8 Ocean Circulation

Only 48 kilometers (30 miles) off the coast of Cornwall at 50° N, these "tropical" gardens on Britain's Scilly Isles lie in the path of the warm waters of the Gulf Stream. Across the Atlantic at nearly the same latitude lays Ontario's Polar Bear Provincial Park, a sanctuary for migrating polar bears. Why the great difference in climate? The air flowing toward Polar Bear Provincial Park loses heat as it passes over the frozen landmass of Canada, but the air moving over the ocean toward the British Isles is heated by contact with the warm Gulf Stream and North Atlantic Current.

The cities of western Europe and Scandinavia are warmed by the energy of tropical sunlight transported to their northern latitudes by winds and by moving masses of water called *currents.* Ireland and England therefore have a mild maritime climate, and polar bears there are found only in zoos.

Study Plan

Preview: Five Main Ideas

1. Ocean circulation is driven by winds and by differences in water density. Along with the winds, ocean currents distribute tropical heat worldwide.
2. Surface currents are wind-driven movements of water at or near the ocean's surface. Thermohaline currents (so named because they depend on density differences caused by variations in water's temperature and salinity) are the slow, deep currents that affect the vast bulk of seawater beneath the pycnocline.
3. Large surface currents move in circular circuits—gyres—along the peripheries of major ocean basins. Wind-driven water moving in a gyre is dynamically balanced between Coriolis effect and the force of gravity.
4. El Niño and La Niña affect ocean and atmosphere. They are exceptions to normal wind and current flow.
5. Water masses form at the ocean surface. Water masses often retain their distinct properties as they sink and sort into identifiable layers.

8.1 Mass Flow of Ocean Water Is Driven by Wind and Gravity

Sailors have long known that the ocean is on the move. The first traders to sail cautiously out of the Mediterranean at Gibraltar noticed a persistent southerly set—they would often drift down the African coast despite the direction of the winds. Pytheas of Massalia, a Greek ship's captain who explored the northeastern Atlantic in the fourth century B.C.E., was the first observer to record this slow, continuous movement and to estimate its speed.

By the early seventeenth century, the massed fishing fleets of Japan were using a northward drift to their advantage to reach rich hauls off the Kamchatka Peninsula. (They returned home by sailing close to shore where the drift was weak.)

More recently, Sir John Murray noted in the *Challenger Report* that the temperature of the ocean's surface water was almost always higher than the temperature of deep water, and that a zone of rapid temperature change (which you know as a thermocline) existed in most areas sampled.

Still later, in a pivotal 1961 article, Klaus Wyrtki answered a persistent question: What keeps the thermocline up? Because of contact conduction of heat, shouldn't water temperature decline *gradually* and *continuously* as depth increases? Cold water is somehow rising from below to lift the warm water toward the ocean surface. Where does this cold water come from?

These ideas are related. The horizontal drift of ships and the vertical movement of cold water are caused by the mass flow of water—a phenomenon we know as ocean **currents.**

Surface currents are wind-driven movements of water at or near the ocean's surface, and *thermohaline currents* (so named because they depend on density differences caused by variations in water's temperature and salinity) are the slow, deep currents that affect the vast bulk of seawater beneath the pycnocline. Both have very important influences on Earth's temperature, climate, and biological productivity.

Brief Review

Before going on to the next section, check your understanding of some of the important ideas presented so far:

1. What causes the two major types of ocean currents?

To check your answers, visit www.cengagebrain.com.

8.2 Surface Currents Are Driven by the Winds

About 10% of the water in the world ocean is involved in **surface currents,** water flowing horizontally in the uppermost 400 meters (1,300 feet) of the ocean's surface, driven mainly by wind friction. Most surface currents move water above the pycnocline, the zone of rapid density change with depth described in Chapter 6.

The primary force responsible for surface currents is wind. As you read in Chapter 7, surface winds form

Gary Blake/Alamy

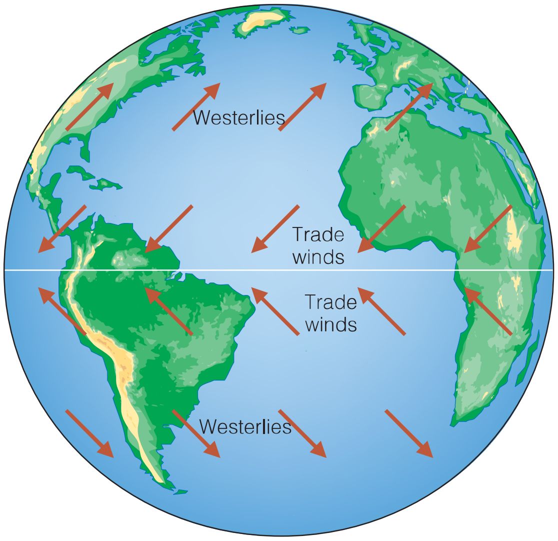


Figure 8.1
Winds, driven by uneven solar heating and Earth's spin, drive the movement of the ocean's surface currents. The prime movers are the powerful westerlies and the persistent trade winds (easterlies).

global patterns within latitude bands (**Figure 8.1;** also see Figure 7.13). Most of Earth's surface wind energy is concentrated in each hemisphere's trade winds (easterlies) and westerlies. Waves on the sea surface transfer some of the energy from the moving air to the water by friction. This tug of wind on the ocean surface begins a mass flow of water. The water flowing beneath the wind forms a surface current.

The moving water "piles up" in the direction the wind is blowing. Water pressure is higher on the "piled-up" side, and the force of gravity pulls the water down the slope—against the *pressure gradient*—in the direction from which it came. But the Coriolis effect intervenes. Because of the Coriolis effect (discussed in Chapter 7), Northern Hemisphere surface currents flow to the *right* of the wind direction. Southern Hemisphere currents flow to the *left.* Continents and basin topography often block continuous flow and help deflect the moving water into a circular pattern. This flow around the periphery of an ocean basin is called a **gyre** (*gyros,* "a circle"). Two gyres are shown in **Figure 8.2.**

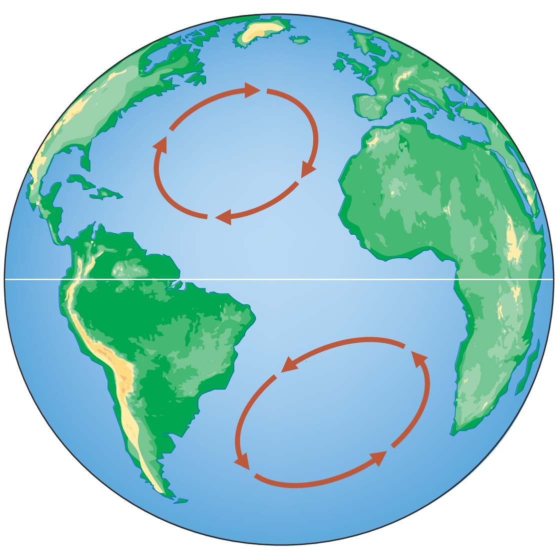


Figure 8.2
A combination of four forces—surface winds, the sun's heat, the Coriolis effect, and gravity—circulates the ocean surface clockwise in the Northern Hemisphere and counterclockwise in the Southern Hemisphere, forming gyres.

Surface Currents Flow around the Periphery of Ocean Basins

Figure 8.3 shows the North Atlantic gyre in more detail. Though the gyre flows continuously without obvious places where one current ceases and another begins, oceanographers subdivide the North Atlantic gyre into four interconnected currents because each has distinct flow characteristics and temperatures. (Gyres in other ocean basins are similarly divided.) Notice that the east–west currents in the North Atlantic gyre flow to the right of the driving winds; once initiated, water flow in these currents continues in a roughly east–west direction. Where their flow is blocked by continents, the currents turn clockwise to complete the circuit.

Why does water flow around the *periphery* of the ocean basin instead of spiraling to the center? After all, the Coriolis effect influences any moving mass *as long as it moves,* so water in a gyre might be expected to curve to the center of the North Atlantic and stop. To understand this aspect of current movement, imagine the forces acting on the surface water at 45° N latitude (point A in **Figure 8.4**). Here the westerlies blow from the southwest, so initially the water will move toward the northeast. The rightward Coriolis deflection then causes the water to flow almost due east. A particle at 15° N latitude (point B in Figure 8.4) responds to the push of the trade winds from the northeast, however, and with Coriolis deflection it will flow almost due west.

Figure 8.3
The North Atlantic gyre, a series of four interconnecting currents with different flow characteristics and temperatures.

Figure 8.4

Surface water blown by the winds at point **A** will veer to the right of its initial path and continue eastward. Water at point **B** veers to the right and continues westward.

Water at the surface can flow at a velocity no greater than about 3% of the speed of the driving wind.

When driven by the wind, the topmost layer of ocean water in the Northern Hemisphere flows at about 45° to the right of the wind direction, a flow consistent with the arrows leading away from points A and B in Figure 8.4. But what about the water in the next layer down? It can't "feel" the wind at the surface; it "feels" only the movement of the water immediately above. This deeper layer of water moves *at an angle to the right* of the overlying water. The same thing happens in the layer below that, and the next layer, and so on, to a depth of about 100 meters (330 feet) at mid-latitudes. Each layer slides horizontally over the one beneath it like cards in a deck, with each lower card moving at an angle slightly to the right of the one above. Because of frictional losses, each lower layer also moves more slowly than the layer above. The resulting situation, portrayed in **Figure 8.5,** is known as **Ekman spiral** after the Swedish oceanographer who worked out the mathematics involved.

The word *spiral* is somewhat misleading; the water itself does not spiral downward in a whirlpool-like motion like water going down a drain. Rather, the spiral is a way of conceptualizing the horizontal movements in a layered water column, each layer moving in a slightly different horizontal direction. An unexpected result of the Ekman spiral is that at some depth (known as the friction depth), water will be flowing in the opposite direction from the surface current!

The *net* motion of the water down to about 100 meters, after allowance for the summed effects of Ekman spiral (the sum of all the arrows indicating water direction in the affected layers), is known as **Ekman transport** (or *Ekman flow*). In theory, the direction of Ekman transport is 90° to the *right* of the wind direction in the Northern Hemisphere and 90° to the *left* in the Southern Hemisphere.

Armed with this information, we can look in more detail at the area around point B in Figure 8.4, which is enlarged in **Figure 8.6.** In nature, Ekman transport in gyres is less than 90°; in most cases, the deflection barely reaches 45°. This deviation from theory occurs because of an interaction between the Coriolis effect and the pressure gradient. Some flowing Atlantic water has turned to the right and forms a hill of water; it followed the rightward dotted arrow in Figure 8.6.

Why does the water now go straight west from point B without turning? Because, as **Figure 8.7a** shows, to turn farther *right,* the water would have to move uphill

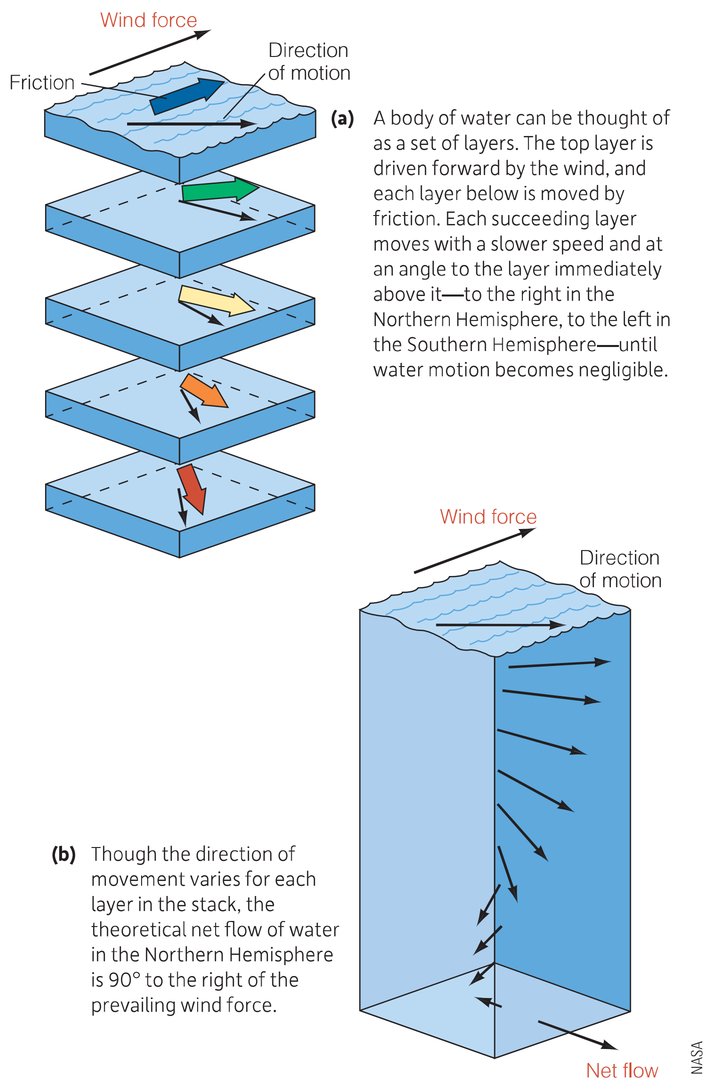
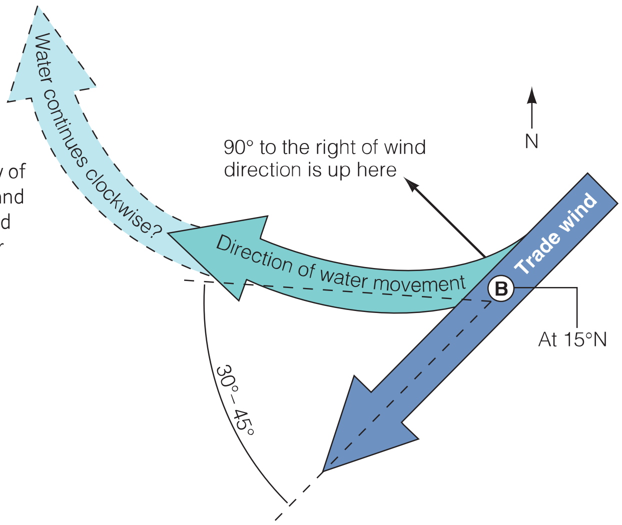


Figure 8.5

The Ekman spiral and the mechanism by which it operates. The length of the arrows in the diagrams is proportional to the speed of the current in each layer. (a. From Laboratory Exercises in Oceanography, 3/e by Pipkin, Gorslin, Casey and Hammond. © 1987 by W. H. Freeman and Company. Reprinted by permission.)

Figure 8.6
The movement of water away from point **B** in Figure 8.4 is influenced by the rightward tendency of the Coriolis effect and the gravity-powered movement of water down the pressure gradient.



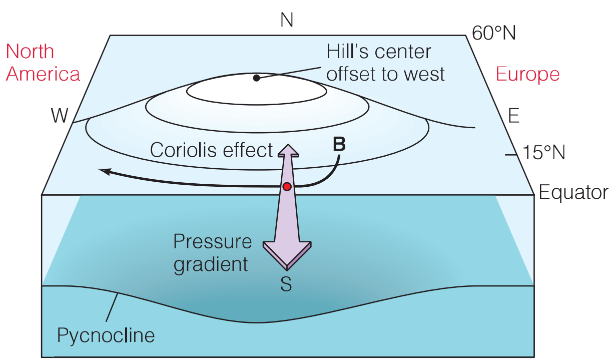
against the pressure gradient (and in defiance of gravity), but to turn *left* in response to the pressure gradient would defy the Coriolis effect. So the water continues westward and then clockwise around the whole North Atlantic gyre, dynamically balanced between the downhill urge of the pressure gradient and the uphill tendency of Coriolis deflection. The hill has consequences for deeper water as well. Water flowing inward to form the hill sinks and depresses the thermocline.

Yes, *there really is* a hill near the middle of the North Atlantic, centered in the area of the Sargasso Sea; satellite images provide the evidence **(Figure 8.7b).** This hill is formed of surface water gathered at the ocean's center of circulation. It is not a steep mountain of water—its maximum height is an unspectacular 2 meters (6.5 feet)—but rather a gradual rise and fall from coastline to open ocean and back to opposite coastline. Its slope is so gradual you wouldn't notice it on a transatlantic crossing.

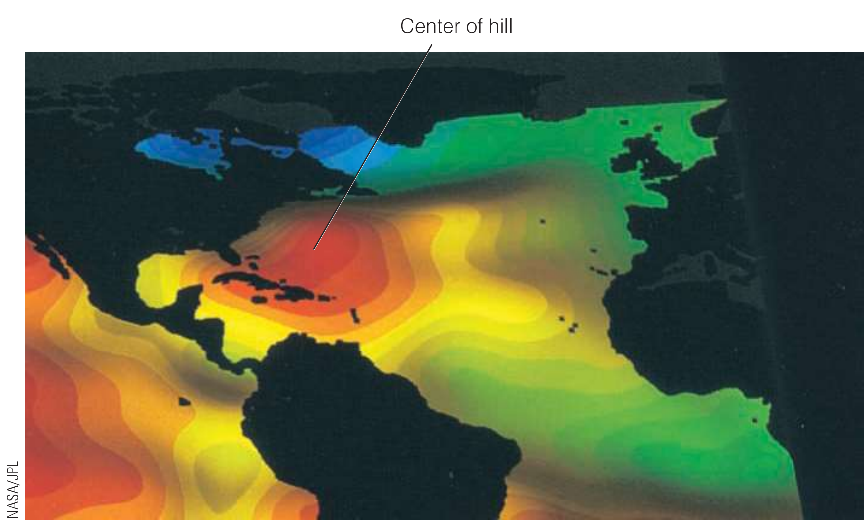
The hill is maintained by wind energy. If the winds did not continuously inject new energy into currents, then friction within the fluid mass and with the surrounding ocean basins would slow the flowing water, gradually converting its motion into heat. The balance of wind energy and friction, and of the Coriolis effect and the pressure gradient (through the effect of gravity), propels the currents of the gyre and holds them along the outside edges of the ocean basin.

Seawater Flows in Six Great Surface Circuits

Gyres in balance between the pressure gradient and the Coriolis effect are called **geostrophic gyres** (*Geos,* "Earth"; *strophe,* "turning"), and their currents are *geo-*

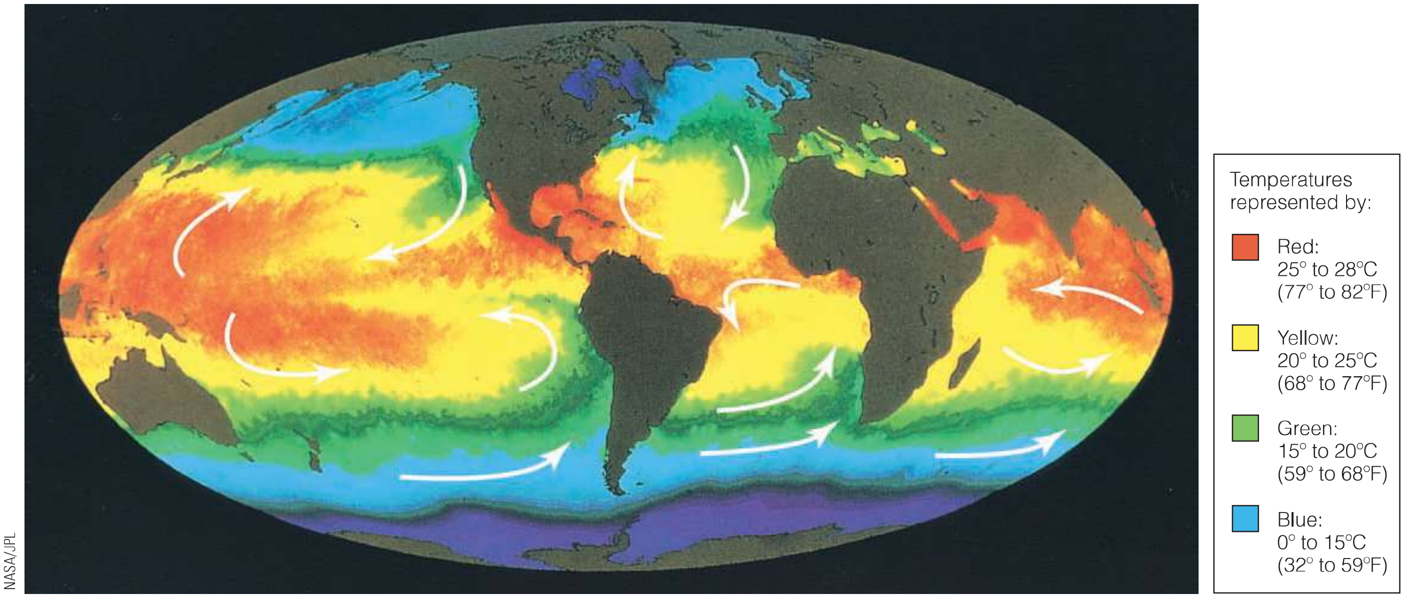


(a) The surface of the North Atlantic is raised through wind motion and Ekman transport to form a low hill. Water from point **B** (see also Figures 8.4 and 8.6) turns westward and flows along the side of this hill. The westward-moving water is balanced between the Coriolis effect (which would turn the water to the right) and flow down the pressure gradient, driven by gravity (which would turn it to the left). Thus, water in a gyre moves along the outside edge of an ocean basin. Water also descends, depressing the pycnocline.

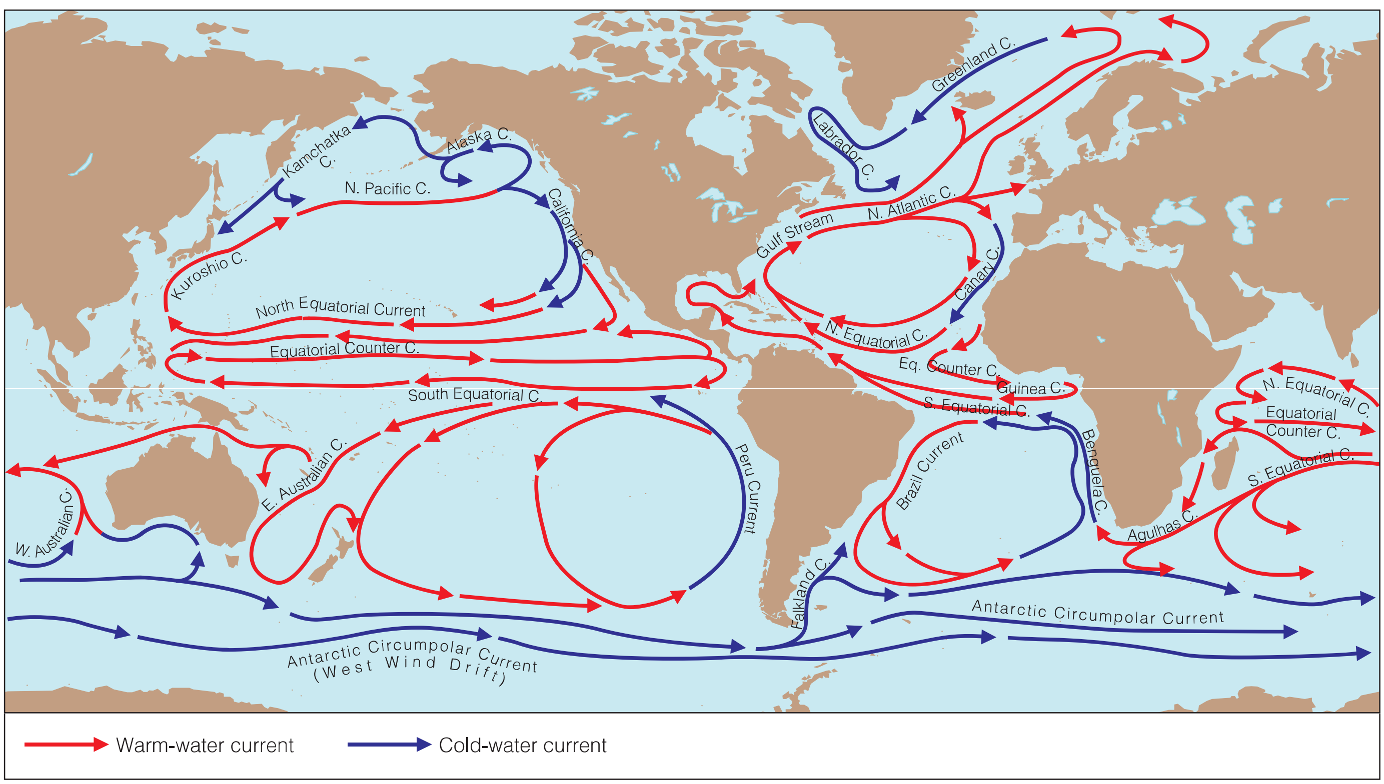


(b) The average height of the surface of the North Atlantic is shown in color in this image derived from data taken in 1992 by the *TOPEX/Poseidon* satellite. Red indicates the highest surface; green and blue, the lowest. Note that the measured position of the hill is offset to the west, as seen in **(a)**. (The westward offset is explained in Figure 8.12.) The gradually sloping hill is only 2 meters (6.5 feet) high and would not be apparent to anyone traveling from coast to coast.

Figure 8.7
The hill of water in the North Atlantic.



(a) An illustration of sea-surface temperature showing the general direction and pattern of surface current flow. Sea-surface temperatures were measured by a radiometer aboard *NOAA-7* in July 1984. The purple color around Antarctica and west of Greenland indicates water below 0°C, the freezing point of fresh water. Note the distortion of the temperature patterns we might expect from the effects of solar heating alone—the patterns twist clockwise in the Northern Hemisphere, counterclockwise in the Southern.



(b) A chart showing the names and usual direction of the world ocean's major surface currents. The powerful western boundary currents flow along the western boundaries of ocean basins in *both* hemispheres.

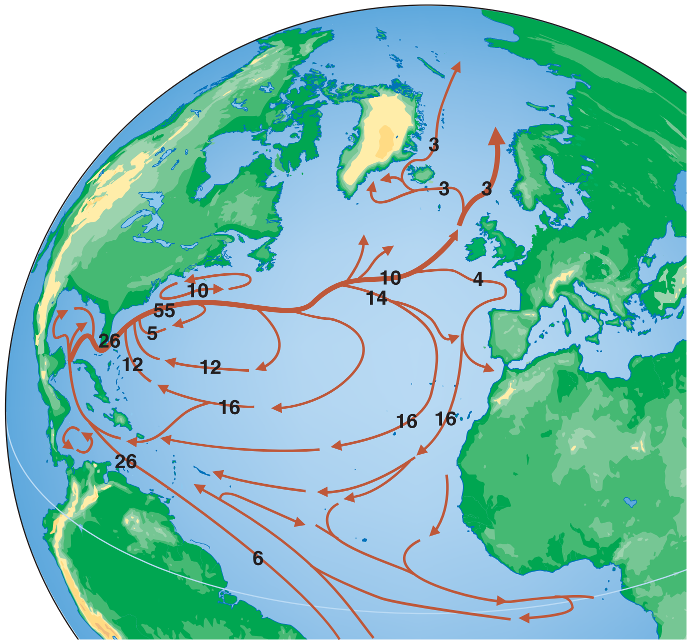
Figure 8.8

Two ways of viewing the major surface currents of the world ocean.

strophic currents. Because of the patterns of driving winds and the present positions of continents, the geostrophic gyres are largely independent of one another in each hemisphere.

There are six great current circuits in the world ocean, two in the Northern Hemisphere and four in the Southern Hemisphere **(Figure 8.8).** Five are geostrophic gyres: the North Atlantic gyre, the South At-

Figure 8.9
The general surface circulation of the North Atlantic. The numbers indicate flow rates in sverdrups (1 sv = 1 million cubic meters of water per second).



lantic gyre, the North Pacific gyre, the South Pacific gyre, and the Indian Ocean gyre. Though it is a closed circuit, the sixth and largest current is technically not a gyre because it does not flow around the periphery of an ocean basin. The **West Wind Drift,** or **Antarctic Circumpolar Current,** as this exception is called, flows endlessly eastward around Antarctica, driven by powerful, nearly ceaseless westerly winds. This greatest of all the surface ocean currents is never deflected by a continent.

Boundary Currents Have Different Characteristics

Because of the different factors that drive and shape them, the currents that form geostrophic gyres have different characteristics. Geostrophic currents may be classified by their position within the gyre as western boundary currents, eastern boundary currents, or transverse currents.

Western Boundary Currents The fastest and deepest geostrophic currents are found at the western boundaries of ocean basins (that is, off the east coast of continents). These narrow, fast, deep currents move warm water poleward in each of the gyres. As shown in Figure 8.8b, there are five large **western boundary currents:** the Gulf Stream (in the North Atlantic), the Japan or Kuroshio Current (in the North Pacific), the Brazil Current (in the South Atlantic), the Agulhas Current (in the Indian Ocean), and the East Australian Current (in the South Pacific).

The **Gulf Stream** is the largest of the western boundary currents. Studies of the Gulf Stream have revealed that off Miami, the Gulf Stream moves at an average speed of 2 meters per second (5 miles per hour) to a depth of more than 450 meters (1,500 feet). Water in the Gulf Stream can move more than 160 kilometers (100 miles) in a day. Its average width is about 70 kilometers (43 miles).

The volume of water transported in western boundary currents is extraordinary. The unit used to express volume transport in ocean currents is the **sverdrup (sv),** named in honor of Harald Sverdrup, one of the last century's pioneering oceanographers. A sverdrup equals 1 million cubic meters per second. The Gulf Stream flow is at least 55 sv (55 million cubic meters per second), about 300 times the usual flow of the Amazon, the greatest of rivers. In **Figure 8.9,** the surface currents of the North Atlantic gyre are shown with their volume transport (in sverdrups) indicated.

Water in a current, especially a western boundary current, can move for surprisingly long distances within well-defined boundaries, almost as if it were a river. In the Gulf Stream, the current-as-river analogy can be startlingly apt: the western edge of the current is often clearly visible. Water within the current is usually warm, clear, and blue, often depleted of nutrients and incapable of supporting much life. By contrast, water over the continental slope adjacent to the current is often cold, green, and teeming with life. **Figure 8.10** shows its distinct appearance.

Long, straight edges are the exception rather than the rule in western boundary currents, however. Unlike rivers, ocean currents lack well-defined banks, and friction with adjacent water can cause a current to form waves along its edges. Western boundary currents meander as they flow poleward. The looping meanders sometimes connect to form turbulent rings, or **eddies,** that trap cold or warm water in their centers and then separate from the main flow. For example, *cold-core eddies* form in the Gulf Stream as it meanders eastward on leaving the coast of North America off Cape Hatteras. *Warm-core eddies* can form north of the Gulf Stream when the warm current loops into the cold water lying to the north. When the loops are cut off, they become free-standing, spinning masses of water. Warm-core eddies rotate clockwise, and cold-core eddies rotate counterclockwise.

The slowly rotating eddies move away from the current and are distributed across the North Atlantic. Some may be 1,000 kilometers (620 miles) in diameter and retain their identity for more than 3 years. In mid-latitudes, as much as one fourth of the surface of the North Atlantic may consist of old, slow-moving, cold-core eddy remnants! Both cold and warm eddies are visible in the satellite image shown in **Figure 8.11a.** Recent research suggests that their influence reaches to the seafloor. Warm- and cold-core eddies may be responsible for slowly moving *abyssal storms,* which leave ripple marks that have been observed in deep sediments. Nutrients brought toward the surface by turbulence in eddies sometimes stimulate the growth of tiny marine plantlike organisms **(Figure 8.11b).**

Eastern Boundary Currents As shown in Figure 8.8b, there are five **eastern boundary currents** at the eastern edge of ocean basins (that is, off the west coast of continents): the Canary Current (in the North Atlantic), the Benguela Current (in the South Atlantic), the California Current (in the North Pacific), the West Australian Current (in the Indian Ocean), and the Peru or Humboldt Current (in the South Pacific).

Eastern boundary currents are the opposite of their western boundary counterparts in nearly every way: They carry cold water equatorward; they are shallow and broad, sometimes more than 1,000 kilometers (620 miles) across; their boundaries are not well defined; and eddies tend not to form. Their total flow is less than that of their western counterparts. The Canary Current in the North Atlantic carries only 16 sv of water at about 2 kilometers (1.2 miles) per hour. The current is so shallow and broad that sailors may not notice it. Contrast the flow rates of the North Atlantic's western and eastern boundary currents in Figure 8.9. **Table 8.1** summarizes the major differences between boundary currents in the Northern Hemisphere.

Transverse Currents As we have seen, most of the power for ocean currents is derived from the trade winds at the fringes of the tropics and from the midlatitude westerlies. The stress of winds on the ocean in these bands gives rise to the **transverse currents**—currents that flow from east to west and west to east, linking the eastern and western boundary currents.

The trade wind–driven North Equatorial Current and South Equatorial Current in the Atlantic and Pacific are moderately shallow and broad, but each transports about 30 sv westward. Because of the thrust of the trades, Atlantic water at Panama is usually 20 centimeters (8 inches) higher, on average, than water across the isthmus in the Pacific. The Pacific's greater expanse of water at the equator and stronger trade winds develop more powerful westward-flowing equatorial currents, and the height differential between the western and eastern Pacific is thought to approach 1 meter (3.3 feet)!

Westerly winds drive the eastward-flowing transverse currents of the mid-latitudes. Because they are not shepherded by the trade winds, eastward-flowing currents are wider and flow more slowly than their equatorial counterparts. The North Pacific and North Atlantic currents are Northern Hemisphere examples.

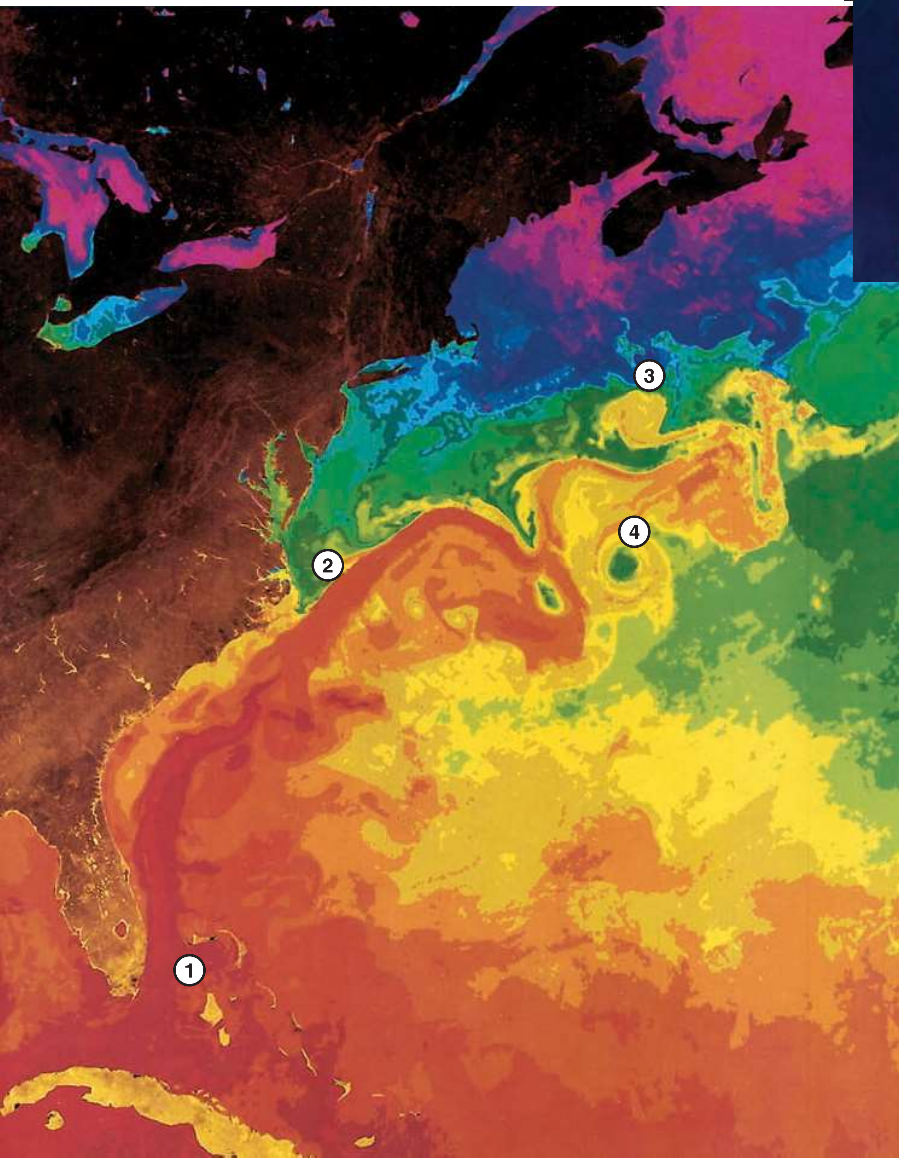
As can be seen in Figure 8.8, the westward flow of the transverse currents near the equator proceeds unimpeded for great distances, but the eastward flow of transverse currents at middle and high latitudes in the northern ocean basins is interrupted by continents and island arcs. In the far south, however, eastward flow is almost completely free. Intense westerly winds over the southern ocean drive the greatest of all ocean currents, the unobstructed West Wind Drift (or Antarctic Circumpolar Current). This current carries more water than any other—at least 100 sv west to east in the Drake Passage between the tip of South America and the adjacent Palmer Peninsula of Antarctica.

Westward Intensification Why should western boundary currents be concentrated and eastern boundary currents be diffuse? The reasons are complex, but as you might expect, the Coriolis effect is involved. Because of the Coriolis effect, which increases as water moves farther from the equator, eastward-moving water on the north side of the North Atlantic Gyre is turned sooner and more strongly toward the equator than westward-flowing water at the equator is turned toward the pole. Therefore, the peak of the hill described in Figure 8.7 is not in the center of the ocean basin but closer to its western edge. Its slope is steeper on the western side. If an equal volume of water flows around the gyre, the current on the eastern

NASA/ORBIMAGE

Figure 8.10
Moving at a speed of about 10 kilometers (6 miles) per hour, the Gulf Stream departs the coast at Cape Hatteras, its warm, clear, blue water contrasting with the cooler, darker, more productive water to the north and west. Clouds form over the warm current as water vapor evaporates from the ocean surface. Look for this area in Figure 8.11.

(a) The Gulf Stream viewed from space. This image is a composite of temperature data returned from NOAA polar orbiting meteorological satellites during the first week of April 1984. The composite image is printed with an artificial color scale: Reds and oranges are a warm 24°C to 28°C (76°–84°F); yellows and greens are 17°C to 23°C (63°–74°F); blues are 10°C to 16°C (50°–61°F); and purples are a cold 2°C to 9°C (36°–48°F). The Gulf Stream appears like a red (warm) river as it moves from the southern tip of Florida (1) north along the east coast. Moving offshore at Cape Hatteras (2), it begins to meander, with some meanders pinching off to form warm-core (3) and cold-core (4) eddies. As it moves northeastward, the water cools dramatically, releasing heat to the atmosphere and mixing with the cooler surrounding waters. By the time it reaches the middle of the North Atlantic, it has cooled so much that its surface temperature can no longer be distinguished from that of the surrounding waters.



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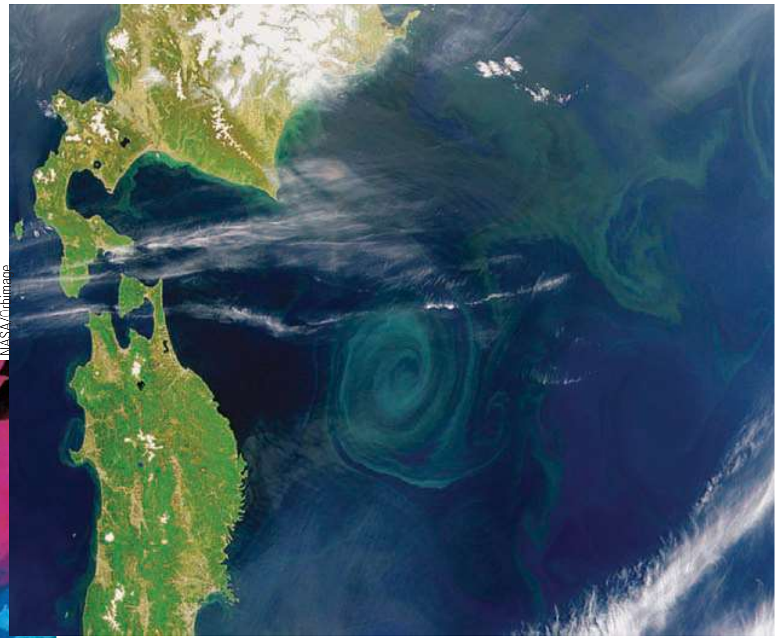


NASA/Orbimage

(b) Eddies in another western boundary current, the Kuroshio, off Japan's east coast. The green color in this natural-color photograph indicates areas in which the growth of small, plantlike organisms has been stimulated by nutrients brought to the surface by turbulence.

Figure 8.11
Eddies in western boundary currents.

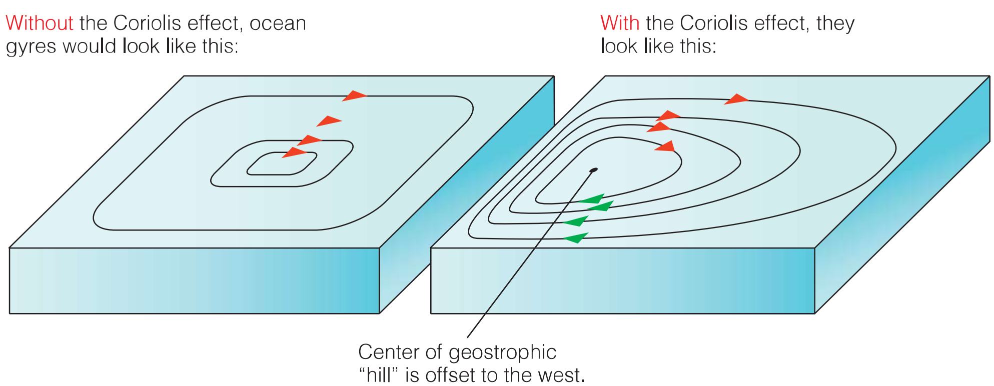
boundary (off the coast of Europe) is spread out and slow, and the current on the western boundary (off the U.S. East Coast) is concentrated and rapid. Western boundary currents are faster (up to 10 times), deeper, and narrower (up to 20 times) than eastern boundary currents. The effect on current flow is known as **westward intensification (Figure 8.12),** a phenomenon clearly visible in Figures 8.7b and 8.9.

Westward intensification does not happen just in the North Atlantic. The western boundary currents in the gyres of both hemispheres are more intense than their eastern counterparts.

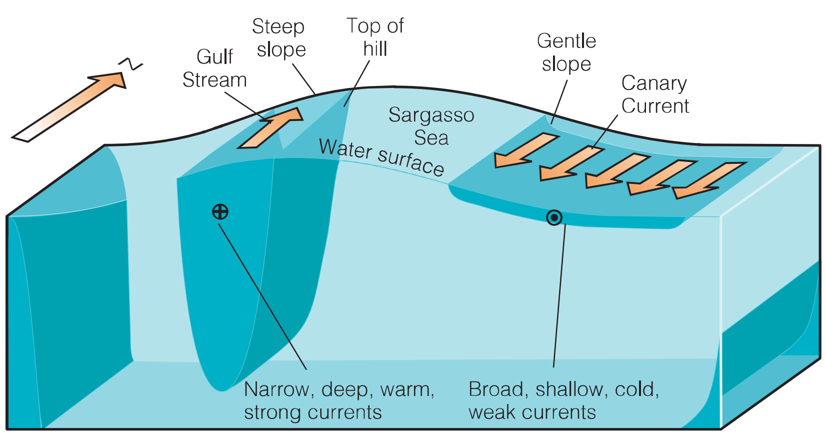
TABLE 8.1 Boundary Currents in the Northern Hemisphere

Type of Current (example)	General Features	Speed	Transport (millions of cubic meters per second)	Special Features
Western Boundary Currents				
Gulf Stream, Kuroshio (Japan) Current	Narrow, <100 km; deep—substantial transport to depths of 2 km	Swift, hundreds of kilometers per day	Large, usually 50 sv or greater	Sharp boundary with coastal circulation system; little or no coastal upwelling; waters tend to be depleted in nutrients, unproductive; waters derived from trade-wind belts
Eastern Boundary Currents				
California Current, Canary Current	Broad, ~1,000 km; shallow, <500 m	Slow, tens of kilometers per day	Small, typically 10–15 sv	Diffuse boundaries separating from coastal currents; coastal upwelling common; waters derived from mid-latitudes

Source: From GROSS, OCEANGRAPHY: VIEW OF THE EARTH, 5th edition, © 1990, p.173. Reprinted by permission of Pearson Education, Inc., Upper Saddle River, NJ.



(a) Without the Coriolis effect, water currents would form a regular and symmetrical gyre. However, because the Coriolis effect is strongest near the poles, water flowing eastward at high latitudes (red arrows) turns sooner to the right (clockwise), "short circuiting" the gyre. And because the Coriolis effect is nonexistent at the equator, water flowing westward near the equator (green arrows) tends not to turn clockwise until it encounters a blocking continent. Western boundary currents are therefore faster and deeper than eastern boundary currents, and the geostrophic hill is offset to the west.



(b) A cross section of geostrophic flow in the North Atlantic. The Gulf Stream, a western boundary current, is narrow and deep and carries warm water rapidly northward. The Canary Current, an eastern boundary current, is shallow and wide and carries cold water at a much more leisurely pace. Although the gradually sloping hill is only 2 meters (6.5 feet) high and would not be apparent to anyone traveling from coast to coast, it is large enough to steer currents in the North Atlantic gyre. (This figure is vertically exaggerated.)

Figure 8.12
The influence of the Coriolis effect on westward intensification.

About the Ocean World: A Student Asks . . .

"Could currents be used as a source of electrical power? With the Gulf Stream so close to Florida, it seems that some way could be devised to take advantage of all that water flow to turn a turbine."

It has been considered. The total energy of the Gulf Stream flowing off Miami has been estimated at 25,000 megawatts! A Woods Hole Oceanographic Institution team has proposed a honeycomb-like array of turbines for the layer between 30 and 130 meters (100 and 430 feet) across 20 kilometers (13 miles) of the current. They estimate a power output of around 1,000 megawatts, equal to the generation potential of two large nuclear power plants. (Engineering difficulties would be prohibitive, however.) Simpler arrangements of smaller turbines operating closer to the coasts are practical, and some of them are operating now.

http://www.utilityweek.co.uk/news

Photo by Jeff J Mitchell/Getty Images

A large turbine designed to generate electrical power from the flow of ocean currents is being prepared for placement among the Orkney Islands in northern Scotland. Figure 10.21 shows even larger turbines for use in tidal generation.

A Final Word on Gyres

Although I have stressed individual currents in our discussion, remember that gyres consist of currents that blend into one another. Flow is continuous without obvious places where one current ceases and another begins. The *balance* of wind energy, friction, the Coriolis effect, and the pressure gradient propels gyres and holds them along the edges of ocean basins.

Brief Review

Before going on to the next section, check your understanding of some of the important ideas presented so far:

2 About what percentage of the world ocean is involved in wind-driven surface currents?

3 What is a gyre? How many large gyres exist in the world ocean? Where are they located?

4 Why does seawater in most surface currents flow around the periphery of ocean basins? How is Coriolis effect involved?

5 Compare and contrast western boundary currents with eastern boundary currents.

6 Name a western boundary current. Name an eastern boundary current.

7 What is meant by "westward intensification?" Why are western boundary currents so fast and deep?

To check your answers, visit www.cengagebrain.com.

8.3 Surface Currents Affect Weather and Climate

Along with the winds, surface currents distribute tropical heat worldwide. Warm water flows to higher latitudes, transfers heat to the air and cools, moves back to low latitudes, and absorbs heat again; then the cycle repeats. The greatest amount of heat transfer occurs at mid-latitudes, where about 10 million billion calories of heat are transferred each second—a million times as much power as is consumed by all the world's human population in the same length of time! This combination of water flow and heat transfer from and to water influences climate and weather in several ways.

In winter, for example, Edinburgh, Dublin, and London are bathed in eastward-moving air only recently in contact with the relatively warm North Atlantic Current. Scotland, Ireland, and England have a maritime climate. As you read in this chapter's opener, they are warmed, in part, by the energy of tropical sunlight transported to high latitudes by the Gulf Stream (clearly visible in Figure 8.8b). If the path of the Gulf Stream or North Atlantic Current changes, so will Europe's climate. You'll read more about that prospect later in this chapter.

At lower latitudes on an ocean's eastern boundary, the situation is often reversed. Mark Twain is supposed to have said that the coldest winter he ever spent was a summer in San Francisco. Summer months in that West Coast city are cool, foggy, and mild, while Washington, D.C., on nearly the same line of latitude (but on the western boundary of an ocean basin), is known for its August heat and humidity. Why the difference? Look at Figure 8.8b and follow the currents responsible. The California Current, carrying cold water from the north, comes close to the coast at San Francisco. Air normally flows clockwise in summer around an offshore zone of high atmospheric pressure. Wind approaching the California coast loses heat to the cold sea and comes ashore to chill San Francisco. Summer air often flows around a similar high off the East Coast (the Bermuda High). Winds approaching Washington, D.C., therefore blow from the south and east. Heat and moisture from the Gulf Stream contribute to the capital's oppressive summers. (In winter, on the other hand, Washington, D.C., is colder than San Francisco because westerly winds approaching Washington are chilled by the cold continent they cross.)

Brief Review

Before going on to the next section, check your understanding of some of the important ideas presented so far:

8 What is the relation between surface currents and the climate of adjacent continents?

9 How does wind blowing over a surface current influence the climate downwind?

To check your answers, visit www.cengagebrain.com.

8.4 Wind Can Cause Vertical Movement of Ocean Water

The wind-driven *horizontal* movement of water can sometimes induce *vertical* movement in the surface water. This movement is called **wind-induced vertical circulation.** Upward movement of water is known as **upwelling;** the process brings deep, cold, usually nutrient-laden water toward the surface. Downward movement is called **downwelling.**

Nutrient-Rich Water Rises Near the Equator

The South Equatorial Currents of the Atlantic and Pacific straddle the equator. Though the Coriolis effect is weak near the equator (and absent *at* the equator), water moving in the currents on either side of the equator is deflected slightly poleward and replaced by deeper water **(Figure 8.13).** Thus, **equatorial upwelling** occurs in these westward-flowing equatorial surface currents. Upwelling is an important process because this water from within and below the pycnocline is often rich in the nutrients needed by marine organisms for growth. The long, thin band of upwelling and biological productivity extending along the equator westward from South America is clearly visible in Figures 8.13 and 8.16. The layers of ooze on the equatorial Pacific seabed (Figure 5.8) are testimony to the biological productivity of surface water there. By contrast, generally poor conditions for growth prevail in most of the open tropical ocean because strong layering isolates deep, nutrient-rich water from the sunlit ocean surface.

Wind Can Induce Upwelling Near Coasts

Wind blowing parallel to shore or offshore can cause **coastal upwelling.** The friction of wind blowing along the ocean surface causes the water to begin moving, the Coriolis effect deflects it to the right (in the Northern Hemisphere), and the resultant Ekman transport moves it offshore. As shown in **Figure 8.14a,** coastal upwelling occurs when this surface water is replaced by water rising along the shore. Again, because the new surface water is often rich in nutrients, prolonged wind can result in increased biological productivity. Coastal upwelling along the coast of California is visible in **Figure 8.14b.**

Upwelling can also influence weather. Wind blowing from the north along the California coast causes offshore movement of surface water and subsequent coastal upwelling. The overlying air becomes chilled, contributing to San Francisco's famous fog banks and cool summers. Wind-induced upwelling is also common in the Peru Current, along the west coast of Antarctica's Palmer Peninsula, in parts of the Mediterranean, and near some large Pacific islands.

Wind Can Also Induce Coastal Downwelling

Water driven toward a coastline will be forced downward, returning seaward along the continental shelf. This downwelling **(Figure 8.15)** helps supply the deeper ocean with dissolved gases and nutrients, and it assists in the distribution of living organisms. Unlike upwelling, downwelling has no direct effect on the climate or productivity of the adjacent coast.

Brief Review

Before going on to the next section, check your understanding of some of the important ideas presented so far:

10 How can wind-driven horizontal movement of water induce vertical movement in surface water?

11 How is the Coriolis effect involved in equatorial upwelling?

To check your answers, visit www.cengagebrain.com.

8.5 El Niño and La Niña Are Exceptions to Normal Wind and Current Flow

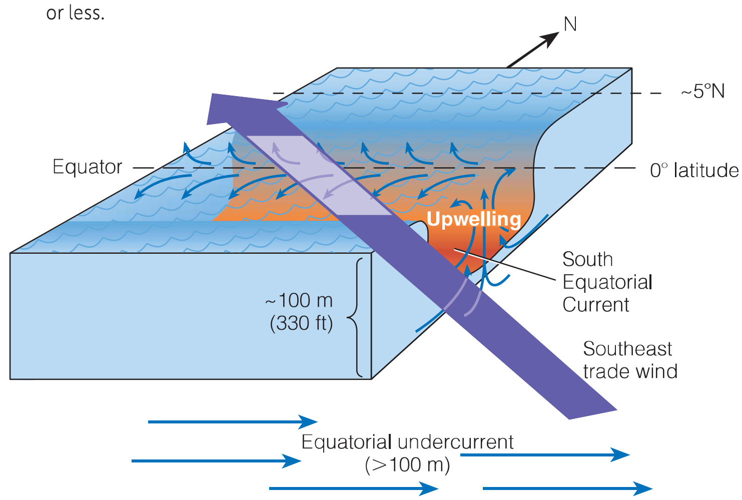
Surface winds across most of the tropical Pacific normally move from east to west (Figure 7.1 again). The trade winds blow from the normally high-pressure area over the eastern Pacific (near Central and South America) to the normally stable low-pressure area over the western Pacific (north of Australia). However, for reasons that are still unclear, these pressure areas change places at irregular intervals of roughly 3 to 8 years: high pressure builds in the western Pacific, and low pressure dominates the eastern Pacific. Winds across the tropical Pacific then reverse direction and blow from west to east; the trade winds weaken or reverse. This change in atmospheric pressure (and thus in wind direction) is called the **Southern Oscillation.** Fifteen of these attention-getting oscillations have occurred since 1950.

The trade winds normally drag huge quantities of water westward along the ocean's surface on each side of the equator, but as the winds weaken, these equatorial currents crawl to a stop. Warm water that has accumulated at the western side of the Pacific—the warmest water in the world ocean—can then build to the east along the equator toward the coasts of Central and South America. The eastward-moving warm water usu-

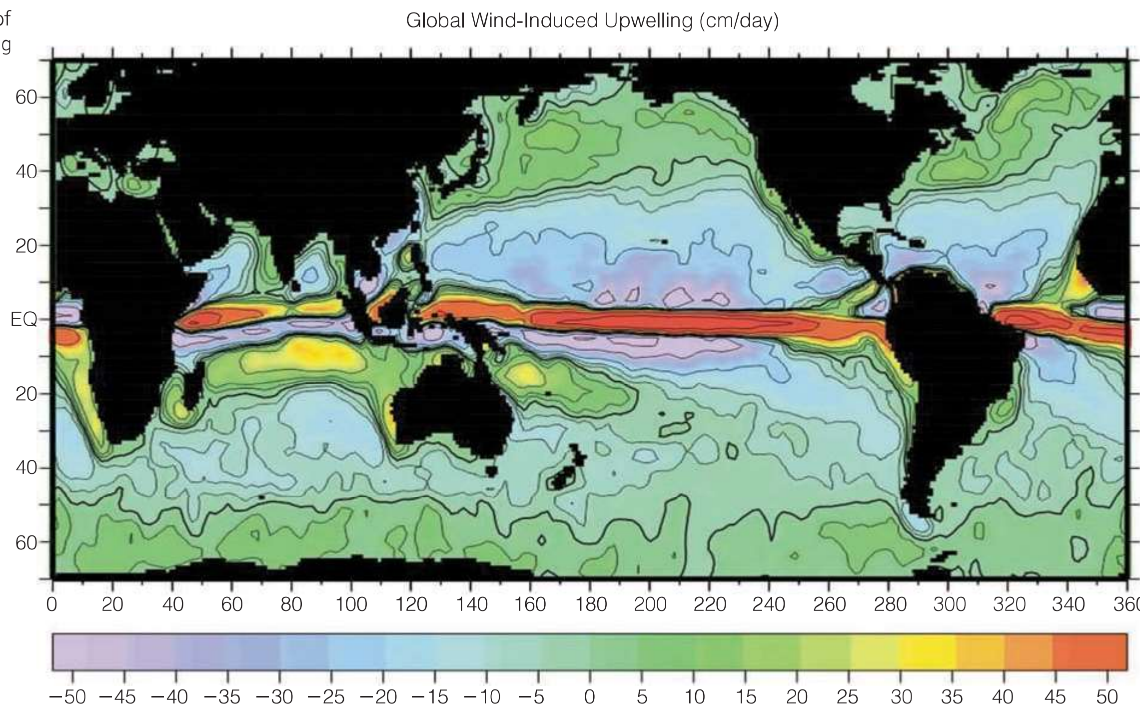
Figure 8.13

Equatorial upwelling.

(a) The South Equatorial Current, especially in the Pacific, straddles the geographical equator (see again Figure 8.8b). Water north of the equator veers to the right (northward), and water to the south veers to the left (southward). Surface water therefore diverges, causing upwelling. Most of the upwelled water comes from the area above the equatorial undercurrent, at depths of 100 meters (330 feet) or less.



(b) The phenomenon of equatorial upwelling is worldwide but most pronounced in the Pacific. The red, orange, and yellow colors mark the areas of greatest upwelling as determined by biological productivity.



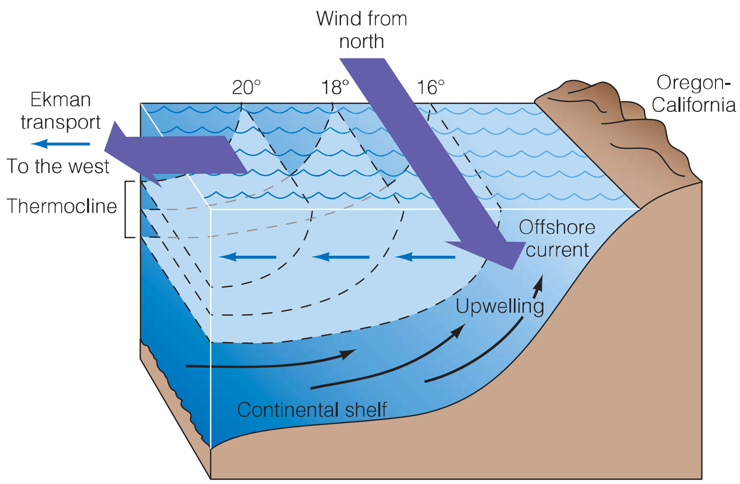
Courtesy William Hsieh and Liusen Xie

ally arrives near the South American coast around Christmastime. In the 1890s, it was reported that Peruvian fishermen were using the expression *Corriente del Niño* ("current of the Christ Child") to describe the flow; that's where the current's name, **El Niño,** came from. The phenomena of the Southern Oscillation and El Niño are coupled, so the terms are often combined to form the acronym **ENSO,** for El Niño/Southern Oscillation. An ENSO event typically lasts about a year, but some have persisted for more than 3 years. The effects are felt not only in the Pacific; all ocean areas at trade wind latitudes in both hemispheres can be affected.

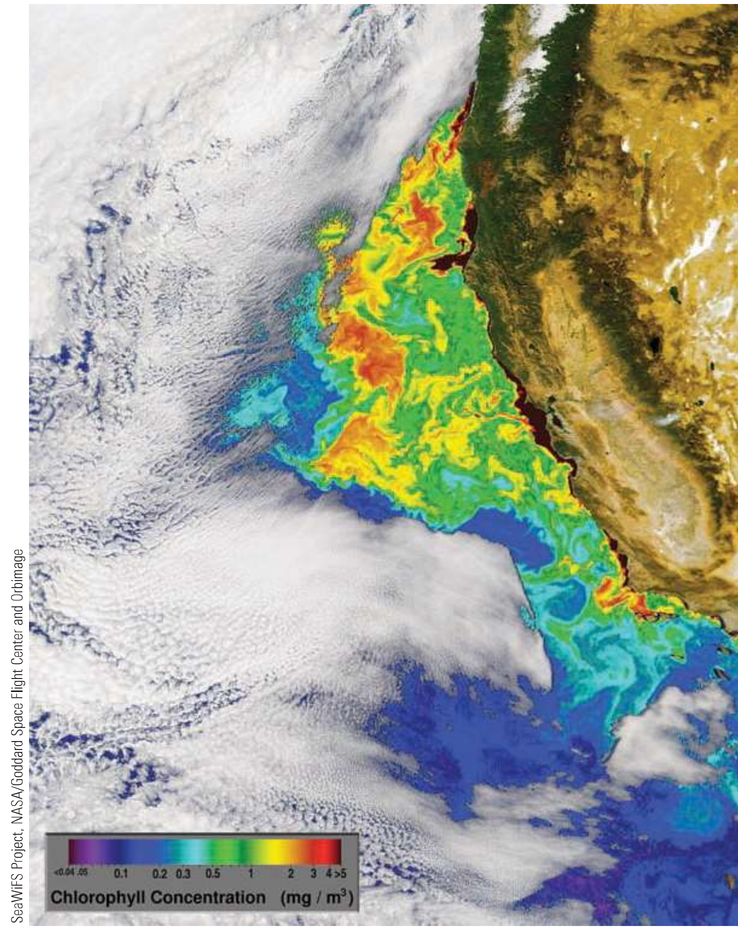
Normally, a current of cold water, rich in upwelled nutrients, flows north and west away from the South American continent **(Figure 8.16).** When the propelling trade winds falter during an ENSO event, warm equatorial water that would normally flow westward in the equatorial Pacific backs up to flow east **(Figure 8.17).**

Figure 8.14

Coastal upwelling.



(a) In the Northern Hemisphere, coastal upwelling can be caused by winds from the north blowing along the west coast of a continent. Water moved offshore by Ekman transport is replaced by cold, deep, nutrient-laden water. In this diagram, temperature of the ocean surface is shown in degrees Celsius. (Vertical exaggeration ~100×.)



(b) A satellite view of the U.S. West Coast shows (in artificial color) the growth of small, plantlike organisms stimulated by upwelled nutrients. The color bar indicates the concentration of chlorophyll in milligrams per cubic meter of seawater. Notice that chlorophyll concentration—and biological productivity—is highest near the coast.

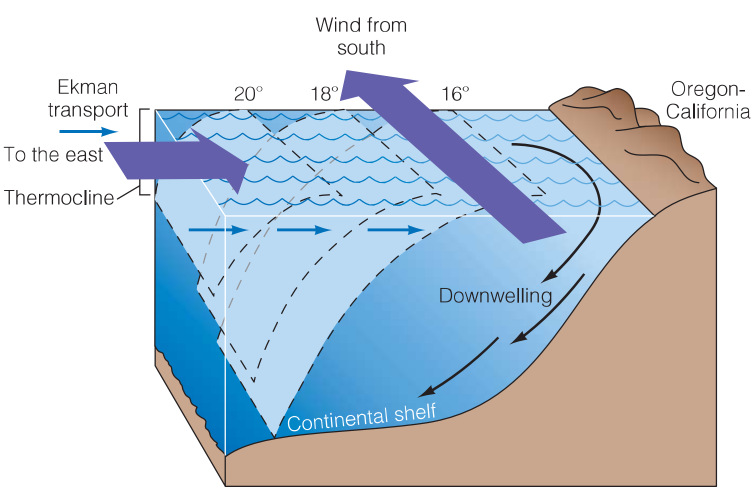
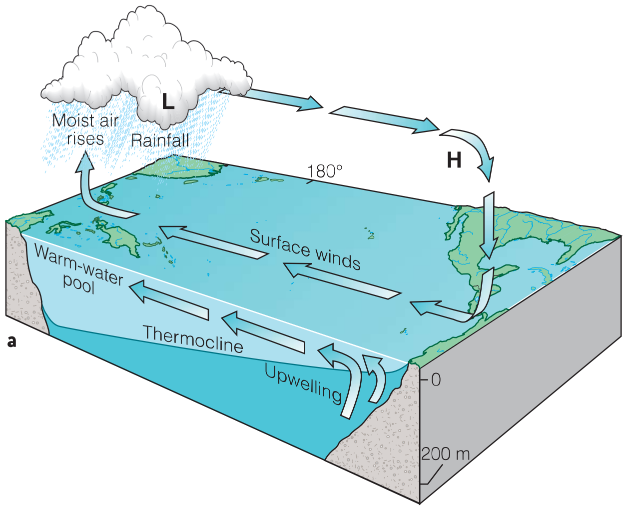


Figure 8.15

Wind blowing from the south along a Northern Hemisphere west coast for a prolonged period can result in downwelling. Areas of downwelling are often low in nutrients and, therefore, relatively low in biological productivity. (Vertical exaggeration ~100×.)



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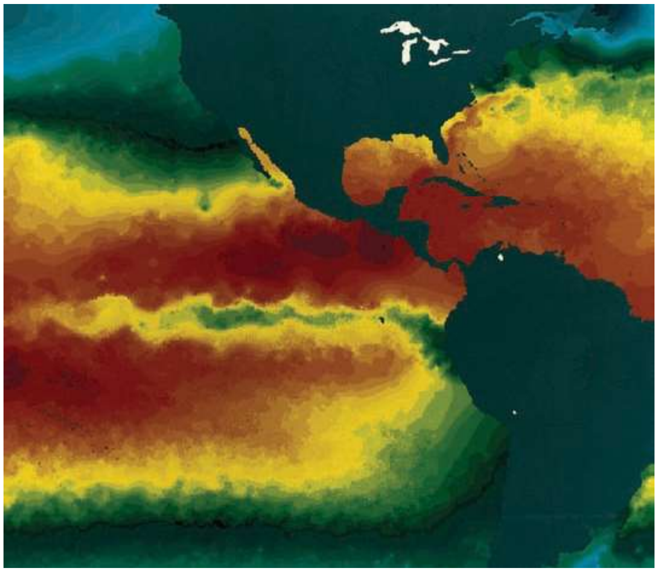

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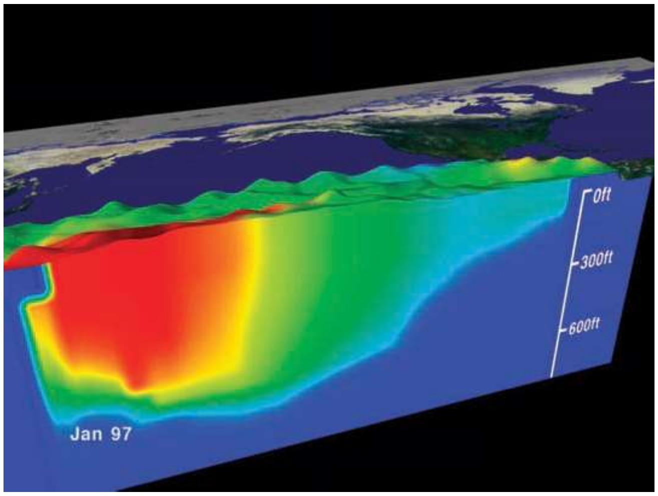

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Figure 8.16

A non–El Niño year.

(a) Normally the air and surface water flow westward, the thermocline rises, and upwelling of cold water occurs along the west coast of Central and South America.

(b) This map from satellite data shows the temperature of the equatorial Pacific on 31 May 1988. The warmest water is indicated by dark red; progressively cooler upwelled water is indicated by yellow and green. Note the coastal upwelling along the coast at the lower right of the map and the tongue of recently upwelled water extending westward along the equator from the South American coast.

(c) A vertical section through the equatorial Pacific in a non–El Niño year (January 1997) shows warmer water to the west and cooler water to the east.

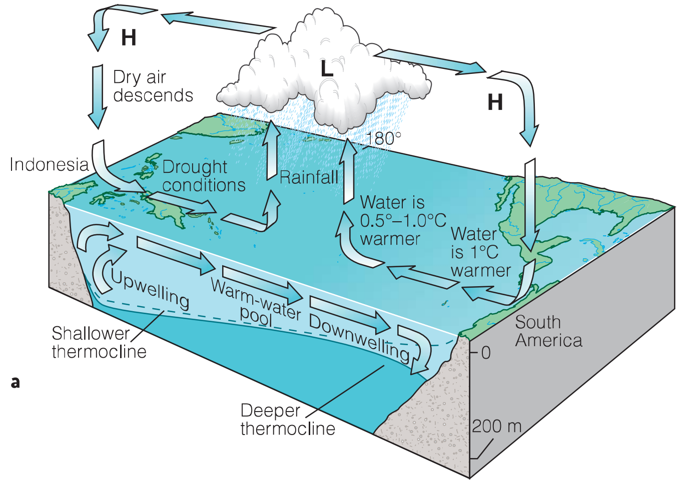
The normal northward flow of the cold Peru Current is interrupted or overridden by the warm water. Upwelling within the nutrient-laden Peru Current is responsible for the great biological productivity of the ocean off the coasts of Peru and Chile. Although upwelling may continue during an ENSO event, the source of the upwelled water is nutrient-depleted water in the thickened surface layer approaching from the west. When the Peru Current slows and its upwelled water lacks nutrients, fish and seabirds dependent on the abundant life it contains die or migrate elsewhere. Peruvian fishermen are never cheered by this Christmas gift!

During major ENSO events, sea level rises in the eastern Pacific, sometimes by as much as 20 centimeters (8 inches) in the Galápagos. Water temperature also increases by up to 7°C (13°F). The warmer water causes more evaporation, and the area of low atmospheric pressure over the eastern Pacific intensifies. Humid air rising in this zone, centered some 2,000 kilometers (1,200 miles) west of Peru, causes high precipitation in normally dry areas. The increased evaporation intensifies coastal storms, and rainfall inland may be much higher than normal. Marine and terrestrial habitats and organisms can be affected by these changes.

The two most severe ENSO events of the last century occurred in 1982–1983 and 1997–1998 (**Figures 8.18** and **8.19**). In both cases, effects associated with El Niño were spectacular over much of the Pacific and some parts of the Atlantic and Indian oceans. In February 1998, 40 people were killed and 10,000 buildings damaged by a "wall" of tornadoes advancing over the southeastern United States. This record-breaking tornado event was spawned by the collision of warm, moist air that had lingered over the warm Pacific and a polar front that dropped from the north. In the eastern Pacific, heavy rains throughout the 1997–1998 winter in Peru left at least 250,000 people homeless, destroyed 16,000 dwellings, and closed every port in the country for at least 1 month. Hawai'i, however, experienced record drought, and some parts of southwestern Africa and Papua New Guinea received so little rain that crops failed completely and whole villages were abandoned because of starvation.

Figure 8.17

An El Niño year.
(a) When the Southern Oscillation develops, the trade winds diminish and then reverse, leading to an eastward movement of warm water along the equator. The surface waters of the central and eastern Pacific become warmer, and storms over land may increase.
(b) Sea-surface temperatures on 13 May 1992, a time of El Niño conditions. The thermocline was deeper than normal, and equatorial upwelling was suppressed. Note the absence of coastal upwelling along the coast and the absence of the tongue of recently upwelled water extending westward along the equator.
(c) A vertical section through the equatorial Pacific in an El Niño year (November 1997) shows warmer water spreading toward the east.



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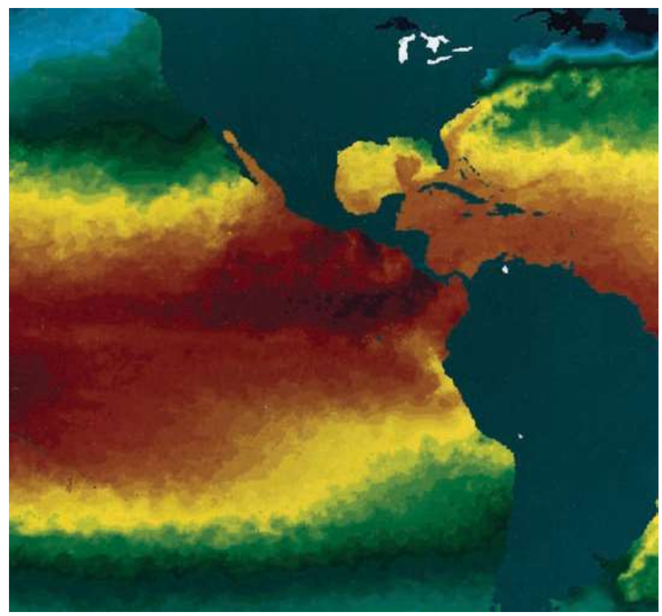

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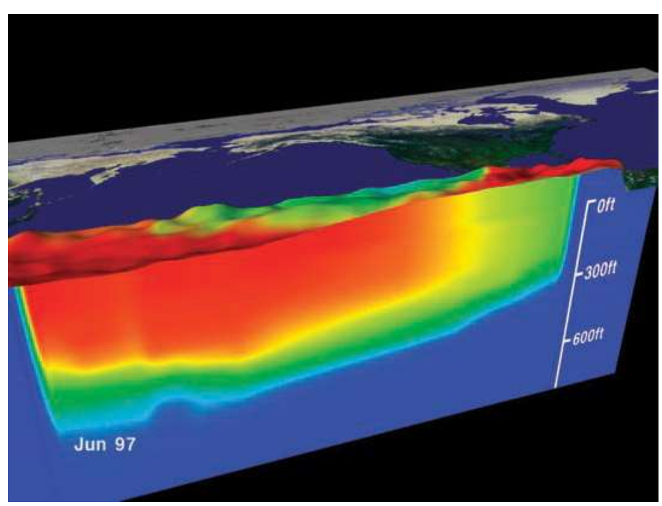

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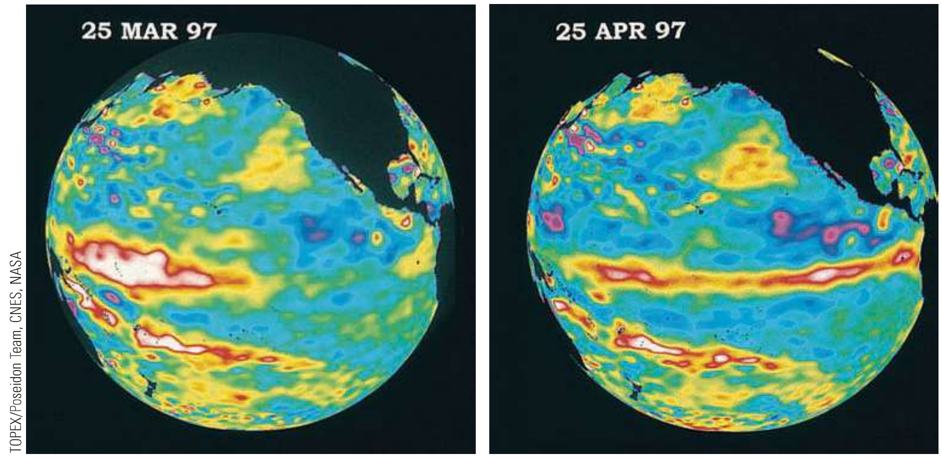
Most of the United States escaped serious consequences—indeed, the Midwestern states, Pacific Northwest, and eastern seaboard enjoyed a relatively mild fall, winter, and spring. But California's trials were widely reported. Greater evaporation of water from the warm ocean surface, combined with an increased number of winter storms steered into the area by the southward-trending jet stream, doubled rainfall amounts in most of the state. Landslides, avalanches, and other weather-related disasters crowded the evening news. Conditions did not return to near normal until the late spring of 1998. Estimates of worldwide 1997–1998 ENSO-related damage exceed 23,000 deaths and US$33 billion.

Normal circulation sometimes returns with surprising vigor, producing strong currents, powerful upwelling, and chilly and dry conditions along the South American coast. These contrasting colder-than-normal events are given a contrasting name: **La Niña** ("the girl"). As conditions to the east cool off, the ocean to the west (north of Australia) warms rapidly. The renewed thrust of the trade winds piles this water on itself, depressing the upper curve of the thermocline to more than 100 meters (328 feet). In contrast, the thermocline during a La Niña event in the eastern equatorial Pacific rests at about 25 meters (82 feet). A vigorous La Niña followed the 1997–1998 El Niño and persisted for nearly a year (Figure 8.18). **Figure 8.20** contrasts how North American weather differs between El Niño and La Niña years.

Studies of the ocean and atmosphere in 1982–1983 and 1997–1998 have given researchers new insight into the behavior and effects of the Southern Oscillation. Some researchers believe that the 1982–1983 event was triggered by the violent 1982 eruption of El Chichón, a Mexican volcano, which injected huge quantities of sun-obscuring dust and sulfur-rich gases into the atmosphere. No similar trigger occurred before the 1997–1998 ENSO, however. Though the exact cause or causes of the Southern Oscillation are not yet understood, subtle changes in the atmosphere permit meteorologists to predict a severe El Niño nearly a year in advance of its most serious effects.

Figure 8.18
Development of the 1997–1998 El Niño, observed by the *TOPEX/Poseidon* satellite.



(a) March 1997. The slackening of the trade winds and westerly wind bursts allow warm water to move away from its usual location in the western Pacific Ocean. Red and white indicate sea level above average height.

(b) April 1997. About a month after it began to move, the leading edge of the warm water reaches South America.

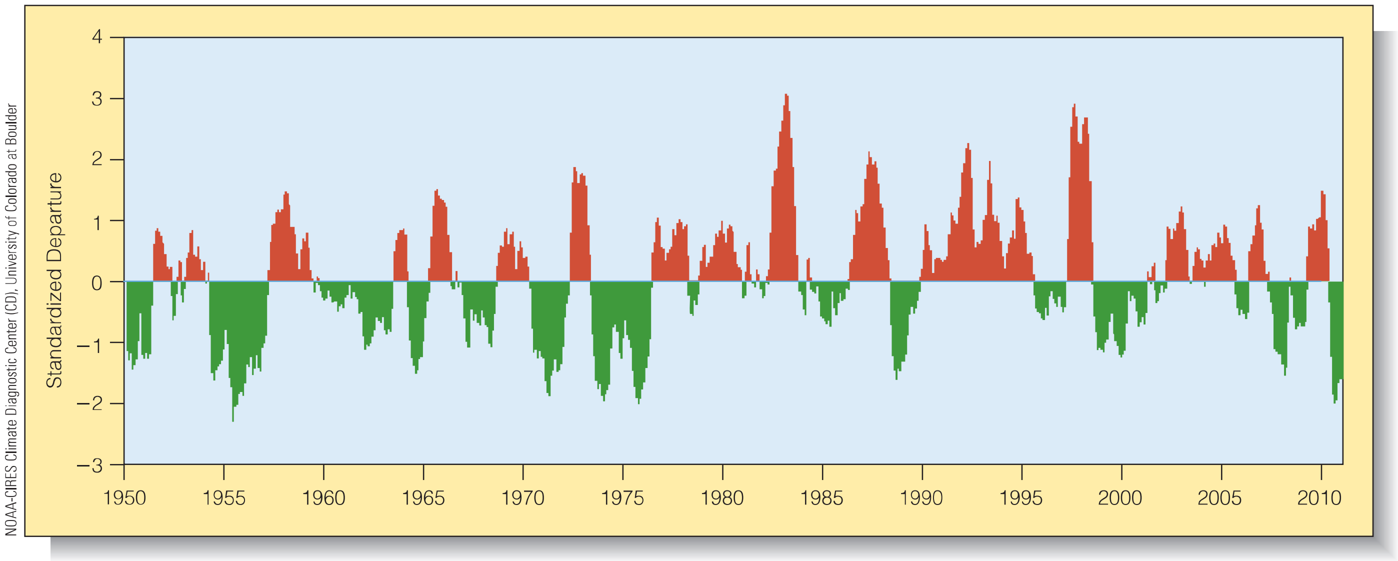


Figure 8.19
El Niño and La Niña events since 1950.

Brief Review

Before going on to the next section, check your understanding of some of the important ideas presented so far:

12 Which way does wind typically blow over the tropical Pacific? How does this flow change during an El Niño event?

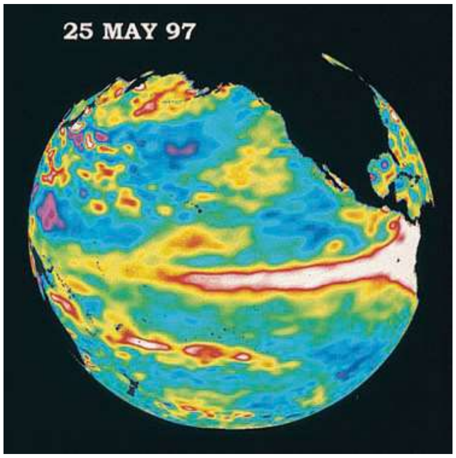
13 What is the Southern Oscillation? How is this related to El Niño?

14 Why do fisheries on South America's west coast decline—often dramatically—in El Niño years?

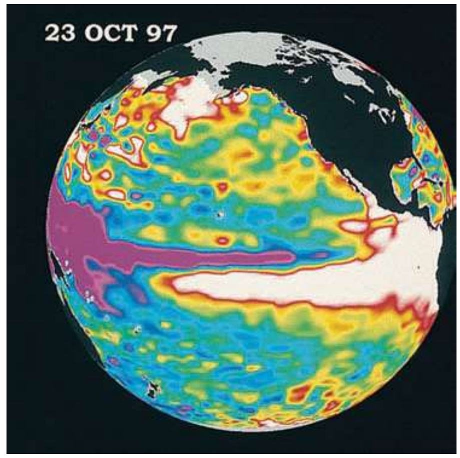
15 How is La Niña different from El Niño?

16 How might weather in the western United States be affected by El Niño?

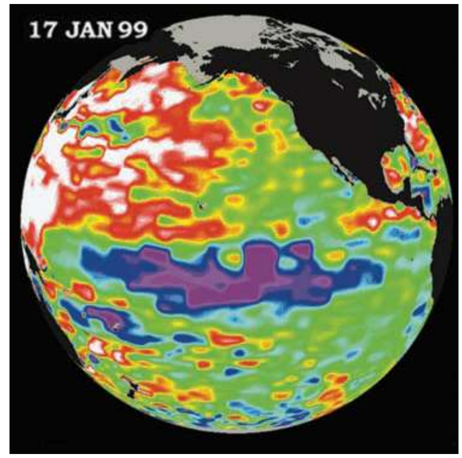
To check your answers, visit www.cengagebrain.com.



(c) May 1997. Warm water piles up against the South American continent. The white area of sea level is 13 to 30 centimeters (5–12 inches) above normal height, and 1.6° to 3°C (3°–5°F) warmer.



(d) October 1997. By October, sea level is as much as 30 centimeters (12 inches) lower than normal near Australia. The bulge of warm water has spread northward along the coast of North America from the equator to Alaska. Fisheries in Peru are severely affected because the warm water prevents upwelling of cold, nutrient-rich water necessary for the support of large fish populations.



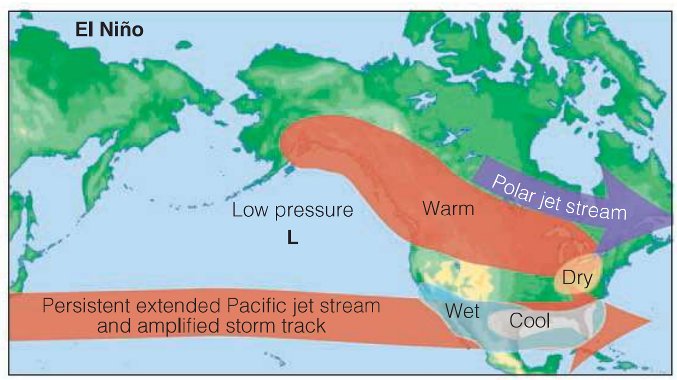
(e) Normal circulation sometimes returns with surprising vigor after an El Niño event, producing strong currents, powerful upwelling, and chilly and stormy conditions along the South American coast. Note the mass of cold surface water and relatively low sea level (purple). Such cold water tends to deflect winds around it, changing the course of weather systems locally and the nature of weather patterns globally.

8.6 Thermohaline Circulation Affects All the Ocean's Water

The surface currents we have discussed affect the uppermost layer of the world ocean (about 10% of its volume), but horizontal and vertical currents also exist below the pycnocline in the ocean's deeper waters. The slow circulation of water at great depths is driven by density differences rather than by wind energy. Because density is largely a function of water temperature and salinity, the movement of water caused by differences in density is called **thermohaline circulation** (*therme,* "heat"; *halos,* "salt"). The whole ocean is involved in slow thermohaline circulation, a process responsible for the large-scale vertical movement of ocean water and the circulation of the global ocean as a whole.

Water Masses Have Distinct, Often Unique Characteristics

As you may recall from Chapter 6, the ocean is density stratified, with the densest water near the seafloor and the least dense near the surface. Each water mass has specific temperature and salinity characteristics. Density stratification is most pronounced at temperate and tropical latitudes because the temperature difference between surface water and deep water is greater there than near the poles.



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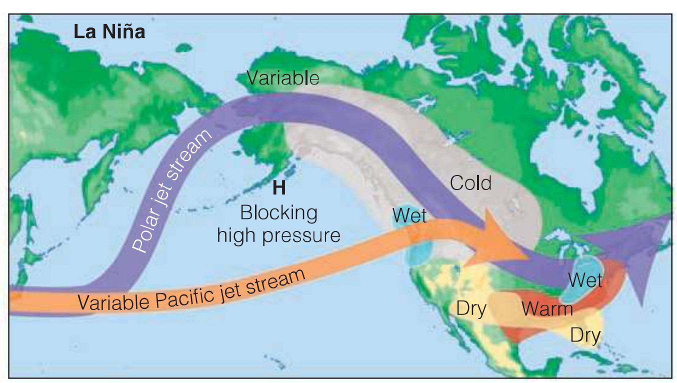

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Figure 8.20
El Niño changes atmospheric circulation and weather patterns. **(a)** During an El Niño, low atmospheric pressure south of Alaska allows storms to move unimpeded to the Pacific Coast of North America. The resulting weather is wet and cool to the south, and warm and dry to the north. **(b)** In La Niña years, high atmospheric pressure south of Alaska blocks the storm track. Winds veer north, lose their warmth over Canada, and sweep down as cold blasts. The Pacific Northwest gets its usual rain, but the southwest suffers drought.

The water masses possess distinct, identifiable properties. Like air masses, water masses do not often mix easily when they meet because of their differing densities; instead, they usually flow above or beneath each other. Water masses can be remarkably persistent and will retain their identity for great distances and long periods. Oceanographers name water masses according to their relative position. In temperate and tropical latitudes, there are five common water masses:

- *Surface water,* to a depth of about 200 meters (660 feet)
- *Central water,* to the bottom of the main thermocline (which varies with latitude)
- *Intermediate water,* to about 1,500 meters (5,000 feet)
- *Deep water,* water below intermediate water but not in contact with the bottom, to a depth of about 4,000 meters (13,000 feet)
- *Bottom water,* water in contact with the seafloor

Surface currents move in the relatively warm upper environment of surface and central water. The boundary between central water and intermediate water is the most abrupt and pronounced.

No matter at what depth water masses are located, the characteristics of each are usually determined by the conditions of heating, cooling, evaporation, and dilution that occurred *at the ocean surface* when the mass was formed. The densest (and deepest) masses were formed by surface conditions that caused the water to become very cold and salty. Water masses near the surface can be warmer and less saline; they may have formed in warm areas where precipitation exceeded evaporation. Water masses at intermediate depths are intermediate in density.

In spite of this differentiation, the relatively cold water masses lying beneath the thermocline exhibit smaller variations in salinity and temperature than the water in the currents that move across the ocean's surface.

Thermohaline Flow and Surface Flow: The Global Heat Connection

As we have seen, swift and narrow surface currents along the western margins of ocean basins carry warm, tropical surface waters toward the poles. In a few places, the water loses heat to the atmosphere and sinks to become deep water and bottom water. This sinking is most pronounced in the North Atlantic. The cold, dense water moves at great depths toward the Southern Hemisphere and eventually wells up into the surface layers of the Indian and Pacific oceans. Almost a thousand years are required for this water to make a complete circuit.

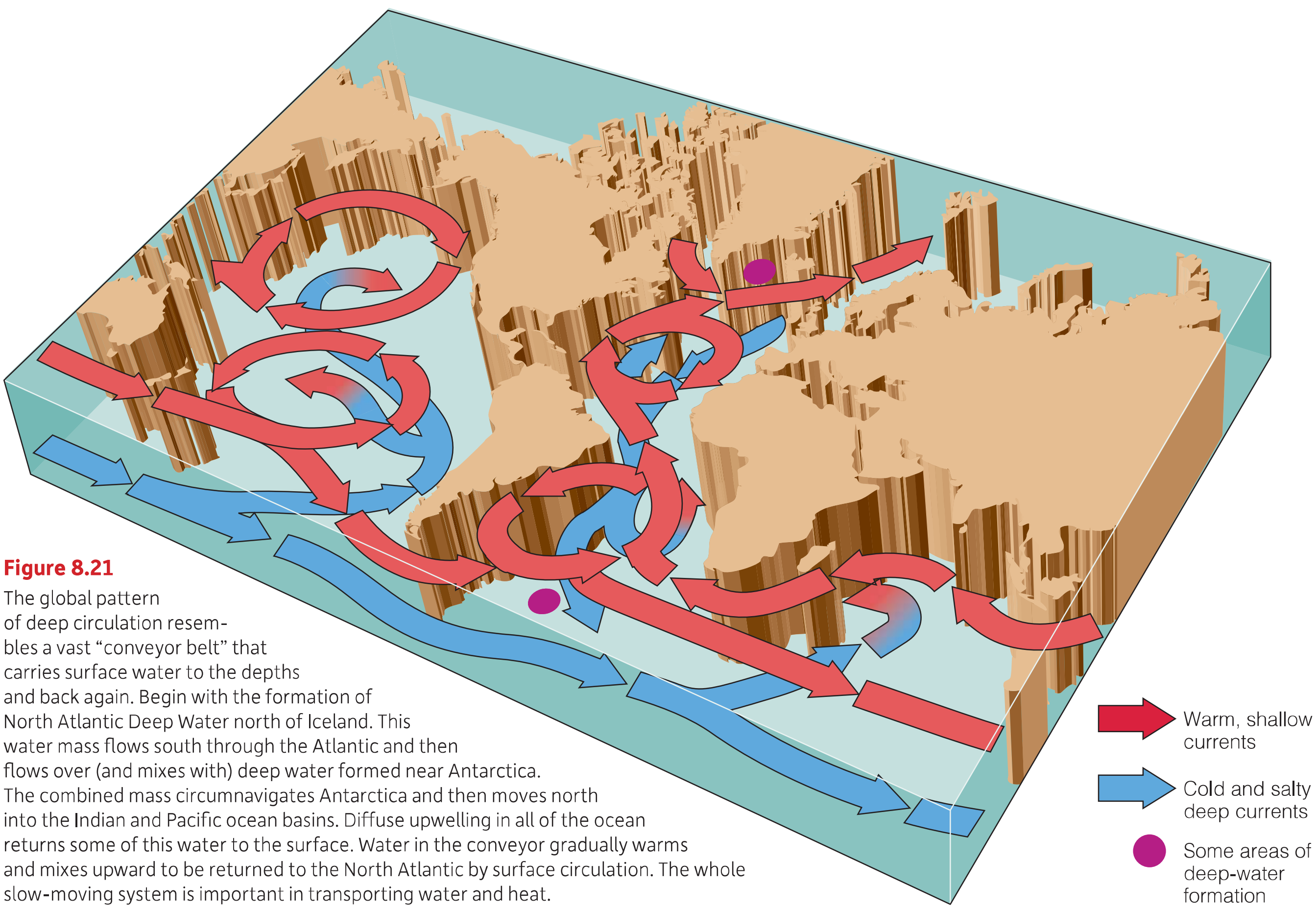

Figure 8.21
The global pattern of deep circulation resembles a vast "conveyor belt" that carries surface water to the depths and back again. Begin with the formation of North Atlantic Deep Water north of Iceland. This water mass flows south through the Atlantic and then flows over (and mixes with) deep water formed near Antarctica. The combined mass circumnavigates Antarctica and then moves north into the Indian and Pacific ocean basins. Diffuse upwelling in all of the ocean returns some of this water to the surface. Water in the conveyor gradually warms and mixes upward to be returned to the North Atlantic by surface circulation. The whole slow-moving system is important in transporting water and heat.

The transport of tropical water to the polar regions is part of a global conveyor belt for heat. A simplified outline of the global circuit, the result of three decades of concentrated effort to understand deep circulation, is shown in **Figure 8.21.** This slow circulation straddles the hemispheres and is superimposed on the more rapid flow of water in surface gyres. Recent analysis of this global circuit suggests that some of the heat warming the coasts of Europe enters the ocean in the vicinity of Indonesia and Australia, travels to the Indian Ocean, and enters the Gulf Stream by way of the Agulhas Current rounding the southern tip of Africa. The surface water that leaves the Pacific is driven, in part, by excess rainfall and river runoff throughout the Pacific basin. The slow, steady, three-dimensional flow of water in the conveyor belt distributes dissolved gases and solids, mixes nutrients, and transports the juvenile stages of organisms among ocean basins.

The Formation and Downwelling of Deep Water Occurs in Polar Regions

Antarctic Bottom Water **Antarctic Bottom Water,** the most distinctive of the deep-water masses, is characterized by a salinity of 34.65‰, a temperature of −0.5°C (30°F), and a density of 1.0279 grams per cubic centimeter. This water is noted for its extreme density (the densest in the world ocean), for the great amount of it produced near Antarctic coasts, and for its ability to migrate north along the seafloor.

Most Antarctic Bottom Water forms near the Antarctic coast south of South America during winter **(Figure 8.22).** Salt is concentrated in pockets between crystals of pure water and then squeezed out of the freezing mass to form a frigid brine. Between 20 and 50 *million* cubic meters of this brine form every sec-

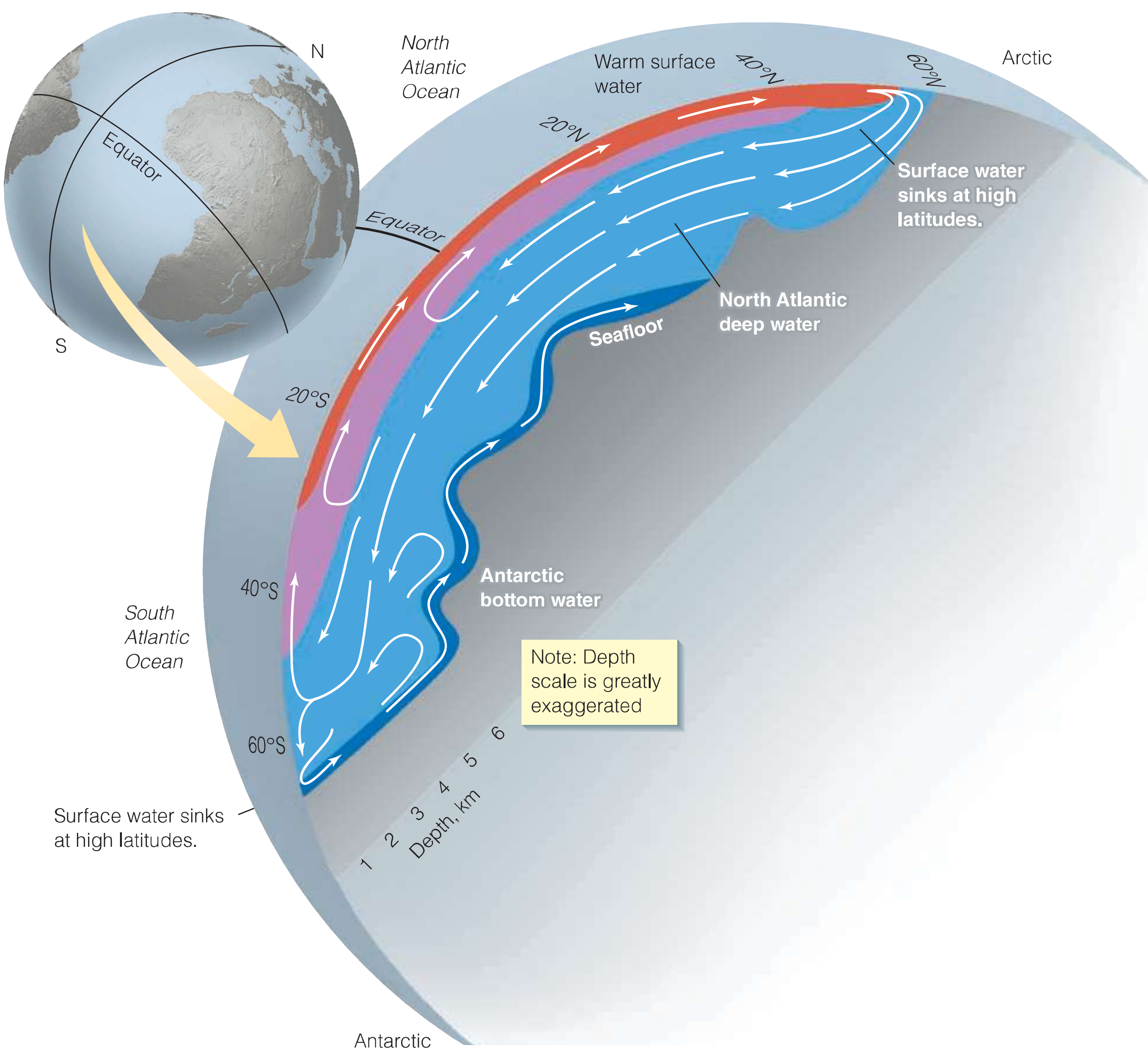

Figure 8.22

A simplified view of thermohaline circulation in the Atlantic. Surface water becomes dense and sinks in the north and south polar regions. Being denser, Antarctic Bottom Water slips beneath North Atlantic Deep Water. The water then gradually rises across a very large area in the tropical and temperate zones, then flows poleward to repeat the cycle. As noted in the text, freshwater arriving in the North Atlantic from rapidly melting polar ice could slow the formation of North Atlantic Deep Water with profound implications for the climate of Europe.

ond! The water's great density causes it to sink toward the continental shelf, where it mixes with nearly equal parts of water from the southern Antarctic Circumpolar Current.

The mixture settles along the edge of Antarctica's continental shelf, descends along the slope, and spreads along the deep-sea bed, creeping north in slow sheets. Antarctic Bottom Water flows many times as slowly as the water in surface currents; in the Pacific, it may take a thousand years to reach the equator. Six hundred years later, it may be as far away as the Aleutian Islands at 50° N! Antarctic Bottom Water also flows into the Atlantic Ocean basin, where it flows north at a faster rate than in the Pacific. Antarctic Bottom Water has been identified as high as 40° *north* latitude on the Atlantic floor, a journey that has taken some 750 years.

North Atlantic Deep Water Some dense bottom water also forms in the northern polar ocean, but the topography of the Arctic Ocean basin prevents most of the bottom water from escaping, except in the deep channels formed in the submarine ridges separating Scotland, Iceland, and Greenland. These channels allow the cold, dense water formed in the Arctic to flow into the North Atlantic to form **North Atlantic Deep Water.**

North Atlantic Deep Water forms when the relatively warm and salty North Atlantic Ocean cools as cold winds from northern Canada sweep over it. Exposed to the chilled air, water at the latitude of Iceland releases heat, cools from 10°C to 2°C (50°F to 36°F), and sinks. (Transferred to the air, this bonus heat makes northern Europe far warmer than its high latitude suggests.) Gulf Stream water that sinks in the north is replaced by warm water flowing clockwise along the U.S. East Coast in the North Atlantic gyre.

Deep Water Formation Can Affect Climate

In 2005, British researchers noticed that the net flow of the northern Gulf Stream had decreased by about 30% since 1957. Coincidentally, scientists at Woods Hole had been measuring the freshening of the North Atlantic as Earth becomes warmer, precipitation increases in the high northern latitudes, and polar ice melts. As we've just seen, the ocean heat conveyor (Figures 8.21 and 8.22) is driven, in part, by the sinking of cold, salty (therefore denser) water in the high North Atlantic vicinity. The sinking water pulls warm, salty Gulf Stream water northward where its waters give up heat to the atmosphere. By flooding the northern seas with lots of extra freshwater (which is less dense and tends not to sink), global warming could, in theory, slow or divert the Gulf Stream and North Atlantic Current waters that usually flow northward past England and Norway, causing them to short-circuit instead back toward the equator. If this happens, Europe's climate would be seriously affected. Here's an instance in which global warming could lead to localized *cooling*. (More on this important and complex topic awaits you in Chapter 15.)

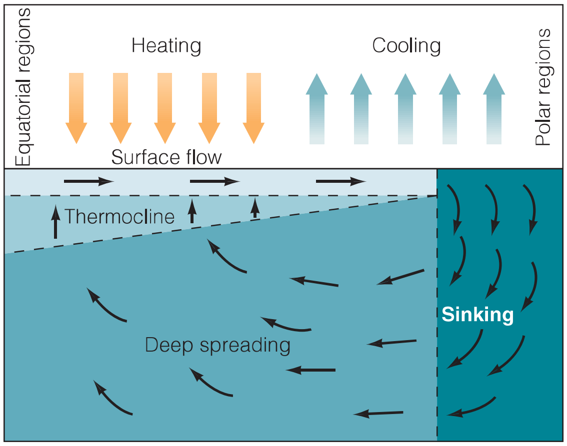

Figure 8.23
The classic model of a pure thermohaline circulation, caused by heating in lower latitudes and cooling in higher latitudes. Compare this figure to the convection cell shown in Figure 7.6.

Water Masses May Converge, Fall, Travel across the Seabed, and Slowly Rise

The great quantities of dense water sinking at polar ocean basin edges must be offset by equal quantities of water rising elsewhere. **Figure 8.23** shows an idealized model of thermohaline flow. Note that water sinks relatively rapidly in a small area where the ocean is very cold, but it rises much more gradually across a very large area in the warmer temperate and tropical zones. It then slowly returns poleward near the surface to repeat the cycle. The continual diffuse upwelling of deep water maintains the existence of the permanent thermocline found everywhere at low and mid-latitudes. This slow upward movement is estimated to be about 1 centimeter (½ inch) per day over most of the ocean. If this rise were to stop, downward movement of heat would cause the thermocline to descend and would reduce its steepness. In a sense, the thermocline is "held up" by the continual slow upward movement of water.

Hundreds of years may pass before water masses complete a circuit or blend to lose their identities. Remember that Antarctic Bottom Water in the Pacific retains its character for up to 1,600 years! The residence time of most deep water is less, however; it takes about 200 to 300 years to rise to the surface. (By contrast, a bit of surface water in the North Atlantic gyre may take only a little more than a year to complete a circuit.)

Courtesy of Philip Richardson, Woods Hole Oceanographic Institution

Figure 8.24

Oceanographers deploy a mooring containing temperature probes from the deck of R/V *Oceanus* during a gale off Cape Hatteras. Its purpose is to measure conditions where the Gulf Stream meets a cold, fresh, southward-moving coastal current.

Brief Review

Before going on to the next section, check your understanding of some of the important ideas presented so far:

17 What drives the vertical movement of ocean water?

18 What is the general pattern of thermohaline circulation?

19 What are water masses? What determines their relative position in the ocean?

20 Where are distinct water masses formed?

21 How does thermohaline circulation force the thermocline toward the ocean's surface?

22 Compare the length of time required for completion of a circuit of surface circulation with that needed for thermohaline circulation.

To check your answers, visit www.cengagebrain.com.

8.7 Studying Currents

Surface currents can be traced with drift bottles or drift cards. These tools are especially useful in determining coastal circulation, but they provide no information on the path the drift bottle or card may have taken between its release and collection points. Researchers who want to know the precise track taken by a drifting object can deploy more elaborate drift devices, such as the buoy arrangement in **Figure 8.24.** These buoys can be tracked continuously by radio direction finders or radar. Surface currents can also be tracked by noting the difference between the daily expected and observed positions of ships at sea.

A newer class of research tools operates autonomously—that is, on their own without human guidance. The first of these, initially deployed in 2003, is the Slocum, named after Joshua Slocum, first person to circumnavigate the globe alone. These little gliders "fly" smoothly up and down through the water column powered by gravity and buoyancy **(Figure 8.25).** Energy to pump ballast overboard, allowing the glider to rise, is provided by a simple heat engine powered by the difference in temperature between ocean surface and great depths. The gliders can fall again as seawater is pumped aboard. Small fleets of Slocum gliders map the ocean's thermohaline depth profiles, chlorophyll content, and other parameters for years, and on their occasional visits to the surface, transmit data to satellites.

More numerous but less maneuverable than Slocum gliders are the 3,000+ floats of the **Argo system.** These smaller floats move vertically in the water column (to depths of 2 kilometers, or about 7,000 feet). The floats return to the surface once every 10 days, measuring temperature and conductivity as they move. Data are uploaded to satellites and used to calculate salinity. Argo floats work with the satellite *Jason 1* as a part of the Integrated Ocean Observing System to measure ocean topography and worldwide climate.

The batteries that power each Argo float's vertical voyages last for around 5 years. About 750 new floats are deployed each year to replace floats that expire or are lost. The floats have an average spacing of 300 kilometers (190 miles), but the exact spacing depends on the random nature of float drift. **Figure 8.26** shows the loca-

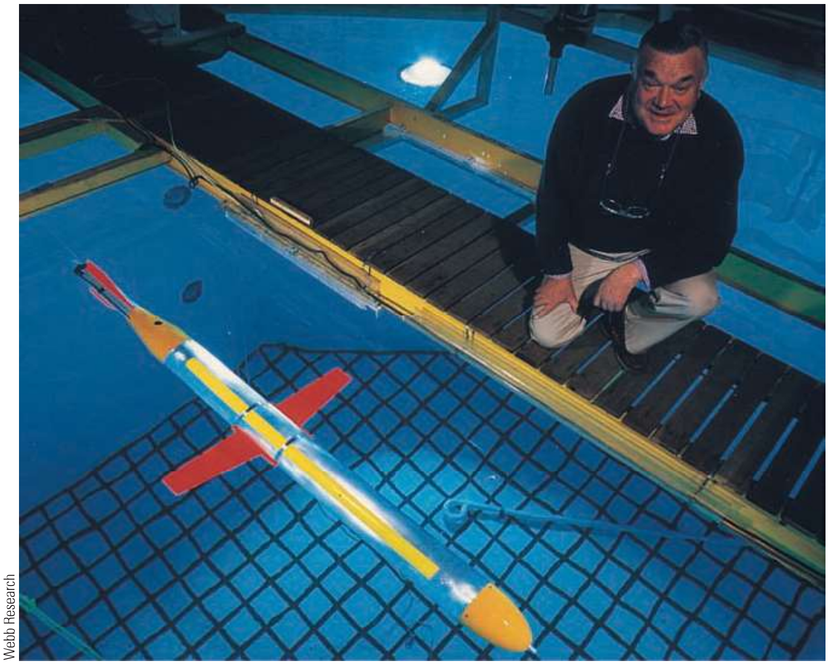

Figure 8.25

A Slocum glider—a probe that uses energy from gravity, buoyancy, heat, and batteries to power long-range exploration of water masses.

tion of the system's 3,261 functioning floats in September 2009.

Yet another method, developed for studying thermohaline circulation, senses the presence in seawater of chemical tracers—artificial substances with known histories of production or release. Because they dissolve easily in seawater, chlorofluorocarbons (CFCs) can be used as such tracers. A totally artificial chemical first produced in the 1930s for use as refrigerants, aerosol propellants, and blowing agents for foam, CFCs spread through the ocean like a dye, following oceanic circulation. The speed of deep currents has been measured by careful analysis of their CFC content.

Currents are the very heart of physical oceanography. Their global effects, great masses of water, complex flow, and possible influence on human migrations make their study of particular importance.

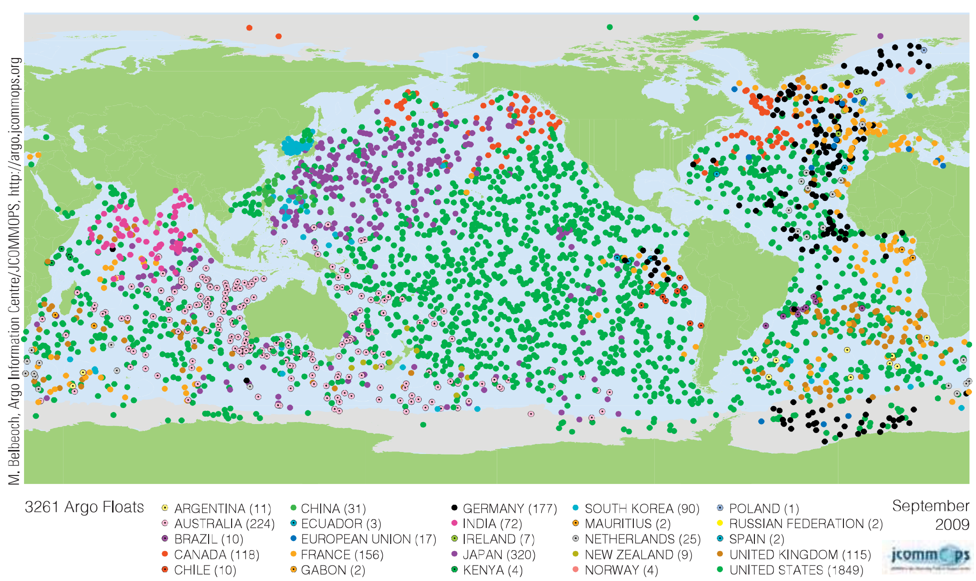

Figure 8.26

The position of 3,261 Argo floats in September 2009. Color codes indicate which member of the international consortium is responsible for each float.

Brief Review

Before going on to the next section, check your understanding of some of the important ideas presented so far:

23 Using common objects, could you conduct research on ocean currents?

24 Traditional methods of studying currents are being replaced with high-tech devices. How do some of these work?

25 How can chlorofluorocarbons (CFCs) be used as such tracers? Would CFC-based methods be equally suitable for analysis of surface currents and thermohaline circulation?

To check your answers, visit www.cengagebrain.com.

More Questions from Students . . .

1 If the Gulf Stream warms Britain during the winter and keeps Baltic ports free of ice, why doesn't it moderate New England winters? After all, Boston is much closer to the warm core of the Gulf Stream than London is.

Yes, but remember the direction of prevailing winds in winter. Winter winds at Boston's latitude are generally from the west, so any warmth is simply blown out to sea. On the other side of the Atlantic, the same winds blow toward London. It does get cold in London, but generally winters in London are much milder than those in Boston.

2 Are there any *non*geostrophic currents? Are any currents not noticeably influenced by gravity, the Coriolis effect, uneven solar heating, planetary winds, and so forth?

Yes, there are small-scale currents that are not noticeably affected. Currents of freshwater from river mouths, rip currents in surf, and tidal currents in small harbors are much more affected by basin and bottom topography than by the Coriolis effect and gravity.

3 Why are western boundary currents strong in *both* hemispheres? I thought things went the other way (counterclockwise) in the Southern Hemisphere. Shouldn't the *eastern* boundary currents be stronger down there?

Western boundary currents are strong, in part, because the "Coriolis hill" is offset to the west, forcing water to move in a relatively narrow path along the ocean's western boundary. Truly, Coriolis effect works in a clockwise direction in the Northern Hemisphere and counterclockwise in the Southern Hemisphere, so the "hill" is offset to the west in both hemispheres. Thus, western boundary currents are strong in both hemispheres.

4 Which takes the lead in producing the hill in the middle of a geostrophic gyre—the pressure gradient or the Coriolis effect?

The question reminds me of the "chicken-and-egg" question—which came first? In ocean currents, both act together, in balance, to form both the hill and the circular flow around its crest. Imagine the situation some 150 million years ago when the Atlantic was first forming—Pangaea was splitting and the rift began to fill with water. Driven by winds, a small amount of water would have turned right to begin forming the hill. A pressure gradient was immediately formed, and water would have been forced back downhill by gravity. On its way back down, that water would achieve a balance with Coriolis effect and come to a "compromise" position of clockwise flow around the apex.

5 A north wind comes from the north, but a north current is going north. Why the difference?

Traditions die hard, it seems. For thousands of years winds have been named by where they come *from*. A north wind comes from the north, and a west wind comes from the west. Currents, though, are named by where they are *going*. A southern current is headed south; a western current is moving west. An exception is the Antarctic Circumpolar Current, or West Wind Drift, which moves eastward. This current, however, is named after the wind that drives it, the powerful polar westerlies.

It may also be a matter of perspective. Ancient peoples took shelter *from* winds (and referred to the wind's place of origin). But early oceanic travelers were aware of where the currents were carrying them *to*.

Chapter Summary

In this chapter, you learned that ocean water circulates in currents. Surface currents affect the uppermost 10% of the world ocean. The movement of surface currents is powered by the warmth of the sun and by winds. Water in surface currents tends to flow horizontally, but it can also flow vertically in response to wind blowing near coasts or along the equator. Surface currents transfer heat from tropical to polar regions, influence weather and climate, distribute nutrients, and scatter organisms. They have contributed to the spread of humanity to remote islands, and they are important factors in maritime commerce.

Circulation of the 90% of ocean water beneath the surface zone is driven by the force of gravity, as dense water sinks and less dense water rises. Because density is largely a function of temperature and salinity, the movement of deep water caused by density differences is called *thermohaline circulation*. Currents near the seafloor flow as slow, river-like masses in a few places, but the greatest volumes of deep water creep through the ocean at an almost imperceptible pace. The Coriolis effect, gravity, and friction shape the direction and volume of surface currents and thermohaline circulation.

In the next chapter, you will learn about ocean waves. The traveling crests produce the appearance of movement we see in a wave. In an ocean wave, a ribbon of *energy* is moving at the speed of the wave, but *water* is not. In a sense, an ocean wave is an illusion. How can you be knocked off your surfboard by an illusion? Well, there's much to learn!

Terms and Concepts to Remember

Antarctic Bottom Water
Antarctic Circumpolar Current (West Wind Drift)
Argo system
coastal upwelling
current
downwelling
eastern boundary current
eddy
Ekman spiral
Ekman transport
El Niño
ENSO
equatorial upwelling
geostrophic gyre
Gulf Stream
gyre
La Niña
North Atlantic Deep Water
Southern Oscillation
surface current
sverdrup (sv)
thermohaline circulation
transverse current
upwelling
western boundary current
westward intensification
West Wind Drift (Antarctic Circumpolar Current)
wind-induced vertical circulation