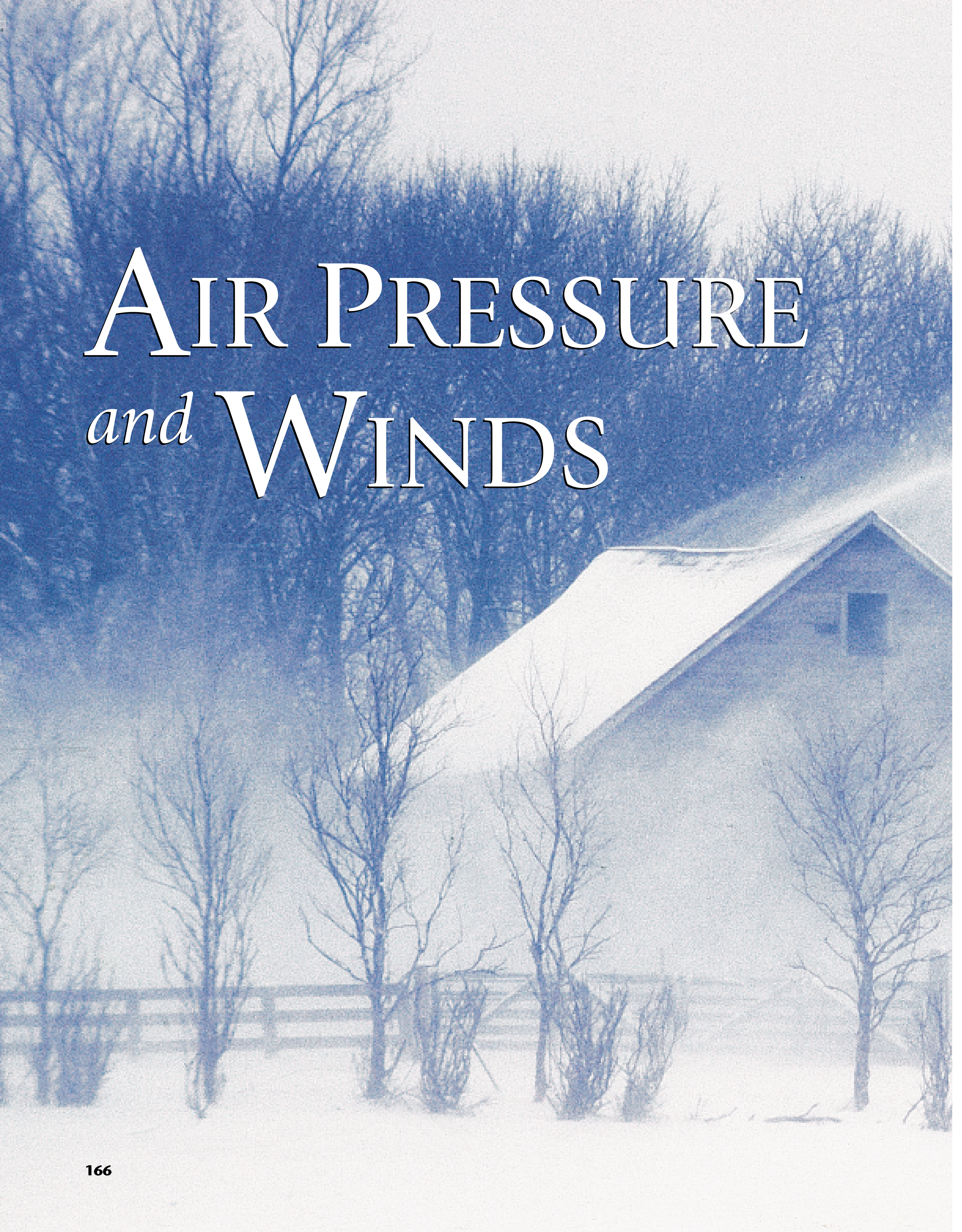
AIR PRESSURE and WINDS



CHAPTER

6

An April blizzard in Minnesota. *(Photo by Jim Brandenburg/Minden Pictures)*

Of the various elements of weather and climate, changes in air pressure are the least noticeable. In listening to a weather report, generally we are interested in moisture conditions (humidity and precipitation), temperature, and perhaps wind. It is the rare person, however, who wonders about air pressure. Although the hour-to-hour and day-to-day variations in air pressure are not perceptible to human beings, they are very important in producing changes in our weather. For example, it is variations in air pressure from place to place that generate winds that in turn can bring changes in temperature and humidity (Figure 6–1). Air pressure is one of the basic weather elements and a significant factor in weather forecasting. As we shall see, air pressure is closely tied to the other elements of weather (temperature, moisture, and wind) in a cause-and-effect relationship.

Understanding Air Pressure

In Chapter 1 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. This is roughly the same pressure that is produced by a 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) 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.

You might be able to visualize this phenomenon better if you imagine a tall aquarium that has the same dimensions as the desktop. 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 situation 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 used by astronauts on space walks are designed to duplicate the atmospheric pressure experienced at Earth's surface. Without these protec-

FIGURE 6-1 Gale force winds created waves that battered the coast at Blackpool, UK in February 2002. *(Photo by John Giles/NewsCom)*

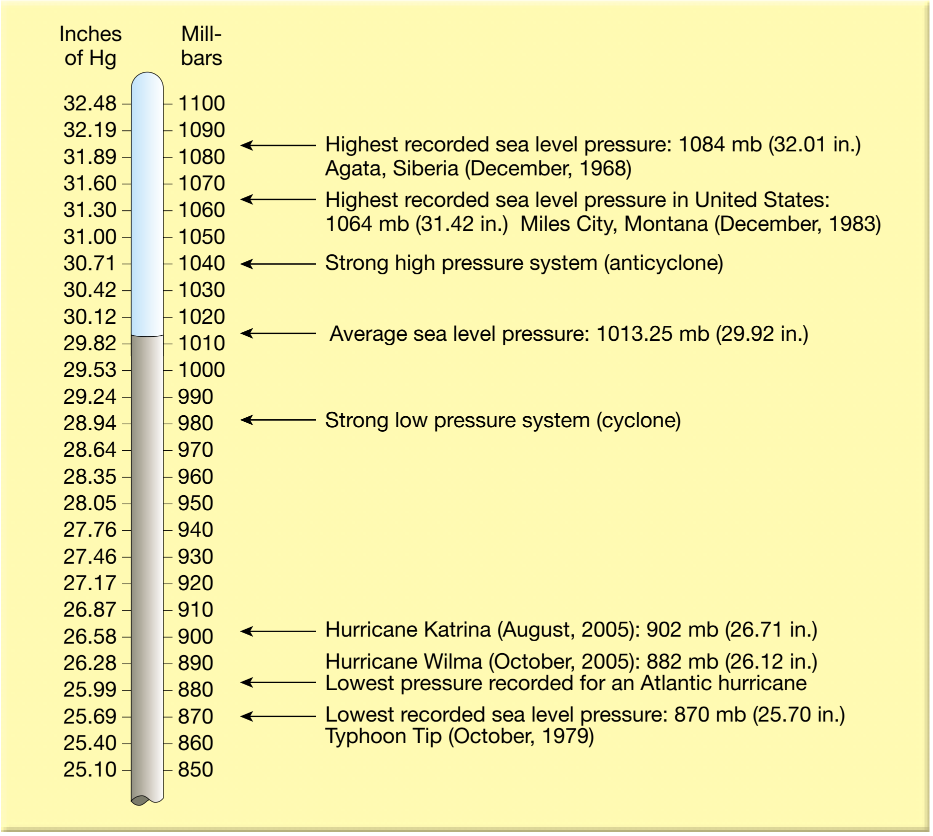


FIGURE 6-2 A comparison of atmospheric pressure in inches of mercury and millibars.

tive suits to keep body fluids from boiling away, astronauts would perish in minutes.

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

Measuring Air Pressure

Air Pressure and Wind

▶ Measuring Air Pressure

To measure atmospheric pressure, meteorologists use a unit of force from the science of physics called the **newton.*** At sea level the standard atmosphere exerts a force of 101,325 newtons per square meter. To simplify this large number, the U.S. National Weather Service adopted the **millibar** (mb), which equals 100 newtons per square meter. Thus, standard sea-level pressure is stated as 1013.25 millibars (Figure 6–2)*. The millibar has been the unit of measure on all U.S. weather maps since January 1940.

Although millibars are used almost exclusively by meteorologists, you might be better acquainted with the expression "inches of mercury," which is used by the media to describe atmospheric pressure. This expression 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 things about us. To measure this force, he closed one end of a glass tube and filled it with mercury. He then inverted the tube into a dish of mercury (Figure 6–3). Torricelli found that the mercury flowed out of the tube until the weight of the mercury column was balanced by the pressure exerted on the surface of the mercury by the air above. In other words, the weight of the mercury in the column equaled the weight of a similar diameter column of air that extended from the ground to the top of the atmosphere.

Torricelli noted that when air pressure increased, the mercury in the tube rose; conversely, when air pressure

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*A newton is the force needed to accelerate a 1 kilogram mass 1 meter per second squared.

*The standard unit of pressure in the SI system is the pascal, which is the name given to a newton per square meter (N/m^2). In this notation a standard atmosphere has a value of 101,325 pascals, or 101.325 kilopascals. If the National Weather Service officially converts to the metric system, it will probably adopt this unit.

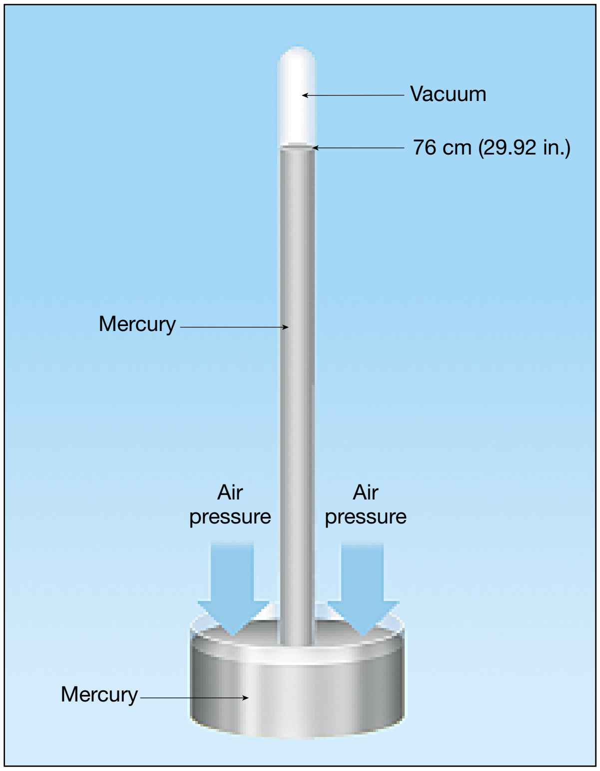


FIGURE 6-3 Simple mercury barometer. The weight of the column of mercury is balanced by the pressure exerted on the dish of mercury by the air above. If the pressure decreases, the column of mercury falls; if the pressure increases, the column rises.

decreased, so did the height of the column of mercury. The length of the column of mercury, therefore, became the measure of the air pressure, or "inches of mercury." 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 (760 millimeters) of mercury. In the United States the National Weather Service converts millibar values to inches of mercury for public and aviation use (Figure 6–3).

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, the aneroid barometer uses a partially evacuated metal chamber (Figure 6–4). The chamber, being very sensitive to variations in air pressure, changes shape, compressing as the pressure increases and expanding as the pressure decreases. A series of levers transmits 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 6–4, the face of an aneroid barometer intended for home use is inscribed with words like *fair, change, rain,* and *stormy.* Notice that "fair weather" corresponds with high-pressure readings, whereas "rain" is associated with low pressures. Although barometric readings may indicate the present weather, this is not always the case. The dial may point to "fair" on a rainy day, or you may be experiencing "fair" weather when the dial indicates "rainy." If you want to "predict" the weather in a local area, 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.

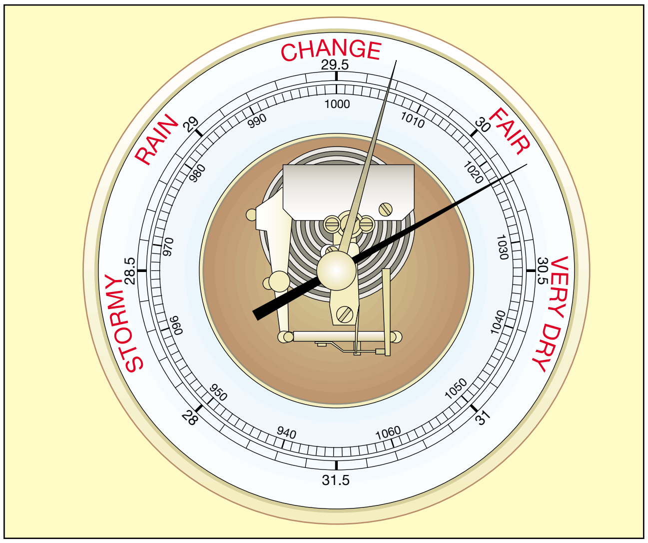
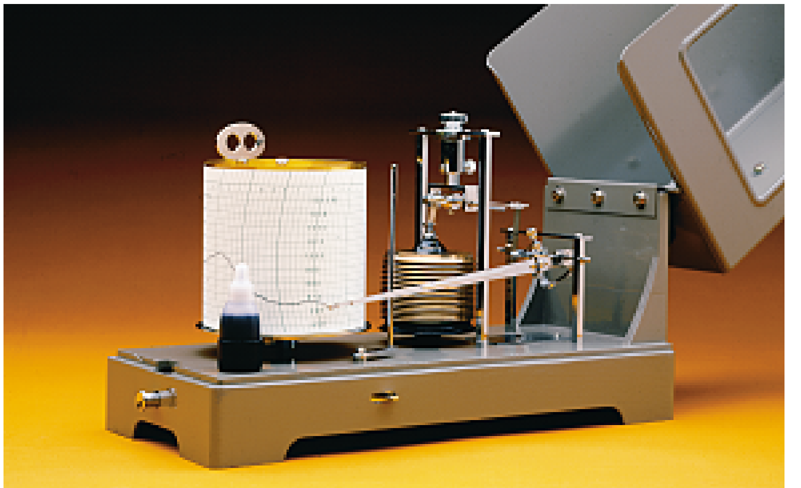


FIGURE 6-4 Aneroid barometer. The aneroid barometer has a partially evacuated chamber that changes shape, compressing as atmospheric pressure increases and expanding as pressure decreases.

One advantage of the 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 6–5). Another important adaptation of the aneroid barometer is its use to indicate altitude for aircraft, mountain climbers, and mapmakers (see Box 6–1).

As we shall see later, meteorologists are most concerned with pressure differences that occur horizontally across the globe. Thus, they obtain pressure readings from a number

FIGURE 6-5 An aneroid barograph makes a continuous record of pressure changes. *(Photo courtesy of Qualimetrics, Inc., Sacramento, California.)*



BOX 6–1 Air Pressure and Aviation

The cockpit of nearly every aircraft contains a *pressure altimeter,* an instrument that allows a pilot to determine the altitude of a plane. A pressure altimeter is essentially an aneroid barometer and, as such, responds to changes in air pressure. Recall that air pressure decreases with an increase in altitude and that the pressure distribution with height is well established. To make an altimeter, an aneroid is simply marked in meters instead of millibars. For example, we see in Table 6–1 that a pressure of 795 millibars "normally" occurs at a height of 2000 meters. Therefore, if such a pressure were experienced, the altimeter would indicate an altitude of 2000 meters.

Because of temperature variations and moving pressure systems, actual conditions are usually different from those represented as standard. Consequently, the altitude of an aircraft is seldom exactly that shown by its altimeter. When the barometric pressure aloft is lower than specified by the standard atmosphere, the plane will be flying lower than the height indicated by the altimeter. This could be especially dangerous if the pilot is flying a small plane through mountainous terrain with poor visibility. To correct for these situations, pilots make altimeter corrections before takeoffs and landings, and in some cases corrections are made en route.

Above 5.5 kilometers (18,000 feet), where commercial jets fly and pressure changes are more gradual, corrections cannot be made as precisely as at lower levels. Consequently, such aircraft have their altimeters set at the standard atmosphere and fly paths of constant pressure instead of constant altitude (Figure 6–A). Stated another way, when an aircraft flies at a constant altimeter setting, a pressure variation will result in a change in the plane's elevation. When pressure increases along a flight path, the plane will climb, and when pressure decreases, the plane will descend. There is little risk of midair collisions because all high-flying aircraft adjust their altitude in a similar manner.

Large commercial aircraft also use radio altimeters to measure heights above the terrain. The time required for a radio signal to reach the surface and return is used to accurately determine the height of the plane above the ground. This system is not without its drawbacks. Because a radio altimeter provides the elevation above the ground rather than above sea level, a knowledge of the underlying terrain is required.

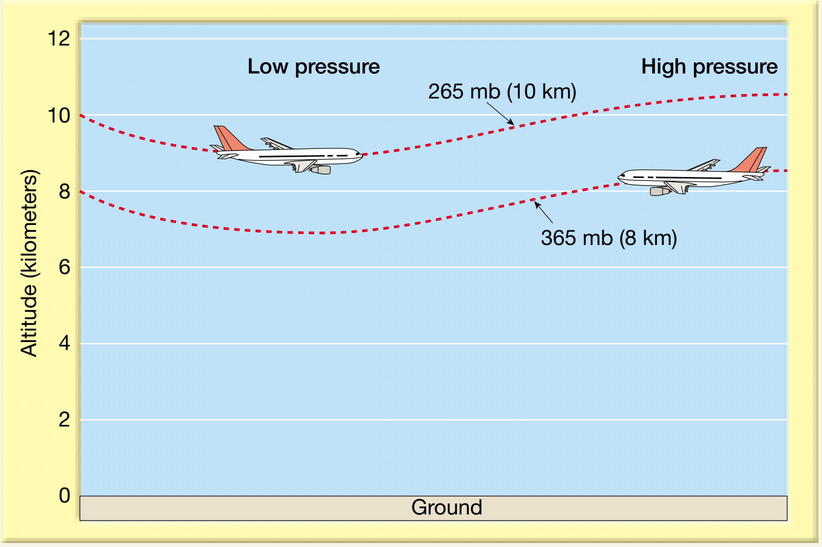


FIGURE 6-A Aircraft above 5.5 kilometers (18,000 feet) generally fly paths of constant pressure instead of constant altitude.

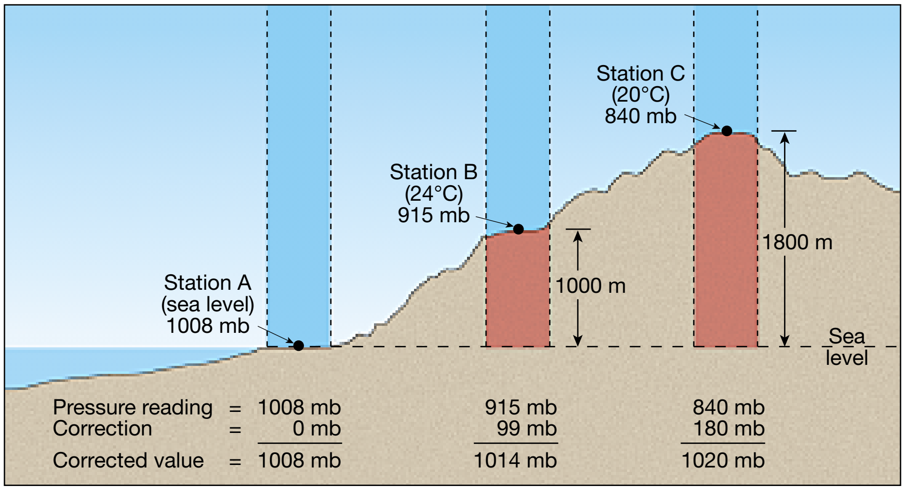


FIGURE 6-6 To compare atmospheric pressures, meteorologists first convert all pressure measurements to sea-level values. This is done by adding the pressure that would be exerted by an imaginary column of air (shown in red) to the station's pressure reading.

of stations. To compare pressure readings from various weather stations, compensation must be made for the *elevation* of each station. This is done by converting all pressure measurements to sea-level equivalents (Figure 6–6). Doing so requires meteorologists to determine the pressure that would be exerted by an imaginary column of air equal in height to the elevation of the recording station and adding it to the station's pressure reading. Because temperature greatly affects the density, and hence the weight of this imaginary column, temperature also must be considered in the calculations. Thus, the corrected reading would give the pressure, at that time, as if it were taken at sea level under the same conditions.*

A comparison of pressure records taken over the globe reveals that horizontal variations in pressure are rather small. Extreme pressure readings are rarely greater than 30 millibars (1 inch of mercury) above average sea-level pressure or 60 millibars (2 inches) below average sea-level pressure. Occasionally, the barometric pressure measured in severe storms, such as hurricanes, is even lower (see Figure 6–2).

Students Sometimes Ask…

Why is mercury used in a barometer? I thought it was poisonous.

You are correct—mercury poisoning can be quite serious. However, the mercury in a barometer is held in a reservoir where the chance of spillage is minimal. A barometer could be constructed using any number of different liquids, including water. The problem with a water-filled barometer is size. Because water is 13.6 times less dense than mercury, the height of a water column at standard sea-level pressure would be 13.6 times taller than that of a mercurial barometer. Consequently, a water-filled barometer would need to be nearly 34 feet tall.

Pressure Changes with Altitude

Let us consider the decrease in pressure with altitude mentioned in Chapter 1. The relationship between air pressure and density largely explains this observed decrease. To illustrate, imagine a cylinder fitted with a movable piston, as shown in Figure 6–7. If the temperature is kept constant and weights are added to the piston, the downward force exerted by gravity will squeeze (compress) the gas molecules together. The result is to increase the density of the gas and hence the number of gas molecules (per unit area) bombarding the cylinder wall as well as the bottom of the piston. Therefore, an increase in density results in an increase in pressure.

The piston will continue to compress the air molecules until the downward force is balanced by the ever increasing gas pressure. If more weight is added to the piston, the air will compress further until the pressure of the gas once again balances the new weight of the piston.

Similarly, *the pressure at any given altitude in the atmosphere is equal to the weight of the air directly above that point.* Recall that at sea level a column of air weighs 14.7 pounds per square inch and therefore exerts that amount of pressure. As we ascend through the atmosphere, we find that the air becomes less dense because of the lesser amount (weight) of air above. As would be expected, there is a corresponding *decrease in pressure with an increase in altitude.*

The fact that density decreases with altitude is why the term "thin air" is normally associated with mountainous regions. Except for the Sherpas (indigenous peoples of Nepal), most of the climbers who have reached the summit of Mount Everest (elevation 8852 meters or 29,029 feet) and survived used supplementary oxygen for the final leg of the journey. Even with the aid of supplementary oxygen, most of these climbers experienced periods of disorientation because of an inadequate supply of oxygen to their brains. The decrease in pressure with altitude also affects the boiling temperature of water, which at sea level is 100°C (212°F). For example, in Denver, Colorado—the Mile High City—water boils at 95°C (203°F). Although water comes to a boil faster

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*Appendix D explains how barometer corrections can be computed.

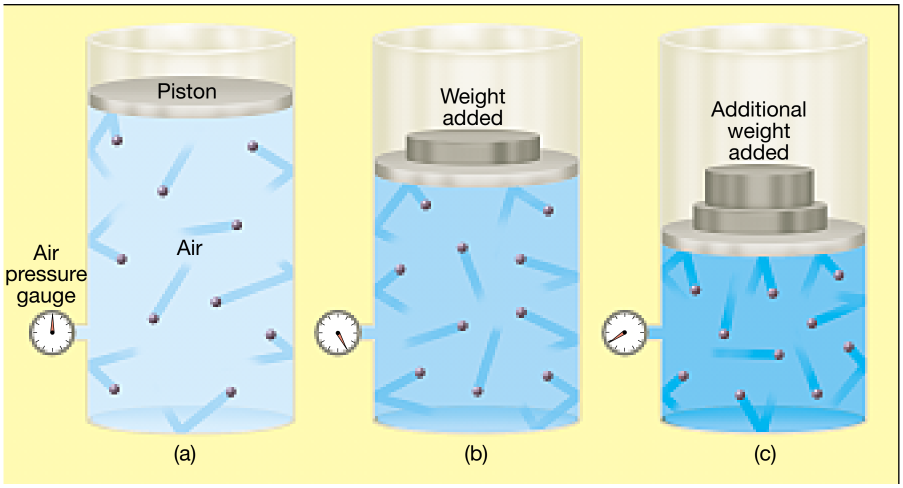

FIGURE 6-7 Schematic drawing showing the relationship between air pressure and density. Cylinder (a) of air fitted with movable piston. As more weight is added (b and c) to the piston, the increased number of molecules per unit volume (density) causes an increase in the pressure exerted on the walls of the cylinder and the gauge.

in Denver than in San Diego because of its lower boiling temperature, it takes longer to cook spaghetti in Denver.

Recall in Chapter 1 that the rate at which pressure decreases with altitude is not a constant. The rate of decrease is much greater near Earth's surface, where pressure is high, than aloft, where air pressure is low. The "normal" decrease in pressure experienced with increased altitude is provided by the standard atmosphere in Table 6–1. The **standard atmosphere** depicts the idealized vertical distribution of atmospheric pressure (as well as temperature and density), which is taken to represent average conditions in the real atmosphere. We see from Table 6–1 that atmospheric pressure is reduced by approximately one-half for each 5-kilometer increase in altitude. Therefore, at 5 kilometers the pressure is one-half its sea-level value; at 10 kilometers it is one-fourth; at 15 kilometers it is one-eighth; and so forth. Thus, at the altitude at which commercial jets fly (10 kilometers), the air exerts a pressure equal to only one-fourth that at sea level.

TABLE 6-1 U.S. standard atmosphere

Height (km)	Pressure (mb)	Temperature (°C)
50.0	0.798	−2
40.0	2.87	−22
35.0	5.75	−36
30.0	11.97	−46
25.0	25.49	−51
20.0	55.29	−56
18.0	75.65	−56
16.0	103.5	−56
14.0	141.7	−56
12.0	194.0	−56
10.0	265.0	−50
9.0	308.0	−43
8.0	356.5	−37
7.0	411.0	−30
6.0	472.2	−24
5.0	540.4	−17
4.0	616.6	−11
3.5	657.8	−8
3.0	701.2	−4
2.5	746.9	−1
2.0	795.0	2
1.5	845.6	5
1.0	898.8	9
0.5	954.6	12
0	1013.2	15

Students Sometimes Ask…

Why do my ears sometimes feel pain when I fly?

When airplanes take off and land, some people experience pain in their ears because of a change in cabin pressure. (Although most commercial airplanes are designed to keep the cabin pressure relatively constant, small changes in pressure do occur.) Normally the air pressure in one's middle ear is the same as the pressure of the surrounding atmosphere because the Eustachian tube connects the ear to the throat. However, when an individual has a cold, his or her Eustachian tubes may become blocked, preventing the flow of air either into or out of the middle ear. The resulting pressure difference can cause mild discomfort or, less often, excruciating pain, which subsides when the ears "pop," equalizing the pressure.

Horizontal Variations in Air Pressure

Although pressure changes with altitude are important, meteorologists are most interested in pressure differences that occur horizontally across the globe. To compare pressure readings from various weather stations, compensation must be made for the *elevation* of each station (see Figure

6–6). The adjusted reading gives the pressure for each locale as if it were taken at sea level.*

A comparison of pressure records from around the globe reveals that pressure differences from place to place are relatively small. Extreme pressure readings are rarely greater than 30 millibars (1 inch of mercury) above average sea-level pressure or 60 millibars (2 inches) below average sea-level pressure. Occasionally, the barometric pressure measured in severe storms, such as hurricanes, is even lower (see Figure 6–2). As we shall discover shortly, these small differences in air pressure can be sufficient to generate violent winds.

Influence of Temperature and Water Vapor on Air Pressure

How do pressure differences arise? One of the easiest ways to envision this is to picture northern Canada in midwinter. Here the snow-covered surface is continually radiating heat to space, while receiving little incoming solar radiation. The frigid ground cools the air above so that daily lows of −34°C (−30°F) are common and extremes of −46°C (−50°F) can occur.

Recall that temperature is a measure of the average molecular motion (kinetic energy) of a substance. Therefore, cold Canadian air is composed of comparatively slow-moving gas molecules that are packed closely together. As the density of a column of air increases, so does the pressure it exerts on the surface (Figure 6–8). Thus, a mass of cold air moving into the Midwest from Canada is quite dense and will be labeled a **High,** for *high barometric pressure,* on a weather map.

In contrast, the air over the Gulf of Mexico in January is relatively warm. Because the gas molecules in warm air have abundant kinetic energy, they are more widely spaced (less dense). Warm air masses that produce *low barometric pressure* are labeled **Low** on a weather map.

It is important to remember, however, that factors other than temperature affect the amount of pressure a column of air will exert. For example, the amount of water vapor contained in a volume of air influences its density. Contrary to popular perception, water vapor *reduces* the density of air. The air may feel "heavy" on hot, humid days, but it is not. You can easily verify this fact for yourself by examining a periodic table of the elements and noting that the molecular weights of nitrogen (N_2) and oxygen (O_2) are greater than that of water vapor (H_2O). In a mass of air the molecules of these gases are intermixed, and each takes up roughly the same amount of space. As the water content of an air mass increases, lighter water vapor molecules displace heavier nitrogen and oxygen molecules. Therefore, humid air is lighter (less dense) than dry air. Nevertheless, even very humid air is only about 2 percent less dense than dry air at the same temperature.

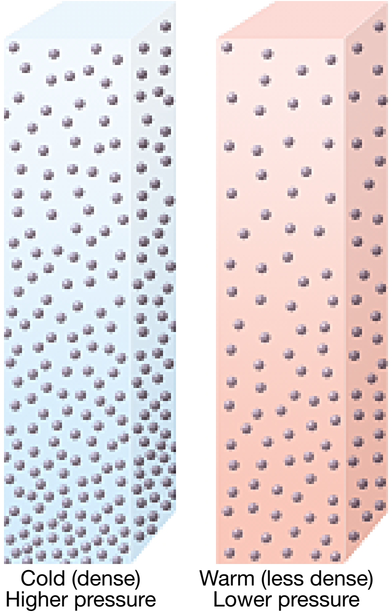

FIGURE 6-8 A comparison of the density of a column of cold air with a column of warm air. All else being equal, cold, dense air exerts more pressure than warm, less dense air.

From the preceding discussion we can conclude that a cold, dry air mass will produce higher surface pressures than a warm, humid air mass. Further, a warm, dry air mass will exhibit higher pressure than an equally warm, but humid, air mass. Consequently, large air masses are responsible for some of the pressure variations observed at Earth's surface.

Airflow and Pressure

The movement of air can also cause variations in air pressure. For example, in situations where there is a net flow of air into a region, a phenomenon called **convergence,** the air piles up. Stated another way, as air converges horizontally, it must increase in height to allow for the decreased area it now occupies. This results in a "taller" and therefore heavier air column that exerts more pressure at the surface. By contrast, in regions where there is a net outflow of air, a situation referred to as **divergence,** the surface pressure drops.

As you might expect, atmospheric processes involve significantly more complex variables than have just been described. Sometimes divergence at the surface is accompanied by convergence higher in the atmosphere. In this situation, surface pressure will rise when convergence outpaces divergence, or fall when divergence exceeds convergence. We will return to this important mechanism for producing areas of high and low pressure later in this chapter.

In summary, cold, dry air masses are dense and associated with high pressure. In contrast, warm, humid air masses are less dense and tend to exhibit low pressure. Further, the pressure at the surface will increase when there is a net convergence in a region and decrease when there is a net divergence.

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*The relationship among pressure, temperature, and density described in this section is stated in the *ideal gas law.* A mathematical treatment of the ideal gas law is provided in Appendix D.

The importance of atmospheric pressure to Earth's weather cannot be overemphasized. As you shall see shortly, differences in air pressure create global winds that become organized into the systems that "bring us our weather." Thus, much of the remainder of this book will consider the relationship between air temperature and air pressure and the effect of air pressure on airflow, and vice versa.

Factors Affecting Wind

GEODe ATMOSPHERE **Air Pressure and Wind**

▶ Factors Affecting Wind

We discussed the upward movement of air and its importance in cloud formation. As important as vertical motion is, far more air is involved in horizontal movement, the phenomenon we call **wind.** Although we know that air will move vertically if it is warmer and thus more buoyant than surrounding air, what causes air to move horizontally?

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 condition when opening a vacuum-packed can of coffee. The noise you hear is caused by air rushing from the area of higher pressure outside the can to the lower pressure inside. Wind is nature's attempt to balance inequalities in air pressure. Because unequal heating of Earth's surface continually 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, air would flow directly from areas of higher pressure to areas of lower pressure. Because both factors exist, however, wind is controlled by a combination of forces, including:

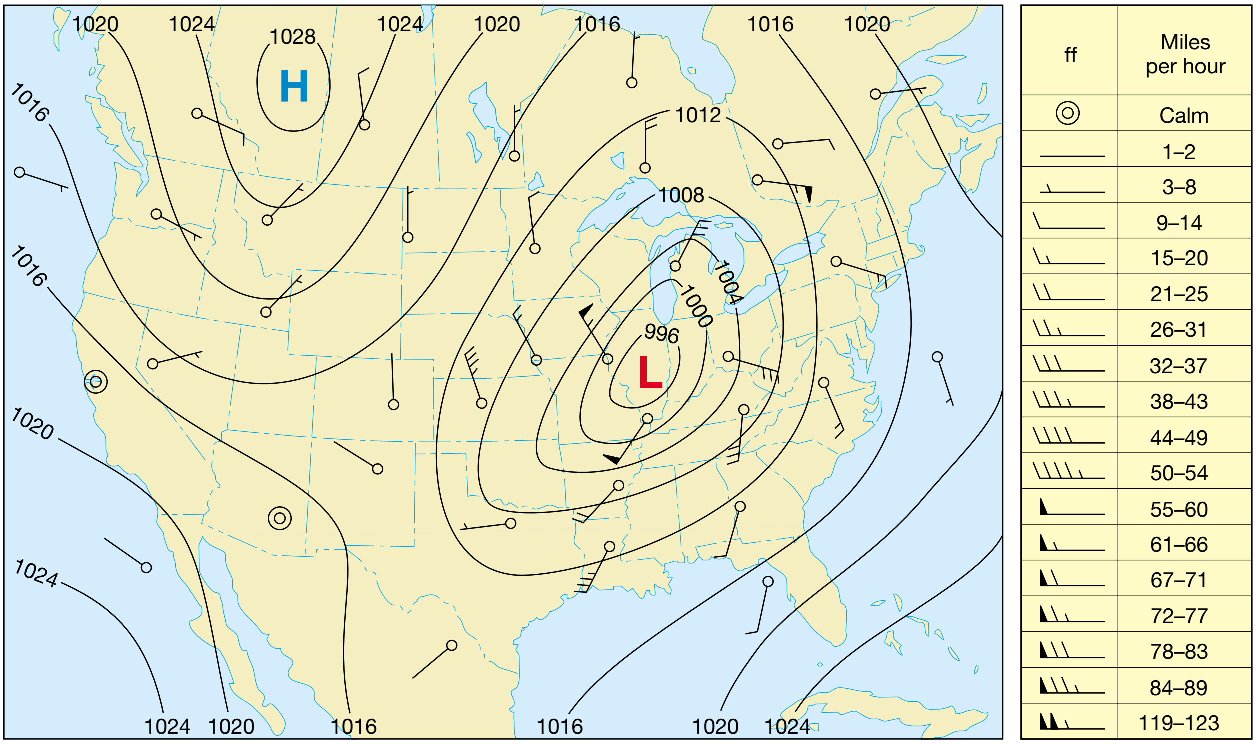
1. the pressure-gradient force
2. the Coriolis force
3. friction

Pressure-Gradient Force

To get anything to accelerate (change its velocity) requires an unbalanced force in one direction. 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 data are shown on surface weather maps by means of isobars. **Isobars** are lines connecting places of equal air pressure (*iso* = equal, *bar* = pressure), as shown in Figure 6–9. The *spacing* of

FIGURE 6-9 Isobars are lines connecting places of equal sea-level pressure. They are used to show the distribution of pressure on daily weather maps. Isobars are seldom straight, but usually form broad curves. Concentric rings of 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.



the isobars indicates the amount of pressure change occurring over a given distance and is expressed as the **pressure gradient.** The mathematical expression of the pressure gradient force is provided in Box 6–2.

You might find it easier to visualize the concept of a pressure gradient if you think of it as being analogous to the slope of 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 6–10 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.

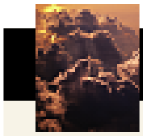
Pressure differences observed on the daily weather map result from complex factors. However, the underlying cause of these differences is simply *unequal heating of Earth's land–sea surface.*

Horizontal Pressure Gradients and Wind. To illustrate how temperature differences can generate a horizontal pressure gradient and thereby create winds, let us look at a common example, the *sea breeze.* Figure 6–11a shows a vertical cross-section of a coastal location just before sunrise. At this time we are assuming that temperatures and pressures do not vary horizontally at any level. This assumption is shown in Figure 6–11a by the horizontal pressure surfaces that indicate the equal pressure at equal heights. Because there is no horizontal variation in pressure (zero horizontal pressure gradient), there is no wind.

After sunrise, however, the unequal rates at which land and water heat will initiate pressure differences and, therefore, airflow (Figure 6–11b). Recall from Chapter 3 that surface temperatures over the ocean change only slightly on a daily basis. On the other hand, land surfaces and the air above can be substantially warmed during a single daylight period. As air over the land warms, it expands, causing a reduction in density. This in turn results in pressure surfaces that are bent upward, as shown in Figure 6–11b. Although this warming does not by itself produce a surface pressure change, a given pressure surface aloft does become elevated over the land compared to over the ocean. The resultant pressure gradient aloft causes the air aloft to move from the land toward the ocean.

The mass transfer of air seaward creates a surface high-pressure area over the ocean, where the air is collecting, and a surface low over the land. The surface circulation that develops from this redistribution of air aloft is from the sea toward the land (sea breeze), as shown in Figure 6–11c. Thus, a simple thermal circulation develops, with a seaward flow aloft and a landward flow at the surface. Note that *vertical* movement also is required to make the circulation complete. (We will consider the vertical pressure gradient next.)

An important relationship exists between pressure and temperature, as you saw in the preceding discussion. Temperature variations create pressure differences and hence wind. The greater these temperature differences, the stronger the horizontal pressure gradient and resultant wind.



BOX 6-2 Pressure-Gradient Force

*Gregory J. Carbone**

The magnitude of the pressure-gradient force is a function of the pressure difference between two points and air density. It can be expressed as

$$F_{PG} = \frac{1}{d} \times \frac{\Delta_p}{\Delta_n}; \text{ where}$$

F_{PG} = pressure-gradient force per unit mass

d = density of air

p = pressure difference between two points

n = distance between two points

Let us consider an example where the pressure 5 kilometers above Little Rock, Arkansas, is 540 millibars, and at 5 kilometers above St. Louis, Missouri, it is 530 millibars. The distance between the two cities is 450 kilometers, and the air density at 5 kilometers is 0.75 kilogram per cubic meter. In order to use the pressure-gradient equation, we must use compatible units. We must first convert pressure from millibars to pascals, another measure of pressure that has units of (kilograms × meters^{-1} × second^2).

In our example, the pressure difference above the two cities is 10 millibars, or 1000 pascals (1000 kg/m · s^2). Thus, we have

$$F_{PG} = \frac{1}{0.75} \times \frac{1000}{450{,}000} = 0.0029\frac{\text{m}}{\text{s}^2}$$

Newton's second law states that force equals mass times acceleration ($F = m \times a$). In our example, we have considered pressure-gradient force *per unit mass;* therefore, our result is an acceleration ($F/m = a$). Because of the small units shown, pressure-gradient *acceleration* is often expressed as centimeters per second squared. In this example, we have 0.296 cm/s^2.

*Professor Carbone is a faculty member in the Department of Geography at the University of South Carolina.

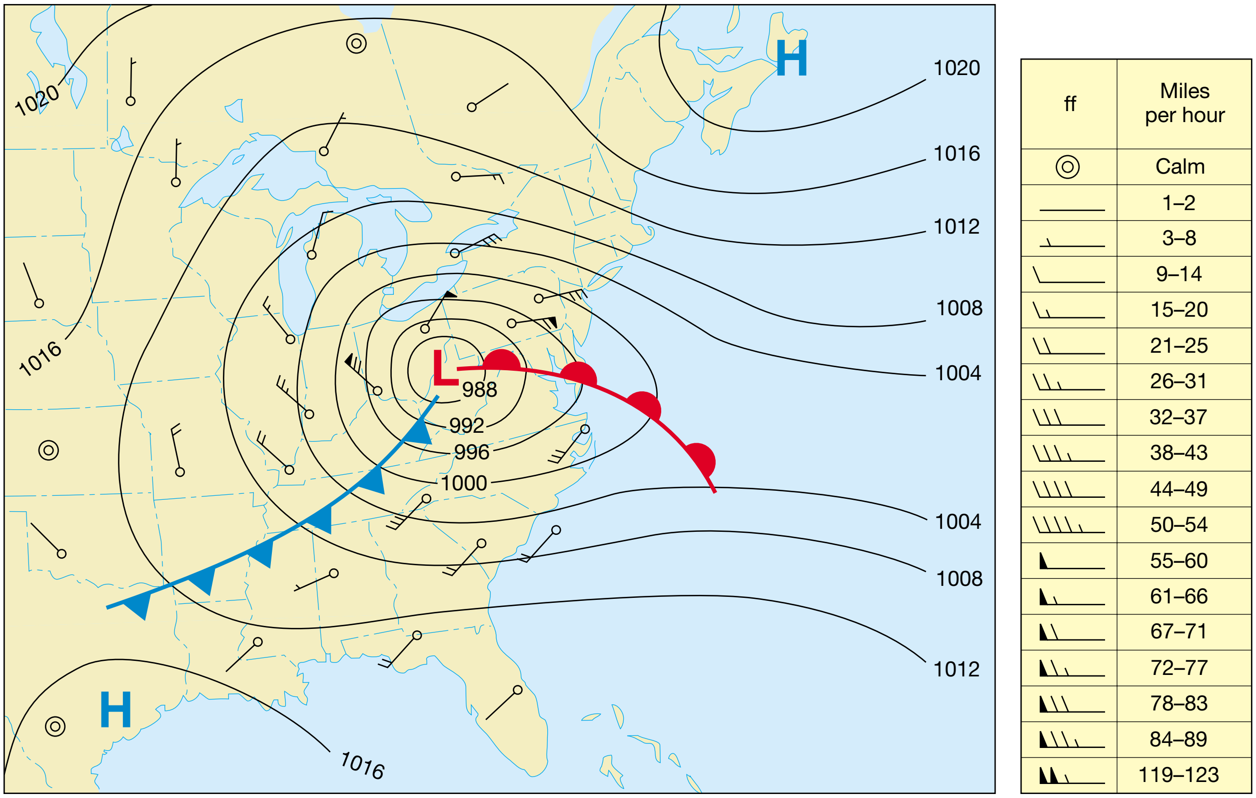


FIGURE 6-10 Pressure-gradient force. Closely spaced isobars indicate a strong pressure gradient and high wind speeds, whereas widely spaced isobars indicate a weak pressure gradient and low wind speeds.

Daily temperature differences and the pressure gradients so generated are generally confined to a zone that is only a few kilometers thick. On a global scale, however, variations in the amount of solar radiation received due to variations in Sun angle with latitude generate the much larger pressure systems that in turn produce the planetary atmospheric circulation. This is the topic of the next chapter.

If the pressure-gradient force was the only force acting on the wind, air would flow directly from areas of higher pressures to areas of lower pressure and the lows would be quickly filled. Thus, the well-developed high and low pressure systems that dominate our daily weather maps could never sustain themselves. Instead, Earth's atmosphere would, at best, develop only very weak and short-lived pressure systems. Therefore, most locations would experience long periods of very still air that would occasionally be disrupted by gentle breezes.

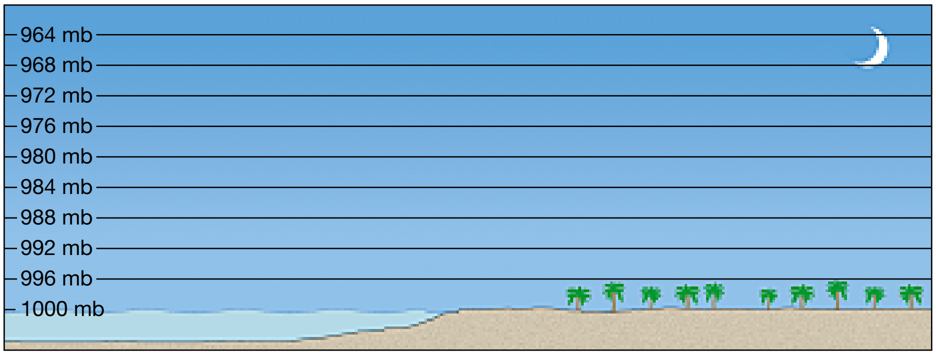
Fortunately, for those of us who like more varied weather, this is not the case. Once the pressure-gradient force starts the air in motion, the Coriolis force, friction, and other forces come into play. Although these forces cannot generate wind (with the exception of gravity), they do *greatly modify airflow.* By doing so, these forces help sustain and even enhance the development of the Earth's pressure systems. We will consider some of these important *modifying* forces shortly.

Vertical Pressure Gradient. As you learned earlier, airflow is from areas of higher pressure to areas of lower pressure. Further, you are aware that air pressure is highest near Earth's surface and gets progressively lower as you move upward through the atmosphere. Combining these two ideas, you might wonder why air does not rapidly accelerate upward and escape into space. In fact, it would do just that if it were not for the force of gravity, which acts in the opposite direction to the upward directed, *vertical pressure gradient.* The important balance that is usually maintained between these two opposing forces is called **hydrostatic equilibrium.**

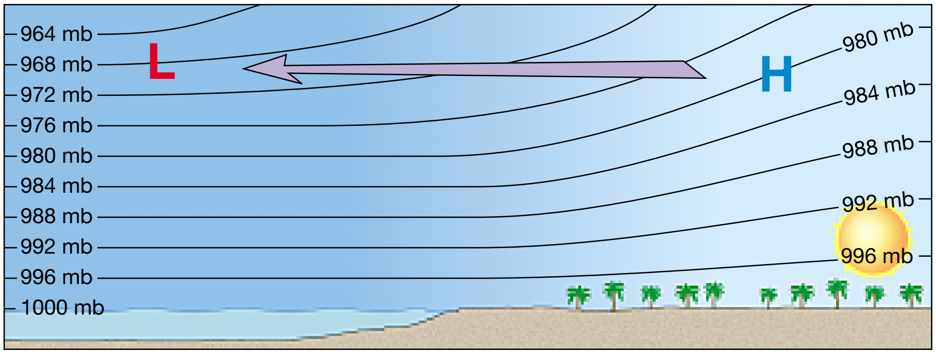
In general, the atmosphere is in or near hydrostatic balance. On those occasions when the gravitational force slightly exceeds the vertical pressure-gradient force, slow downward airflow results. This occurs, for example, within a dense Arctic air mass, where cold air is subsiding and spreading out at the surface. Most large-scale downward (and upward) motions are slow, averaging a few centimeters per second (less than 1 mile per day). However, some smaller-scale vertical motions are much more rapid. For example, strong updrafts and downdrafts associated with severe thunderstorms can reach 100 kilometers (62 miles) per hour or more. Fortunately, these phenomena are sporadic and localized. Overall, the state of the atmosphere is in hydrostatic equilibrium, where the upward pressure-gradient force is balanced by the downward force of gravity.

In summary, the horizontal pressure gradient is the driving force of wind. It has both magnitude and direction. Its magnitude is determined from the spacing of isobars, and

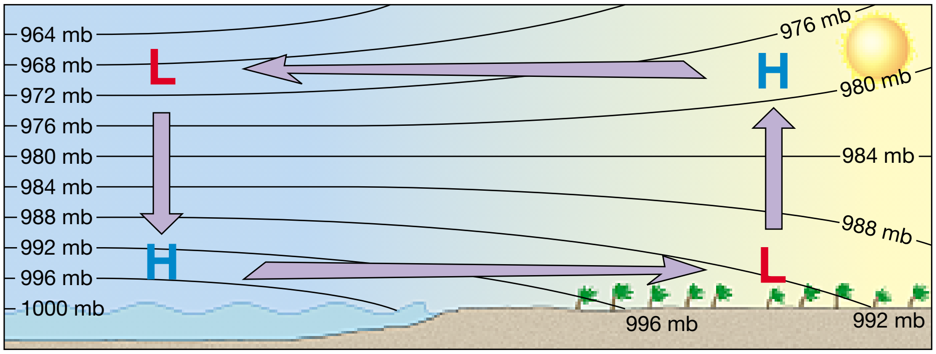
FIGURE 6-11 Cross-sectional view illustrating the formation of a sea breeze. (a) Just before sunrise; (b) after sunrise; (c) sea breeze established.



(a) Before sunrise



(b) Shortly after sunrise



(c) Sea breeze established

the direction of force is always from areas of higher pressure to areas of lower pressure and at right angles to the isobars. By contrast, the vertical pressure gradient is usually in, or near, balance with gravity. Thus, upward and downward flow in the atmosphere is comparatively slow (with the exception of localized updrafts and downdrafts).

Coriolis Force

The weather map in Figure 6–9 shows the typical air movements associated with surface 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. This deviation is the result of Earth's rotation and has been named the **Coriolis force** after the French scientist Gaspard Gustave Coriolis, who first expressed its magnitude quantitatively.

All free-moving objects, including wind, are deflected to the *right* of their path of motion in the Northern Hemisphere and 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 on the equator (Figure 6–12). If the rocket took an hour to reach its target, Earth would have rotated 15° to the east during its flight. To someone standing on Earth, it would look as if the rocket veered off its path and hit Earth 15° west of its target. The true path of the rocket was straight and would appear so to someone out in space looking down at Earth. It was Earth turning under the rocket that gave it its apparent deflection. Note that the rocket was deflected to the right of its path of motion because of the counterclockwise rotation of the Northern Hemisphere. Clockwise rotation produces a similar deflection in the Southern Hemisphere, but to the left of the path of motion.

Although it is usually easy for people to visualize the Coriolis deflection when the motion is from north to south, as in our rocket example, it is not so easy to see how a west-to-east flow would be deflected. Figure 6–13 illustrates this situation using winds blowing eastward at four different

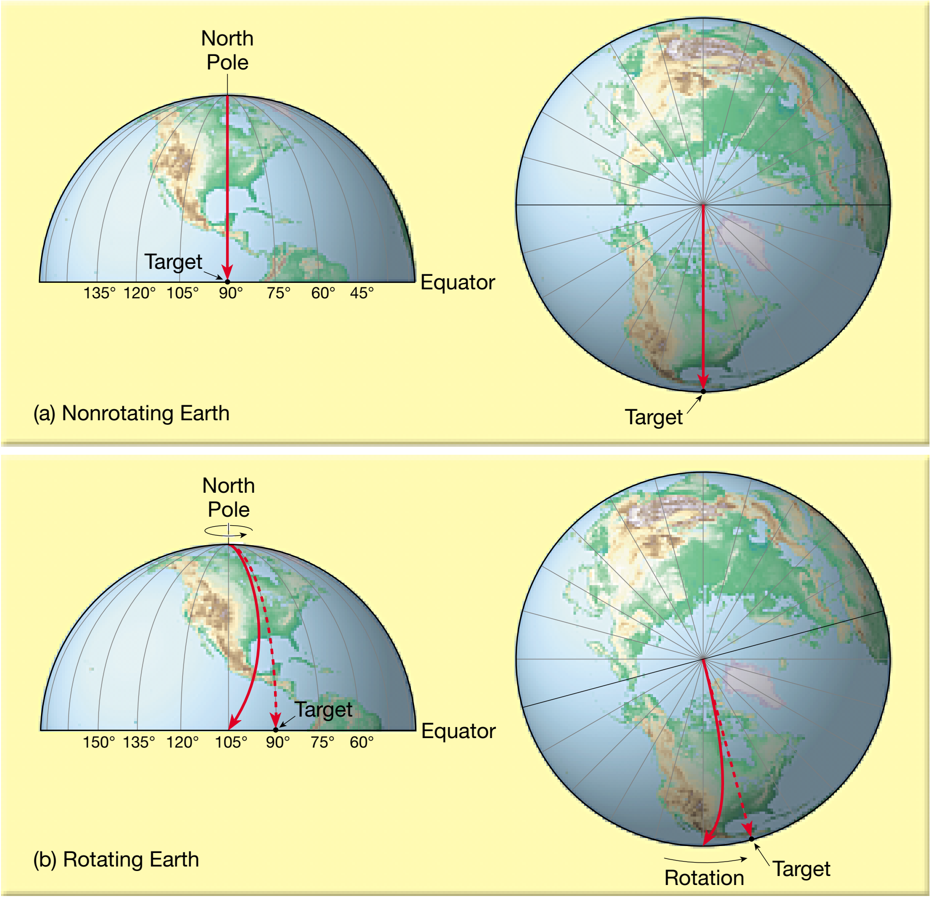
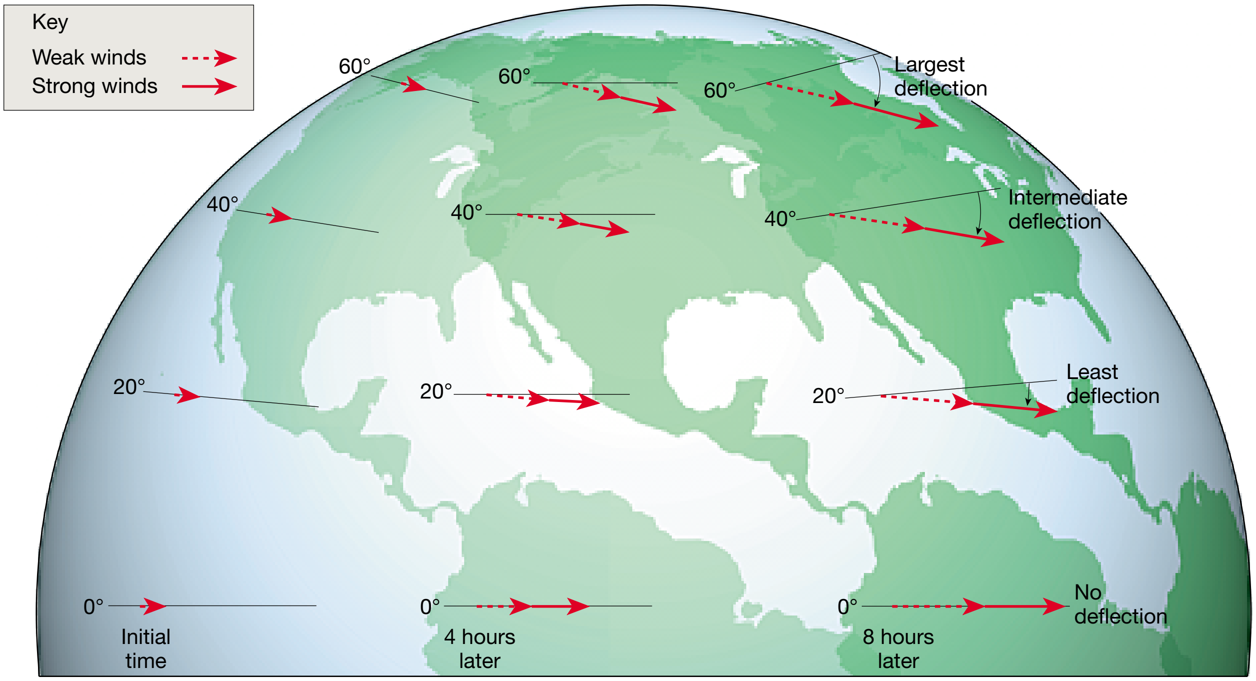


FIGURE 6-12 The Coriolis force illustrated using the one-hour flight of a rocket traveling from the North Pole to a location on the equator. (a) On a nonrotating Earth the rocket would travel straight to its target. (b) However, Earth rotates 15° each hour. Thus, although the rocket travels in a straight 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.

FIGURE 6-13 Coriolis deflection of winds blowing eastward at different latitudes. After a few hours the winds along the 20th, 40th, and 60th parallels appear to veer off course. This deflection (which does not occur at the equator) is caused by Earth's rotation, which changes the orientation of the surface over which the winds are moving.



latitudes (0°, 20°, 40°, and 60°). Notice that after a few hours the winds along the 20th, 40th, and 60th parallels appear to be veering off course. However, when viewed from space, it is apparent that these winds have maintained their original direction. It is the North American continent changing its orientation as Earth turns on its axis that produces the deflection we observe.

We can also see in Figure 6–13 that the amount of deflection is greater at 60° latitude than at 40° latitude, which is greater than at 20°. Furthermore, there is no deflection observed for the airflow along the equator. We conclude, therefore, that the magnitude of the deflecting force (Coriolis force) is dependent on latitude; it is strongest at the poles, and it weakens equatorward, where it eventually becomes nonexistent. We can also see that the amount of Coriolis deflection increases with wind speed. This results because faster winds cover a greater distance than do slower winds in the same time period. A mathematical treatment of the Coriolis force is provided in Box 6–3.

It is of interest to point out that any "free-moving" object will experience a similar deflection. This fact was dramatically discovered by our navy 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 force is relatively small. Nevertheless, in the middle latitudes this deflecting force is great enough to potentially affect the outcome of a baseball game. A ball hit a horizontal distance of 100 meters (330 feet) in 4 seconds down the right field line will be deflected 1.5 centimeters (more than 1/2 inch) to the right by the Coriolis force. This could be just enough to turn a potential home run into a foul ball!

BOX 6–3

Coriolis Force As a Function of Wind Speed and Latitude

*Gregory J. Carbone**

Figure 6–13 shows how wind speed and latitude conspire to affect the Coriolis force. Consider a west wind at four different latitudes (0°, 20°, 40°, and 60°). After several hours Earth's rotation has changed the orientation of latitude and longitude of all locations except the equator such that the wind appears to be deflected to the right. The degree of deflection for a given wind speed increases with latitude because the orientation of latitude and longitude lines changes more at higher latitudes. The degree of deflection of a given latitude increases with wind speed because greater distances are covered in the period of time considered.

We can show mathematically the importance of latitude and wind speed on Coriolis force:

$$F_{CO} = 2v\,\Omega\sin\phi$$

where F_{CO} = Coriolis force *per unit mass of air*

v = wind speed

Ω = Earth's rate of rotation or angular velocity (which is 7.29×10^{-5} radians per second)

ϕ = latitude

[Note that sin ϕ is a trigonometric function equal to zero for an angle of 0° (equator) and 1 when $\phi = 90°$ (poles).]

As an example, the Coriolis force per unit mass that must be considered for a 10-meter-per-second (m/s) wind at 40° is calculated as:

$$F_{CO} = 2\Omega\sin\phi v$$

$$F_{CO} = 2\Omega\sin 40 \times 10\text{ m/s}$$

$$F_{CO} = 2(7.29 \times 10^{-5}\text{ s}^{-1})\;0.64(10/\text{ms})$$

$$F_{CO} = 0.00094\text{ meter per second squared}$$

$$= 0.094\text{ cm s}^{-2}$$

The result (0.094 cm s^{-2}) is expressed as an acceleration because we are considering force per unit mass and force = mass × acceleration.

Using this equation, one could calculate the Coriolis force for any latitude or wind speed. Consider Table 6–A, which shows the Coriolis force per unit mass for three specific wind speeds at various latitudes. All values are expressed in centimeters per second squared (cm s^{-2}). Because pressure gradient and Coriolis force approximately balance under geostrophic conditions, we can see from our table that the pressure-gradient force (per unit mass) of 0.296 cm s^{-2} illustrated in Box 6–2 would produce relatively high winds.

TABLE 6-A Coriolis force for three wind speeds at various latitudes

Wind speed		**Latitude (ϕ)**			
		0°	**20°**	**40°**	**60°**
(m/s)	**(kph)**		**Coriolis force (cm/s^2)**		
5	18	0	0.025	0.047	0.063
10	36	0	0.050	0.094	0.126
25	90	0	0.125	0.235	0.316

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In summary, on a rotating Earth the Coriolis force acts to change the direction of a moving body to the right in the Northern Hemisphere and to the left in the Southern Hemisphere. This deflecting force (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 deflecting force); and (4) is strongest at the poles and weakens equatorward, becoming nonexistent at the equator.

Students Sometimes Ask…

I've been told that water goes down a sink in one direction in the Northern Hemisphere and in the opposite direction in the Southern Hemisphere. Is that true?

No! The origin of this myth comes from applying a scientific principle to a situation where it does not fit. Recall that the Coriolis deflection causes cyclonic systems to rotate counterclockwise in the Northern Hemisphere and clockwise in the Southern Hemisphere. It was inevitable that someone would suggest (without checking) that a sink should drain in a similar manner. However, a cyclone is more than 1000 kilometers in diameter and may exist for several days. By contrast, a typical sink is less than a meter in diameter and drains in a matter of seconds. On this scale, the Coriolis force is minuscule. Therefore, the shape of the sink and how level it is has more to do with the direction of water flow than the Coriolis force.

Friction

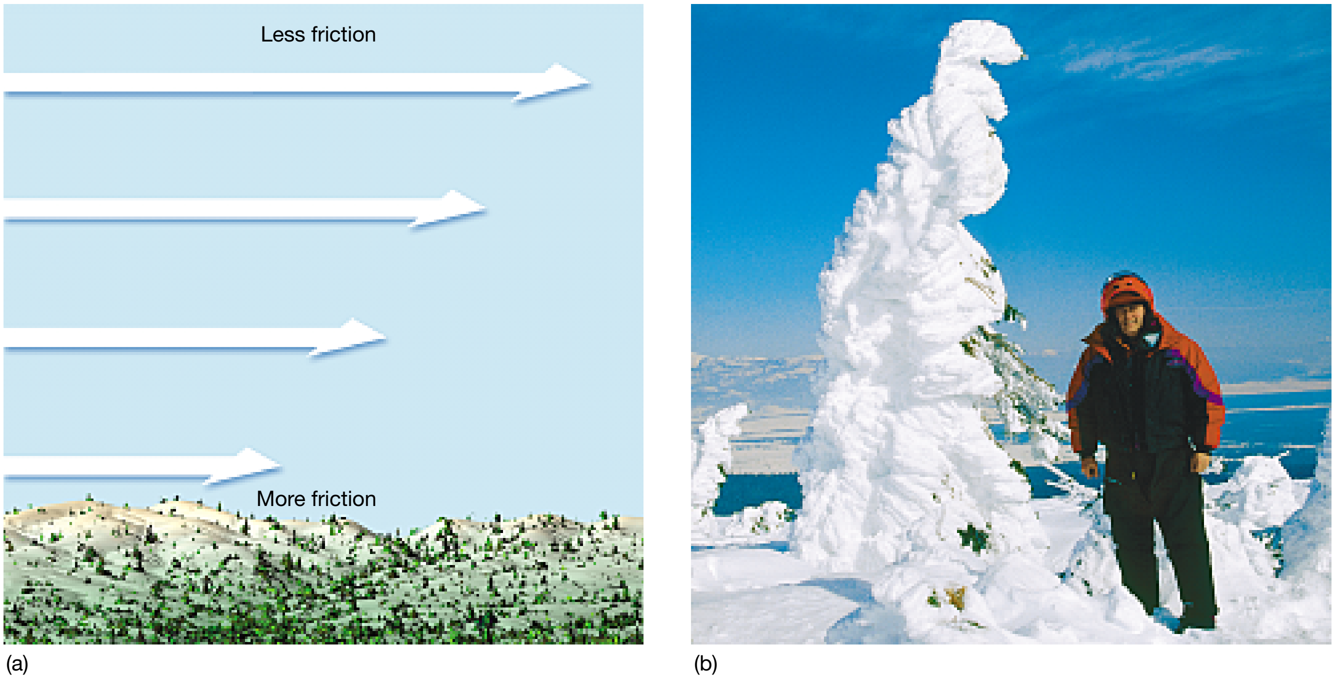
Earlier we stated that the pressure-gradient force is the primary driving force of the wind. As an unbalanced force, it causes air to accelerate from regions of higher pressure to regions of lower pressure. Thus, wind speeds should continually increase (accelerate) for as long as this imbalance exists. But we know from personal experience that winds do not become faster indefinitely. Some other force, or forces, must oppose the pressure-gradient force to moderate airflow. From our everyday experience we know that friction acts to slow a moving object. Although friction significantly influences airflow near Earth's surface, its effect is negligible above a height of a few kilometers (Figure 6–14). For this reason, we will divide our discussion. First, we will examine the flow aloft, where the effect of friction is small. Then we will analyze surface winds, where friction significantly influences airflow.

Winds Aloft and Geostrophic Flow

This section will deal only with airflow above a few kilometers, where the effects of friction are small enough to disregard.

Aloft, the Coriolis force is responsible for balancing the pressure-gradient force and thereby directing airflow. Figure 6–15 shows how a balance is reached between these opposing forces. For illustration only, we assume a nonmoving parcel of air at the starting point in Figure 6–15. (Remember

FIGURE 6-14 (a) Wind increases in strength with an increase in altitude because it is less affected by friction from objects near Earth's surface. (b) This snow-covered tree shows the effects of strong winds in a high mountain setting. *(Photo by E. J. Tarbuck)*



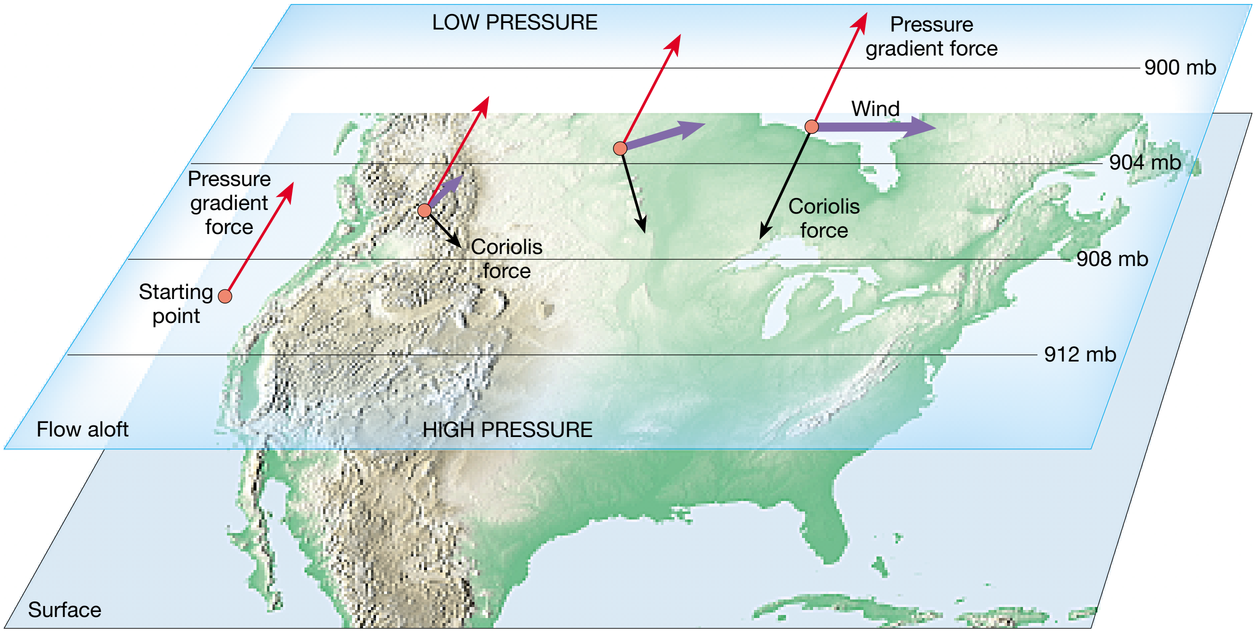


FIGURE 6-15 The geostrophic wind. The only force acting on a stationary parcel of air is the pressure-gradient force. Once the air begins to accelerate, the Coriolis force deflects it to the right in the Northern Hemisphere. Greater wind speeds result in a stronger Coriolis force (deflection) until the flow is parallel to the isobars. At this point the pressure-gradient force and Coriolis force are in balance and the flow is called a *geostrophic wind*. It is important to note that in the "real" atmosphere, airflow is continually adjusting for variations in the pressure field. As a result, the adjustment to geostrophic equilibrium is much more irregular than shown.

that air is rarely stationary in the atmosphere.) Because our parcel of air has no motion, the Coriolis force exerts no influence; only the pressure-gradient force can act at the starting point. Under the influence of the pressure-gradient force, which is always directed perpendicularly to the isobars, the parcel begins to accelerate directly toward the area of low pressure. As soon as the flow begins, the Coriolis force comes into play and causes a deflection to the right for winds in the Northern Hemisphere. As the parcel continues to accelerate, the Coriolis force intensifies (recall that the magnitude of the Coriolis force is proportional to wind speed). Thus, the increased speed results in further deflection.

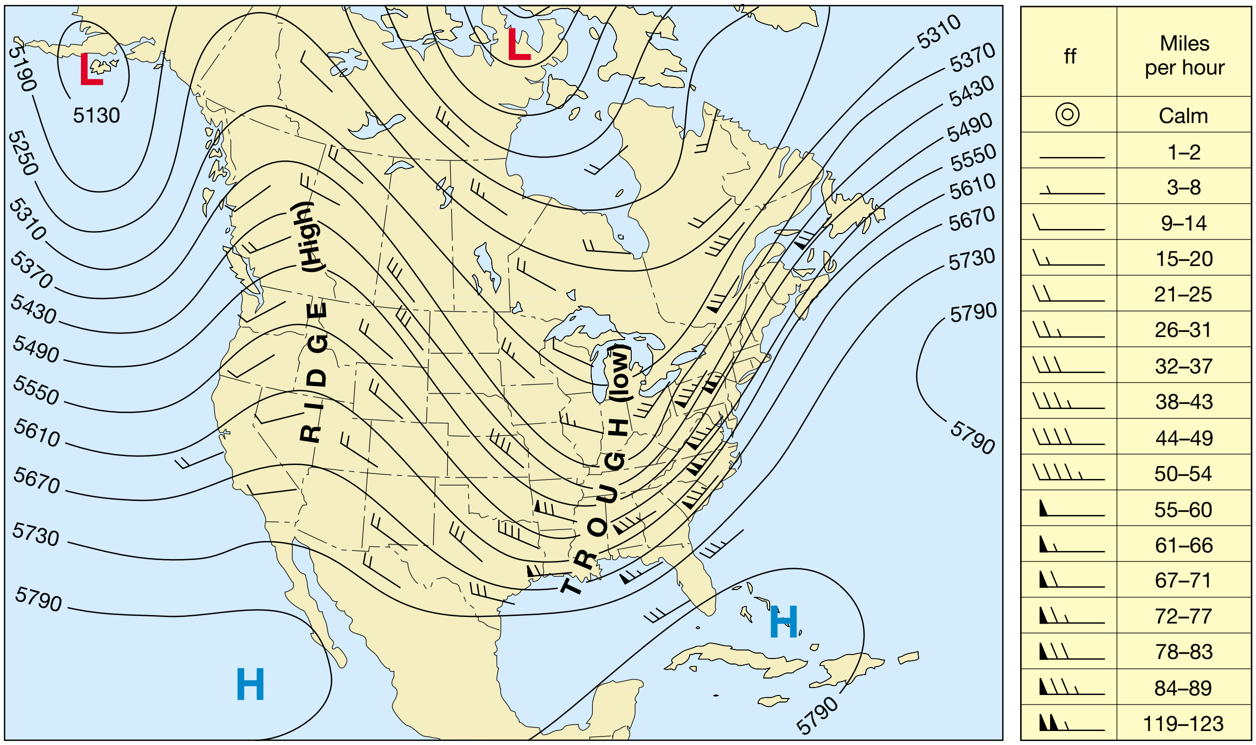
Eventually the wind turns so that it is flowing parallel to the isobars. When this occurs, the pressure-gradient force is balanced by the opposing Coriolis force, as shown in Figure 6–15. As long as these forces remain balanced, the resulting wind will continue to flow parallel to the isobars at a constant speed. Stated another way, the wind can be considered to be coasting (not accelerating or decelerating) along a pathway defined by the isobars.

Under these idealized conditions, when the Coriolis force is exactly equal and opposite to the pressure-gradient force, the airflow is said to be in *geostrophic balance*. The winds generated by this balance are called **geostrophic winds** (geostrophic means "turned by Earth"). Geostrophic winds flow in a straight path, parallel to the isobars, with velocities proportional to the pressure-gradient force. A steep pressure gradient creates strong winds, and a weak pressure gradient produces light winds.

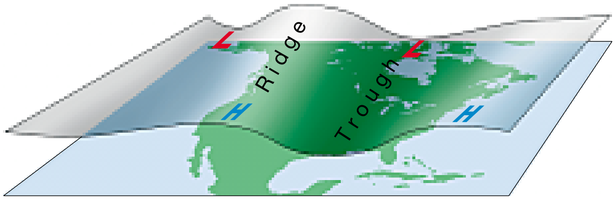
It is important to note that the geostrophic wind is an idealized model that only approximates the actual behavior of airflow aloft. In the real atmosphere, winds are never purely geostrophic. Nonetheless, the geostrophic model offers a useful approximation of the actual winds aloft. By measuring the pressure field (orientation and spacing of isobars) that exists aloft, meteorologists can determine both wind direction and speed (Figure 6–16).

The idealized geostrophic flow predicts winds parallel to the isobars with speeds that depend on isobaric spacing. That is, the closer the isobars, the higher the wind speed (Figure 6–16). Of equal importance to meteorologists is that the same method can be used in reverse. In other words, the distribution of pressure aloft can be determined from airflow measurements. The interrelationship between pressure and wind greatly enhances the reliability of upper-air weather charts by providing checks and balances. In addition, it minimizes the number of direct observations required to describe adequately the conditions aloft, where accurate data are most expensive and difficult to obtain.

As we have seen, wind direction is directly linked to the prevailing pressure pattern. Therefore, if we know the wind direction, we can, in a crude sort of way, also establish the pressure distribution. This rather straightforward relationship between wind direction and pressure distribution was first formulated by the Dutch meteorologist Buys Ballot in 1857. Essentially, **Buys Ballot's law** states: In the Northern Hemisphere *if you stand with your back to the wind, low pressure will be found to your left and high pressure to*



(a) Upper-level weather chart



(b) Representation of upper-level chart

FIGURE 6-16 Upper-air weather chart. (a) 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 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) are experiencing higher pressures than places where the height contours indicate lower altitudes. Thus, *higher-elevation* contours indicate *higher* pressures, and *lower-elevation* contours indicate *lower* pressures. (b) Representation of the 500-millibar surface shown in the upper-air weather chart above.

your right. In the Southern Hemisphere, the situation is reversed.

Although Buys Ballot's law holds for airflow aloft, it must be used with caution when applied to surface winds. At the surface, friction and topography interfere with the idealized circulation. At the surface, if you stand with your back to the wind, then turn clockwise about 30°, low pressure will be to your left and high pressure to your right.

In summary, winds above a few kilometers can be considered geostrophic—that is, they flow in a straight path parallel to the isobars at speeds that can be calculated from the pressure gradient. The major discrepancy from true geostrophic winds involves the flow along highly curved paths, a topic considered next.

Curved Flow and the Gradient Wind

Even a casual glance at a weather map shows that the isobars are not generally straight; instead, they make broad, sweeping curves (see Figure 6–9). Occasionally the isobars connect to form roughly circular cells of either high or low pressure. Thus, unlike geostrophic winds that flow in a straight path, winds around cells of high or low pressure follow curved paths in order to parallel the isobars. Winds of this nature, which blow at a constant speed parallel to curved isobars, are called **gradient winds.**

Let us examine how the pressure-gradient force and Coriolis force combine to produce gradient winds. Figure 6–17a

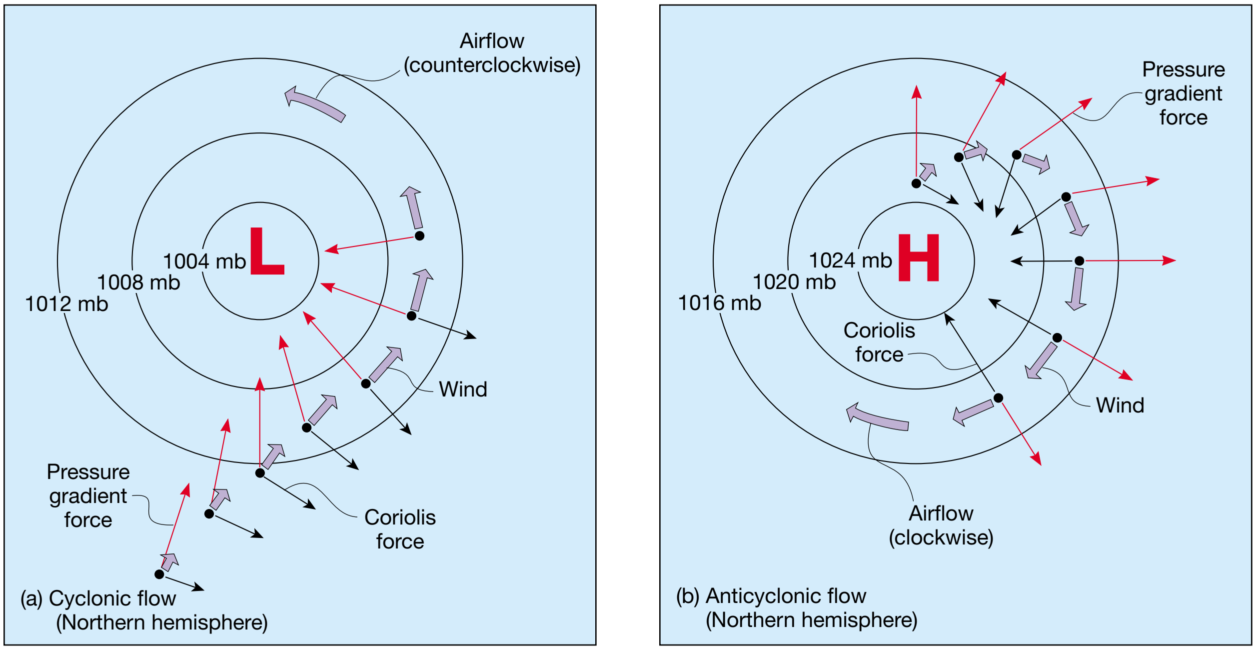


FIGURE 6-17 Idealized illustration showing expected airflow aloft around low- and high-pressure centers. It is important to note that in the "real" atmosphere, airflow is continually adjusting for variations in the pressure field. As a result, the adjustment to gradient balance is much more irregular than shown.

shows the gradient flow around a center of low pressure. As soon as the flow begins, the Coriolis force causes the air to be deflected. In the Northern Hemisphere, where the Coriolis force deflects the flow to the right, the resulting wind blows counterclockwise about a low (Figure 6–17a). Conversely, around a high-pressure cell, the outward-directed pressure-gradient force is opposed by the inward-directed Coriolis force, and a clockwise flow results (Figure 6–17b).

Because the Coriolis force deflects the winds to the left in the Southern Hemisphere, the flow is reversed there—clockwise around low-pressure centers and counterclockwise around high-pressure centers.

It is common practice to call all centers of low pressure **cyclones** and the flow around them cyclonic. **Cyclonic flow** has the same direction of rotation as Earth: counterclockwise in the Northern Hemisphere and clockwise in the Southern Hemisphere. Centers of high prsssure are frequently called **anticyclones** and exhibit **anticyclonic flow** (opposite that of Earth's rotation). Whenever isobars curve to form elongated regions of low and high pressure, these areas are called **troughs** and **ridges,** respectively (Figure 6–16). The flow about a trough is cyclonic; the flow around a ridge is anticyclonic.

Now let us consider the forces that produce the gradient flow associated with cyclonic and anticyclonic circulations. Wherever the flow is curved, a force has deflected the air (changed its direction), even when no change in speed results. This is a consequence of Newton's first law of motion, which states that a moving object will continue to move in a straight line unless acted upon by an unbalanced force. You have undoubtedly experienced the effect of Newton's law when the automobile in which you were riding made a sharp turn and your body tried to continue moving straight ahead (see Appendix E).

Referring back to Figure 6–17a, we see that in a low-pressure center, the inward-directed pressure-gradient force is opposed by the outward-directed Coriolis force. But to keep the path curved (parallel to the isobars), the inward pull of the pressure-gradient force must be strong enough to balance the Coriolis force as well as to turn (accelerate) the air inward. The inward turning of the air is called *centripetal acceleration.* Stated another way, the pressure-gradient force must exceed the Coriolis force to overcome the air's tendency to continue moving in a straight line.*

The opposite situation exists in anticyclonic flows, where the inward-directed Coriolis force must balance the pressure-gradient force as well as provide the inward acceleration needed to turn the air. Notice in Figure 6–17 that the pressure-gradient and Coriolis force are not balanced (the arrow lengths are different), as they are in geostrophic flow. This imbalance provides the change in direction (centripetal acceleration) that generates curved flow.

Despite the importance of centripetal acceleration in establishing curved flow aloft, near the surface, friction comes into play and greatly overshadows this much weaker force. Consequently, except for rapidly rotating storms such as tornadoes and hurricanes, the effect of centripetal acceleration is negligible and therefore is not considered in the discussion of surface circulation.

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*The tendency of a particle to move in a straight line when rotated creates an imaginary outward force called *centrifugal force.*

BOX 6-4 Do Baseballs Really Fly Farther at Denver's Coors Field?

Since Denver's Coors Field was built, in 1995, it has become known as the "homerun hitter's ballpark" (Figure 6–B). This notoriety is warranted since Coors Field led all major-league ballparks in both the total home runs and home runs per at-bat during seven of its first eight seasons.

In theory, a well-struck baseball should travel roughly 10 percent farther in Denver (elevation 5280 feet) than it would in a ballpark at sea level. This so-called elevation enhancement results from low air density at mile-high Coors Field. According to Robert Adair, Sterling Professor Emeritus of Physics at Yale University, a 400-foot blast in Atlanta could carry perhaps 425 feet in Denver, although Adair admits that calculating the actual difference is tricky for reasons having to do with subtleties of fluid dynamics.

Recently a group of researchers at the University of Colorado at Denver tested the assumption that batted balls travel farther in the "thin air" at Coors Field than in ballparks near sea level. They concluded that the assumed elevation enhancement of flyball distance has been greatly overestimated. Instead, they suggest that the hitter-friendly conditions should be attributed to the prevailing weather conditions of the nearby Front Range of the Rocky Mountains and the effects of low air density on the act of pitching a baseball.

For example, wind can make or break a home run. According to Professor Adair, if there's a 10-mile-an-hour breeze behind a batter, it will add an extra 30 feet to a 400-foot home run. Conversely, if the wind is blowing in toward home plate at 10 miles per hour, the flight of the ball will be reduced by about 30 feet. During the summer months winds most frequently blow from the south and southwest in the Denver area. Because of the orientation of Coors Field, these winds are blowing toward the outfield, thus aiding the hitters rather than the pitchers. Speaking of pitchers, the act of pitching a baseball is also greatly affected by air density. In particular, part of what determines how much a curveball will curve is air density. At higher elevations, thinner air causes a ball to break less, which makes it easier for a batter to hit a pitch.

In summary, it appears that several factors have contributed to Coors Field being known as a hitter's paradise.

FIGURE 6–B Denver's Coors Field, home of the Colorado Rockies, is nearly one mile above sea-level. It is known as a "hitter's ballpark." *(Photo by Ronald Martinez/Getty Images)*

Surface Winds

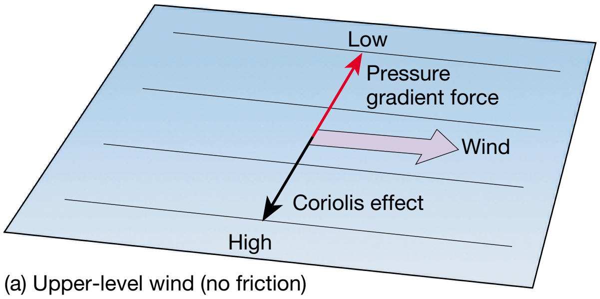
Friction as a factor affecting wind is important only within the first few kilometers of Earth's surface. We know that friction acts to slow the movement of air (Figure 6–18). By slowing air movement, friction also reduces the Coriolis force, which is proportional to wind speed. Because the pressure-gradient force is not affected by wind speed, it wins the tug of war against the Coriolis force and wind direction changes (Figure 6–19). The result is the movement of air at an angle across the isobars, toward the area of lower pressure.

The roughness of the terrain determines the angle at which the air will flow across the isobars as well as influence the speed at which it will move. Over the relatively smooth ocean surface, where friction is low, air moves at an angle of 10° to 20° to the isobars and at speeds roughly two-thirds of geostrophic flow. Over rugged terrain, where friction is high, the angle can be as great as 45° from the isobars, with wind speeds reduced by as much as 50 percent.

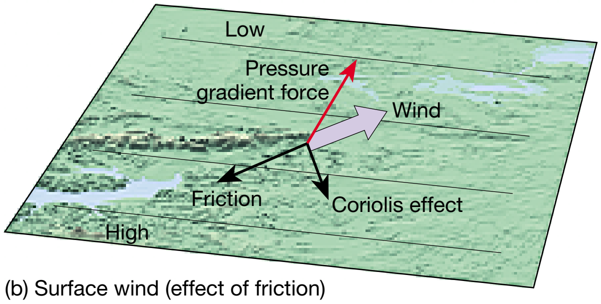
Near the surface, friction plays a major role in redistributing air within the atmosphere by changing the direction of airflow. This is especially noticeable when considering the motion around surface cyclones and anticyclones, two of the most common features on surface weather maps.

We have learned that above the friction layer in the Northern Hemisphere, winds blow counterclockwise around a cyclone and clockwise around an anticyclone, with winds nearly parallel to the isobars. When we add the effect of friction, we notice that the airflow crosses the isobars at varying angles, depending on the roughness of the terrain, but always from higher to lower pressure. In a cyclone, in which pressure decreases inward, friction causes a net flow *toward* its center (Figure 6–20). In an anticyclone just the opposite is true: The pressure decreases outward, and friction causes a net flow *away* from the center. Therefore, the resultant winds blow into and counterclockwise about a surface cyclone (Figure 6–21), and outward and clockwise about a surface anticyclone. Of course, in the Southern Hemisphere the Coriolis force deflects the winds to the left and reverses the direction of flow.

In whatever hemisphere, however, friction causes a net inflow (*convergence*) around a cyclone and a net outflow (*divergence*) around an anticyclone. This very important relationship between cyclonic flow and convergence and anticyclonic flow and divergence will be considered again.



(a) Upper-level wind (no friction)



(b) Surface wind (effect of friction)

FIGURE 6-19 Comparison between upper-level winds and surface winds showing the effects of friction on airflow. Friction slows surface wind speed, which weakens the Coriolis force, causing the winds to cross the isobars.

FIGURE 6-18 A snow fence slows the wind, thereby decreasing the wind's ability to transport snow. As a result, snow accumulates on the downwind side of the fence. *(Photo by Stephen Trimble)*

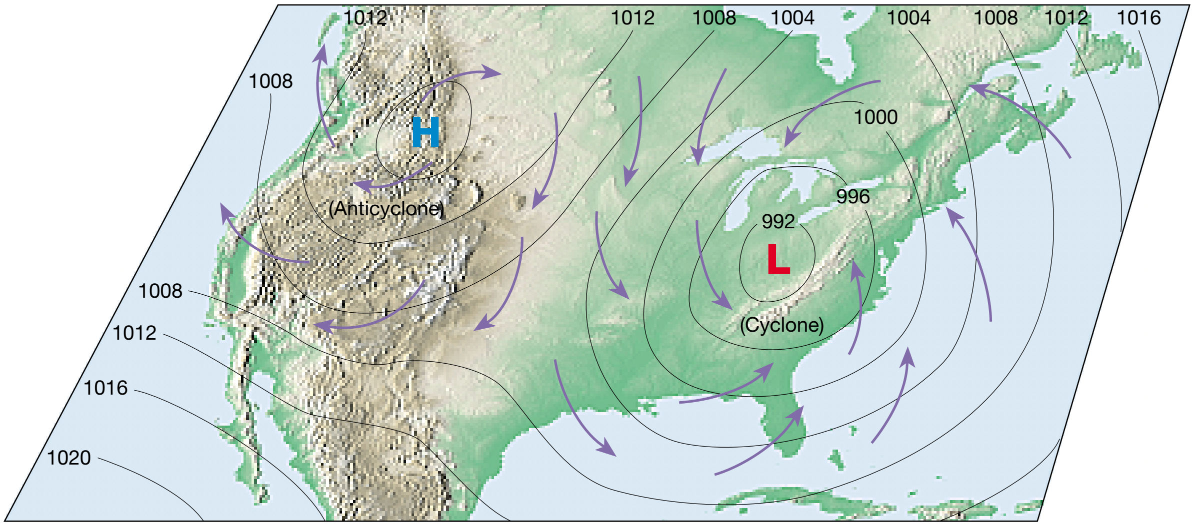


FIGURE 6-20 Cyclonic and anticyclonic winds in the Northern Hemisphere. Arrows show the winds blowing inward and counterclockwise around a low, and outward and clockwise around a high.

How Winds Generate Vertical Air Motion

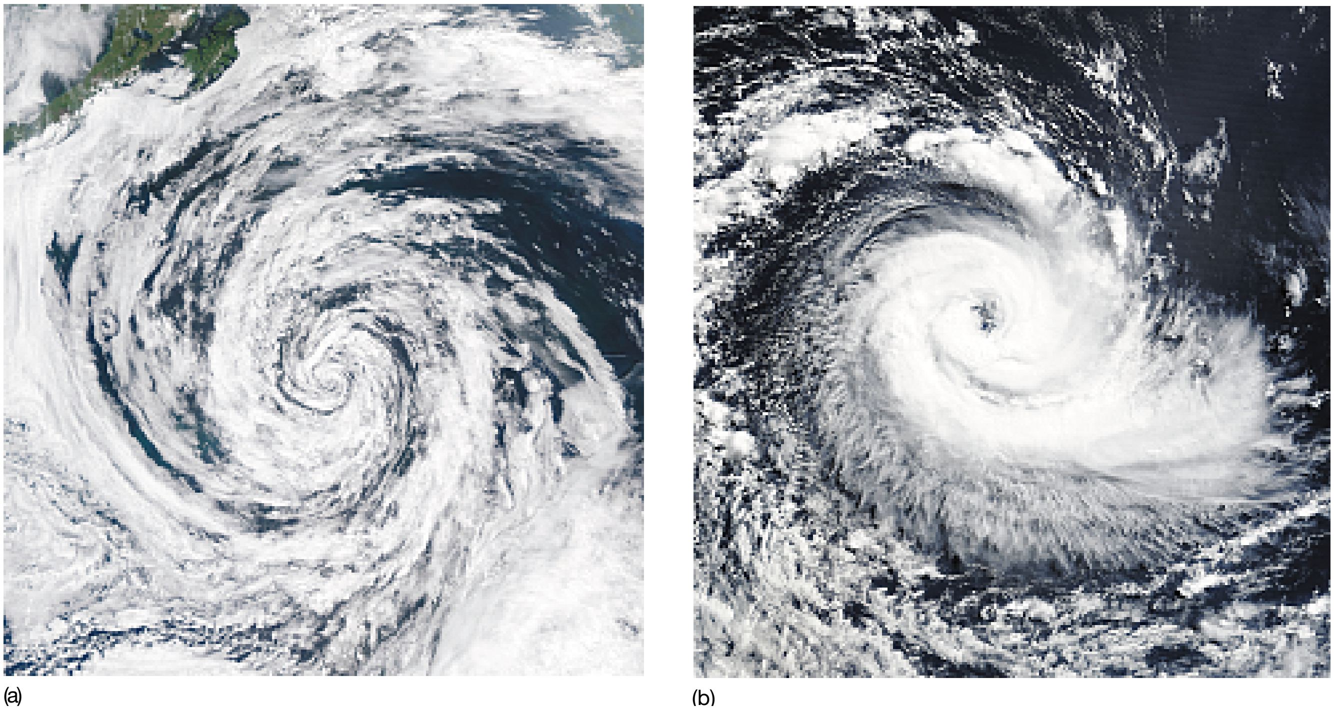
Air Pressure and Wind

▸ Highs and Lows

So far we have discussed wind without regard to how airflow in one region might affect airflow elsewhere. As one researcher put it, a butterfly flapping its wings in South America can generate a tornado in the United States. Although this is an exaggeration, it does illustrate how airflow in one region might cause a change in weather at some later time and at a different location.

Of particular importance is the question of how horizontal airflow (winds) relates to vertical flow. Although vertical transport is small compared to horizontal motion, it is very important as a weather maker. Rising air is associated with cloudy conditions and precipitation, whereas subsidence produces adiabatic heating and clearing conditions.

FIGURE 6-21 Cyclonic circulation in the Northern and Southern hemispheres. The cloud patterns in these images allow us to “see” the circulation pattern in the lower atmosphere. (a) This satellite image shows a large low-pressure center in the Gulf of Alaska on August 17, 2004. The cloud pattern clearly shows an inward and *counterclockwise* spiral. (b) This image from March 26, 2004, shows a strong cyclonic storm in the South Atlantic near the coast of Brazil. The cloud pattern reveals an inward and *clockwise* circulation. *(NASA Images)*



In this section we will discern how the movement of air (dynamic effect) can itself create pressure change and hence generate winds. In doing so, we will examine the interrelationship between horizontal and vertical flow and its effect on the weather.

Vertical Airflow Associated with Cyclones and Anticyclones

Let us first consider the situation around a surface low-pressure system (cyclone) in which the air is spiraling inward (see Figure 6–20). Here the net inward transport of air causes a shrinking of the area occupied by the air mass, a process called *horizontal convergence* (Figure 6–22). Whenever air converges horizontally, it must pile up—that is, it must increase in height to allow for the decreased area it now occupies. This process generates a "taller" and therefore heavier air column, yet a surface low can exist only as long as the column of air above remains light. We seem to have encountered a paradox—low-pressure centers cause a net accumulation of air, which increases their pressure. Consequently, a surface cyclone should quickly eradicate itself in a manner not unlike what happens to the vacuum in a coffee can when it is opened.

You can see that for a surface low to exist for very long, compensation must occur aloft. For example, surface convergence could be maintained if *divergence* (spreading out) aloft occurred at a rate equal to the inflow below. Figure 6–22 diagrammatically shows the relationship between surface convergence (inflow) and the divergence aloft (outflow) 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.

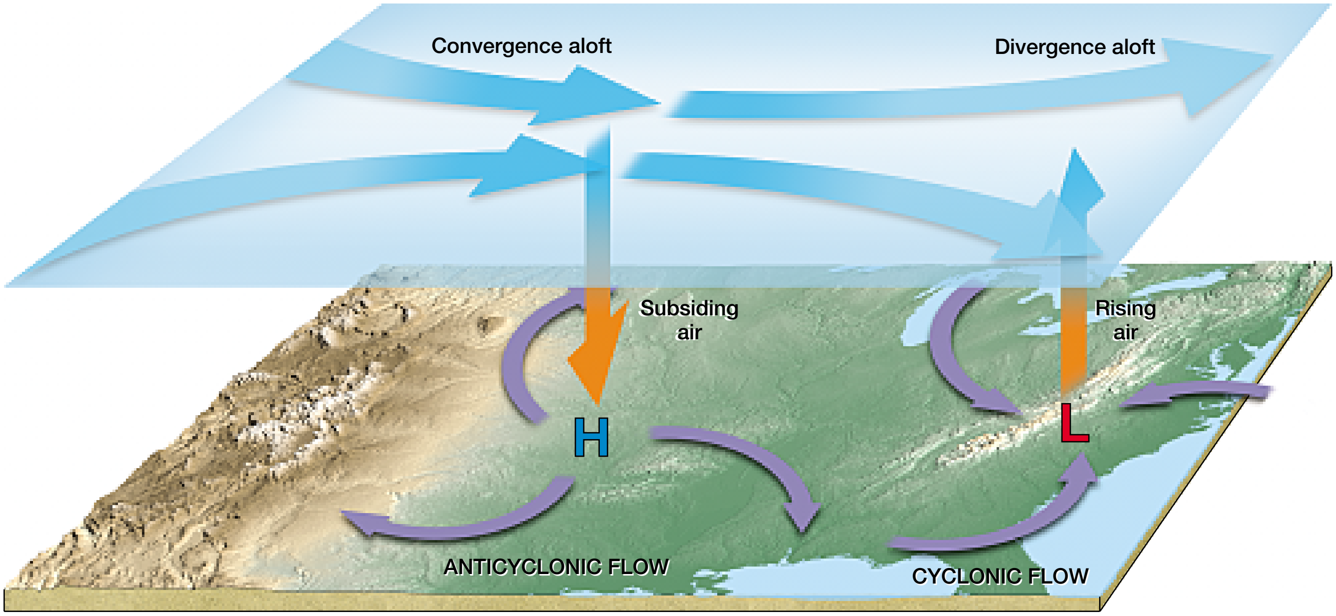
Note that surface convergence about a cyclone causes a *net upward movement.* The rate of this vertical movement is slow, generally less than 1 kilometer per day. (Recall that updrafts in thunderstorms sometimes exceed 100 kilometers per hour.) Nevertheless, because rising air often results in cloud formation and precipitation, the passage of a low-pressure center generally is related to unstable conditions and stormy weather.

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 also be maintained from above. Outflow near the surface is accompanied by convergence aloft and general subsidence of the air column (Figure 6–22). 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 system.

For reasons that should now be obvious, it has been common practice to write the word "stormy" at the low end of household barometers and "fair" at the high end (Figure 6–23). By noting the pressure trend—rising, falling, or steady—we have a good indication of forthcoming weather. Such a determination, called the **pressure tendency** or **barometric tendency,** is useful in short-range weather prediction. The generalizations relating cyclones and anticyclones to weather conditions are stated nicely in this verse ("glass" refers to the barometer):

FIGURE 6-22 Airflow associated with surface cyclones and anticyclones. A low, or cyclone, has converging surface winds and rising air causing cloudy conditions. A high, or anticyclone, has diverging surface winds and descending air, which leads to clear skies and fair weather.




(a) (b)

FIGURE 6-23 These two photographs illustrate the basic weather generalizations associated with pressure centers. (a) A sea of umbrellas on a rainy day in Shanghai, China. Centers of low pressure are frequently associated with cloudy conditions and precipitation. *(Photo by Stone/Getty Images, Inc.-Stone Allstock)* (b) By contrast, clear skies and "fair" weather may be expected when an area is under the influence of high pressure. Sunbathers on a beach at Cape Henlopen, Delaware. *(Photo by Mark Gibson/DRK Photo)*

When the glass falls low,
Prepare for a blow;
When it rises high,
Let all your kites fly.

In conclusion, you should now be better able to understand why local television weather broadcasters emphasize the positions and projected paths of cyclones and anticyclones. The "villain" on these weather programs is always the cyclone, which produces "bad" weather in any season. Lows move in roughly a west-to-east direction across the United States and require from a few days to more than a week for the journey. Because their paths can be erratic, accurate prediction of their migration is difficult and yet essential for short-range forecasting. Meteorologists must also determine if the flow aloft will intensify an embryo storm or act to suppress its development.

Factors That Promote Vertical Airflow

Because of the close tie between vertical motion in the atmosphere and our daily weather, we will consider some other factors that contribute to surface convergence (uplifting) and surface divergence (subsidence).

Friction can cause convergence and divergence in several ways. When air moves from the relatively smooth ocean surface onto land, for instance, the increased friction causes an abrupt drop in wind speed. This reduction of wind speed downstream results in a pile-up of air upstream. Thus, converging winds and ascending air accompany flow off the ocean. This effect contributes to the cloudy conditions over land often associated with a sea breeze in a humid region like Florida. Conversely, when air moves from land onto the ocean, general divergence and subsidence accompany the seaward flow of air because of lower friction and increasing wind speed over the water. (It should be noted that if cool air moves over a comparatively warm water body, heating from below tends to destabilize the air.)

Mountains also hinder the flow of air and cause divergence and convergence. As air passes over a mountain range, it is compressed vertically, which produces horizontal spreading (divergence) aloft. On reaching the lee side of the mountain, the air experiences vertical expansion, which causes horizontal convergence. This effect greatly influences the weather in the United States east of the Rocky Mountains, as we shall examine later. When air flows equatorward, where the Coriolis force is weakened, divergence and subsidence prevail; during poleward migration, convergence and slow uplift are favored.

As a result of the close tie between surface conditions and those aloft, great emphasis has been placed on understanding total atmospheric circulation, especially in the midlatitudes. Once we have examined the workings of global atmospheric circulation in the next chapter, we will again consider the close tie between horizontal airflow and vertical motion in light of this information.

FIGURE 6-24 Wind vane (right) and cup anemometer (left). The wind vane shows wind direction, and the anemometer measures wind speed. *(Photo by Belfort Instrument Company)*

Students Sometimes Ask…

What causes "mountain sickness"?

When visitors drive up to a mountain pass above 3000 meters (10,000 feet) and take a walk, they typically notice a shortness of breath and possibly fatigue. These symptoms are caused by breathing air that has roughly 30 percent less oxygen than at sea level. At these altitudes our bodies try to compensate for air that is deficient in oxygen by breathing more deeply and increasing the heart rate, thereby pumping more blood to the body's tissues. The additional blood is thought to cause brain tissues to swell, resulting in headaches, insomnia, and nausea—the main symptoms of *acute mountain sickness.* Mountain sickness is generally not life threatening and usually can be alleviated with a night's rest at a lower altitude. Occasionally people become a victim of *high-altitude pulmonary edema.* This life-threatening condition involves a buildup of fluid in the lungs and requires prompt medical attention.

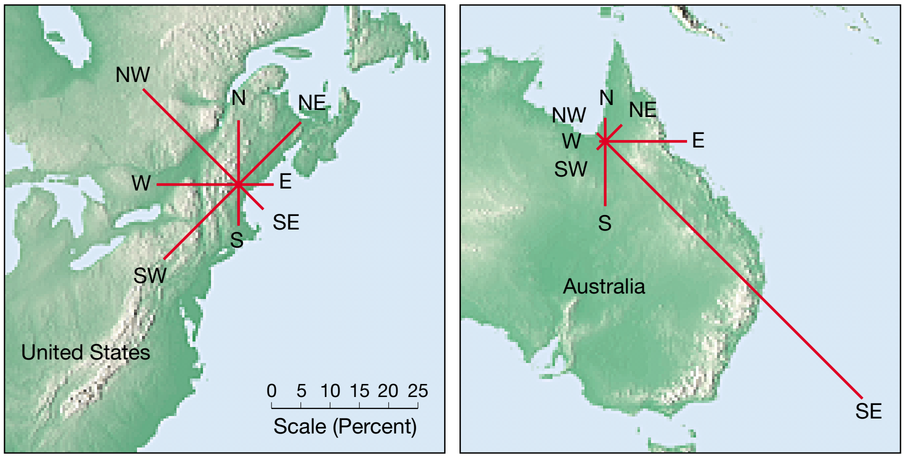
Wind Measurement

Two basic wind measurements—direction and speed—are important to the weather observer. Winds are always labeled by the direction *from* which they blow. A north wind blows from the north toward the south; an east wind blows from the east toward the west. One instrument that is commonly used to determine wind direction is the **wind vane** (Figure 6–24). This instrument, which is a common sight on many buildings, always points into the wind. Sometimes the wind direction is shown on a dial that is connected to the wind vane. The dial indicates the direction of the wind either by points of the compass—that is, N, NE, E, SE, and so on—or by a scale of 0 to 360°. On the latter scale 0° (or 360°) is north, 90° is east, 180° is south, and 270° is west.

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 mid-latitudes. In the United States, for example, these winds consistently move the "weather" 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 6–25.

A *wind rose* provides a method of representing prevailing winds by indicating the percentage of time the wind blows from various directions (Figure 6–25). The length of the lines on the wind rose indicates the percentage of time the wind blew from that direction. Knowledge of the wind patterns for a particular area can be useful. For example, during the construction of an airport, the runways are aligned with the prevailing wind to

FIGURE 6-25 Wind roses showing the percentage of time airflow is from various directions. (a) Wind frequency for the winter in the eastern United States. (b) Wind frequency for the winter in northern Australia. Note the reliability of the southeast trades in Australia as compared to the westerlies in the eastern United States. *(Data from G. T. Trewartha)*



(a) Westerlies (winter)

(b) Southeast Trades (winter)

FIGURE 6-26 An aerovane. *(Photo by Warren Faidley/ Weatherstock)*

assist in takeoffs and landings. Furthermore, prevailing winds greatly affect the weather and climate of a region. North–south trending mountain ranges, such as the Cascade Range of the Pacific Northwest, for example, causes the ascent of the prevailing westerlies. Thus, the windward (west) slopes of these ranges are rainy, whereas the leeward (east) sides are dry.

Wind speed is often measured with a **cup anemometer** (Figure 6–24). The wind speed is read from a dial much like the speedometer of an automobile. Sometimes an **aerovane** is used instead of a wind vane and cup anemometer. As can be seen in Figure 6–26, this instrument resembles a wind vane with a propeller at one end. The fin keeps the propeller facing into the wind, allowing the blades to rotate at a rate that is proportional to the wind speed. This instrument is commonly attached to a recorder to keep a continuous record of wind speed and direction. Places where winds are steady and speeds are relatively high are potential sites for tapping wind energy (see Box 6–5).

At small airstrips *wind socks* are frequently used. They consist of a cone-shaped bag that is open at both ends and free to change position with shifts in wind direction. The degree to which the sock is inflated is an indication of the strength of the wind.

Recall that 70 percent of Earth's surface is covered by water where conventional methods of measuring wind speed are not possible. Although weather buoys and ships at sea do provide some coverage, weather forecasts have improved dramatically since the 1990s due to the availability of satellite-derived wind data. One way wind speed and direction can be established is by using satellite images to track cloud movements. This is currently being accomplished by comparing a sequence of GOES images separated by intervals of 5 to 30 minutes (Figure 6–27). This innovation has been especially useful in predicting the timing and location of where a hurricane will make landfall.

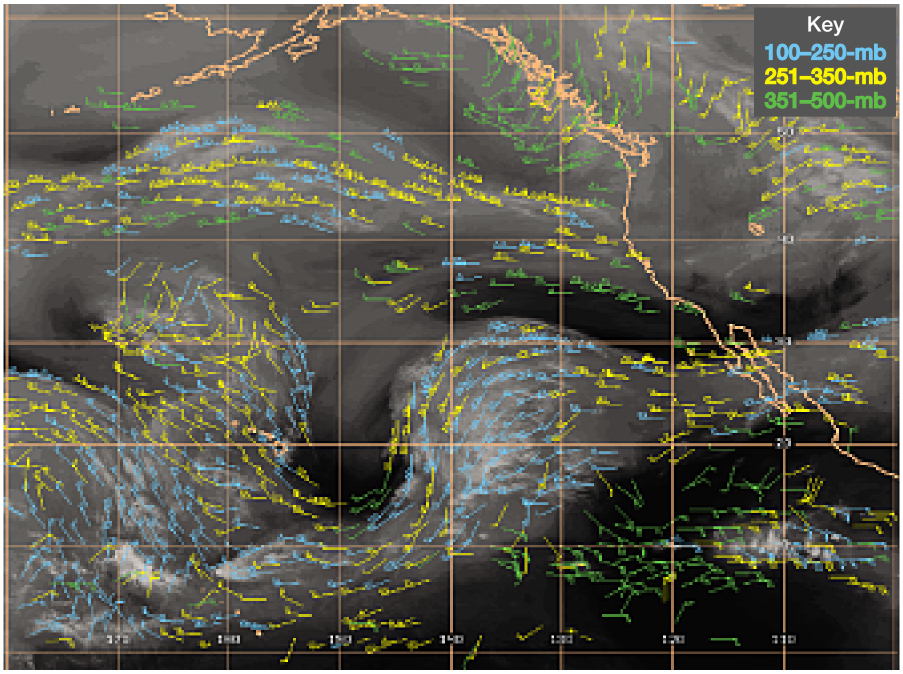


FIGURE 6–27 Upper-level winds obtained from the GOES meteorological satellite.

BOX 6-5 Wind Energy: An Alternative with Potential

Air has mass, and when it moves (that is, when the wind blows), it contains the energy of that motion—kinetic energy. A portion of that energy can be converted into other forms—mechanical force or electricity—that we can use to perform work (Figure 6–C).

Mechanical energy from wind is commonly used for pumping water in rural or remote places. The "farm windmill," still a familiar site in many rural areas, is an example. Mechanical energy converted from wind can also be used for other purposes, such as sawing logs, grinding grain, and propelling sailboats. By contrast, wind-powered electric turbines generate electricity for homes, businesses, and for sale to utilities.

Approximately 0.25 percent (one-quarter of 1 percent) of the solar energy that reaches the lower atmosphere is transformed into wind. Although it is just a minuscule percentage, the absolute amount of energy is enormous. According to one estimate, North Dakota alone is theoretically capable of producing enough wind-generated power to meet more than one-third of U.S. electricity demand. Wind speed is a crucial element in determining whether a place is a suit-

FIGURE 6-C These wind turbines are operating near Palm Springs, California. California is the state in which the most wind-power development has occurred. As of January 2004, California had a total of 2043 megawatts of installed capacity (nearly one-third of total U.S. capacity). That's enough electricity to supply between 500,000 and 600,000 average American households. *(Photo by John Mead/Science Photo Library/Photo Researchers, Inc.)*

able site for installing a wind-energy facility. Generally a minimum, annual average wind speed of 21 kilometers (13 miles) per hour is necessary for a utility-scale wind-power plant.

> The power available in the wind is proportional to the cube of its speed. Thus, a turbine operating at a site with an average wind speed of 12 mph could in theory generate about 33 percent more electricity than one at an 11-mph site, because the cube of 12 (1768) is 33 percent larger than the cube of 11 (1331). (In the real world, the turbine will not produce quite that much more electricity, but it will still generate much more than the 9 percent difference in wind speed.) The important thing to understand is that what seems like a small difference in wind speed can mean a large difference in available energy and in electricity produced, and therefore a large difference in the cost of the electricity generated. Also, there is little energy to be harvested at very low wind speeds (6-mph winds contain less than one-eighth the energy of 12-mph winds).*

As technology has improved, efficiency has increased and the costs of wind-generated electricity have become more competitive. Between 1983 and 2004 technological advances cut the cost of wind power by more than 85 percent. As a result, the growth of installed capacity has grown dramatically. Worldwide the total amount of installed wind power grew more than 600 percent from 7636 megawatts in 1997 to 47,000 megawatts in 2004 (Table 6–B). 47,000 megawatts is enough to supply 10.5 million average American households, or as much as could be generated by 14 large nuclear power plants.

By the end of 2005, U.S. capacity reached nearly 9200 megawatts (Figure 6–D). By 2008 or 2009 the United States is expected to add at least 3000 megawatts of new utility wind-power projects.

The U.S. Department of Energy has announced a goal of obtaining 5 percent of U.S. electricity from wind by the year 2020—a goal that seems consistent with the current growth rate of wind energy nationwide. Thus, wind-generated electricity seems to be shifting from being an “alternative” to being a “mainstream” energy source.

TABLE 6-B World leaders in wind capacity (2004)

Country	Capacity (megawatts*)
Germany	16,629
Spain	8,263
United States	6,740
Denmark	3,117
India	3,000
Italy	1125
Netherlands	1078
United Kingdom	888
Japan	874
China	764

*1 megawatt is enough electricity to supply 250–300 average American households. The “top 10” nations listed in this table account for over 95 percent of the total wind energy produced.

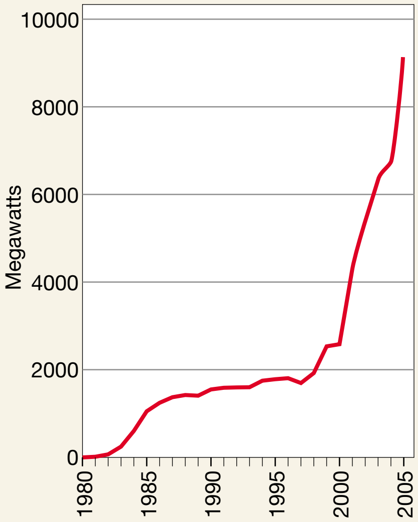


FIGURE 6-D U.S.-installed wind-power capacity (in megawatts at the end of 2005). Growth in recent years has been dramatic. *(Data from U.S. Department of Energy and American Wind Energy Association)*

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*American Wind Energy Association. “Wind Energy Basics” http://www.awea.org/faq/tutorial/wwt_basics.html

Chapter Summary

- *Air pressure* is 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. Another way to define air pressure is that it is the force exerted against a surface by the continuous collision of gas molecules.
- The *newton* is the unit of force used by meteorologists to measure atmospheric pressure. A *millibar* (mb) equals 100 newtons per square meter. Standard sea-level pressure is 1013.25 millibars. Two instruments used to measure atmospheric pressure are the *mercury barometer*, where the height of a mercury column provides a measure of air pressure (standard atmospheric pressure at sea level equals 29.92 inches or 760 millimeters), and the *aneroid barometer*, which uses a partially evacuated metal chamber that changes shape as air pressure changes.
- The pressure at any given altitude is equal to the weight of the air above that point. Furthermore, the rate at which pressure decreases with an increase in altitude is much greater near Earth's surface. The "normal" decrease in pressure experienced with increased altitude is provided by the *standard atmosphere*, which depicts the idealized vertical distribution of atmospheric pressure.
- In calm air, the two factors that largely determine the amount of air pressure exerted by an air mass are temperature and humidity. A cold, dry air mass will produce higher surface pressures than a warm, humid air mass.
- *Wind* is the result of horizontal differences in air pressure. If Earth did not rotate and there were no friction, air would flow directly from areas of higher pressure to areas of lower pressure. However, because both factors exist, wind is controlled by a combination of (1) the *pressure-gradient force*, (2) the *Coriolis force*, and (3) *friction*. The pressure-gradient force is the primary driving force of wind that results from pressure differences that occur over a given distance, as depicted by the spacing of *isobars*, lines drawn on maps that connect places of equal air pressure. The spacing of isobars indicates the amount of pressure change occurring over a given distance, expressed as the *pressure gradient*. Closely spaced isobars indicate a steep pressure gradient and strong winds; widely spaced isobars indicate a weak pressure gradient and light winds. There is also an upward-directed vertical pressure gradient, which is usually balanced by gravity in what is referred to as *hydrostatic equilibrium*. On those occasions when the gravitational force slightly exceeds the vertical pressure gradient force, slow downward airflow results. The Coriolis force produces a 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). The amount of deflection is greatest at the poles and decreases to zero at the equator. The amount of Coriolis deflection also increases with wind speed. 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 effect of friction on airflow is small enough to disregard. Here, as the wind speed increases, the deflection caused by the Coriolis force also increases. Winds in which the Coriolis force is equal to and opposite the pressure gradient force are called *geostrophic winds*. Geostrophic winds flow in a straight path, parallel to the isobars, with velocities proportional to the pressure-gradient force.
- Winds that blow at a constant speed parallel to curved isobars are termed *gradient winds*. In centers of low pressure, called *cyclones*, the circulation of air, referred to as *cyclonic flow*, is counterclockwise in the Northern Hemisphere and clockwise in the Southern Hemisphere. Centers of high pressure, called *anticyclones*, exhibit *anticyclonic flow*, which is clockwise in the Northern Hemisphere and counterclockwise in the Southern Hemisphere. Whenever isobars curve to form elongated regions of low and high pressure, these areas are called *troughs* and *ridges*, respectively.
- Near the surface, friction plays a major role in redistributing air within the atmosphere by changing the direction of airflow. The result is a movement of air at an angle across the isobars, toward the area of lower pressure. Therefore, the resultant winds blow into and counterclockwise about a Northern Hemisphere surface cyclone. In a Northern Hemisphere surface anticyclone, winds blow outward and clockwise. Regardless of the hemisphere, friction causes a net inflow (*convergence*) around a cyclone and a net outflow (*divergence*) around an anticyclone.
- A surface low-pressure system with its associated horizontal convergence is maintained or intensified by divergence (spreading out) aloft. Inadequate divergence aloft will weaken the accompanying cyclone. Because surface convergence about a cyclone accompanied by divergence aloft causes a net upward movement of air, the passage of a low pressure center is often associated with stormy weather. By contrast, fair weather can usually be expected with the approach of a high-pressure system. As a result of the general weather patterns usually associated with cyclones and anticyclones, the *pressure tendency* or *barometric tendency* (the nature of the change of the barometer over the past several hours) is useful in short-range weather prediction.
- Two basic wind measurements—direction and speed—are important to the weather observer. Wind direction is commonly determined using a *wind vane*. When the wind consistently blows more often from one direction than from any other, it is called a *prevailing wind*. Wind speed is often measured with a *cup anemometer*.

Vocabulary Review

aerovane (p. 191)
air pressure (p. 168)
aneroid barometer (p. 170)
anticyclone (p. 184)
anticyclonic flow (p. 184)
barograph (p. 170)
barometric tendency (p. 188)
Buys Ballot's law (p. 182)
convergence (p. 174)
Coriolis force (p. 178)
cup anemometer (p. 191)
cyclone (p. 184)
cyclonic flow (p. 184)
divergence (p. 174)
geostrophic wind (p. 182)
gradient wind (p. 183)
high (p. 174)
hydrostatic equilibrium (p. 177)
isobar (p. 175)
low (p. 174)
mercury barometer (p. 169)
millibar (p. 169)
newton (p. 169)
pressure gradient (p. 176)
pressure tendency (p. 188)
prevailing wind (p. 190)
ridge (p. 184)
standard atmosphere (p. 173)
trough (p. 184)
wind (p. 175)
wind vane (p. 190)

Review Questions

1. What is standard sea-level pressure in millibars? In inches of mercury? In pounds per square inch?
2. Describe the operating principles of the mercury barometer and the aneroid barometer. List two advantages of the aneroid barometer.
3. Explain why air pressure decreases with an increase in altitude.
4. Explain why a cold, dry air mass produces a higher surface pressure than a warm, humid air mass.
5. Compare convergence with divergence.
6. What force is responsible for *generating* wind?
7. Write a generalization relating the spacing of isobars to the speed of wind.
8. Temperature variations create pressure differences, which in turn produce winds. On a small scale, the sea breeze illustrates this principle nicely. Describe how a sea breeze forms.
9. Although vertical pressure differences may be great, such variations do not generate strong vertical currents. Explain.
10. Briefly describe how the Coriolis force modifies the movement of air.
11. Which two factors influence the magnitude of the Coriolis force?
12. Explain the formation of a geostrophic wind.
13. Unlike winds aloft, which blow nearly parallel to the isobars, surface winds generally cross the isobars. Explain what causes this difference.
14. Prepare a diagram (isobars and wind arrows) showing the winds associated with surface cyclones and anticyclones in both the Northern and Southern Hemispheres.
15. For surface low pressure to exist for an extended period, what condition must exist aloft?
16. What are the general weather conditions to be expected when the pressure tendency is rising? When the pressure tendency is falling?
17. Converging winds and ascending air are often associated with the flow of air from the oceans onto land. Conversely, divergence and subsidence often accompany the flow of air from land to sea. What causes this convergence over land and divergence over the ocean?
18. A southwest wind blows from the _____ (direction) toward the _____ (direction).
19. The wind direction is 315°. From what compass direction is the wind blowing?

Problems

1. Calculate the magnitude of the pressure-gradient force (per unit mass) between two cities 500 kilometers apart if pressure at the respective cities is 1010 mb and 1017 mb?
2. Calculate the magnitude of Coriolis force acting on air moving at:
   - **a.** 36 kilometers per hour (10 meters per second) at 35° latitude.
   - **b.** 36 kilometers per hour (10 meters per second) at 65° latitude.
   - **c.** 54 kilometers per hour (15 meters per second) at 35° latitude.

Atmospheric Science Online

The Atmosphere 10e web site uses the resources and flexibility of the Internet to aid in your study of the topics in this chapter. Written and developed by meteorology instructors, this site will help improve your understanding of meteorology. Visit **http://www.prenhall.com/lutgens** and click on the cover of *The Atmosphere 10e* to find:

- **Online review quizzes**
- **Critical thinking exercises**
- **Links to chapter-specific web resources**
- **Internet-wide key term searches**

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