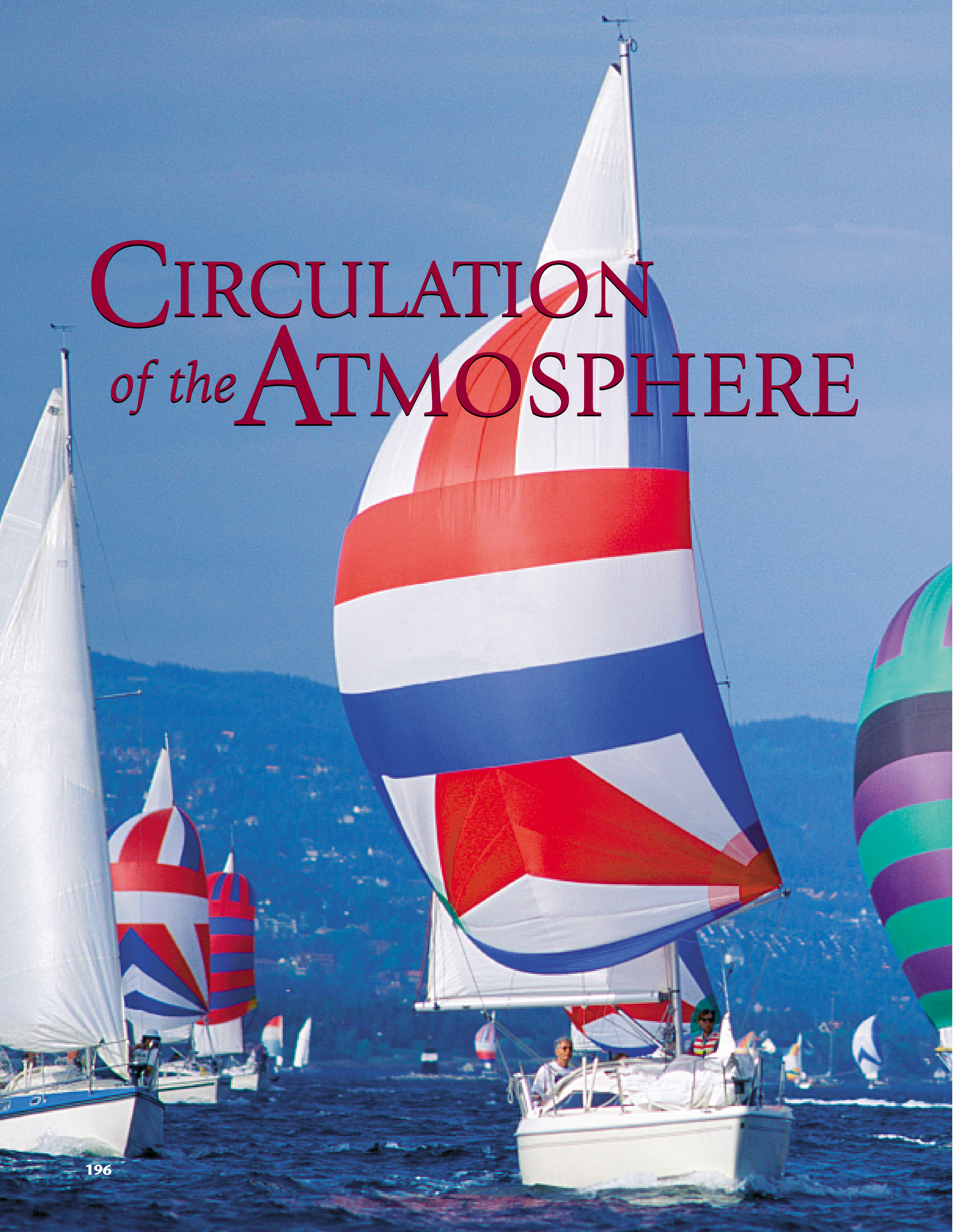
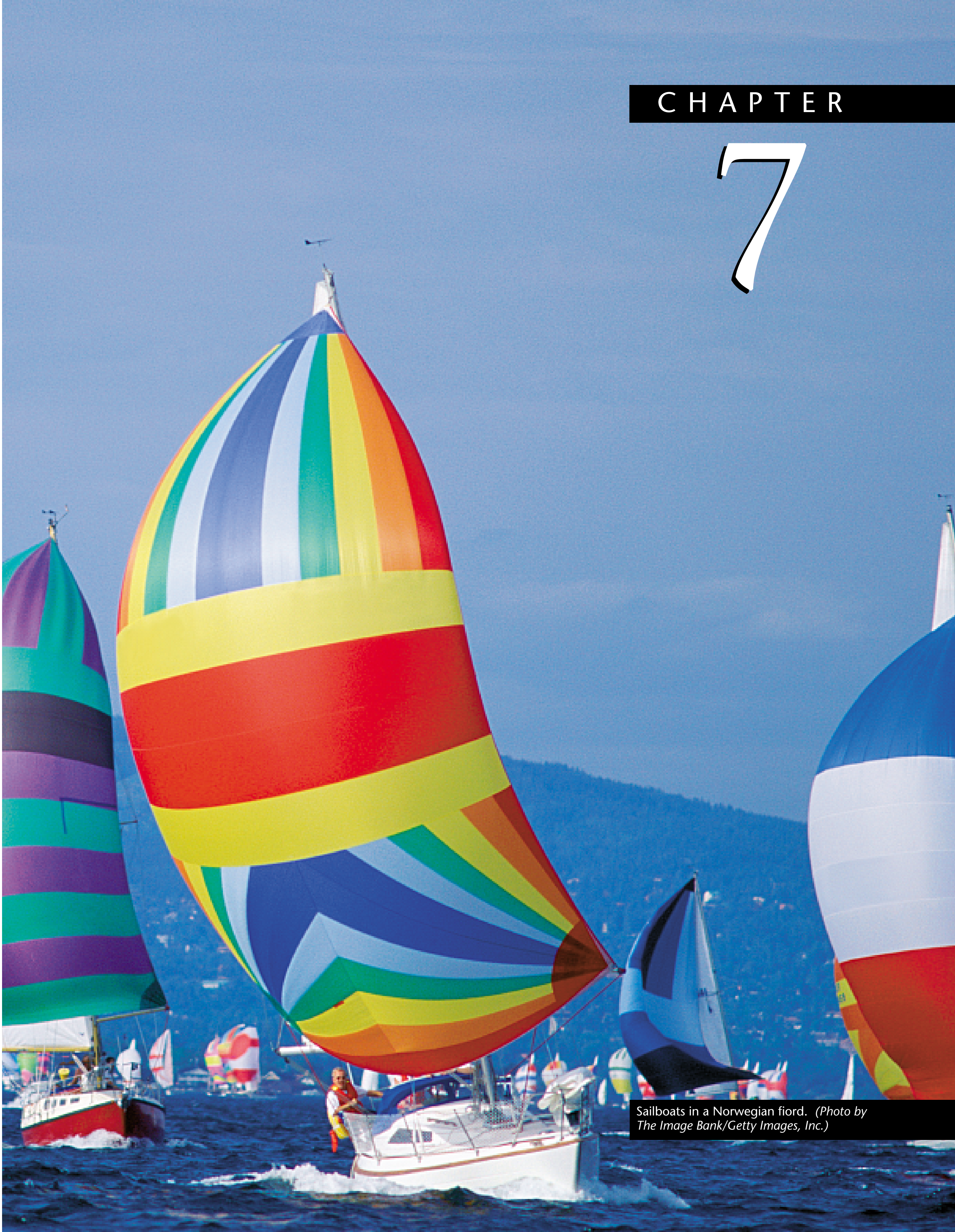


CIRCULATION of the ATMOSPHERE

CHAPTER

7



Sailboats in a Norwegian fiord. *(Photo by The Image Bank/Getty Images, Inc.)*

The main goal of this chapter is to gain an understanding of Earth's highly integrated wind system. Global atmospheric circulation can be thought of as a series of deep rivers of air that encircle the planet. Embedded in the main currents are vortices of various sizes including hurricanes, tornadoes, and midlatitude cyclones (Figure 7–1). Like eddies in a stream, these rotating wind systems develop and die out with somewhat predictable regularity. In general, the smallest eddies, such as dust devils, last only a few minutes, whereas larger and more complex systems, such as hurricanes, may survive for several days.

Recall from Chapter 6 that winds are generated by pressure differences that arise because of unequal heating of Earth's surface. Global winds are generated because the tropics receive more solar radiation than Earth's polar regions. Thus, Earth's winds blow in an unending attempt to balance inequalities in surface temperatures. Because the zone of maximum solar heating migrates with the seasons—moving northward during the Northern Hemisphere summer and southward as winter approaches—the wind patterns that make up the general circulation also migrate latitudinally.

Although we will focus on the global circulation, local wind systems will also be considered. The chapter concludes with a discussion of global precipitation patterns. As you will see, the global distribution of precipitation is closely linked to the patterns of atmospheric pressure and thus the global wind system.

Scales of Atmospheric Motion

Those who live in the United States are familiar with the term "westerlies" to describe the winds that predominately blow from west to east. But all of us have experienced winds from the south and north and even directly from the east. You may even recall being in a storm when shifts in wind direction and speed came in such rapid succession that it was impossible to determine the wind's direction. With such variations, how can we describe our winds as westerly? The answer lies in our attempt to simplify descriptions of the atmospheric circulation by sorting out events according to *size*. On the scale of a weather map, for instance, where observing stations are spaced about 150 kilometers apart, small whirlwinds that carry dust skyward are far too small to show up. Instead, weather maps reveal larger-scale wind patterns, such as those associated with traveling cyclones and anticyclones.

Not only do we separate winds according to the size of the system, but equal consideration is also given to the time frame in which they occur. In general, large weather patterns have longer life spans than do their smaller counterparts. For

FIGURE 7-1 In this satellite image, low clouds reveal a swirling wind pattern on the lee of Guadalupe Island. The airflow develops substantial rotation when it is too stable to flow over the top of a barrier such as this isolated island. *(Photo courtesy of NASA/Visuals Unlimited, Inc.)*

TABLE 7-1 Time and space scales for atmospheric motions

Scale	Time scale	Distance scale	Examples
Macroscale			
Planetary	Weeks or longer	1000–40,000 km	Westerlies and trade winds
Synoptic	Days to weeks	100–5000 km	Mid-latitude cyclones, anticyclones, and hurricanes
Mesoscale	Minutes to hours	1–100 km	Thunderstorms, tornadoes, and land–sea breeze
Microscale	Seconds to minutes	<1 km	Turbulence, dust devils, and gusts

example, dust devils usually last a few minutes and rarely occur for more than an hour. By contrast, midlatitude cyclones typically take a few days to cross the United States and occasionally dominate the weather for a week or longer. The time and size scales we will use for atmospheric motions are provided in Table 7–1.

Large- and Small-Scale Circulation

The wind systems shown in Figure 7–2 illustrate the three major categories of atmospheric circulation: macroscale, mesoscale and microscale. *Macroscale* circulation includes large planetary-scale flow, such as the trade winds that blow consistently for weeks or longer as well as smaller features like hurricanes (Figure 7–2a). *Mesoscale* circulation is associated with tornadoes, thunderstorms, and numerous *local winds* that generally last from minutes to hours. Finally, *microscale* events have life spans of from a few seconds to minutes and include dust devils, gusts, and general atmospheric turbulence.

Macroscale Winds. The largest wind patterns, called **macroscale winds,** are exemplified by the westerlies and trade winds that carried sailing vessels back and forth across the Atlantic during the opening of the New World. These *planetary-scale* flow patterns extend around the entire globe and can remain essentially unchanged for weeks at a time.

A somewhat smaller macroscale circulation is called *synoptic scale,* or *weather-map scale.* Two well-known synoptic scale systems are the individual traveling cyclones and anticyclones that appear on weather maps as areas of low and high pressure, respectively. These weather producers are found in the middle latitudes where they move from west to east as part of the larger westerly flow. Furthermore, these rotating systems usually persist for days or occasionally weeks and have a horizontal dimension of hundreds to thousands of kilometers. Recall that the direction of surface flow around a cyclone is toward the center with a general upward component. Anticyclones, in contrast, are areas of subsidence associated with outward flow near the surface. The average rate of vertical motion within these systems is slow, typically less than 1 kilometer per day.

Somewhat smaller macroscale systems are the tropical cyclones and hurricanes that develop in late summer and early fall over the warm tropical oceans. Airflow in these systems is inward and upward as in the larger midlatitude cyclones. However, the rate of horizontal flow associated with hurricanes is usually more rapid than that of their more poleward cousins.

Mesoscale Winds. **Mesoscale winds** generally last for several minutes and may exist for hours. These middle-size phenomena are usually less than 100 kilometers (62 miles) across. Further, some mesoscale winds—for example, thunderstorms and tornadoes—also have a strong vertical component (Figure 7–2b). It is important to remember that thunderstorms and tornadoes are always imbedded within and thus move as part of the larger macroscale circulation. Further, much of the vertical air movement within a midlatitude cyclone, or hurricane, is provided by thunderstorms, where updrafts in excess of 100 kilometers (62 miles) per hour have been measured. Land and sea breezes, as well as mountain and valley winds, also fall into this category and will be discussed in the next section along with other mesoscale winds.

Microscale Winds. The smallest scale of air motion is referred to as **microscale circulation.** These small, often chaotic winds normally last for seconds or at most minutes. Examples include simple gusts, which hurl debris into the air (Figure 7–2c) and small, well-developed vortices such as dust devils (see Box 7–1).

Structure of Wind Patterns

Although it is common practice to divide atmospheric motions according to scale, remember that global winds are a composite of all scales of motion—much like a meandering river that contains large eddies composed of smaller eddies containing still smaller eddies. For example, let us examine the flow associated with hurricanes that form over the North Atlantic. When we view one of these tropical cyclones on a satellite image, the storm appears as a large whirling cloud migrating slowly across the ocean (see Figure 7–2a). From this perspective, which is at the weather-map (synoptic) scale, the general counterclockwise rotation of the storm can be easily seen.

When we average the winds of hurricanes, we find that they often have a net motion from east to west, thereby indicating that these larger eddies are embedded in a still larger flow (planetary scale) that is moving westward across the tropical portion of the North Atlantic.

(a) (b) (c)

FIGURE 7-2 Three scales of atmospheric motion. (a) Satellite image of Hurricane Nora, an example of macroscale circulation. (b) Tornadoes exemplfy mesoscale wind systems. (c) Gusts illustrate microscale winds. *(Photos by (a) NASA/Science Photo Library/Photo Researchers, Inc., (b) A. and J. Verkaik/CORBIS/The Stock Market, (c) E.J. Tarbuck)*

If we examine a hurricane more closely by flying an airplane through it, some of the small-scale aspects of the storm become noticeable. As the plane approaches the outer edge of the system, it becomes evident that the large rotating cloud that we saw in the satellite images is made of many individual cumulonimbus towers (thunderstorms). Each of these mesoscale phenomena lasts for only a few hours and must be continually replaced by new ones if the hurricane is to persist. As we fly into these storms, we quickly realize that the individual clouds are made up of even smaller-scale turbulences. The small thermals of rising air that occur in these clouds make for a rather rough trip.

Thus, a typical hurricane exhibits several scales of motion, including many mesoscale thunderstorms, which, in turn, consist of numerous microscale turbulences. Furthermore, the counterclockwise circulation of the hurricane (weather-map scale) is imbedded in the global winds (planetary scale) that flow from east to west in the tropical North Atlantic.

Students Sometimes Ask…

What is the highest wind speed ever recorded?

The highest wind speed recorded at a surface station is 372 kilometers (231 miles) per hour, measured April 12, 1934, at Mount Washington, New Hampshire. Located at an elevation of 1879 meters (6,262 feet), the observatory atop Mount Washington has an average wind speed of 56 kilometers (35 miles) per hour. Faster wind speeds have undoubtedly occurred on mountain peaks, but no instruments were in place to record them.

Local Winds

Before examining the large macroscale circulation for Earth, let us turn to some mesoscale winds (time frame of minutes to hours and size of 1 to 100 kilometers—Table 7–1). Remem-

BOX 7-1 Dust Devils

A common phenomenon in arid regions of the world is the whirling vortex called the *dust devil* (Figure 7–A). Although they resemble tornadoes, dust devils are generally much smaller and less intense than their destructive cousins. Most dust devils are only a few meters in diameter and reach heights no greater than about 100 meters (300 feet). Further, these whirlwinds are usually short-lived microscale phenomena. Most form and die out within minutes. In rare instances dust devils have lasted for hours.

Unlike tornadoes, which are associated with convective clouds, dust devils form on days when clear skies dominate. Further, these whirlwinds form from the ground upward, exactly opposite of tornadoes. Because surface heating is critical to their formation, dust devils occur most frequently in the afternoon when surface temperatures are highest.

Recall that when the air near the surface is considerably warmer than the air a few dozen meters overhead, the layer of air near Earth's surface becomes unstable. In this situation warm surface air begins to rise, causing air near the ground to be drawn into the developing whirlwind. The rotating winds that are associated with dust devils are produced by the same phenomenon that causes ice skaters to spin faster as they pull their arms closer to their body. (For an expanded discussion of this process, see Box 11–1, Chapter 11.) As the inwardly spiraling air rises, it carries sand, dust, and other loose debris dozens of meters into the air. It is this material that makes a dust devil visible. Occasionally, dust devils form above vegetated surfaces. Under these conditions, the vortices may go undetected unless they interact with objects at the surface.

Most dust devils are small and short-lived; consequently, they are not generally destructive. Occasionally, however, these whirlwinds grow to be 100 meters or more in diameter and over a kilometer high. With wind speeds that may reach 100 kilometers (60 miles) per hour, large dust devils can do considerable damage. Fortunately, such occurrences are few and far between.

FIGURE 7-A Dust devil. Although these whirling vortices resemble tornadoes, they have different origins and are much smaller and less intense. *(Courtesy of St. Meyers/Okapia/Photo Researchers, Inc.)*

ber that all winds have the same cause: pressure differences that arise because of temperature differences caused by unequal heating of Earth's surface. Local winds are medium-scale winds produced by a locally generated pressure gradient.

Although many winds are given local names, some are actually part of the global wind system. The "norther" of Texas, for instance, is a cold southward flow produced by the circulation around anticyclones that invade the United States from Canada in the winter. Because these winds are not locally generated, they cannot be considered true local winds. Others, like those about to be described, are truly mesoscale and are caused either by topographic effects or variations in local surface composition.

Recall that winds are named for the direction *from which they blow.* This holds true for local winds. Thus, a sea breeze originates over water and blows toward the land, whereas a valley breeze blows upslope away from its source.

Land and Sea Breezes

The daily temperature contrast between the land and the sea, and the pressure pattern that generates a sea breeze, was discussed in the preceding chapter (see Figure 6–11). Recall that land is heated more intensely during daylight hours than is an adjacent body of water. As a result, the air above the land surface heats and expands, creating an area of low pressure. A **sea breeze** then develops, as cooler air over the water moves onto the land (Figure 7–3a). At night, the reverse may take place; the land cools more rapidly than the sea and a **land breeze** develops (Figure 7–3b).

The sea breeze has a significant moderating influence on coastal temperatures. Shortly after the breeze begins, air temperatures over the land may drop by as much as 5° to 10°C. However, the cooling effect of these breezes generally reaches a maximum of only about 100 kilometers (60 miles) inland in the tropics and often less than half that distance in the middle latitudes. These cool sea breezes generally begin shortly before noon and reach their greatest intensity, about 10 to 20 kilometers per hour, in the midafternoon.

Smaller-scale sea breezes can also develop along the shores of large lakes. People who live in a city near the Great Lakes, such as Chicago, recognize the "lake effect," especially in the summer. Residents are reminded daily by reports of the cooler temperatures near the lake compared to warmer outlying areas. In many places sea breezes also affect the amount of cloud cover and rainfall. The peninsula of Florida, for example, experiences a summer precipitation maximum caused partly by the convergence of sea breezes from both the Atlantic and Gulf coasts.

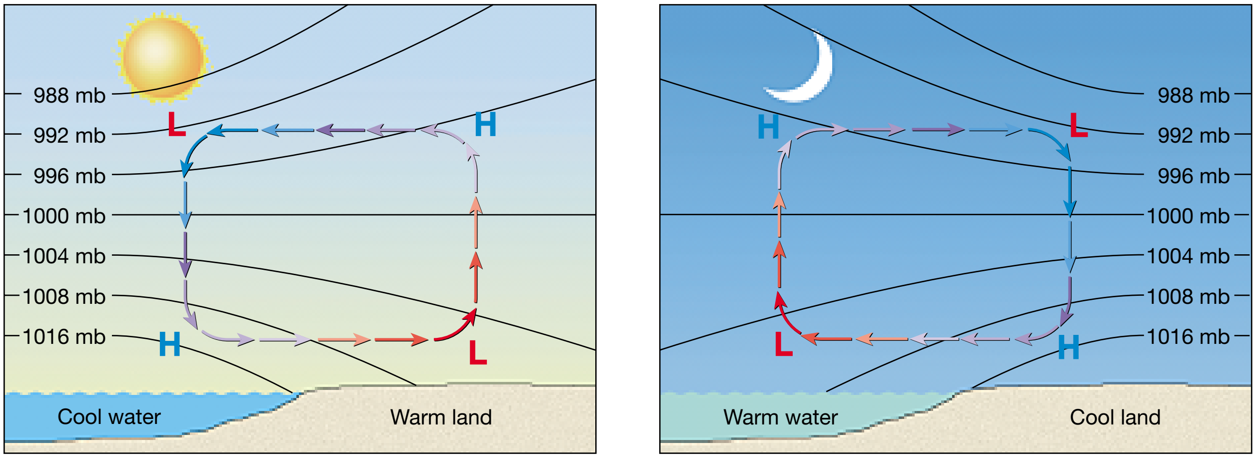
The intensity and extent of land and sea breezes depend on the location and the time of year. Tropical areas where intense solar heating is continuous throughout the year experience more frequent and stronger sea breezes than do midlatitude locations. The most intense sea breezes develop along tropical coastlines adjacent to cool ocean currents. In the middle latitudes, sea breezes are most common during the warmest months, but the counterpart, the land breeze, is often missing, for the land does not always cool below the ocean temperature. In the higher middle latitudes the frequent migration of high- and low-pressure systems dominates the circulation, so land and sea breezes are less noticeable.

Mountain and Valley Breezes

A daily wind similar to land and sea breezes occurs in many mountainous regions. During the day, air along mountain slopes is heated more intensely than air at the same elevation over the valley floor (Figure 7–4a). This warmer air glides up along the mountain slope and generates a **valley breeze.** The occurrence of these daytime upslope breezes can often be identified by the isolated cumulus clouds that develop over adjacent mountain peaks (Figure 7–5). This also causes the late afternoon thundershowers so common on warm summer days in the mountains. After sunset the pattern is reversed. Rapid radiation heat loss along the mountain slopes cools the air, which drains into the valley below and causes a **mountain breeze** (Figure 7–4b). Similar cool air drainage can occur in regions that have little slope. The result is that the coldest pockets of air are usually found in the lowest spots, a phenomenon you likely have experienced while walking in hilly terrain. Consequently, low areas are the first to experience radiation fog and are the most likely spots for frost damage to crops.

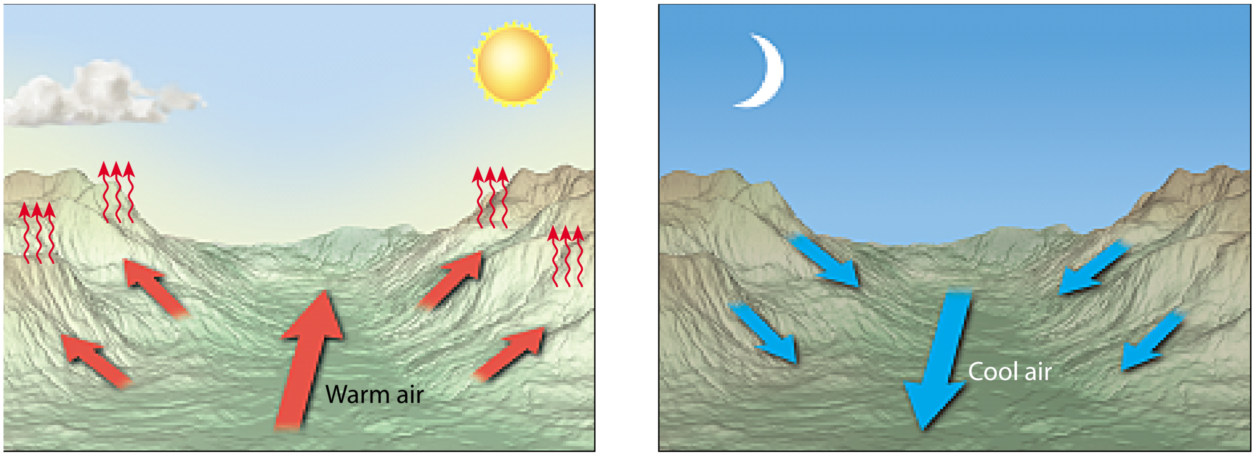
Like many other winds, mountain and valley breezes have seasonal preferences. Although valley breezes are most common during the warm season when solar heating is most intense, mountain breezes tend to be more frequent during the cold season.

FIGURE 7-3 Illustration of a sea breeze and a land breeze. (a) During the daylight hours the air above the land heats and expands, creating an area of lower pressure. Cooler and denser air over the water moves onto the land, generating a sea breeze. (b) At night the land cools more rapidly than the sea, generating an offshore flow called a *land breeze.*



(a) Sea breeze

(b) Land breeze



(a) Valley breeze

(b) Mountain breeze

FIGURE 7-4 Valley and mountain breezes. (a) Heating during the daylight hours warms the air along the mountain slopes. This warm air rises, generating a valley breeze. (b) After sunset, cooling of the air near the mountain can result in cool air drainage into the valley, producing the mountain breeze.

Chinook (Foehn) Winds

Warm, dry winds sometimes move down the east slopes of the Rockies, where they are called **chinooks,** and the Alps, where they are called **foehns.** Such winds are often created when a strong pressure gradient develops in a mountainous region. As the air descends the leeward slopes of the mountains, it is heated adiabatically (by compression). Because condensation may have occurred as the air ascended the windward side, releasing latent heat, the air descending the leeward side will be warmer and drier than at a similar elevation on the windward side. Although the temperature of these winds is generally less than 10°C (50°F), which is not particularly warm, they usually occur in the winter and spring when the affected area may be experiencing subfreezing temperatures. Thus, by comparison, these dry, warm winds often bring drastic change. Within minutes of the arrival of a chinook, the temperature may climb 20°C (36°F). When the ground has a snow cover, these winds melt it in short order. The Native American word *chinook* means "snoweater."

The chinook is viewed by some as beneficial to ranchers east of the Rockies, for it keeps their grasslands clear of snow during much of the winter, but this benefit is offset by the loss of moisture that the snow would bequeath to the land if it remained until the spring melt.

Another chinooklike wind that occurs in the United States is the **Santa Ana.** Found in southern California, these hot, desiccating winds greatly increase the threat of fire in this already dry area (see Box 7–2).

Students Sometimes Ask…

A friend who lives in Colorado talks about "snow eaters." What are they?

"Snow eaters" is a local term for chinooks, the warm, dry winds that descend the eastern slopes of the Rockies. These winds have been known to melt more than a foot of snow in a single day. A chinook that moved through Granville, North Dakota, on February 21, 1918, caused the temperature to rise from −33°F to 50°F, an increase of 83°F!

Katabatic (Fall) Winds

In the winter, areas adjacent to highlands may experience a local wind called a **katabatic wind** or **fall wind.** These winds originate when cold air, situated over a highland area such as the ice sheets of Greenland or Antarctica, is set in motion. Under the influence of gravity, the cold air cascades over the rim of a highland like a waterfall. Although the air is heated adiabatically, as are chinooks, the initial temperatures are so low that the wind arrives in the lowlands still colder and more dense than the air it displaces. In fact, this air *must* be colder than the air it invades, for it is the air's greater density that causes it to descend. As this frigid air descends, it occasionally is channeled into narrow valleys, where it acquires velocities capable of great destruction.

FIGURE 7-5 The occurrence of a daytime upslope (valley) breeze is identified by cloud development on mountain peaks, sometimes progressing to a midafternoon thunderstorm. *(Photo by James E. Patterson/James Patterson Collection)*

BOX 7-2 Atmospheric Hazard: Santa Ana Winds and Wildfires

FIGURE 7-B Ten large wildfires rage across southern California in this image taken on October 27, 2003, by NASA's *Aqua* satellite. *(Photo courtesy of NASA)*

A few of the better-known katabatic winds have local names. Most famous is the **mistral,** which blows from the French Alps toward the Mediterranean Sea. Another is the **bora,** which originates in the mountains of Yugoslavia and blows to the Adriatic Sea.

Country Breezes

One mesoscale wind, called a **country breeze,** is associated with large urban areas. As the name implies, this circulation pattern is characterized by a light wind blowing into the city from the surrounding countryside. The country breeze is best developed on relatively clear, calm nights. Under these conditions cities, because they contain massive buildings composed of rocklike materials, tend to retain the heat accumulated during the day more than the less built up outlying areas (see Box 3–4 on the urban heat island). The result is that the warm, less dense air over the city rises, which in turn initiates the country-to-city flow.

One investigation in Toronto showed that heat accumulated within this city created a rural/city pressure difference that was sufficient to cause an inward and counterclockwise circulation centered on the downtown area. One of the unfortunate consequences of the country breeze is that pollutants emitted near the urban perimeter tend to drift in and concentrate near the city's center.

Global Circulation

Our knowledge of global winds comes from two sources: the patterns of pressure and winds observed worldwide, and theoretical studies of fluid motion. We first consider the classical model of global circulation that was developed largely from average worldwide pressure distribution. We then add to this idealized circulation more recently discovered aspects of the atmosphere's complex motions.

People living in southern California are well aware of chinook-type winds called the *Santa Anas*. These hot, dry, dust-bearing winds invade California most often in autumn when they bring temperatures that often approach 32°C (90°F) and may occasionally exceed 38°C (100°F). When a strong anticyclone is centered over the Great Basin, the clockwise flow directs desert air from Arizona and Nevada westward toward the Pacific. The wind gains speed as it is funneled through the canyons of the Coast Ranges, in particular the Santa Ana Canyon, from which the winds derive their name. Compressional heating of this already warm, dry air as it descends mountain slopes further accentuates the already parched conditions. Vegetation, seared by the summer heat, is dried even further by these desiccating winds.

In late October 2003, Santa Anas began blowing toward the coast of southern California, with speeds that sometimes exceeded 100 kilometers (60 miles) per hour. Much of this area is covered by brush known as chaparral and related shrubs. It didn't take much—a careless camper or motorist, a lightning strike, or an arsonist—to ignite a fire. Soon a number of outbreaks occurred in portions of Los Angeles, San Bernardino, Riverside, and San Diego counties (Figure 7–B). Several developed quickly into wildfires that moved almost as fast as the ferocious Santa Ana winds sweeping through the canyons.

FIGURE 7-C Flames from a wildfire fanned by Santa Ana winds move toward a home south of Valley Center, California, on October 27, 2003. *(Photo by Denis Poroy/Associated Press)*

Within a few days more than 13,000 firefighters were on firelines that extended from north of Los Angeles to the Mexican border. Nearly two months later, when all the fires were officially extinguished, more than 742,000 acres had been scorched, over 3000 homes destroyed, and 26 people killed (Figure 7–C). The Federal Emergency Management Agency put the dollar losses at over $2.5 billion. The 2003 southern California wildfires became the worst fire disaster in the state's history.

Strong Santa Ana winds, coupled with dry summers, have produced wildfires in southern California for a millennia. These fires are nature's way of burning out chaparral thicket and sage scrub to prepare the land for new growth. The problem began when people started to crowd into the fire-prone area between Santa Barbara and San Diego. Residents have compounded the danger by landscaping their yards with highly flammable eucalyptus and pine trees. Furthermore, successful fire prevention has allowed the buildup of even more flammable material. Clearly, wildfires will remain a major threat in these areas into the foreseeable future.

Students Sometimes Ask…

What is a haboob?

A haboob is a type of local wind that occurs in arid regions. The name was originally applied to strong dust storms in the African Sudan, where one city experiences an average of 24 per year. (The name comes form the Arabic word *habb,* meaning "wind.") Haboobs generally occur when downdrafts from large thunderstorms swiftly move across the desert. Tons of silt, sand, and dust are lifted, forming a whirling wall of debris hundreds of meters high. These dense, dark "clouds" can completely engulf desert towns and deposit enormous quantities of sediment. The deserts of the southwestern United States occasionally experience dust storms produced in this manner.

Single-Cell Circulation Model

One of the first contributions to the classical model of global circulation came from George Hadley in 1735. Hadley was well aware that solar energy drives the winds. He proposed that the large temperature contrast between the poles and the equator creates one large *convection cell* in each hemisphere (Northern and Southern), as shown in Figure 7–6.

In Hadley's model, intensely heated equatorial air rises until it reaches the tropopause, where it begins to spread toward the poles. Eventually, this upper-level flow would reach the poles, where cooling would cause it to sink and spread out at the surface as equatorward-moving winds. As this cold polar air approached the equator, it would be reheated and rise again. Thus, the circulation proposed by Hadley has upper-level air flowing poleward and surface air moving equatorward.

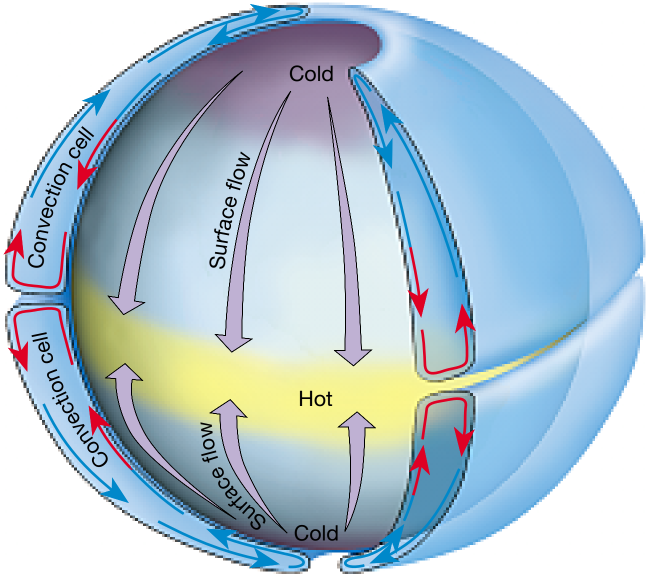


FIGURE 7-6 Global circulation on a nonrotating Earth. A simple convection system is produced by unequal heating of the atmosphere on a nonrotating Earth.

Although correct in principle, Hadley's model does not take into account the fact that Earth rotates on its axis. (Hadley's model would better approximate the circulation of a *nonrotating* planet.) As Earth's pressure and wind patterns became better known, it was clear that the single-cell model (in each hemisphere) could not create the global circulation that was actually observed. Consequently, the Hadley model was replaced by a model that better fit observations.

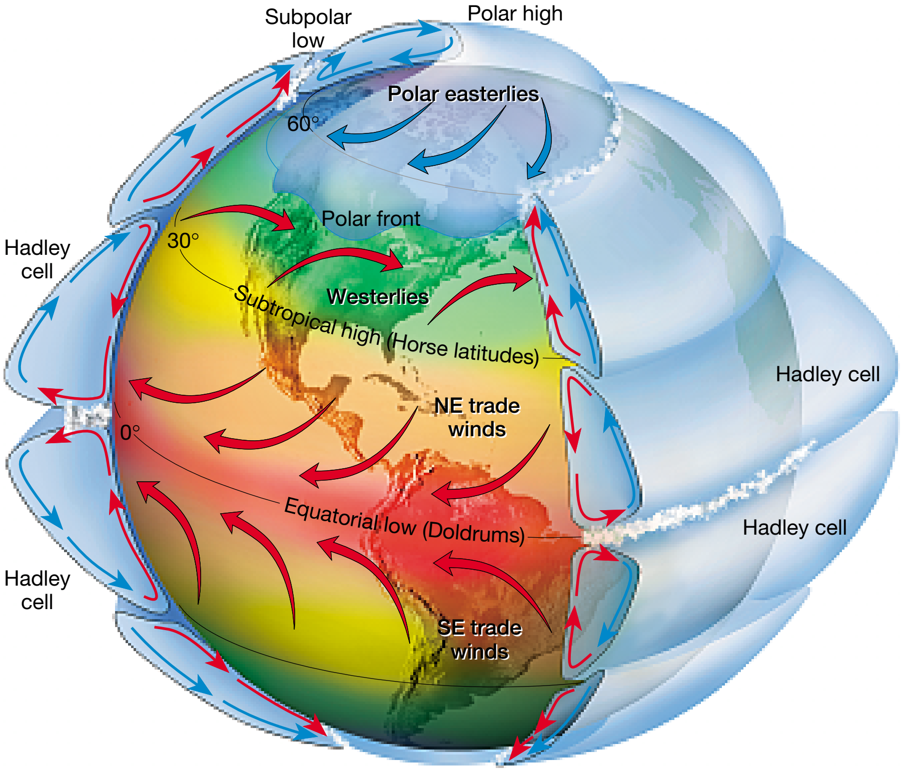
Three-Cell Circulation Model

In the 1920s a three-cell circulation model (for each hemisphere) was proposed. Although this model has been modified to fit upper-air observations, it remains a useful way to examine global circulation. Figure 7–7 illustrates the idealized three-cell model and the surface winds that result.

In the zones between the equator and roughly 30° latitude north and south, the circulation closely resembles the model used by Hadley for the whole Earth. Consequently, the name **Hadley cell** is generally applied. Near the equator, the warm rising air that releases latent heat during the formation of cumulus towers is believed to provide the energy to drive the Hadley cells. The clouds also provide the rainfall that maintains the lush vegetation of the rain forests of southeast Asia, equatorial Africa, and South America's Amazon Basin.

As the flow aloft in Hadley cells moves poleward, it begins to subside in a zone between 20° and 35° latitude. Two factors contribute to this general subsidence: (1) As upper-level flow moves away from the stormy equatorial region, where the release of latent heat of condensation keeps the air warm and buoyant, radiation cooling increases the density of the air. Satellites that monitor radiation emitted in the upper troposphere record considerable outward-emitted radiation over the tropics. (2) Because the Coriolis force becomes stronger with increasing distance from the equator, the poleward-moving upper air is deflected into a nearly west-to-east flow by the time it reaches 25° latitude. Thus, a restricted poleward flow of air ensues. Stated another way, the Coriolis force causes a general pileup of

FIGURE 7-7 Idealized global circulation proposed for the three-cell circulation model of a rotating Earth.



air (convergence) aloft. As a result, general subsidence occurs in the zones located between 20° and 35° latitude.

This subsiding air is relatively dry, because it has released its moisture near the equator. In addition, the effect of adiabatic heating during descent further reduces the relative humidity of the air. Consequently, this zone of subsidence is the site of the world's subtropical deserts. The Sahara Desert of North Africa and the Great Australian Desert are located in these regions of sinking air.

Because winds are generally weak and variable near the center of this zone of descending air, this region is popularly called the **horse latitudes.** The name is believed to have been coined by Spanish sailors, who, while crossing the Atlantic, were sometimes becalmed in these waters and reportedly were forced to throw horses overboard when they could no longer water or feed them.

From the center of the horse latitudes, the surface flow splits into a poleward branch and an equatorward branch. The equatorward flow is deflected by the Coriolis force to form the reliable **trade winds,** so called because they enabled early sailing ships to trade between continents. In the Northern Hemisphere, the trades blow from the northeast, where they provided the sail power for exploration of the New World in the sixteenth and seventeenth centuries. In the Southern Hemisphere, the trades are from the southeast. The trade winds from both hemispheres meet near the equator in a region that has a weak pressure gradient. This region is called the **doldrums.** Here light winds and humid conditions provide the monotonous weather that is the basis for the expression "down in the doldrums."

In the three-cell model the circulation between 30° and 60° latitude (north and south) is more complicated than that within the Hadley cells (Figure 7–7). The net surface flow is poleward, and because of the Coriolis force, the winds have a strong westerly component. These **prevailing westerlies** were known to Benjamin Franklin, perhaps the first American weather forecaster, who noted that storms migrated from west to east across the colonies. Franklin also observed that the westerlies were much more sporadic and, therefore, less reliable than the trade winds for sail power. We now know that it is the migration of cyclones and anticyclones across the midlatitudes that disrupts the general westerly flow at the surface. Because of the importance of the midlatitude circulation in producing our daily weather, we will consider the westerlies in more detail in a later section.

Relatively little is known about the circulation in high (polar) latitudes. It is generally understood that subsidence near the poles produces a surface flow that moves equatorward and is deflected into the **polar easterlies** of both hemispheres. As these cold polar winds move equatorward, they eventually encounter the warmer westerly flow of the midlatitudes. The region where the flow of warm air clashes with cold air has been named the **polar front.** The significance of this region will be considered later.

Observed Distribution of Pressure and Winds

As you might expect, Earth's global wind patterns are associated with a distinct distribution of surface air pressure. To simplify this discussion, we will first examine the idealized pressure distribution that would be expected if Earth's surface were uniform, that is, composed of all sea or all smooth land.

Idealized Zonal Pressure Belts

If Earth had a uniform surface, two latitudinally oriented belts of high and two of low pressure would exist (Figure 7–8a). Near the equator, the warm rising branch of the Hadley cells is associated with the pressure zone known as the **equatorial low.** This region of ascending moist, hot air is marked by abundant precipitation. Because it is the region where the trade winds converge, it is also referred to as the **intertropical convergence zone (ITCZ)**. In Figure 7–9, the ITCZ is visible as a band of heavy precipitation north of the equator.

In the belts about 20° to 35° on either side of the equator, where the westerlies and trade winds originate and go their separate ways, are the pressure zones known as the **subtropical highs.** These zones of high pressure are caused mainly by the Coriolis deflection, which restricts the poleward movement of the upper-level branch of the Hadley cells. As a result, a high-level pileup of air occurs around 20° to 35° latitude. Here a subsiding air column and diverging winds at the surface result in warm and clear weather. Recall that many large deserts lie near 30° latitude, within this zone of sinking air. Generally the rate at which air accumulates in the upper troposphere exceeds the rate at which the air descends and spreads out at the surface. Thus, the subtropical highs exist throughout most of the year and are regarded as *semipermanent* features of the general circulation.

Another low-pressure region is situated at about 50° to 60° latitude, in a position corresponding to the polar front. Here the polar easterlies and westerlies clash to form a convergent zone known as the **subpolar low.** As you will see later, this zone is responsible for much of the stormy weather in the middle latitudes, particularly in the winter.

Finally, near Earth's poles are the **polar highs,** from which the polar easterlies originate (Figure 7–8a). The high-pressure centers that develop over the cold polar areas are generated by entirely different processes than those that create the subtropical highs. Recall that the high-pressure zones in the subtropics result because the rate at which air piles up aloft exceeds the rate at which it spreads out at the surface. Stated another way, more air accumulates near 30° latitude than leaves these air columns. By contrast, the polar highs exhibit high surface pressure mainly because of surface cooling. Because air near the poles is cold and dense, it exerts a higher than average pressure.

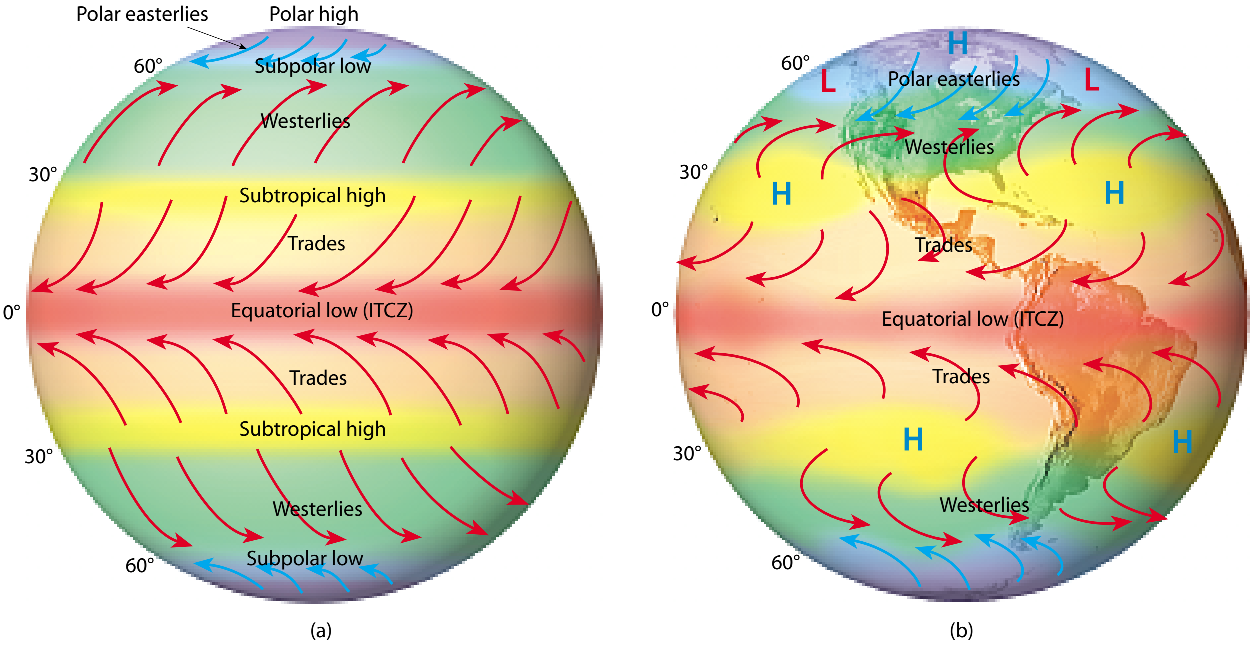


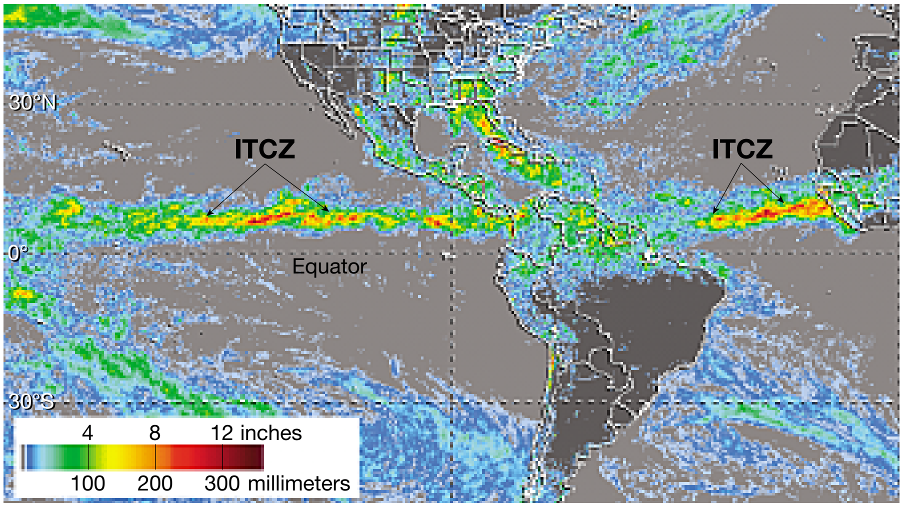
FIGURE 7-8 (a) An imaginary uniform Earth with idealized zonal (continuous) pressure belts. (b) The real Earth with disruptions of the zonal pattern caused by large landmasses. These disruptions break up pressure zones into semipermanent high- and low-pressure cells.

Semipermanent Pressure Systems: The Real World

Up to this point, we have considered the global pressure systems as if they were continuous belts around Earth. However, because Earth's surface is not uniform, the only true zonal distribution of pressure exists along the subpolar low in the Southern Hemisphere, where the ocean is continuous. To a lesser extent, the equatorial low is also continuous. At other latitudes, particularly in the Northern Hemisphere, where there is a higher proportion of land compared to ocean, the zonal pattern is replaced by semipermanent cells of high and low pressure.

The idealized pattern of pressure and winds for the "real" Earth is illustrated in Figure 7–8b. Although representative, the pattern shown is always in a state of flux because of seasonal temperature changes, which serve to either strengthen or weaken these pressure cells. In addition, the latitudinal position of these pressure systems moves either poleward or equatorward along with the seasonal migration of the zone of maximum solar heating. This is particularly true of the low-pressure belt associated with the intertropical convergence zone. The position of this thermally produced belt of low pressure is highly dependent on solar heating. As a consequence of these factors, Earth's pressure patterns vary in strength or

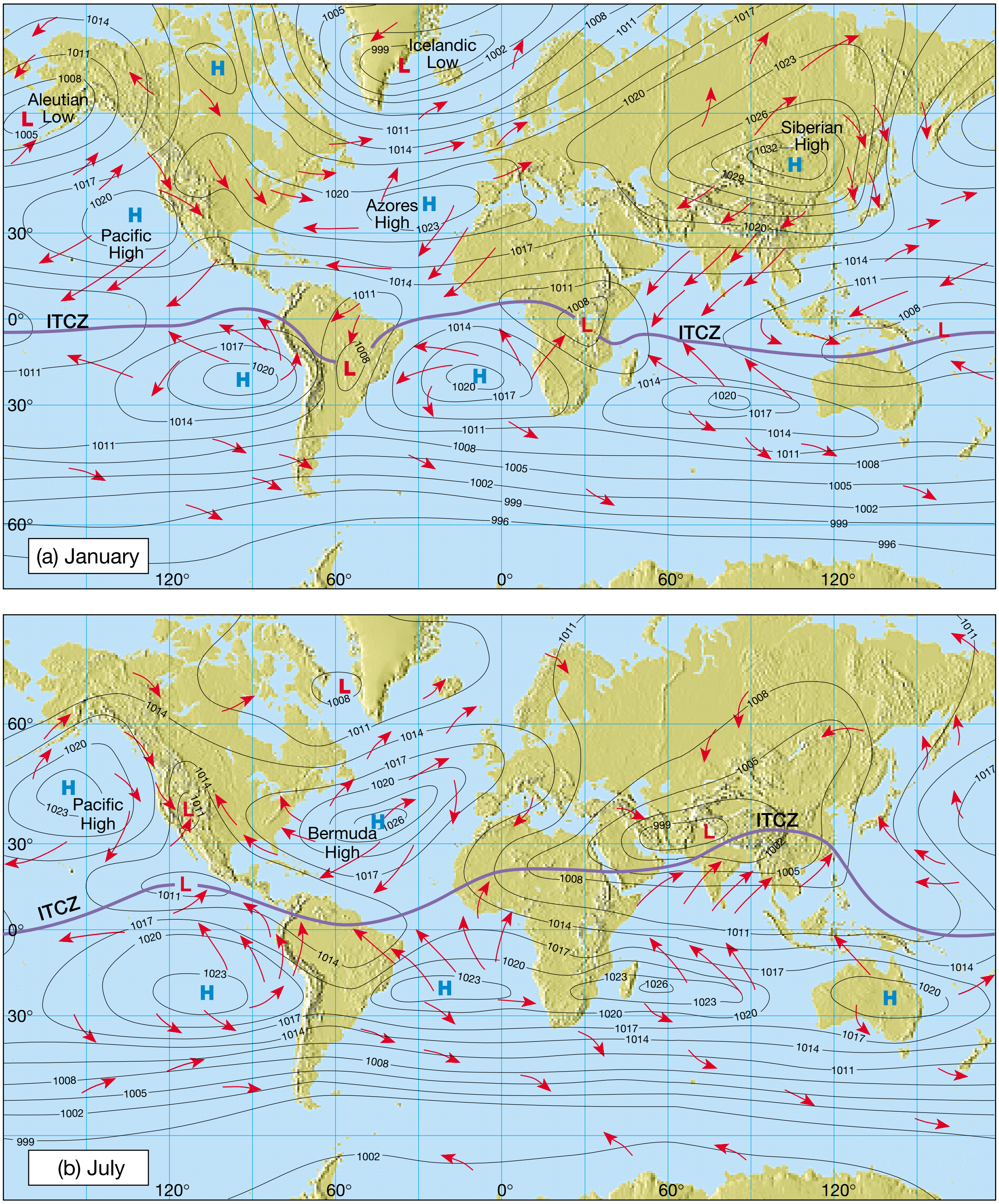
FIGURE 7-9 The Intertropical Convergence Zone (ITCZ) is seen as the band of heavy rainfall shown in reds and yellows, which extends east–west just north of the equator. *(Courtesy of NOAA)*



location during the course of the year. A view of the average global pressure patterns and resulting winds for the months of January and July are shown in Figure 7–10. Notice on these pressure maps that, for the most part, the observed pressure regimes are cellular (or elongated) instead of zonal. The most prominent features on both maps are the subtropical highs. These systems are centered between 20° and 35° latitude over all the larger subtropical oceans.

When we compare Figures 7–10a (January) and 7–10b (July), we see that some pressure cells are more or less year-round features, like the subtropical highs. Others, however,

FIGURE 7-10 Average surface pressure and associated global circulation for (a) January and (b) July.



are seasonal, such as the low over the southwestern United States in the summer, which appears on only the July map. Relatively little pressure variation occurs from midsummer to midwinter in the Southern Hemisphere, a fact we attribute to the dominance of water in that hemisphere. Numerous departures from the idealized zonal pattern are evident in the Northern Hemisphere. The main cause of these variations is the seasonal temperature fluctuations experienced over the landmasses, especially those in the middle and higher latitudes.

January Pressure and Wind Patterns. On the January pressure map shown in Figure 7–10a, note that a very strong high-pressure center, called the **Siberian high,** is positioned over the frozen landscape of northern Asia. A weaker polar high is located over the chilled North American continent. These cold anticyclones consist of very dense air that accounts for the weight of these air columns. In fact, the highest sea-level pressure ever measured, 1084 millibars (32.01 inches of mercury) was recorded in December 1968 at Agata, Siberia.

The polar highs are prominent features of the winter circulation over the northern continents. Subsidence within these air columns results in clear skies and divergent surface flow. The resulting winds are called *polar easterlies.*

As the Arctic highs strengthen over the continents, a weakening is observed in the subtropical anticyclones situated over the oceans. Further, the average position of the subtropical highs tends to be closer to the eastern margin of the oceans in January than in July. Notice in Figure 7–10a that the center of the subtropical high located in the North Atlantic (sometimes called the **Azores high**) is positioned close to the northwest coast of Africa.

Also shown on the January map but absent in July are two intense semipermanent low-pressure centers (Figure 7–10). Named the **Aleutian** and **Icelandic lows,** these cyclonic cells are situated over the North Pacific and North Atlantic, respectively. They are not stationary cells, but rather the composite of numerous cyclonic storms that traverse these regions. In other words, so many cyclones are present that these regions of the globe are almost always experiencing low pressure, hence the term *semipermanent.* Remember that cyclones are traveling low-pressure centers with low-level convergence and an upward flow. As a result, the areas affected by the Aleutian and Icelandic lows experience cloudy conditions and abundant winter precipitation.

The cyclones that form the Aleutian low are produced as frigid air, directed by the Siberian high, flows off the continent of Asia and overruns comparatively warm air over the Pacific. The strong temperature contrast creates a steep pressure gradient that becomes organized into a counterclockwise rotating storm cell. Just how a cyclone of this type is generated from the clash of two different air masses will be considered in Chapter 9. Nevertheless, with the large number of cyclonic storms that form over the North Pacific and travel eastward, it should be no surprise that the coastal areas of southern Alaska receive abundant precipitation. This fact is exemplified by the climate data for Sitka, Alaska, a coastal town that receives 215 centimeters (85 inches) of precipitation each year, over five times that received in Churchill, Manitoba, Canada. Although both towns are situated at roughly the same latitude, Churchill is located in the continental interior far removed from the influence of the Aleutian low.

July Pressure and Wind Patterns. The pressure pattern over the Northern Hemisphere changes dramatically with the onset of summer as increased amounts of radiation strike the northern landmasses (Figure 7–10b). High surface temperatures over the continents generate lows that replace the winter highs. These thermal lows consist of warm ascending air that induces inward directed surface flow. The strongest of these low-pressure centers develops over southern Asia. A weaker thermal low is also found in the southwestern United States.

Notice in Figure 7–10 that during the summer months, the subtropical highs in the Northern Hemisphere migrate westward and become more intense than during the winter months. These strong high-pressure centers dominate the summer circulation over the oceans and pump warm moist air onto the continents that lie to the west of these highs. This results in an increase in precipitation over parts of eastern North America and Southeast Asia.

During the peak of the summer season, the subtropical high found in the North Atlantic is positioned near the island of Bermuda, hence the name **Bermuda high.** (Bermuda is located about 1500 kilometers, or 900 miles, east of the South Carolina coast.) Recall that in the Northern Hemisphere winter the Bermuda high is located near Africa and goes by the alias *Azores high* (Figure 7–10).

Monsoons

The greatest *seasonal* change in Earth's global circulation is the monsoon. Contrary to popular belief, **monsoon** does not mean "rainy season"; rather, it refers to a wind system that exhibits a pronounced seasonal reversal in direction. In general, winter is associated with winds that blow predominantly off the continents and that produce a dry winter monsoon. By contrast, in summer, warm moisture-laden air blows from the sea toward the land. Thus, the summer monsoon, which is usually associated with abundant precipitation, is the source of the misconception.

The Asian Monsoon

The best-known and most pronounced monsoon circulation is found in southern and southeastern Asia. Like all winds, the Asian monsoon is driven by pressure differences that are generated by unequal heating of Earth's surface. As summer approaches, the temperatures in India and surrounding Southeast Asia soar. For example, summertime temperatures at New Delhi, India, often exceed 40°C (104°F). This intense solar heating generates a low-pressure area over southern Asia. Recall that thermal lows form because intense surface heating causes expansion of the overlying air column. This in turn generates outflow aloft that encourages inward flow at the surface. With the development of the low-pressure center over India, moisture-laden air from the Indian Ocean flows landward, thereby generating a pattern of precipitation typical of the summer monsoon.

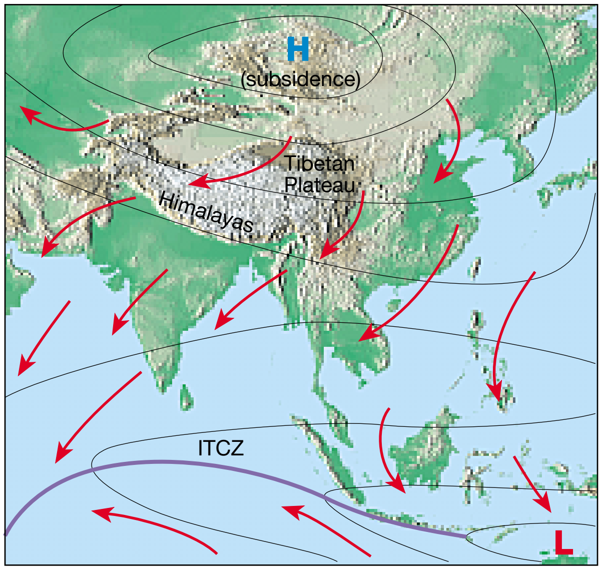
One of the world's rainiest regions is found on the slopes of the Himalayas where orographic lifting of moist air from the India Ocean produces copious precipitation. Cherrapunji, India, once recorded an annual rainfall of 25 meters (82.5 feet), most of which fell during the four months of the summer monsoon (Figure 7–11b).

As winter approaches, long nights and low sun angles result in the accumulation of frigid air over the vast landscape of northern Russia. This generates a cold anticyclone called the *Siberian high,* which begins to dominate the winter circulation over Asia. The subsiding dry air of the Siberian high produces surface flow that moves across southern Asia producing predominantly offshore winds (Figure 7–11a). By the time this flow reaches India, it has warmed considerably but remains extremely dry. For example, Bombay, India, receives less than 1 percent of its annual precipitation in the winter. The remainder comes in the summer, with the vast majority falling from June through September.

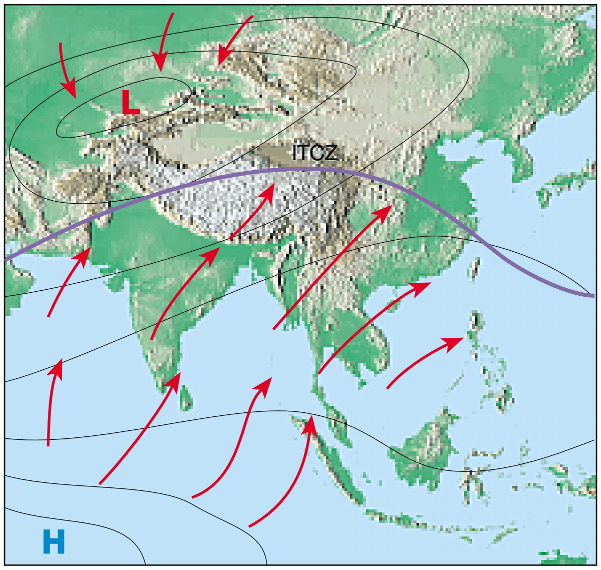
The Asian monsoon is complex and is strongly influenced by the seasonal change in the amount of solar heating received by the vast Asian continent. However, another factor, related to the annual migration of the Sun, also contributes to the pronounced monsoon circulation of southeastern Asia. As shown in Figure 7–11, the Asian monsoon is associated with a larger than average seasonal migration of the intertropical convergence zone (ITCZ). With the onset of summer the ITCZ moves northward over the continent and is accompanied by peak rainfall. The opposite occurs in the Asian winter as the ITCZ moves south of the equator. (Recall the ITCZ is a belt of low pressure and rising air that drives the Hadley cells.)

The migration of the ITCZ is accompanied by a dramatic change in pressure. The strong high-pressure system and subsidence that dominates the winter flow is replaced by low pressure and convergence during the summer months. This significant shift in pressure is thought to aid the northward movement of the ITCZ.

Of major importance are the Himalaya Mountains and the huge Tibetan Plateau, which have an *average* elevation that is higher than the highest peaks in the Colorado Rockies. During the winter months these topographic barriers contribute to the extreme temperature difference that exists between the cold continental interior and the milder coastal areas. This temperature contrast produces a strong jet stream that becomes anchored over these highlands. The role that this jet stream plays in the dry winter monsoon is not known with certainty. Nevertheless, in the summer, as the temperature differential over the continent diminishes, the jet stream breaks down. Clearly, these topographic barriers and the resulting upper airflow play a major role in the migration of the ITCZ.



(a) Winter monsoon



(b) Summer monsoon

FIGURE 7-11 Asia's monsoon circulation occurs in conjunction with the seasonal shift of the intertropical convergence zone (ITCZ). (a) In January a strong high pressure develops over Asia and cool, dry continental air generates the dry winter monsoon. (b) With the onset of summer, the ITCZ migrates northward and draws warm, moist air onto the continent.

Nearly half the world's population inhabits regions affected by monsoonal circulation. Further, many of these people depend on subsistence agriculture for their livelihood. Therefore, the timely arrival of the monsoon rains often means the difference between adequate nutrition and widespread malnutrition.

The North American Monsoon

Many regions of the globe experience seasonal wind shifts like those associated with the Asian monsoon. Although none are as dramatic as the Asian monsoon, these smaller features are important elements of the global circulation and affect most of Earth's landmasses.

For example, a relatively small seasonal wind shift influences a portion of North America. Sometimes called the *North American monsoon,* this circulation pattern produces a dry spring followed by a comparatively rainy summer that impacts large areas of the southwestern United States and northwestern Mexico.* This is illustrated by Tucson, Arizona, which typically receives almost sixty times more precipitation in July than in May. As shown in Figure 7–12, these summer rains typically last into September when drier conditions reestablish themselves.

Summer daytime temperatures in the American Southwest, particularly in the low deserts, can be extremely hot. This intense surface heating generates a low-pressure center over Arizona. The resulting circulation pattern brings warm, moist air from the Gulf of California (Figure 7–13). The Gulf of Mexico is also thought to be a source of some of the moisture responsible for the summer precipitation. The supply of atmospheric moisture from nearby marine sources, coupled with the convergence and upward flow of the thermal low, is conducive to generating the precipitation this region experiences during the hottest months. Although often associated with the state of Arizona, this monsoon is actually strongest in northwestern Mexico and is quite pronounced in New Mexico.

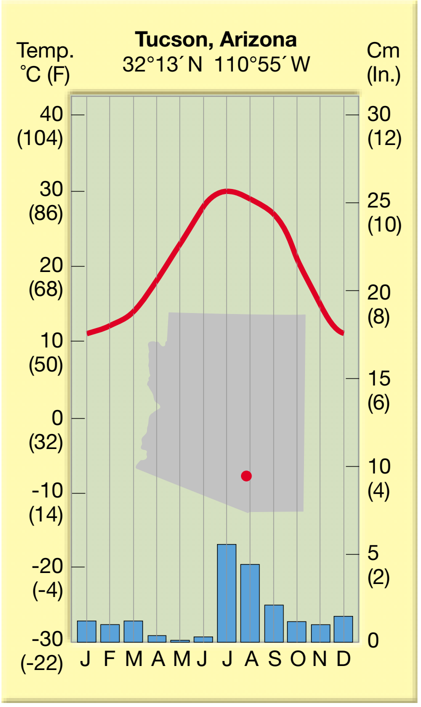


FIGURE 7-12 Climate diagram for Tucson, Arizona, showing a summer precipitation maximum produced by monsoon circulation that draws moist air in from the Gulf of California and to a lesser extent from the Gulf of Mexico.

Students Sometimes Ask...

Does monsoon mean "rainy season"?

No. Regions that experience monsoons typically have both a wet and a dry season. Monsoon refers to a wind system that exhibits a pronounced seasonal reversal in direction. In general, winter is associated with winds that blow predominantly off the continents and produce a dry winter monsoon. By contrast, in summer, warm moisture-laden air blows from the sea toward the land. Thus, the summer monsoon, which is usually associated with abundant precipitation, is the source of the misconception.

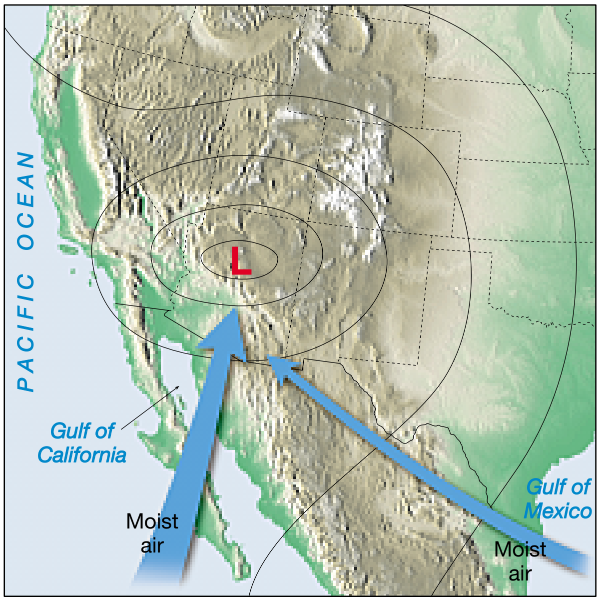
The Westerlies

Prior to World War II, upper-air observations were scarce. Since then, aircraft and radiosondes have provided a great deal of data about the upper troposphere. Among the most important discoveries was that airflow aloft in the middle latitudes has a strong west-to-east component, thus the name *westerlies.*

Why Westerlies?

Let us consider the reason for the predominance of westerly flow aloft. Recall that winds are created and maintained by pressure differences that are a result of temperature differences. In the case of the westerlies, it is the temperature contrast between the poles and equator that drives these winds. Figure 7–14 illustrates the pressure distribution with height over the cold polar region as compared to the much

FIGURE 7-13 High summer temperatures over the southwestern United States create a thermal low that draws moisture from the Gulf of California and the Gulf of Mexico. This summer monsoon produces an increase in precipitation, which often comes in the form of thunderstorms, over the southwestern United States and northwestern Mexico.



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*This event is also called the *Arizona monsoon* and the *Southwest monsoon* because it has been extensively studied in this part of the United States.

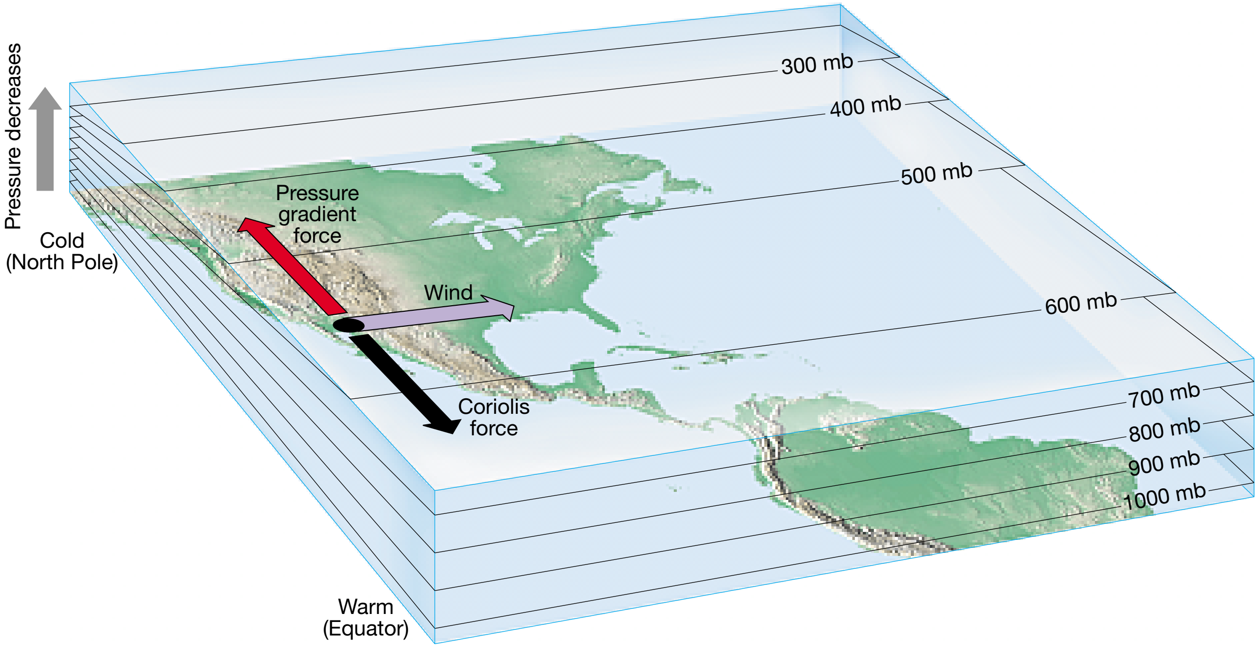


FIGURE 7-14 Idealized pressure gradient that develops aloft because of density differences between cold polar air and warm tropical air. Notice that the poleward-directed pressure-gradient force is balanced by an equatorward-directed Coriolis force. The result is a prevailing flow from west to east, which is called the *westerlies.*

warmer tropics. Because cold air is more dense (compact) than warm air, air pressure decreases more rapidly in a column of cold air than in a column of warm air. The pressure surfaces (planes) in Figure 7–14 represent a grossly simplified view of the pressure distribution we would expect to observe from pole to equator.

Over the equator, where temperatures are higher, air pressure decreases more gradually than over the cold polar regions. Consequently, at the same altitude above Earth's surface, higher pressure exists over the tropics and lower pressure is the norm above the poles. Thus, the resulting pressure gradient is directed from the equator (area of higher pressure) toward the poles (area of lower pressure).

Once the air from the tropics begins to advance poleward in response to this pressure gradient force (red arrow in Figure 7–14), the Coriolis force comes into play to change the direction of airflow. Recall that in the Northern Hemisphere the Coriolis force causes winds to be deflected to the right. Eventually, a balance is reached between the poleward-directed pressure-gradient force and the Coriolis force to generate a wind with a strong west-to-east component (Figure 7–14). Recall that such winds are called *geostrophic winds.* Because the equator-to-pole temperature gradient shown in Figure 7–14 is typical over the globe, a westerly flow aloft should be expected, and on most occasions it is observed.

It can also be shown that the pressure gradient increases with altitude; as a result, so should wind speeds. This increase in wind speed continues only to the tropopause, where it starts to decrease upward into the stratosphere.

Jet Streams

Imbedded within the westerly flow aloft are narrow ribbons of high-speed winds that meander for thousands of kilometers (Figure 7–15a). These fast streams of air once were considered analogous to jets of water and thus were named **jet streams.** These high-speed air currents have widths that vary from less than 100 kilometers (60 miles) to over 500 kilometers (300 miles) and are generally a few kilometers thick. Wind speeds are frequently in excess of 200 kilometers (120 miles) per hour but rarely exceed 400 kilometers (240 miles) per hour.

Although jet streams had been predicted earlier, their existence was first dramatically illustrated during World War II. American bombers heading westward toward Japanese-occupied islands occasionally made little headway. On abandoning their missions, the planes on their return flight experienced westerly tail winds that sometimes exceeded 300 kilometers per hour. Even today commercial aircraft use these strong tail winds to increase their speed when making eastward flights around the globe. On westward flights, of course, these fast currents of air are avoided when possible.

Origin of the Polar Jet Stream

What is the origin of these distinctive, energetic winds that exist within the slower, general westerly flow? The key is that large temperature contrasts at the surface produce steep pressure gradients aloft and hence faster upper air winds. In winter it is not unusual to have a warm balmy day

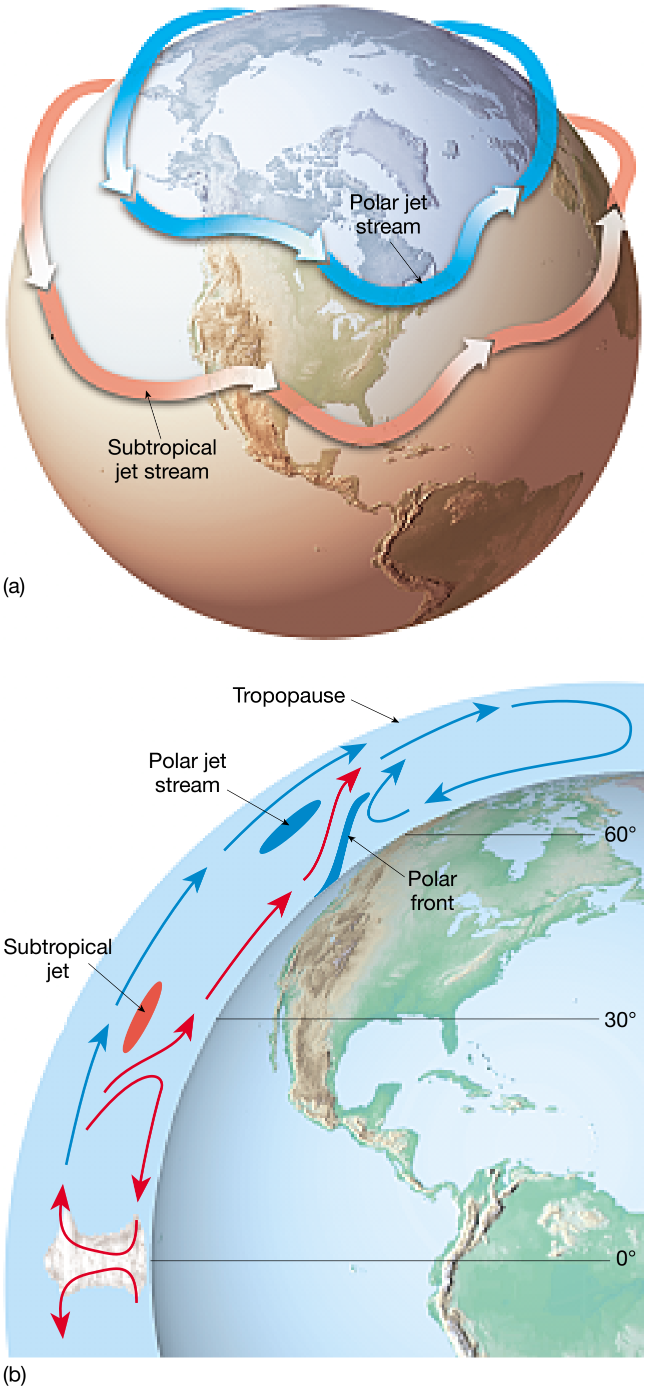


FIGURE 7-15 Jet streams. (a) Approximate positions of the polar and subtropical jet streams. Note that these fast-moving currents are generally not continuous around the entire globe. (b) A cross-sectional view of the polar and subtropical jets.

in southern Florida and near-freezing temperatures in Georgia, only a few hundred kilometers to the north. Such large wintertime temperature contrasts lead us to expect faster westerly flow at that time of year. Observations substantiate these expectations. In general, the fastest upper air winds are located above regions of the globe having large temperature contrasts across very narrow zones. Stated another way, jet streams are located in regions of the atmosphere where large horizontal temperature differences occur over short distances.

These large temperature contrasts occur along linear zones called *fronts.* The best-known jet stream occurs along a major frontal zone called the *polar front* and is appropriately named the **polar jet stream,** or simply the *polar jet* (Figure 7–15b). Because this jet stream occurs mainly in the middle latitudes it is also known as the *mid-latitude jet stream.* Recall that the polar front is situated between the cool winds of the polar easterlies and the relatively warm westerlies. Instead of flowing nearly straight west-to-east, the polar jet stream usually has a meandering path. Occasionally, it flows almost due north–south. Sometimes it splits into two jets that may, or may not, rejoin. Like the polar front, this jet is not continuous around the globe.

Occasionally, the polar jet exceeds 500 kilometers (300 miles) per hour. On the average, however, it travels at 125 kilometers (75 miles) per hour in the winter and roughly half that speed in the summer (Figure 7–16). This seasonal difference is due to the much stronger temperature gradient that exists in the middle latitudes during the winter.

Because the location of the polar jet roughly coincides with that of the polar front, its latitudinal position migrates with the seasons. Thus, like the zone of maximum solar heating, the jet moves northward during summer and southward in winter. During the cold winter months, the polar jet stream may extend as far south as 30° north latitude (Figure 7–16). With the coming of spring, the zone of maximum solar heating and therefore the jet begins a gradual northward migration. By midsummer, its average position is about 50° north latitude, but it may penetrate much farther poleward.

As the polar jet shifts northward, there is a corresponding change in the region where outbreaks of severe thunderstorms and tornadoes occur. For example, in February most tornadoes occur in the states bordering the Gulf of Mexico. By midsummer the center of this activity shifts to

FIGURE 7-16 The position and speed of the polar jet stream changes with the seasons, migrating freely between about 30° and 70° latitude. Shown are flow patterns that are common for summer and winter.

the northern plains and Great Lakes states. As you can see, the polar jet stream plays a very important role in the weather of the midlatitudes. In addition to supplying energy to the circulation of surface storms, it also directs their paths of movement. Consequently, determining changes in the location and flow pattern of the polar jet is an important part of modern weather forecasting.

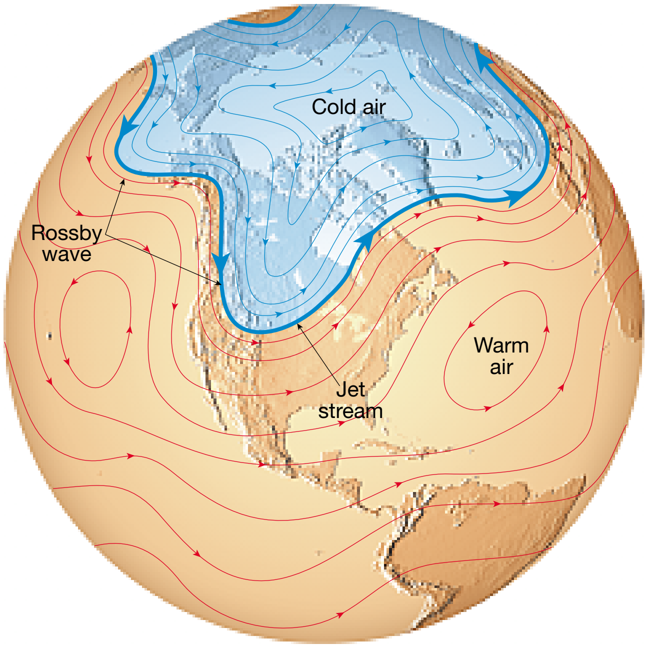
Subtropical Jet Stream

Other jet streams are known to exist, but none have been studied in as much detail as the polar jet stream. A semipermanent jet exists over the subtropics and as such is called the **subtropical jet** (see Figure 7–15b). The subtropical jet is mainly a wintertime phenomenon. Due to the weak summertime temperature gradient, the subtropical jet is relatively weak during the warm season. Somewhat slower than the polar jet, this west-to-east flowing current is centered at 25° latitude at an altitude of about 13 kilometers (8 miles).

Waves in the Westerlies

It is important to remember that the midlatitude jet stream is an integral part of the westerlies. It is not a dramatic anomaly like a hurricane. In fact, the jet stream can be more accurately described as the fast core of the overall westerly flow, like the fastest moving portion of a river (Figure 7–17). Studies of upper-level wind charts reveal that the westerlies follow wavy paths that have rather long wavelengths. Much of our knowledge of these large-scale motions is attributed to C. G. Rossby, who first explained the nature of these waves. The longest wave patterns (called *Rossby waves*) have wavelengths of 4000 to 6000 kilometers, so that three to six waves will fit around the globe (Figure 7–17). Although the air flows eastward along this wavy path, these long waves tend to remain stationary or move slowly.

FIGURE 7-17 Idealized airflow of the westerlies at the 500-millibar level. The five long-wavelength undulations, called *Rossby waves,* compose this flow. The jet stream is the fast core of this wavy flow.



In addition to Rossby waves, shorter waves occur in the middle and upper troposphere. These shorter waves are often associated with cyclones at the surface and, like these storms, they travel from west to east around the globe at rates of up to 15° of longitude per day.

Although much remains to be learned about the wavy flow of the westerlies, its basic features are understood with some certainty. Among the most obvious characteristics of the flow aloft are its seasonal changes. The higher wind speeds in the cool season are depicted on upper-air charts by more closely spaced contour lines, as shown in Figure 7–18. The summer-to-winter change in wind speed is a consequence of the seasonal contrasts of the temperature gradients. The steep temperature gradient across the middle latitudes in winter corresponds to a stronger flow aloft.

In addition to seasonal changes in the strength of its flow, the position of the polar jet stream also shifts from summer to winter. With the approach of winter, the jet migrates equatorward. As summer nears, it moves back toward the poles (Figure 7–16). By midwinter the jet core may penetrate as far south as central Florida. Because the paths of cyclonic systems are guided by the flow aloft, we can expect the southern tier of states to encounter most of their severe weather in the winter. During hot summer months, the storm track is across the northern states, and some cyclones never leave Canada. In addition to seasonal changes in storm tracks, the number of cyclones generated also varies seasonally. The largest number form in the cooler months when temperature contrasts are most pronounced.

As you might expect, a close relationship exists between the location of the polar jet stream and conditions near the surface, particularly temperatures. When the midlatitude jet is situated equatorward of your location, the weather will usually be colder and stormier than normal. Conversely, when the polar jet moves poleward of your location, warmer and drier conditions are likely to prevail. Further, when the position of the jet stream remains fixed for extended periods, weather extremes can result. Thus, depending on the position of the jet stream, the weather could be hotter, colder, drier, or wetter than normal. We shall return later to this important relationship between the jet stream and middle latitude weather.

Westerlies and Earth's Heat Budget

Now let us return to the wind's function of maintaining Earth's heat budget by transporting heat from the equator toward the poles. In Chapter 2 we showed that the equator receives more solar radiation than it radiates back into space,

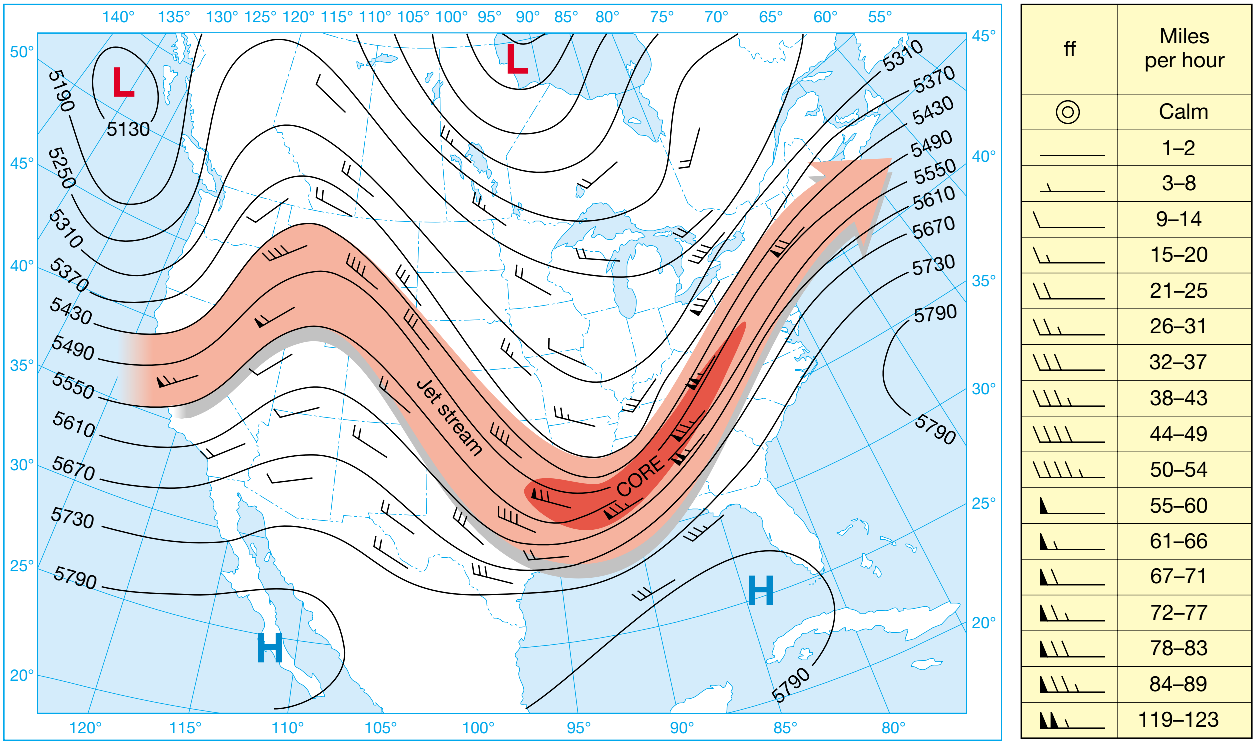


FIGURE 7-18 Simplified 500-millibar height-contour chart for January. The position of the jet-stream core is shown in dark red.

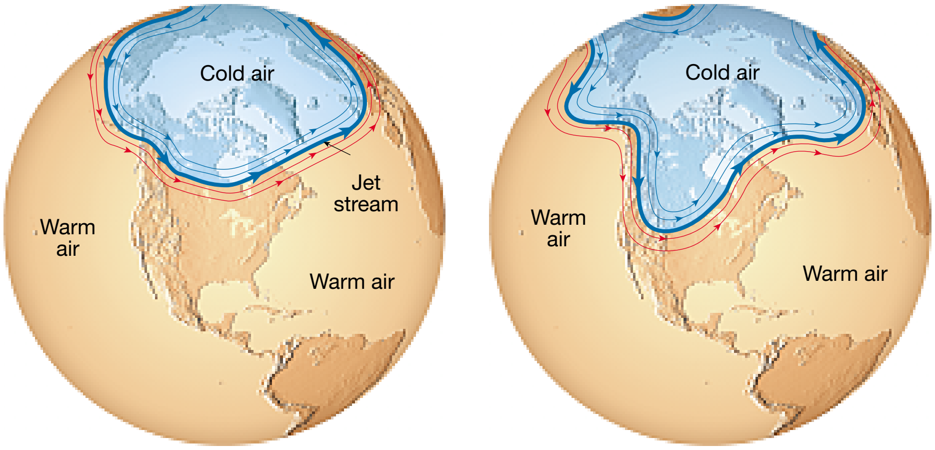
whereas the poles experience the reverse situation. Thus, the equator has excess heat, whereas the poles experience a deficit. Although the flow near the equator is somewhat *meridional* (north to south), at most other latitudes the flow is *zonal* (west to east). The reason for the zonal flow, as we have seen, is the Coriolis force. The question we now consider is: *How can wind with a west-to-east flow transfer heat from south to north?*

In addition to its seasonal migrations, the polar jet can change positions on shorter time scales as well. There may be periods of a week or more when the flow is nearly west to east, as shown in Figure 7–19a. When this condition prevails, relatively mild temperatures occur and few disturbances are experienced in the region south of the jet stream. Then without warning, the flow aloft begins to meander and produces large-amplitude waves and a general north-to-south flow (Figure 7–19b and c). Such a change allows cold air to advance southward. Because this influx intensifies the temperature gradient, the flow aloft is also strengthened. Recall that strong temperature contrasts create steep pressure gradients that organize into rotating cyclonic systems. The jet stream supports these lows by providing divergence aloft that enhances the inward flow at the surface.

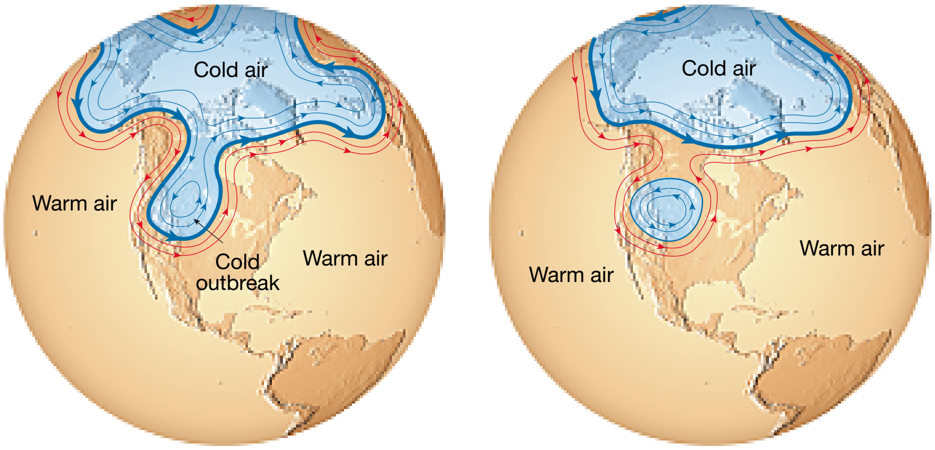
During these periods, cyclonic activity dominates the weather. For a week or more, cyclonic storms redistribute large quantities of heat across the middle latitudes by moving cold air equatorward and warm air poleward. This redistribution eventually results in a weakened temperature gradient and a return to a flatter flow aloft and less intense weather at the surface (Figure 7–19d). Cycles such as these, which consist of alternating periods of calm and stormy weather, can last from one to six weeks.

Laboratory experiments using rotating fluids to simulate Earth's circulation support the existence of waves and eddies that carry on the task of heat transfer in the middle latitudes. In these studies, called *dishpan experiments,* a large circular pan is heated around the outer edge to represent the equator and the center is cooled to duplicate a pole. Colored particles are added so that the flow can be easily observed and photographed. When the pan is heated, but not rotated, a simple convection cell forms to redistribute the heat. This cell is similar to the Hadley cell considered earlier. When the pan is rotated, however, the simple circulation breaks down and the flow develops a wavy pattern with eddies embedded between meanders, as seen in Figure 7–20. These experiments indicate that changing the rate of rotation and varying the temperature gradient largely determine the flow pattern produced. Such studies have added greatly to our understanding of global circulation.

In summary, we now understand that the wavy flow aloft is largely responsible for producing surface weather patterns. During periods when the flow aloft is relatively flat (small-amplitude waves), little cyclonic activity is generated at the surface. Conversely, when the flow exhibits large-amplitude waves having short wavelengths, vigorous cyclonic storms are created. This important relationship between the flow aloft and cyclonic storms is considered in more detail in Chapter 9.



(a) Gently undulating upper airflow (b) Meanders form in jet stream



(c) Strong waves form in upper airflow (d) Return to a period of flatter flow aloft

FIGURE 7-19 Cyclic changes that occur in the upper-level airflow of the westerlies. The flow, which has the jet stream as its axis, starts out nearly straight and then develops meanders and cyclonic activity that dominate the weather.

Students Sometimes Ask…

Why do pilots of commercial aircraft always remind passengers to keep their seat belts fastened, even in ideal flying conditions?

The reason for this request is a phenomenon known as *clear air turbulence.* Clear air turbulence occurs when airflow in two adjacent layers is moving at different velocities. This can happen when the air at one level is traveling in a different direction than the air above or below it. More often however, it occurs when air at one level is traveling faster than air in an adjacent layer. Such movements create eddies (turbulence) that can cause the plane to move suddenly up or down.

Global Winds and Ocean Currents

Where the atmosphere and ocean are in contact, energy is passed from moving air to the water through friction. As a consequence, the drag exerted by winds blowing steadily across the ocean causes the surface layer of water to move (see Box 7–3). Thus, because winds are the primary driving force of **ocean currents,** a relationship exists between the oceanic circulation and the general atmospheric circulation. A comparison of Figures 7–21 and 7–10 illustrates this. A further clue to the influence of winds on ocean circulation is provided by the currents in the northern Indian Ocean, where there are seasonal wind shifts known as the *summer* and *winter monsoons.* When the winds change directions, the surface currents also reverse direction. North and south of the equator are two westward-moving currents, the North and South Equatorial currents, which derive their energy principally from the trade winds that blow from the northeast and southeast, respectively, toward the equator. These equatorial currents can be thought of as the backbone of the system of ocean currents. Because of the Coriolis force, these currents are deflected poleward to form clockwise spirals in the Northern Hemisphere and counterclockwise spirals in the Southern Hemisphere. These nearly circular ocean currents are found in each of the major ocean basins centered around the subtropical high-pressure systems (Figure 7–21).

In the North Atlantic, the equatorial current is deflected northward through the Caribbean, where it becomes the *Gulf Stream.* As the Gulf Stream moves along the eastern coast of the United States, it is strengthened by the prevailing westerly winds and is deflected to the east (to the right)

FIGURE 7-20 Photograph obtained from a *dishpan experiment.* The pan is heated around the edge to represent the equator, and the center is cooled to duplicate the poles. When the pan is rotated, a wavy flow develops with eddies embedded between meanders, as shown. This flow pattern closely parallels that produced in the "real" atmosphere, where the meanders represent the wavy flow of the westerlies and the eddies are cyclonic and anticyclonic systems embedded within this larger circulation. *(Courtesy of D. H. Fultz, University of Chicago Hydrodynamics Laboratory)*

between 35° north and 45° north latitude (Figure 7–22). As it continues northeastward beyond the Grand Banks, it gradually widens and decreases speed until it becomes a vast, slowly moving current known as the North Atlantic Drift. As the North Atlantic Drift approaches Western Europe, it splits, with part moving northward past Great Britain and Norway. The other part is deflected southward as the cool Canaries current. As the Canaries current moves south, it eventually merges into the North Equatorial current.

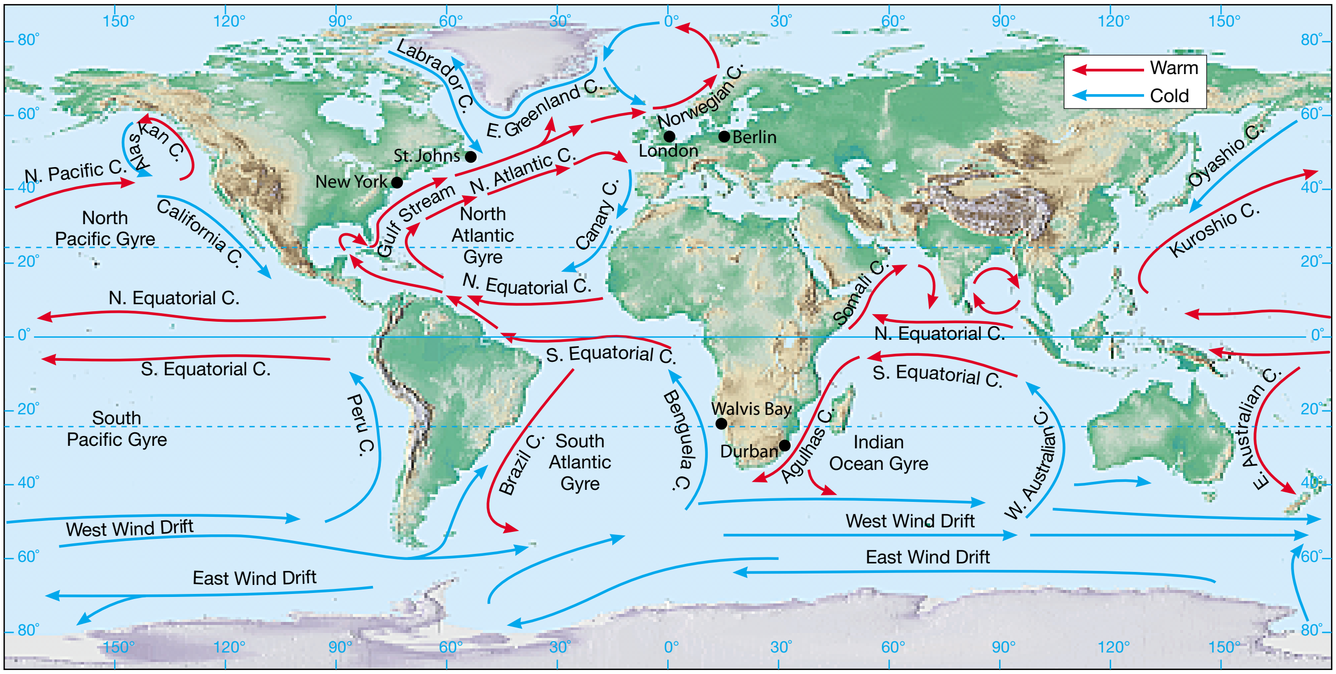
The Importance of Ocean Currents

In addition to being significant considerations in ocean navigation, currents have an important effect on climate. The moderating effect of poleward-moving warm ocean currents is well known. The North Atlantic Drift, an extension of the warm Gulf Stream, keeps Great Britain and much of northwestern Europe warmer than one would expect for their latitudes.

In addition to influencing temperatures of adjacent land areas, cold currents have other climatic influences. For example, where tropical deserts exist along the west coasts of continents, cold ocean currents have a dramatic impact. The principal west-coast deserts are the Atacama in Peru and Chile, and the Namib in southern Africa. The aridity along these coasts is intensified because the lower air is chilled by cold offshore waters. When this occurs, the air becomes very stable and resists the upward movements necessary to create precipitation-producing clouds. In addition, the presence of cold currents causes temperatures to approach and often reach the dew point. As a result, these areas are characterized by high relative humidities and much fog. Thus, not all tropical deserts are hot with low humidities and clear skies. Rather, the presence of cold currents transforms some tropical deserts into relatively cool, damp places that are often shrouded in fog.

Ocean currents also play a major role in maintaining Earth's heat balance. They accomplish this task by transferring heat from the tropics, where there is an excess of heat, to the polar regions, where a deficit exists. Ocean water

FIGURE 7-21 Major ocean currents. Poleward-moving currents are warm, and equatorward-moving currents are cold.



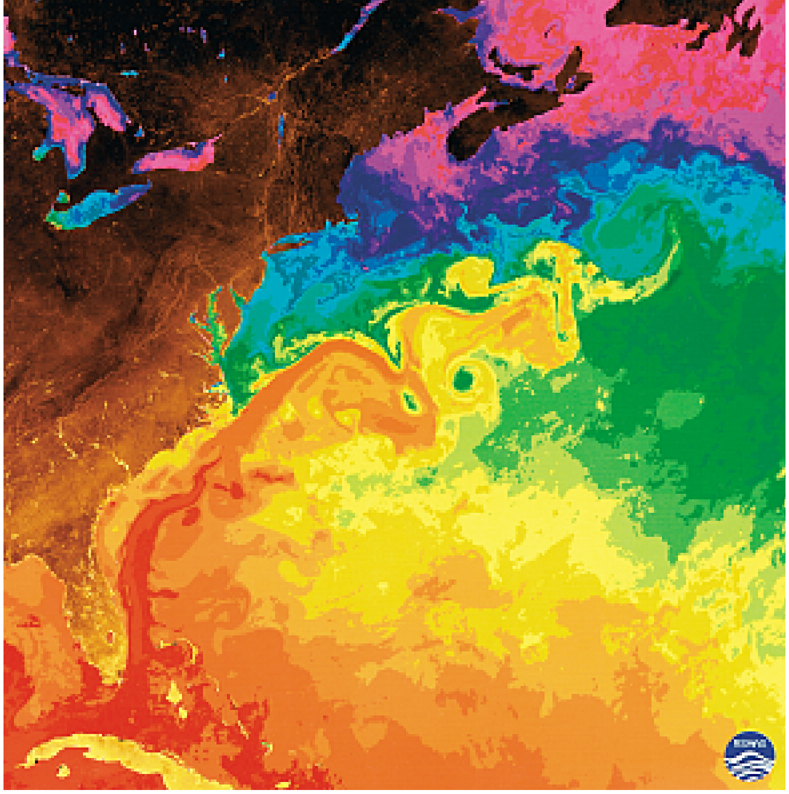


FIGURE 7-22 Enhanced satellite image of the complex flow of the Gulf Stream. Reds and yellows indicate warmer waters. Note that the Gulf Stream flows northward along the Florida coast (lower left) and then diagonally toward the upper right of the image. *(Courtesy of O. Brown, R. Evans, and M. Carle/Rosenstiel School of Marine and Atmospheric Science)*

movements account for about a quarter of this total heat transport and winds the remaining three-quarters.

Ocean Currents and Upwelling

In addition to producing surface currents, winds can also cause vertical water movements. **Upwelling,** the rising of cold water from deeper layers to replace warmer surface water, is a common wind-induced vertical movement. It is most characteristic along the eastern shores of the oceans, most notably along the coasts of California, Peru, and West Africa.

Upwelling occurs in these areas when winds blow toward the equator parallel to the coast. Because of the Coriolis force, the surface-water movement is directed away from the shore. As the surface layer moves away from the coast, it is replaced by water that "upwells" from below the surface. This slow upward flow from depths of 50 to 300 meters (165 to 1000 feet) brings water that is cooler than the original surface water and creates a characteristic zone of lower temperatures near the shore.

For swimmers who are accustomed to the waters along the mid-Atlantic shore of the United States, a dip in the Pacific off the coast of central California can be a chilling surprise. In August, when temperatures in the Atlantic are 21°C (70°F) or higher, central California's surf is only about 15°C (60°F). Coastal upwelling also brings to the ocean surface greater concentrations of dissolved nutrients, such as nitrates and phosphates. These nutrient-enriched waters from below promote the growth of plankton, which in turn supports extensive populations of fish.

El Niño and La Niña

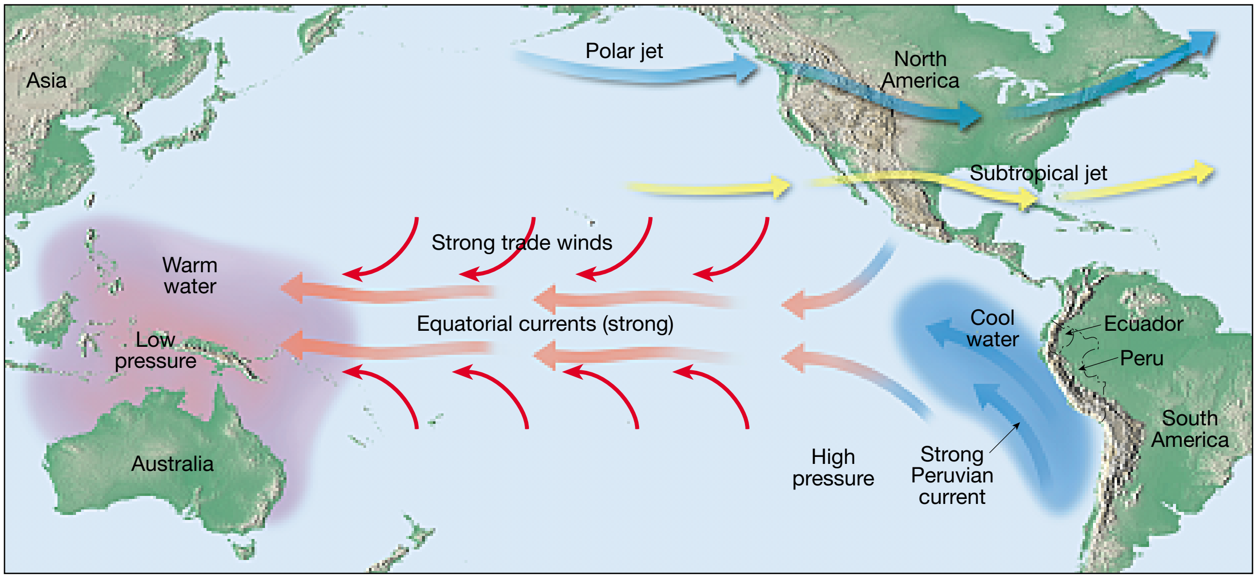
As can be seen in Figure 7–23a, the cold Peruvian current flows equatorward along the coast of Ecuador and Peru. This flow encourages upwelling of cold nutrient-filled waters that serve as the primary food source for millions of fish, particularly anchovies. Near the end of each year, however, a warm current that flows southward along the coasts of Ecuador and Peru replaces the cold Peruvian current. During the nineteenth century the local residents named this warm countercurrent El Niño ("the child") after the Christ child because it usually appeared during the Christmas season. Normally, these warm countercurrents last for at most a few weeks when they again give way to the cold Peruvian flow. However, at irregular intervals of three to seven years, these countercurrents become unusually strong and replace normally cold offshore waters with warm equatorial waters (Figure 7–23b). Today scientists use the term **El Niño** for these episodes of ocean warming that affect the eastern tropical Pacific.

The onset of El Niño is marked by abnormal weather patterns that drastically affect the economies of Ecuador and Peru. As shown in Figure 7–23b, these unusually strong undercurrents amass large quantities of warm water that block the upwelling of colder, nutrient-filled water. As a result, the anchovies starve, devastating the fishing industry. At the same time, some inland areas that are normally arid receive an abnormal amount of rain. Here, pastures and cotton fields have yields far above the average. These climatic fluctuations have been known for years, but they were originally considered local phenomena. Today, we know that El Niño is part of the global circulation and affects the weather at great distances from Peru and Ecuador.

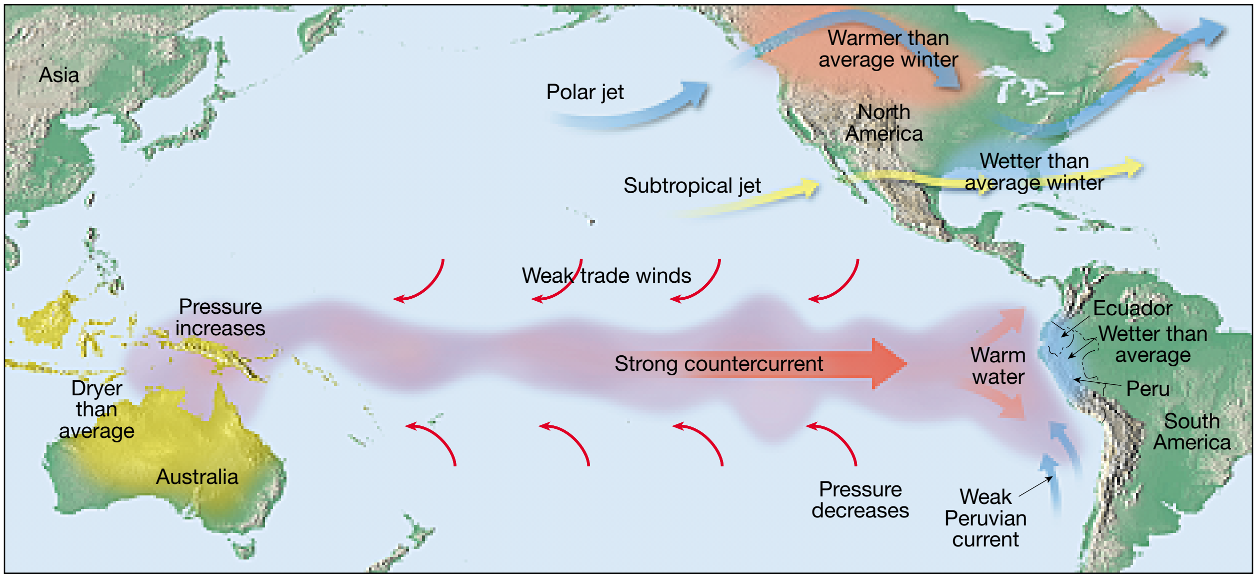
Two of the strongest El Niño events on record occurred between 1982–83 and 1997–98, and were responsible for weather extremes of a variety of types in many parts of the world. During the 1982–83 El Niño event, heavy rains and flooding plagued normally dry portions of Ecuador and Peru. Some locations that usually receive only 10 to 13 centimeters of rain each year had as much as 350 centimeters of precipitation. At the same time, severe drought beset Australia, Indonesia, and the Philippines. Huge crop losses, property damage, and much human suffering were recorded.

The 1997–98 El Niño brought ferocious storms that struck the California coast, causing unprecedented beach erosion, landslides, and floods. In the southern United States, heavy rains also brought floods to Texas and the Gulf states. The same energized jet stream that produced storms in the South, upon reaching the Atlantic, sheared off the northern portions of hurricanes, destroying the storms. It was one of the quietest Atlantic hurricane seasons in years.

Major El Niño events, such as the one in 1997 and 1998, are intimately related to the large-scale atmospheric circulation. Each time an El Niño occurs, the barometric pressure drops over large portions of the southeastern Pacific, whereas in the western Pacific, near Indonesia and northern Australia, the pressure rises (Figure 7–24). Then, as a major El Niño event comes to an end, the pressure difference between these two regions swings back in the opposite direction. This seesaw



(a) Normal conditions



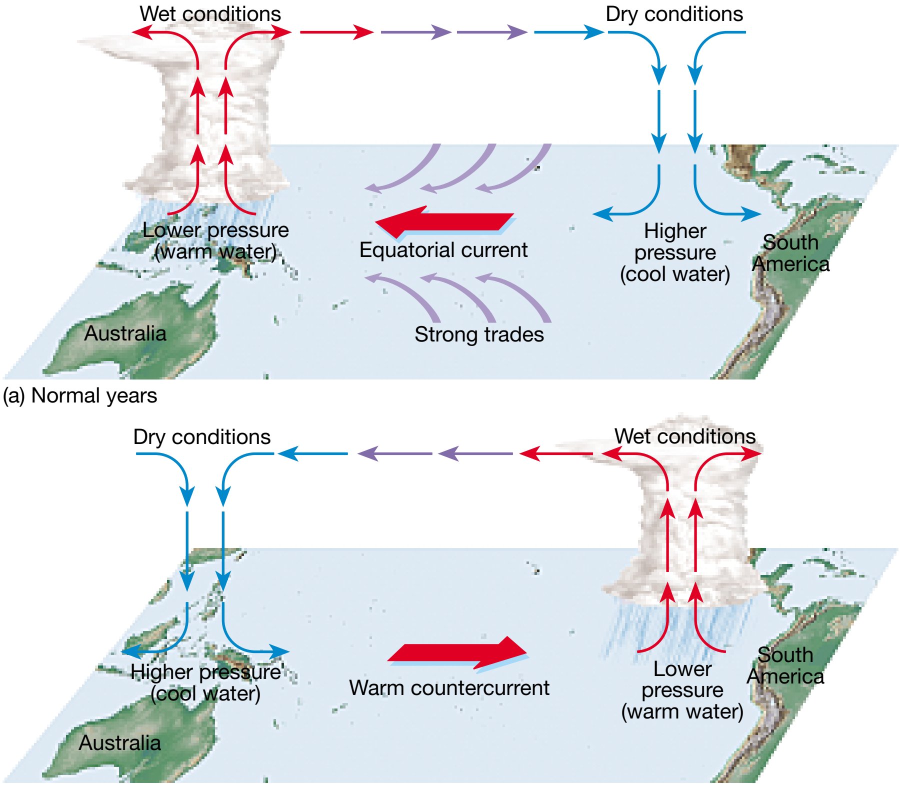
(b) El Niño

FIGURE 7-23 The relationship between the Southern Oscillation and El Niño is illustrated on these simplified maps. (a) Normally, the trade winds and strong equatorial currents flow toward the west. At the same time, the strong Peruvian current causes upwelling of cold water along the west coast of South America. (b) When the Southern Oscillation occurs, the pressure over the eastern and western Pacific flip-flops. This causes the trade winds to diminish, leading to an eastward movement of warm water along the equator. As a result, the surface waters of the central and eastern Pacific warm, with far-reaching consequences to weather patterns.

pattern of atmospheric pressure between the eastern and western Pacific is called the **Southern Oscillation.** It is an inseparable part of the El Niño warmings that occur in the central and eastern Pacific every three to seven years. Therefore, this phenomenon is often termed El Niño/Southern Oscillation, or ENSO for short.

Winds in the lower atmosphere are the link between the pressure change associated with the Southern Oscillation and the extensive ocean warming associated with El Niño (see Box 7–4). During a typical year the trade winds converge near the equator and flow westward toward Indonesia (Figure 7–24a). This steady westward flow creates a warm surface current that moves from east to west along the equator. The result is a “piling up” of a thick layer of warm surface water that produces higher sea levels (by 30 centimeters) in the western Pacific. Meanwhile, the eastern Pacific is characterized by a strong Peruvian current, upwelling of cold water, and lower sea levels.

Then when the Southern Oscillation occurs, the normal situation just described changes dramatically. Barometric pressure rises in the Indonesian region, causing the pressure gradient along the equator to weaken or even to reverse. As a consequence, the once-steady trade winds diminish and may even change direction. This reversal creates a major change in



(a) Normal years

(b) El Niño years

FIGURE 7-24 Simplified illustration of the seesaw pattern of atmospheric pressure between the eastern and western Pacific, called the *Southern Oscillation.* (a) During average years, high pressure over the eastern Pacific causes surface winds and warm equatorial waters to flow westward. The result is a pileup of warm water in the western Pacific, which promotes the lowering of pressure. (b) An El Niño event begins as surface pressure increases in the western Pacific and decreases in the eastern Pacific. This air pressure reversal weakens, or may even reverse the trade winds, and results in an eastward movement of the warm waters that had accumulated in the western Pacific.

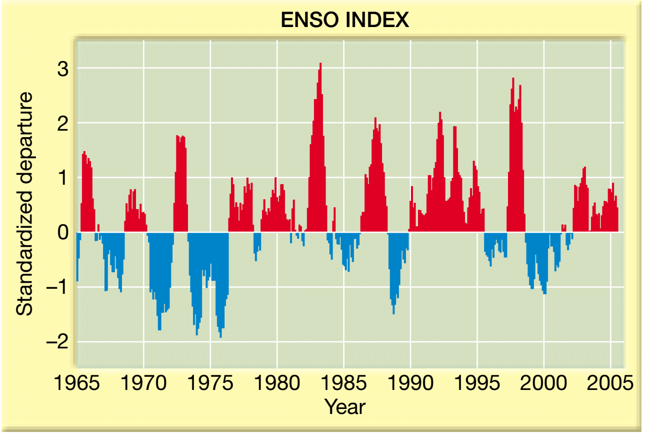
the equatorial current system, with warm water flowing eastward (Figure 7–24b). With time, water temperatures in the central and eastern Pacific increase and sea level in the region rises. This eastward shift of the warmest surface water marks the onset of El Niño and sets up changes in atmospheric circulation that affect areas far outside the tropical Pacific.

When an El Niño began in the summer of 1997, forecasters predicted that the pool of warm water over the Pacific would displace the paths of both the subtropical and polar jet streams, which steer weather systems across North America (Figure 7–23). As predicted, the subtropical jet brought rain to the Gulf Coast, where Tampa, Florida, received more than three times its normal winter precipitation. Furthermore, the midlatitude jet pumped warm air far north into the continent. As a result, winter temperatures west of the Rockies were significantly above normal.

The effects of El Niño are somewhat variable depending in part on the temperatures and size of the warm pools. Nevertheless, some locales appear to be affected more consistently. In particular, during most El Niños, warmer-than-normal winters occur in the northern United States and Canada. In addition, normally arid portions of Peru and Ecuador, as well as the eastern United States, experience wet conditions. By contrast, drought conditions are generally observed in Indonesia, Australia, and the Philippines. One major benefit of the circulation associated with El Niño is a suppression of the number of Atlantic hurricanes.

The opposite of El Niño is an atmospheric phenomenon known as **La Niña** Figure 7–25. Once thought to be the normal conditions that occur between two El Niño events, meteorologists now consider La Niña an important atmospheric phenomenon in its own right. Researchers have come to recognize that when surface temperatures in the eastern Pacific are *colder than average,* a La Niña event is triggered that has a distinctive set of weather patterns. A typical La Niña winter blows colder than normal air over the Pacific Northwest and the northern Great Plains while warming much of the rest of the United States. Further, greater precipitation is expected in the Northwest. During the La Niña winter of 1998–99, a world record snowfall for one season occurred

FIGURE 7-25 This graph illustrates the cyclical nature of El Niño/Southern Oscillation (ENSO). Negative values (blue) represent the cold La Niña phase, while positive values (red) represent the warm El Niño phase. The graph was created by analyzing six variables, including sea-surface temperatures and sea-level pressures. *(After Wolter and Timlin/NOAA)*

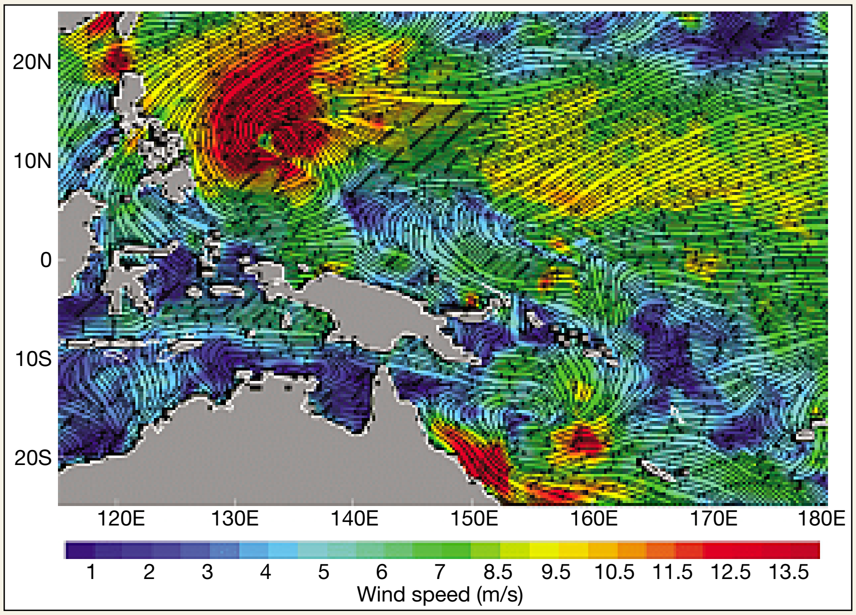


BOX 7-3 Monitoring Winds from Space

The global ocean makes up 71 percent of Earth's surface. Winds moving over the sea surface effectively move heat and moisture from place to place, while driving ocean currents and ultimately weather and climate. Surface-based methods of monitoring winds using ships and data buoys provide only a glimpse of the wind patterns over the ocean. Today instruments aboard NASA's *QuickSCAT* spacecraft can continuously and accurately map wind speed and direction under most atmospheric conditions over 90 percent of Earth's ice-free oceans.

QuickSCAT carries the *SeaWinds* scaterometer, a specialized type of radar that operates by transmitting microwave pulses to the ocean surface and measuring the amount of energy that is bounced back (or echoed) to the satellite. Smooth ocean surfaces return weaker signals because less energy is reflected, while rough water returns a stronger signal. From such data, scientists can compute wind speed and direction (Figure 7–D). By measuring global sea-surface winds, *SeaWinds* helps researchers more

FIGURE 7-D Map produced from *SeaWinds* data showing wind patterns over a portion of the western Pacific on March 4, 2002. The strongest winds in this image (red area) are about 50 kilometers (30 miles) per hour.



in Washington State. Another La Niña impact is greater hurricane activity. A recent study concluded that the cost of hurricane damages in the United States is 20 times greater in La Niña years as compared to El Niño years.

In summary, the effects of El Niño and La Niña on world climate are widespread and variable. There is no place on Earth where the weather is indifferent to air and ocean conditions in the tropical Pacific. Events associated with El Niño and La Niña are now understood to have a significant influence on the state of weather and climate almost everywhere.

Global Distribution of Precipitation

A casual glance at Figure 7–26a reveals a complex pattern for the distribution of precipitation. Although the map appears to be complicated, the general features of the pattern can be explained using our knowledge of global winds and pressure systems. In general, regions influenced by high pressure, with its associated subsidence and divergent winds, experience dry conditions. Conversely, regions under the influence of low pressure and its converging winds and ascending air receive ample precipitation. However, if the wind-pressure regimes were the only control of precipitation, the pattern shown in Figure 7–26a would be much simpler.

The inherent nature of the air is also important in determining precipitation potential. Because cold air has a low capacity for moisture compared with warm air, we would expect a latitudinal variation in precipitation, with low latitudes receiving the greatest amounts of precipitation and high latitudes receiving the least. Figure 7–26a indeed reveals heavy precipitation in equatorial regions and meager moisture near the landmasses poleward of 60° latitude. A noticeably arid region, however, is also found in the subtropics. This situation can be explained by examining the global wind-pressure regimes.

accurately predict marine phenomena that have the potential to affect human endeavors. For example, the satellite's instruments provide meteorologists with a method to identify areas of gale-force winds over the entire ocean. These real-time data can be used to give advance warning of high waves to vessels at sea and to coastal communities.

In addition, these snapshots of ocean winds help researchers better understand and predict the development of large storm systems, such as mid-latitide cyclones and hurricanes, as well as aid in our understanding of global weather events such as El Niño (Figure 7–E).

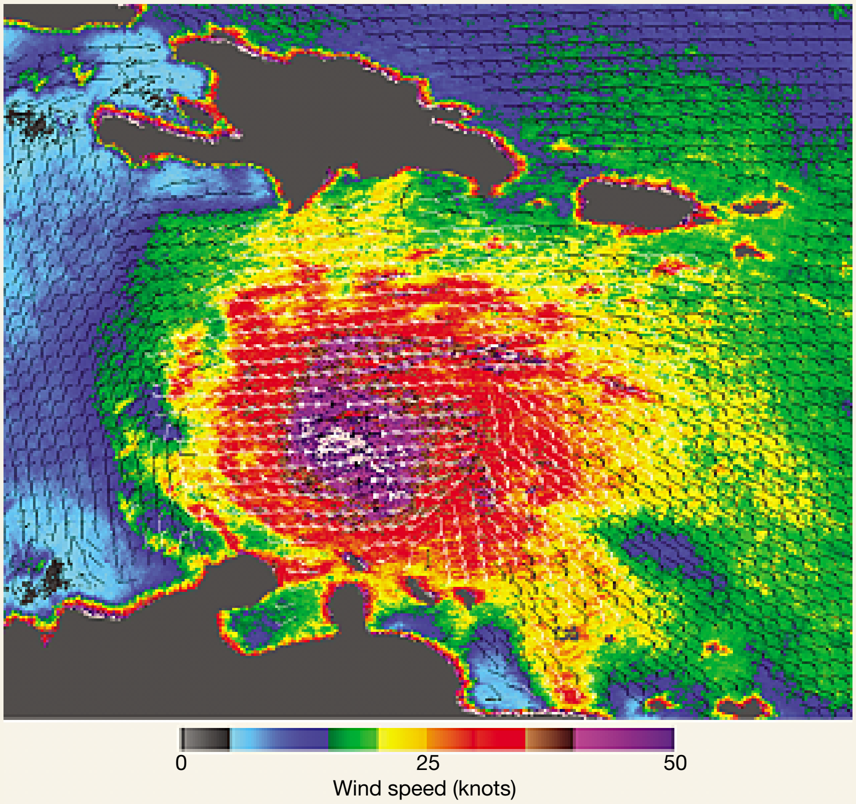


FIGURE 7-E This image shows Hurricane Ivan as it roared through the Caribbean as a deadly Category 5 storm early on September 9, 2004. Data from the *SeaWinds* scatterometer aboard NASA's *QuickSCAT* spacecraft augments traditional satellite images of clouds by providing direct measurements of surface winds to compare with observed cloud patterns in an effort to better determine a storm's structure and strength.

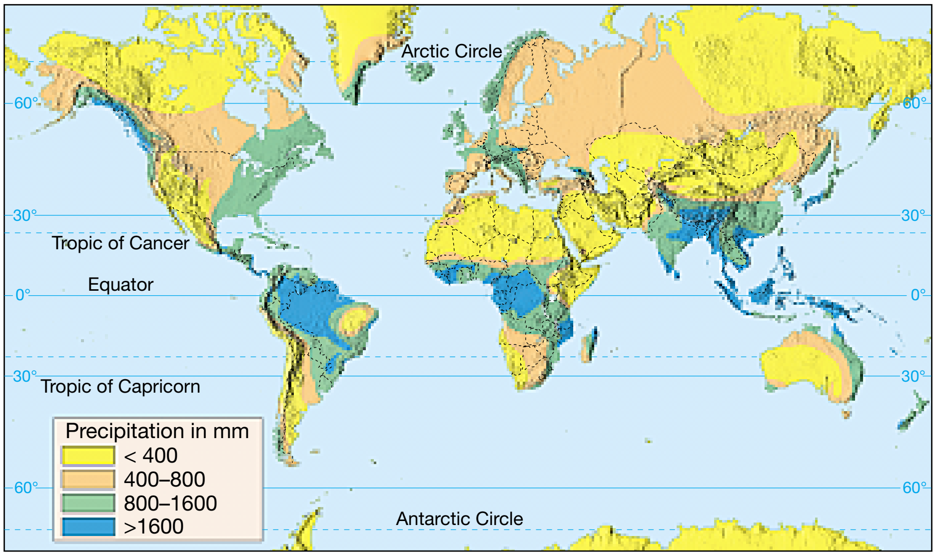
In addition to latitudinal variations in precipitation, the distribution of land and water complicates the precipitation pattern. Large landmasses in the middle latitudes commonly experience decreased precipitation toward their interiors. For example, central North America and central Eurasia receive considerably less precipitation than do coastal regions at the same latitude. Furthermore, the effects of mountain barriers alter the idealized precipitation regimes we would expect solely from the global wind systems. Windward mountain slopes receive abundant precipitation, whereas leeward slopes and adjacent lowlands are usually deficient in moisture.

Zonal Distribution of Precipitation

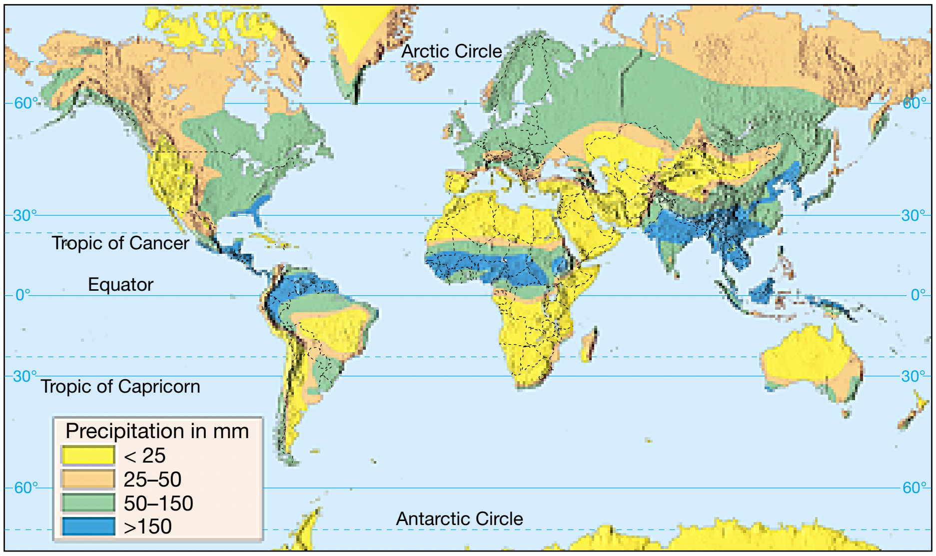
Let us first examine the zonal distribution of precipitation that we would expect on a uniform Earth, and then add the variations caused by land and water influences. Recall from our earlier discussion that on a uniform Earth, four major pressure zones emerge in each hemisphere (see Figure 7–8a). These zones include the equatorial low (ITCZ), the subtropical high, the subpolar low, and the polar high. Also, remember that these pressure belts show a marked seasonal shift toward the summer hemisphere.

The idealized precipitation regimes expected from these pressure systems are shown in Figure 7–27, in which we can see that the equatorial regime is centered over the equatorial low throughout most of the year. In this region, where the trade winds converge (ITCZ), heavy precipitation is experienced in all seasons. Poleward of the equatorial low in each hemisphere lie the belts of subtropical high pressure. In these regions, subsidence contributes to the dry conditions found there throughout the year. Between the wet equatorial regime and the dry subtropical regime lies a zone that is influenced by both pressure systems. Because the pressure systems migrate seasonally with the Sun, these transitional regions receive most of their precipitation in the summer when they are under the

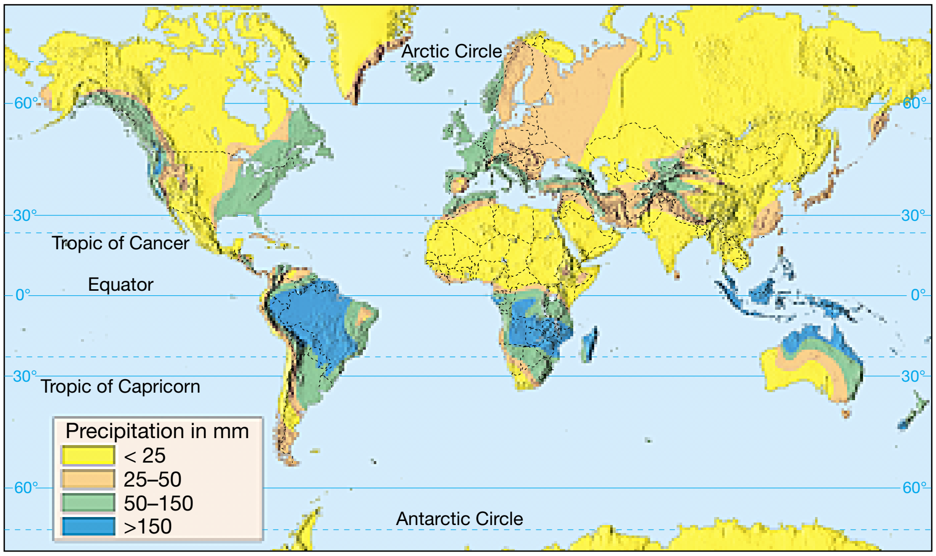
FIGURE 7-26 Global distribution of precipitation: (a) annual, (b) July, and (c) January.



(a) Annual

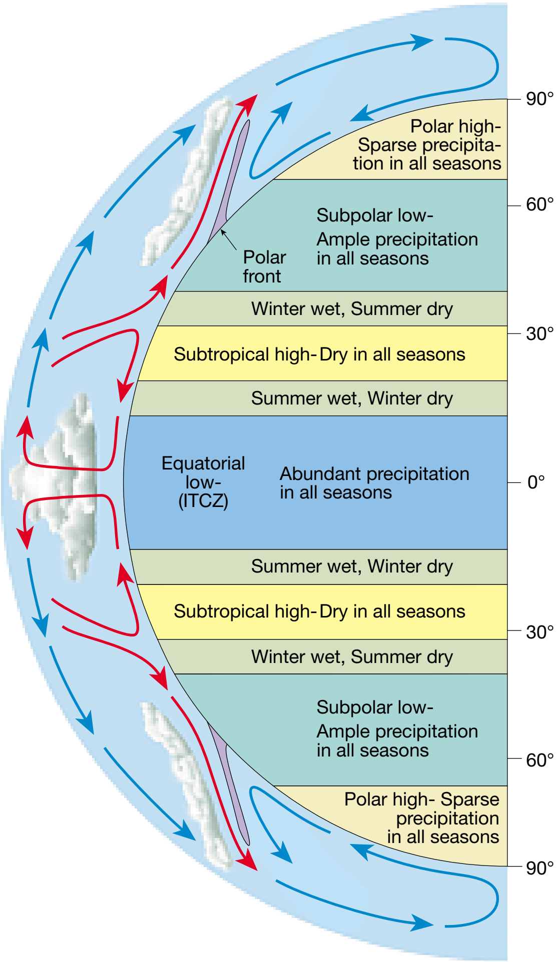


(b) July



(c) January

FIGURE 7-27 Zonal precipitation patterns.



influence of the ITCZ. They experience a dry season in the winter when the subtropical high moves equatorward.

The midlatitudes receive most of their precipitation from traveling cyclonic storms (Figure 7–28). This region is the site of the polar front, the convergent zone between cold polar air and the warmer westerlies. It is along the polar front that cyclones are frequently generated. Because the position of the polar front migrates freely between approximately 30° and 70° latitude, most midlatitude areas receive ample precipitation. But the mean position of this zone also moves north and south with the Sun, so that a narrow belt between 30° and 40° latitude experiences a marked seasonal fluctuation in precipitation.

In winter, this zone receives precipitation from numerous cyclones as the position of the polar front moves equatorward. During the summer, however, this region is dominated by subsidence associated with the dry subtropical high. Compare the July and January precipitation data for the west coast of North America by referring to Figure 7–26b and c.

The polar regions are dominated by cold air that holds little moisture. Throughout the year, these regions experience only meager precipitation. Even in the summer, when temperatures rise, these areas of ice and snow are dominated by high pressure that blocks the movement of the few cyclones that do travel poleward.

Distribution of Precipitation over the Continents

The zonal pattern outlined in the previous section roughly approximates general global precipitation. Abundant precipitation occurs in the equatorial and midlatitude regions, whereas substantial portions of the subtropical and polar realms are relatively dry. Yet numerous exceptions to this idealized zonal pattern are obvious in Figure 7–26a.

For example, several arid areas are found in the midlatitudes. The desert region of southern South America, known as Patagonia, is one example. Midlatitude deserts such as Patagonia exist mostly on the leeward (rain shadow) side of a mountain barrier or in the interior of a continent, cut off from a source of moisture. Most other departures from the idealized zonal scheme result from the distribution of continents and oceans.

The most notable anomaly in the zonal distribution of precipitation occurs in the subtropics. Here we find not only many of the world's great deserts but also regions of abundant rainfall (Figure 7–26a). This pattern results because the subtropical high-pressure centers that dominate the circulation in these latitudes have different characteristics on their eastern and western flanks (Figure 7–29). Subsidence is most pronounced on the eastern side of these oceanic highs, and a strong temperature inversion is encountered very near the surface and results in stable atmospheric conditions. The upwelling of cold water along the west coasts of the adjacent continents cools the air from below and adds to the stability on the eastern sides of these highs.

Because these anticyclones tend to crowd the eastern side of an ocean, particularly in the winter, we find that the western sides of the continents adjacent to these subtropical highs are arid (Figure 7–29). Centered at approximately 25° north or south latitude on the western side of their respective continents, we find the Sahara Desert of North Africa, the Namib of southwest Africa, the Atacama of South America, the deserts of the Baja Peninsula of North America, and the Great Desert of Australia.

On the western side of these highs, however, subsidence is less pronounced, and convergence with associated rising air appears to be more prevalent. In addition, as this air travels over a large expanse of warm water, it acquires moisture through evaporation that acts to enhance its instability. Consequently, the eastern regions of subtropical continents generally receive ample precipitation throughout the year. Southern Florida is a good example.

Precipitation Regimes on a Hypothetical Continent

When we consider the influence of land and water on the distribution of precipitation, the pattern illustrated in Figure 7–30 emerges. This figure is a highly idealized precipitation scheme for a hypothetical continent located in the Northern Hemisphere. The "continent" is shaped as it is to approximate the percentage of land found at various latitudes.

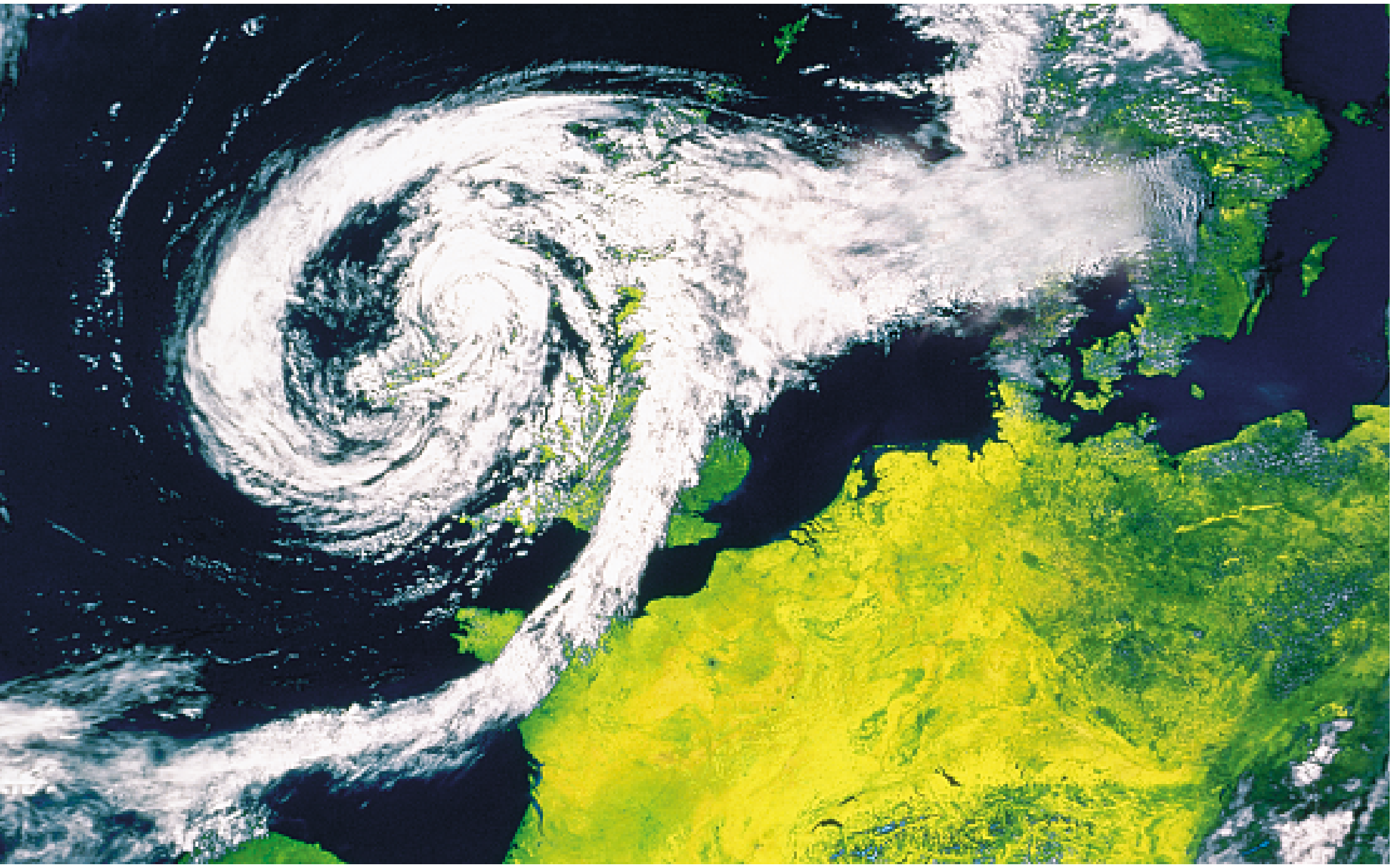
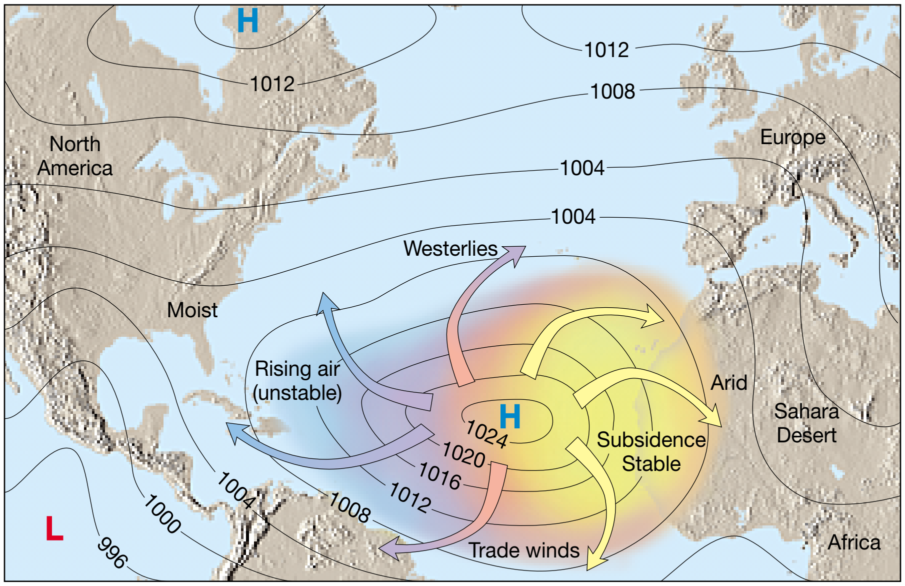


FIGURE 7-28 Satellite image of a well-developed mid-latitude cyclone over the British Isles. These traveling storms produce most of the precipitation in the middle latitudes. *(Courtesy of European Space Agency/Science Photo Library/Photo Researchers, Inc.)*

Notice that this hypothetical landmass has been divided into seven zones. Each zone represents a different precipitation regime. Stated another way, all locations within the same zone (precipitation regime) experience roughly the same precipitation pattern. As we shall see, the odd shape and size of these zones reflect the way precipitation is normally distributed across landmasses located in the Northern Hemisphere. The cities shown are representatives of the precipitation pattern of each location. With this in mind, we will now examine each precipitation regime (numbered 1 through 7) to see

FIGURE 7-29 Characteristics of subtropical high-pressure systems. Subsidence on the east side of these systems produces stable conditions and aridity. Convergence and uplifting on the western flank promote uplifting and instability.



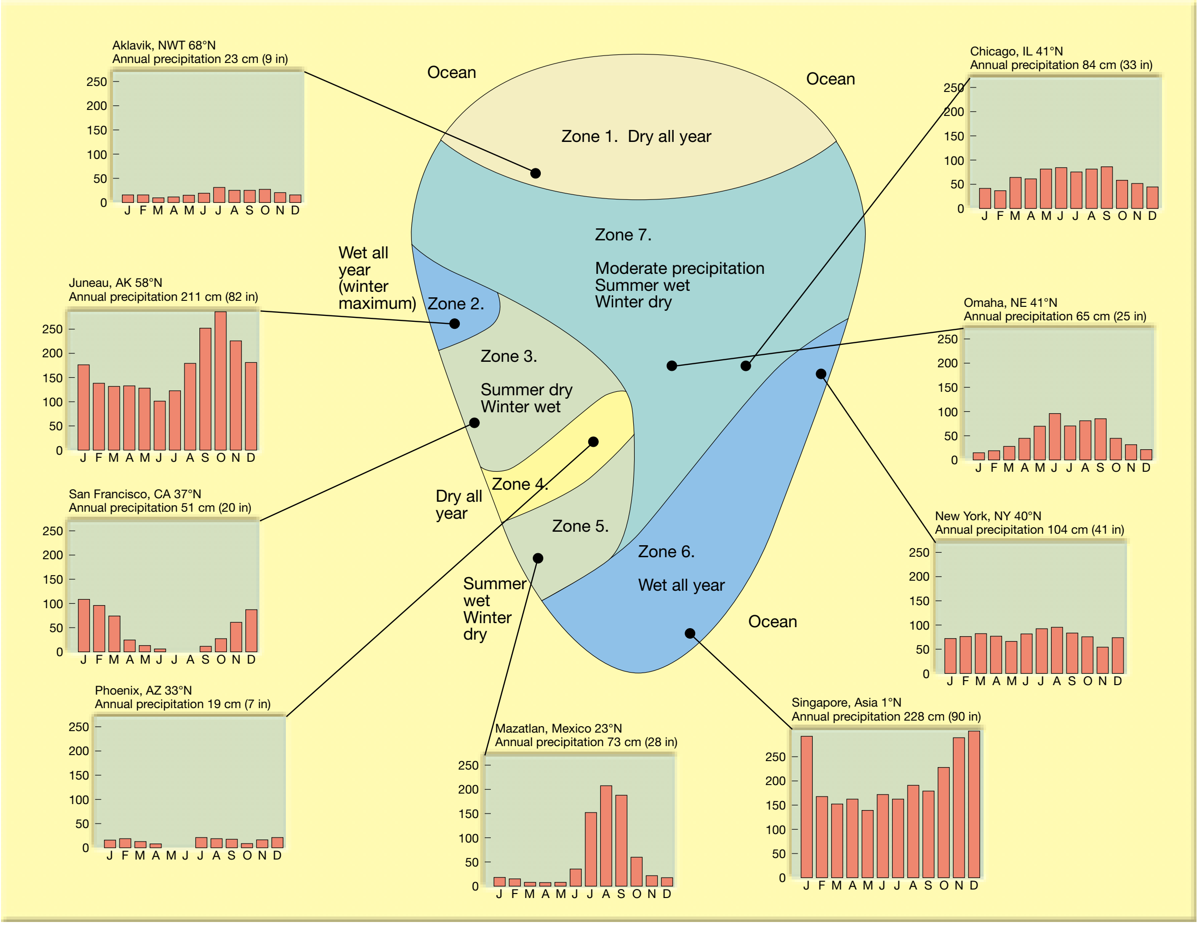


FIGURE 7-30 Idealized precipitation regimes for a hypothetical landmass in the Northern Hemisphere.

the influences of land and water on the distribution of precipitation.

First, compare the precipitation patterns for the nine cities. Notice that the precipitation regimes for west coast locations correspond to the zonal pressure and precipitation pattern shown in Figure 7–27: Zone 6 equates to the equatorial low (wet all year); Zone 4 matches the subtropical high (dry all year), and so on.

For illustration, Aklavik, Canada, which is strongly influenced by the polar high, has scant moisture, whereas Singapore, near the equator, has plentiful rain every month. Also note that precipitation varies seasonally with both latitude and each city's location with respect to the ocean.

For example, precipitation graphs for San Francisco and Mazatlan, Mexico, illustrate the marked seasonal variations found in Zones 3 and 5. Recall that it is the seasonal migration of the pressure systems that causes these fluctuations. Notice that Zone 2 shows a precipitation maximum in the fall and early winter, as illustrated by data for Juneau, Alaska. This pattern occurs because cyclonic storms over the North Pacific are more prevalent in the coolest half of the year. Further, the average path of these storms moves equatorward during the winter, impacting locations as far south as southern California.

The eastern half of the continent shows a marked contrast to the zonal precipitation pattern on the western side. Only the dry polar regime (Zone 1) is similar in size and position on both the Eastern and Western seaboards. The most noticeable departure from the zonal pattern is the absence of the arid subtropical region from the East Coast. As noted earlier, this difference is caused by the behavior of subtropical anticyclones located over the oceans. Recall that southern Florida, which is located on the east coast of the continent, receives ample precipitation year-round, whereas the Baja Peninsula on the West Coast is arid. Moving inland from the East Coast, observe how precipitation decreases (compare total precipitation westward for New York, Chicago, and Omaha). This decrease, however, does not hold true for mountainous regions; even relatively small ranges, like the Appalachians, are able to extract a greater share of precipitation.

Another variation is seen with latitude. As we move poleward along the eastern half of our hypothetical continent, note the decrease in precipitation (compare Singapore, New York, and Aklavik). This is the decrease we would expect with cooler air temperatures and corresponding lower moisture capacities. We do not, however, find a similar decrease in precipitation in the higher middle latitudes along the West Coast. Because this region lies in the westerly wind belt, the West Coasts of midlatitude regions, such as Alaska, Canada, and Norway, receive abundant moisture from storms that originate over the adjacent oceans. In fact, some of the rainiest

BOX 7-4 Tracking El Niño from Space

The images in Figure 7–F show the progression of the 1997–98 El Niño as derived from the TOPEX/Poseidon satellite.* This satellite uses radar altimeters to bounce radar signals off the ocean surface to obtain precise measurements of the distance between the satellite and the sea surface. This information is combined with high-precision orbital data from the Global Positioning System (GPS) of satellites to produce maps of sea-surface height. Such maps show the topography of the sea surface. Elevated topography ("hills") indicates warmer-than-average water, whereas areas of low topography ("valleys") indicate cooler-than-normal water. With this detailed information, scientists can determine the speed and direction of surface ocean currents.

The colors represented in these images show sea-level height relative to average. Remember, "hills" are warm and "valleys" are cool. The white and red areas indicate places of higher-than-normal sea-surface heights ("hills"). In the white areas the sea surface is between 14 and 32 centimeters above normal; in the red areas sea level is elevated by about 10 centimeters. Green areas indicate average conditions, whereas purple shows zones that are at least 18 centimeters below average sea level.

The images depict the progression of the large warm water mass from west to east across the equatorial Pacific. At its peak in November 1997, the surface area covered by the warm water mass was about one and a half times the size of the contiguous 48 states. The added amount of warm water in the eastern Pacific with a temperature between 21° and 30°C was about 30 times the combined volume of the water in all of the U.S. Great Lakes.

*This box is based on material published by NASA's Goddard Space Flight Center.

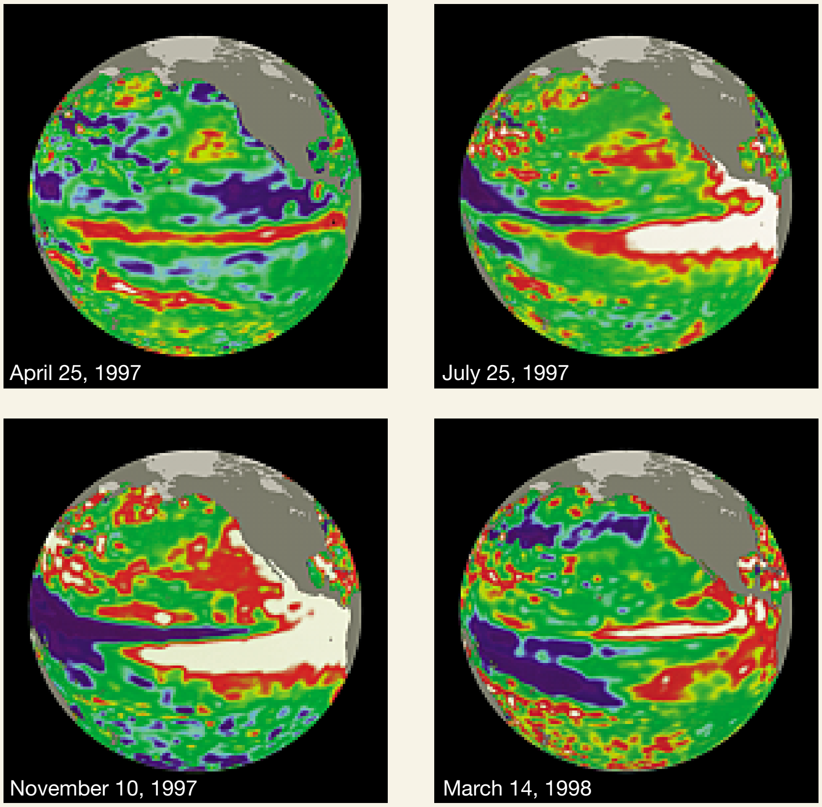


FIGURE 7-F The image for April 25, 1997, shows the Pacific on the eve of the 1997–98 El Niño event. By examining the images for July 25 and November 10, you can see the dramatic buildup of warm water (white and red areas) in the eastern Pacific and the enlarging region of cool water (purple) in the western Pacific. By the time of the March 14, 1998, image, the area of warm water in the eastern Pacific was *much* smaller. *(Courtesy of NASA Goddard Space Flight Center)*

regions on Earth are found in such settings. In contrast, the east coasts of mid-latitude locations experience temperature and moisture regimes more typical of continental locations, particularly in the winter when the airflow is off the land.

Consider next the continental interior, which shows a somewhat different precipitation pattern, especially in the middle latitudes. Because cyclones are more common in the winter, we would expect mid-latitude locations also to experience maximum precipitation in the winter. The precipitation regimes of the interior, however, are affected to a degree by a type of monsoon circulation. Cold winter temperatures and dominance of flow off the land in the winter make it the drier season (Omaha and Chicago). Although cyclonic storms frequent the continental interior in the winter, they do not become precipitation producers until they have drawn in abundant moist air from the Gulf of Mexico. Thus, most of the winter precipitation falls in the eastern one-third of the United States. The lack of abundant winter precipitation in the Plains states, compared with the East, can be seen in the data for Omaha and New York City.

In the summer, the inflow of warm, moist air from the ocean is aided by the thermal low that develops over the land and causes a general increase in precipitation over the midcontinent. The dominance of summer monsoon-type precipitation is evident when we compare the patterns for India in summer and winter by using Figure 7–26b and c. In the United States, places in the Southeast begin their rainy season in early spring, whereas more northerly and westerly locations do not experience their peak precipitation until summer or early fall.

Chapter Summary

- The largest planetary-scale wind patterns, called *macroscale winds,* include the westerlies and trade winds. A somewhat smaller macroscale circulation is called *synoptic scale,* or *weather-map scale. Mesoscale winds,* such as thunderstorms, tornadoes, and land and sea breezes, influence smaller areas and often exhibit intense vertical flow. The smallest scale of air motion is the *microscale.* Examples of these very local, often chaotic winds include gusts and dust devils.
- All winds have the same cause: pressure differences that arise because of temperature differences that are caused by unequal heating of Earth's surface. In addition to *land* and *sea breezes* brought about by the daily temperature contrast between land and water, other mesoscale winds include *mountain* and *valley breezes, chinook (foehn)* winds, *katabatic (fall)* winds, and *country breezes.* Mountain and valley breezes develop as air along mountain slopes is heated more intensely than air at the same elevation over the valley floor. Chinooks are warm, dry winds that sometimes move down the east slopes of the Rockies. In the Alps, winds similar to chinooks are called foehns. Katabatic (fall) winds originate when cold air, situated over a highland area such as the ice sheets of Greenland and Antarctica, is set in motion under the influence of gravity. Country breezes are associated with large urban areas where the circulation pattern is characterized by a light wind blowing into the city from the surrounding countryside.
- A simplified view of global circulation is a three-cell circulation model for each hemisphere. Because the circulation patterns between the equator and roughly 30° latitude north and south closely resemble a single-cell model developed by George Hadley in 1735, the name *Hadley cell* is generally applied. According to the three-cell circulation model, in each hemisphere, atmospheric circulation cells are located between the equator and 30° latitude, 30° and 60° latitude, and 60° latitude and the pole. The areas of general subsidence in the zone between 20° and 35° are called the *horse latitudes.* In each hemisphere, the equatorward flow from the horse latitudes forms the reliable *trade winds.* Convergence of the trade winds from both hemispheres near the equator produces a region of light winds called the *doldrums.* The circulation between 30° and 60° latitude (north and south) results in the *prevailing westerlies.* Air that moves equatorward from the poles produces the *polar easterlies* of both hemispheres. The area where the cold polar easterlies clash with the warm westerly flow of the midlatitudes is referred to as the *polar front,* an important meteorological region.
- If Earth's surface were uniform, two latitudinally oriented belts of high and two of low pressure would exist. Beginning at the equator, the four belts would be the (1) *equatorial low,* also referred to as the *intertropical convergence zone (ITCZ),* because it is the region where the trade winds converge, (2) *subtropical high,* at about 20° to 35° on either side of the equator, (3) *subpolar low,* situated at about 50° to 60° latitude, and (4) *polar high,* near Earth's poles.
- In reality, the only true zonal pattern of pressure exists along the subpolar low in the Southern Hemisphere. At other latitudes, particularly in the Northern Hemisphere, where there is a higher proportion of land compared to ocean, the zonal pattern is replaced by semipermanent cells of high and low pressure. January pressure and wind patterns show a very strong high-pressure center, called the *Siberian High,* positioned over the frozen landscape of northern Asia. Also evident in January, but absent in July, are two intense semipermanent low-pressure centers, the *Aleutian* and *Icelandic lows,* situated over the North Pacific and North Atlantic, respectively. With the onset of summer the pressure pattern over the Northern Hemisphere changes dramatically and high temperatures over the continents generate lows that replace the winter highs. During the peak summer season, the subtropical high found in the North Atlantic (called the

Azores high in winter) is positioned near the island of Bermuda and is called the *Bermuda high.*

- The greatest seasonal change in Earth's global circulation is the development of *monsoons,* wind systems that exhibit a pronounced seasonal reversal in direction. The best-known and most pronounced monsoonal circulation, the *Asian monsoon* found in southern and southeastern Asia, is a complex seasonal change that is strongly influenced by the amount of solar heating received by the vast Asian continent. The *North American monsoon* (also called the *Arizona monsoon* and *Southwest monsoon*), a relatively small seasonal wind shift, produces a dry spring followed by a comparatively rainy summer that impacts large areas of southwestern United States and northwestern Mexico.
- The temperature contrast between the poles and equator drives the westerly winds (*westerlies*) located in the middle latitudes. Imbedded within the westerly flow aloft are narrow ribbons of high-speed winds, called *jet streams,* that meander for thousands of kilometers. The key to the origin of polar jet streams is found in great temperature contrasts at the surface. In the region between 30° and 70°, the *polar jet stream* occurs in association with the *polar front.*
- Studies of upper-level wind charts reveal that the westerlies follow wavy paths that have rather long wavelengths. The longest wave patterns are called *Rossby waves.* During periods when the flow aloft is relatively flat, little cyclonic activity is generated at the surface. Conversely, when the flow exhibits large-amplitude waves having short wavelengths, vigorous cyclonic storms are created. In addition to seasonal changes in the strength of its flow, the position of the polar jet also shifts from summer to winter.
- Because winds are the primary driving force of ocean currents, a relationship exists between the oceanic circulation and the general atmospheric circulation. In general, in response to the circulation associated with the subtropical highs, ocean currents form clockwise spirals in the Northern Hemisphere and counterclockwise spirals in the Southern Hemisphere. In addition to influencing temperatures of adjacent land areas, cold ocean currents also transform some subtropical deserts into relatively cool, damp places that are often shrouded in fog. Furthermore, ocean currents play a major role in maintaining Earth's heat balance. In addition to producing surface currents, winds may also cause vertical water movements, such as the *upwelling* of cold water from deeper layers to replace warmer surface water.
- *El Niño* refers to episodes of ocean warming caused by a warm countercurrent flowing southward along the coasts of Ecuador and Peru that replaces the cold Peruvian current. The events are part of the global circulation and related to a seesaw pattern of atmospheric pressure between the eastern and western Pacific called the *Southern Oscillation.* El Niño events influence weather at great distances from Peru and Ecuador. Two of the strongest El Niño events (1982–83 and 1997–98) were responsible for a variety of weather extremes in many parts of the world. When surface temperatures in the eastern Pacific are colder than average, a *La Niña* event is triggered. A typical La Niña winter blows colder than normal air over the Pacific Northwest and the northern Great Plains while warming much of the rest of the United States.
- The general features of the global distribution of precipitation can be explained by global winds and pressure systems. In general, regions influenced by high pressure, with its associated subsidence and divergent winds, experience dry conditions. On the other hand, regions under the influence of low pressure and its converging winds and ascending air receive ample precipitation.
- On a uniform Earth throughout most of the year, heavy precipitation would occur in the equatorial region, the mid-latitudes would receive most of their precipitation from traveling cyclonic storms, and polar regions would be dominated by cold air that holds little moisture. The most notable anomaly to this zonal distribution of precipitation occurs in the subtropics, where many of the world's great deserts are located. In these regions, pronounced subsidence on the eastern side of subtropical high-pressure centers results in stable atmospheric conditions. Upwelling of cold water along the west coasts of the adjacent continents further adds to the stable and dry conditions. On the other hand, the east coast of the adjacent continent receives abundant precipitation year-round due to the convergence and rising air associated with the western side of the oceanic high.

Vocabulary Review

Aleutian low (p. 210)
Azores high (p. 210)
bora (p. 204)
Bermuda high (p. 210)
chinook (p. 203)
country breeze (p. 204)
doldrums (p. 207)
El Niño (p. 219)
equatorial low (p. 207)
foehn (p. 203)
Hadley cell (p. 206)
horse latitudes (p. 207)
Icelandic low (p. 210)
intertropical convergence zone (ITCZ) (p. 207)
jet stream (p. 213)
katabatic or fall wind (p. 203)
land breeze (p. 202)
La Niña (p. 221)
macroscale winds (p. 199)
mesoscale winds (p. 199)
microscale circulation (p. 199)
mistral (p. 204)
monsoon (p. 210)
mountain breeze (p. 202)
ocean currents (p. 217)
polar easterlies (p. 207)
polar front (p. 207)
polar high (p. 207)
polar jet stream (p. 214)
prevailing westerlies (p. 207)
Santa Ana (p. 203)
sea breeze (p. 202)

Siberian high (p. 210)
Southern Oscillation (p. 221)
subpolar low (p. 207)
subtropical high (p. 207)
subtropical jet stream (p. 215)
trade winds (p. 207)
upwelling (p. 219)
valley breeze (p. 202)

Review Questions

1. Distinguish among macroscale, mesoscale, and microscale winds. Give an example of each.
2. If you were to view a weather map of the entire world for any single day of the year, would the global pattern of winds likely be visible? Explain your answer.
3. Why is the well-known Texas "norther" not a true local (mesoscale) wind?
4. The most intense sea breezes develop along tropical coasts adjacent to cool ocean currents. Explain.
5. What are katabatic (fall) winds? Name two examples.
6. Explain how cities create their own local winds.
7. Briefly describe the idealized global circulation proposed by George Hadley. What are the shortcomings of the Hadley model?
8. Which factors cause air to subside between 20° and 35° latitude?
9. If Earth rotated more rapidly, the Coriolis force would be stronger. How would a faster rate of rotation affect the location (latitude) of Earth's belts of subtropical high pressure?
10. Referring to the idealized three-cell model of atmospheric circulation, most of the United States is situated in which belt of prevailing winds?
11. Briefly explain each of the following statements that relate to the global distribution of surface pressure:
    - **a.** The only true zonal distribution of pressure exists in the region of the subpolar low in the Southern Hemisphere.
    - **b.** The subtropical highs are stronger in the North Atlantic in July than in January.
    - **c.** The subpolar low in the Northern Hemisphere is represented by individual cyclonic storms that are more common in the winter.
    - **d.** A strong high-pressure cell develops in the winter over northern Asia.
12. Explain the cause of the Asian monsoon. In which season (summer or winter) does it rain?
13. What area of North America experiences a pronounced monsoon circulation?
14. Why is the flow aloft predominantly westerly?
15. At what time of year should we expect the fastest westerly flow? Explain.
16. Describe the situation in which jet streams were first encountered.
17. Describe the manner in which pressure distribution is shown on upper-air charts. How are high- and low-pressure areas depicted on these charts?
18. What were the *dishpan experiments* and what have we learned from them?
19. Describe how a major El Niño event in the tropical Pacific might affect the weather in other parts of the globe.
20. How is La Niña different from El Niño?
21. What factors, other than global wind and pressure systems, exert an influence on the world distribution of precipitation?

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