over them, which permits air to flow onto the land. These seasonal changes in wind direction are known as monsoons.
- In the middle latitudes, between 30° and 60° latitude, the general west-to-east flow of the westerlies is interrupted by the migration of cyclones and anticyclones. The paths taken by these cyclonic and anticyclonic systems is closely correlated to upper-level airflow and the polar jet stream. The average position of the polar jet stream, and hence the paths followed by cyclones, migrates southward with the approach of winter and northward as summer nears.

18.5 LOCAL WINDS

List three types of local winds and describe their formation.

KEY TERMS: local wind, sea breeze, land breeze, valley breeze, mountain breeze, chinook, Santa Ana

- Local winds are small-scale winds produced by a locally generated pressure gradient. Sea and land breezes form along coasts and are brought about by temperature contrasts between land and water. Valley and mountain breezes occur in mountainous areas where the air along slopes heats differently than does the air at the same elevation over the valley floor. Chinook and Santa Ana winds are warm, dry winds created when air descends the leeward side of a mountain and warms by compression.

Q It is late afternoon on a warm summer day and you are enjoying some time at the beach. Until the last hour or two, winds were calm. Then a breeze began to develop. Is it more likely a cool breeze from the water or a warm breeze from the adjacent land area? Explain.

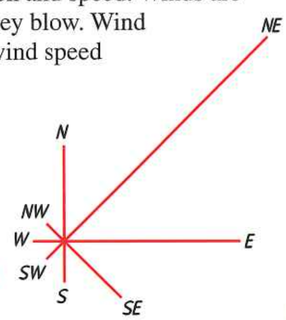
18.6 MEASURING WIND

Describe the instruments used to measure wind. Explain how wind direction is expressed using compass directions.

KEY TERMS: wind vane, cup anemometer, prevailing wind

- The two basic wind measurements are direction and speed. Winds are always labeled by the direction from which they blow. Wind direction is measured with a wind vane, and wind speed is measured using a cup anemometer.

Q When designing an airport, it is important to have planes take off *into* the wind. Refer to the accompanying wind rose and describe the orientation of the runway and the direction planes would usually travel when they took off. Where on Earth might you find a wind rose like this?



18.7 EL NIÑO AND LA NIÑA AND THE SOUTHERN OSCILLATION

Describe the Southern Oscillation and its relationship to El Niño and La Niña. List the climate impacts to North America of El Niño and La Niña.

KEY TERMS: El Niño, La Niña, Southern Oscillation

- El Niño refers to episodes of ocean warming in the eastern Pacific along the coasts of Ecuador and Peru. It is associated with weak trade winds, a strong eastward moving equatorial countercurrent, a weakened Peru Current, and diminished upwelling along the western margin of South America.
- A La Niña event is associated with colder-than-average surface temperatures in the eastern Pacific. La Niña is linked to strong trade winds, a strong westward-moving equatorial current, and a strong Peru Current with significant coastal upwelling.
- El Niño and La Niña events are part of the global circulation and are related to a seesaw pattern of atmospheric pressure between the eastern and western Pacific called the Southern Oscillation. El Niño and La Niña events influence weather on both sides of the tropical Pacific Ocean as well as weather in the United States.


Torsten Blackwood/AFP/Getty Images

Q This image shows floods occurring in eastern Australia. Is this region more likely being influenced by La Niña or El Niño?

18.8 GLOBAL DISTRIBUTION OF PRECIPITATION

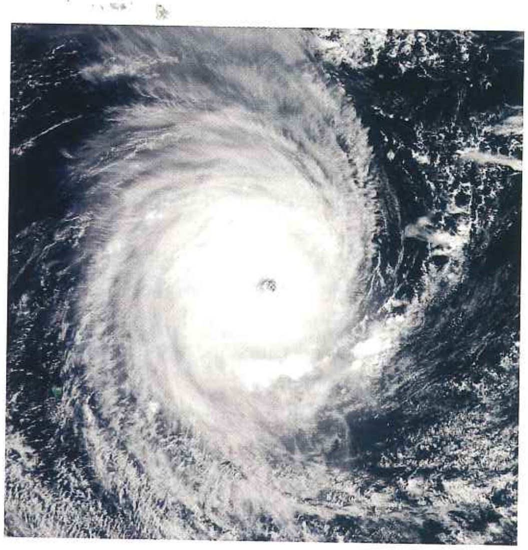
Discuss the major factors that influence the global distribution of precipitation.

- The general features of the global distribution of precipitation can be explained by global winds and pressure systems. In general, regions influenced by high pressure, with its associated subsidence and divergent winds, experience dry conditions. Regions under the influence of low pressure and its converging winds and ascending air receive ample precipitation.
- Air temperature, the distribution of continents and oceans, and the location of mountains also influence the distribution of precipitation.

Q Why do most high-latitude regions receive relatively meager precipitation?

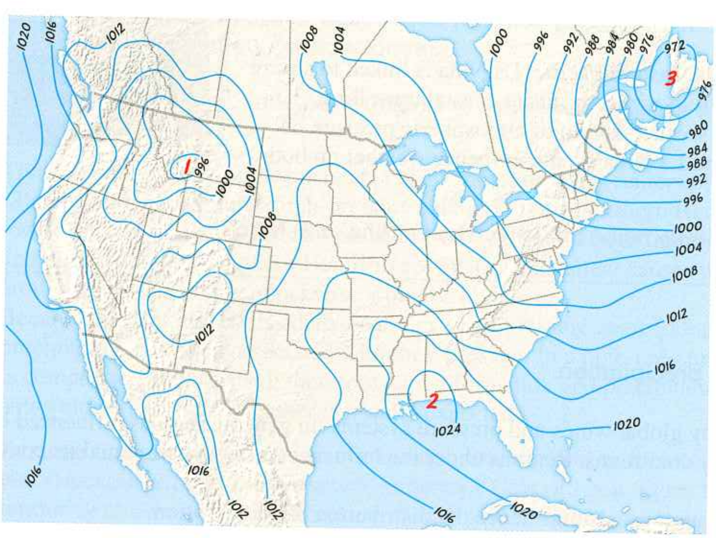
GIVE IT SOME **THOUGHT**

1. Mercury is 13.5 times denser (heavier) than water. If you built a barometer using water rather than mercury, how tall, in inches, would it have to be to record standard sea-level pressure?
2. This satellite image shows a tropical cyclone (hurricane).
   a. Examine the cloud pattern and determine whether the flow is clockwise or counterclockwise.
   b. In which hemisphere is the storm located?
   c. What factor determines whether the flow is clockwise or counterclockwise?

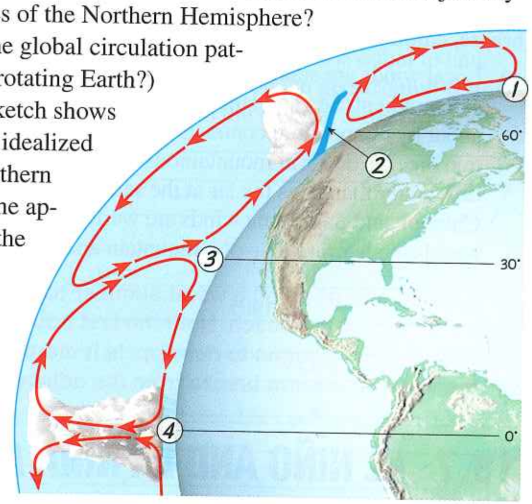


NASA

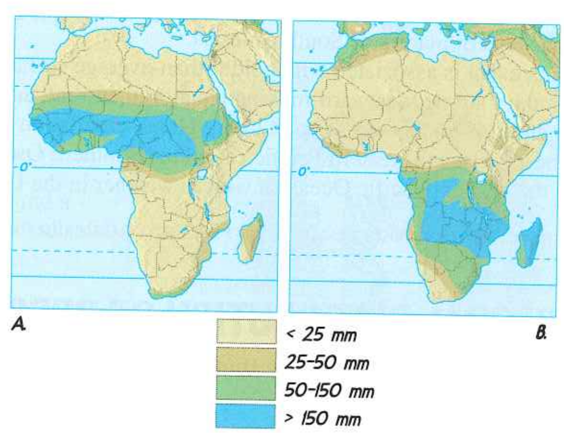
3. If divergence in the jet stream above a surface low-pressure center exceeds convergence at the surface, will surface winds likely get stronger or weaker? Explain.
4. The accompanying map is a simplified surface weather map for April 2, 2011, on which three pressure cells are numbered.
   a. Identify which of the pressure cells are anticyclones (highs) and which are cyclones (lows).



   b. Which pressure cell has the steepest pressure gradient and therefore the strongest winds?
   c. Refer to Figure 18.2 to determine whether pressure cell 3 should be considered strong or weak.
5. You and a friend are watching TV on a rainy day, when the weather reporter says, "The barometric pressure is 28.8 inches and rising." Hearing this, you say, "It looks like fair weather is on its way." Your friend responds with the following questions: "I thought air pressure had something to do with the weight of air. How does inches relate to weight? And why do you think the weather is going to improve?" How would you respond to your friend's queries?
6. If you live in the Northern Hemisphere and are directly west of the center of a cyclone, what is the probable wind direction at your location? What if you were west of an anticyclone?
7. If Earth did not rotate on its axis and if its surface were completely covered with water, what direction would a boat drift if it started its journey in the middle latitudes of the Northern Hemisphere? (*Hint:* What would the global circulation pattern be like for a nonrotating Earth?)
8. The accompanying sketch shows a cross section of the idealized circulation in the Northern Hemisphere. Match the appropriate number on the sketch to each of the following features:
   a. equatorial low
   b. polar front
   c. subtropical high
   d. polar high

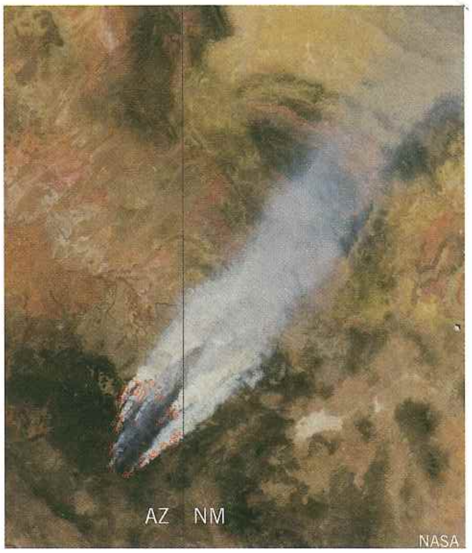


9. The accompanying maps of Africa show the distribution of precipitation for July and January. Which map represents July, and which represents January? How were you able to figure this out?

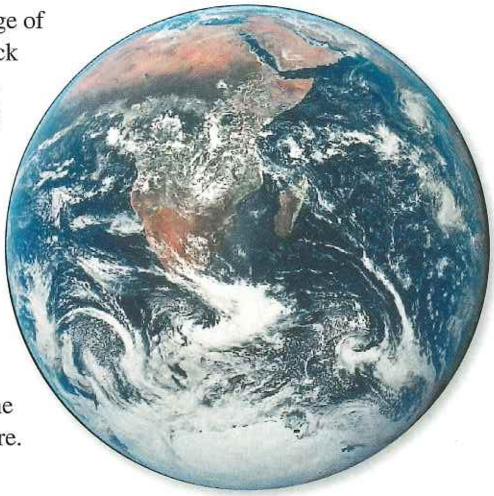


EXAMINING THE **EARTH SYSTEM**

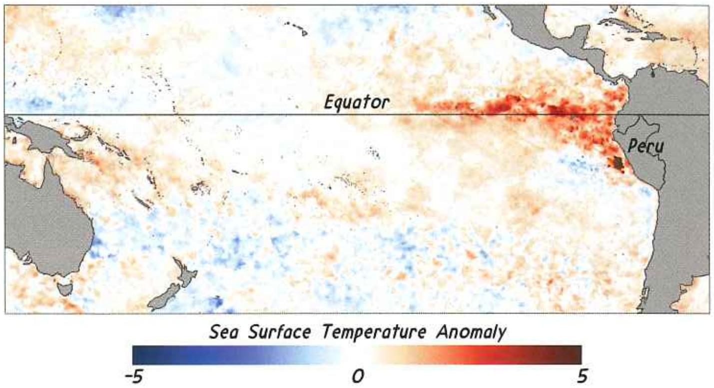
1. This satellite image shows a portion of a wildfire that occurred in May and June 2011. Known as the Wallow Fire, it burned more than 538 thousand acres (840 square miles) in southeastern Arizona. It was the largest wildfire in Arizona history. Suggest two ways that wind contributed to this wildfire. How might this event influence the geosphere and the biosphere?



2. Examine this classic image of Africa from space and pick out the region dominated by the equatorial low and the areas influenced by the subtropical highs in each hemisphere. What clue(s) did you use? Speculate on the differences in the biosphere between the regions dominated by high pressure and the zone influenced by low pressure.



3. The accompanying map shows wintertime sea-surface temperature anomalies (differences from average) over the equatorial Pacific Ocean. Based on this map, answer the following questions:
   - **a.** In what phase was the Southern Oscillation (El Niño or La Niña) when this image was made?
   - **b.** Would the trade winds be strong or weak at this time?
   - **c.** If you lived in Australia during this event, what weather conditions would you expect?
   - **d.** If you were attending college in the southeastern United States during winter months, what type of weather conditions would you expect? (*Hint:* See Figure 18.25.)



4. How are global winds related to surface ocean currents? What is the *ultimate* source of energy that drives both of these circulations?

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