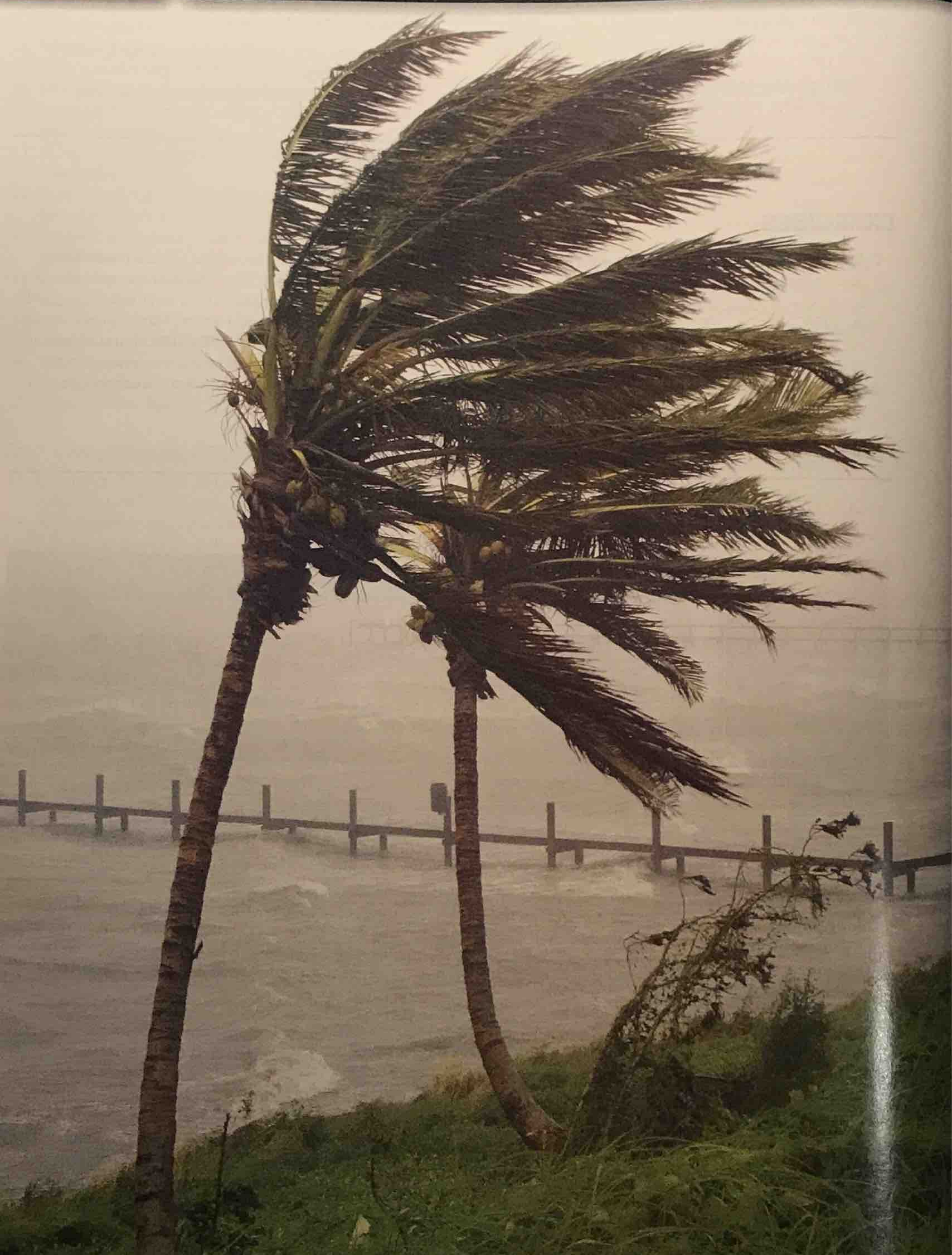
# Chapter 5

# ATMOSPHERIC PRESSURE AND WIND



TO THE LAYPERSON, ATMOSPHERIC PRESSURE IS THE MOST difficult element of weather and climate to comprehend. The other three—temperature, wind, and moisture—are more readily understood because our bodies are much more sensitive to them. We can feel warmth, air movement, and moisture, and we are quick to recognize variations in these elements. Pressure, on the other hand, is a phenomenon of which we are usually unaware—our bodies cannot sense the relatively small changes in atmospheric pressure that can be responsible for significant changes in the atmosphere. We're usually only aware of pressure changes when we experience rapid vertical movement, as in an elevator or an airplane, when the difference in pressure inside and outside our ears causes them to "pop."

Despite its inconspicuousness, pressure is an important feature of the atmosphere. It is tied closely to the other weather elements, acting on them and responding to them. Pressure has an intimate relationship with wind: spatial variations in pressure are responsible for air movements. Hence, pressure and wind are often discussed together, as is done in this chapter.

The general circulation pattern of global wind and pressure discussed here is a component of several major Earth systems. For example, the movement of the atmosphere is not only a consequence of the receipt of solar energy, it is one of the key mechanisms of energy transfer itself. Further, patterns of wind and pressure are key aspects of the hydrologic cycle—the systematic movement of water around the planet.

As you study this chapter, think about these key questions:

- **What influences the development of high pressure cells and low pressure cells near Earth's surface?**
- **How and why are wind patterns different near the surface and in the upper atmosphere?**
- **What is the pattern of wind and vertical air movement within cyclones and anticyclones?**
- **How do the Hadley cells fit in with the general circulation patterns of wind and pressure around the world?**
- **What causes seasonal shifts of global wind and pressure systems, and the development of monsoons?**
- **How can differences in temperature lead to local winds such as land and sea breezes?**
- **What happens in the ocean and atmosphere during El Niño?**
- **How do long-term atmospheric and oceanic cycles such as the Pacific Decadal Oscillation influence regional weather conditions?**

**Seeing Geographically**

Hurricane Frances strikes the Florida coast near Fort Pierce with 145 kilometer per hour (90 mile per hour) winds. Describe how the wind appears to be affecting the waves coming on shore. What characteristics of palm trees that you can see helps explain why they can survive hurricanes?

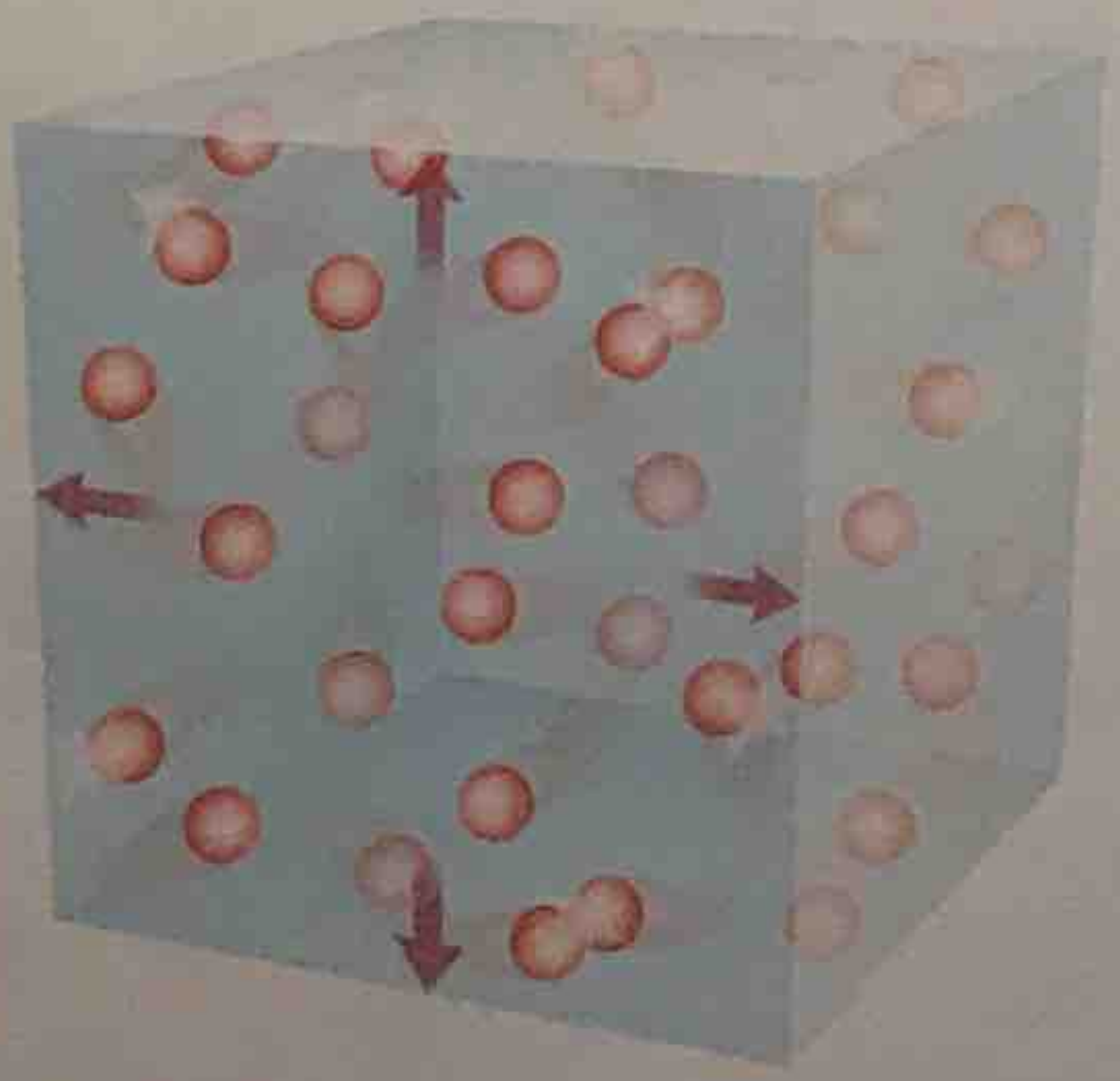
## The Impact of Pressure and Wind on the Landscape

The influence of atmospheric pressure on the landscape is significant but indirect. This influence is manifested mostly by wind, which responds to pressure changes. Wind has the energy to transport solid particles in the air and thus has a visible component to its activity. Vegetation may bend in the wind and loose material such as dust or sand may be shifted from one place to another. The results are nearly always short-run and temporary, however, and usually have no lasting effect on the landscape except at the time of a severe storm. Nevertheless, pressure and wind are major elements of weather and climate, and their interaction with other atmospheric components and processes cannot be overestimated.

# THE NATURE OF ATMOSPHERIC PRESSURE

Gas molecules, unlike those of a solid or liquid, are not strongly bound to one another. Instead, they are in continuous motion, colliding frequently with one another and with any surfaces to which they are exposed. Consider a container in which a gas is confined, as in Figure 5-1. The molecules of the gas zoom around inside the container and collide again and again with the walls. The pressure of the gas is the force the gas exerts on the container walls.

The atmosphere is made up of gases that have mass, and so the atmosphere has *weight* because this mass is pulled toward Earth by gravity. **Atmospheric pressure** is the force exerted by the weight of these gas molecules on a unit of area of Earth's surface or on any other body—including yours! At sea level, the pressure (the "weight") exerted by the atmosphere is about 14.7 pounds per square inch, or in S.I. units, about 10 newtons (N) per square centimeter (1 newton is the force required to accelerate a 1-kilogram mass 1 meter per second per second).[1] This value decreases with increasing altitude because the farther away you get from Earth and its gravitational pull, the fewer gas molecules are present in the atmosphere.



**▲ Figure 5-1** Gas molecules are always in motion. In this closed container, they bounce around, colliding with one another and with the walls of the container. These collisions give rise to the pressure exerted by the gas.

**▲ Figure 5-2** The empty plastic bottle on the left was opened and then sealed tightly at an elevation of 3030 meters (9945 feet); when the bottle is brought down to sea level, the surrounding higher atmospheric pressure partially collapses the bottle. The bottle on the right contains air at sea-level pressure.

The atmosphere exerts pressure on every surface it touches. The pressure is exerted equally in all directions—up, down, sideways, and obliquely. This means that every square centimeter of any exposed surface—animal, vegetable, or mineral—at sea level is subjected to atmospheric pressure (Figure 5-2). We are not sensitive to this ever-present burden of pressure because our bodies contain solids and liquids that are not significantly compressed and air spaces that are at the same pressure as the surrounding atmosphere; in other words, outward pressure and inward pressure balance exactly.

**Learning Check 5-1** **Explain why *atmospheric pressure* decreases with altitude. (Answer on p. AK-2)**

## Factors Influencing Atmospheric Pressure

The pressure, temperature, and density of a gas are all related to each other—if one of those variables changes, it can cause changes in the other two.

**The Ideal Gas Law:** The relationship between pressure, temperature, and density can be summarized by an equation called the *ideal gas law*:

$$P = \rho RT$$

where P is pressure, ρ ("rho") is density, R is the constant of proportionality, and T is temperature. Explained with words, this equation says that pressure (P) will increase if

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[1] In the definition of a newton, the term "per second per second" may seem strange. However, a newton describes the force required to *accelerate* a mass: in other words, the force required to change its speed or direction. Thus, the newton describes a rate of change, not a speed.

density remains constant but temperature (T) increases, and that pressure will increase if temperature remains constant but density (ρ) increases.

In a closed container (a sealed jar, for example), the relationship between pressure, temperature, and density is straightforward. However, the atmosphere is not a closed container in which any of these variables can be easily held constant and so the cause-and-effect relationships are actually quite complex. It may be useful, however, to examine some of the possibilities one at a time, looking at how pressure varies with density, with temperature, and with the vertical movement of air.

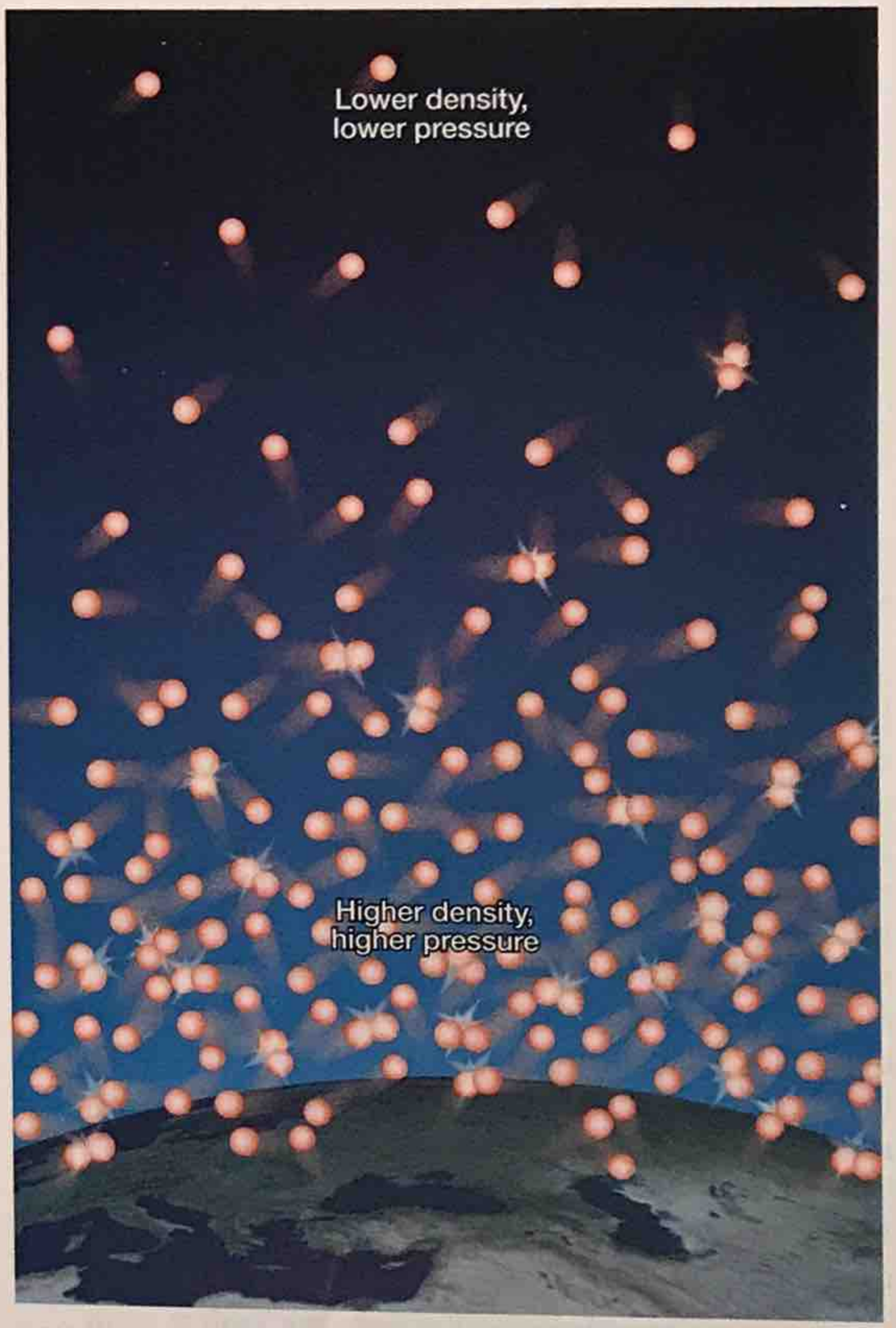
**Density and Pressure Relationships:** Density is the mass of matter in a unit volume. For example, if you have a 10-kilogram cube of material with edge lengths of 1 meter, the density of that material is 10 kilograms per cubic meter (10 kg/m³). The density of solid material is the same on Earth or the moon or in space; that of liquids varies very slightly from one place to another, but that of gases varies greatly with location. Gas density changes easily because a gas is free to expand as far as the environmental pressure will allow.

For example, if you have 10 kg of gas in a container that has a volume of 1 cubic meter, the gas density is 10 kg/m³. If you were to transfer all the gas to a container having twice the volume (2 cubic meters), the gas expands to fill the larger volume. The same number of gas molecules are now spread through a volume twice as large, and so the gas density is half what it was before, or 5 kg/m³ (10 kg divided by 2 cubic meters).

The pressure exerted by a gas is proportional to its density. The denser the gas, the greater the pressure it exerts. The atmosphere is held to Earth by the force of gravity which prevents the gas molecules from escaping into space. At lower altitudes, the gas molecules of the atmosphere are packed more densely together (Figure 5-3). Because the density is higher, there are more molecular collisions and therefore higher pressure at lower altitudes. At higher altitudes, the air is less dense and there is a corresponding decrease in pressure.

**Temperature and Pressure Relationships:** If air is warmed, as we noted in the preceding chapter, the molecules become more agitated and their speed increases. This increase in speed produces a greater force to their collisions and results in higher pressure. Therefore, if other conditions remain the same (in particular, if volume is held constant), an increase in the temperature of a gas produces an increase in pressure, and a decrease in temperature produces a decrease in pressure.

Knowing this, you might conclude that the air pressure will be high on warm days and low on cold days. Such is not usually the case, however; warm air is generally associated with low atmospheric pressure and cool air with high atmospheric pressure. Although this seems contradictory, recall that we made the qualifying statement "if other conditions remain the same" in describing how temperature and pressure are related. When air is warmed in the atmosphere, it will expand, which decreases its density. Thus, the increase in temperature may be accompanied by a decrease in pressure caused by the decrease in density.



▲ **Figure 5-3** In the upper atmosphere, gas molecules are far apart and collide with each other infrequently, a condition that produces relatively low pressure. In the lower atmosphere, the molecules are closer together, and there are many more collisions, a condition that produces high pressure.

**Dynamic Influences on Air Pressure:** Surface air pressure may also be influenced by "dynamic" factors. In other words, air pressure may be influenced by the movement of the air—especially the vertical movement of air associated with different rates of air convergence and divergence at the surface and in the upper troposphere. As a generalization, descending air tends to be associated with relatively high pressure at the surface, whereas rising air tends to be associated with relatively low pressure at the surface.

In short, atmospheric pressure is affected by differences in air density, air temperature, and air movement. It is important for us to be alert to these linkages, but it is often difficult to predict how a change in one variable will influence the others in a specific instance. Nevertheless, some useful generalizations about the factors associated with areas of high pressure and low pressure near the surface can be made:

- Strongly descending air is usually associated with high pressure at the surface—a **dynamic high**.

- Very cold surface conditions are often associated with high pressure at the surface—a **thermal high**.
- Strongly rising air is usually associated with low pressure at the surface—a **dynamic low**.
- Very warm surface conditions are often associated with relatively low pressure at the surface—a **thermal low**.

Surface pressure conditions usually can be traced to one of these factors being dominant.

**Learning Check 5-2** **Is descending air more likely to be associated with high or low atmospheric pressure at the surface? Rising air?**

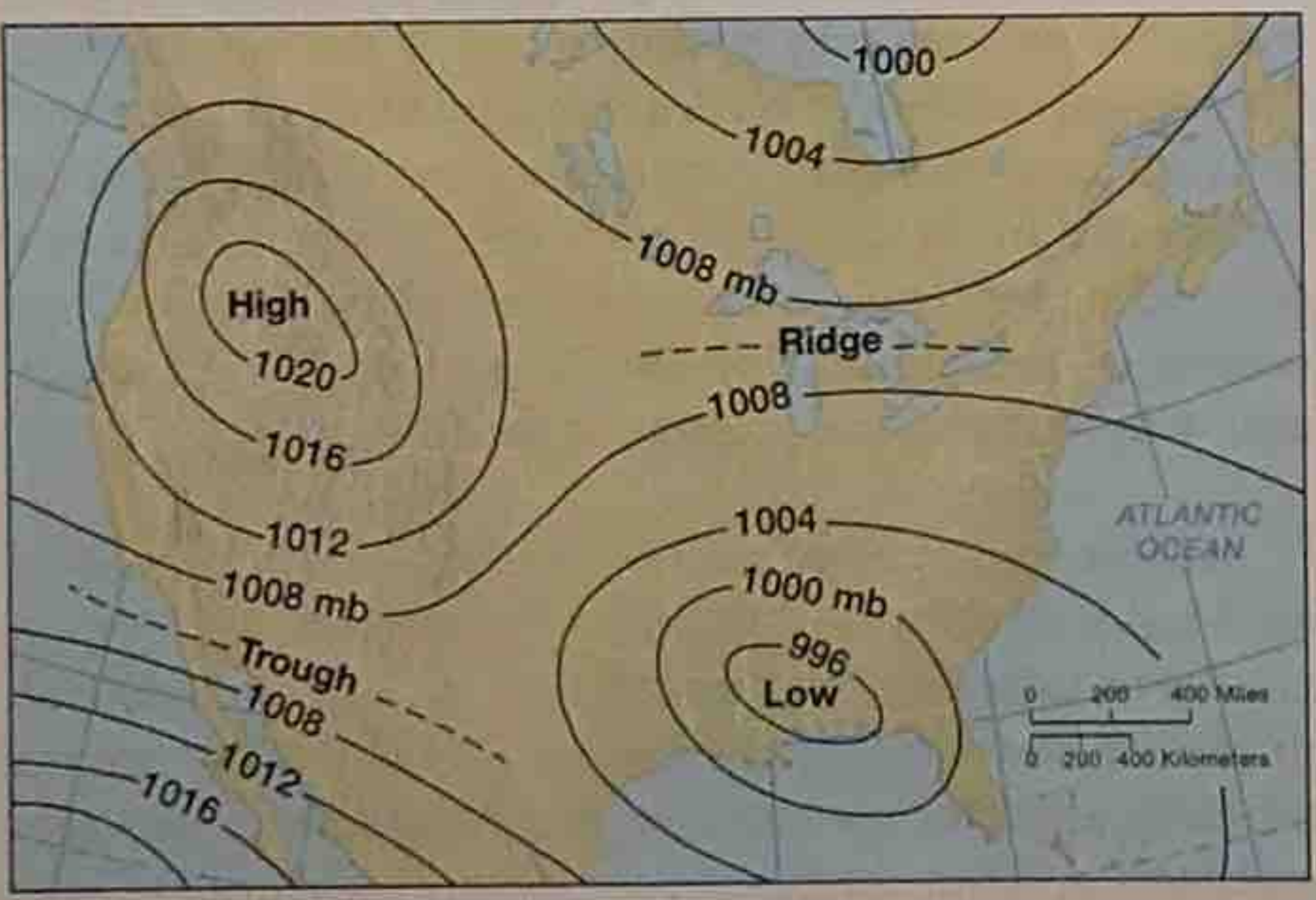
## Mapping Pressure with Isobars

Atmospheric pressure is measured with instruments called **barometers**. The first liquid-filled barometers date back to the 1600s, and measurement scales based on the height of a column of mercury are still in use (average sea-level pressure using a mercury barometer is 760 millimeters or 29.92 inches). For meteorologists in the United States, however, the most common unit of measure for atmospheric pressure is the **millibar**. The millibar (mb) is an expression of force per surface area. One millibar is defined as 1000 dynes per square centimeter (1 dyne is the force required to accelerate 1 gram of a mass 1 centimeter per second per second). Average sea-level pressure is 1013.25 millibars. The S.I. unit used to describe pressure is the *pascal* (Pa; 1 Pa = newton/m$^2$) and in some countries the *kilopascal* is used in meteorology (kPa; 1 kPa = 10 mb).

**Highs and Lows:** Once pressure in millibars is plotted on a weather map, it is then possible to draw isolines of equal pressure called **isobars**, as shown in Figure 5-4. The pattern of the isobars reveals the horizontal distribution of pressure in the region under consideration. Prominent on such maps are roughly circular or oval areas characterized as being either "high pressure" or "low pressure." These **highs** and **lows** represent relative conditions—pressure that is higher or lower than that of the surrounding areas. In a similar way, a **ridge** is an elongated area of relatively high pressure, whereas a **trough** is an elongated area of relatively low pressure. It is important to keep the relative nature of pressure centers in mind. For example, a pressure reading of 1005 millibars could be either "high" or "low," depending on the pressure of the surrounding areas.

**TABLE 5-1 Atmospheric Pressure Variation with Altitude**

| Altitude Kilometers | Miles | Pressure (millibars) |
|---|---|---|
| 18 | 11 | 76 |
| 16 | 10 | 104 |
| 14 | 8.7 | 142 |
| 12 | 7.4 | 194 |
| 10 | 6.2 | 265 |
| 8 | 5.0 | 356 |
| 6 | 3.7 | 472 |
| 4 | 2.5 | 617 |
| 2 | 1.2 | 795 |
| 0 | 0 | 1013 |



▲ **Figure 5-4** Isobars are lines connecting points of equal atmospheric pressure. When they have been drawn on a weather map, it is easy to determine the location of high-pressure and low-pressure centers. This simplified weather map shows pressure in millibars.

**Pressure Decrease with Altitude:** On most maps of air pressure, actual pressure readings are adjusted to represent pressures at a common elevation, usually sea level. This is done because, as we first saw in Chapter 3, with only minor localized exceptions, pressure decreases rapidly with increasing altitude (Table 5-1); consequently significant variations in pressure readings are likely at different weather stations simply because of differences in elevation. This pressure change is most rapid at lower altitudes, and the rate of decrease diminishes significantly above about 3 kilometers (10,000 feet).

As with other types of isolines, the relative closeness of isobars indicates the horizontal rate of pressure change, or **pressure gradient**. The pressure gradient can be thought of as representing the "steepness" of the pressure "slope" (or more correctly, the abruptness of the pressure change over a distance), a characteristic that has a direct influence on wind, the topic to which we turn next.

# THE NATURE OF WIND

The atmosphere is virtually always in motion. Air is free to move in any direction, its specific movements being shaped by a variety of factors. Some airflow is weak and brief; some is strong and persistent. Atmospheric motions often involve both horizontal and vertical movement.

Animation
Development of Wind Patterns

**Wind** refers to horizontal air movement; it has been described whimsically as "air in a hurry." Instead of being called wind, small-scale vertical motions are normally referred to as *updrafts* and *downdrafts*; large-scale vertical motions are *ascents* and *subsidences*. The term *wind* is applied only to horizontal movements. Although both vertical and horizontal motions are important in the atmosphere, much more air is involved in horizontal movements than in vertical.

## Direction of Movement

Insolation is the ultimate cause of wind because all winds originate from the same basic sequence of events: unequal heating of different parts of Earth's surface brings about temperature gradients that generate pressure gradients, and these pressure gradients set air into motion. Wind represents nature's attempt to even out the uneven distribution of air pressure across Earth's surface.

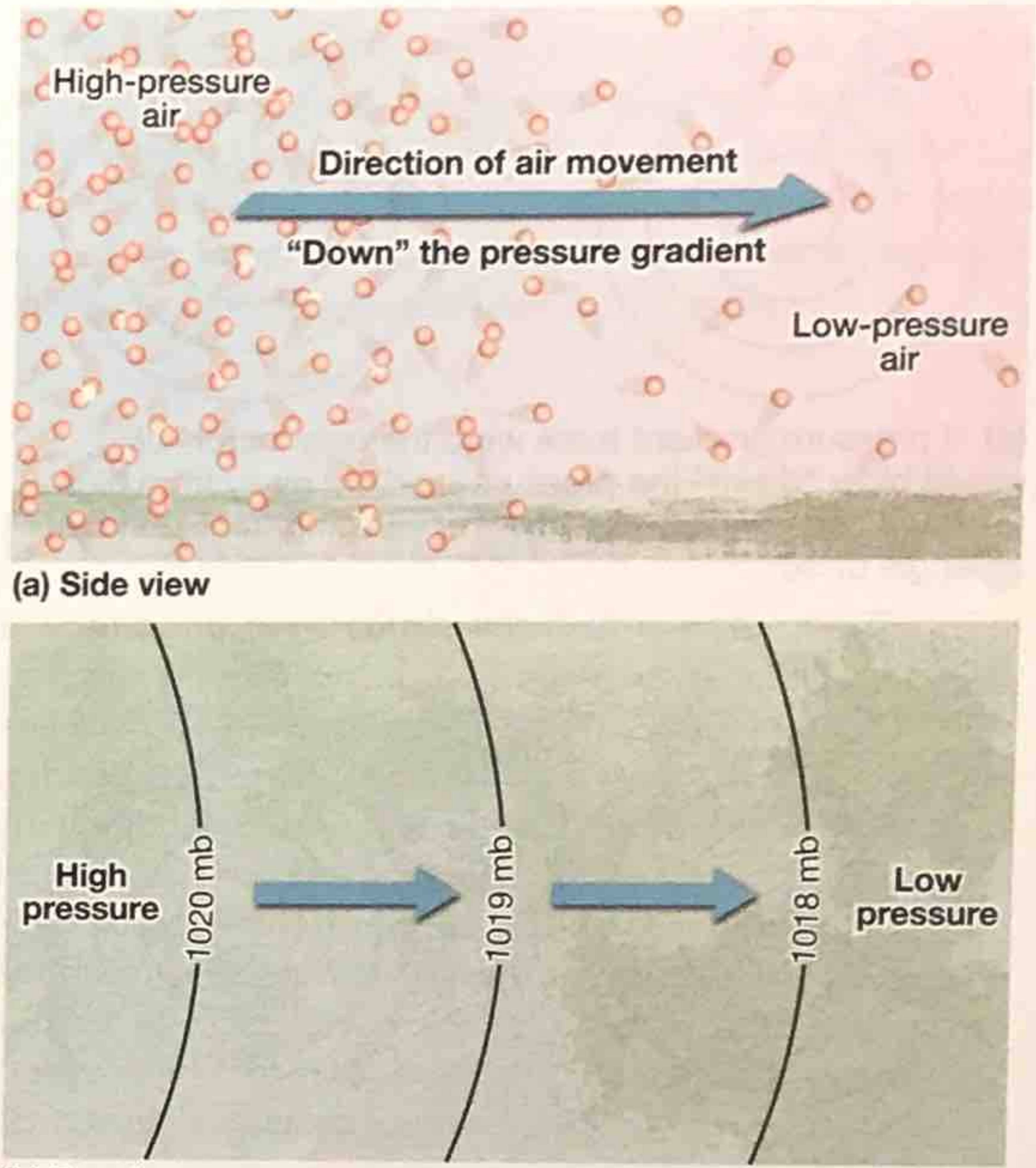
Air generally begins to flow from areas of higher pressure toward areas of lower pressure. If Earth did not rotate and if friction did not exist, that is precisely what would happen—a direct movement of air from a high-pressure region to a low-pressure region. However, rotation and friction both exist, and so this general statement is usually not completely accurate. The direction of wind movement is determined principally by the interaction of three factors: the pressure gradient, the Coriolis effect, and friction.

**Pressure Gradient:** If there is higher pressure in one area than in another, air will begin to move from the higher pressure toward the lower pressure in response to the *pressure gradient force*, as shown in Figure 5-5. If you visualize a high-pressure area as a pressure "hill" and a low-pressure area as a pressure "valley," it is not difficult to imagine air flowing "down" the pressure gradient in the same manner that water flows down a hill (keep in mind that these terms are metaphorical—air is not necessarily actually flowing downhill).

The pressure-gradient force acts at right angles to the isobars in the direction of the lower pressure. If there were no other factors to consider, that is the way the air would move, crossing the isobars at 90° (Figure 5-6a). However, such a flow rarely occurs in the atmosphere.

**The Coriolis Effect:** Because Earth rotates, any object moving freely near Earth's surface appears to deflect to the right in the Northern Hemisphere and to the left in the Southern Hemisphere. Recall from Chapter 3 the significant aspects of the Coriolis effect:

- Regardless of the initial direction of motion, any freely moving object appears to deflect to the right in the Northern Hemisphere and to the left in the Southern Hemisphere.
- The apparent deflection is strongest at the poles and decreases progressively toward the equator, where deflection is zero.
- The Coriolis effect is proportional to the speed of the object, and so a fast-moving object is deflected more than a slower one.
- The Coriolis effect influences direction of movement only; it does not change the speed of an object.



▲ **Figure 5-5** (a) Air tends to move from areas of higher pressure toward areas of lower pressure. We say this movement is "down the pressure gradient." (b) If pressure gradient were the only force involved, air would flow perpendicular to the isobars (would cross the isobars at 90°).

The Coriolis effect has an important influence on the direction of wind flow. The Coriolis effect deflection acts at 90° from the direction of movement—to the right in the Northern Hemisphere and to the left in the Southern Hemisphere. There is an eternal battle, then, between the pressure-gradient force moving air from high toward low pressure and the deflection of the Coriolis effect 90° from its pressure-gradient path: the Coriolis effect keeps the wind from flowing directly down a pressure gradient, whereas the pressure gradient force prevents the Coriolis effect from turning the wind back "up" the pressure slope. Where these two factors are in balance—as is usually the case in the upper atmosphere—wind moves parallel to the isobars and is called a geostrophic wind[2] (Figure 5-6b).

Most winds in the atmosphere are geostrophic or nearly geostrophic in that they flow nearly parallel to the isobars. Only near the surface is another factor significant—friction—to further complicate the situation.

**Friction:** In the lowest portions of the troposphere, a third force influences wind direction—*friction*. The frictional drag of Earth's surface slows wind movement and so the influence

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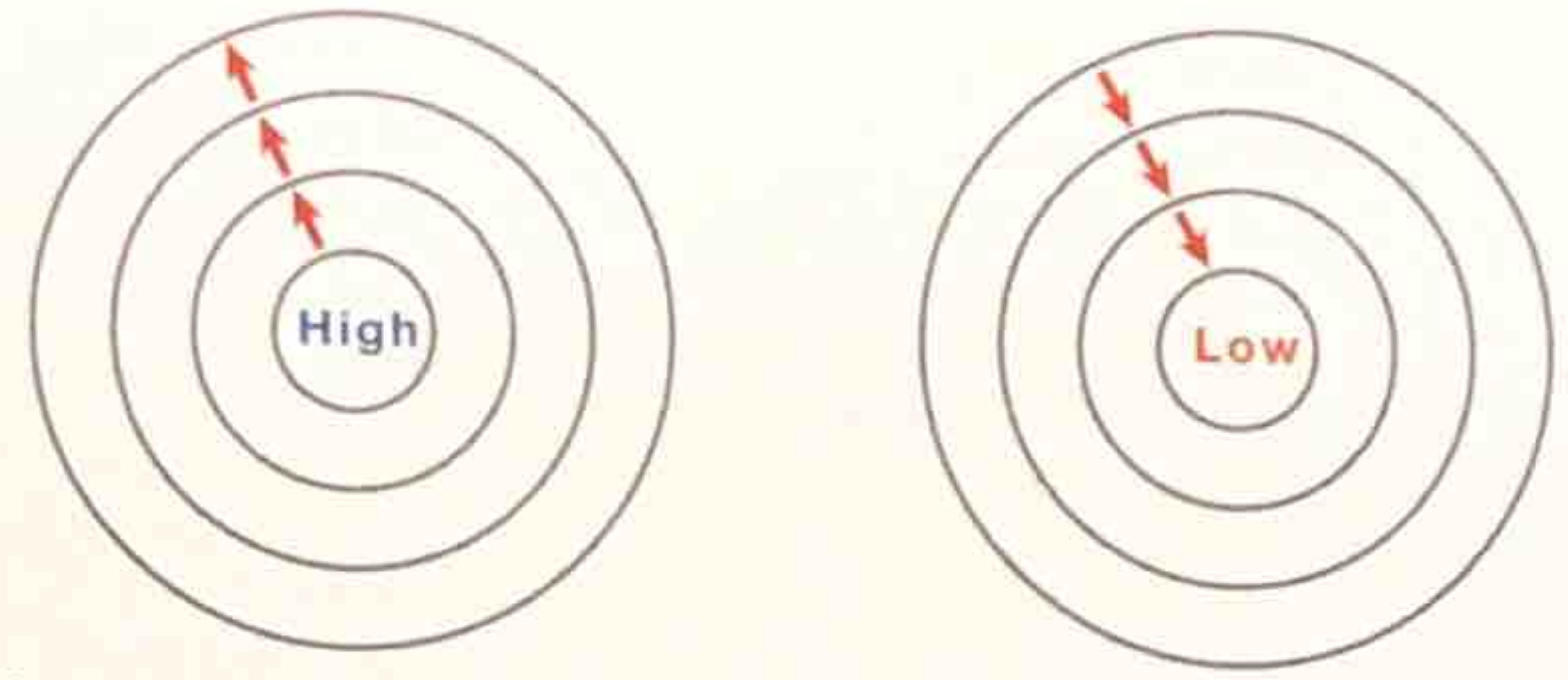
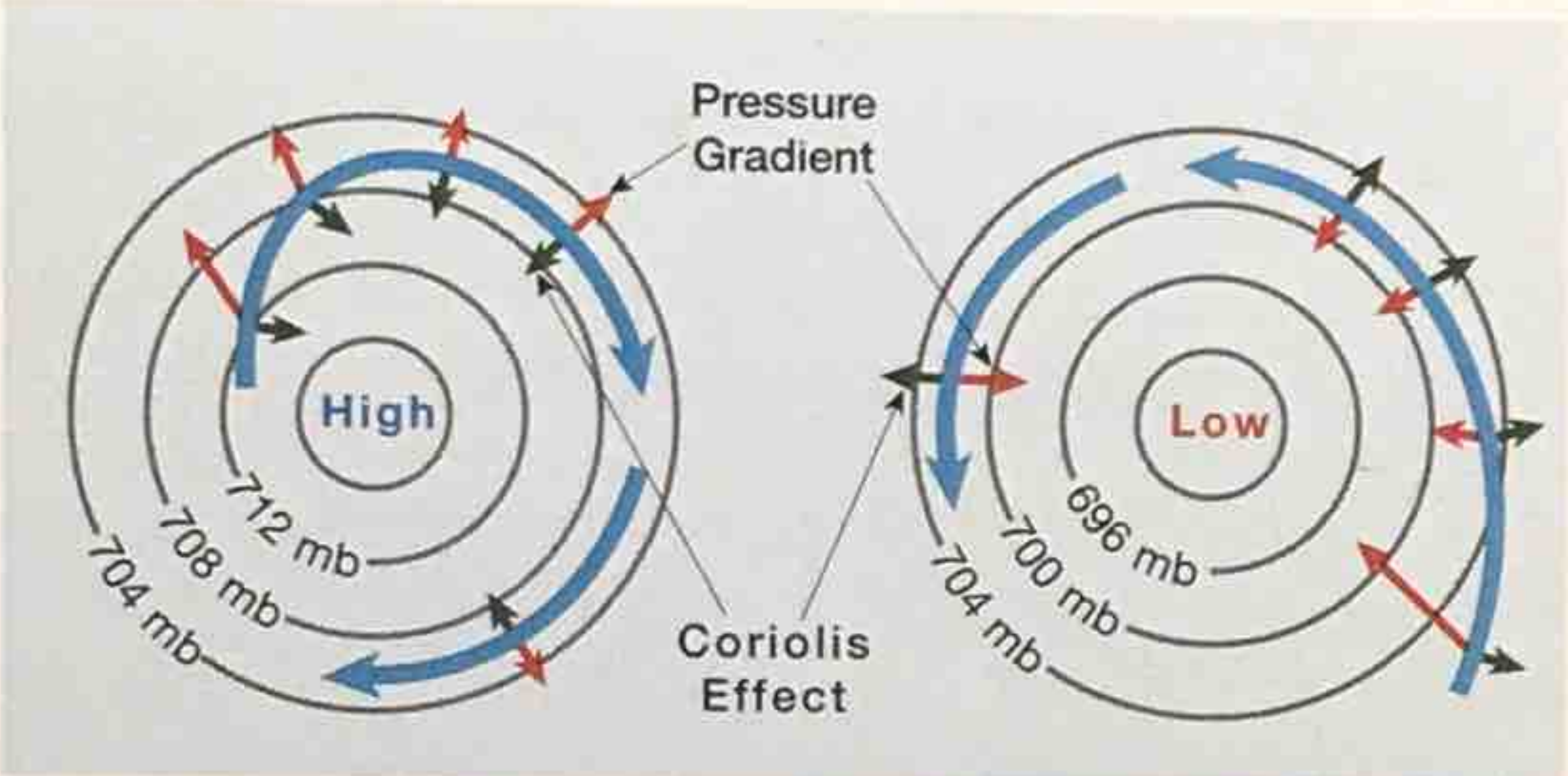
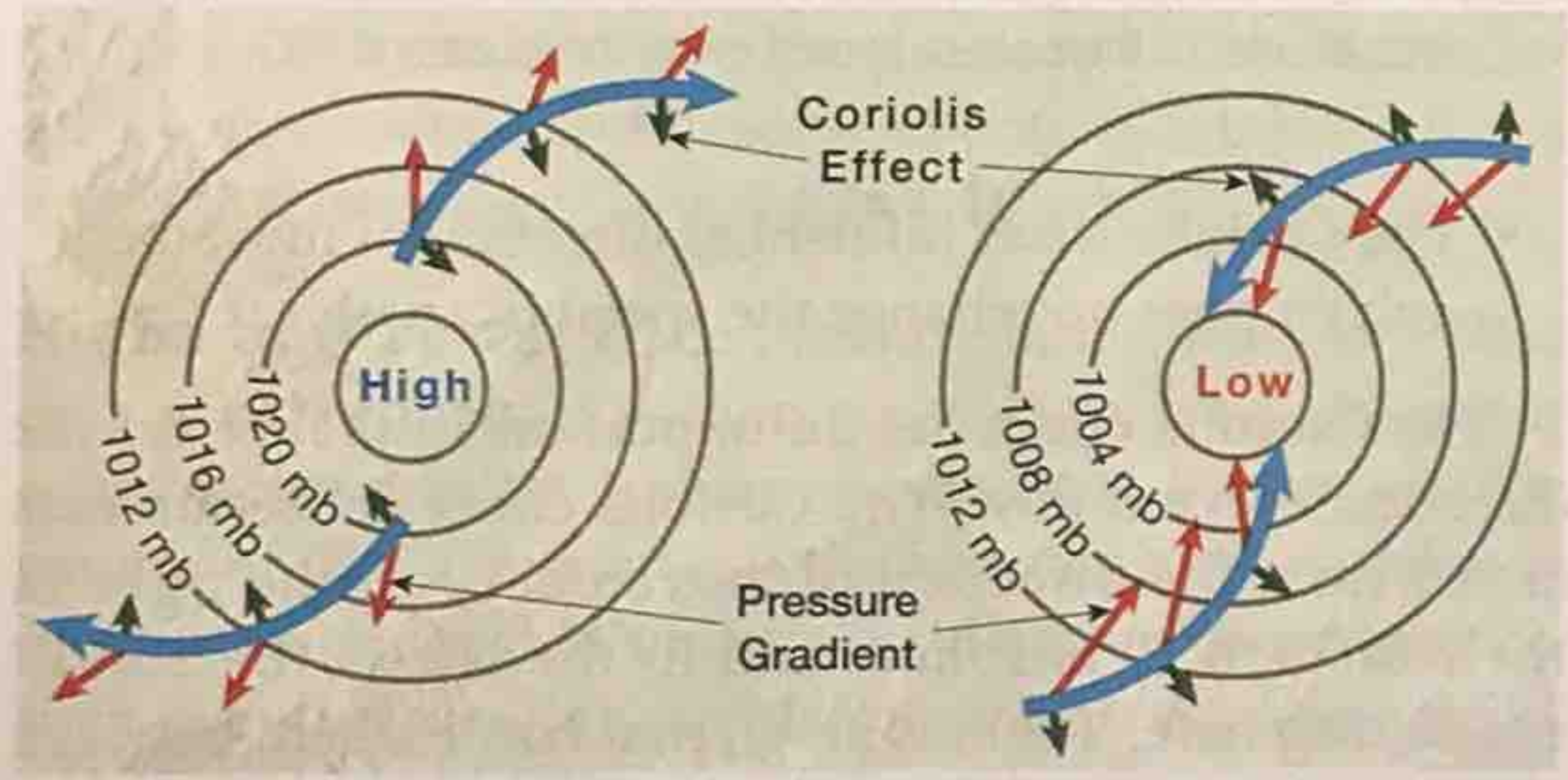
[2] Strictly speaking, geostrophic wind is only found in areas where the isobars are parallel and straight; the term *gradient wind* is a more general term used to describe wind flowing parallel to the isobars. In this book we use the term *geostrophic* to mean all wind blowing parallel to the isobars.



**(a)** If pressure gradient force were the only factor, wind would blow "down" the pressure gradient away from high pressure and toward low pressure, crossing the isobars at an angle of 90°.

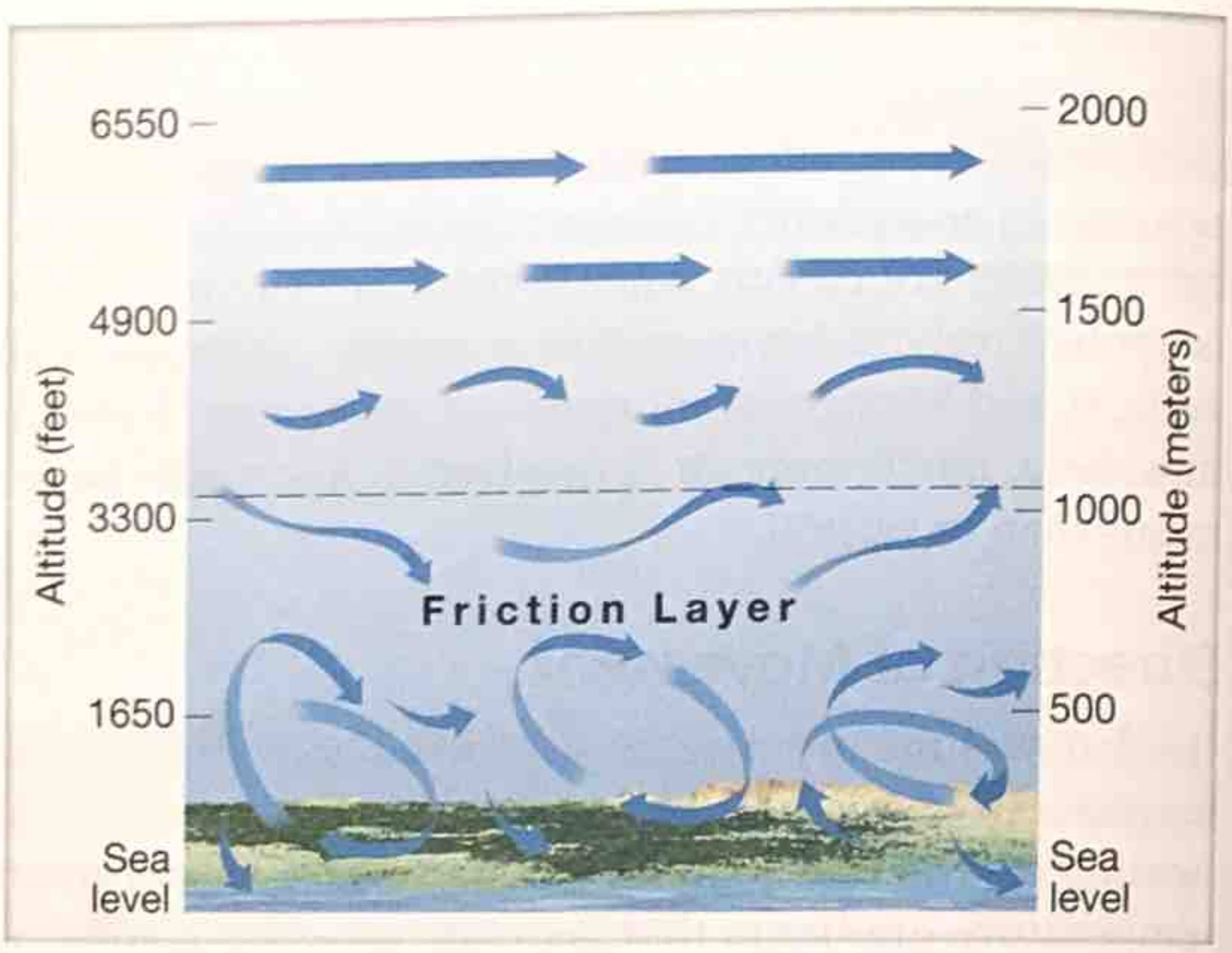


**(b)** In the upper atmosphere the balance between the pressure gradient force and the Coriolis effect results in geostrophic wind blowing parallel to the isobars.



**(c)** In the lower atmosphere, friction slows the wind (which results in less Coriolis effect deflection) and so wind diverges clockwise out of a high and converges counterclockwise into a low in the Northern Hemisphere.

▲ **Figure 5-6** The direction of wind flow is influenced by a combination of three factors: pressure gradient force, Coriolis effect, and friction. (a) Hypothetical pattern if pressure gradient force was the only factor. (b) In the upper atmosphere (above about 1000 m/3300 ft.), a balance develops between the pressure gradient force and the Coriolis effect, resulting in geostrophic wind blowing parallel to the isobars. (c) In the lower atmosphere, friction slows the wind (which results in less Coriolis effect deflection) and so wind diverges out of a high and converges into a low.



▲ **Figure 5-7** Near Earth's surface friction causes wind flow to be turbulent and irregular. Above the friction layer (altitudes higher than about 1000 m/3300 ft.), the wind flow is generally smoother and faster.

of the Coriolis effect is reduced (recall that rapidly moving objects are deflected more by the Coriolis effect than are slowly moving objects). Instead of blowing perpendicular to the isobars (in response to the pressure gradient) or parallel to them (where pressure gradient force and the Coriolis effect are in balance), the wind takes an intermediate course between the two and crosses the isobars at angles between 0° and 90° (Figure 5-6c). In essence, friction reduces wind speed, which in turn reduces the Coriolis effect deflection—thus, although the Coriolis effect does introduce a deflection to the right (in the Northern Hemisphere), the pressure gradient "wins the battle" and air flows into an area of low pressure and away from an area of high pressure.

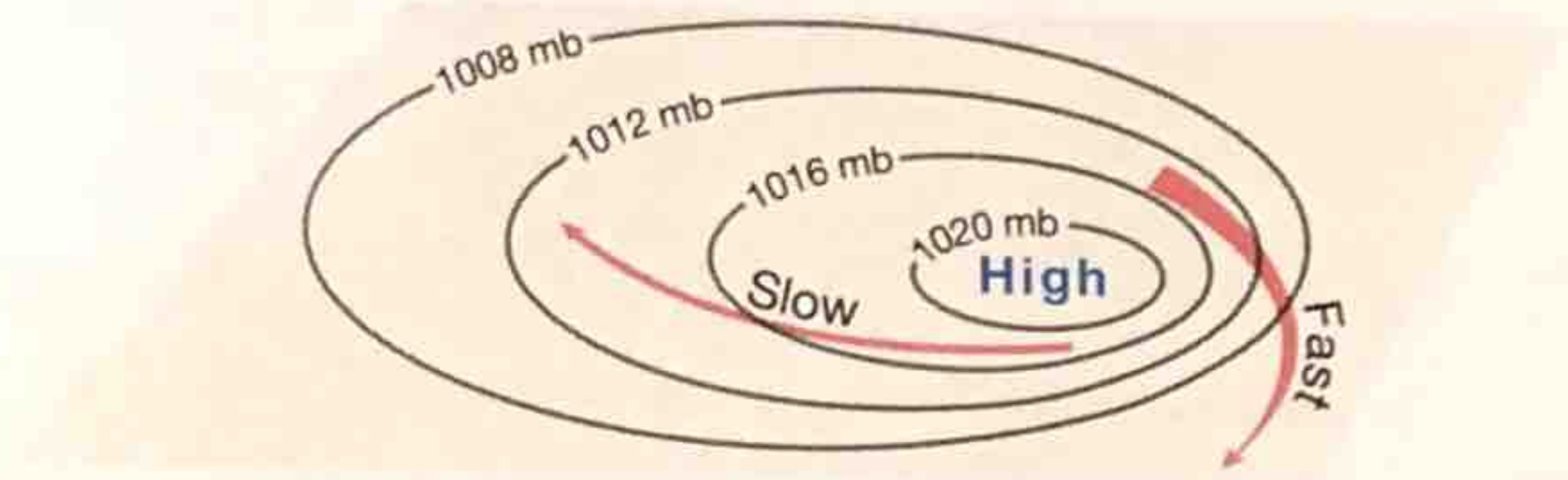
As a general rule, the frictional influence is greatest near Earth's surface and diminishes progressively upward (Figure 5-7). Thus, the angle of wind flow across the isobars is greatest (closest to 90°) at low altitudes and becomes smaller at increasing elevations. The **friction layer** of the atmosphere extends to only about 1000 meters (approximately 3300 feet) above the surface. Higher than that, most winds follow a geostrophic or near-geostrophic course.

**Learning Check 5-3** **How does friction influence the direction of wind flow?**

## Wind Speed

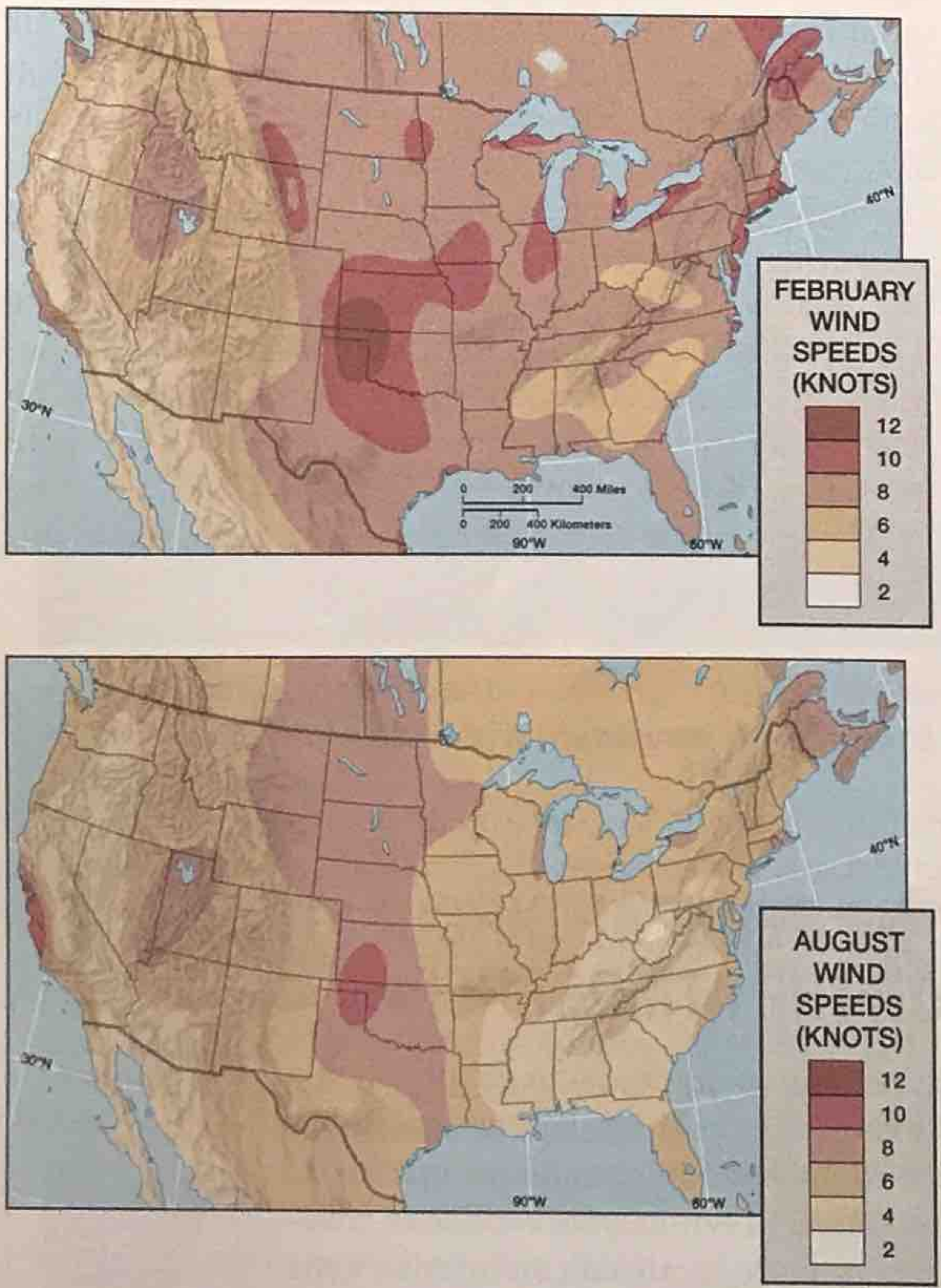
Thus far, we have been considering the direction of wind movement and paying little attention to speed. Although some complications are introduced by factors such as *inertia* (the tendency of an object to resist changes in its motion), it is accurate to say that the speed of wind flow is determined primarily by the pressure gradient. If the gradient is steep, the air accelerates swiftly; if the gradient is gentle, acceleration is slow. This relationship can be portrayed in the simple diagram of Figure 5-8. The closeness of the isobars indicates the steepness of the pressure gradient.

**Describing Wind Speed:** In meteorology, wind speed is frequently described in terms of *knots* (nautical miles per hour). Recall from Chapter 1 that a nautical mile is a bit longer than a "statute" mile, so one knot is equivalent to 1.15 statute miles per hour, or 1.85 kilometers per hour. You may have noticed that when speeds are given for ships and airplanes, knots is also the most common unit of measurement.



▲ **Figure 5-8** Wind speed is determined by the pressure gradient, which is indicated by the spacing of isobars. Where isobars are close together, the pressure gradient is "steep" and wind speed is high; where isobars are far apart, the pressure gradient is "gentle" and wind speed is low.

**Global Variations in Wind Speed:** Over most of the world most of the time, surface winds are relatively gentle. As Figure 5-9 shows, for instance, annual average wind speed in North America is generally between 6 and 12 knots. Cape Dennison in Antarctica holds the dubious distinction of being the windiest place on Earth, with an annual average wind speed of 38 knots. The most persistent winds are usually in coastal areas or high mountains. Locations with persistent winds are often suitable for facilities that generate electricity using wind power—see the box, "Energy for the 21st Century: Wind Power."



▲ **Figure 5-9** Average North American wind speeds in February and August. Wind speed tends to be higher in winter than in summer due to greater temperature contrasts and more frequent storms. The Great Plains tend to have the highest speed winds in all seasons; the strong summer winds in California result from heating in the interior Central Valley (such sea breezes are discussed later in this chapter).

Wind speed is quite variable from one altitude to another and from time to time, usually increasing with height. Winds tend to move faster above the friction layer. As we shall see in subsequent sections, the very strongest tropospheric winds are usually found at intermediate levels in what are called *jet streams* or in violent storms near Earth's surface.

## CYCLONES AND ANTICYCLONES

FG7

Animation
Cyclones and Anticyclones

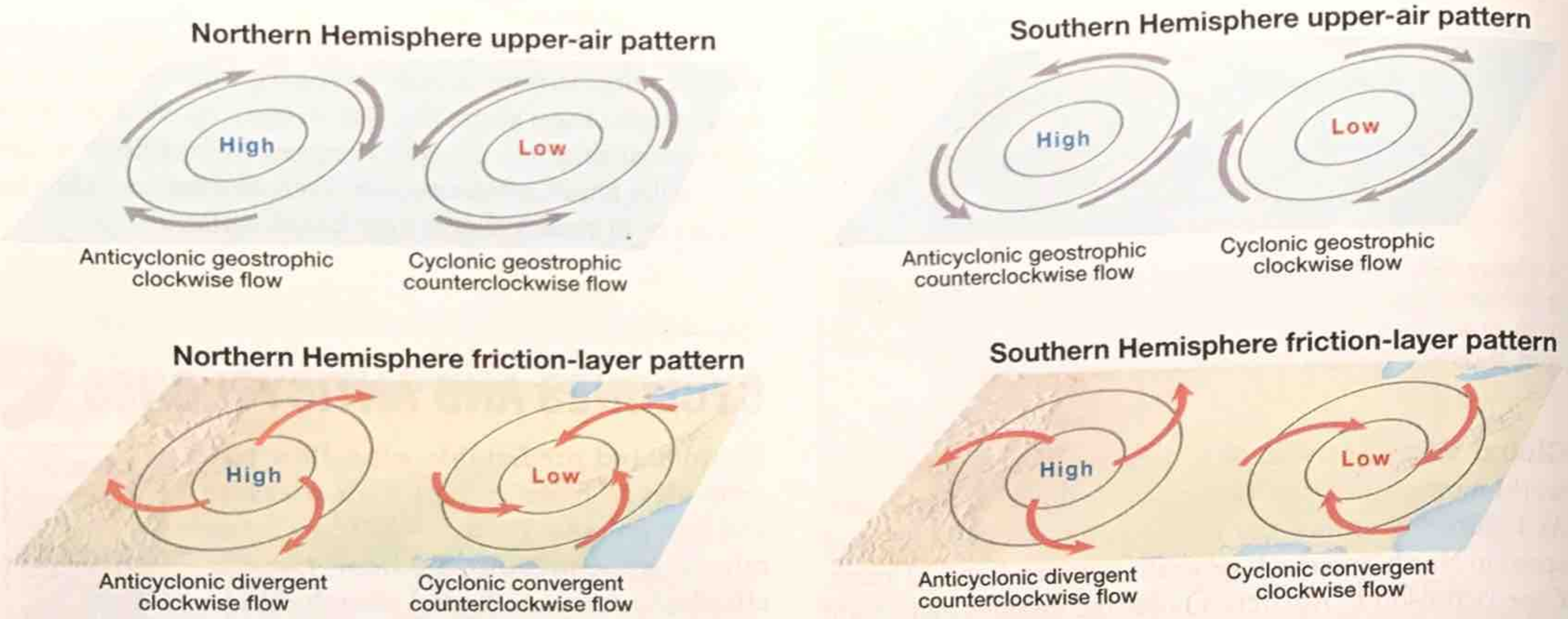
Distinct and predictable wind-flow patterns develop around all high-pressure and low-pressure centers—patterns determined by the pressure gradient, Coriolis effect, and friction. A total of eight circulation patterns are possible: four in the Northern Hemisphere and four in the Southern Hemisphere. Within each hemisphere, two patterns are associated with high-pressure centers and two patterns associated with low-pressure centers, as shown in Figure 5-10.

**High-Pressure Wind Patterns:** A high-pressure center is known as an **anticyclone**, and the flow of air associated with it is described as being *anticyclonic*. The four patterns of anticyclonic circulation are shown in Figure 5-10:

1. In the upper atmosphere of the Northern Hemisphere, the winds move clockwise in a geostrophic manner parallel to the isobars.
2. In the friction layer (lower altitudes) of the Northern Hemisphere, there is a divergent clockwise flow, with the air spiraling out away from the center of the anticyclone.
3. In the upper atmosphere of the Southern Hemisphere, there is a counterclockwise, geostrophic flow parallel to the isobars.
4. In the friction layer of the Southern Hemisphere, the pattern is a mirror image of the Northern Hemisphere, with air diverging in a counterclockwise pattern.

**Low-Pressure Wind Patterns:** Low-pressure centers are called **cyclones**, and the associated wind movement is said to be *cyclonic*. As with anticyclones, Northern Hemisphere cyclonic circulations are mirror images of their Southern Hemisphere counterparts:

5. In the upper atmosphere of the Northern Hemisphere, air moves counterclockwise in a geostrophic pattern parallel to the isobars.
6. In the friction layer of the Northern Hemisphere, a converging counterclockwise flow exists.
7. In the upper atmosphere of the Southern Hemisphere, a clockwise, geostrophic flow occurs paralleling the isobars.
8. In the friction layer of the Southern Hemisphere, the winds converge in a clockwise spiral.

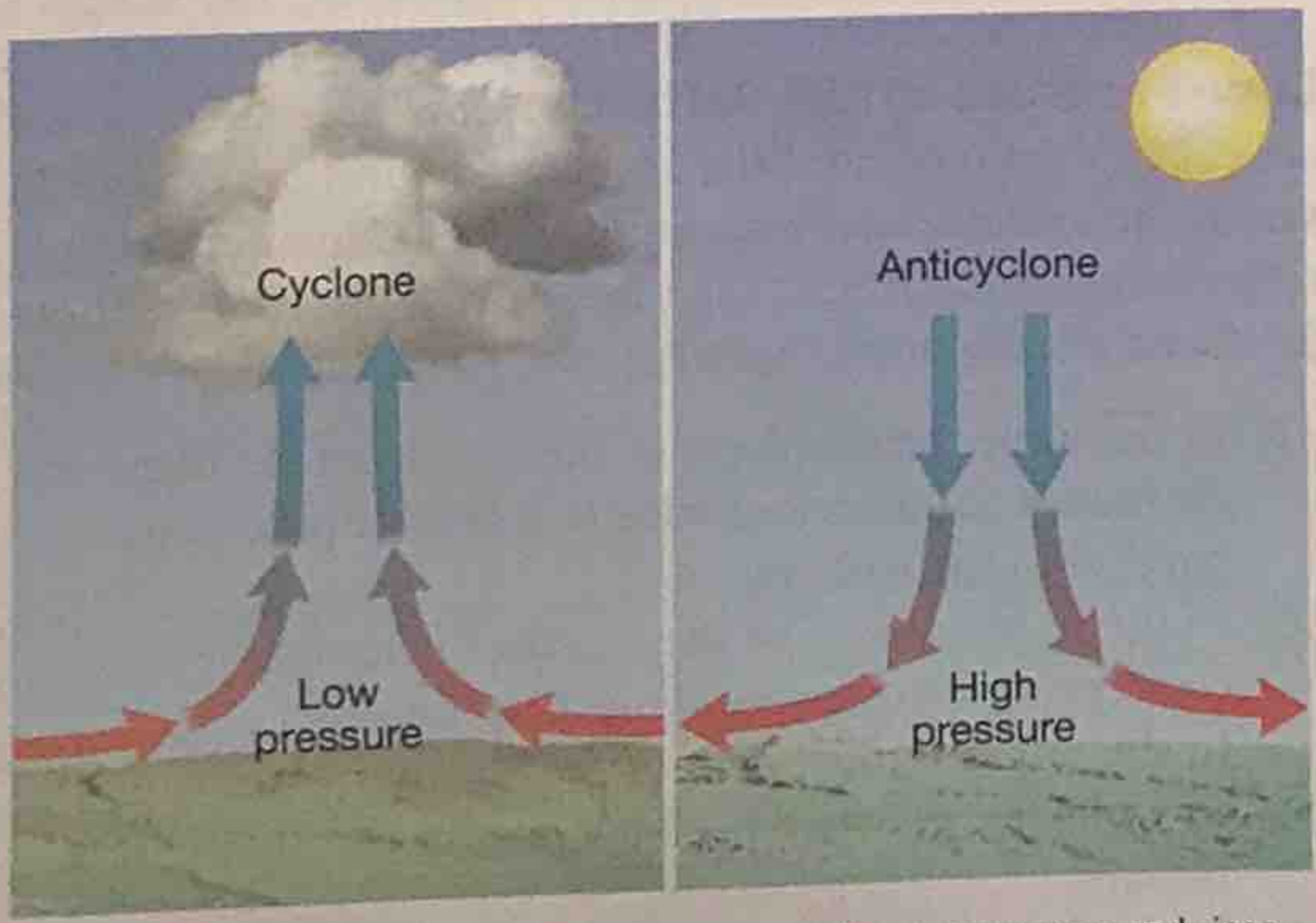


▲ **Figure 5-10** The eight basic patterns of air circulation around pressure cells in the upper atmosphere (above the friction layer) and in lower atmosphere of the Northern and Southern Hemispheres. Upper-atmosphere winds are geostrophic, blowing parallel to the isobars, whereas near the surface, wind diverges from highs and converges into lows.

Cyclonic patterns in the lower troposphere may at first glance appear to be puzzling because the arrows seem to defy the Coriolis effect: in the Northern Hemisphere, the arrows seem to "bend" to the left, whereas we know that the Coriolis deflection is to the right. Remember, however, that wind patterns are the balance of several different forces acting in different directions: as air begins to flow down the pressure gradient into a low, the Coriolis effect does indeed deflect wind to the right—and this introduces the counterclockwise flow in the Northern Hemisphere (see Figure 5-6c).

**Learning Check 5-4** **What is the pattern of wind circulation associated with a surface *cyclone* in the Northern Hemisphere?**

**Vertical Movement within Cyclones and Anticyclones:** A prominent vertical component of air movement is also associated with cyclones and anticyclones. As Figure 5-11 shows, air descends in anticyclones and rises in cyclones. Such motions are particularly notable in the lower troposphere. The anticyclonic pattern can be visualized as upper air sinking down into the center of the high and then diverging near the ground surface. Opposite conditions prevail in a low-pressure center, with the air converging horizontally into the cyclone and then rising. Note that these patterns match our earlier generalizations about pressure: descending air is associated with high pressure at the surface and that rising air is associated with low pressure at the surface.



▲ **Figure 5-11** In a cyclone (low-pressure cell), air converges and rises. In an anticyclone (high-pressure cell), air descends and diverges.

Notice in Figure 5-11 that cyclones and rising air are associated with clouds, whereas anticyclones and descending air are associated with clear conditions—the reasons for this will be explained in Chapter 6. Note also that well-developed cyclones and anticyclones often "lean" with height, which is to say that they are not absolutely vertical in orientation.

**Learning Check 5-5** **Describe the direction of vertical air movement within an *anticyclone*.**

## THE GENERAL CIRCULATION OF THE ATMOSPHERE

Earth's atmosphere is an extraordinarily dynamic medium. It is constantly in motion, responding to the various forces described previously as well as to a variety of more localized conditions. Some atmospheric motions are broadscale and sweeping; others are minute and momentary. Most important to an understanding of geography is the general pattern of circulation, which involves major semipermanent conditions of both

Animation
Global Atmospheric Circulation

## ENERGY FOR THE 21ST CENTURY

# Wind Power

▸ Stephen Stadler, Oklahoma State University

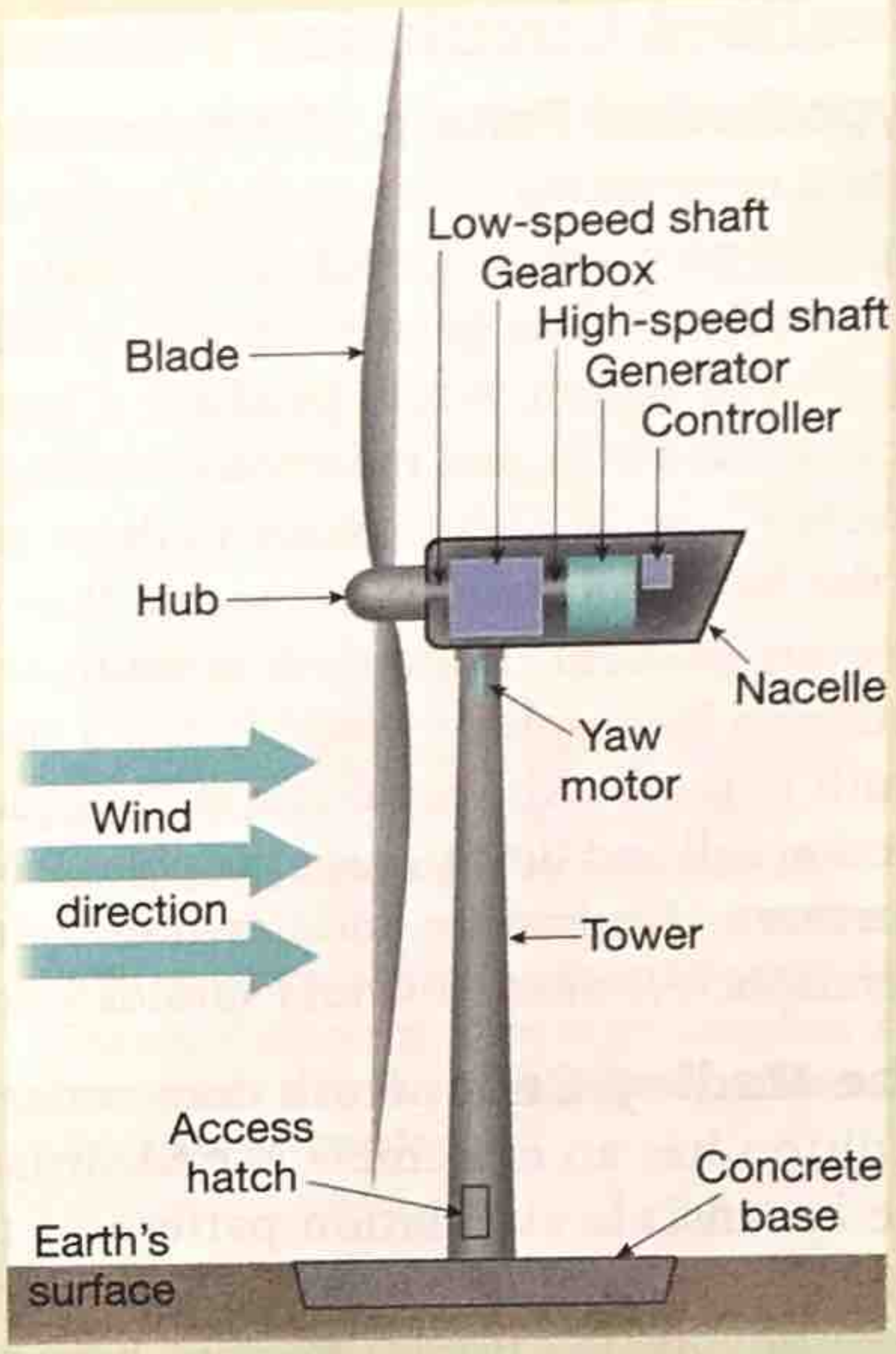
Wind has been used as a mechanical power source for thousands of years. Ships have used sails for at least 6000 years and wind-powered mills have ground grain and pumped water for more than a millennium. Wind has generated electricity since 1888, but it was in the latter part of the twentieth century that it became a significant power source.

Rather than being an energy fad, wind is the world's fastest-growing source of electrical power generation because of long-term concerns with the supply of fossil fuels and their environmental consequences (Figure 5-A). Wind power generates more than 3 percent of the world's electricity, and that amount is expected to increase significantly in the coming decades.

▲ **Figure 5-A** Wind turbines at the port of Copenhagen, Denmark. The Danes now generate more than 20 percent of their electricity from wind and are aiming at 50 percent by 2025.

**Wind Geography:** In wind power generation, it can be said that geography is everything. Physical geography is directly relevant because windier climates can help turbines generate more electricity. The most advantageous turbine placements are on high ground away from trees and other obstructions. This increases wind velocity by minimizing friction with Earth's surface. Human geography also plays a large role in the siting of turbines. Some windy places are not exploited because of distance from significant populations. Where electrical power from fossil fuels is expensive, wind turbines can be cost-competitive even in areas of moderate winds. Some windy places have little installed wind power because there are other, inexpensive sources of energy such as hydropower.

**Wind Turbines:** Today's utility-scale turbines are massive machines costing millions of dollars per unit. Figure 5-B illustrates the major parts of a large turbine. Turbines are placed on tall towers because wind availability increases dramatically with elevation above the surface. A large turbine has three blades mounted 50 meters (164 feet) or more from the surface. The blades may be more than 35 meters (115 feet) long and are made from light but strong carbon-fiber composites. The blades turn 12 to 15 revolutions per minute (rpm) and power a low-speed shaft attached to the hub. In a gearbox, low rpms are converted to high rpms on a shaft turning an electrical turbine. Most turbines in the United States commonly generate over 1.5 megawatts, enough to power a couple of thousand homes. Typically, the electricity from large turbines goes directly to the power grid—battery storage is very expensive.



▲ **Figure 5-B** Schematic of modern wind turbine with distance between blade tip and ground not to scale. (After Michael Larson, Oklahoma State University Cartography Service.)

**Advantages of Wind Power:** Electricity from wind power has some notable advantages. First, "fuel" is the wind and is always free. Second, wind power has no "carbon footprint" because no fuel is burned. Third, wind power is now economically competitive with fossil fuel costs at windy sites. Fourth, wind generation holds much promise for the developing world where smaller turbines can serve rural populations not well-connected to regional power transmission grids.

**Disadvantages of Wind Power:** Wind power's biggest drawback is that wind is not constant, even in the windiest areas. If an uninterrupted power supply is necessary, then wind generation must be mixed with other power sources. The windiest places (such as the Great Plains of the United States and Canada) are seldom densely populated, so wind-generated electricity must sometimes be transported over long distances to population centers via expensive transmission lines. It is possible that the blades are a hazard to birds or bats, although the towering heights of modern turbines and the ready visibility of the large blades has minimized this problem. Finally, there is an aesthetic perspective: although the machines appear graceful and useful to some, they are noisy and ugly to others.

wind and pressure. This circulation is the principal mechanism for both latitudinal and longitudinal heat transfer and is exceeded only by the global pattern of insolation as a control of world climate patterns.

## Idealized Circulation Patterns

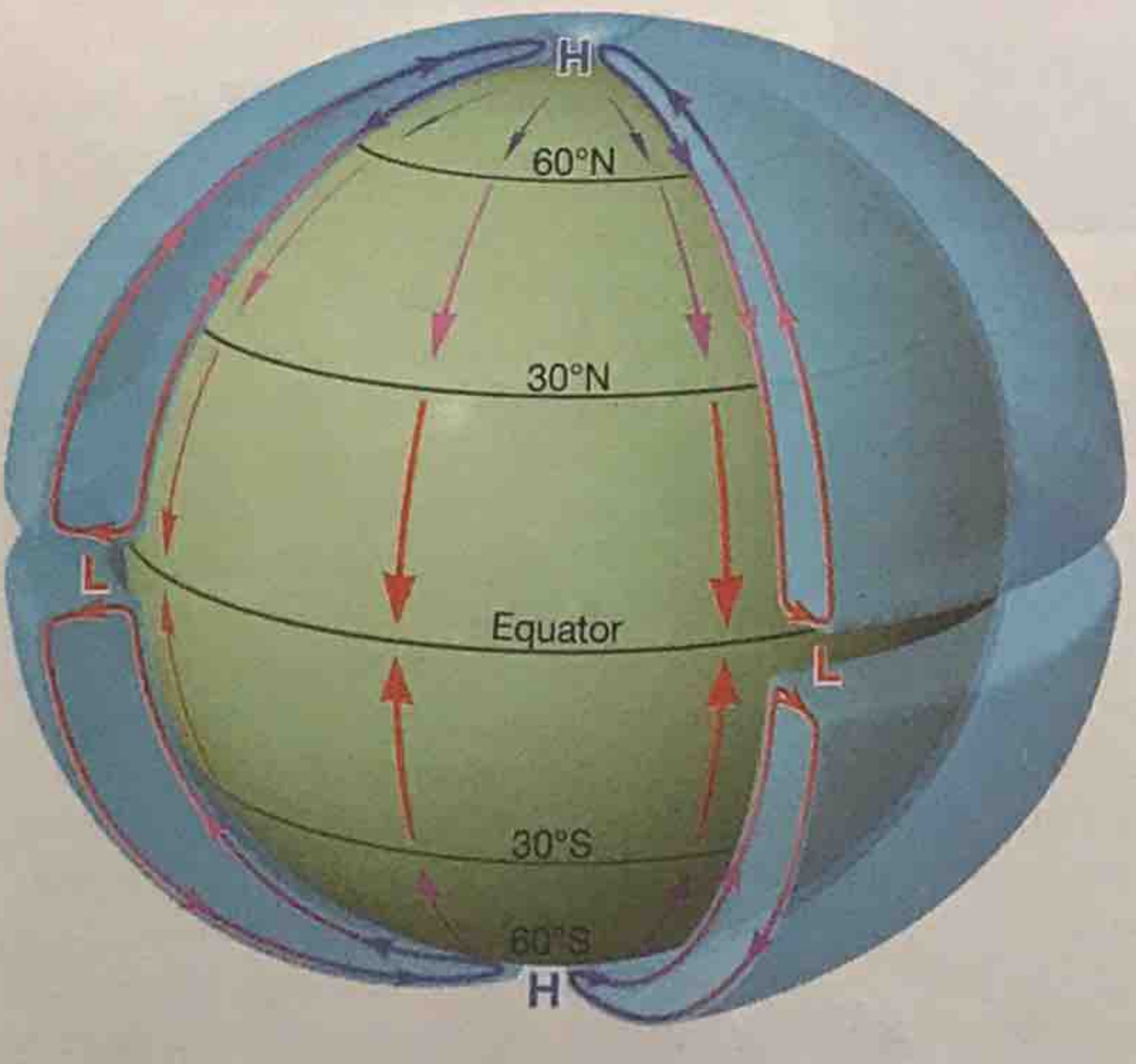
**Hypothetical Pattern of Nonrotating Earth:** If Earth were a nonrotating sphere with a uniform surface, we could expect a very simple global atmospheric circulation pattern (Figure 5-12). The greater amount of solar warming in the equatorial region would produce a band of low pressure around the world, and radiational cooling at the poles would develop a cap of high pressure in those areas. Surface winds in the Northern Hemisphere would flow directly "down the pressure gradient" from north to south, whereas those in the Southern Hemisphere would follow a similar gradient from south to north. Air would rise at the equator in a large convection cell and flow toward the poles (south to north in the Northern Hemisphere and north to south in the Southern Hemisphere), where it would subside into the polar highs.

**The Hadley Cells:** Earth does rotate, however, and in addition has an extremely varied surface. Consequently, the broadscale circulation pattern of the atmosphere is much more complex than that shown in Figure 5-12. Apparently only the tropical regions have a complete vertical convective circulation cell. Similar cells have been postulated for the middle and high latitudes, but observations indicate that the midlatitude and high-latitude cells either do not exist or are weakly and sporadically developed.

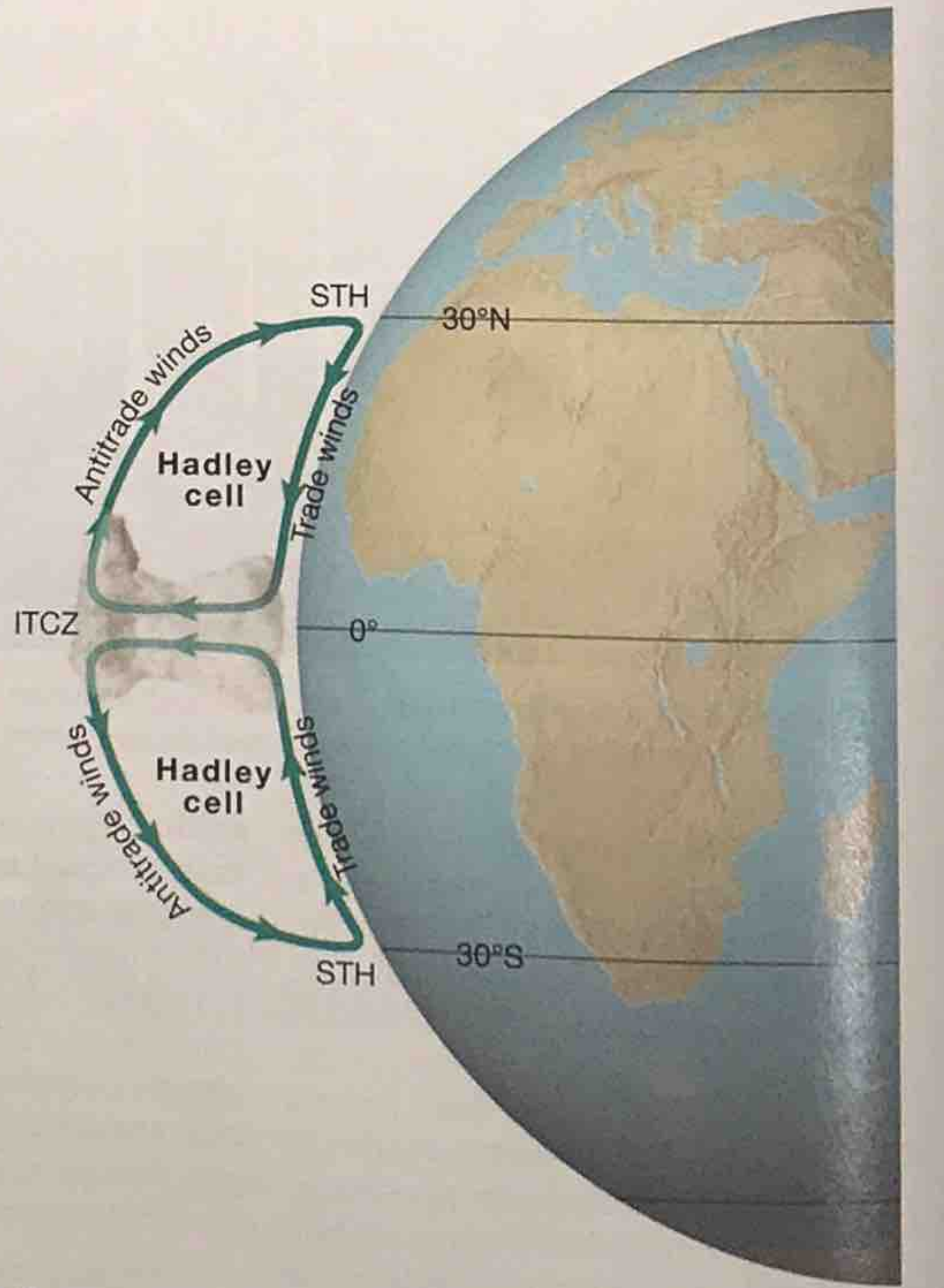
The low-latitude cells—one north and one south of the equator—are gigantic convection systems (Figure 5-13). These two prominent tropical convection cells are called **Hadley cells**, after George Hadley (1685–1768), an English meteorologist who first conceived the idea of enormous convective circulation cells in 1735.

Around the world in equatorial latitudes, warm air rises, producing a region of relative low pressure at the surface. This air ascends to great heights, mostly in thunderstorm updrafts. By the time this air reaches the upper troposphere at elevations of about 15 kilometers (50,000 feet), it has cooled. The air then spreads north and south and moves poleward, eventually descending at latitudes of about 30° N and S, where it forms bands of high pressure at the surface (Figure 5-14). One portion of the air diverging from these surface high-pressure zones flows toward the poles, whereas another portion flows back toward the equator—where the Northern and Southern Hemisphere components converge and the warm air rises again.

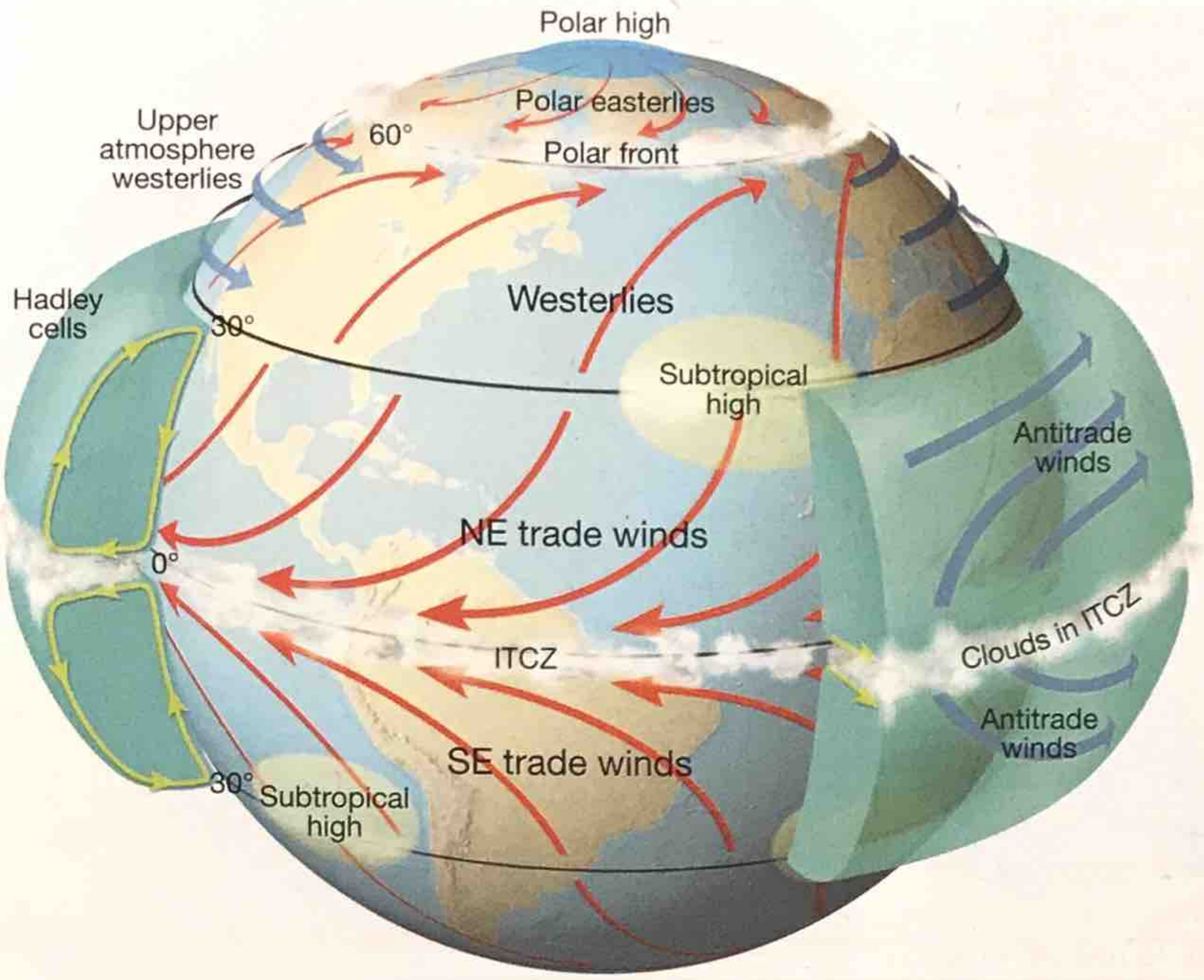
**Learning Check 5-6 Describe the pattern of air movement within the *Hadley* cells.**



▲ **Figure 5-12** Wind circulation patterns would be simple if Earth's surface were uniform (no distinction between continents and oceans) and if the planet did not rotate. High pressure at the poles and low pressure at the equator would produce northerly surface winds in the Northern Hemisphere and southerly surface winds in the Southern Hemisphere.



▲ **Figure 5-13** Distinct cells of vertical circulation occur in tropical latitudes; they are called Hadley cells. The equatorial air rises to some 12 to 15 kilometers (40,000 to 50,000 feet) in the intertropical convergence zone (ITCZ) before spreading poleward. This air descends at about 30° N and S into subtropical high-pressure (STH) cells. The vertical dimension of the Hadley cells is considerably exaggerated in this idealized diagram.



◀ **Figure 5-14** Idealized global circulation. Rising air of the ITCZ in the Hadley cell is deflected aloft and forms westerly antitrade winds, while surface winds diverging from the STH form easterly trade winds and the westerlies. The upper atmosphere flow of the westerlies is shown with faint blue arrows. (Vertical dimension exaggerated considerably.)

## Seven Components of the General Circulation

Although the Hadley cell model is a simplification of reality, it is a useful starting point for understanding the main components of the general circulation of the atmosphere. The basic pattern has seven surface components of pressure and wind, intimately linked together. The Northern Hemisphere and Southern Hemisphere patterns are mirror images of each other. From the equator to the poles, the seven components are

1. Intertropical convergence zone (ITCZ)
2. Trade winds
3. Subtropical highs
4. Westerlies
5. Polar front (Subpolar lows)
6. Polar easterlies
7. Polar highs

The pattern general circulation within the troposphere is essentially a closed system, with neither a beginning nor an end, and so we could begin describing it almost anywhere. Rather than start at the equator or the poles, however, it is helpful to begin our discussion of the general circulation in the subtropical latitudes of the five major ocean basins—where the descending air of the Hadley cells becomes the "source" of the major surface winds of the planet.

## Subtropical Highs

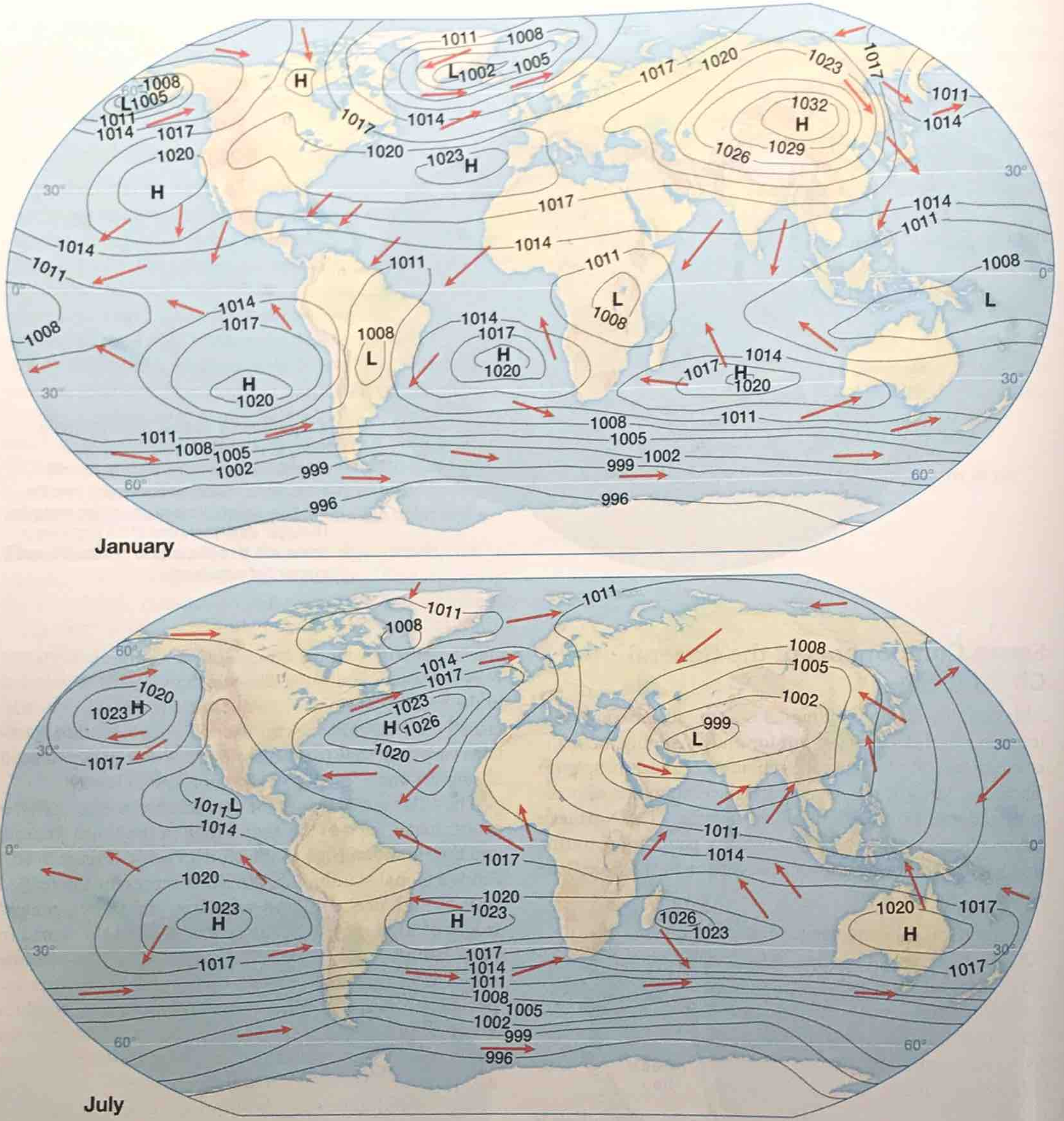
Each ocean basin has a large semipermanent high-pressure cell centered at about 30° of latitude called a **subtropical high (STH)** (Figure 5-15). These gigantic anticyclones, with an average diameter of perhaps 3200 kilometers (2000 miles), develop from the descending air of the Hadley cells. They are usually elongated east–west and tend to be centered in the eastern portions of an ocean basin (in other words, just off the west coasts of continents). Their latitudinal positions vary from time to time, shifting a few degrees poleward in summer and a few degrees equatorward in winter.

The STHs are so persistent that some have been given a proper name, such as the *Azores High* in the North Atlantic and the *Hawaiian High* in the North Pacific (Figure 5-16). From a global standpoint, the STHs represent intensified cells of high pressure (and subsiding air) in two general ridges of high pressure that extend around the world in these latitudes, one in each hemisphere. The high-pressure ridges are significantly broken up over the continents, especially in summer when inland temperatures produce lower air pressure, but the STHs normally persist over the ocean basins throughout the year because temperatures and pressures there remain nearly constant.

Associated with these high-pressure cells is a general subsidence of air from higher altitudes in the form of a broadscale, gentle downdraft. A permanent feature of the STHs is a subsidence temperature inversion that covers wide areas in the subtropics.

**Weather of the Subtropical Highs:** Within an STH, the weather is nearly always clear, warm, and calm. We shall see in the next chapter that subsiding air is not conducive to the development of clouds or the production of rain. Instead, these areas are characterized by warm, subtropical sunshine. Thus, it comes as no surprise that these anticyclonic, subsiding-air regions coincide with many of the world's major deserts.

Subtropical highs are also characterized by an absence of wind: in the center of an STH air is primarily subsiding;

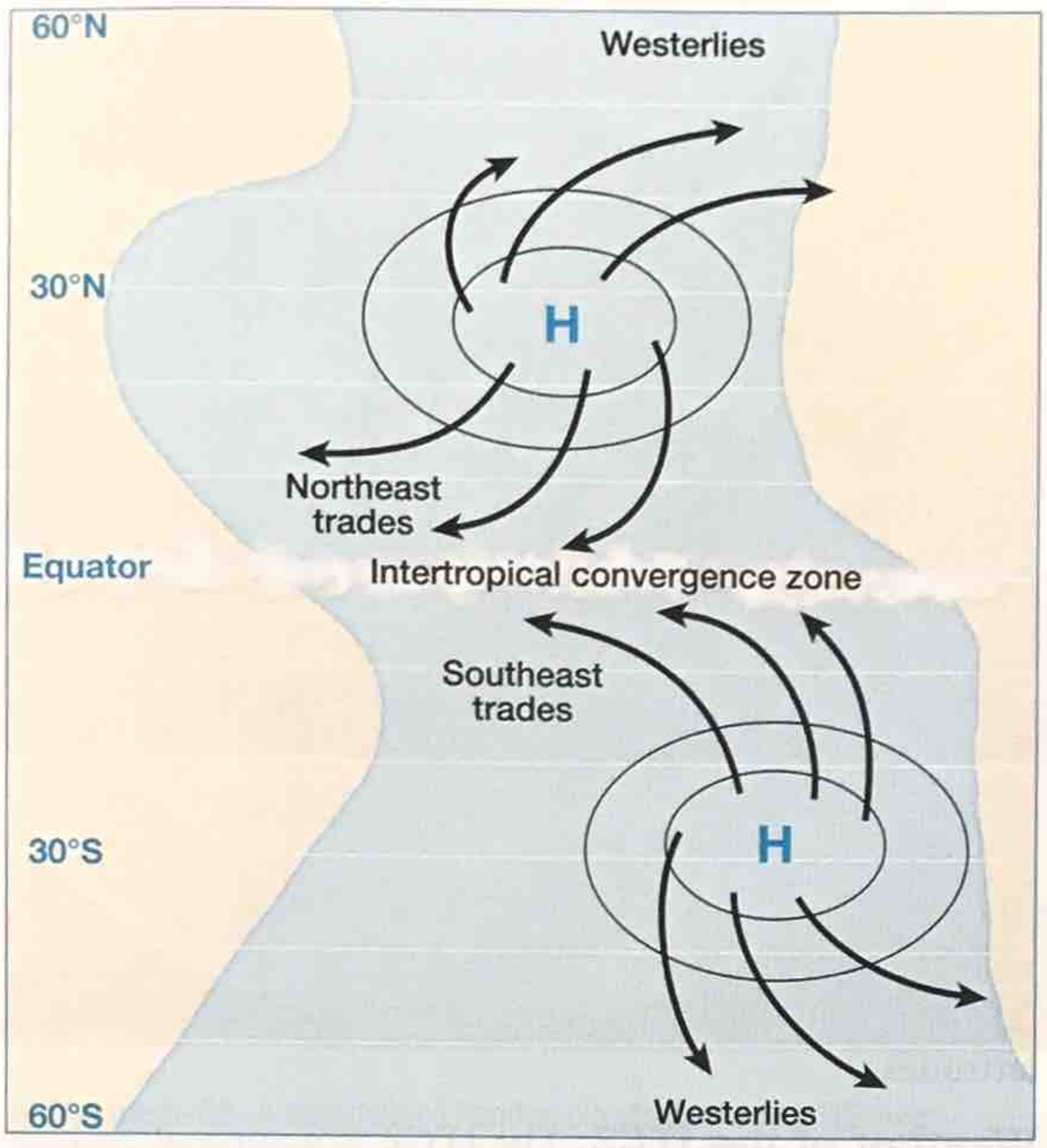


▲ **Figure 5-15** Average atmospheric pressure and wind direction in January and July. Pressure is reduced to sea-level values and shown in millibars. Arrows indicate generalized surface wind movements.

horizontal air movement and divergence begin toward the edges. These regions are sometimes called the **horse latitudes**, presumably because sixteenth- and seventeenth-century sailing ships were sometimes becalmed there and their cargos of horses were thrown overboard to conserve drinking water.

The air circulation pattern around an STH is anticyclonic: diverging clockwise in the Northern Hemisphere

▶ **Figure 5-16** The subtropical highs are generally located over ocean basins at latitudes of about 30° N and S; also called the horse latitudes.



▲ **Figure 5-17** The air that descends and diverges out of the subtropical highs is the source of the surface trade winds and westerlies. This map shows the generalized location of the intertropical convergence zone, trade winds, subtropical highs, and westerlies in hypothetical Northern and Southern Hemisphere ocean basins.

and counterclockwise in the Southern Hemisphere. In essence, the STHs can be thought of as gigantic "wind wheels" whirling in the lower troposphere, fed with air sinking down from above and spinning off winds horizontally in all directions (Figure 5-17). The winds are not dispersed uniformly around an STH, however; instead, they are concentrated on the northern and southern sides.

Although the global flow of air is essentially a closed circulation from a viewpoint at Earth's surface, the STHs can be thought of as the source of two of the world's three major surface wind systems: the *trade winds* and the *westerlies*.

**Learning Check 5-7 Describe the general locations and the kind of weather associated with the *subtropical highs*.**

## Trade Winds

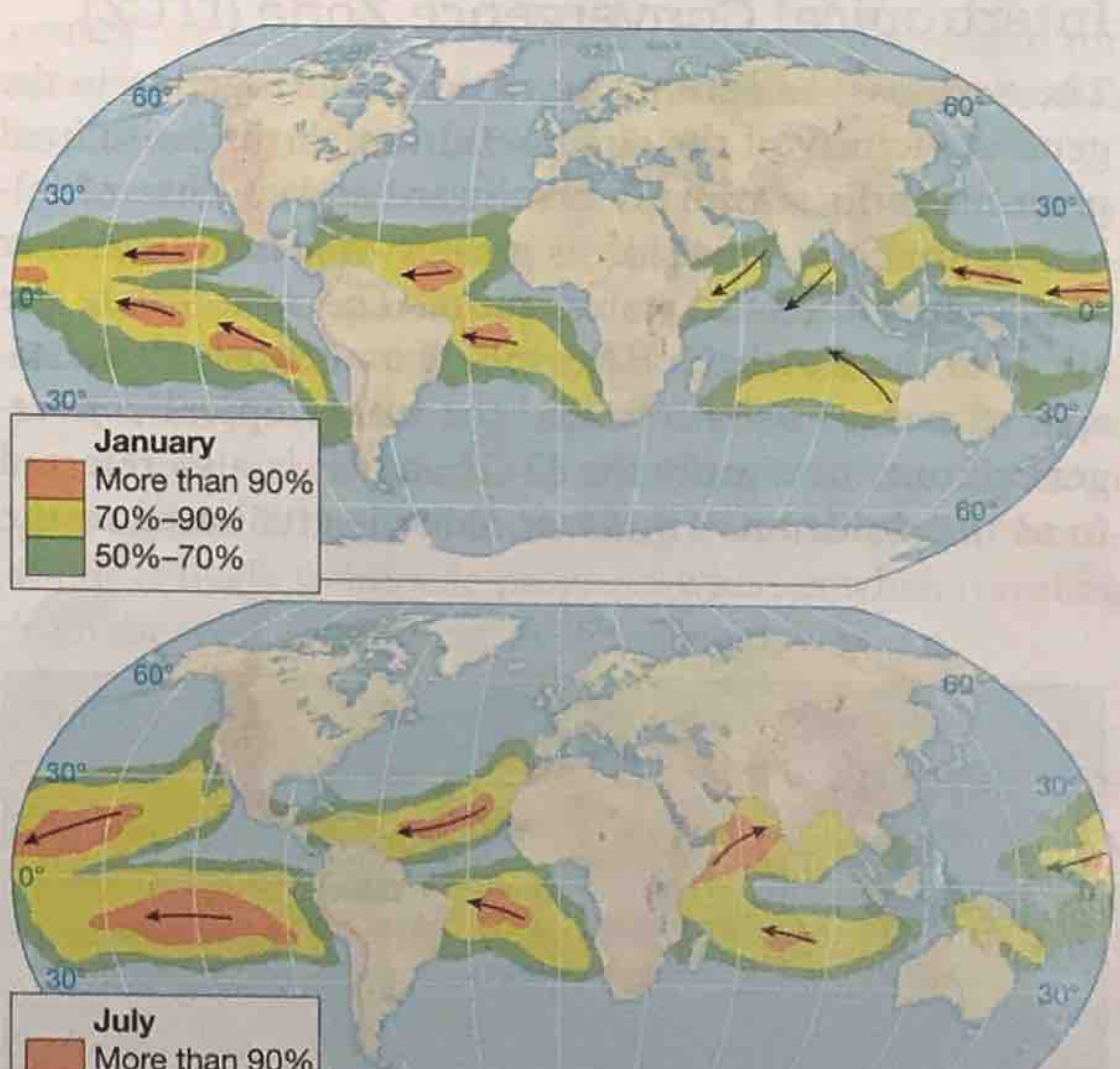
Diverging from the equatorward sides of the subtropical highs is the major wind system of the tropics—the trade winds. These winds cover most of Earth between about latitude 25° N and latitude 25° S (see Figure 5-17). They are particularly prominent over oceans but tend to be significantly interrupted and modified over landmasses. Because of the vastness of Earth in tropical latitudes and because most of this expanse is oceanic, the trade winds dominate more of the globe than any other wind system.

The trade winds are predominantly "easterly" winds—that is, they generally blow from east to west. In meteorology winds are named for the direction *from which they blow*: an easterly wind blows from east to west, a westerly wind blows from the west, and so forth.

In the Northern Hemisphere, the trade winds usually blow from the northeast (and are sometimes called the *northeast trades*); south of the equator, they are from the southeast (the *southeast trades*). There are exceptions to this general pattern, especially over the Indian Ocean, where westerly winds sometimes prevail, but for the most part the flow is easterly over the tropical oceans.

**Consistency of Trade Winds:** The trade winds are by far the most "reliable" of all winds. They are extremely consistent in both direction and speed, as Figure 5-18 shows. They blow most of the time in the same direction at the same speed, day and night, summer and winter (Figure 5-19). This steadiness is reflected in their name: trade winds really means "winds of commerce." Mariners of the sixteenth century recognized early that the quickest and most reliable route for their sailing vessels from Europe to the Americas lay in the belt of northeasterly winds of the southern part of the North Atlantic Ocean. Similarly, the trade winds were used by Spanish galleons in the Pacific Ocean, and the name became applied generally to these tropical easterly winds.

The trades originate as warming, drying winds capable of holding an enormous amount of moisture. As they blow across the tropical oceans, they evaporate vast quantities of moisture and therefore have a tremendous potential for storminess and precipitation. They do



▲ **Figure 5-18** The trade winds are the most consistent of the major wind systems. These maps show their frequency of consistency for the midseason months of January and July. In the orange areas, for instance, the wind blows in the indicated direction more than 90 percent of the time. Note the monsoon wind reversal in southern Asia during July (discussed later in this chapter).

▶ **Figure 5-19** Tropical coastal areas often experience the ceaseless movement of the trade winds. This breezy scene is at Cairns on the northeastern coast of Queensland, Australia.

not release the moisture, however, unless forced to do so by being uplifted by a topographic barrier or some sort of pressure disturbance (the reasons for this will be explained in Chapter 6). Low-lying islands in the trade-wind zone are often desert islands because the moisture-laden winds pass over them without dropping any rain. If there is even a slight topographic irregularity, however, the air that is forced to rise may release abundant precipitation (Figure 5-20). Some of the wettest places in the world are windward slopes in the trade winds, such as in Hawai'i (see Figure 3-21).

## Intertropical Convergence Zone (ITCZ)

The northeast and southeast trades come together in the general vicinity of the equator, although the latitudinal position shifts seasonally northward and southward following the Sun. This shift is greater over land than over sea because the land warms more. The zone where the air from the Northern Hemisphere and Southern Hemisphere meet is usually called the **intertropical convergence zone**, or simply the ITCZ, but it is also referred to as the **doldrums** (this last name is attributed to the fact that sailing ships were often becalmed in these latitudes).

**Weather of the ITCZ:** The ITCZ is a zone of convergence and weak horizontal airflow characterized by feeble and erratic winds. It is a globe-girdling zone of warm surface conditions, low pressure associated with high rainfall, instability, and rising air in the Hadley cells (see Figure 5-14). It is not a region of continuously ascending air, however. Almost all the rising air of the tropics ascends in the updrafts that occur in thunderstorms in the ITCZ, and these updrafts pump an enormous amount of sensible heat and latent heat of condensation into the upper troposphere, where much of it spreads poleward.

The ITCZ often appears as a well-defined, relatively narrow cloud band over the oceans near the equator (Figure 5-21). Over continents, however, it is likely to be more diffused and indistinct, although thunderstorm activity is common.

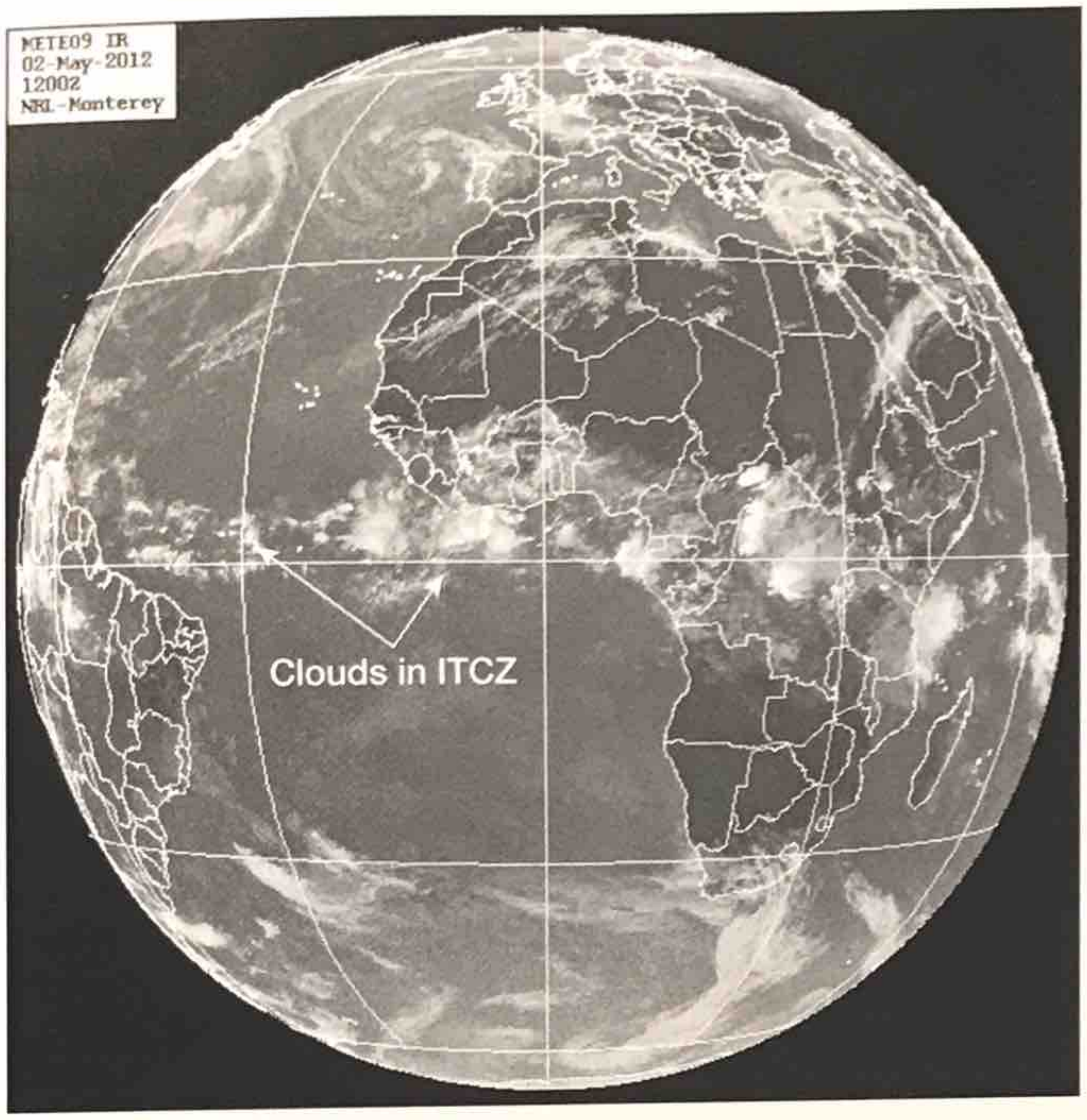
**Learning Check 5-8** **Describe the general location and kind of weather associated with the ITCZ.**

▲ **Figure 5-20** Trade winds are usually heavily laden with moisture, but usually do not produce clouds and rain unless forced to rise. Thus, they may blow across a low-lying island with little or no visible effect. An island of greater elevation, however, causes the air to rise up the side of the mountain, and the result is usually a heavy rain.

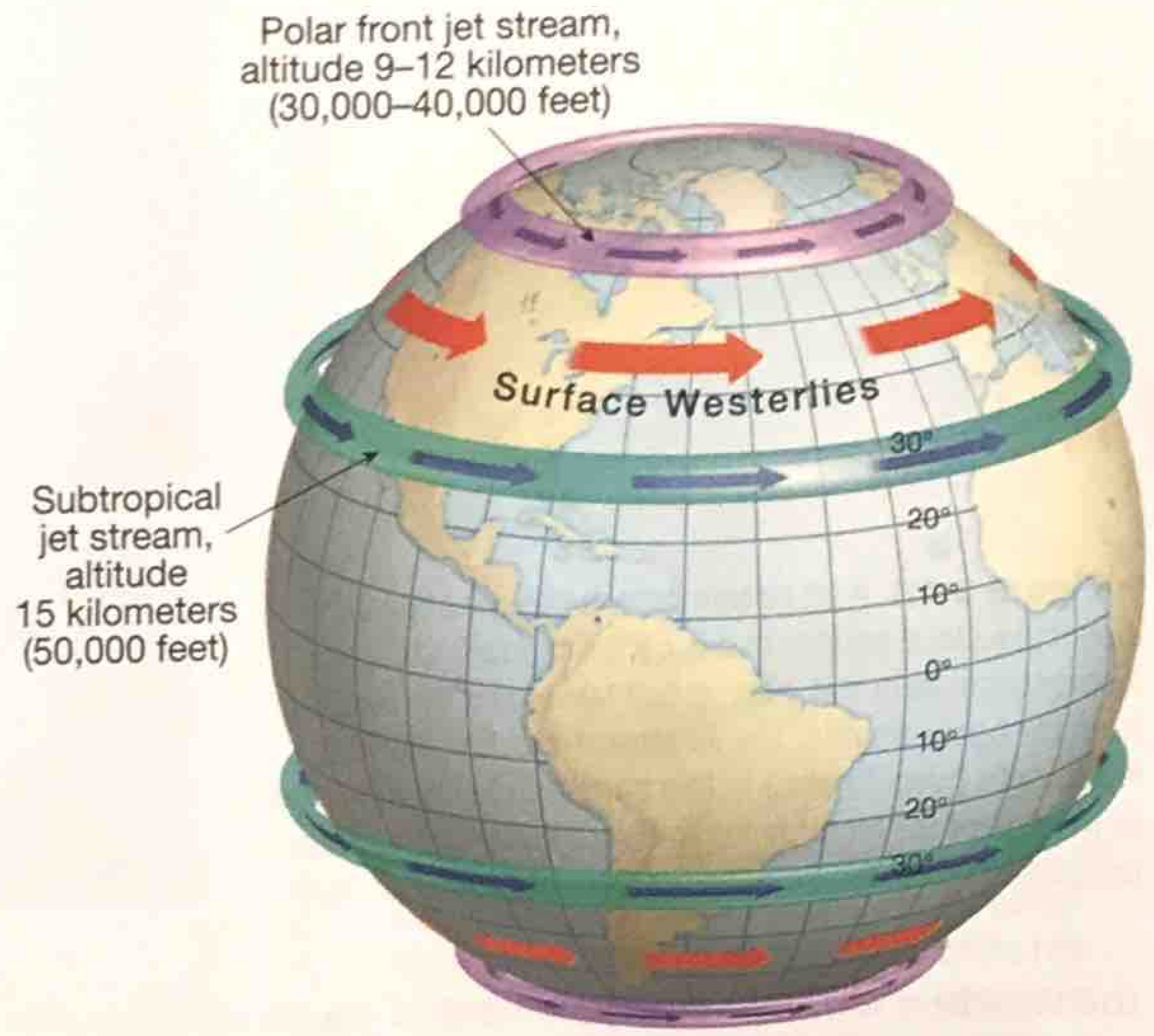
## The Westerlies

Animation
The Jet Stream and Rossby Waves

The fourth component of the general atmospheric circulation is the great wind system of the midlatitudes, commonly called the westerlies, represented by the arrows that issue from the poleward sides of the STHs in Figure 5-17. These winds flow basically from west to east around the world in the latitudinal zone between about 30° and 60° both north and south of the equator. Because the circumference of Earth is smaller at these latitudes than in the tropics, the westerlies are less extensive than the trades; nevertheless, they cover much of Earth.



▲ **Figure 5-21** A well-defined band of clouds marks the ITCZ over equatorial Africa in this infrared satellite image (darker shades of gray indicate warmer surface temperatures). This image was taken during the Northern Hemisphere summer, so the ITCZ has shifted slightly north of the equator. Note the generally clear skies off the west coasts of northern and southern Africa, corresponding to the areas of the subtropical highs, and the cloudiness and storms in the band of westerlies in the midlatitudes.



▲ **Figure 5-22** Neither jet stream is centered in the band of the westerlies. The polar front jet stream is closer to the poleward boundary, and the subtropical jet stream is closer to the equatorward boundary of this wind system. The two jet streams are not at the same altitude; the subtropical jet stream is at a higher altitude than the polar front jet stream.

The surface westerlies are much less constant and persistent than the trades, which is to say that in the midlatitudes surface winds do not always flow from the west but may come from almost any point of the compass. Near the surface there are interruptions and modifications of the westerly flow, which can be likened to eddies and countercurrents in a river. These interruptions are caused by surface friction, by topographic barriers, and especially by migratory pressure systems, which produce airflow that is not westerly.

**Learning Check 5-9** **What is the relationship of the subtropical highs to the *trade winds* and the *westerlies*?**

**Jet Streams:** Although the surface westerlies are somewhat variable, the geostrophic winds aloft, however, blow very prominently from the west. Moreover, there are two remarkable "cores" of high-speed winds in each hemisphere called **jet streams**: one called the *polar front jet stream* (or simply the *polar jet stream*) and the other called the *subtropical jet stream*, at high altitudes in the westerlies (Figure 5-22). The belt of the westerlies can therefore be thought of as a meandering river of air moving generally from west to east around the world in the midlatitudes, with the jet streams as its fast-moving cores.

The polar front jet stream, which usually occupies a position 9 to 12 kilometers (30,000 to 40,000 feet) high, is not centered in the band of the westerlies; it is displaced poleward, as Figure 5-22 shows (the name comes from its location near the polar front). This jet stream is a feature of the upper troposphere located over the area of greatest horizontal temperature gradient—that is, cold just poleward and warm just equatorward.

A jet stream is not always the sharply defined narrow ribbon of wind, as often portrayed on weather maps; rather it is a zone of strong winds within the upper troposphere westerly flow. Jet stream speed is variable. Sixty knots is generally considered as the minimum speed required for recognition as a jet stream, but wind speeds five times that fast have been recorded (Figure 5-23).

Commercial air travel can be significantly influenced by the high-speed flow of upper tropospheric winds. The cruising altitude of commercial jetliners is usually 9 to 12 kilometers (30,000 to 40,000 feet)—a typical elevation for the polar front jet stream. It generally takes longer to fly from east to west across North America than it does to fly from west to east. When one is traveling from the east, a "headwind" is likely to impede progress, whereas when traveling from the west, a "tailwind" may reduce travel time.

**Rossby Waves:** The polar front jet stream shifts its latitudinal position with some frequency, and this change has considerable influence on the path of the westerlies. Although the basic direction of movement is west to east, frequently sweeping undulations develop in the westerlies and produce a meandering jet stream path that wanders widely north and south (Figure 5-24). These curves are very large and are generally referred to as *long waves* or **Rossby waves** (after the Chicago meteorologist C. G. Rossby, who first explained their nature).

At any given time, there are usually from three to six Rossby waves in the westerlies of each hemisphere. These waves can be thought of as separating cold polar air from warmer tropical air. When the polar front jet stream path is more directly west–east, there is a *zonal flow* pattern in

**Figure 5-23** A jet stream sometimes generates a distinctive cloud pattern that is conspicuous evidence of its presence, as in this photograph taken over the Red Sea from the space shuttle. The jet stream was flowing from left to right (west to east) in this photograph. Equatorward of the axis of the jet air tends to rise, a condition that can produce thin clouds. Poleward of the axis, the air is clear.

the weather, with cold air poleward of warm air. However, when the jet stream begins to oscillate and the Rossby waves develop significant amplitude (which means a prominent north–south component of movement) there is a *meridional flow*: cold air is brought equatorward and warm air moves poleward, bringing frequent and severe weather changes to the midlatitudes.

The subtropical jet stream is usually located at high altitudes—just below the tropopause, as Figure 5-25a shows—over the poleward margin of the subsiding air of the STH. It has less influence on surface weather patterns because there is less temperature contrast in the associated air streams. Sometimes, however, the polar front jet and the subtropical jet merge, as shown in Figure 5-25b, to produce a broad belt of high-speed winds in the upper troposphere—a condition that can intensify the weather conditions associated with either zonal or meridional flow of the Rossby waves.

All things considered, no other portion of Earth experiences such short-run variability of weather as the midlatitudes.

**Learning Check 5-10 What are *jet streams* and where they are usually found?**

## Polar Highs

Situated over both polar regions are high-pressure cells called **polar highs** (see Figure 5-14). The Antarctic high, which forms over an extensive, high-elevation, very cold continent, is strong, persistent, and almost a permanent feature above the Antarctic continent. The Arctic high is much less pronounced and more transitory, particularly in winter. It tends to form over northern continental areas rather than over the Arctic Ocean. Air movement associated with these cells is typically anticyclonic. Air from above sinks down into the high and diverges horizontally near the surface, clockwise in the Northern Hemisphere and counterclockwise in the Southern Hemisphere, forming the third of the world's wind systems, the polar easterlies.

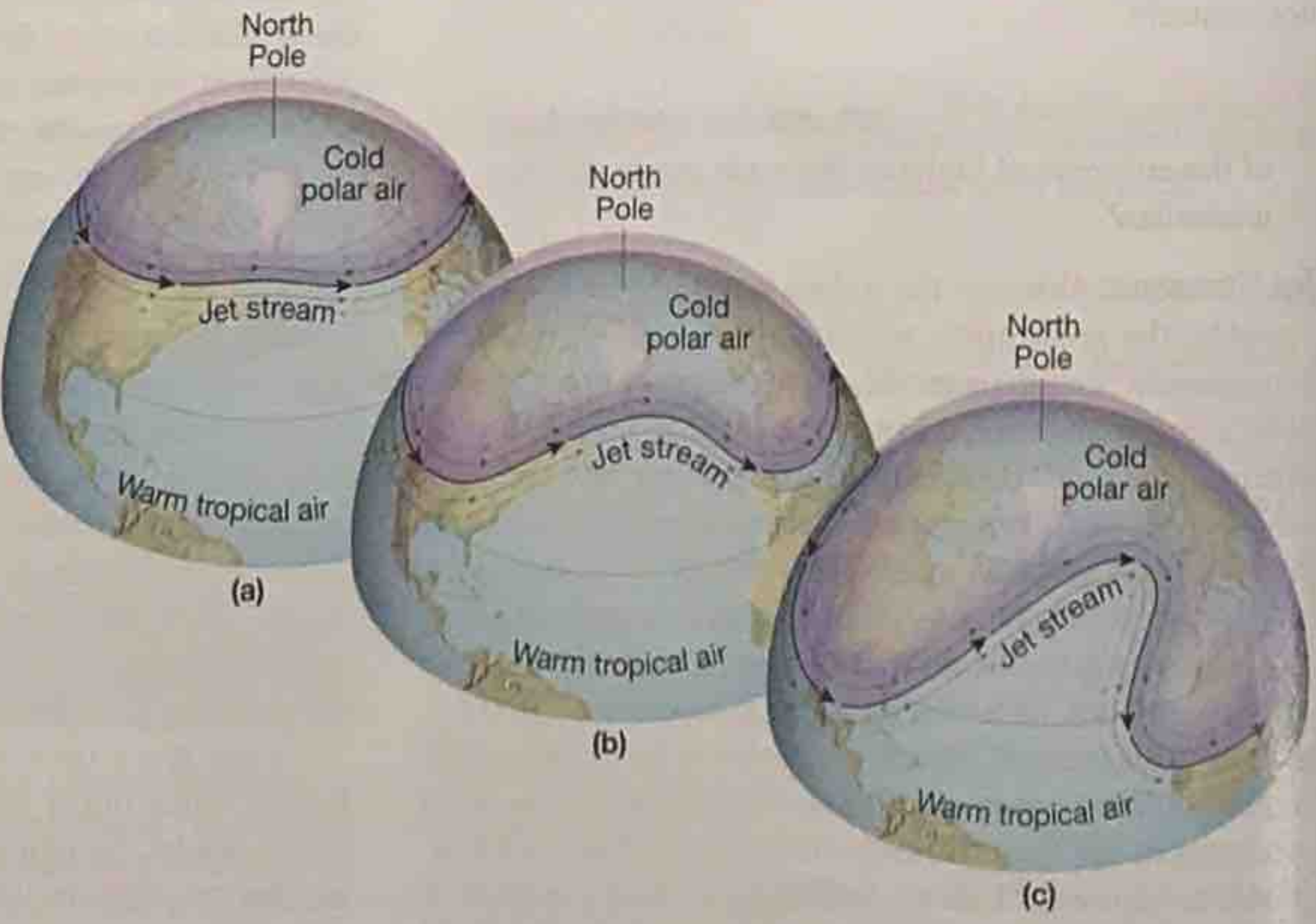


**Figure 5-24** Rossby waves as part of the general flow (particularly the upper-airflow) of the westerlies. (a) When there are few waves and their amplitude (north–south component of movement) is small, cold air usually remains poleward of warm air. (b) This distribution pattern begins to change as the Rossby waves grow. (c) When the waves have great amplitude, cold air pushes equatorward and warm air moves poleward.

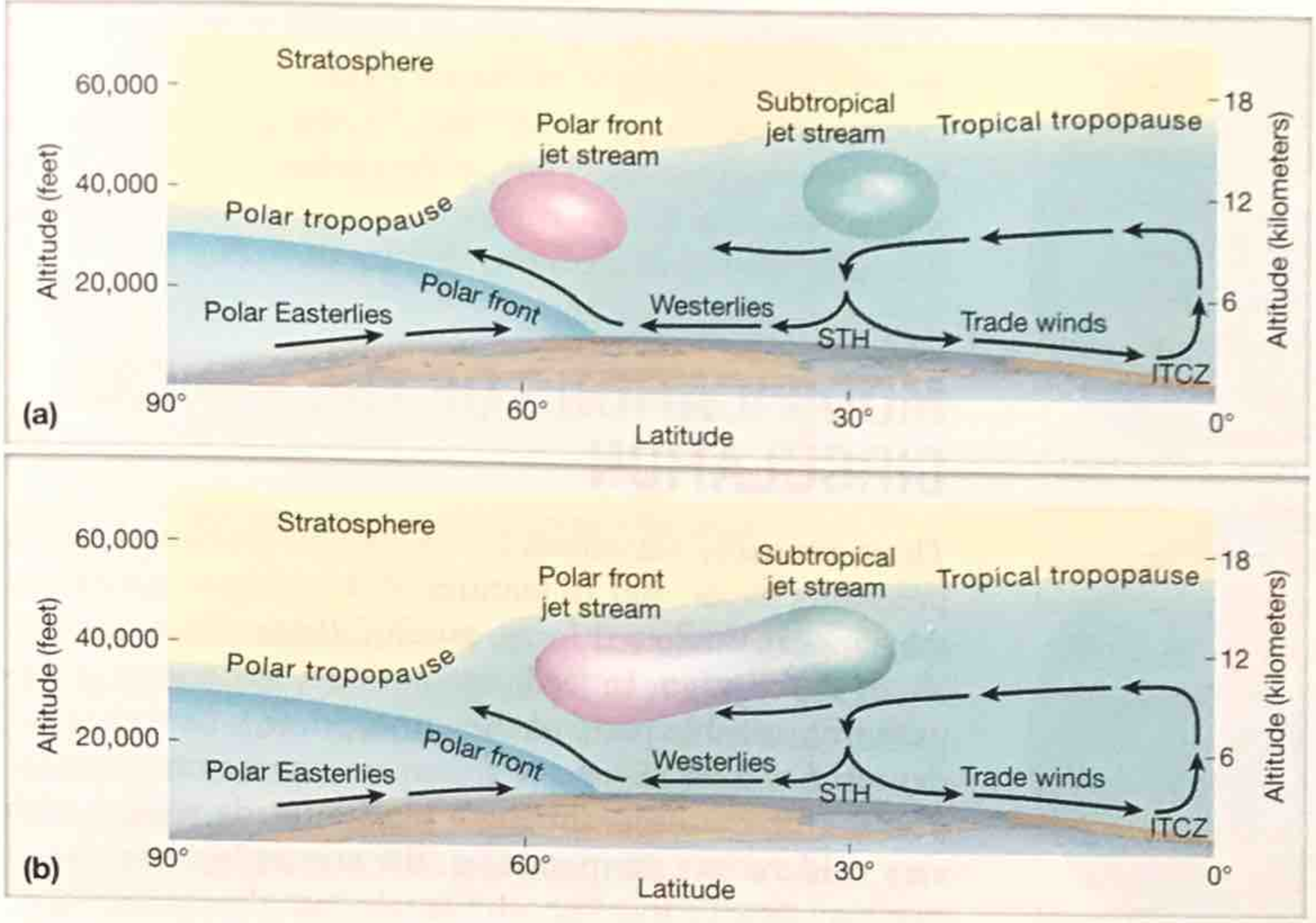


**Figure 5-25** (a) A vertical cross section of the atmosphere from the equator to the poles showing the usual relative positions of the two jet streams. (b) The two jet streams sometimes merge, and the result is intensified weather conditions.

## Polar Easterlies

The third broad-scale global wind system occupies most of the area between the polar highs and about 60° of latitude (Figure 5-26). The winds move generally from east to west and are called the **polar easterlies**. They are typically cold and dry but quite variable.

## Polar Front

The final surface component of the general pattern of atmospheric circulation is a zone of low pressure at about 50° to 60° of latitude in both Northern and Southern Hemispheres. The zone is commonly called the **polar front**, although it is sometimes most clearly visible by the presence of semipermanent zones of low pressure called the **subpolar lows**.

The polar front is a meeting ground and zone of conflict between the cold winds of the polar easterlies and the relatively warmer westerlies. The subpolar low of the Southern Hemisphere is nearly continuous over the uniform ocean surface of the cold seas surrounding Antarctica. In the Northern Hemisphere, however, the low-pressure zone is discontinuous, being interrupted by the continents. It is much more prominent in winter than in summer and is best developed over the northernmost reaches of the Pacific and Atlantic Oceans, forming the *Aleutian Low* and the *Icelandic Low*, respectively.

The polar front area is characterized by rising air, widespread cloudiness, precipitation, and generally unsettled or stormy weather conditions (Figure 5-27). Many of the migratory storms that travel with the westerlies have their origin in the conflict zone of the polar front.

## Vertical Patterns of the General Circulation

As we have seen, over tropical regions, between the equator and 20° to 25° of latitude, surface winds generally blow from the east. In the midlatitudes, the surface winds are

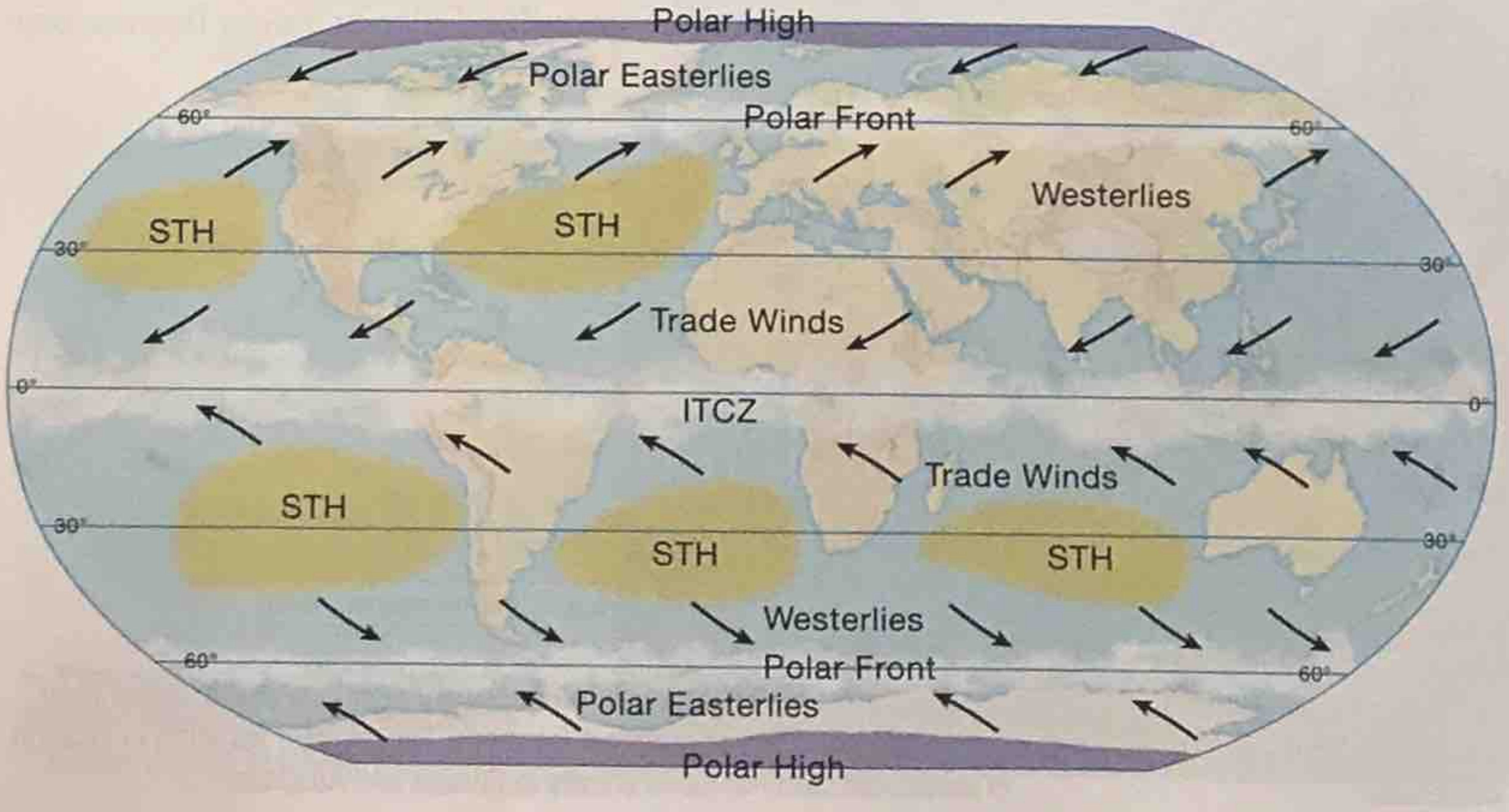
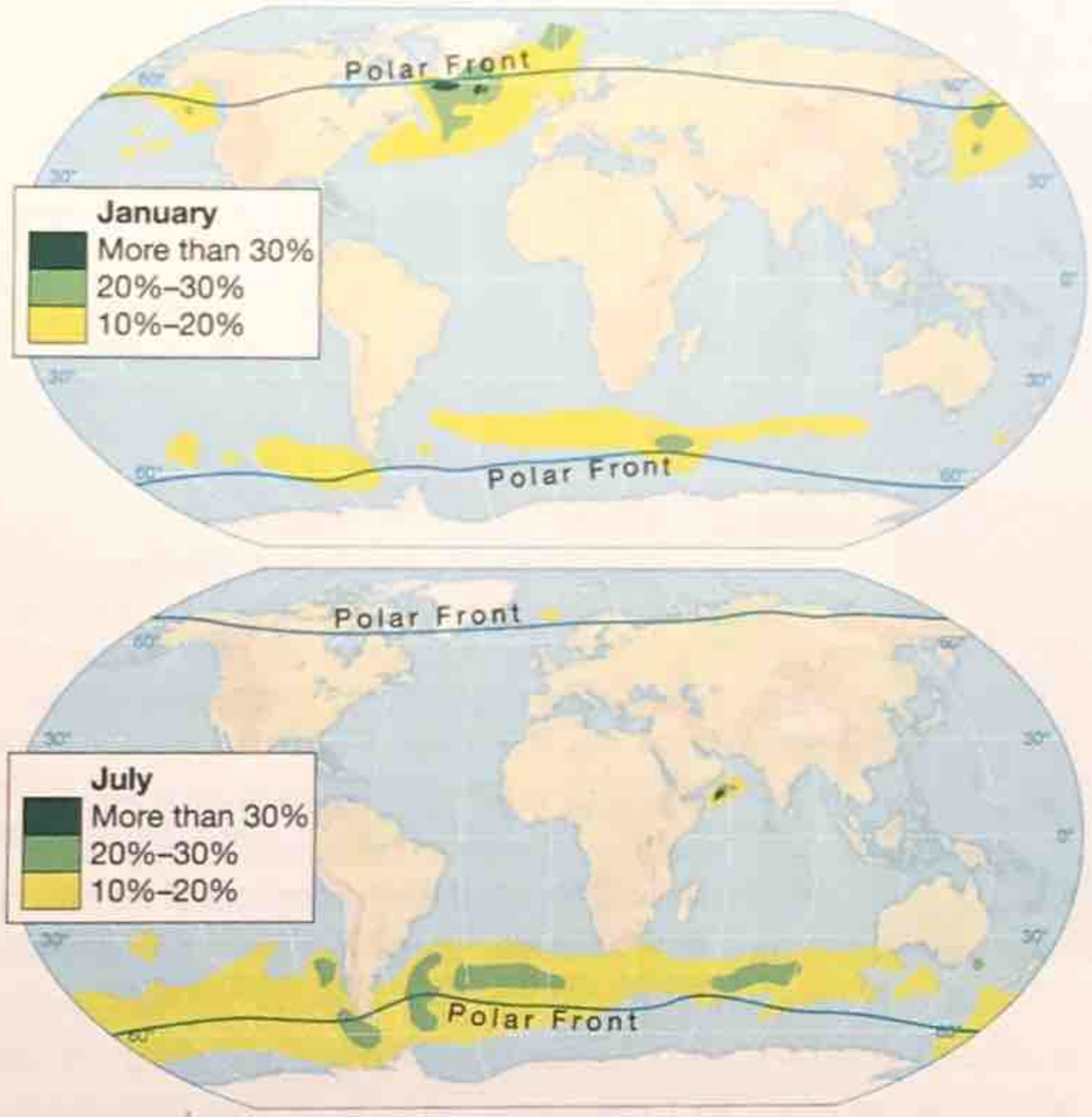


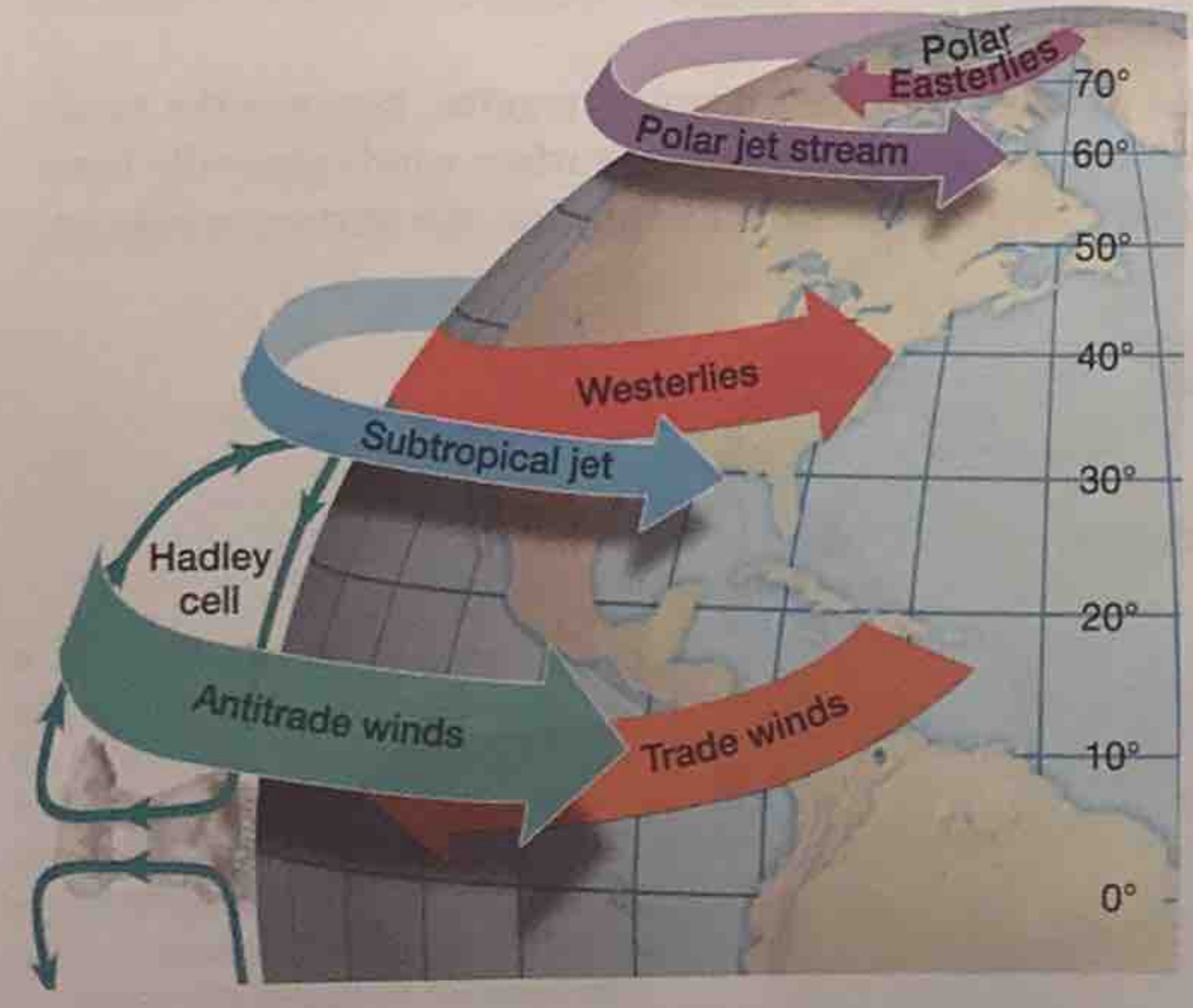
**Figure 5-26** Map showing the generalized locations of the seven components of the general circulation patterns of the atmosphere. (In this map projection, the areal extent of the high-latitude components—polar high, polar easterlies, polar front—is considerably exaggerated.)



▲ **Figure 5-27** Frequency of gale-force (34 knot) winds over the oceans in January and July. It is clear from this map that the strongest oceanic winds are associated with activities along the polar front (subpolar lows).

generally westerly, whereas in the highest latitudes, surface winds are again easterly. In the upper altitudes of the troposphere, however, the wind patterns are somewhat different from the surface winds (Figure 5-28).

The most dramatic difference is seen over the tropics. After equatorial air has risen in the ITCZ, the high-elevation poleward flow of air in the Hadley cell is deflected by the Coriolis effect (see Figure 5-14). This results in upper-elevation winds blowing from the southwest in the Northern Hemisphere and from the northwest in the Southern Hemisphere in the **antitrade winds**. This flow eventually becomes more westerly and encompasses the subtropical jet stream. Thus, at the surface within the tropics, winds are generally from the east, whereas high above, the antitrade winds are blowing from the west.



▲ **Figure 5-28** A generalized cross section through the troposphere, showing the dominant wind directions at different latitudes near the surface and in the upper troposphere. Surface winds in the tropics are generally easterly, but high above, the antitrade winds are blowing from the west, as are the upper troposphere jet streams of the westerlies.

# MODIFICATIONS OF THE GENERAL CIRCULATION

There are many variations to the pattern discussed on the preceding pages, and all features of the general circulation may appear in altered form, much different from the idealized description. Indeed, components sometimes disappear from sizable parts of the atmosphere where they are expected to exist. Even the tropopause sometimes "disappears" (for example, during a high-latitude winter with very cold surface temperatures, the atmospheric temperature may steadily increase with height into the stratosphere; in such cases the tropopause cannot be identified).

Nevertheless, the generalized pattern of global wind and pressure systems comprises the seven components described above. To understand how real-world weather and climate differ from this general picture, it is necessary to discuss two important modifications of the generalized scheme.

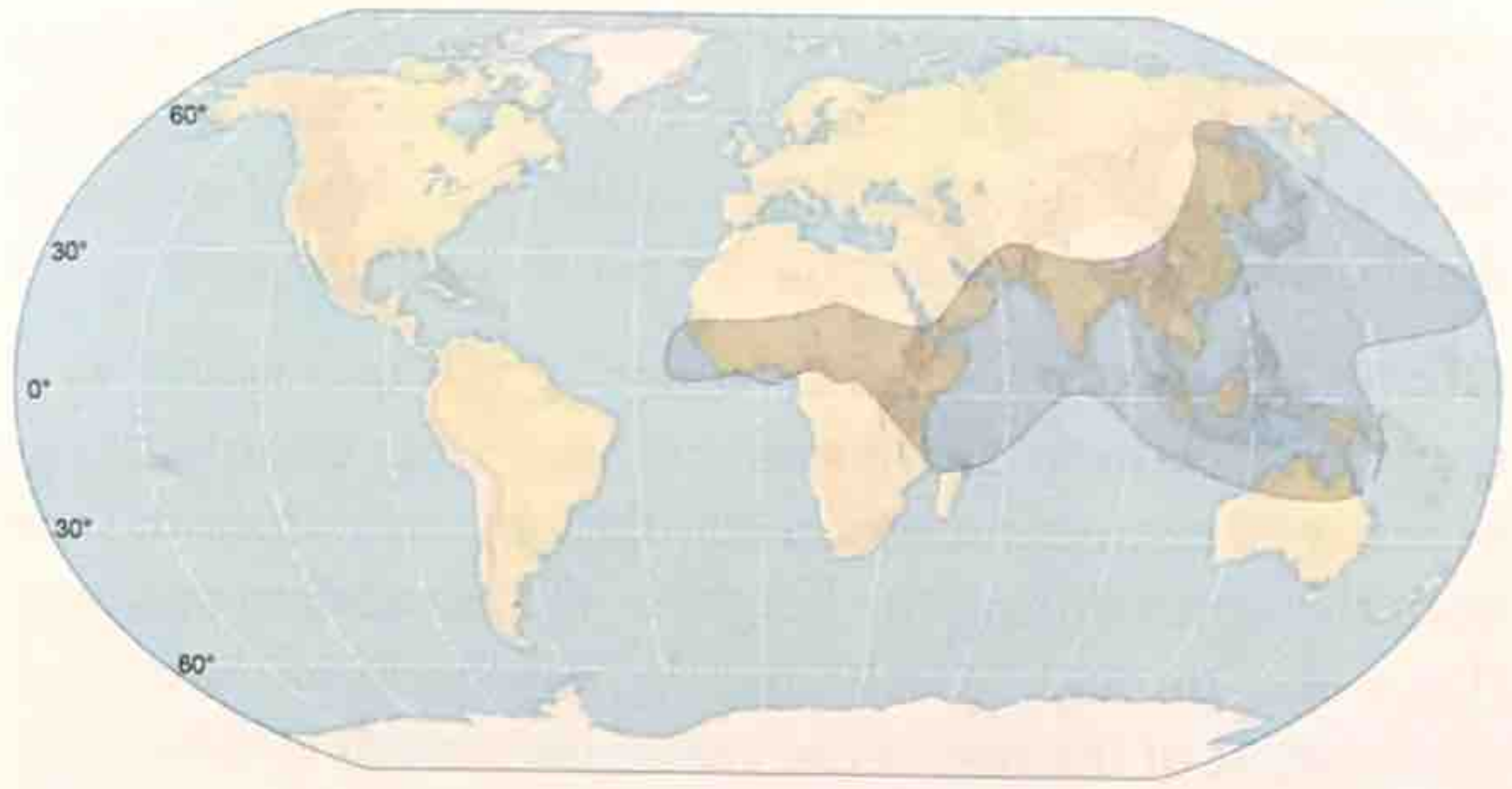
## Seasonal Variations in Location

FG11

Animation
Seasonal Pressure and Precipitation Patterns

The seven surface components of the general circulation shift latitudinally with the changing seasons. When sunlight, and therefore surface warming, is concentrated in the Northern Hemisphere (Northern Hemisphere summer), all components are displaced northward; during the opposite season (Southern Hemisphere summer), everything is shifted southward. The displacement is greatest in the low latitudes and least in the polar regions. The ITCZ, for example, can be found as much as 25° north of the equator in July and 20° south of the equator in January (Figure 5-29), while the polar highs experience little or no latitudinal displacement from season to season.

▲ **Figure 5-29** Typical maximum poleward positions of the intertropical convergence zone at its seasonal extremes. The greatest variation in location is associated with monsoon activity in Eurasia and Australia.



▲ **Figure 5-30** The principal monsoon areas of the world.

Weather is affected by shifts in the general circulation components only minimally in polar regions, but the effects can be quite significant in the tropics and midlatitudes. For example, as we will see in Chapter 8, regions of *mediterranean climate* found along the west coasts of continents at about 35° N and S latitude, have warm, rainless summers while under the influence of the STH; in winter, however, the belt of the westerlies shifts equatorward, bringing changeable and frequently stormy weather to these regions (see Figure 5-15). Also, as we will see, the shift of the ITCZ is closely tied to seasonal rainfall patterns in large areas within the tropics.

**Learning Check 5-11** **Why does the location of the ITCZ shift north during the Northern Hemisphere summer?**

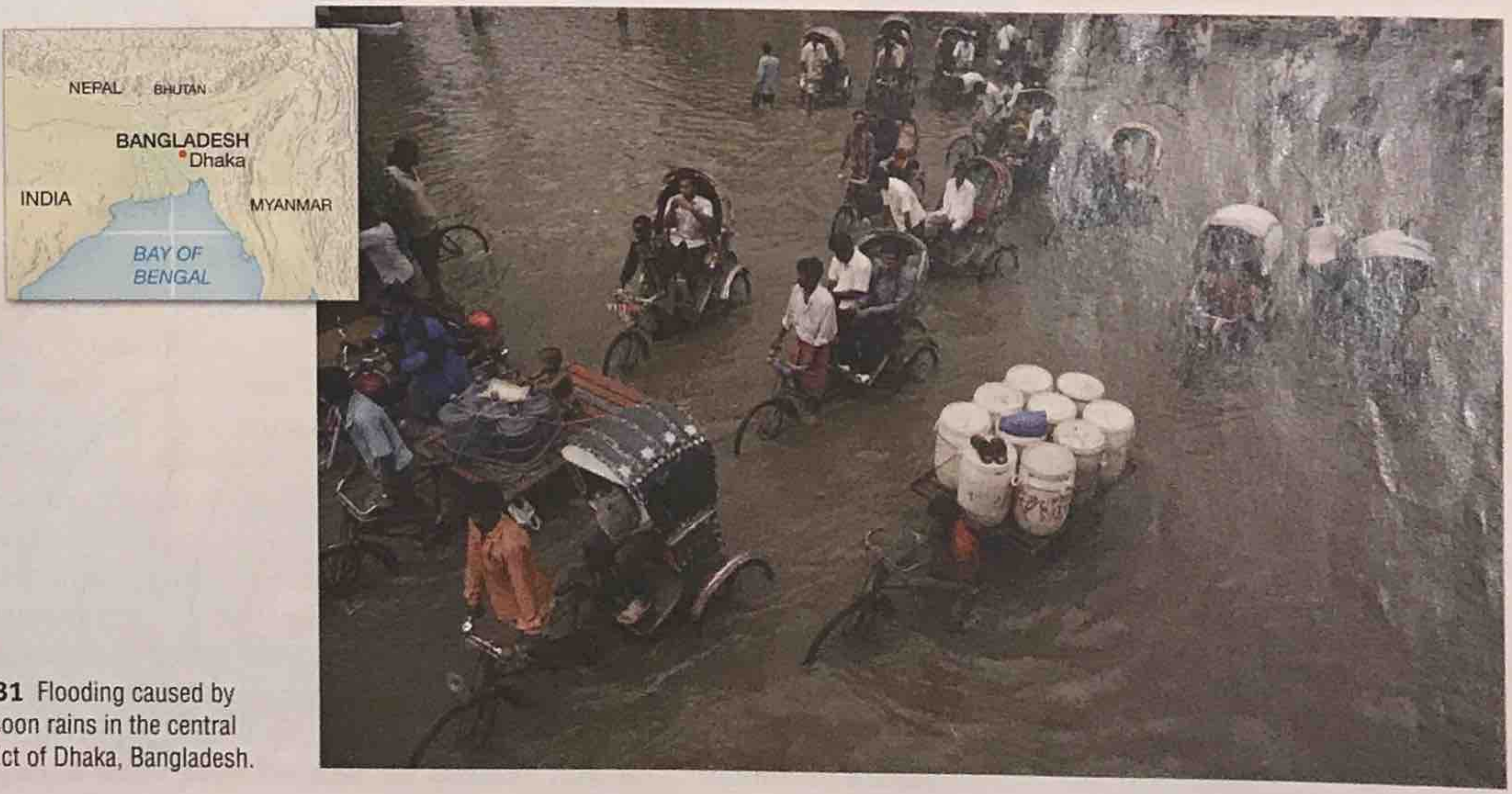
## Monsoons

By far the most significant deviation from the pattern of general circulation is the development of **monsoons** in certain parts of the world, particularly southern and eastern Eurasia (Figure 5-30). The word *monsoon* is derived from the Arabic *mawsim* (meaning "season") and has come to mean a seasonal reversal of winds, a general sea-to-land movement—called *onshore flow*—in summer and a general land-to-sea movement—called *offshore flow*—in winter. Associated with the monsoon wind pattern is a distinctive seasonal precipitation regime—heavy summer rains derived from the moist maritime air of the onshore flow and a pronounced winter dry season when continental air moving seaward dominates the circulation.

**Causes of Monsoons:** It would be convenient to explain monsoon circulation simply on the basis of the unequal warming of continents and oceans. A strong thermal (warm surface) low-pressure cell generated over a continental landmass in summer attracts oceanic air onshore; similarly, a prominent thermal anticyclone in winter over a continent produces an offshore circulation. It is clear that these thermally induced pressure differences contribute to monsoon development (see Figure 5-15), but they are not the whole story.

Monsoon winds essentially represent unusually large latitudinal migrations of the trade winds associated with the large seasonal shifts of the ITCZ over southeastern Eurasia. The Himalayas evidently also play a role—this significant topographic barrier allows greater winter temperature contrasts between South Asia and the interior of the continent to the north, and this in turn may influence the location and persistence of the subtropical jet stream in this region.

**Significance of Monsoons:** It is difficult to overestimate the importance of monsoon circulation to humankind. More than half of the world's population inhabits the regions in which climates are largely controlled by monsoons. Moreover, these are generally regions in which the majority of the populace depends on agriculture for its livelihood. Their lives are intricately bound up with the reality of monsoon rains, that are essential for both food production and cash crops (Figure 5-31). The failure, or even late arrival,



▶ **Figure 5-31** Flooding caused by summer monsoon rains in the central business district of Dhaka, Bangladesh.

of monsoon moisture inevitably causes widespread hunger and economic disaster.

Although the causes are complex, the characteristics of monsoons are well known, and it is possible to describe the monsoon patterns with some precision. There are two major monsoon systems (one in South Asia and the other in East Asia), two minor systems (in Australia and West Africa), and several other regions where monsoon patterns develop (especially in Central America and the southwest United States).

**South Asian Monsoon:** The most notable environmental event each year in South Asia is the annual burst of the summer monsoon, illustrated in Figure 5-32a. In this first of the two major monsoon systems, prominent onshore winds spiral in from the Indian Ocean, bringing life-giving rains to the parched subcontinent. In winter, South Asia is dominated by outblowing dry air diverging generally from the northeast. This flow is not very different from normal northeast trades except for its low moisture content.

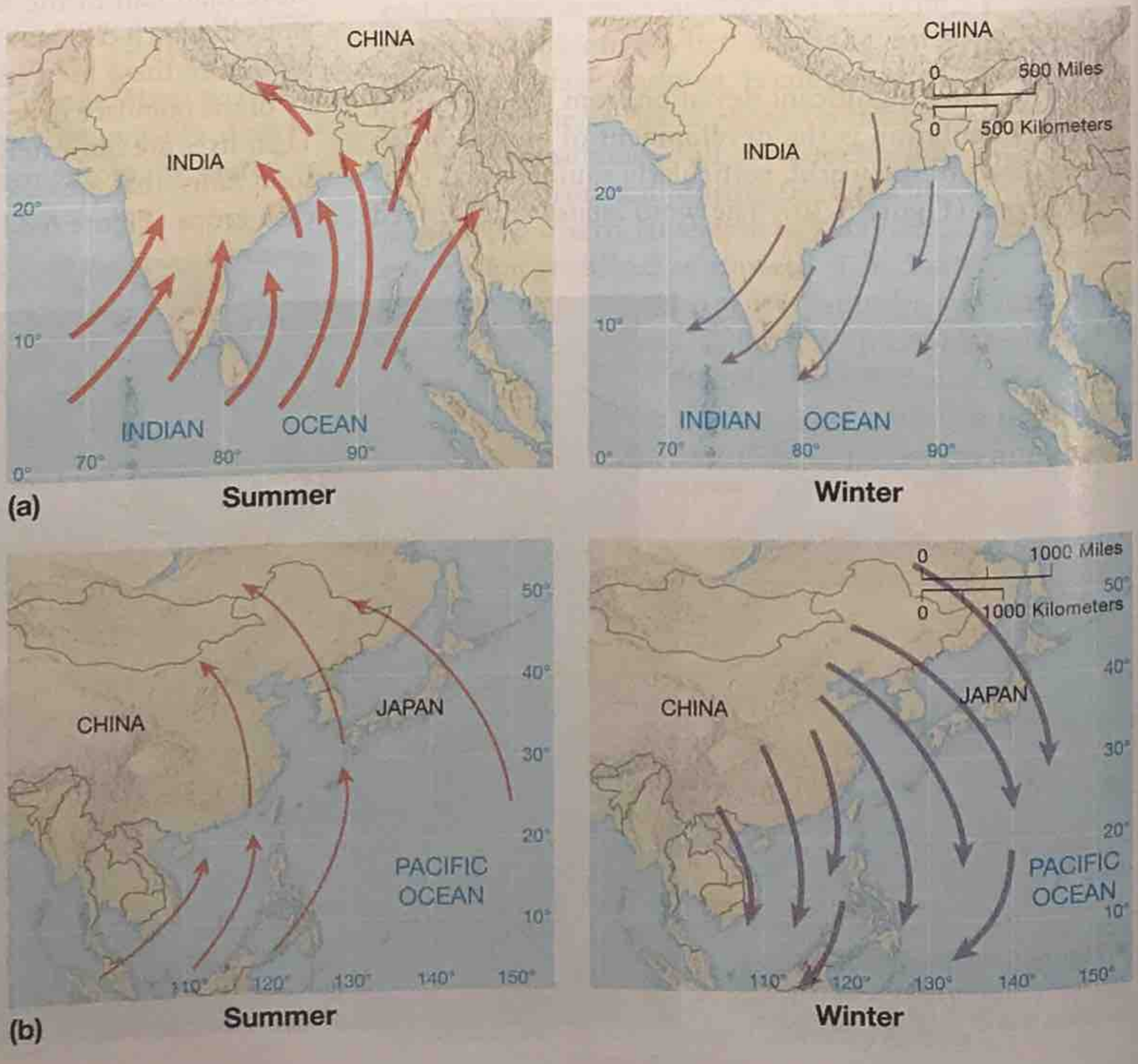
**East Asian Monsoon:** Turning to the second of the two major monsoon systems, we see that winter is the more prominent season in the East Asian monsoon system, which primarily affects China, Korea, and Japan and is illustrated in Figure 5-32b. A strong outflow of dry continental air, largely from the northwest, is associated with anticyclonic circulation around the massive thermal high-pressure cell over western Eurasia called the Siberian High. The onshore flow of maritime air in summer is not as notable as that in South Asia, but it does bring southerly and southeasterly winds, as well as considerable moisture, to the region.

**Other Monsoon Areas:** In one of the two minor systems, the northern quarter of the Australian continent experiences a distinct monsoon circulation, with onshore flow from the north during the height of the Australian summer (December through March) and dry, southerly, offshore flow during most of the rest of the year. This system is illustrated in Figure 5-33a.

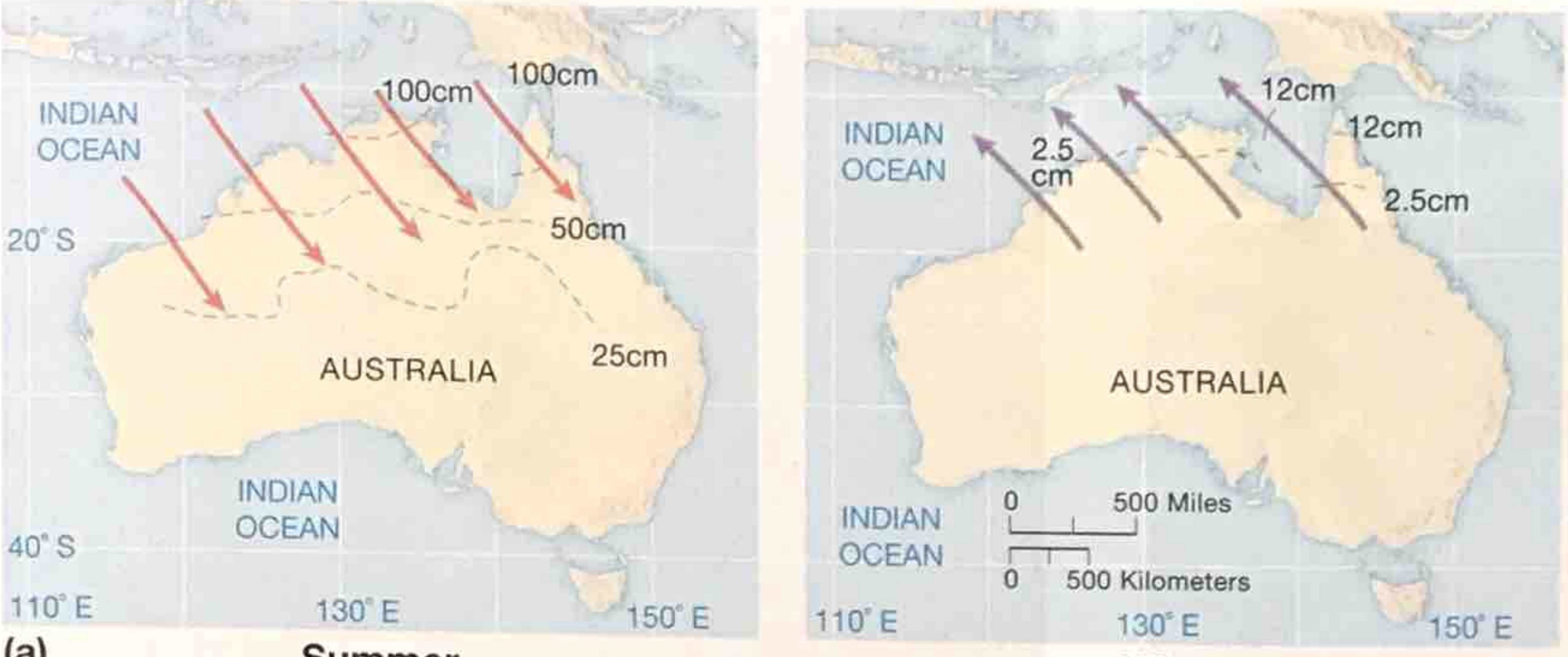
The south-facing coast of West Africa is dominated within about 650 kilometers (400 miles) of the coast by the second minor monsoonal circulation. This system is shown in Figure 5-33b. Moist oceanic air flows onshore from the south and southwest during summer, and dry, northerly, continental flow prevails in the opposite season.

The so-called "Arizona Monsoon" of the southwestern United States is actually part of a broader minor monsoon pattern called the North American Monsoon. These onshore winds in summer carry moisture from the Gulf of California and the Gulf of Mexico into New Mexico, Arizona, and northwestern Mexico, bringing bursts of thunderstorm activity.

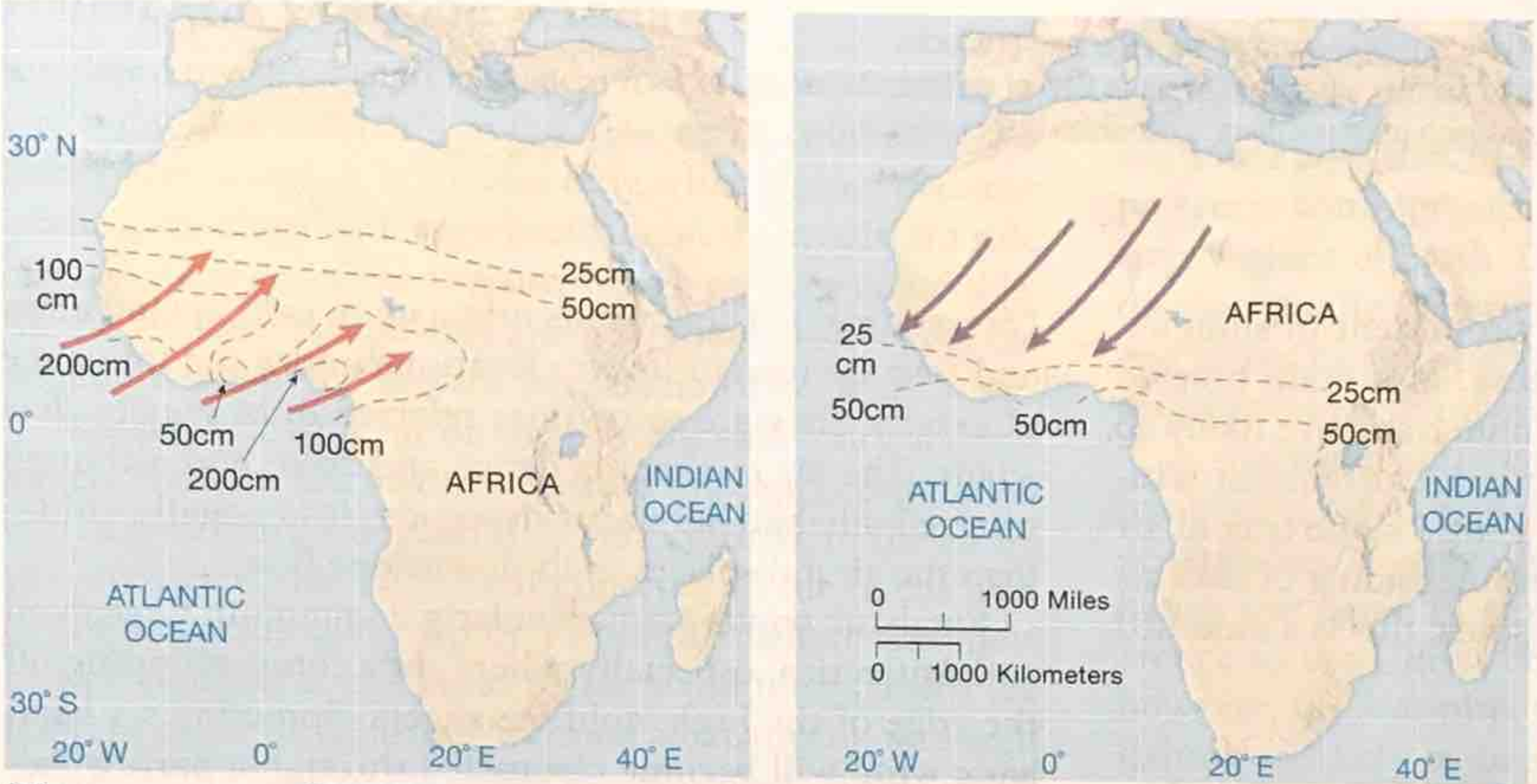
**Learning Check 5-12** **How does wind direction in South Asia different from summer to winter?**



▶ **Figure 5-32** The two major monsoon systems. (a) The South Asian monsoon is characterized by a strong onshore flow in summer (rainy season) and a somewhat less pronounced offshore flow in winter (dry season). (b) In East Asia, the outblowing winter monsoon is stronger than the inblowing summer monsoon.



**(a)** **Summer** **Winter**



**(b)** **Summer** **Winter**

◀ **Figure 5-33** The two minor monsoon systems, showing 3-month seasonal rainfall isohyets (lines of equal rainfall). (a) In Australia, northwesterly summer winds bring the wet season to northern Australia; dry southeasterly flow dominates in winter. (b) In West Africa, summer winds are from the southwest and winter winds are from the northeast.

# LOCALIZED WIND SYSTEMS

The preceding sections have dealt with only the broadscale wind systems that make up the global circulation and influence the climatic pattern of the world. Many kinds of lesser winds, however, are of considerable significance to weather and climate at a more localized scale. Such winds are the result of local pressure gradients that develop in response to topographic configurations in the immediate area, sometimes in conjunction with wider circulation conditions.

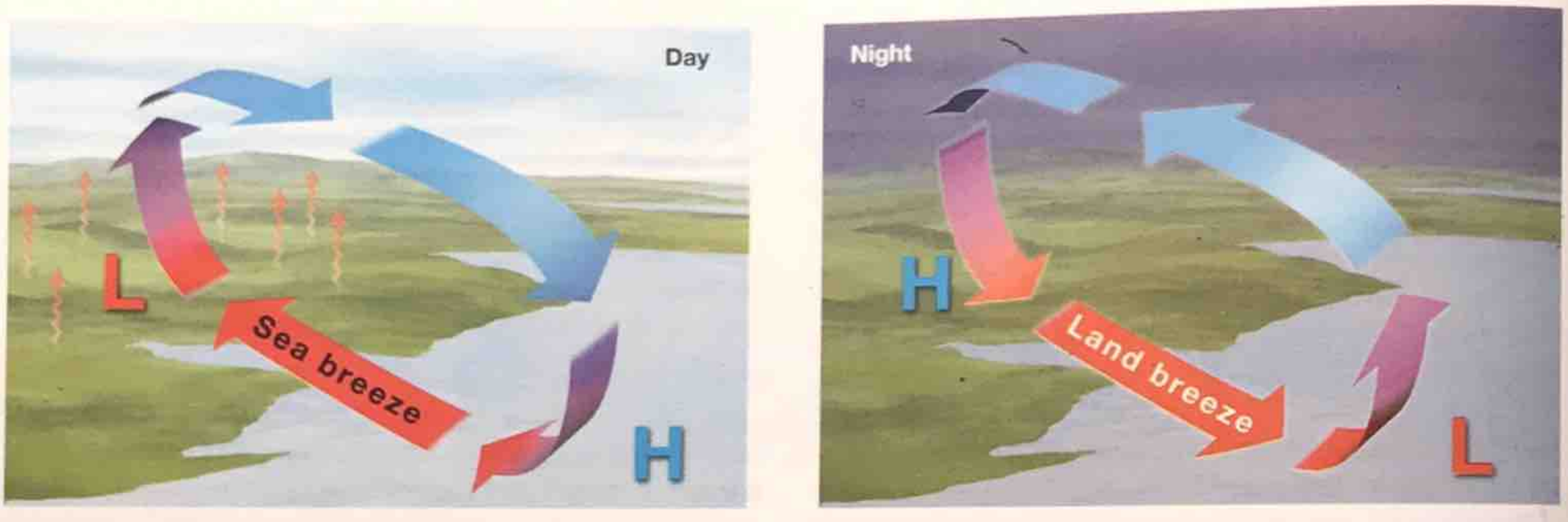
## Sea and Land Breezes

A common local wind system along tropical coastlines and to a lesser extent during the summer in midlatitude coastal areas is the cycle of **sea breezes** during the day and **land breezes** at night (Figure 5-34). (As is usual with winds, the name tells the direction from which the wind comes: a sea breeze blows from sea to land, and a land breeze blows from land to sea.) This is essentially a convectional circulation caused by the differential warming of land and water surfaces. The land warms up rapidly during the day, warming the air above by conduction and reradiation. This warming causes the air to expand and rise, creating low pressure that attracts surface breezes from over the adjacent water body. Because the onshore flow is relatively cool and moist, it holds down daytime temperatures in the coastal zone and provides moisture for afternoon showers. Sea breezes are sometimes strong, but they rarely are influential for more than 15 to 30 kilometers (10 to 20 miles) inland.

The reverse flow at night is normally considerably weaker than the daytime wind. The land and the air above it cool more quickly than the adjacent water body, producing relatively higher pressure over land. Thus, air flows offshore in a land breeze.

## Valley and Mountain Breezes

Another notable daily cycle of airflow is characteristic of many hill and mountain areas. During the day, conduction and reradiation from the land surface cause air near the mountain slopes to warm more than air over the valley floor (Figure 5-35). The warmed air rises, creating a low-pressure area, and then cooler air from the valley floor flows upslope from the high-pressure area to the low-pressure area. This upslope flow is called a **valley breeze**. The rising air often causes clouds to form around the peaks, and afternoon showers are common in the high country as a result. After dark, the pattern is reversed. The mountain slopes lose warmth rapidly through radiation, which chills the adjacent air, causing it to slip downslope as a **mountain breeze**.



▲ **Figure 5-34** In a typical sea–land breeze cycle, daytime warming over the land produces relatively low pressure there, and this low-pressure center attracts an onshore flow of air from the sea. Later, nighttime cooling over the land causes high pressure there, a condition that creates an offshore flow of air.

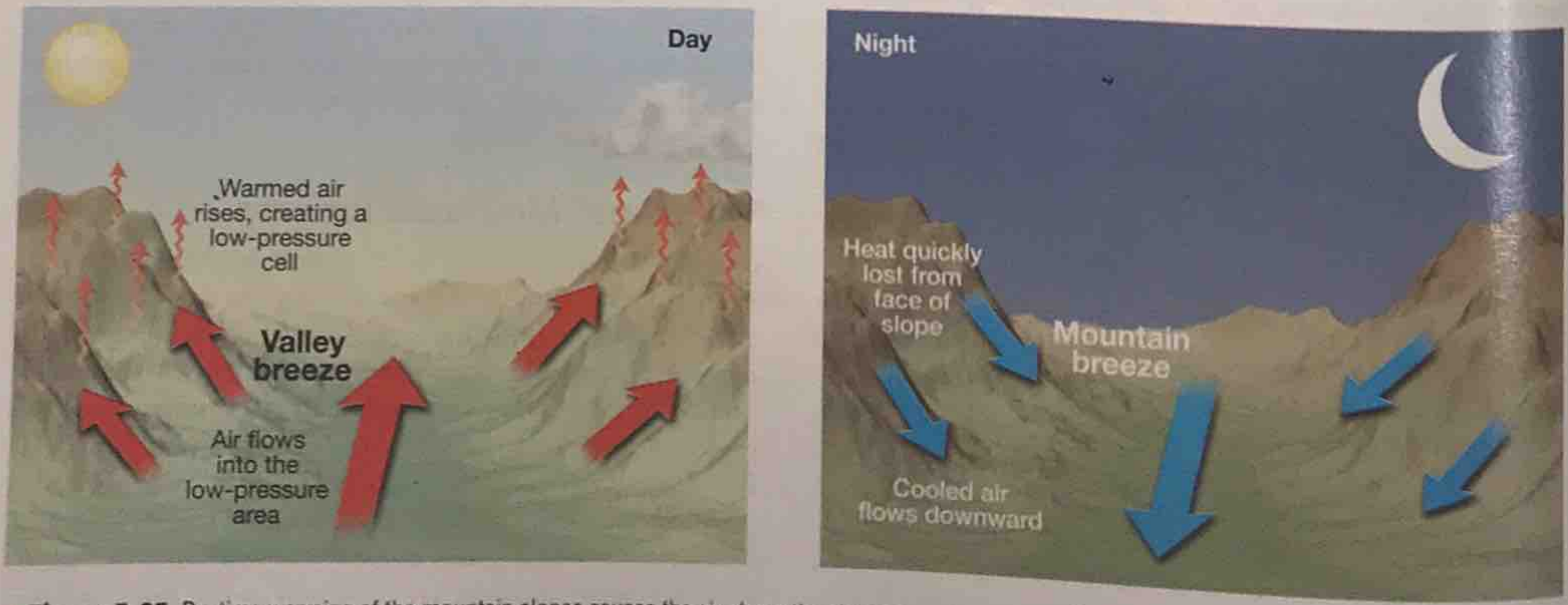
Valley breezes are particularly prominent in summer, when solar warming is most intense. Mountain breezes are often weakly developed in summer and are likely to be more prominent in winter. Indeed, a frequent winter phenomenon in areas of even gentle slope is cold air drainage, which is simply the nighttime sliding of cold air downslope to collect in the lowest spots; this is a modified form of mountain breeze.

**Learning Check 5-13** **How do *sea breezes* form?**

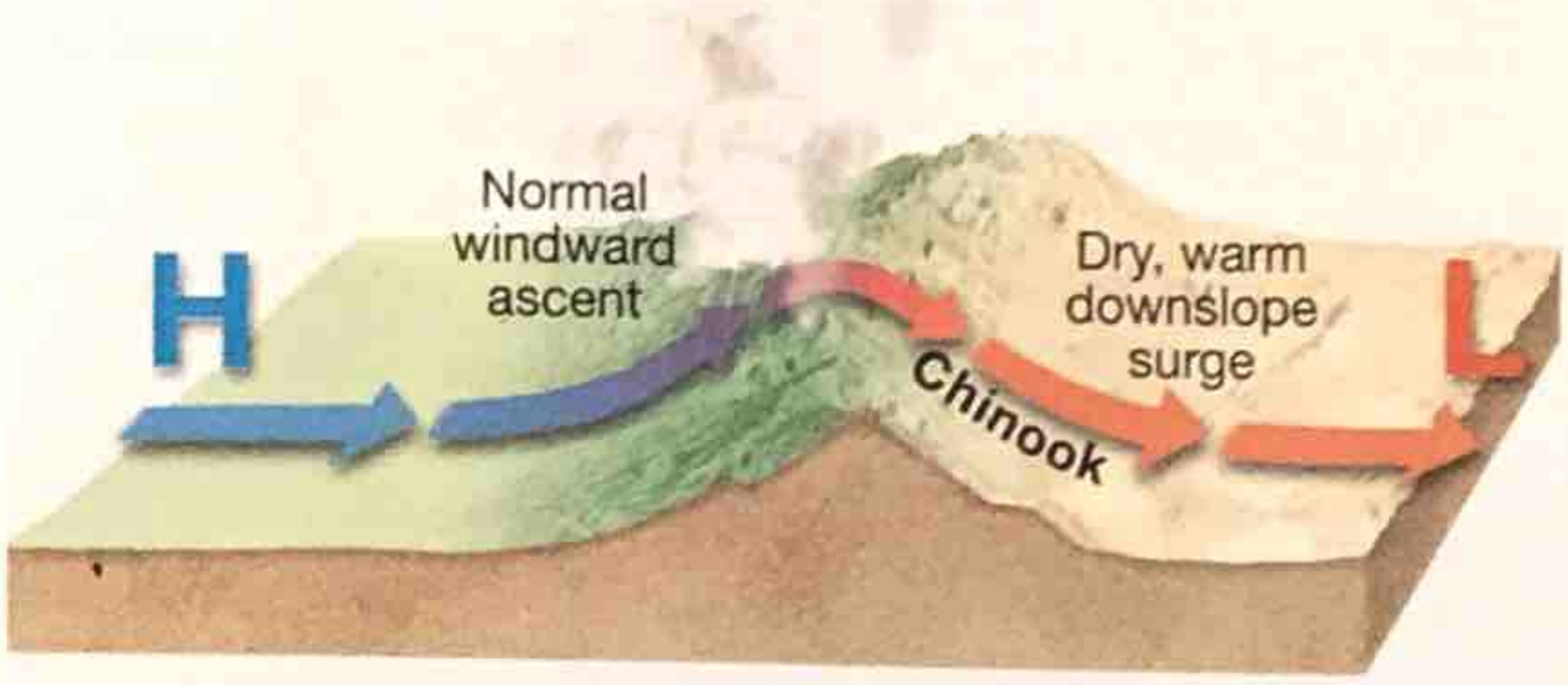
## Katabatic Winds

Related to simple air drainage is the more general and powerful spilling of air downslope in the form of katabatic winds (from the Greek *katabatik*, which means "descending"). These winds originate in cold upland areas and cascade toward lower elevations under the influence of gravity; they are sometimes referred to as *gravity-flow winds*. The air in them is dense and cold, and although warmed adiabatically as it descends, it is usually colder than the air it displaces in its downslope flow.

Katabatic winds are particularly common in Greenland and Antarctica, especially where they come whipping off the edge of the high, cold ice sheets. Sometimes a katabatic wind will become channeled through a narrow valley where it may develop high speed and considerable destructive power. An infamous example of this phenomenon is the *mistral*, which sometimes surges down France's Rhône Valley from the Alps to the Mediterranean Sea. Similar winds are called *bora* in the Adriatic region and *taku* in southeastern Alaska.



▲ **Figure 5-35** Daytime warming of the mountain slopes causes the air above the slopes to warm and rise, creating lower air pressure than over the valley. Cooler valley air then flows along the pressure gradient (in other words, up the mountain slope) in what is called a valley breeze. At night, the slopes radiate their warmth away and as a result the air just above them cools. This cooler, denser air flows down into the valley in what is called a mountain breeze.



▲ **Figure 5-36** A chinook is a rapid downslope movement of relatively warm air. It is caused by a pressure gradient on the two faces of a mountain.

## Foehn and Chinook Winds

Another downslope wind is called a **foehn** (pronounced as in fern but with a silent "r") in the Alps, and a **chinook** in the Rocky Mountains. It originates only when a steep pressure gradient develops with high pressure on the windward side of a mountain and a low-pressure trough on the leeward side. Air moves down the pressure gradient, which means from the windward side to the leeward side, as shown in Figure 5-36.

The downflowing air on the leeward side is dry and relatively warm: it has lost its moisture through precipitation on the windward side, and it is warm relative to the air on the windward side because it contains all the latent heat of condensation given up by the condensing of the snow or rain that fell at the peak. As the wind blows down the leeward slope, it is further warmed adiabatically, and so it arrives at the base of the range as a warming, drying wind. It can produce a remarkable rise of temperature leeward of the mountains in just a few minutes. It is known along the Rocky Mountains front as a "snow-eater" because it not only melts the snow rapidly but also quickly dries the resulting mud.

## Santa Ana Winds

FG7

Similar drying winds in California, known as **Santa Ana winds**, develop when a cell of high pressure persists over the interior of the western United States for several days. The wind diverges clockwise out of the high, bringing dry, warm northerly or easterly winds to the coast (instead of the more typical cool, moist air off the ocean from the westerlies). The Santa Anas are noted for high speed, high temperature, and extreme dryness. Their presence provides ideal conditions for wildfires. Virtually every year they make headlines by fanning large brush fires that destroy dozens of homes in late summer and fall and occasionally in spring.

# EL NIÑO–SOUTHERN OSCILLATION

One of the basic tenets of physical geography is the interrelatedness of the various elements of the environment. So far in our look at weather and climate, we have introduced patterns of temperature, ocean circulation, wind, and pressure without fully exploring important feedback mechanisms that are a part of such interactions. Nor have we explored the complexity introduced by cyclical variations in oceanic and atmospheric patterns, occurring over periods of years or even decades.

Animation
El Niño

A prize example of this interrelatedness and complexity is **El Niño**, an episodic atmospheric and oceanic phenomenon of the equatorial Pacific Ocean, particularly prominent along the west coast of South America.

## Effects of El Niño

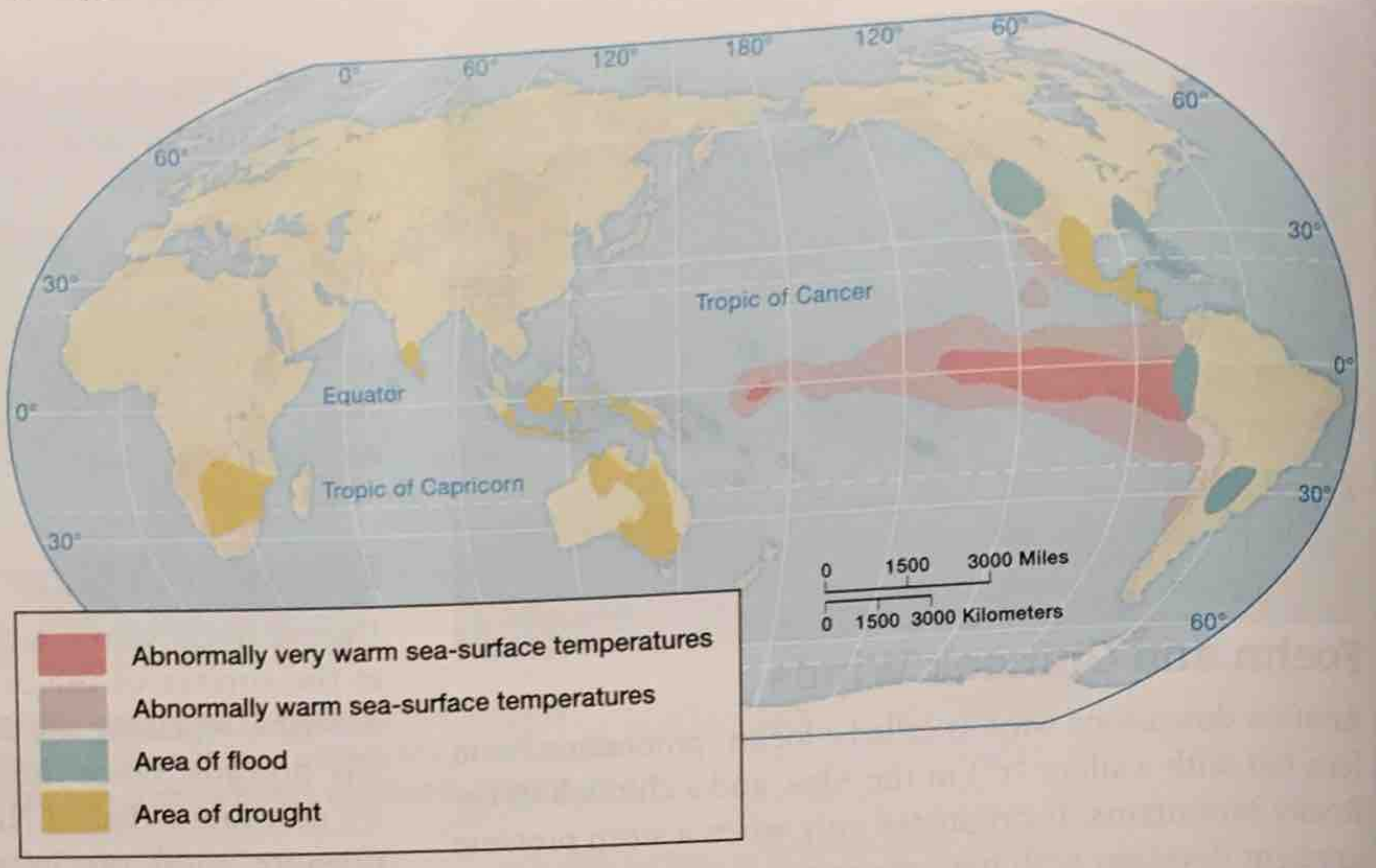
During an El Niño event, abnormally warm water appears at the surface of the ocean off the west coast of South America, replacing the cold, nutrient-rich water that usually prevails. Once thought to be a local phenomenon, we now know that El Niño is associated with changes in pressure, wind, precipitation, and ocean conditions over large regions of Earth. During a strong El Niño event, productive Pacific fisheries off South America are disrupted and heavy rains come to some regions of the world while drought comes to others.

A slight periodic warming of Pacific coastal waters has been noticed by South American fishermen for many generations. It typically occurs around Christmastime—hence the name *El Niño* (Spanish for "the boy" in reference to the Christ child). Every three to seven years, however, the warming of the ocean is much greater, and fishing is likely to be much poorer. Historical records have documented the effects of El Niño for several hundred years, with archeological and paleoclimatological evidence pushing the record back several thousand years.

It was not until the major 1982–1983 event, however, that El Niño received worldwide attention (Figure 5-37). Over a period of several months, there were crippling droughts in Australia, India, Indonesia, the Philippines, Mexico, Central America, and southern Africa; devastating floods in the western and southeastern United States, Cuba, and northwestern South America; destructive tropical cyclones in parts of the Pacific (such as in Tahiti and Hawai'i) where they are normally rare; and a vast sweep of ocean water as much as 8°C (14°F) warmer than normal stretched over 13,000 kilometers (8000 miles) of the equatorial Pacific, causing massive die-offs of fish, seabirds, and coral. Directly attributable to these events were more than 1500 human deaths, damage estimated at nearly $9 billion, and vast ecological changes.

In 1997–1998, another strong El Niño cycle took place. This time worldwide property damage exceeded $30 billion, at least 2100 people died, and tens of thousands of people were displaced. There were severe blizzards in the Midwest, devastating tornadoes in the southeastern United States, and much higher than average rainfall in California.

So what happens during El Niño that correlates with such widespread changes in the weather?

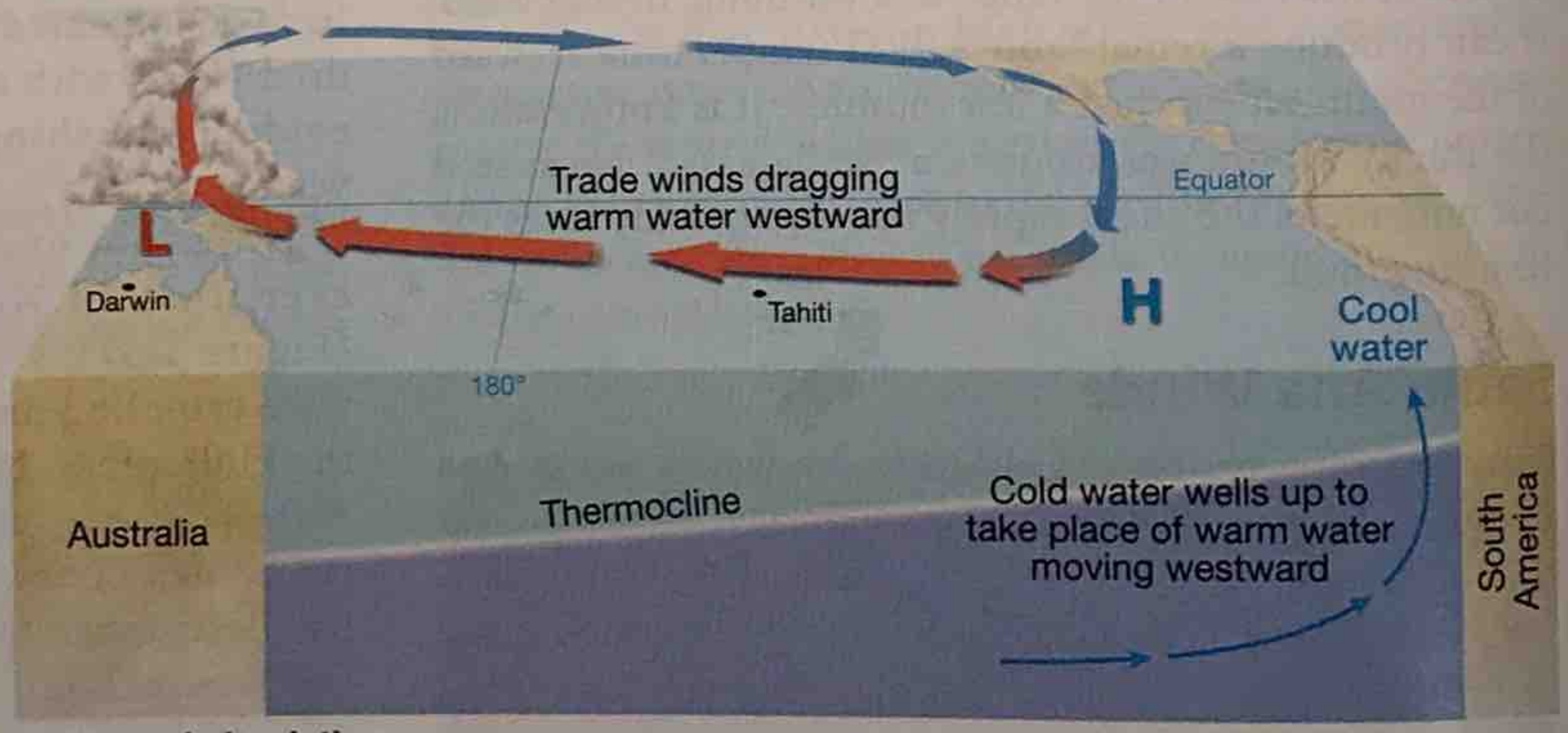


▶ **Figure 5-37** The ocean and atmospheric conditions associated with a major El Niño event, here generalized after the 1982–1983 event. Abnormally warm ocean water in the eastern equatorial Pacific is the most readily recognizable characteristic.

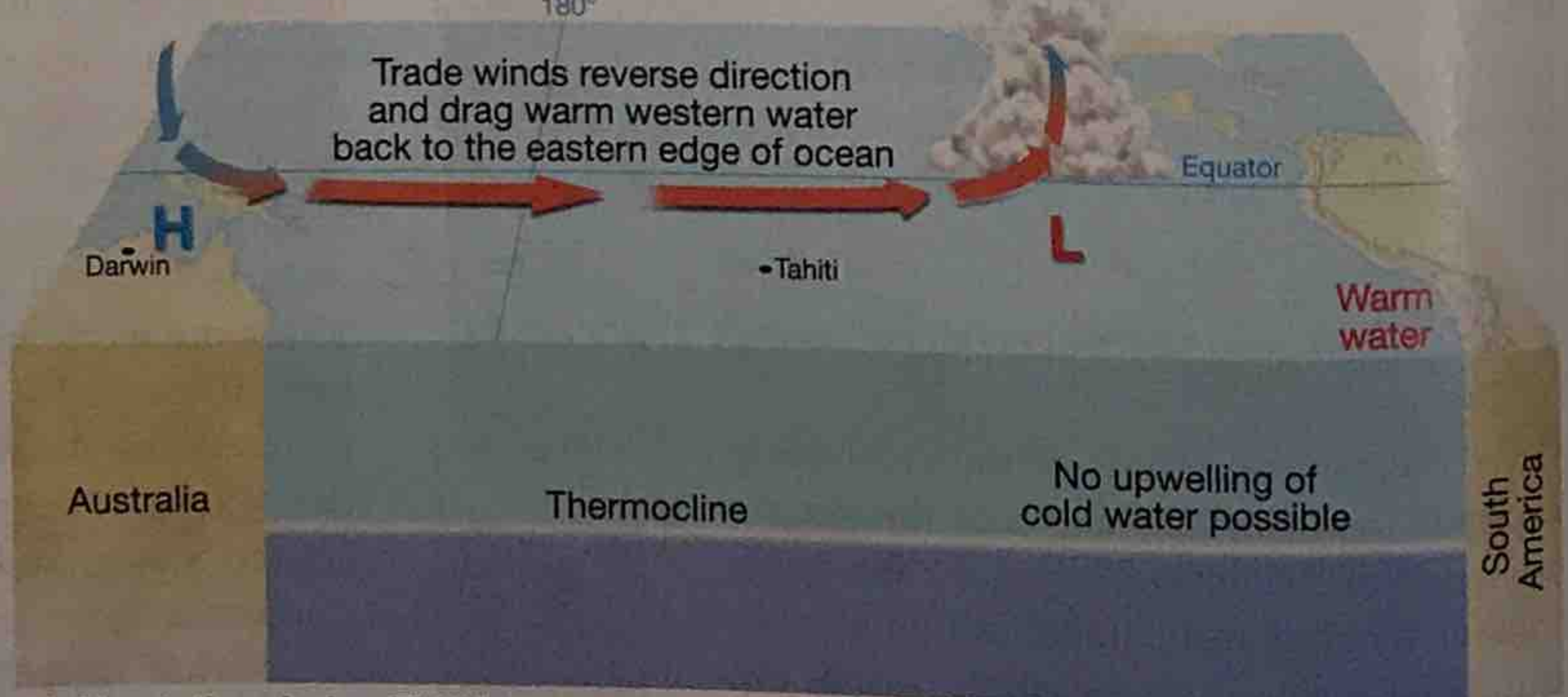
## Normal Pattern

To understand El Niño, we begin with a description of the normal conditions in the Pacific Ocean basin (Figure 5-38a). As we saw in Chapter 4, usually the waters off the west coast of South America are cool. The wind and pressure patterns in this region are dominated by the persistent subtropical high (STH) associated with the subsiding air of the Hadley cell circulation (see Figure 5-17).

**Cool Water off West Coast:** As the trade winds diverge from the STH, they flow from east to west across the Pacific—this tropical airflow drags surface ocean water westward across the Pacific basin in the warm Equatorial



**(a) Normal circulation**



**(b) Circulation during El Niño**

▶ **Figure 5-38** (a) Normal conditions in the South Pacific. The trade winds carry warm equatorial water across the Pacific from east to west. (b) These conditions either weaken or reverse during an El Niño event. The upwelling of cold water off of South America diminishes, the thermocline boundary between near-surface and cold deep water lowers, and much warmer water than usual is present there.

Current (introduced in Chapter 4; see Figure 4-26). As surface water pulls away from the coast of South America, an upwelling of cold, nutrient-rich ocean water rises into the already cool Peru current. This combination of cool water and high pressure result in relatively dry conditions along much of the west coast of South America.

In contrast to the cold water and high pressure near South America, in a normal year on the other side of the Pacific Ocean near Indonesia things are quite different. The trade winds and the Equatorial Current pile up warm water, raising sea level in the Indonesian region as much as 60 centimeters (about 2 feet) higher than near South America, turning the tropical western Pacific into an immense storehouse of energy and moisture.

**The Walker Circulation:** Warm water and persistent low pressure prevail around northern Australia and Indonesia; local convective thunderstorms develop in the intertropical convergence zone (ITCZ), producing high annual rainfall in this region of the world. After this air rises in the ITCZ, it begins to flow poleward but is deflected by the Coriolis effect into the upper-atmosphere westerly *antitrade* winds; some of this airflow aloft eventually subsides into the STH on the other side of the Pacific (see Figure 5-14). This general circuit of airflow is called the **Walker Circulation**, after the British meteorologist Gilbert Walker (1868–1958) who first described these circumstances. (Although Figure 5-38a shows the Walker Circulation as a closed convection cell, recent studies suggest that this is probably too simplistic—although the upper atmosphere is generally flowing from west to east, a closed "loop" of airflow probably does not exist.)

## El Niño Pattern

Every few years, the normal pressure patterns in the Pacific change (Figure 5-38b). High pressure develops over northern Australia and low pressure develops to the east near Tahiti. This "seesaw" of pressure is known as the **Southern Oscillation**. It was first recognized by Gilbert Walker in the first decade of the twentieth century.

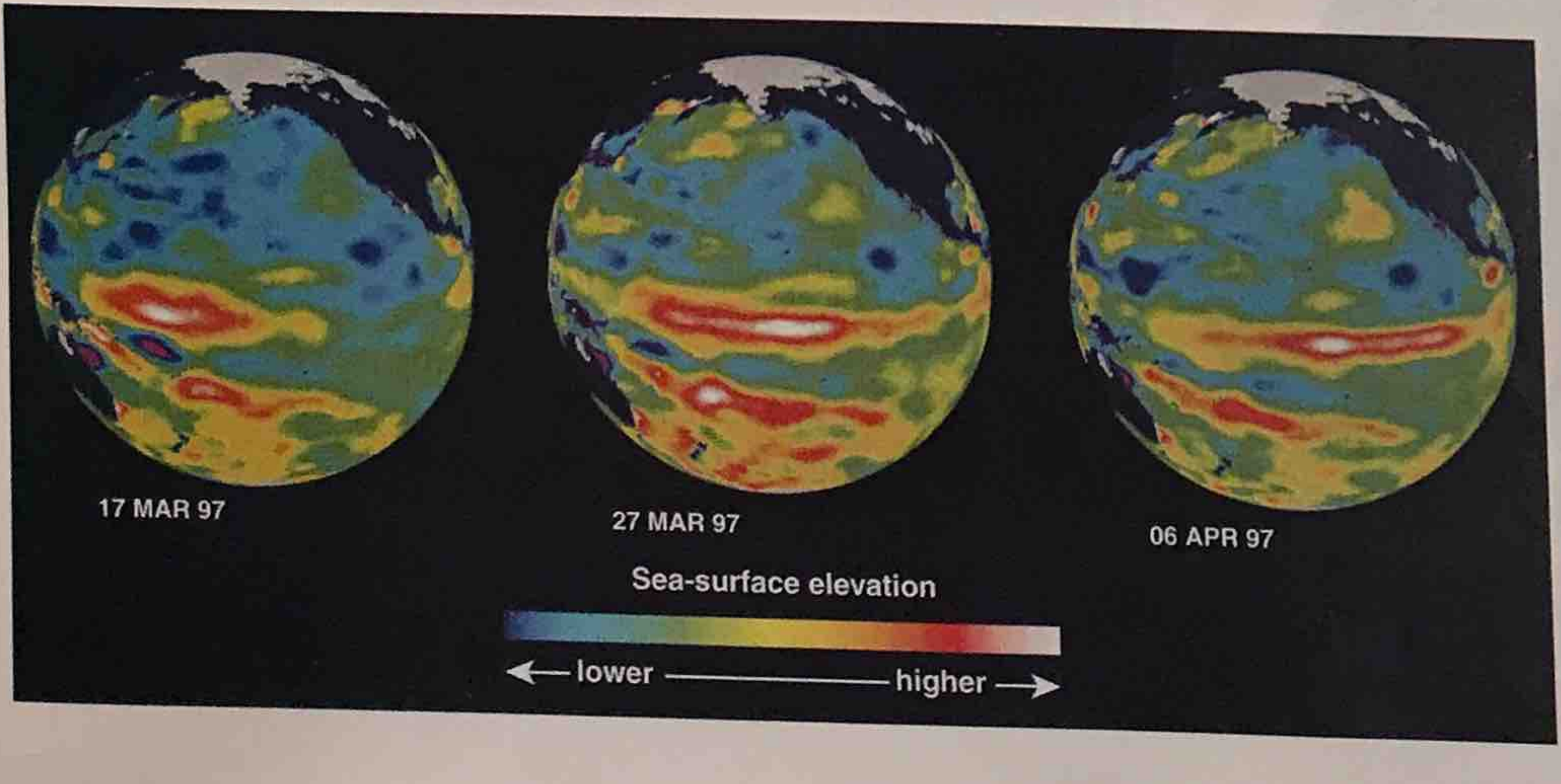
Video
El Niño

Walker had become director of the Meteorological Service in colonial India in 1903, where a search was underway for a method to predict the monsoon—when the life-giving South Asian monsoon failed to develop, drought and famine ravaged India. In the global meteorological records, Walker thought that he saw a pattern: in most years pressure is low over northern Australia (specifically, Darwin, Australia) and high over Tahiti, and in these years, the monsoon usually comes as expected.

However, in some years pressure is high in Darwin and low in Tahiti, and in these years the monsoon would often—but not always—fail. As it turned out, Walker's observed correlation between the monsoons in India and the Southern Oscillation of pressure was not reliable enough to predict the monsoons. However, by the 1960s meteorologists recognized a connection between Walker's Southern Oscillation and the occurrence of strong El Niño warming near South America. This overall coupled ocean-atmosphere pattern is now known as the **El Niño-Southern Oscillation** or simply ENSO.

**Learning Check 5-14** **How do the trade winds differ during an El Niño event compared with the normal pattern?**

**Onset of El Niño Event:** Although no two ENSO events are exactly alike, we can describe a typical El Niño cycle. For many months before the onset of an El Niño, the trade winds pile up warm water in the western Pacific near Indonesia. A bulge of warm equatorial water perhaps 25 centimeters (10 inches) high then begins to move to the east across the Pacific toward South America. Such slowly moving bulges of warm water are known as *Kelvin waves*. A Kelvin wave might take two or three months to arrive off the coast of South America (Figure 5-39). The bulge of warm water in a Kelvin wave spreads out little as it moves across the ocean since the Coriolis effect effectively funnels the eastward-moving water toward the equator in both hemispheres.



◄ **Figure 5-39** Progress of a Kelvin wave during the 1997–1998 El Niño. These satellite images from the California Institute of Technology, Jet Propulsion Laboratory, show the bulge of warm water in a Kelvin wave slowly moving across the equatorial Pacific Ocean.

**Arrival of El Niño Conditions:** When the Kelvin wave arrives at South America, sea level rises as the warm water pools. The usual high pressure in the subtropics has weakened; upwelling no longer brings cold water to the surface, so ocean temperature increases still further—an El Niño is under way. By this time, the trade winds have weakened or even reversed directions and started to flow from the west—blowing moist air into the deserts of coastal Peru. The thermocline boundary between near-surface and cold deep ocean waters lowers. Pressure increases over Indonesia and the most active portion of the ITCZ in the Pacific shifts from the now-cooler western Pacific, toward the now-warmer central and eastern Pacific basin. Drought strikes northern Australia and Indonesia; the South Asian monsoon may fail or develop weakly. The subtropical jet stream over the eastern Pacific shifts its path, guiding winter storms into the southwestern United States—California and Arizona experience more powerful winter storms than usual, resulting in high precipitation and flooding.

## La Niña

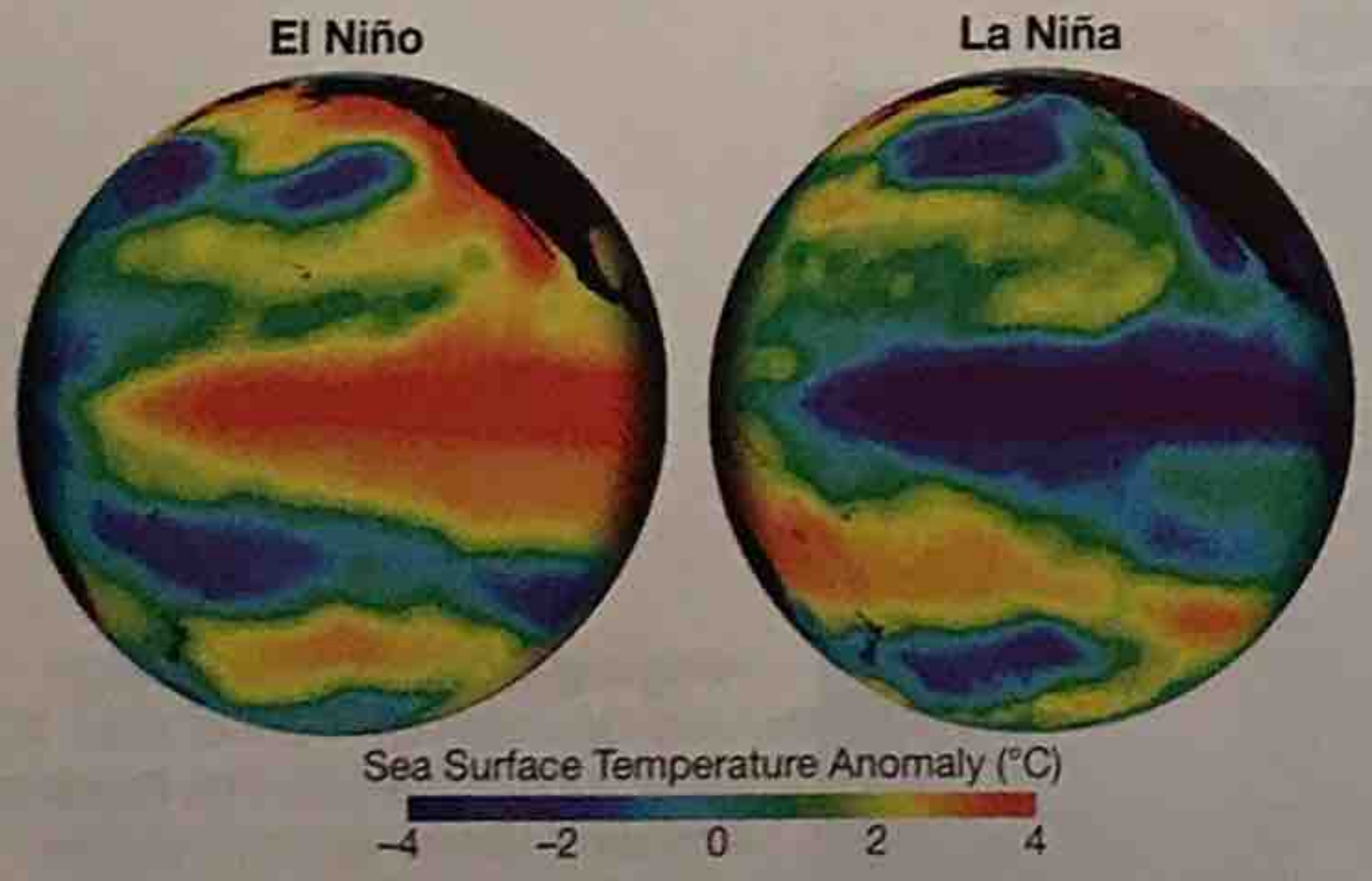
Video
La Niña

Adding to the complexity is a more recently recognized component of the ENSO cycle, **La Niña**. In some ways, La Niña is simply the opposite of El Niño: the waters off South America become unusually cool (Figure 5-40); the trade winds are stronger than usual; the waters off Indonesia are unusually warm; the southwestern United States is drier than usual while Southeast Asia and northern Australia are wetter.

Because El Niño and La Niña conditions are generally identified by sea-surface temperature trends, sometimes El Niño is referred to as the "warm" phase of ENSO while La Niña is referred to as the "cold" phase.

## Causes of ENSO

So which comes first with the onset of an El Niño event—the change in ocean temperature or the change in pressure and wind? The "trigger" of an ENSO event is not clear since atmospheric pressure and wind patterns are tied together with the ocean in a complex feedback loop with no clear starting point: if atmospheric pressure changes, wind changes; when wind changes, ocean currents and ocean temperature may change; when ocean temperature changes, atmospheric pressure changes—and that in turn may change wind patterns still more. In short, the causes of ENSO are not fully understood.



▲ **Figure 5-40** In contrast to the warm ocean conditions in the equatorial eastern Pacific during an El Niño event, ocean conditions are much cooler during a La Niña. These images show the temperature anomalies, or differences from average, during major El Niño and La Niña events.

Not only are the causes of ENSO elusive, even the effects are not completely predictable. For example, while a strong El Niño generally brings high precipitation to the southwestern United States, a mild or moderate El Niño could bring either drought or floods. Further, although we can generalize that during a strong El Niño high rainfall is more likely in California than in La Niña years, very wet winters can occur in any year no matter what ENSO is doing. In other words, El Niño might "open the storm door" every few years, but there is no guarantee that the storms will actually come.

## Teleconnections

As more has been learned about ENSO over the last few decades, its connections with oceanic and atmospheric conditions inside and outside the Pacific basin are increasingly being recognized (Figure 5-41). Drought in Brazil; cold winters in the southeastern United States; high temperatures in the Sahel; a weak monsoon in India; tornadoes in Florida; fewer hurricanes in the North Atlantic—all seem to correlate quite well with a strong El Niño event. Such coupling of weather and oceanic events in one part of the world with those in another are termed **teleconnections**. Adding to the complexity of these teleconnections is growing evidence that long-term ENSO patterns may be influenced by other ocean-atmosphere cycles, such as the *Pacific Decadal Oscillation* (discussed below).

Over the last century, El Niño events have occurred on average once every two to seven years. It appears that El Niños have been becoming more frequent and progressively warmer in recent decades—the 1997–1998 event was probably the strongest El Niño of the last 200 years, and it developed more rapidly than any in the last 50 years—although the reasons for this are not yet clear. A much weaker El Niño took place in 2002–2003, and a mild El Niño occurred in 2009–2010. Some scientists speculate that global warming may be influencing the intensity of the El Niño cycle, but a clear connection has not yet been found.

Over the last 30 years, great strides have been taken toward forecasting El Niño events months in advance—largely because of better satellite monitoring of ocean conditions and the establishment of the TAO/TRITON array of oceanic buoys in the tropical Pacific (see the box, "People and the Environment: Forecasting El Niño"). Although much remains to be learned, a clearer understanding of cause and effect, of countercause and countereffect of ENSO, is gradually emerging.

**Learning Check 5-15** **What is a *teleconnection?* Describe one example of a teleconnection.**

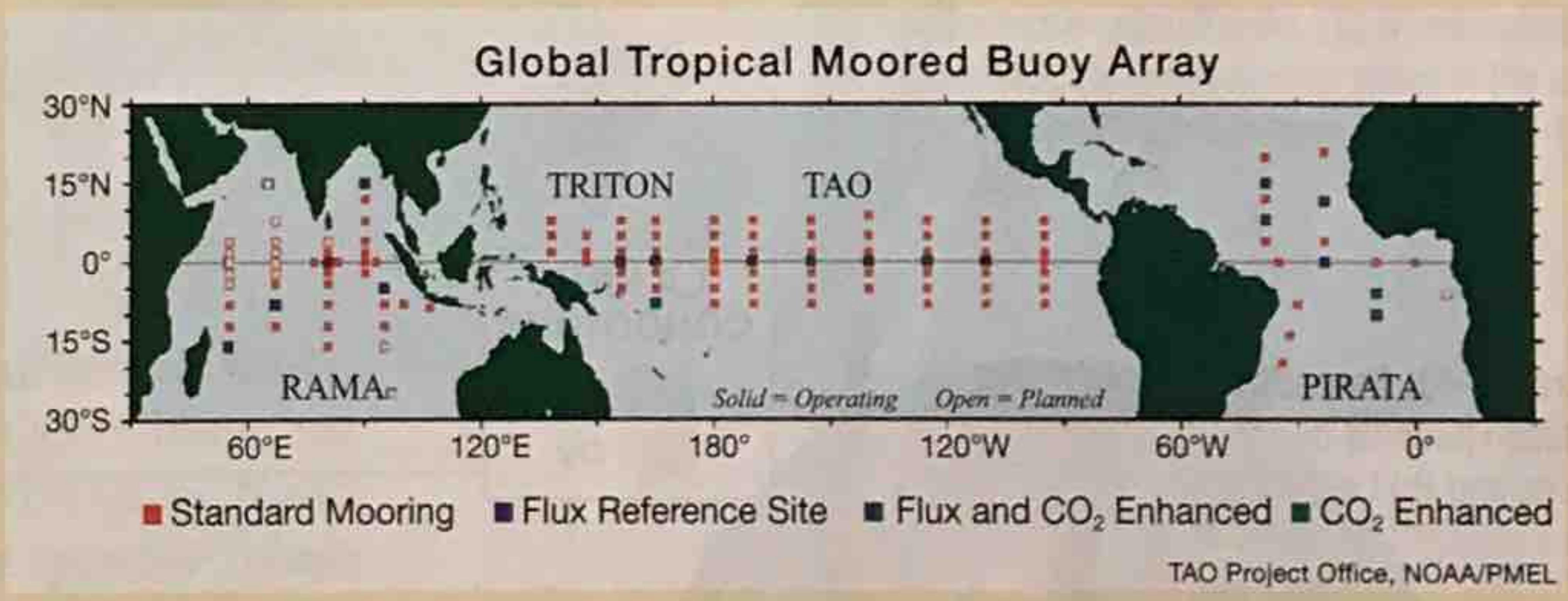
## PEOPLE AND THE ENVIRONMENT

# Forecasting El Niño

After the powerful El Niño of 1982–1983 caught large populations unprepared, a concerted multinational effort was undertaken to understand El Niño and its teleconnections. Part of this effort included anchoring some 70 instrument buoys in the tropical Pacific Ocean. Beginning in 1985, the initial installations were part of the Tropical Atmosphere Ocean Array (TOA) administered by the National Oceanic and Atmospheric Administration (NOAA), but the array was soon expanded to include the Triangle Trans Ocean Buoy Network (TRITON) maintained by Japan. The combined TAO/TRITON array monitors ocean and atmospheric conditions—especially sea-surface temperature and wind direction—across the tropical Pacific Ocean (Figure 5-C).

By 1994, sufficient data had been gathered to develop computer models to predict the onset of an El Niño event several months in advance. These efforts were rewarded in 1997: by that spring, the TAO/TRITON buoys were recording a surge of warm water moving to the east across the equatorial Pacific (Figure 5-D). Months in advance of its arrival, the onset of the strong 1997–1998 El Niño was announced by NOAA's Climate Prediction Center, and preparations were made for the series of powerful storms that eventually struck southwestern North America that winter. Because of this early success, the TAO/TRITON network was expanded to include the Research Moored Array for African-Asian-Australian Monsoon Analysis (RAMA) in the Indian Ocean, and the Prediction and Research Moored Array in the Atlantic (PIRATA), forming a complete Global Tropical Moored Buoy Array (see Figure 5-C).

**Changing El Niño Patterns:** Using data gathered by the TAO/TRITON array, by the late 1990s scientists were noticing a different kind of El Niño pattern than in previous decades; during some El Niño events, the warmest water is found in the central Pacific Ocean rather than the usual location in the eastern Pacific. For example, the 2009–2010 El Niño was very warm in the central Pacific, but only modestly so in the eastern Pacific (Figure 5-E). One hypothesis explaining this change is that climate change may be shifting the region of warmest water during an El Niño. If this is the case, forecasting the effects of El Niño may become more difficult until this new pattern is understood. The data supplied by the TAO/TRITON array will be indispensable in this quest to fully understand El Niño, as well as to understand the atmospheric and oceanic conditions in the tropical Pacific in general.



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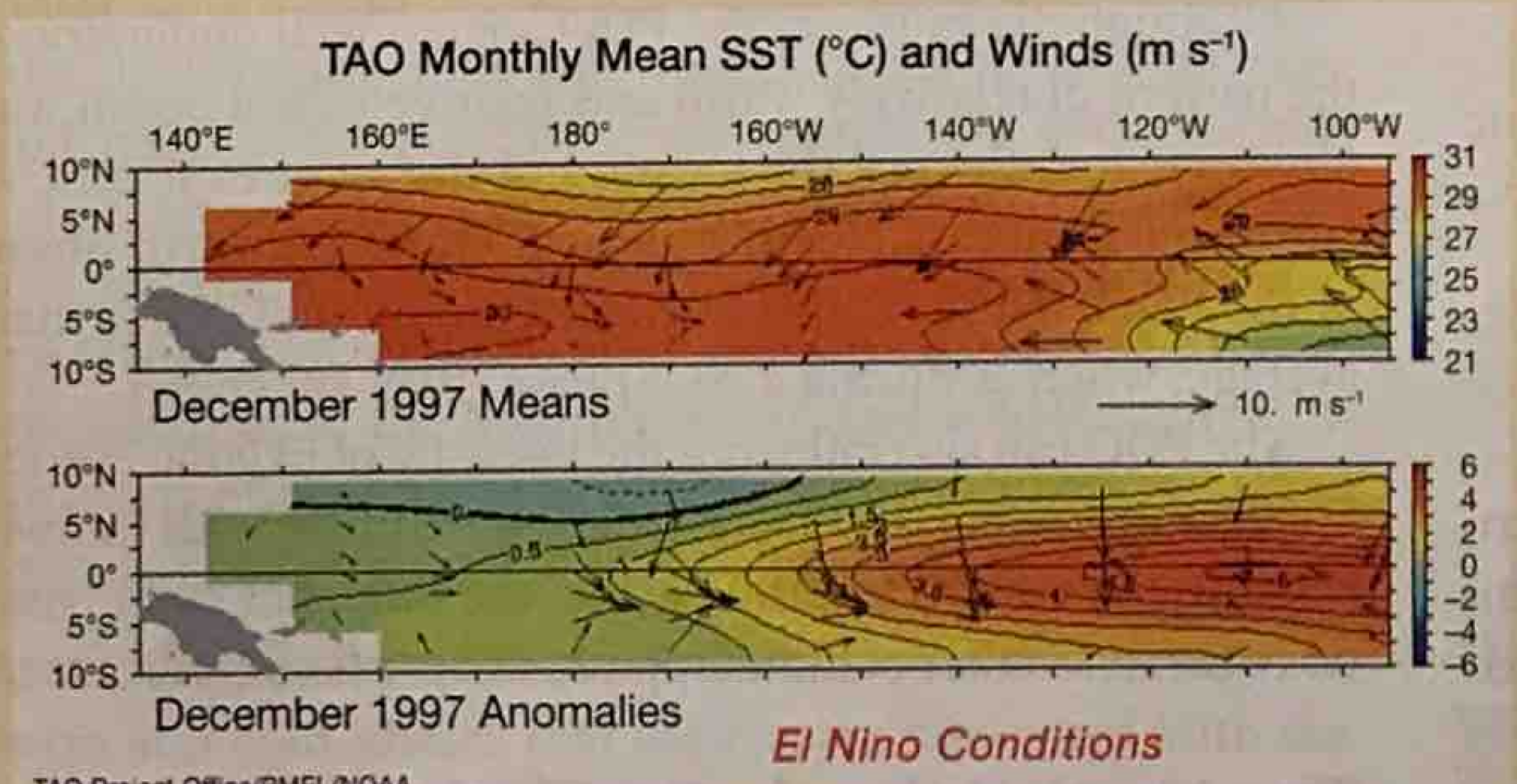
▲ **Figure 5-C** The TAO/TRITON Array of instrument buoys in the tropical Pacific Ocean is part of a Global Tropical Moored Buoy Array.



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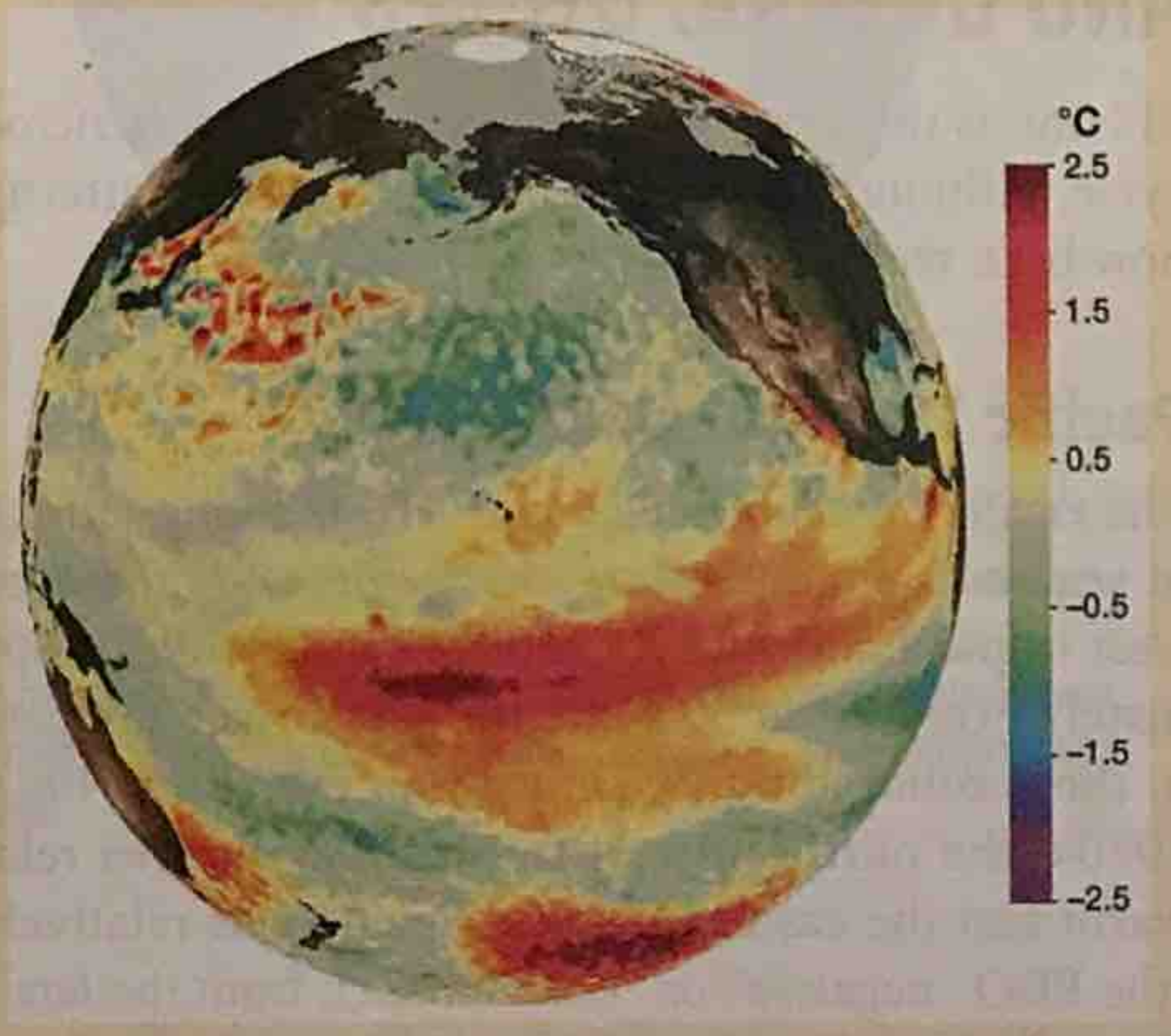
▲ **Figure 5-D** El Niño conditions in the tropical Pacific Ocean in December 1997; sea-surface temperature and wind measured by the TAO/TRITON Array. Orange areas represent warmer surface water temperatures.



▲ **Figure 5-E** Sea-surface temperature anomaly at the peak of the 2009–2010 El Niño. The greatest warming was in the central Pacific Ocean rather than the eastern Pacific.

# Chapter 5 LEARNING REVIEW

After studying this chapter, you should be able to answer the following questions. Key terms from each text section are shown in **bold type**. Definitions for key terms are also found in the glossary at the back of the book.

## KEY TERMS AND CONCEPTS

### The Nature of Atmospheric Pressure (*p. 110*)

1. What generally happens to **atmospheric pressure** with increasing altitude?
2. Explain how atmospheric pressure is related to air density and air temperature.
3. What causes a **thermal high** near the surface? A **thermal low**?
4. What causes a **dynamic high** near the surface? A **dynamic low**?
5. Define the following terms: **barometer**, **millibar**, **isobar**.
6. When referring to air pressure, what is a **high**, a **low**, a **ridge**, and a **trough**?
7. What is meant by a **pressure gradient**?

### The Nature of Wind (*p. 112*)

8. What three factors influence the direction of **wind** flow?
9. How and why are **friction layer** (surface) winds different from upper-atmosphere **geostrophic winds**?
10. Describe the relationship between the "steepness" of a pressure gradient and the speed of the wind along that pressure gradient. Describe the general wind speed associated with a gentle (gradual) pressure gradient and a steep (abrupt) pressure gradient.

### Cyclones and Anticyclones (*p. 115*)

11. Describe and explain the pattern of wind flow in the Northern Hemisphere around:
    - a surface high
    - a surface low
    - an upper atmosphere high
    - an upper atmosphere low

    *(You should be able to sketch in wind direction on isobar maps of highs and lows near the surface and in the upper atmosphere for both the Northern and Southern Hemispheres.)*
12. What is the reason for the difference in wind flow patterns in the Northern Hemisphere and the Southern Hemisphere?
13. What is a **cyclone**? An **anticyclone**?
14. Describe the pattern of vertical air movement within a cyclone and within an anticyclone.

### The General Circulation of the Atmosphere (*p. 116*)

15. What are the **Hadley cells**, and what generally causes them?
16. Describe the general location and characteristics of the following atmospheric circulation components:
    - **intertropical convergence zone (ITCZ)**
    - **trade winds**
    - **subtropical highs**
    - **westerlies**

    *(You should be able to sketch in the location of these four components on a blank map of an ocean basin.)*
17. Discuss the characteristic weather associated with the ITCZ and the characteristic weather associated with subtropical highs.
18. What are meant by the **horse latitudes** and the **doldrums**?
19. Describe the general location and characteristics of the **jet streams** of the westerlies.
20. What are **Rossby waves**?
21. Briefly describe the location and general characteristics of the high-latitude components of the general circulation patterns of the atmosphere:
    - **polar front (subpolar lows)**
    - **polar easterlies**
    - **polar highs**
22. Differentiate between trade winds and **antitrade winds**.

### Modifications of the General Circulation (*p. 126*)

23. Describe and explain the seasonal shifts of the general circulation patterns; especially note the significance of the seasonal shifts of the ITCZ and the subtropical highs.
24. Describe and explain the South Asian **monsoon**.

### Localized Wind Systems (*p. 129*)

25. Explain the origin of **sea breezes** and **land breezes**.
26. In what ways are sea breezes and land breezes similar to **valley breezes** and **mountain breezes**?
27. What is a **katabatic wind** and where are such winds commonly found?

28. In what ways are **Santa Ana winds** similar to **foehn** and **chinook** winds?

## El Niño–Southern Oscillation (*p. 131*)

29. What is the **Walker Circulation**?
30. Why is **El Niño** commonly referred to as **El Niño-Southern Oscillation (ENSO)**?
31. Contrast the oceanic and atmospheric conditions in the tropical Pacific Ocean basin during an El Niño event with those of a normal pattern.
32. Contrast the oceanic and atmospheric conditions during an El Niño event with those of a **La Niña** event.
33. What is meant by **teleconnections**?

## Other Multiyear Atmospheric and Oceanic Cycles (*p. 136*)

34. What are the conditions and weather effects of the "warm" phase and the "cool" phase of the Pacific Decadal Oscillation?