Atmospheric Pressure, Winds, and Circulation Patterns

5

CHAPTER PREVIEW

Latitudinal differences in temperature (as a result of differential receipt of insolation) provide a partial explanation for latitudinal differences in pressure.

- What is the relationship between temperature and pressure?
- Why is this only a partial explanation?

The fact that land heats and cools more rapidly than water is of significance not only to world patterns of temperature but also to world patterns of pressure, winds, and precipitation.

- How can you explain this fact?
- What effect does this fact have on world patterns?

Planetary (global) wind systems in association with global pressure patterns play a major role in global circulation.

- What are the six major planetary (global) wind belts or zones, and what are their chief characteristics?
- Why do the wind belts migrate with the seasons?

Upper air winds and atmospheric circulation play a major role in controlling surface weather and climatic conditions.

- What is upper air circulation like?
- How do ocean currents affect atmospheric conditions of land areas?

El Niños can have a devastating impact on our global weather.

- What is an El Niño?
- How does it influence global weather?

◀ **Opposite: The swirling circulation patterns seen in Earth's atmosphere are created by changes in pressure and winds.**
NASA/GSFC

An individual gas molecule weighs almost nothing; however, the atmosphere as a whole has considerable weight and exerts an average pressure of 1034 grams per square centimeter (14.7 lb/sq in.) on Earth's surface. The reason why people are not crushed by this atmospheric pressure is that we have air and water inside us—in our blood, tissues, and cells—exerting an equal outward pressure that balances the inward pressure of the atmosphere. Atmospheric pressure is important because variation in pressure within the Earth–atmosphere system creates our atmospheric circulation and thus plays a major role in determining our weather and climate. It is the differences in *atmospheric pressure* that create our *winds*. Further, the movement of the winds drives our *ocean currents,* and thus atmospheric pressure works its way into several of Earth's systems.

In 1643, Evangelista Torricelli, a student of Galileo, performed an experiment that was the basis for the invention of the *mercury barometer,* an instrument that measures atmospheric (also called barometric) pressure. Torricelli took a tube filled with mercury and inverted it in an open pan of mercury. The mercury inside the tube fell until it was at a height of about 76 centimeters (29.92 in.)

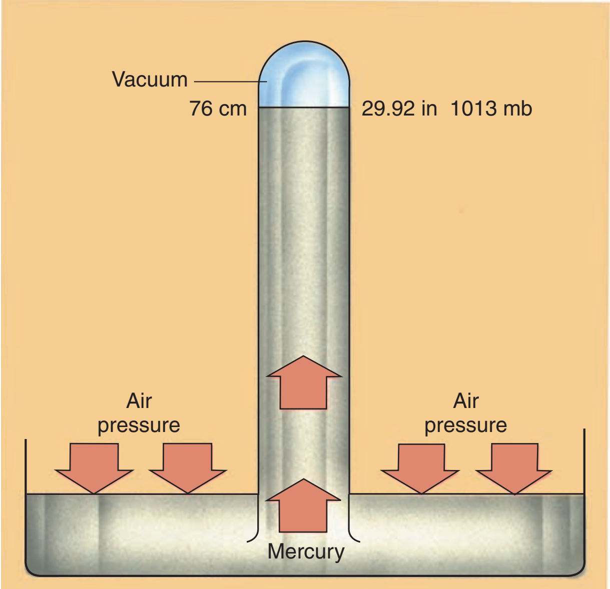
above the mercury in the pan, leaving a vacuum bubble at the closed end of the tube (● Fig. 5.1). At this point, the pressure exerted by the atmosphere on the open pan of mercury was equal to the pressure from the mercury trying to drain from the tube. Torricelli observed that as the air pressure increased, it pushed the mercury up higher into the tube, increasing the height of the mercury until the pressure exerted by the mercury (under the pull of gravity) would equal the pressure of the air. On the other hand, as the air pressure decreased, the mercury level in the column dropped.

In the strictest sense, a mercury barometer does not actually measure the pressure exerted by the atmosphere on Earth's surface, but instead measures the *response* to that pressure. That is, when the atmosphere exerts a specific pressure, the mercury will respond by rising to a specific height (● Fig. 5.2). Meteorologists usually prefer to work with actual pressure units. The unit most often used is the millibar (mb). Standard sea-level pressure of 1013.2 millibars will cause the mercury to rise 76 centimeters (29.92 in.).

Our study of the atmospheric elements that combine to produce weather and climate has to this point focused on the fundamental influence of solar energy on the global distributional patterns of temperature. The unequal receipt of insolation by latitude over Earth's surface produces temperature patterns that vary from the equator to the poles. In this chapter, we learn that these temperature differences are one of the major causes of the development of patterns of higher and lower pressure that also vary with latitude. In addition, we examine patterns of another kind—patterns of movement or, more properly, circulation, in which both energy and matter travel cyclically through Earth subsystems.

Geographers are particularly interested in circulation patterns because they illustrate spatial interaction, one of geography's major themes introduced in Chapter 1. Patterns of movement between one place and another reveal that the two places have a relationship and prompt geographers to seek both the nature and effect of that relationship. It is also important to understand the causes of the spatial interaction taking place. As we examine the circulation patterns featured later in this chapter, you should make a special effort once again to trace each pattern back to the fundamental influence of solar energy.

● **FIGURE 5.1**
A simple mercury barometer. Standard sea-level pressure of 1013.2 millibars will cause the mercury to rise 76 centimeters (29.92 in.) in the tube.
When air pressure increases, what happens to the mercury in the tube?



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● **FIGURE 5.2**
This mercury barometer is bolted to the wall of the College Heights Weather Station in Bowling Green, Kentucky.
Why must this instrument be so tall to work properly?

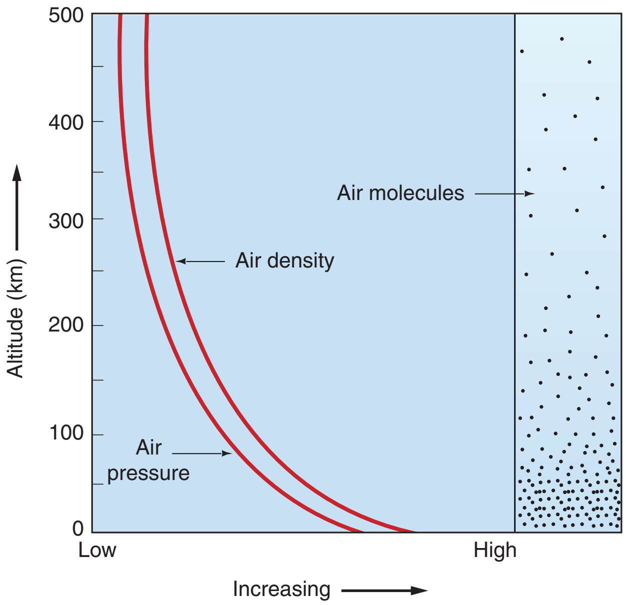
Variations in Atmospheric Pressure

Vertical Variations in Pressure

Imagine a pileup of football players during a game. The player on the bottom gets squeezed more than a player near the top because he has the weight of all the others on top of him. Similarly, air pressure decreases with elevation, for the higher we go, the more diffused, and more widely spaced the air molecules become. The increased intermolecular space results in lower air density and lower air pressure (● Fig. 5.3). In fact, at the top of Mount Everest (elevation 8848 m, or 29,028 ft), the air pressure is only about one third the pressure at sea level.

Humans are usually not sensitive to small, everyday variations in air pressure. However, when we climb or fly to altitudes significantly above sea level, we become aware of the effects of air pressure on our system. When jet aircraft fly at 10,000 meters (33,000 ft), they have to be pressurized and nearly airtight so that a near-sea-level pressure can be maintained. Even then, the pressurization may not work perfectly, so our ears may pop as they adjust to a rapid change in pressure when ascending or descending. Hiking or skiing at heights that are a few thousand meters in elevation will affect us if we are used to the air pressure at sea level. The reduced air pressure means less oxygen is contained in each breath of air. Thus, we sometimes find that we get out of breath far more easily at high elevations until our bodies adjust to the reduced air pressure and corresponding drop in oxygen level.

● FIGURE 5.3
Both air pressure and air density decrease rapidly with increasing altitude.
By approximately how much does density drop between 0 and 100 km?



Changes in air pressure are not solely related to altitude. At Earth's surface, small but important variations in pressure are related to the intensity of insolation, the general movement of global circulation, and local humidity and precipitation. Consequently, a change in air pressure at a given locality often indicates a change in the weather. Weather systems themselves can be classified by the structure and tendency toward change of their pressure.

Horizontal Variations in Pressure

The causes of horizontal variation in air pressure are grouped into two types: thermal (determined by temperature) and dynamic (related to motion of the atmosphere).

We look at the simpler thermal type first. In Chapter 4, we saw that Earth is heated unevenly because of unequal distribution of insolation, differential heating of land and water surfaces, and different albedos of surfaces. One of the basic laws of gases is that the pressure and density of a given gas vary inversely with temperature. Thus, during the day, as Earth's surface heats the air in contact with it, the air expands in volume and decreases in density. Such air has a tendency to rise as its density decreases. When the warmed air rises, there is less air near the surface, with a consequent decrease in surface pressure. The equator is an area where such low pressure occurs regularly.

In an area with cold air, there is an increase in density and a decrease in volume. This causes the air to sink and pressure to increase. The poles are areas where such high pressures occur regularly. Thus, the constant low pressure in the equatorial zone and the high pressure at the poles are thermally induced.

From this we might expect a gradual increase in pressure from the equator to the poles to accompany the gradual decrease in average annual temperature. However, actual readings taken at Earth's surface indicate that pressure does not increase in a regular fashion poleward from the equator. Instead, there are regions of high pressure in the subtropics and regions of low pressure in the subpolar regions. The dynamic causes of these zones, or *belts,* of high and low pressure are more complex than the thermal causes.

These dynamic causes are related to the rotation of Earth and the broad patterns of circulation. For example, as air rises steadily at the equator, it moves toward the poles. Earth's rotation, however, causes the poleward-flowing air to drift to the east. In fact, by the time it is over the subtropical regions, the air is flowing from west to east. This bending of the flow as it moves poleward impedes the northward movement and causes the air to pile up over the subtropics, which results in increased pressure at Earth's surface there.

With high pressure over the polar and subtropical regions, dynamically induced areas of low pressure are created between them, in the subpolar region. As a result, air sinks into and flows from the highs to the lows, where it enters and rises. Thus, both the subtropical and subpolar pressure regions are dynamically induced. This example describes horizontal pressure variations on a global scale. We concentrate on this scale later in this chapter.

Basic Pressure Systems

Before we begin our discussion of circulation patterns leading up to the global scale, we must start by describing the two basic types of pressure systems: the **low,** or **cyclone,** and the **high,** or **anticyclone.** These are represented by the capital letters **L** and **H** that we commonly see on TV, newspaper, and official weather maps.

A low, or cyclone, is an area where air is ascending. As air moves upward away from the surface, it relieves pressure from that surface. In this case, barometer readings will begin to fall. A high, or anticyclone, is just the opposite. In a high, air is descending toward the surface and thus barometer readings will begin to rise, indicating an increased pressure on the surface. Lows and highs are illustrated in ● Figure 5.4.

Convergent and Divergent Circulation

As we have just seen, winds blow toward the center of a cyclone and can be said to *converge* toward it. Hence, a cyclone is a closed pressure system whose center serves as the focus for **convergent wind circulation.** The winds of an anticyclone blow away from the center of high pressure and are said to be *diverging.* In the case of an anticyclone, the center of the system serves as the source for **divergent wind circulation.** Figure 5.4 shows converging and diverging winds moving in straight paths. This is not a true picture of reality. In fact, winds moving out of a high and into a low do so in a spiraling motion created by another force, which we cover in the chapter section on wind.

Mapping Pressure Distribution

Geographers and meteorologists can best study pressure systems when they are mapped. In mapping air pressure, we reduce all pressures to what they would be at sea level, just as we changed temperature to sea level in order to eliminate altitude as a factor. The adjustment to sea level is especially important for atmospheric pressure because the variations due to altitude are far greater than those due to atmospheric dynamics and would tend to mask the more meteorologically important regional differences.

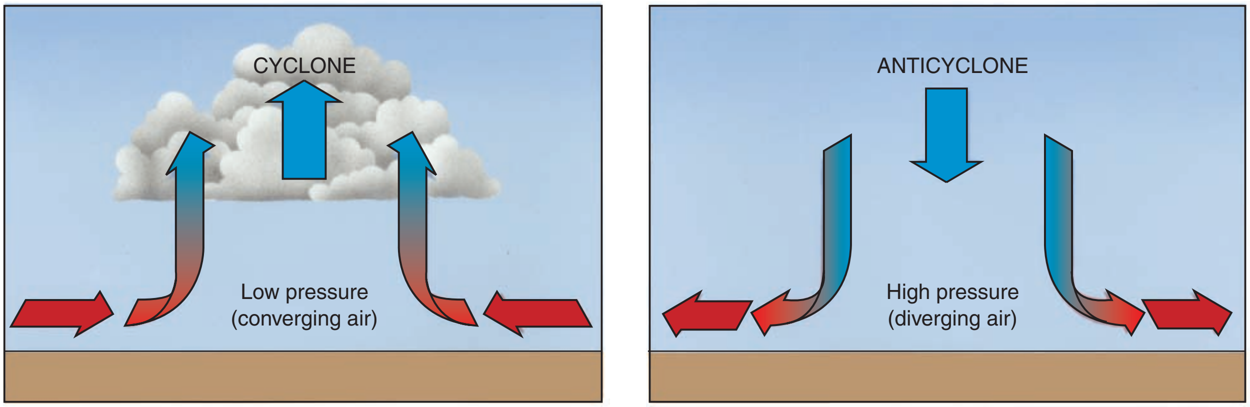
Isobars (from Greek: *isos,* equal; *baros,* weight) are lines drawn on maps to connect places of equal pressure. When the isobars appear close together, they portray a significant difference in pressure between places, hence a strong **pressure gradient.** When the isobars are far apart, a weak pressure gradient is indicated. When depicted on a map, high and low pressure cells are outlined by concentric isobars that form a closed system around centers of high or low pressure.

Wind

Wind is the horizontal movement of air in response to differences in pressure. Winds are the means by which the atmosphere attempts to balance the uneven distribution of pressure over Earth's surface. The movements of the wind also play a major role in correcting the imbalances in radiational heating and cooling that occur over Earth's surface. On average, locations below 38° latitude receive more radiant energy than they lose, whereas locations poleward of 38° lose more than they gain (see again Fig. 4.14). Our global wind system transports energy poleward to help maintain an energy balance. The global wind system also gives rise to the ocean currents, which are another significant factor in equalizing the energy imbalance. Thus, without winds and their associated ocean currents, the equatorial regions would get hotter and the polar regions colder through time.

Besides serving a vital function in the advectional (horizontal) transport of heat energy, winds also transport water vapor from the air above bodies of water, where it has evaporated, to land surfaces, where it condenses and precipitates. This allows greater precipitation over land surfaces than could otherwise occur. In addition, winds exert influence on the rate of evaporation itself. Furthermore, as we become more aware of and concerned about the effect that the burning of fossil fuels has on our atmosphere, we look for alternate energy sources. Natural sources such as water, solar energy, and wind become increasingly attractive alternatives to fossil fuels. They are clean, abundant, and renewable.

● **FIGURE 5.4**
Winds converge and ascend in cyclones (low pressure centers) and descend and diverge from anticyclones (high pressure centers).
How is temperature related to the density of air?



GEOGRAPHY'S ENVIRONMENTAL SCIENCE PERSPECTIVE

Harnessing the Wind

For centuries, windmills provided the power to pump water and grind grain in rural areas throughout the world. But the widespread availability of inexpensive electricity changed the role of most windmills to that of a nostalgic tourist attraction. Should we then conclude that energy from the wind is only a footnote in the history of power? In no way is that a reasonable assumption. The mounting needs for electricity and increasing problems from atmospheric pollution associated with fossil fuels must be taken into consideration.

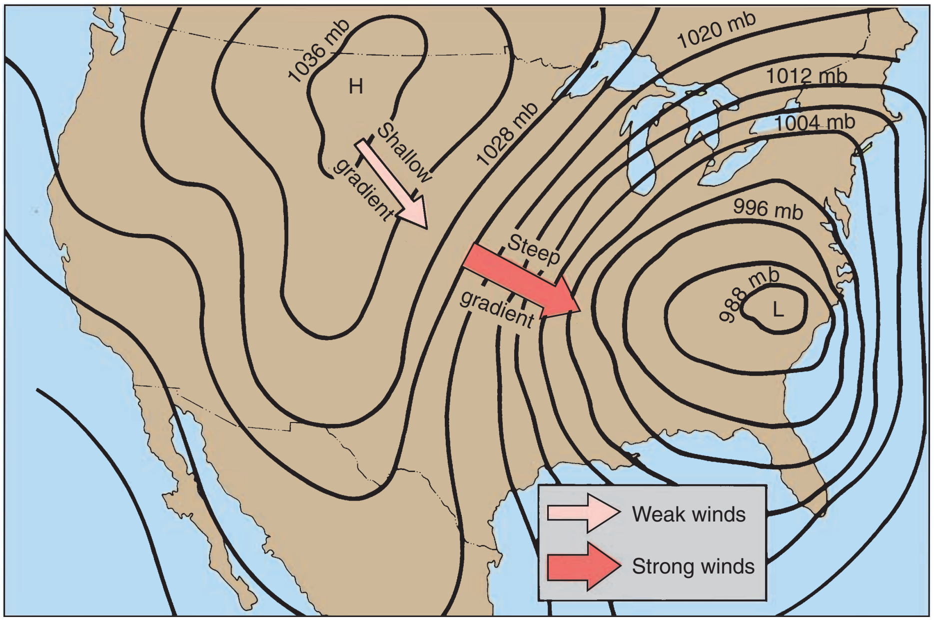
Wind power is an inexhaustible source of clean energy. Although the cost of electrical energy produced by the wind depends on favorable sites for the location of wind turbines, wind power is already cost competitive with power produced from fossil fuels. One expert calls wind generation the fastest-growing electricity-producing technology in the world. During the last decade, power production from the wind increased more than 25%. Much of the growth was in Europe, where most of the world's 17,000 megawatts of wind power are generated. As examples, 13% of Denmark's power and more than 20% of the power in the Netherlands, Spain, and Germany is supplied by the wind.

Two criteria are more important than others in the location of wind turbines. The site must have persistent strong winds, and it must be in an already developed region so that the power from the turbines can be linked directly to an existing electrical grid system. Although individual wind turbines (such as those located on farms scattered throughout the Midwest and Great Plains of the United States) can be found producing electricity, most wind power is generated from *wind farms*. These are long rows, or more concentrated groups, of as many as 50 or more turbines. Each turbine can economically extract up to 60% of the wind's energy at minimum wind speeds of 20 kilometers (12 mi) per hour, although higher wind speeds are desirable. Because the power generated is proportional to the cube of the wind speed, a doubling of wind velocity increases energy production eight times.

Although North America currently lags far behind Europe in the production of energy from the wind, the continent has great potential. Excellent sites for the location of wind farms exist throughout the open plains of North America's interior and along its coasts from the Maritime Provinces of Canada to Texas and from California to the Pacific Northwest. In addition, the newest wind-power technology places wind farms out of sight and sound in offshore locations that avoid navigation routes and marine-life sanctuaries. And North America has some of the largest coastlines in the world with major adjacent power needs. The sites are available, the technology has been developed, the costs are competitive, and the resolve to shift from fossil fuels is growing. Is it not time for power from the winds to come to North America?

Fields of windmills, like this one in Southern California that is used to generate electricity, are called wind farms.

Windmills like this, used to pump well water on ranches and farms, are in semiarid and arid regions of North America.



• **FIGURE 5.5**
The relationship of wind to the pressure gradient: The steeper the pressure gradient, the stronger will be the resulting wind.
Where else on this figure (other than the area indicated) would winds be strong?

Pressure Gradients and Winds

Winds vary widely in velocity, duration, and direction. Much of their strength depends on the size or strength of the pressure gradient to which they are responding. As we noted previously, *pressure gradient* is the term applied to the rate of change of atmospheric pressure between two points (at the same elevation). The greater this change—that is, the steeper the pressure gradient—the greater will be the wind response (• Fig. 5.5). Winds tend to flow down a pressure gradient from high pressure to low pressure, just as water flows down a slope from a high point to a low one. A useful little rhyme, "Winds always blow, from high to low," will always remind you of the direction of surface winds. The steeper the pressure gradients involved, the faster and stronger will be the winds. Yet wind does not flow directly from high to low, as we might expect, because other factors also affect the direction of wind.

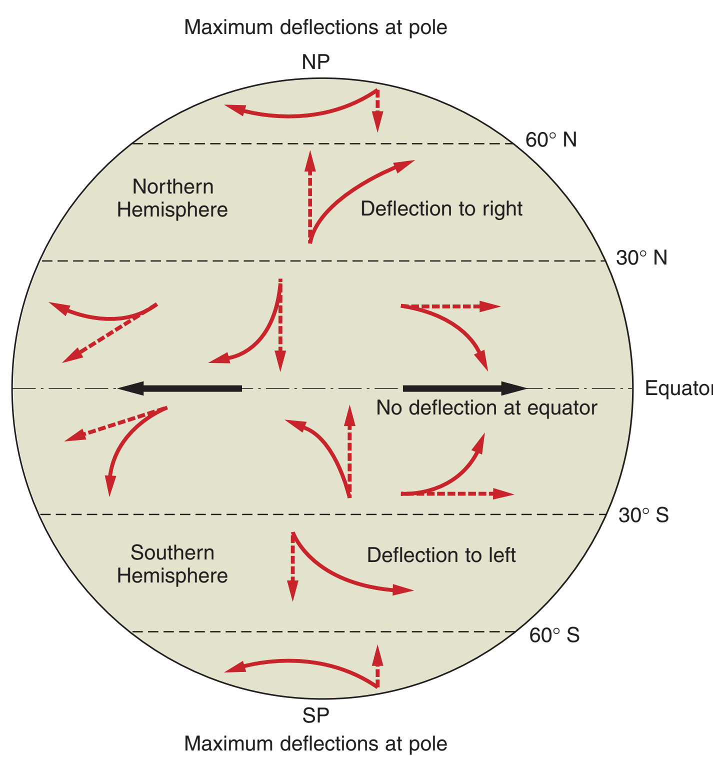
The Coriolis Effect and Wind

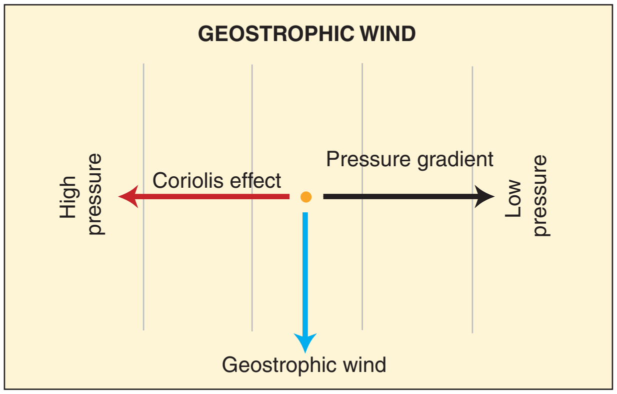
Two factors, both related to our Earth's rotation, greatly influence wind direction. First, our fixed-grid system of latitude and longitude is constantly rotating. Thus, our frame of reference for tracking the path of any free-moving object—whether it is an aircraft, a missile, or the wind—is constantly changing its position. Second, the speed of rotation of Earth's surface increases as we move equatorward and decreases as we move toward the poles (see again Fig. 3.11). Thus, to use our previous example, someone in St. Petersburg (60°N latitude), where the distance around a parallel of latitude is about half that at the equator, moves at about 840 kilometers per hour (525 mph) as Earth rotates, while someone in Kampala, Uganda, near the equator, moves at about 1680 kilometers per hour (1050 mph).

Because of these Earth rotation factors, anything moving horizontally appears to be deflected to the right of the direction in which it is traveling in the Northern Hemisphere and to the left in the Southern Hemisphere. This apparent deflection is termed the **Coriolis effect.** The degree of deflection, or curvature, is a function of the speed of the object in motion and the latitudinal location of the object. The higher the latitude, the greater will be the Coriolis effect (• Fig. 5.6). In fact, not only does the Coriolis effect decrease at lower latitudes, but it does not exist at the equator. Also, the faster the object is moving, the greater will be the apparent deflection, and the greater the distance something must travel, the greater will be the Coriolis effect.

As we have said, anything that moves horizontally over Earth's surface exhibits the Coriolis effect. Thus, both the atmosphere and the oceans are deflected in their

• **FIGURE 5.6**
Schematic illustration of the apparent deflection (Coriolis effect) of an object caused by Earth's rotation when an object (or the wind) moves north, south, east, or west in both hemispheres.
If no Coriolis effect exists at the equator, where would the maximum Coriolis effect be located?





● **FIGURE 5.7**
This Northern Hemisphere example illustrates that in a geostrophic wind, the Coriolis effect causes it to veer to the right until the pressure gradient and Coriolis effect reach an equilibrium and the wind flows between (and parallel to) the isobars.

movements. Winds in the Northern Hemisphere moving across a gradient from high to low pressure are apparently deflected to the right of their expected path (and to the left in the Southern Hemisphere). In addition, when considering winds at Earth's surface, we must take into account another force. This force, **friction,** interacts with the pressure gradient and the Coriolis effect.

Friction and Wind

Above Earth's surface, frictional drag is of little consequence to wind development. At this level, the wind starts down the pressure gradient and turns 90° in response to the Coriolis effect. At this point, the pressure gradient is balanced by the Coriolis effect, and the wind, termed a **geostrophic wind,** flows parallel to the isobars (● Fig. 5.7).

However, at or near Earth's surface (up to about 1000 m above the surface), frictional drag is important because it reduces the wind speed. A reduced wind speed in turn reduces the Coriolis effect, but the pressure gradient is not affected. With the pressure gradient and Coriolis effect no longer in balance, the wind does not flow between the isobars like its upper-level counterpart. Instead, a surface wind flows obliquely (about a 30° angle) across the isobars toward an area of low pressure.

Wind Terminology

Winds are named after their source. Thus, a wind that comes out of the northeast is called a northeast wind. One coming from the south, even though going toward the north, is called a south (or southerly) wind. It is helpful for students to use the phrase "out of" when describing a wind direction. That phrase will help students to keep the correct direction. For example, if the winds are blowing to the south, then by saying, "the winds are out of the north," automatically makes the student think about the direction of the wind's origin.

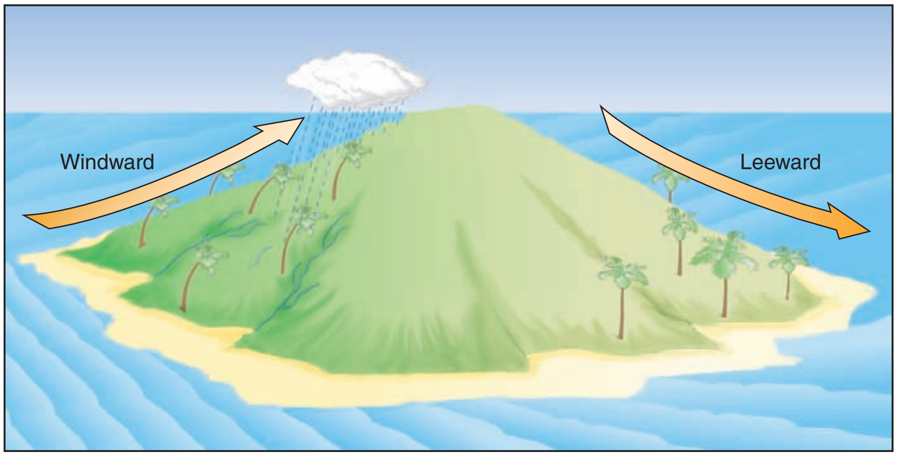
Windward refers to the direction from which the wind blows. The side of something that faces the direction from which the wind is coming is called the *windward* side. Thus, a windward slope is the side of a mountain against which the wind blows (● Fig. 5.8). **Leeward,** on the other hand, means the direction toward which the wind is blowing. Thus, when the winds are coming out of the west, the *leeward* slope of a mountain would be the east slope. We know that winds can blow from any direction, yet in some places winds may tend to blow more from one direction than any other. We speak of these as the **prevailing winds.**

Cyclones, Anticyclones, and Winds

Imagine a high pressure cell (anticyclone) in the Northern Hemisphere in which the air is moving from the center in all directions down pressure gradients. As it moves, the air will be deflected to the right, no matter which direction it was originally going. Therefore, the wind moving out of an anticyclone in the Northern Hemisphere will move from the center of high pressure in a clockwise spiral (● Fig. 5.9).

Air tends to move down pressure gradients from all directions toward the center of a low pressure area (cyclone). However, because the air is apparently deflected to the right in the Northern Hemisphere, the winds move into the cyclone in a counterclockwise spiral. Because all objects including air and water are apparently deflected to the left in the Southern Hemisphere, spirals there are reversed. Thus, in the Southern Hemisphere, winds moving away from an anticyclone do so in a counterclockwise spiral, and winds moving into a cyclone move in a clockwise spiral.

● **FIGURE 5.8**
Illustration of the meaning of windward (facing into the wind) and leeward (facing away from the wind).
How might vegetation differ on the windward and leeward sides of an island?



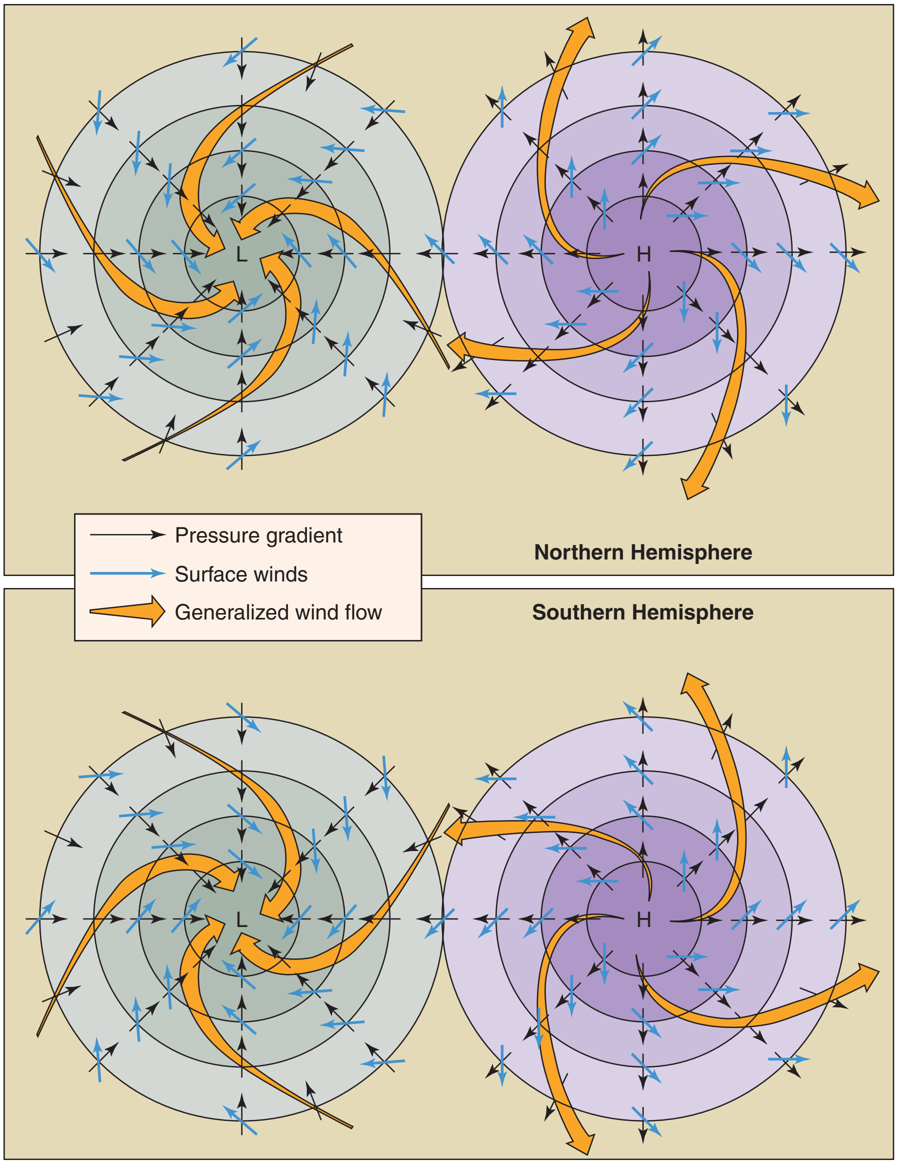


FIGURE 5.9
Movement of surface winds associated with low pressure centers (cyclones) and high pressure centers (anticyclones) in the Northern and Southern Hemispheres. Note that the surface winds are to the right of the pressure gradient in the Northern Hemisphere and to the left of the pressure gradient in the Southern Hemisphere.
What do you think might happen to the diverging air of an anticyclone if there is a cyclone nearby?

Global Pressure Belts

Idealized Global Pressure Belts

Using what we have learned about pressure on Earth's surface, we can construct a theoretical model of the pressure belts of the world (Fig. 5.10). Later, we see how real conditions depart from our model and examine why these differences occur.

Centered approximately over the equator in our model is a belt of low pressure, or a **trough.** Because this is the region on Earth of greatest annual heating, we can conclude that the low pressure of this area, the **equatorial low (equatorial trough),** is determined primarily by thermal factors, which cause the air to rise.

North and south of the equatorial low and centered on the so-called horse latitudes, about 30°N and 30°S, are cells of relatively high pressure. These are the **subtropical highs,** which are the result of dynamic factors related to the sinking of convectional cells initiated at the equatorial low.

Poleward of the subtropical highs in both the Northern and Southern Hemispheres are large belts of low pressure that extend through the upper-middle latitudes. Pressure decreases through these **subpolar lows** until about 65° latitude. Again, dynamic factors play a role in the existence of subpolar lows.

In the polar regions are high pressure systems called the **polar highs.** The extremely cold temperatures and consequent sinking of the dense polar air in those regions create the higher pressures found there.

This system of pressure belts that we have just developed is a generalized picture. Just as temperatures change from month to month, day to day, and hour to hour, so do pressures vary through time at any one place. Our long-term global model disguises these smaller changes, but it does give an idea of broad pressure patterns on the surface of Earth.

The Global Pattern of Atmospheric Pressure

As our idealized model suggests, the atmosphere tends to form belts of high and low pressure along east–west axes in areas where there are no large bodies of land. These belts are arranged by latitude and generally maintain their bandlike pattern. However, where there are continental landmasses, belts of pressure are broken and tend to form cellular pressure systems. The landmasses affect the development of belts of atmospheric pressure in several ways. Most influential is the effect of the differential heating of land and water surfaces. In addition, landmasses affect the movement of air and consequently the development of pressure systems through friction with their surfaces. Landform barriers such as mountain ranges also block the movement of air and thereby affect atmospheric pressure.

Seasonal Variations in the Pattern

In general, the global atmospheric pressure belts shift northward in July and southward in January, following the changing position of the sun's direct rays as they migrate between the Tropics of Cancer and Capricorn. Thus, there are thermally induced sea-

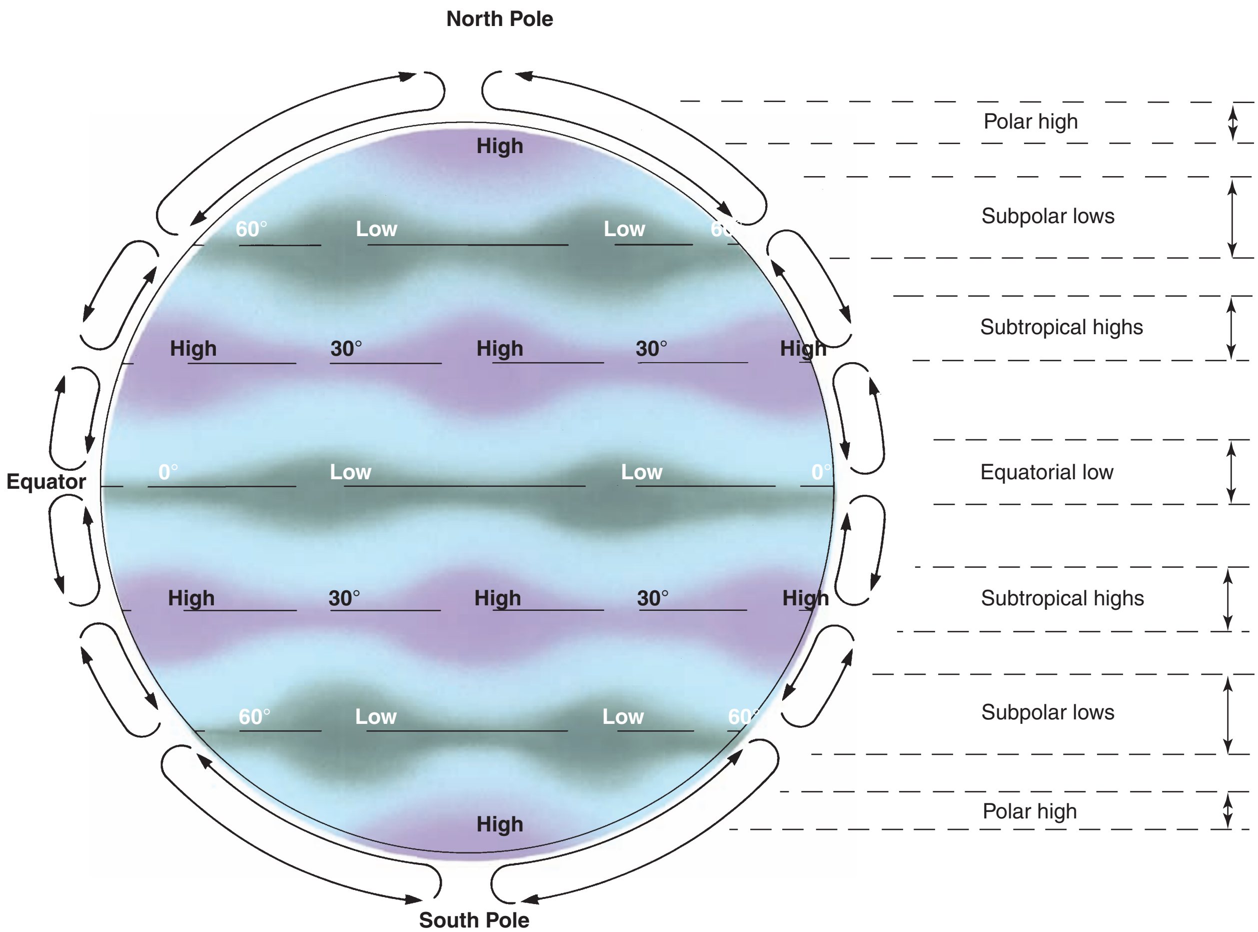


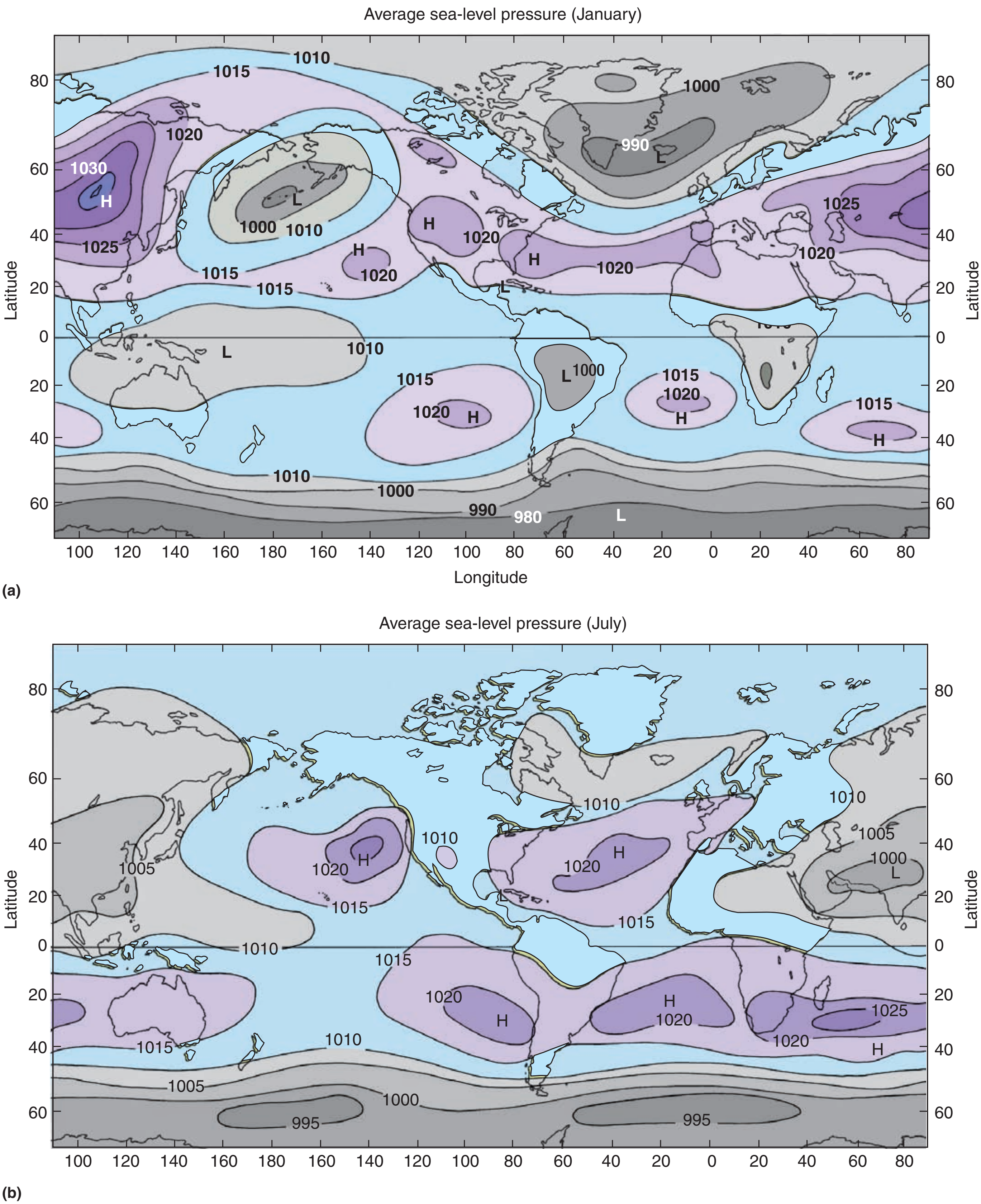
FIGURE 5.10
Idealized world pressure belts. Note the arrows on the perimeter of the globe that illustrate the cross-sectional flow associated with the surface pressure belts.
Why do most of these pressure belts come in pairs?

sonal variations in the pressure patterns, as seen in Figures 5.11a and b. These seasonal variations tend to be small at low latitudes, where there is little temperature variation, and large at high latitudes, where there is an increasing contrast in length of daylight and angle of the sun's rays. Furthermore, landmasses tend to alter the general pattern of seasonal variation. This is an especially important factor in the Northern Hemisphere, where land accounts for 40% of the total Earth surface, as opposed to less than 20% in the Southern Hemisphere.

January Because continents cool more quickly than the oceans, their temperatures will be lower in winter than those of the surrounding seas. Figure 5.11a shows that in the middle latitudes of the Northern Hemisphere this variation leads to the development of cells of high pressure over the land areas. In contrast, the subpolar lows develop over the oceans because they are comparatively warmer. Over eastern Asia, there is a strongly developed anticyclone during the winter months that is known as the **Siberian High.** Its equivalent in North America, known as the **Canadian High,** is not nearly so well developed because the North American landmass is considerably smaller than the Eurasian continent.

In addition to the Canadian High and the Siberian High, two low pressure centers develop: one in the North Atlantic, called the **Icelandic Low,** and the other in the North Pacific, called the **Aleutian Low.** The air in them has relatively lower pressure than either the subtropical or the polar high systems. Consequently, air moves toward these low pressure areas from both north and south. Such low pressure regions are associated with cloudy, unstable weather and are a major source of winter storms, whereas high pressure areas are associated with clear, blue-sky days; calm, starry nights; and cold, stable weather. Therefore, during the winter months, cloudy and sometimes dangerously stormy weather tends to be associated with the two oceanic lows and clear weather with the continental highs.

We can also see that the polar high in the Northern Hemisphere is well developed. This development is due primarily to thermal factors because January is the coldest time of the year. The subpolar lows have developed into the Aleutian and Icelandic cells described earlier. At the same time, the subtropical highs of the Northern Hemisphere appear slightly south of their average annual position because of the migration of the sun toward the Tropic of Capricorn. The equatorial trough also appears centered south of its average annual position over the geographic equator.



• FIGURE 5.11

(a) Average sea-level pressure (in millibars) in January. (b) Average sea-level pressure (in millibars) in July. **What is the difference between the January and July average sea-level pressures at your location? Why do they vary?**

In January in the Southern Hemisphere, the subtropical belt of high pressure appears as three cells centered over the oceans because the belt of high pressure has been interrupted by the continental landmasses where temperatures are much higher and pressure tends to be lower than over the oceans. Because there is virtually no land between 45°S and 70°S latitude, the subpolar low circles Earth as a belt of low pressure and is not divided into cells by any landmasses. There is little seasonal change in this belt of low pressure other than in January (summer in the Southern Hemisphere), when it lies a few degrees north of its July position.

July The anticyclone over the North Pole is greatly weakened during the summer months in the Northern Hemisphere, primarily because of the lengthy (24-hour days) heating of the oceans and landmasses in that region (Fig. 5.11b). The Aleutian and Icelandic Lows nearly disappear from the oceans, while the landmasses, which developed high pressure cells during the cold winter months, have extensive low pressure cells slightly to the south during the summer. In Asia, a low pressure system develops, but it is divided into two separate cells by the Himalayas. The low pressure cell over northwest India is so strong that it combines with the equatorial trough, which has moved north of its position 6 months earlier. The subtropical highs of the Northern Hemisphere are more highly developed over the oceans than over the landmasses. In addition, they migrate northward and are highly influential factors in the climate of landmasses nearby. In the Pacific, this subtropical high is termed the **Pacific High;** this system of pressure plays an important role in moderating the temperatures of the West Coast of the United States. In the Atlantic Ocean, the corresponding cell of high pressure is known as the **Bermuda High** to North Americans and as the **Azores High** to Europeans and West Africans. As we have already mentioned, the equatorial trough of low pressure moves north in July, following the migration of the sun's vertical rays, and the subtropical highs of the Southern Hemisphere lie slightly north of their January locations.

In examining pressure systems at Earth's surface, we have seen that there are essentially seven belts of pressure (two polar highs, two subpolar lows, two subtropical highs, and one equatorial low), which are broken into cells of pressure in some places primarily because of the influence of certain large landmasses. We have also seen that these belts and cells vary in size, intensity, and location with the seasons and with the migration of the sun's vertical rays over Earth's surface. Since these global-scale pressure systems migrate by latitude with the position of the direct sun angle, they are sometimes referred to as *semipermanent pressure systems* because they are never permanently fixed in the same location.

Global Surface Wind Systems

The planetary, or global, wind system is a response to the global pressure patterns and also plays a role in the maintenance of those same pressures. This wind system, which is the major means of transport for energy and moisture through Earth's atmosphere, can be examined in an idealized state. To do so, however, we must ignore the influences of landmasses and seasonal variations in solar energy. By assuming, for the sake of discussion, that Earth has a homogeneous surface and that there are no seasonal variations in the amount of solar energy received at different latitudes, we can examine a theoretical model of the atmosphere's planetary circulation. Such an understanding will help explain specific features of climate such as the rain and snow of the Sierra Nevada and Cascade Mountains and the existence of arid regions farther to the east. It will also account for the movement of great surface currents in our oceans that are driven by this atmospheric engine.

Idealized Model of Atmospheric Circulation

Because winds are caused by pressure differences, various types of winds are associated with different kinds of pressure systems. Therefore, a system of global winds can be demonstrated using the model of pressures that we previously developed (see again Fig. 5.10).

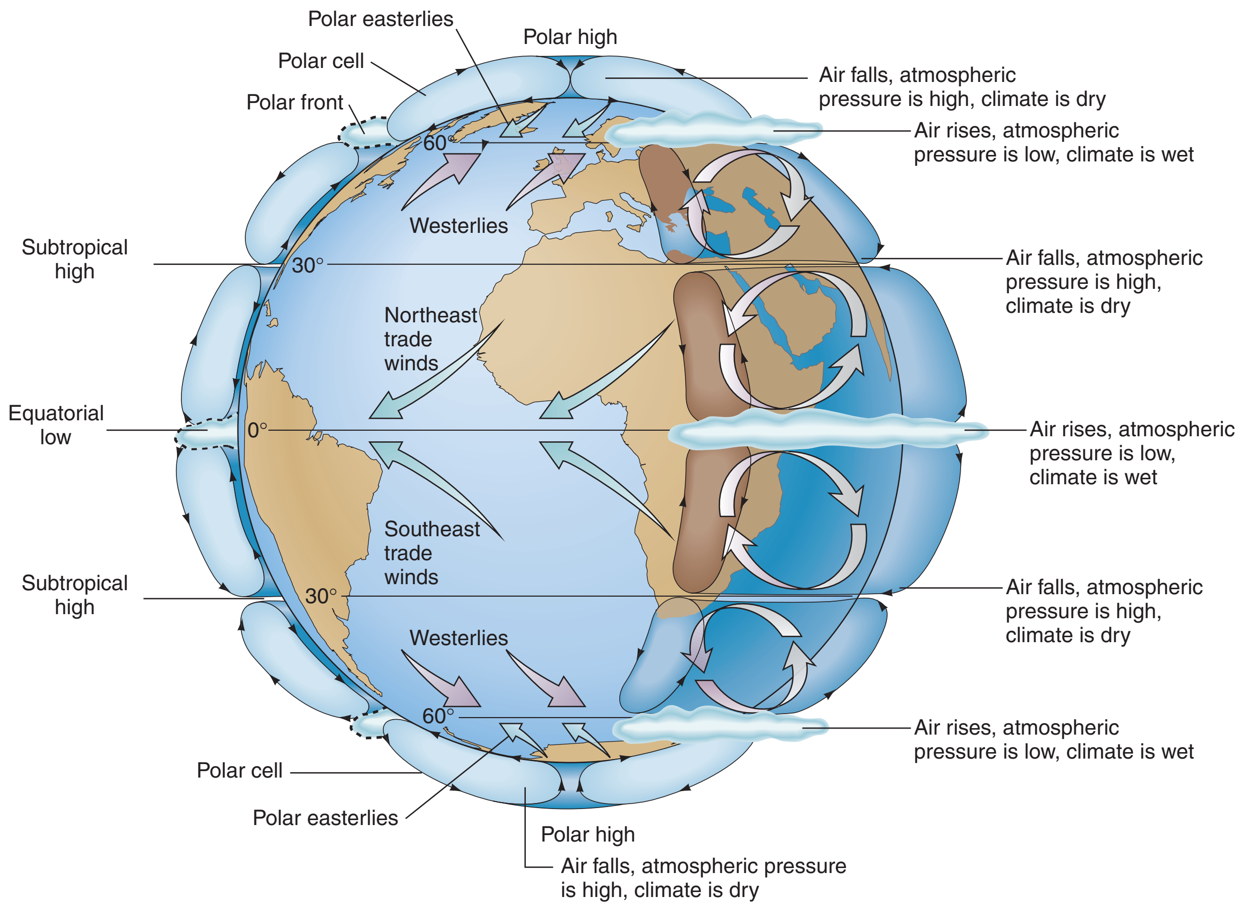
The characteristics of convergence and divergence are very important to our understanding of global wind patterns. Surface air diverges from zones of high pressure and converges on areas of low pressure. We also know that, because of the pressure gradient, surface winds always blow from high pressure to low pressure.

Knowing that surface winds originate in areas of high pressure and taking into account the global system of pressure cells, we can develop our model of the wind systems of the world (● Fig. 5.12). This model takes into account differential heating, Earth rotation, and atmospheric dynamics. Note that the winds do not blow in a straight north–south line. The variation is due of course to the Coriolis effect, which causes an apparent deflection to the right in the Northern Hemisphere and to the left in the Southern Hemisphere.

Our idealized model of global atmospheric circulation includes six wind belts, or zones, in addition to the seven pressure zones that we have previously identified. Two wind belts, one in each hemisphere, are located where winds move out of the polar highs and down the pressure gradients toward the subpolar lows. As these winds are deflected to the right in the Northern Hemisphere and to the left in the Southern, they become the **polar easterlies.**

The remaining four wind belts are closely associated with the divergent winds of the subtropical highs. In each hemisphere, winds flow out of the poleward portions of these highs toward the subpolar lows. Because of their general movement from the west, the winds of the upper-middle latitudes are labeled the **westerlies.** The winds blowing from the highs toward the equator have been called the **trade winds.** Because of the Coriolis effect, they are the **northeast trades** in the Northern Hemisphere and the **southeast trades** south of the equator.

Our model does not conform exactly to actual conditions. First, as we know, the vertical rays of the sun do not stay precisely over the equator but migrate as far north as the Tropic of Cancer in June and south to the Tropic of Capricorn in December. Therefore, the pressure systems, and consequently the winds, must move to adjust to the change in the position of the sun. Then, as we have already discovered, the existence of the continents, especially in



• FIGURE 5.12
The general circulation of Earth's atmosphere.

the Northern Hemisphere, causes longitudinal pressure differentials that affect the zones of high and low pressure.

Conditions within Latitudinal Zones

Trade Winds A good place to begin our examination of winds and associated weather patterns as they actually occur is in the vicinity of the subtropical highs. On Earth's surface, the trade winds, which blow out of the subtropical highs toward the equatorial trough in both the Northern and Southern Hemispheres, can be identified between latitudes 5° and 25°. Because of the Coriolis effect, the northern trades move away from the subtropical high in a clockwise direction out of the northeast. In the Southern Hemisphere, the trades diverge out of the subtropical high toward the equatorial trough from the southeast, as their movement is counterclockwise. Because the trades tend to blow out of the east, they are also known as the **tropical easterlies.**

The trade winds tend to be constant, steady winds, consistent in their direction. This is most true when they cross the eastern sides of the oceans (near the eastern portion of the subtropical high). The area of the trades varies somewhat during the solar year, moving north and south a few degrees of latitude with the sun. Near their source in the subtropical highs, the weather of the trades is clear and dry, but after crossing large expanses of ocean, the trades have a high potential for stormy weather.

Early Spanish sea captains depended on the northeast trade winds to drive their galleons to destinations in Central and South America in search of gold, spices, and new lands. Going eastward toward home, navigators usually tried to plot a course using the westerlies to the north. The trade winds are one of the reasons that the Hawaiian Islands are so popular with tourists; the steady winds help keep temperatures pleasant, even though Hawaii is located south of the Tropic of Cancer.

Doldrums Where the trade winds converge in the equatorial trough (or tropical low) lies a zone of calm and weak winds of no prevailing direction. Here the air, which is very moist and heated by the sun, tends to expand and rise, maintaining the low pressure of the area. These winds, which are roughly between 5°N and 5°S, are generally known as the **doldrums.** This area is called the **intertropical convergence zone (ITCZ),** or the "equatorial belt of variable winds and calms." Because of the converging moist air and high potential for rainfall in the doldrums, this region coincides with the world's latitudinal belt of heaviest precipitation and most persistent cloud cover.

Old sailing ships often remained becalmed in the doldrums for days at a time. It is interesting to note that the word *doldrums* in the English language means a bored or depressed state of mind. The sailors were in the doldrums in more ways than one.

Subtropical Highs The areas of subtropical high pressure, generally located between latitudes 25° and 35°N and S, and from which winds blow poleward to become the westerlies and equatorward as the trade winds, are often called the subtropical belts of variable winds, or the "horse latitudes." This name comes from the occasional need by the Spanish conquistadors to eat their horses or throw them overboard in order to conserve drinking water and lighten the weight when their ships were becalmed in these latitudes. The subtropical highs are areas, like the doldrums, in which there are no strong prevailing winds. However, unlike the doldrums, which are characterized by convergence, rising air, and heavy rainfall, the subtropical highs are areas of sinking and settling air from higher altitudes, which tend to build up the atmospheric pressure. Weather conditions are typically clear, sunny, and rainless, especially over the eastern portions of the oceans where the high pressure cells are strongest.

Westerlies The winds that flow poleward out of the subtropical high pressure cells in the Northern Hemisphere are deflected to the right and thus blow from the southwest. Those in the Southern Hemisphere are deflected to the left and blow out of the northwest. Thus, these winds have been correctly labeled the westerlies. They tend to be less consistent in direction than the trades, but they are usually stronger winds and may be associated with stormy weather. The westerlies occur between about 35° and 65°N and S latitudes. In the Southern Hemisphere, where there is less land than in the Northern Hemisphere to affect the development of winds, the westerlies attain their greatest consistency and strength. Much of Canada and most of the United States—except Florida, Hawaii, and Alaska—are under the influence of the westerlies.

Polar Winds Accurate observations of pressure and wind are sparse in the two polar regions; therefore, we must rely on remotely sensed information (mainly by weather satellite imagery). Our best estimate is that pressures are consistently high throughout the year at the poles and that prevailing easterly winds blow from the polar regions to the subpolar low pressure systems.

Polar Front Despite our limited knowledge of the wind systems of the polar regions, we do know that the winds can be highly variable, blowing at times with great speed and intensity. When the cold air flowing out of the polar regions and the warmer air moving in the path of the westerlies meet, they do so like two warring armies: One does not absorb the other. Instead, the denser, heavier cold air pushes the warm air upward, forcing it to rise rapidly. The line along which these two great wind systems battle is appropriately known as the **polar front.** The weather that results from the meeting of the cold polar air and the warmer air from the subtropics can be very stormy. In fact, most of the storms that move slowly through the middle latitudes in the path of the prevailing westerlies are born at the polar front.

The Effects of Seasonal Migration

Just as insolation, temperature, and pressure systems migrate north and south as Earth revolves around the sun, Earth's wind systems also migrate with the seasons. During the summer months in the Northern Hemisphere, maximum insolation is received north of the equator. This condition causes the pressure belts to move north as well, and the wind belts of both hemispheres shift accordingly. Six months later, when maximum heating is taking place south of the equator, the various wind systems have migrated south in response to the migration of the pressure systems. Thus, seasonal variation in wind and pressure conditions is one important way in which actual atmospheric circulation differs from our idealized model.

The seasonal migration will most affect those regions near the boundary zone between two wind or pressure systems. During the winter months, such a region will be subject to the impact of one system. Then, as summer approaches, that system will migrate poleward and the next equatorward system will move in to influence the region. Two such zones in each hemisphere have a major effect on climate. The first lies between latitudes 5° and 15°, where the wet equatorial low of the high-sun season (summer) alternates with the dry subtropical high and trade winds of the low-sun season (winter). The second occurs between 30° and 40°, where the subtropical high dominates in summer but is replaced by the wetter westerlies in winter.

California is an example of a region located within a zone of transition between two wind or pressure systems (● Fig. 5.13). During the winter, this region is under the influence of the westerlies blowing out of the Pacific High. These winds, turbulent and full of moisture from the ocean, bring winter rains and storms to "sunny" California. As summer approaches, however, the subtropical high and its associated westerlies move north. As California comes under the influence of the calm and steady high pressure system, it experiences again the climate for which it is famous: day after day of warm, clear, blue skies. This alternation of moist winters and dry summers is typical of the western sides of all landmasses between 30° and 40° latitude.

Longitudinal Differences in Winds

We have seen that there are sizable latitudinal differences in pressure and winds. In addition, there are significant longitudinal variations, especially in the zone of the subtropical highs.

As was previously noted, the subtropical high pressure cells, which are generally centered over the oceans, are much stronger on their eastern sides than on their western sides. Thus, over the eastern portions of the oceans (west coasts of the continents) in the subtropics, subsidence and divergence are especially noticeable. The above-surface temperature inversions so typical of anticyclonic circulation are close to the surface, and the air is calm and clear. The air moving equatorward from this portion of the high produces the classic picture of the steady trade winds with clear, dry weather.

Over the western portions of the oceans (eastern sides of the continents), conditions are markedly different. In its passage

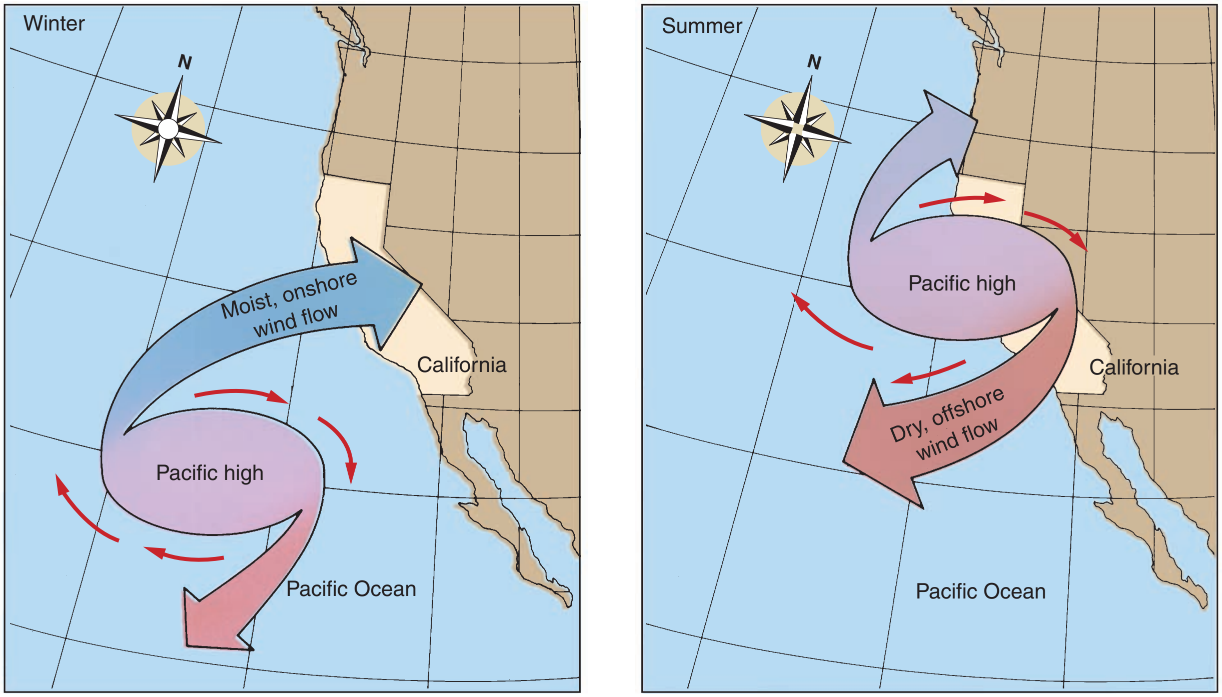
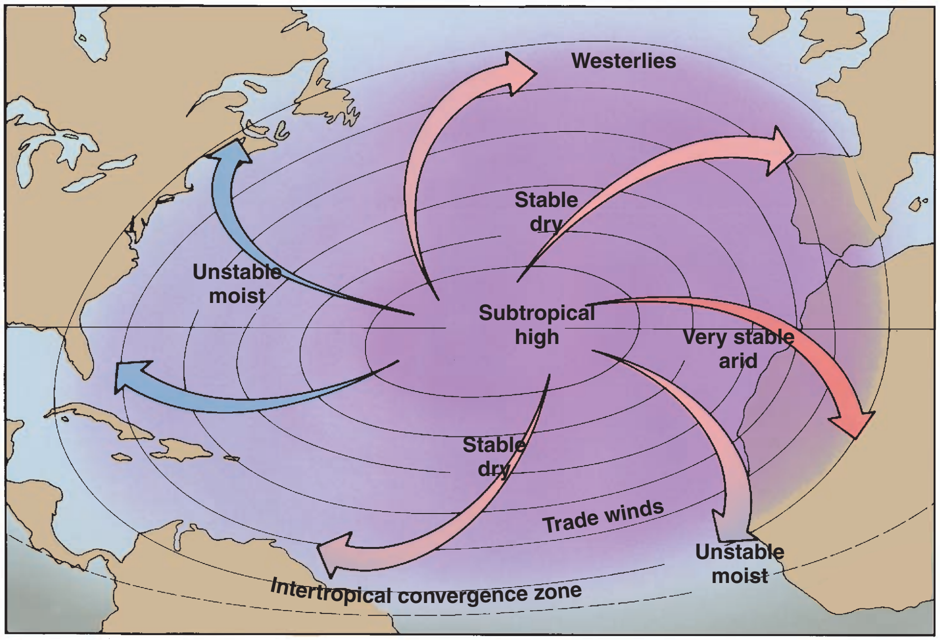


FIGURE 5.13
Winter and summer positions of the Pacific anticyclone in relation to California. In the winter, the anticyclone lies well to the south and feeds the westerlies that bring the cyclonic storms and rain from the North Pacific to California. The influence of the anticyclone dominates during the summer. The high pressure blocks cyclonic storms and produces warm, sunny, and dry conditions.
In what ways would the seasonal migration of the Pacific anticyclone affect agriculture in California?

FIGURE 5.14
Circulation pattern in a Northern Hemisphere subtropical anticyclone. Subsidence of air is strongest in the eastern part of the anticyclone, producing calm air and arid conditions over adjacent land areas. The southern margin of the anticyclone feeds the persistent northeast trade winds.
What wind system is fed by the northern margin?



over the ocean, the diverging air is gradually warmed and moistened; turbulent and stormy weather conditions are likely to develop. As indicated in Figure 5.14, wind movement in the western portions of the anticyclones may actually be poleward and directed toward landmasses. Hence, the trade winds in these areas are especially weak or nonexistent much of the year.

As we have pointed out in discussing Figures 5.11 and 5.12, there are great land–sea contrasts in temperature and pressure throughout the year farther toward the poles, especially in the Northern Hemisphere. In the cold continental winters, the land is associated with pressures that are higher than those over the oceans, and thus there are strong, cold winds from the land to the sea. In the summer, the situation changes, with relatively low pressure existing over the continents because of higher temperatures. Wind directions are thus greatly affected, and the pattern is reversed so that winds flow from the sea toward the land.

Upper Air Winds and Jet Streams

Thus far, we have closely examined the wind patterns near Earth's surface. Of equal, or even greater, importance is the flow of air above Earth's surface—in particular, the flow of air at altitudes above 5000 meters (16,500 ft), and higher in the upper troposphere. The formation, movement, and decay of surface cyclones and anticyclones in the middle latitudes depend to a great extent on the flow of air high above Earth's surface.

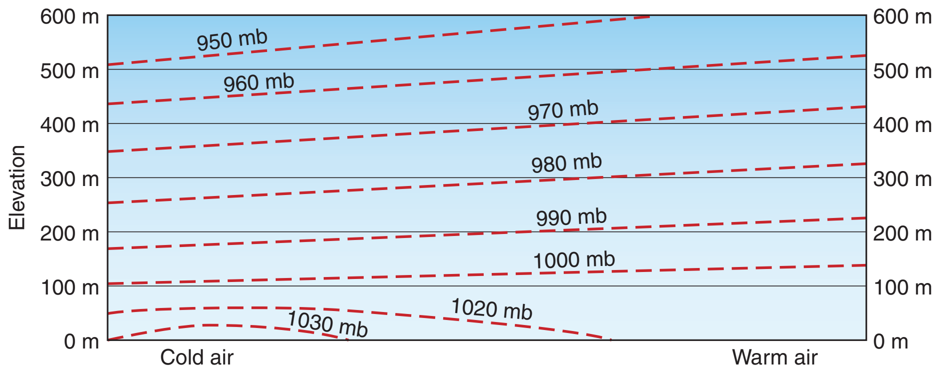
The circulation of the upper air winds is a far less complex phenomenon than surface wind circulation. In the upper troposphere, an average westerly flow, the *upper air westerlies,* is maintained poleward of about 15°–20° latitude in both hemispheres. Because of the reduced frictional drag, the upper air westerlies move much more rapidly than their surface counterparts. Between 15° and 20°N and S latitudes are the *upper air easterlies,* which can be considered the high-altitude extension of the trade winds. The flow of the upper air winds became very apparent during World War II when high-altitude bombers moving eastward were found to cover similar distances faster than those flying westward. Pilots had encountered the upper air westerlies, or perhaps even the **jet streams**—very strong air currents embedded within the upper air westerlies.

The upper air westerlies form as a response to the temperature difference between warm tropical air and cold polar air. The air in the equatorial latitudes is warmed, rises convectively to high altitudes, and then flows toward the polar regions. At first this seems to contradict our previous statement, relative to surface winds, that air flows from cold areas (high pressure) toward warm areas (low pressure). This apparent discrepancy disappears, however, if you recall that the pressure gradient, down which the flow takes place, must be assessed between two points *at the same elevation*. A column of cold air will exert a higher pressure at Earth's surface than a column of warm air. Consequently, the pressure gradient established at Earth's surface will result in a flow from the cooler air toward the warmer air. However, cold air is denser and more compact than warm air. Thus, pressure decreases with height more rapidly in cold air than in warm air. As a result, at a specific height above Earth's surface, a lower pressure will be encountered above cold surface air than above warm surface air. This will result in a flow (pressure gradient) from the warmer surface air toward the colder surface air at that height. ● Figure 5.15 illustrates this concept.

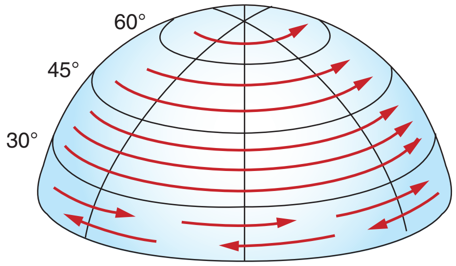
Returning to our real-world situation, as the upper air winds flow from the equator toward the poles (down the pressure gradient), they are turned eastward because of the Coriolis effect. The net result is a broad circumpolar flow of westerly winds throughout most of the upper atmosphere (● Fig. 5.16). Because the upper air westerlies form in response to the thermal gradient between tropical and polar areas, it is not surprising that they are strongest in winter (the low-sun season), when the thermal contrast is greatest. During the summer (the high-sun season), when the contrast in temperature over the hemisphere is much reduced, the upper air westerlies move more slowly.

The temperature gradient between tropical and polar air, especially in winter, is not uniform but rather is concentrated where the warm tropical air meets cold polar air. This boundary, called the polar front, with its stronger pressure gradient, marks the location of the **polar front jet stream.** Ranging from 40 to 160 kilometers (25–100 mi) in width and up to 2 or 3 kilometers (1–2 mi) in depth, the polar front jet stream can be thought of as a faster, internal current of air within the upper air westerlies. While the polar front jet stream flows over the middle latitudes, another westerly **subtropical jet stream** flows above the sinking air of the subtropical highs in the lower-middle latitudes. Like the upper air westerlies, both jets are best developed in winter when hemispherical temperatures exhibit their steepest gradient (● Fig. 5.17). During the summer, both jets weaken in intensity. The subtropical jet stream frequently disappears completely, and the polar front jet tends to migrate northward.

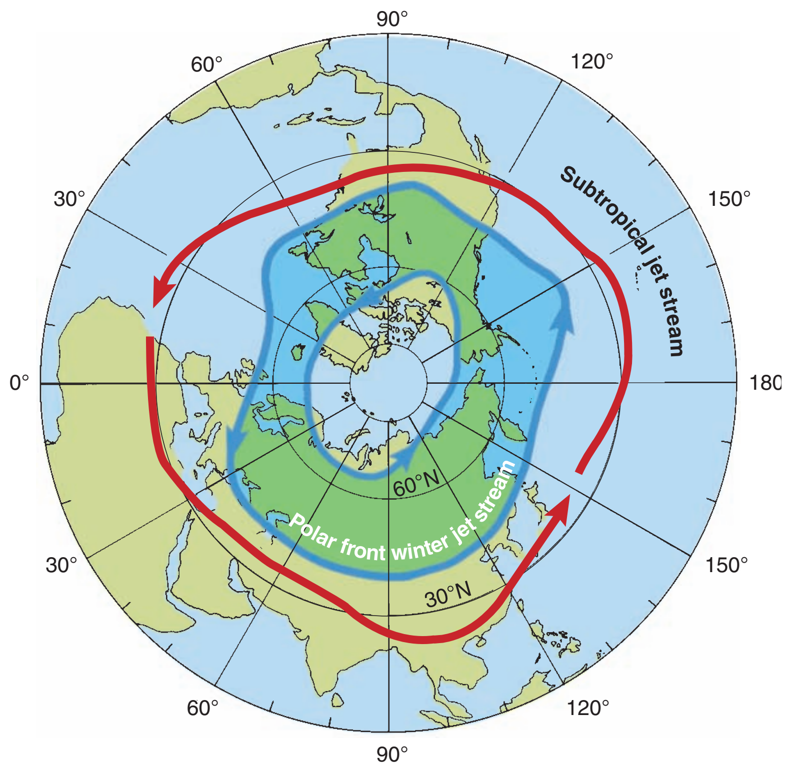
We can now go one step further and combine our knowledge of the circulation of the upper air and surface to yield a more realistic portrayal of the vertical circulation pattern of our atmosphere (● Fig. 5.18). In general, the upper air westerlies and the associated polar jet stream flow in a fairly smooth pattern (● Fig. 5.19a). At times, however, the upper air westerlies develop oscillations, termed *long waves,* or **Rossby waves,** after the Swedish meteorologist Carl Rossby who first proposed and then proved



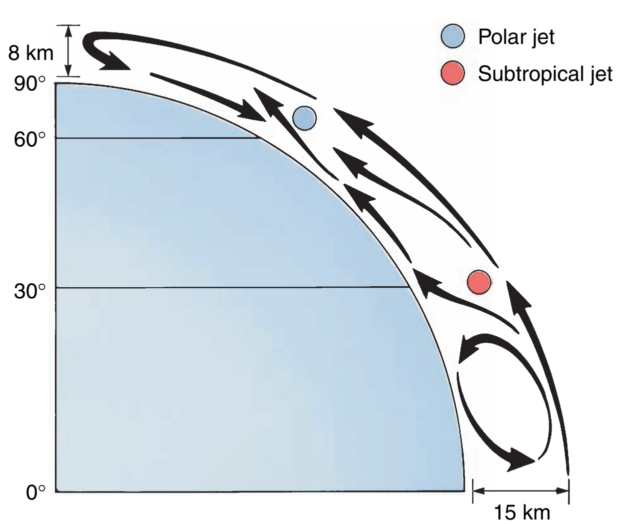
● **FIGURE 5.15**
Variation of pressure surfaces with height. Note that the horizontal pressure gradient is from cold to warm air at the surface and in the opposite direction at higher elevations (such as 400 m).
In what direction would the winds flow at 300 meters?



● **FIGURE 5.16**
The upper air westerlies form a broad circumpolar flow throughout most of the upper atmosphere.



• FIGURE 5.17
Approximate location of the subtropical jet stream and area of activity of the polar front jet stream (shaded) in the Northern Hemisphere winter.
Which jet stream is most likely to affect your home state?



• FIGURE 5.18
A more realistic schematic cross section of the average circulation in the atmosphere.

their existence (• Fig. 5.19b). Rossby waves result in cold polar air pushing into the lower latitudes and forming *troughs* of low pressure, while warm tropical air moves into higher latitudes, forming *ridges* of high pressure. It is when the upper air circulation is in this configuration that surface weather is most influenced. We will examine this influence in more detail in Chapter 7.

Eventually, the upper air oscillations become so extreme that the "tongues" of displaced air are cut off, forming upper air cells of warm and cold air (Fig. 5.19c and d). This process helps maintain a net poleward flow of energy from equatorial and tropical areas. The cells eventually dissipate, and the pattern returns to normal (see again Fig. 5.19a). The complete cycle takes approximately 4–8 weeks. Although it is not completely clear why the upper atmosphere goes into these oscillating patterns, we are currently gaining additional insights. One possible cause is variation in ocean-surface temperatures. If the oceans in, say, the northern Pacific or near the equator become unusually warm or cold (for example, El Niño or La Niña, discussed later in this chapter), this apparently triggers oscillations, which continue until the ocean-surface temperature returns to normal. Other causes are being investigated at this time.

In addition to this influence on weather, jet streams are important to study for other reasons. They can carry pollutants, such as radioactive wastes or volcanic dust, over great distances and at relatively rapid rates. It was the polar jet stream that carried ash from the Mount St. Helens eruption (in 1980) eastward across the United States and Southern Canada. Nuclear fallout from the Chernobyl incident in the former Soviet Union could be monitored in succeeding days as it crossed the Pacific, and later the United States, in the jet streams. Pilots flying eastward—for example, from North America to Europe—take advantage of the jet stream, so the flying times in this direction may be significantly shorter than those in the reverse direction.

Subglobal Surface Wind Systems

As we have seen, winds develop whenever differential heating causes differences in pressure. The global wind system is a response to the constant temperature imbalance between tropical and polar regions. On a smaller, or subglobal, scale, additional wind systems develop. We begin with a discussion of monsoon winds, which are continental in size and develop in response to the seasonal variations in temperature and pressure. Last, on the smallest scale are local winds, which develop in response to the diurnal (daily) variation in heating and its local effects upon pressure and winds.

Monsoon Winds

The term *monsoon* comes from the Arabic word *mausim,* meaning season. This word has been used by Arab sailors for many centuries to describe seasonal changes in wind direction across the Arabian Sea between Arabia and India. As a meteorological term, **monsoon** refers to the directional shifting of winds from one season to the next. Usually, the monsoon occurs when a humid wind blowing from the ocean toward the land in the summer shifts to a dry, cooler wind blowing seaward off the land in the winter, and it involves a full 180° direction change in the wind.

The monsoon is most characteristic of southern Asia although it occurs on other continents as well. As the large landmass of Asia

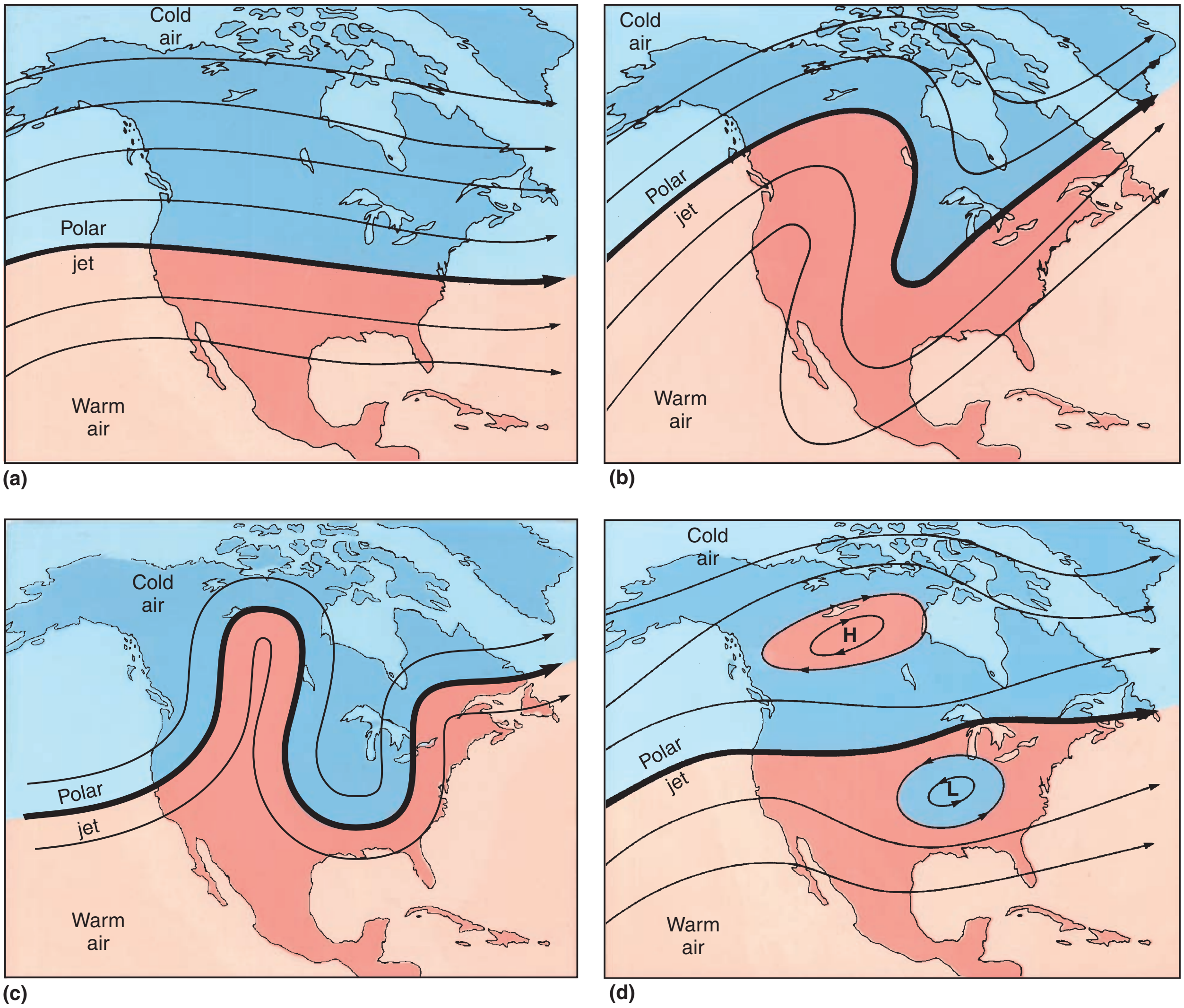


FIGURE 5.19
Development and dissipation of Rossby waves in the upper air westerlies. (a) A fairly smooth flow prevails. (b) Rossby waves form, with a ridge of warm air extending into Canada and a trough of cold air extending down to Texas. (c) The trough and ridge may begin to turn back on themselves. (d) The trough and ridge are cut off and will eventually dissipate. The flow will then return to a pattern similar to (a).
How are Rossby waves closely associated with the changeable weather of the central and eastern United States?

cools more quickly than the surrounding oceans, the continent develops a strong center of high pressure from which there must be an outflow of air in winter (Fig. 5.20). This outflow blows across much land toward the tropical low before reaching the oceans. It brings cold, dry air south.

In summer the Asian continent heats quickly and develops a large low pressure center. This development is reinforced by a poleward shift of the warm, moist tropical air to a position over southern Asia. Warm, moist air from the oceans is attracted into this low. Though full of water vapor, this air does not in itself cause the wet summers with which the monsoon is associated. However, any turbulence or landform barrier that makes this moist air rise and, as a result, cool down will bring about precipitation. This precipitation is particularly noticeable in the foothills of the Himalayas, the western Ghats of India, and the Annamese Highlands of Vietnam.

In the lower latitudes, a monsoonal shift in winds can come about as a reaction to the migration of the direct rays of the sun. For example, the winds of the equatorial zone migrate during the summer months northward toward the southern coast of Asia, bringing with them warm, moist, turbulent air. The winds of the Southern Hemisphere also migrate north with the sun, some crossing the equator. They also bring warm, moist air (from their trip over the ocean) to the southern and especially the southeastern coasts of India. In the winter months, the equatorial and tropical winds migrate south, leaving southern Asia under the influence of the dry, calm winds of the tropical Northern Hemisphere. Asia and northern Australia are true monsoon areas, with a full 180° wind shift with changes from summer to winter. Other regions, like the southern United States and West Africa, have “monsoonal tendencies,” but are not monsoons in the true meaning of the term.

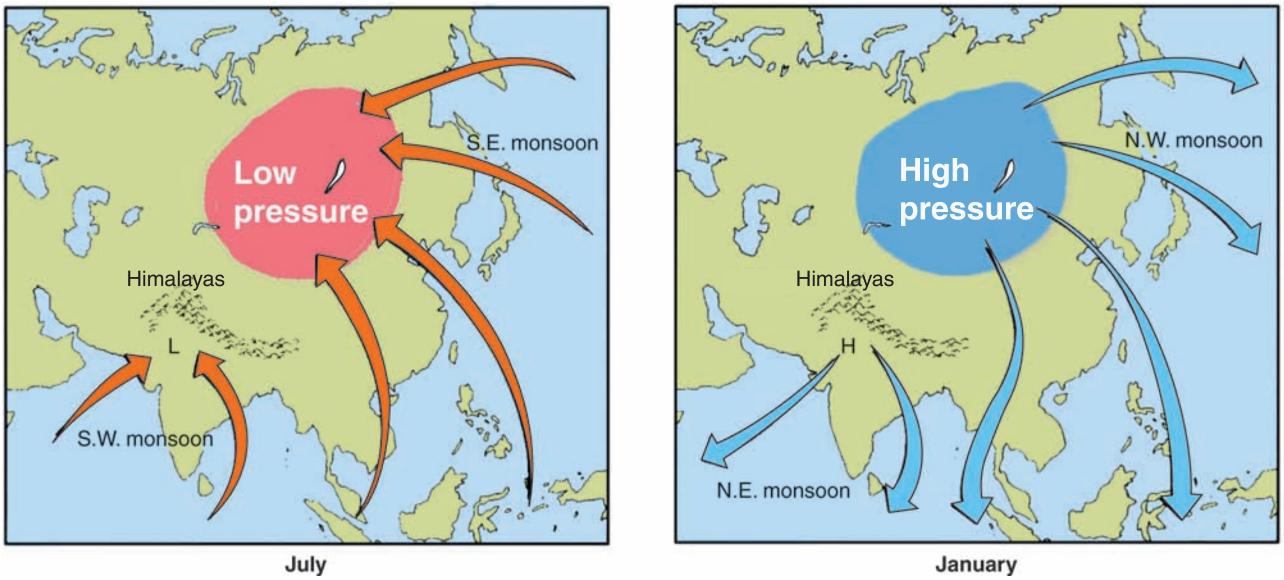


FIGURE 5.20
Seasonal changes in surface wind direction that create the Asiatic monsoon system. The "burst" of the "wet monsoon," or the sudden onshore flow of tropical humid air in July, is apparently triggered by changes in the upper air circulation, resulting in heavy precipitation. The offshore flow of dry continental air in winter creates the "dry monsoon" and drought conditions in southern Asia.
How do the seasonal changes of wind direction in Asia differ from those of the southern United States?

The phenomenon of monsoon winds and their characteristic seasonal shifting cannot be fully explained by the differential heating of land and water, however, or by the seasonal shifting of tropical and subtropical wind belts. Some aspects of the monsoon system—for example, its "burst" or sudden transition between dry and wet in southern Asia—must have other causes. Meteorologists looking for a more complete explanation of the monsoon are examining the role played by the jet stream and other wind movements of the upper atmosphere.

Local Winds

Earlier, we discussed the major circulation patterns of Earth's atmosphere. This knowledge is vital to understanding the climate regions of Earth and the fundamental climatic differences between those regions. Yet we are all aware that there are winds that affect weather on a far smaller scale. These *local winds* are often a response to local landform configurations and add further complexity to the problem of understanding the dynamics of weather.

Chinooks and Other Warming Winds

One type of local wind is known by several names in different parts of the world—for example, **Chinook** in the Rocky Mountain area and **foehn** (pronounced "fern") in the Alps. Chinook-type winds occur when air originating elsewhere must pass over a mountain range. As these winds flow down the leeward slope after crossing the mountains, the air is compressed and heated at a greater rate than it was cooled when it ascended the windward slope (Fig. 5.21). Thus, the air enters the valley below as warm, dry winds. The rapid temperature rise brought about by such winds has been known to damage crops, increase forest-fire hazard, and set off avalanches.

An especially hot and dry wind is the **Santa Ana** of Southern California. It forms when high pressure develops over the interior desert regions of Southern California. The clockwise circulation of the high drives the air of the desert southwest over the mountains of eastern California, accentuating the dry conditions as the air moves down the western slopes. The hot, dry Santa Ana winds are notorious for fanning forest and brush fires, which plague the southwestern United States, especially in California.

Drainage Winds

Also known as **katabatic winds, drainage winds** are local to mountainous regions and can occur only under calm, clear conditions. Cold, dense air will accumulate in a high valley, plateau, or snowfield within a mountainous area. Because the cold air is very dense, it tends to flow downward, escaping through passes and pouring out onto the land below. Drainage winds can be extremely cold and strong, especially when they result from cold air accumulating over ice sheets such as Greenland and Antarctica. These winds are known by many local names; for example, on the Adriatic coast, they are called the *bora;* in France, the *mistral;* and in Alaska, the *Taku.*

Land Breeze–Sea Breeze

The **land breeze–sea breeze cycle** is a diurnal (daily) one in which the differential heating of land and water again plays a role (Fig. 5.22). During the day, when the land—and consequently the air above it—is heated more quickly and to a higher temperature than the nearby ocean (sea or large lake), the air above the land expands and rises.

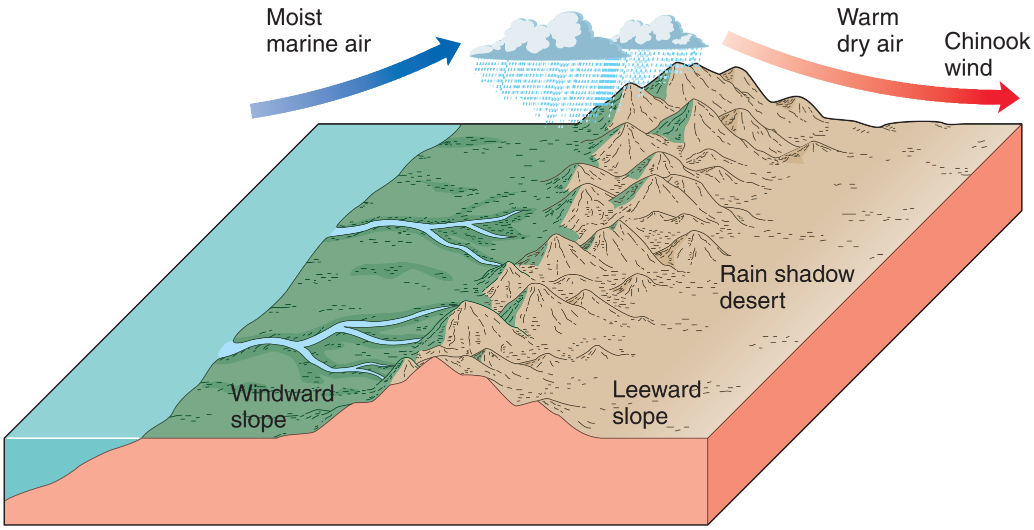


FIGURE 5.21
Chinook (or foehn) winds result when air ascends a mountain barrier, becoming cooler as it expands and losing some of its moisture through condensation and precipitation. As the air descends the leeward side of the range, its relative humidity becomes lower as the air compresses and warms. This produces the relatively warm, dry conditions with which foehn winds are associated.
The term Chinook, a type of foehn wind, means "snow eater." Can you offer an explanation for how this name came about?

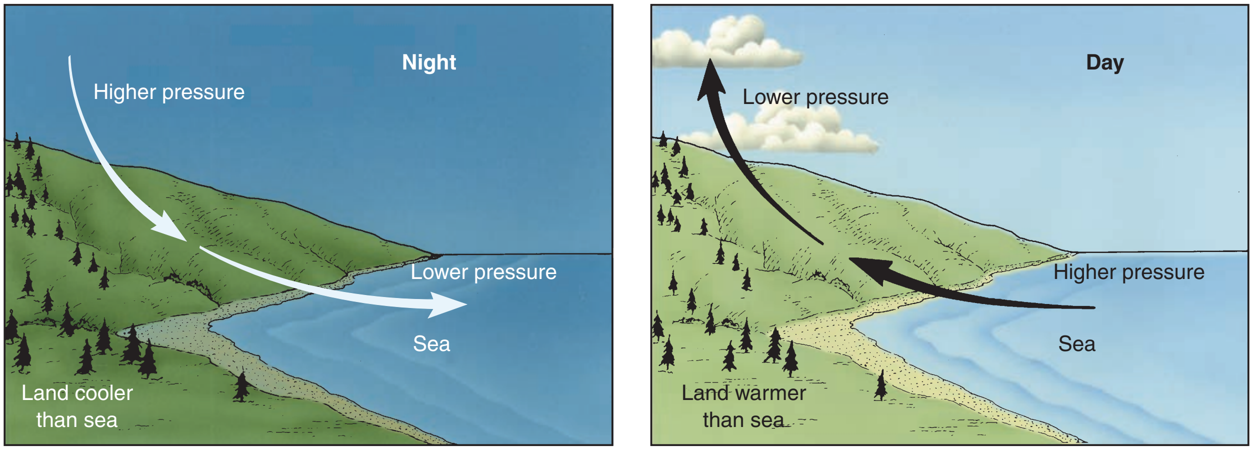


FIGURE 5.22
Land and sea breezes. This day-to-night reversal of winds is a consequence of the different rates of heating and cooling of land and water areas. The land becomes warmer than the sea during the day and colder than the sea at night; the air flows from the cooler to the warmer area.
What is the impact on daytime coastal temperatures of the land and sea breeze?

This process creates a local area of low pressure, and the rising air is replaced by the denser, cooler air from over the ocean. Thus, a sea breeze of cool, moist air blows in over the land during the day. This sea breeze helps explain why seashores are so popular in summer; cooling winds help alleviate the heat. At times, however, sea breezes are responsible for afternoon cloud cover and light rain, spoiling an otherwise sunny day at the shore. These winds can mean a 5°C–9°C (9°F–16°F) reduction in temperature along the coast, as well as a lesser influence on land perhaps as far from the sea as 15–50 kilometers (9–30 mi). During hot summer days, such winds cool cities like Chicago, Milwaukee, and Los Angeles. At night, the land and the air above it cool more quickly and to a lower temperature than the nearby water body and the air above it. Consequently, the pressure builds higher over the land and air flows out toward the lower pressure over the water, creating a land breeze. For thousands of years, sailboats have left their coasts at dawn, when there is still a land breeze, and have returned with the sea breeze of the late afternoon.

GEOGRAPHY'S SPATIAL SCIENCE PERSPECTIVE

The Santa Ana Winds and Fire

Wildfires require three factors to occur: *oxygen, fuel,* and an *ignition source.* The conditions for all three factors vary geographically, so their spatial distributions are not equal everywhere. In locations where all three factors have the potential to exist, the danger from wildfires is high. Oxygen in the atmosphere is constant, but winds, which supply more oxygen as a fire consumes it, vary with location, weather, and terrain. High winds cause fires to spread faster and make them difficult to extinguish. Fuel in wild land fires is usually supplied by dry vegetative litter (leaves, branches, and dry annual grasses). Certain environments have more of this fuel than others. Dense vegetation tends to support the spread of fires. Growing vegetation can also become desiccated—dried out by transpiration losses during a drought or an annual dry season. In addition, once a fire becomes large, extreme heat in the areas where it is spreading causes vegetation along the edges of the burning area to lose its moisture through evaporation. Ignition sources are the means by which a fire is started. Lightning and human causes, such as campfires and trash fires, provide the main ignition sources for wildfires.

Southern California offers a regional example of how conditions related to these three factors combine with the local physical geography to create an environment that is conducive to wildfire hazard. This is also a region where many people live in forested or scrub-covered locales or along the urban–wild land fringe—areas that are very susceptible to fire. High pressure, warm weather, and low relative humidity dominate the Mediterranean climate of Southern California's coastal region for much of the year. When these conditions occur, this region experiences high fire potential because of the warm dry air and the vegetation that has dried out during the arid summer season.

The most dangerous circumstances for wildfires in Southern California occur when high winds are sweeping the region. When a strong cell of high pressure forms east of Southern California, the clockwise (anticyclonic) circulation directs winds from the north and east toward the coast. These warm, dry winds (called Santa Ana winds) blow down from nearby high-desert regions, becoming adiabatically warmer and drier as they descend into the coastal lowlands. The Santa Ana winds are most common in fall and winter, and wind speeds can be 50–90 kilometers per hour (30–50 mph) with stronger local wind gusts reaching 160 kilometers per hour (100 mph). Just like using a bellows or blowing on a campfire to get it started, the Santa Ana winds produce fire weather that can cause the spread of a wildfire to be extremely rapid after ignition. Most people take great care during these times to avoid or strictly control any activities that could cause a fire to start, but occasionally accidents, acts of arson, or lightning strikes ignite a wildfire. Given the physical geography of the Los Angeles region, when the Santa Ana winds are blowing, the fire danger is especially extreme.

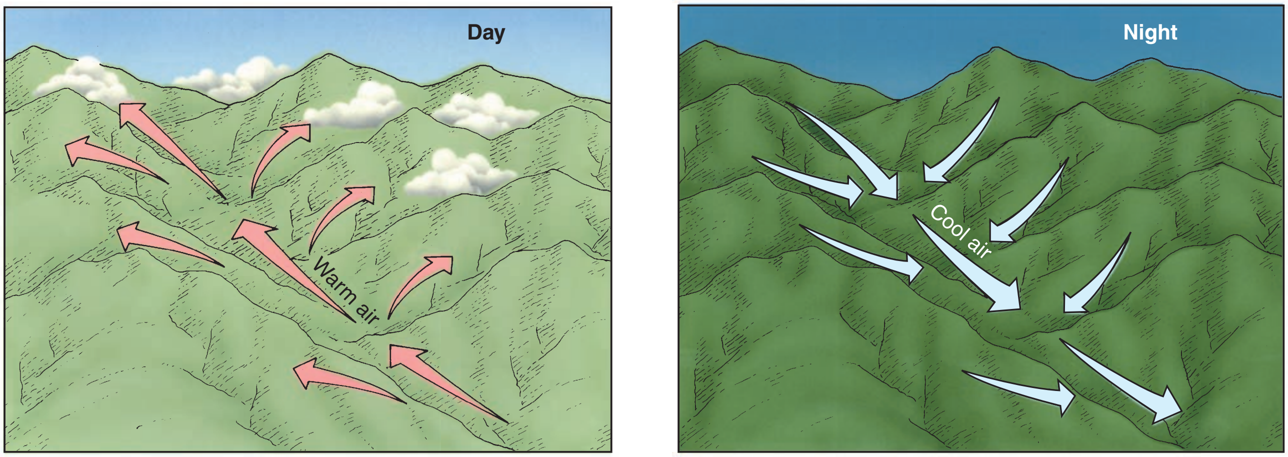
Ironically, although the Santa Ana winds create dangerous fire conditions, they also provide some benefits to local residents because the winds tend to blow air pollutants offshore and out of the urban region. In addition, because they are strong winds flowing opposite to the direction of ocean waves, experienced surfers can enjoy higher than normal waves during those periods when Santa Ana winds are present.

Credit: Julie Stone, USACE

Geographic setting and wind direction for Santa Ana winds.

Image courtesy of MODIS Rapid Response Project at NASA/GSFC

This satellite image shows strong Santa Ana winds from the northeast fanning wildfires in Southern California and blowing the smoke offshore for many kilometers.



● **FIGURE 5.23**
Mountain and valley breezes. This daily reversal of winds results from heating of mountain slopes during the day and their cooling at night. Warm air is drawn up slopes during the day, and cold air drains down the slopes at night. **How might a green, shady valley floor and a bare, rocky mountain slope contribute to these changes?**

Mountain Breeze–Valley Breeze Under the calming influence of a high pressure system, there is a daily **mountain breeze–valley breeze cycle** (● Fig. 5.23), that is somewhat similar in mechanism to the land breeze–sea breeze cycle just discussed. During the day, when the valleys and slopes of mountains are heated by the sun, the high exposed slopes are heated faster than the lower shadier valley. The air on the slope expands and rises, drawing air from the valley up the sides of the mountains. This warm daytime breeze is the *valley breeze,* named for its place of origin. Clouds, which can often be seen hiding mountain peaks, are actually the visible evidence of condensation in the warm air rising from the valleys. At night, the valley and slopes are cooled because Earth is giving off more radiation than it is receiving, thus the air cools and sinks once again into the valley as a cool *mountain breeze.*

There is no question that winds, both local and global, are effective elements of atmospheric dynamics. We all know that a hot, breezy day is not nearly as unpleasant as a hot day without any wind. This difference exists because winds increase the rate of evaporation and thus the rate of removal of heat from our bodies, the air, animals, and plants. For the same reason, the wind on a cold day increases our discomfort.

Ocean–Atmosphere Relationships

Most of Earth's surface acts as an interface between two fluids, the atmosphere and the oceans. The dynamics of fluids, both gases in our atmosphere and the waters of our oceans, follow the same laws of physics and react to the same mathematical equations. The major difference lies in their densities. Water, whose molecules are much more closely packed together, is over 800 times higher in density than air. Nonetheless, movements in our atmosphere can affect movements in the oceans, and the oceans in turn affect the atmosphere in many ways. In recent decades, oceanographers, geographers, and atmospheric scientists have combined their expertise to research some of these ocean–atmosphere relationships.

One of the best known relationships is the constant motion of the winds that creates waves and affects major ocean currents. Because water density is so much greater than air density, the faster movements in the atmosphere are reflected as much slower movements in the oceans. Ocean–atmosphere relationships exist on a large scale with respect to both time and geographical area, and it will take many years before they are fully understood. The remainder of this chapter will discuss some of these very important and powerful relationships.

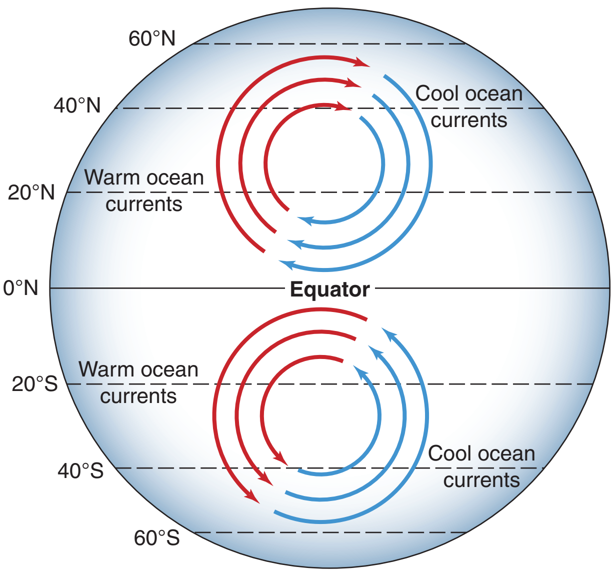
Ocean Currents

Like the planetary wind system, surface-ocean currents play a significant role in helping equalize the energy imbalance between the tropical and polar regions. In addition, surface-ocean currents greatly influence the climate of coastal locations.

Earth's surface-wind system is the primary control of the major surface currents and drifts. Other controls are the Coriolis effect and the size, shape, and depth of the sea or ocean basin. Other currents may be caused by differences in density due to variations in temperature and salinity, tides, and wave action.

The major surface currents move in broad circulatory patterns, called **gyres,** around the subtropical highs. Because of the Coriolis effect, the gyres flow clockwise in the Northern Hemisphere and counterclockwise in the Southern Hemisphere (● Fig. 5.24). As a general rule, the surface currents do not cross the equator.

Waters near the equator in both hemispheres are driven west by the tropical easterlies or the trade winds. The current thus produced is called the Equatorial Current. At the western margin of the ocean, its warm tropical waters are deflected poleward along the coastline. As these warm waters move into higher latitudes,



● **FIGURE 5.24**
The major ocean currents flow in broad gyres in opposite directions in the Northern and Southern Hemispheres.
What controls the direction of these gyres?

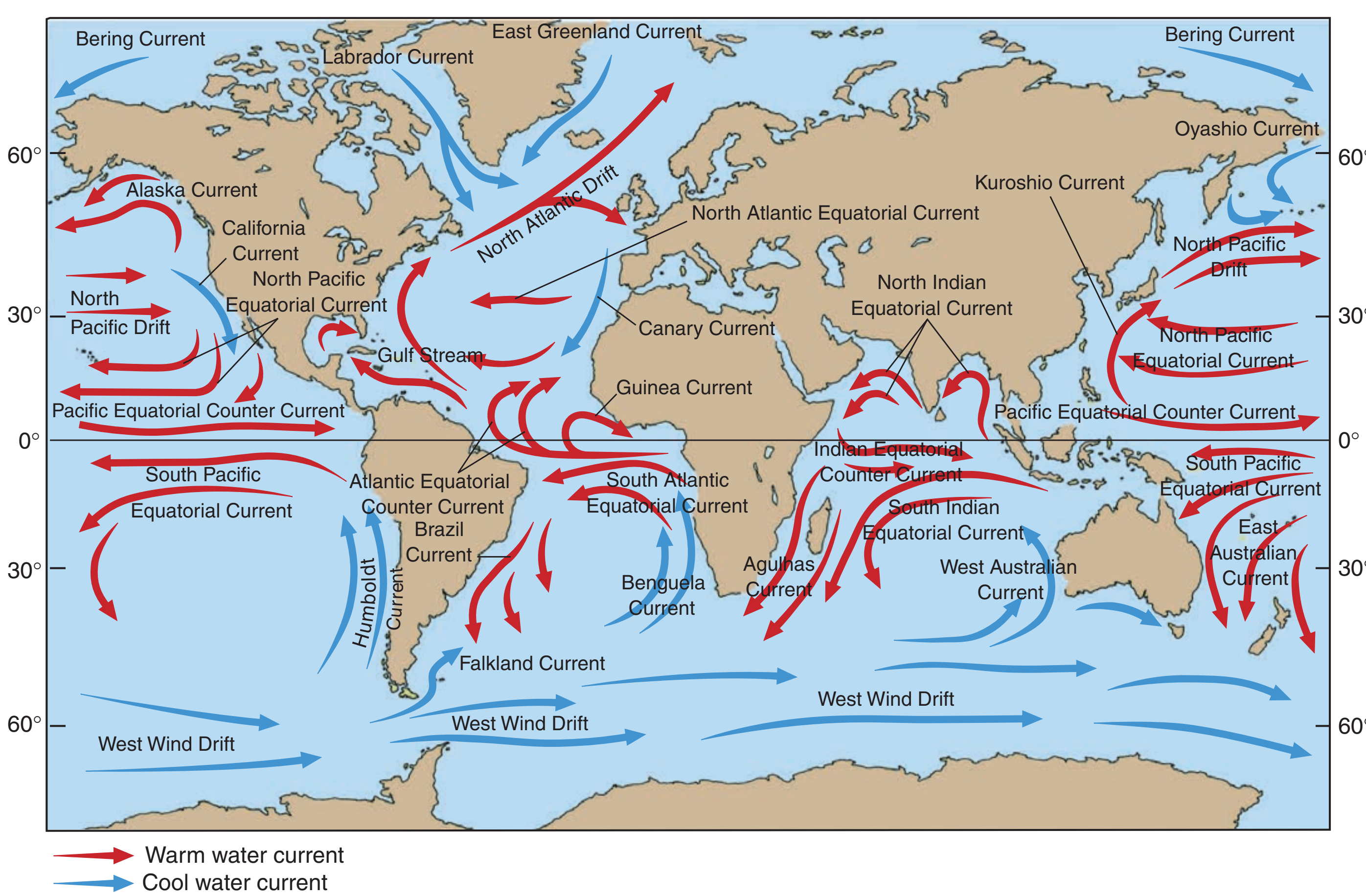
they move through waters cooler than themselves and are identified as *warm currents* (● Fig. 5.25).

In the Northern Hemisphere, warm currents, such as the Gulf Stream and the Kuroshio Current, are deflected more and more to the right (or east) because of the Coriolis effect. At about 40°N, the westerlies begin to drive these warm waters eastward across the ocean, as in the North Atlantic Drift and the North Pacific Drift. Eventually, these currents run into the land at the eastern margin of the ocean, and most of the waters are deflected toward the equator. By this time, these waters have lost much of their warmth, and as they move equatorward into the subtropical latitudes, they are cooler than the adjacent waters. They have become *cool,* or *cold, currents.* These waters complete the circulation pattern when they rejoin the westward-moving Equatorial Current.

On the eastern side of the North Atlantic, the North Atlantic Drift moves into the seas north of the British Isles and around Scandinavia, keeping those areas warmer than their latitudes would suggest. Some Norwegian ports north of the Arctic Circle remain ice free because of this warm water. Cold polar water—the Labrador and Oyashio Currents—flows southward into the Atlantic and Pacific oceans along their western margins.

The circulation in the Southern Hemisphere is comparable to that in the Northern except that it is counterclockwise. Also,

● **FIGURE 5.25**
Map of the major world ocean currents, showing warm and cool currents.
How does this map of ocean currents help explain the mild winters in London, England?



because there is little land poleward of 40°S, the West Wind Drift (or Antarctic Circumpolar Drift) circles Earth as a cool current across all three major oceans almost without interruption. It is cooled by the influence of the Antarctic ice sheet.

In general then, warm currents move poleward as they carry tropical waters into the cooler waters of higher latitudes, as in the case of the Gulf Stream or the Brazil Current. Cool currents deflect water equatorward, as in the California Current and the Humboldt Current. Warm currents tend to have a humidifying and warming effect on the east coasts of continents along which they flow, whereas cool currents tend to have a drying and cooling effect on the west coasts of the landmasses. The contact between the atmosphere and ocean currents is one reason why subtropical highs have a strong side and a weak side. Subtropical highs on the west coast of continents are in contact with cold ocean currents, which cool the air and make the eastern side of a subtropical high more stable and stronger. On the east coasts of continents, contacts with warm ocean currents cause the western sides of subtropical highs to be less stable and weaker.

The general circulation just described is consistent throughout the year, although the position of the currents follows seasonal shifts in atmospheric circulation. In addition, in the North Indian Ocean, the direction of circulation reverses seasonally according to the monsoon winds.

The cold currents along west coasts in subtropical latitudes are frequently reinforced by **upwelling.** As the trade winds in these latitudes drive the surface waters offshore, the wind's frictional drag on the ocean surface displaces the water to the west. As surface waters are dragged away, deeper, colder water rises to the surface to replace them. This upwelling of cold waters adds to the strength and effect of the California, Humboldt (Peru), Canary, and Benguela Currents.

El Niño

As you can see in Figure 5.25, the cold Humboldt Current flows equatorward along the coasts of Ecuador and Peru. When the current approaches the equator, the westward-flowing trade winds cause upwelling of nutrient-rich cold water along the coast. Fishing, especially for anchovies, is a major local industry.

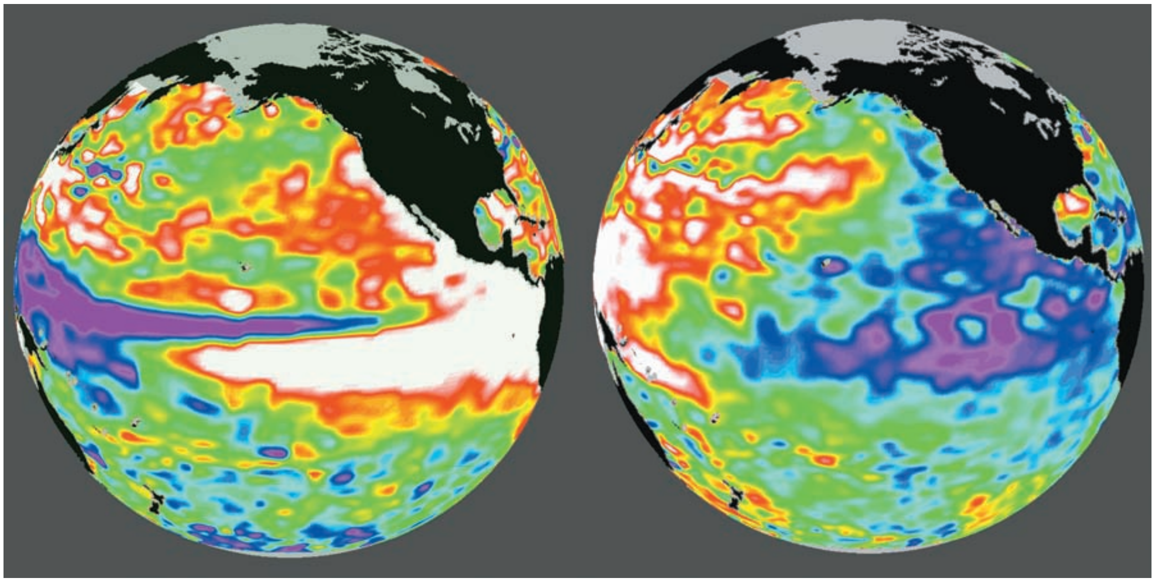
Every year usually during the months of November and December, a weak warm countercurrent replaces the normally cold coastal waters. Without the upwelling of nutrients from below to feed the fish, fishing comes to a standstill. Fishermen in this region have known of the phenomenon for hundreds of years. In fact, this is the time of year they traditionally set aside to tend to their equipment and await the return of cold water. The residents of the region have given this phenomenon the name **El Niño,** which is Spanish for "The Child," because it occurs about the time of the celebration of the birth of the Christ Child.

The warm-water current usually lasts for 2 months or less, but occasionally the disruption to the normal flow lasts for many months. In these situations, water temperatures are raised not just along the coast but for thousands of kilometers offshore (● Fig. 5.26). Over the past decade, the term *El Niño* has come to describe these exceptionally strong episodes and not the annual event. During the past 50 years, approximately 18 years qualify as having El Niño conditions (with sea-surface temperatures 0.5°C higher, or warmer, than normal for 6 consecutive months).

● FIGURE 5.26

These enhanced satellite images show a significant El Niño (left) and La Niña (right) episodes in the Tropical Pacific. The red and white shades display the warmer sea surface temperatures, while the blues and purples mark areas of cooler temperatures.

From what continent does an El Niño originate?

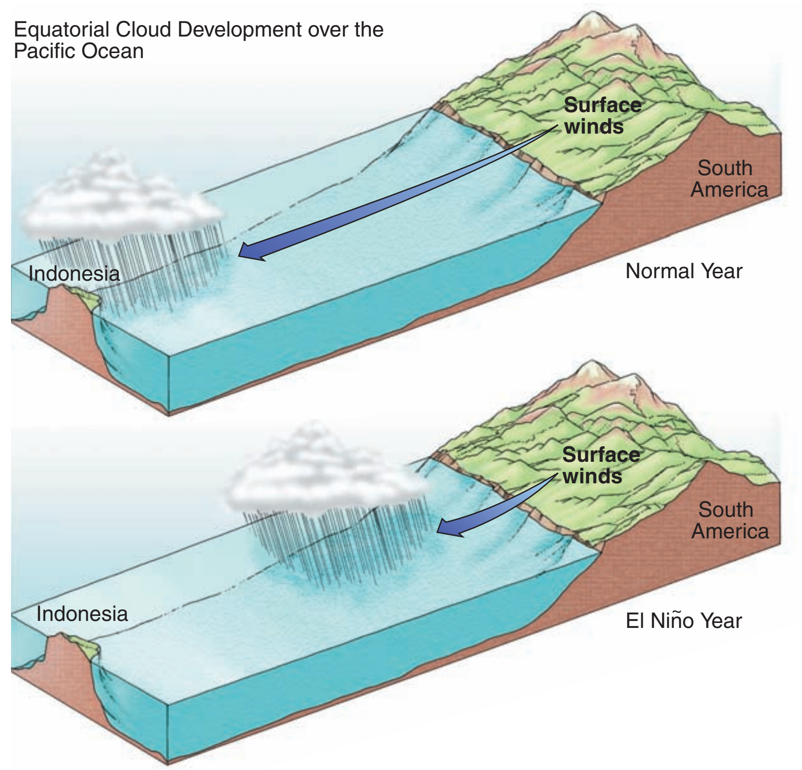


NASA/GSFC

Not only do the El Niños affect the temperature of the equatorial Pacific, but the strongest of them also impact worldwide weather.

El Niño and the Southern Oscillation To completely understand the processes that interact to produce an El Niño requires that we study conditions all across the Pacific, not just in the waters off South America. In the 1920s, Sir Gilbert Walker, a British scientist, discovered a connection between surface-pressure readings at weather stations on the eastern and western sides of the Pacific. He noted that a rise in pressure in the eastern Pacific is usually accompanied by a fall in pressure in the western Pacific and vice versa. He called this seesaw pattern the **Southern Oscillation.** The link between El Niño and the Southern Oscillation is so great that they are often referred to jointly as ENSO (*El Niño/Southern Oscillation*). These days the atmospheric pressure values from Darwin, Australia, are compared to those recorded on the Island of Tahiti, and the relationship between these two values defines the Southern Oscillation.

During a typical year, the eastern Pacific has a higher pressure than the western Pacific. This east-to-west pressure gradient enhances the trade winds over the equatorial Pacific waters. This results in a surface current that moves from east to west at the equator. The western Pacific develops a thick, warm layer of water while the eastern Pacific has the cold Humboldt Current enhanced by upwelling.



● **FIGURE 5.27**
During El Niño, the easterly surface winds weaken and retreat to the eastern Pacific, allowing the central Pacific to warm and the rain area to migrate eastward.
Near what country or countries does El Nino begin?

Then, for unknown reasons, the Southern Oscillation swings in the opposite direction, dramatically changing the usual conditions described above, with pressure increasing in the western Pacific and decreasing in the eastern Pacific. This change in the pressure gradient causes the trade winds to weaken or, in some cases, to reverse. This causes the warm water in the western Pacific to flow eastward, increasing sea-surface temperatures in the central and eastern Pacific. This eastward shift signals the beginning of El Niño.

In contrast, at times and for reasons we do not fully know, the trade winds will intensify. These more powerful trade winds will cause even stronger upwelling than usual to occur. As a result, sea-surface temperatures will be even colder than normal. This condition is known as **La Niña** (in Spanish, "Little Girl," but scientifically simply the opposite of El Niño). La Niña episodes will at times, but not always, bring about the opposite effects of an El Niño episode (see again Fig. 5.26).

El Niño and Global Weather Cold ocean waters impede cloud formation. Thus, under normal conditions, clouds tend to develop over the warm waters of the western Pacific but not over the cold waters of the eastern Pacific. However, during an El Niño, when warm water migrates eastward, clouds develop over the entire equatorial region of the Pacific (● Fig. 5.27). These clouds can build to heights of 18,000 meters (59,000 ft). Clouds of this magnitude can disrupt the high-altitude wind flow above the equator. As we have seen, a change in the upper air wind flow in one portion of the atmosphere will trigger wind flow changes in other portions of the atmosphere. Alterations in the upper air winds result in alterations to surface weather.

Scientists have tried to document as many past El Niño events as possible by piecing together bits of historical evidence, such as sea-surface temperature records, daily observations of atmospheric pressure and rainfall, fisheries' records from South America, and even the writings of Spanish colonists living along the coasts of Peru and Ecuador dating back to the 15th century. Additional evidence comes from the growth patterns of coral and trees in the region. Researchers are constantly discovering new techniques to identify El Niños through history.

Based on this historical evidence, we know that El Niños have occurred as far back as records go. One disturbing fact is that they appear to be occurring more often. Records indicate that during the 16th century, an El Niño occurred, on average, every 6 years. Evidence gathered over the past few decades indicates that El Niños are now occurring, on average, every 2.2 years. Even more alarming is the fact that they appear to be getting stronger. The record-setting El Niño of 1982–1983 was recently surpassed by the one in 1997–1998.

The 1997–1998 El Niño brought copious and damaging rainfall to the southern United States, from California to Florida. Snowstorms in the northeast portion of the United States were more frequent and stronger than in most years. The warm El Niño winters fueled Hurricane Linda, which devastated the western coast of Mexico. Linda was the strongest hurricane ever recorded in the eastern Pacific.

In recent years, scientists have become better able to monitor and forecast El Niño and La Niña events. An elaborate network of ocean-anchored weather buoys plus satellite observations provide an enormous amount of data that can be analyzed by computer to help predict the formation and strength of El Niño and La Niña events.

North Atlantic Oscillation

Our improved observation skills have led to the discovery of the **North Atlantic Oscillation (NAO)**—a relationship between the Azores (subtropical) High and the Icelandic (subpolar) Low. The east-to-west, seesaw motion of the Icelandic Low and the Azores High control the strength of the westerly winds and the direction of storm tracks across the North Atlantic. There are two recognizable phases associated with the established NAO index.

A positive NAO index phase is identified by higher than average pressure in the Azores High and lower than average pressure in the Icelandic Low. The increased pressure difference between the two systems results in stronger winter storms, occurring more often and following a more northerly track (● Fig. 5.28a). This promotes warm and wet winters in Europe, but cold, dry winters in Canada and Greenland. The eastern United States may experience a mild and wet winter. The negative NAO index phase occurs with a weak Azores High and higher pressure in the Icelandic Low. The smaller pressure gradient between these two systems will weaken the westerlies resulting in fewer and weaker winter storms (Fig. 5.28b). Northern Europe will experience cold air with moist air moving into the Mediterranean. The East Coast of the United States will experience more cold air and snowy winters. This index varies from year to year but also has a tendency to stay in one phase for periods lasting several years in a row.

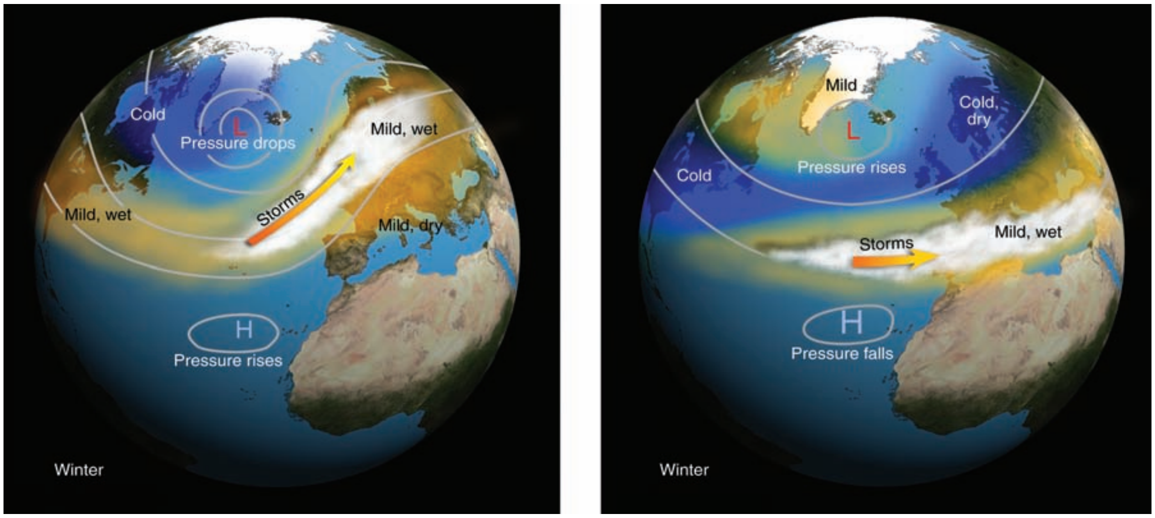
The North Atlantic Oscillation (NAO) is not as well understood as ENSO. Truly, both oscillations require more research in the future if scientists are to better understand how these ocean phenomena affect weather and climate. Will scientists ever be able to predict the occurrence of such phenomena as ENSO or the NAO? No one can answer that question, but as our technology improves, our forecasting ability will also increase. We have made tremendous progress: In the past few decades, we have come to recognize the close association between the atmosphere and hydrosphere as well as to better understand the complex relationship between these Earth systems.

This chapter began with an examination of the behavior of atmospheric gases as they respond to solar radiation and other dynamic forces. This information enabled a definition and thorough discussion of global pressure systems and their accompanying winds. This discussion in turn permitted a description of atmospheric circulation patterns on the global and subglobal scale. Once again, we can recognize the interactions among Earth's systems. Earth's radiation budget helps create movements in our atmosphere, which in turn help drive ocean circulation, which in turn creates feedback with the atmosphere:

Solar radiation → Atmosphere → Hydrosphere →
Back to the atmosphere

In following chapters, we will examine the role of the atmospheric systems in controlling variations in weather and climate and, later, weather and climate systems as they affect surface landforms.

● **FIGURE 5.28**
Positions of the pressure systems and winds involved with the (a) positive and (b) negative phases of the North Atlantic Oscillation (NAO).
Which two pressure systems are used to establish the NAO phases?



(a) Positive phase **(b) Negative phase**