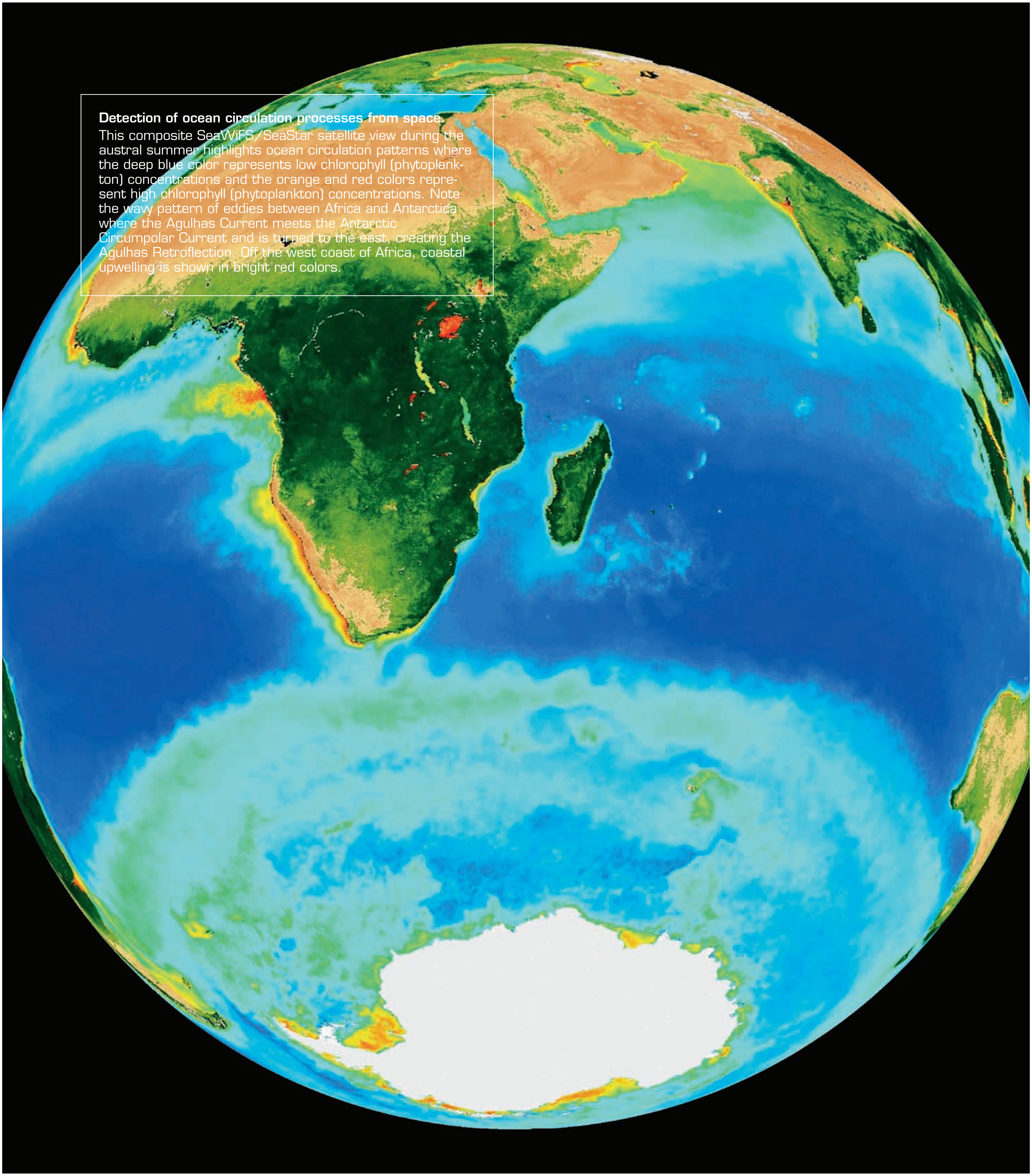


Detection of ocean circulation processes from space. This composite SeaWiFS/SeaStar satellite view during the austral summer highlights ocean circulation patterns where the deep blue color represents low chlorophyll (phytoplankton) concentrations and the orange and red colors represent high chlorophyll (phytoplankton) concentrations. Note the wavy pattern of eddies between Africa and Antarctica where the Agulhas Current meets the Antarctic Circumpolar Current and is turned to the east, creating the Agulhas Retroflection. Off the west coast of Africa, coastal upwelling is shown in bright red colors.

"The coldest winter I ever spent was a summer in San Francisco."

—Anonymous, but often attributed to Mark Twain; said in reference to San Francisco's cool summer weather caused by coastal upwelling

7 OCEAN CIRCULATION

CHAPTER AT A GLANCE

- Ocean surface currents are organized into circular-moving loops of water called gyres that are influenced by the major wind belts of the world and are important for redistributing heat around the globe.
- Distinctive components of surface circulation include the Atlantic Ocean's Gulf Stream, the Indian Ocean's monsoons, and the Pacific Ocean's El Niño–Southern Oscillation.
- Thermohaline circulation describes the movement of deep currents, which form at the surface in high latitudes where they become cold and dense, so they sink.

Ocean currents are masses of ocean water that flow from one place to another. The amount of water can be large or small, currents can be at the surface or deep below, and the phenomena that create them can be simple or quite complex. Simply put, currents are *water masses in motion*.

Huge current systems dominate the surfaces of the major oceans. These currents transfer heat from warmer to cooler areas on Earth, just as the major wind belts of the world do. Wind belts transfer about two-thirds of the total amount of heat from the tropics to the poles; ocean surface currents transfer the other third. Ultimately, energy from the Sun drives surface currents and they closely follow the pattern of the world's major wind belts. As a result, the movement of currents has aided the travel of prehistoric people across ocean basins. Ocean currents also influence the abundance of life in surface waters by affecting the growth of microscopic algae, which are the basis of most oceanic food webs.

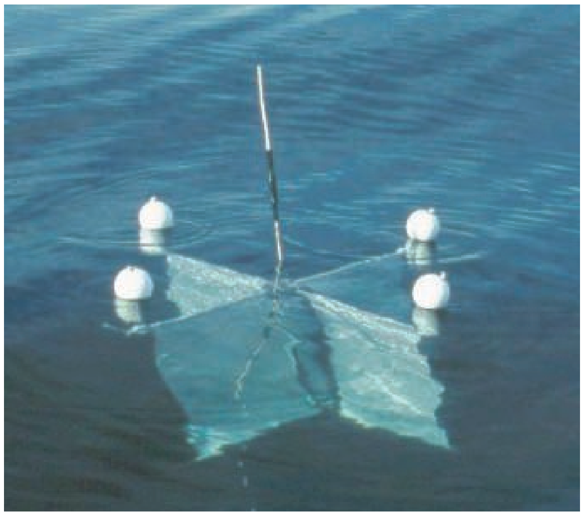
More locally, surface currents affect the climates of coastal continental regions. Cold currents flowing toward the equator on the western sides of continents produce arid conditions. Conversely, warm currents flowing poleward on the eastern sides of continents produce warm, humid conditions. Ocean currents, for example, contribute to the mild climate of northern Europe and Iceland, whereas conditions at similar latitudes along the Atlantic coast of North America (such as Labrador) are much colder. Additionally, water sinks in high-latitude regions, initiating deep currents that help regulate the planet's climate.

7.1 How Are Ocean Currents Measured?

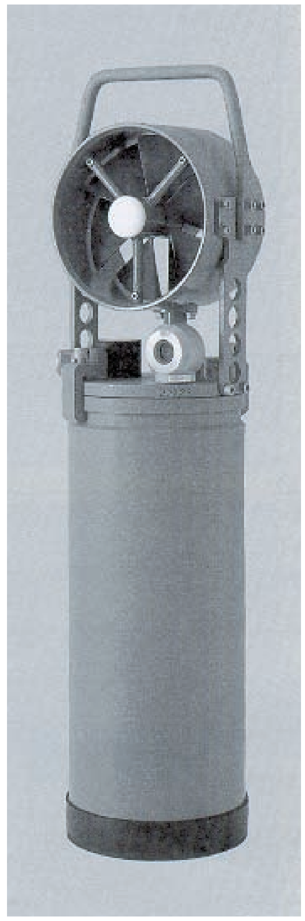
Ocean currents are either *wind driven* or *density driven*. Moving air masses—particularly the major wind belts of the world—set wind-driven currents in motion. Wind-driven currents move water horizontally and occur primarily in the ocean's surface waters, so these currents are called **surface currents**. Density-driven circulation, on the other hand, moves water vertically and accounts for the thorough mixing of the deep masses of ocean water. Some surface waters become high in density—through low temperature and/or high salinity—and so sink beneath the surface. This dense water sinks and spreads slowly beneath the surface, so these currents are called **deep currents**.

Surface Current Measurement

Surface currents rarely flow in the same direction and at the same rate for very long, so measuring average flow rates can be difficult. Some consistency, however, exists in the *overall* surface current pattern worldwide. Surface currents can be measured directly or indirectly.



(a)



(b)

FIGURE 7.1 Current-measuring devices. **(a)** Drift current meter. Depth of metal vanes is 1 meter (3.3 feet). **(b)** Propeller-type flow meter. Length of instrument is 0.6 meter (2 feet).

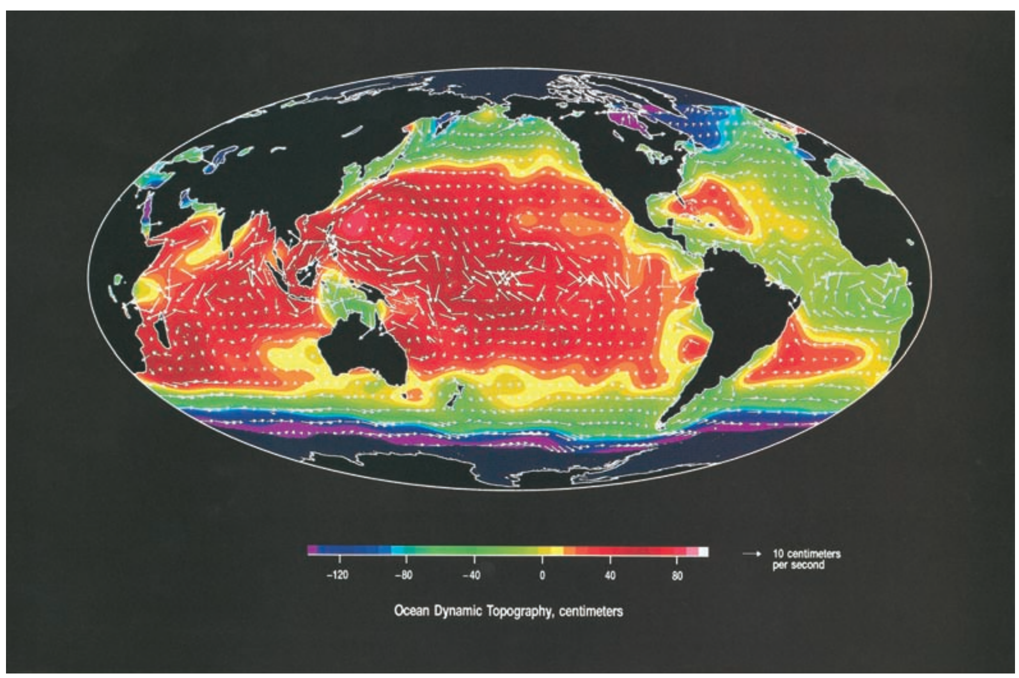
DIRECT METHODS Two main methods are used to measure currents *directly*. In one, a floating device is released into the current and tracked through time. Typically, radio-transmitting float bottles or other devices are used (Figure 7.1a), but other accidentally released items also make good drift meters (Box 7.1). The other method is done from a fixed position (such as a pier) where a current-measuring device, such as the propeller flow meter shown in Figure 7.1b, is lowered into the water. Propeller devices can also be towed behind ships, and the ship's speed is then subtracted to determine a current's true flow rate.

INDIRECT METHODS Three different methods can be used to measure surface currents *indirectly*. Water flows parallel to a pressure gradient, so one method is to determine the internal distribution of density and the corresponding pressure gradient across an area of the ocean. A second method uses radar altimeters—such as those launched aboard Earth-observing satellites today—to determine the lumps and bulges at the ocean surface, which are a result of the shape of the underlying sea floor (see Box 7.1) as well as current flow. From these data, *dynamic topography* maps can be produced that show the speed and direction of surface currents (Figure 7.2). A third method uses a *Doppler flow meter* to transmit low-frequency sound signals through the water. The flow meter measures the shift in frequency between the sound waves emitted and those backscattered by particles in the water to determine current movement.

Deep Current Measurement

The great depth at which deep currents exist makes them even more difficult to measure than surface currents. Most often, they are mapped using underwater floats that are carried within deep currents. One such unique oceanographic

FIGURE 7.2 Satellite view of ocean dynamic topography. Map showing TOPEX/Poseidon radar altimeter data in centimeters from September 1992 to September 1993. Red colors are areas that have higher than normal sea level; blue colors are areas that are lower than normal. White arrows indicate the flow direction of currents, with longer arrows indicating faster flow rates.



7.1 OCEANS AND PEOPLE

RUNNING SHOES AS DRIFT METERS: JUST DO IT

Any floating object can serve as a makeshift drift meter, as long as it is known where the object entered the ocean and where it was retrieved. The path of the object can then be inferred, providing information about the movement of surface currents. If the time of release and retrieval are known, the speed of currents can also be determined. Oceanographers have long used *drift bottles* (a floating "message in a bottle" or a radio-transmitting device set adrift in the ocean) to track the movement of currents.

Many objects have inadvertently become drift meters when ships lose cargo at sea. Worldwide, in fact, as many as 10,000 shipping containers are lost overboard each year. In this way, Nike athletic shoes and colorful floating bathtub toys (Figure 7A, *right inset*) have advanced the understanding of current movement in the North Pacific Ocean.

In May 1990, the container vessel *Hansa Carrier* was en route from Korea to Seattle, Washington, when it encountered a severe North Pacific storm. The ship was transporting 12.2-meter (40-foot)-long rectangular metal shipping containers, many of which were lashed to the ship's deck for the voyage. During the storm, the ship lost 21 deck containers overboard, including five that held Nike athletic shoes. The shoes floated, so those that were released from their containers were carried east by the North Pacific Current. Within six months, thousands of the shoes began to wash up along the beaches of Alaska, Canada, Washington, and Oregon (Figure 7A, *map*), more than 2400 kilometers (1500 miles) from the site of the spill. A few shoes were found on beaches in northern California, and over two years later, shoes from the spill were even recovered from the north end of the Big Island of Hawaii!

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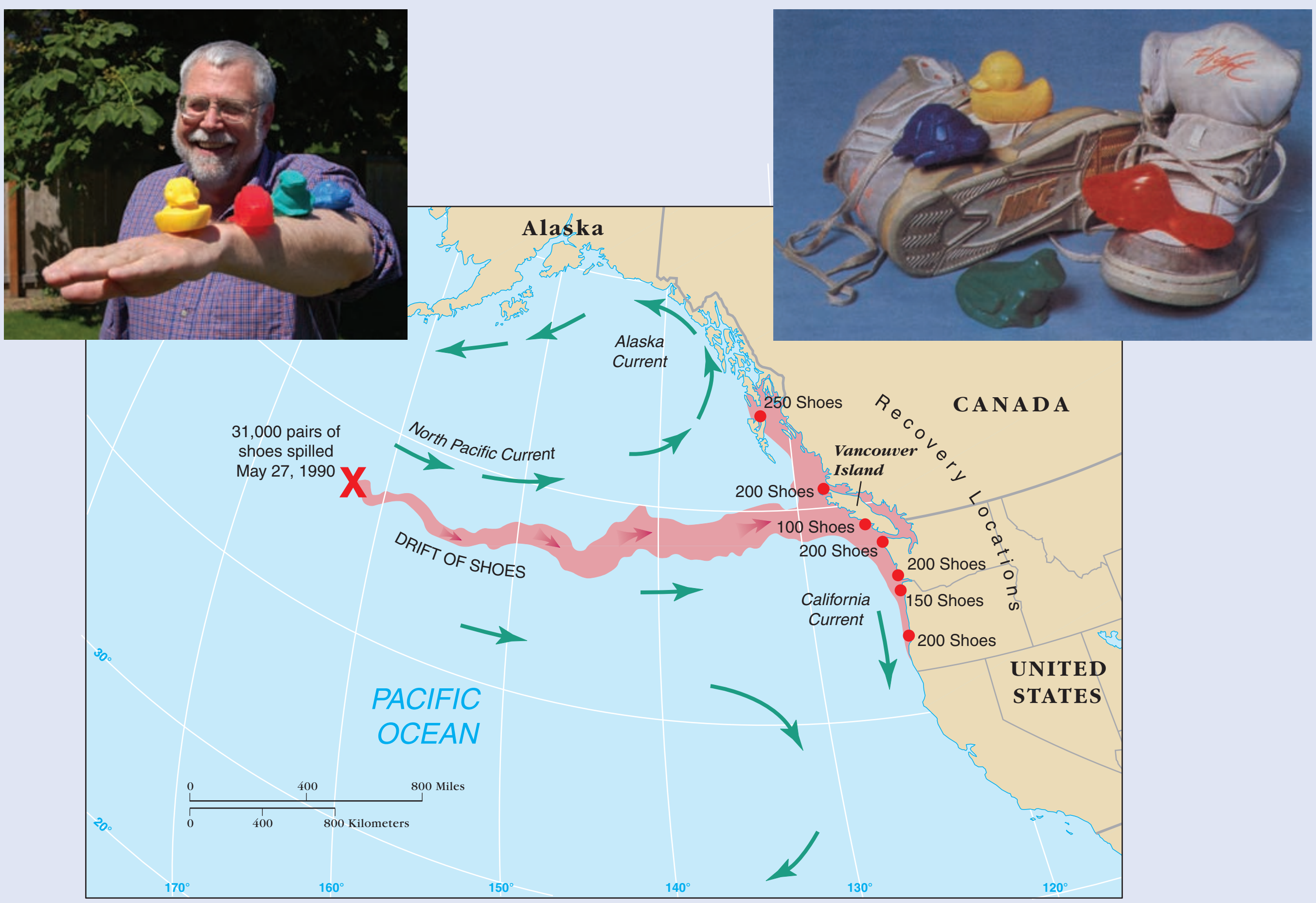


FIGURE 7A Oceanographer Curtis Ebbesmeyer (*left inset*), path of drifting shoes and recovery locations from the 1990 spill (*map*), and recovered shoes and plastic bathtub toys (*right inset*).

Continued from page 195 . . .

Even though the shoes had spent considerable time drifting in the ocean, they were in good shape and wearable (after barnacles and oil were removed). Because the shoes were not tied together, many beachcombers found individual shoes or pairs that did not match. Many of the shoes retailed for around $100, so people interested in finding matching pairs placed ads in newspapers or attended local swap meets.

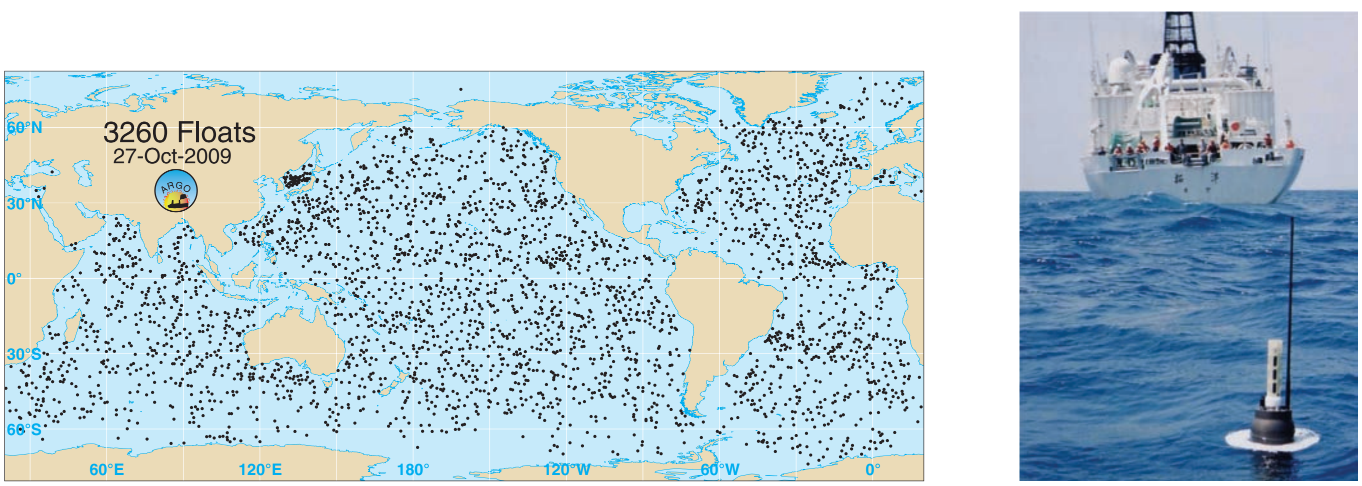
With help from the beachcombing public (as well as lighthouse operators), information on the location and number of shoes collected was compiled during the months following the spill. Serial numbers inside the shoes were traced to individual containers, and they indicated that only four of the five containers had released their shoes; evidently, one entire container sank without opening. Thus, a maximum of 30,910 pairs of shoes (61,820 individual shoes) were released. The almost instantaneous release of such a large number of drift items helped oceanographers refine computer models of North Pacific circulation. Before the shoe spill, the largest number of drift bottles purposefully released at one time by oceanographers was about 30,000. Although only 2.6% of the shoes were recovered, this compares favorably with the 2.4% recovery rate of drift bottles released by oceanographers conducting research.

In January 1992, another cargo ship lost 12 containers during a storm to the north of where the shoes had previously spilled. One of these containers held 29,000 packages of small, floatable, colorful plastic bathtub toys in the shapes of blue turtles, yellow ducks, red beavers, and green frogs (Figure 7A, *insets*). Even though the toys were housed in plastic packaging glued to a cardboard backing, studies showed that after 24 hours in seawater, the glue deteriorated and more than 100,000 of the toys were released.

The floating bathtub toys began to come ashore in southeast Alaska 10 months later, verifying the computer models. The models indicate that many of the bathtub toys will continue to be carried by the Alaska Current, eventually dispersing throughout the North Pacific Ocean. Some may find their way into the Arctic Ocean, where they could spend time within the Arctic Ocean ice pack. From there, the toys may drift into the North Atlantic, eventually washing up on beaches in northern Europe, thousands of kilometers from where they were accidentally released into the ocean.

Oceanographers such as Curtis Ebbesmeyer (Figure 7A, *left inset*) continue to study ocean currents by tracking these and other floating items spilled by cargo ships (see Web Table 7.1).

program that began in 2000 is called **Argo**, which is a global array of free-drifting profiling floats (Figure 7.3b) that move vertically and measure the temperature, salinity, and other water characteristics of the upper 2000 meters (6600 feet) of the ocean. Once deployed, each float sinks to a particular depth, drifts for up to 10 days collecting data, then resurfaces and transmits data on its location and ocean variables, which are made publically available within hours. Each float then sinks back down to a programmed depth and drifts for up to another 10 days collecting more data before resurfacing and repeating the cycle. In 2007, the goal of the program was achieved with the launch of the 3000th Argo float; currently, there are nearly 3300 floats operating worldwide (Figure 7.3a). The program will allow



(a) (b)

FIGURE 7.3 The Argo system of free-drifting submersible floats. (a) Map showing the locations of Argo floats, which can dive to 2000 meters (6600 feet) and collect data on ocean properties before resurfacing and transmitting their data. **(b)** Floats are deployed from research or cargo vessels.

oceanographers to develop a forecasting system for the oceans analogous to weather forecasting on land.

Other techniques used for measuring deep currents include identifying the distinctive temperature and salinity characteristics of a deep-water mass or by tracking telltale chemical tracers. Some tracers are naturally absorbed into seawater, while others are intentionally added. Some useful tracers that have inadvertently been added to seawater include tritium (a radioactive isotope of hydrogen produced by nuclear bomb tests in the 1950s and early 1960s) and chlorofluorocarbons (freons and other gases now thought to be depleting the ozone layer).

KEY CONCEPT
Wind-induced surface currents are measured with floating objects, by satellites, or by other techniques. Density-induced deep currents are measured using submerged floats, water properties, or chemical tracers.

7.2 How Are Ocean Surface Currents Organized?

Surface currents occur within and above the *pycnocline* (layer of rapidly changing density) to a depth of about 1 kilometer (0.6 mile) and affect only about 10% of the world's ocean water.

Origin of Surface Currents

In a simplistic case, surface currents develop from friction between the ocean and the wind that blows across its surface. Only about 2% of the wind's energy is transferred to the ocean surface, so a 50-knot[1] wind will create a 1-knot current. You can simulate this on a tiny scale simply by blowing gently and steadily across a cup of coffee.

If there were no continents on Earth, the surface currents would generally follow the major wind belts of the world. In each hemisphere, therefore, a current would flow between 0 and 30 degrees latitude as a result of the trade winds, a second would flow between 30 and 60 degrees latitude as a result of the prevailing westerlies, and a third would flow between 60 and 90 degrees latitude as a result of the polar easterlies.

In reality, however, ocean surface currents are driven by more than just the wind belts of the world. The distribution of continents on Earth is one factor that influences the nature and the direction of flow of surface currents in each ocean basin. As an example, Figure 7.4 shows how the trade winds and prevailing westerlies create large circular-moving loops of water in the Atlantic Ocean basin, which is bounded by the irregular shape of continents. These same wind belts affect the other ocean basins, so a similar pattern of surface current flow also exists in the Pacific and Indian Oceans. Other factors that influence surface current patterns include gravity, friction, and the Coriolis effect.

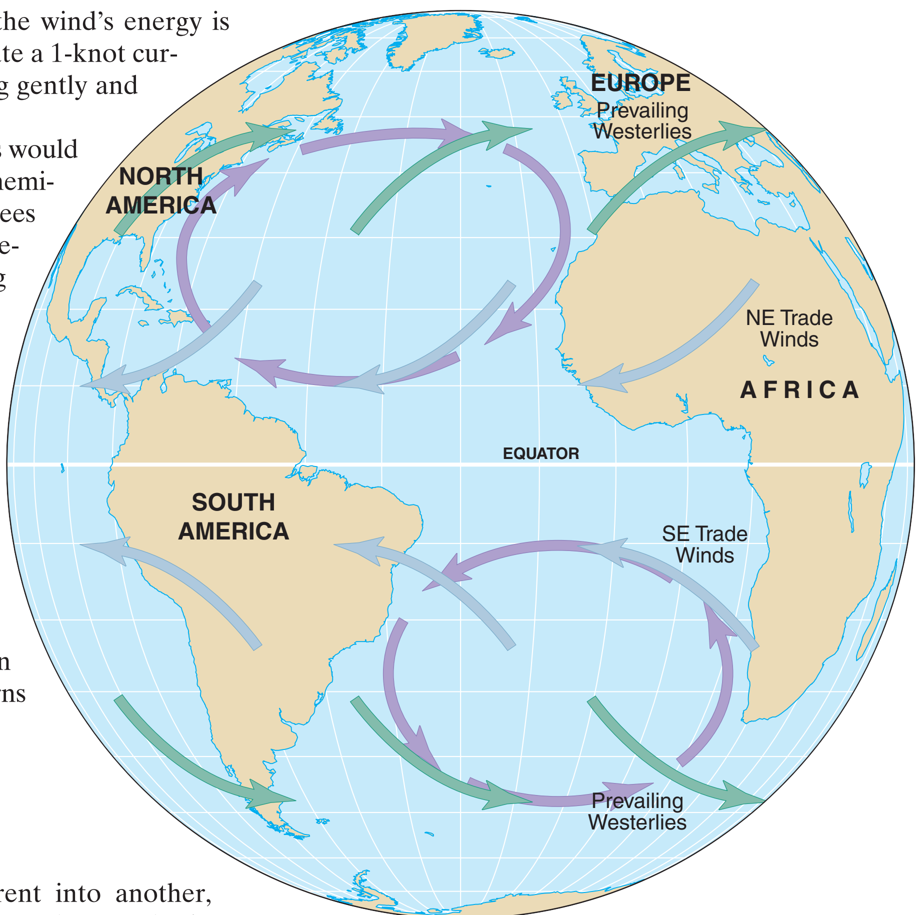


FIGURE 7.4 Atlantic Ocean surface circulation pattern. The trade winds (*blue arrows*) in conjunction with the prevailing westerlies (*green arrows*) create circular-moving loops of water (*underlying purple arrows*) at the surface in both parts of the Atlantic Ocean basin. If there were no continents, the ocean's surface circulation pattern would closely match the major wind belts of the world.

Main Components of Ocean Surface Circulation

Although ocean water continuously flows from one current into another, ocean currents can be organized into discrete patterns within each ocean basin.

SUBTROPICAL GYRES The large, circular-moving loops of water shown in Figure 7.4 that are driven by the major wind belts of the world are called

[1]A *knot* is a speed of 1 nautical mile per hour. A nautical mile is defined as the distance of 1 minute of latitude and is equivalent to 1.15 statute (land) miles or 1.85 kilometers.

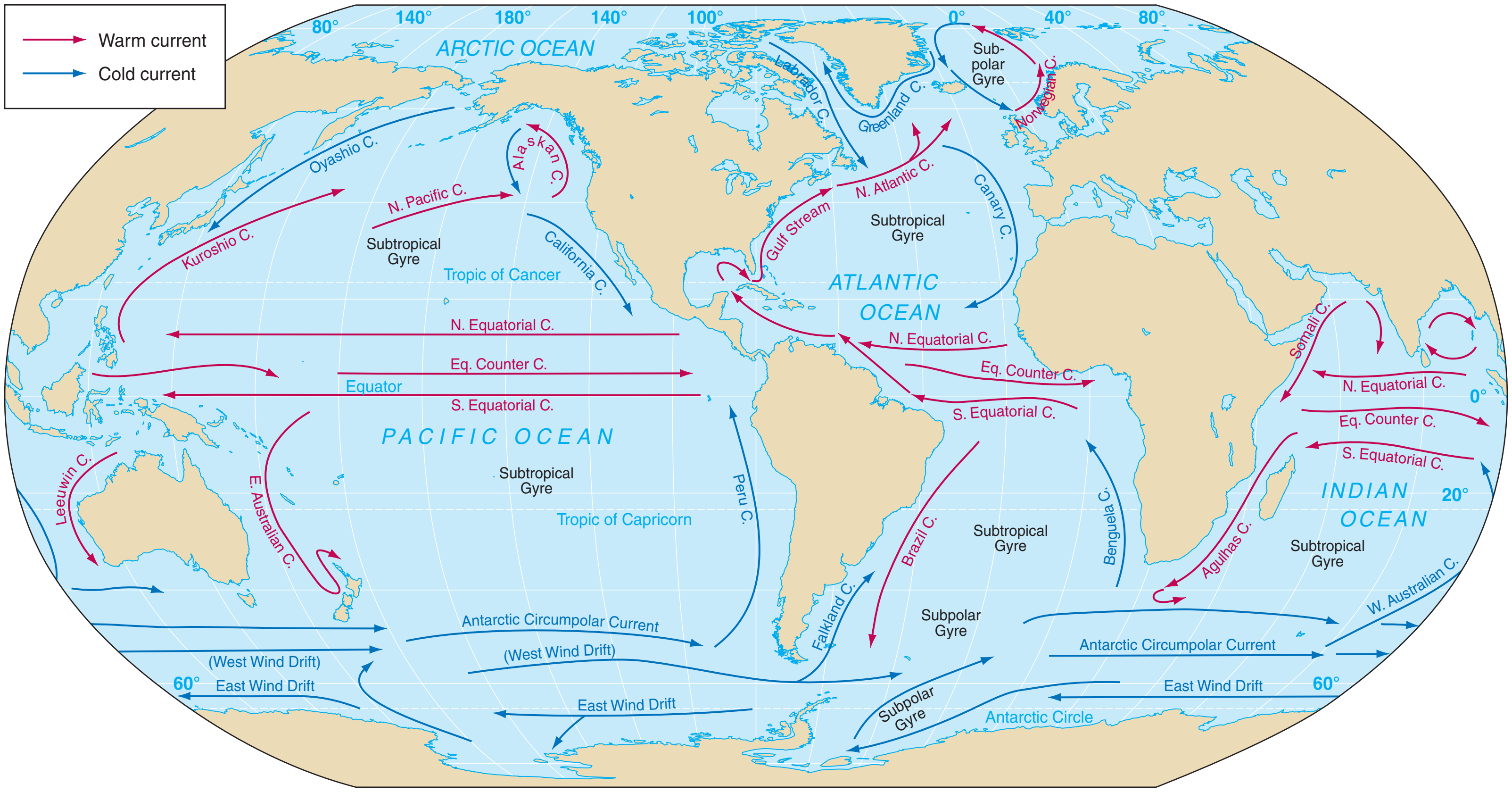


FIGURE 7.5 Wind-driven surface currents. Major wind-driven surface currents of the world's oceans during February–March. The five major subtropical gyres are: (1) the North Pacific (Turtle) Gyre, (2) the South Pacific (Heyerdahl) Gyre, (3) the North Atlantic (Columbus) Gyre, (4) the South Atlantic (Navigator) Gyre, and (5) the Indian Ocean (Majid) Gyre. Smaller subpolar gyres rotate in the reverse direction of their adjacent subtropical gyres.

Ocean Circulation

gyres (*gyros* = a circle). Figure 7.5 shows the world's five **subtropical gyres**: (1) the *North Atlantic Subtropical Gyre*, (2) the *South Atlantic Subtropical Gyre*, (3) the *North Pacific Subtropical Gyre*, (4) the *South Pacific Subtropical Gyre*, and (5) the *Indian Ocean Subtropical Gyre* (which is mostly within the Southern Hemisphere). The reason they are called subtropical gyres is because the center of each gyre coincides with the subtropics at 30 degrees north or south latitude. As shown in Figures 7.4 and 7.5, subtropical gyres rotate clockwise in the Northern Hemisphere and counterclockwise in the Southern Hemisphere. Studies of floating objects (see Box 7.1) indicate that the average drift time in a smaller subtropical gyre such as the North Atlantic Gyre is about three years, whereas in larger subtropical gyres such as the North Pacific Gyre it is about six years.

Oceanographers have given names to the gyres to honor explorers and seafarers—both human and nonhuman, but especially drifters—who have circled and traversed their great expanses:

- The North Atlantic Subtropical Gyre is named the *Columbus Gyre* after the first mariner to exploit its currents in both outbound and homeward journeys (see Box 6.1).
- The South Atlantic Subtropical Gyre is named the *Navigator Gyre* after Portugal's Prince Henry the Navigator, who founded Europe's first navigational school and launched oceanography's Age of Discovery (see Chapter 1).
- The North Pacific Subtropical Gyre is named the *Turtle Gyre* in honor of sea turtles that cross the widest ocean leaving and returning to their ancient breeding beaches in Japan (see Box 2.1).
- The South Pacific Subtropical Gyre is named the *Heyerdahl Gyre* after Thor Heyerdahl, a fearless explorer–scientist that proved an ancient voyage from South America to Polynesia was possible by reenacting it (see Chapter 1).
- The Indian Ocean's gyre is named the *Majid Gyre* after the great 15th-century Arab mariner and author Ahmad Bin Majid, whose maps guided the Portuguese in their globe-spanning voyages.

TABLE 7.1 SUBTROPICAL GYRES AND SURFACE CURRENTS

Pacific Ocean	Atlantic Ocean	Indian Ocean
North Pacific (Turtle) Gyre	**North Atlantic (Columbus) Gyre**	**Indian Ocean (Majid) Gyre**
North Pacific Current	North Atlantic Current	South Equatorial Current
California Current[a]	Canary Current[a]	Agulhas Current[b]
North Equatorial Current	North Equatorial Current	West Wind Drift
Kuroshio (Japan) Current[b]	Gulf Stream[b]	West Australian Current[a]
South Pacific (Heyerdahl) Gyre	**South Atlantic (Navigator) Gyre**	**Other Major Currents**
South Equatorial Current	South Equatorial Current	Equatorial Countercurrent
East Australian Current[b]	Brazil Current[b]	North Equatorial Current
West Wind Drift	West Wind Drift	Leeuwin Current
Peru (Humboldt) Current[a]	Benguela Current[a]	Somali Current
Other Major Currents	**Other Major Currents**	
Equatorial Countercurrent	Equatorial Countercurrent	
Alaskan Current	Florida Current	
Oyashio Current	East Greenland Current	
	Labrador Current	
	Falkland Current	

[a]Denotes an eastern boundary current of a gyre, which is relatively *slow*, *wide*, and *shallow* (and is also a *cold-water* current).
[b]Denotes a western boundary current of a gyre, which is relatively *fast*, *narrow*, and *deep* (and is also a *warm-water* current).

Generally, *each subtropical gyre is composed of four main currents* that flow progressively into one another (Table 7.1). The North Atlantic (Columbus) Gyre, for instance, is composed of the North Equatorial Current, the Gulf Stream, the North Atlantic Current, and the Canary Current (Figure 7.5). Let's examine each of the four main currents that comprise subtropical gyres.

Equatorial Currents The trade winds, which blow from the southeast in the Southern Hemisphere and from the northeast in the Northern Hemisphere, set in motion the water masses between the tropics. The resulting currents are called **equatorial currents**, which travel westward along the equator and form the equatorial boundary current of subtropical gyres (Figure 7.5). They are called north or south equatorial currents, depending on their position relative to the equator.

Western Boundary Currents When equatorial currents reach the western portion of an ocean basin, they must turn because they cannot cross land. The Coriolis effect deflects these currents away from the equator as **western boundary currents**, which comprise the western boundaries of subtropical gyres. Western boundary currents are so named because they travel along the western boundary of their respective ocean basins.[2] For example, the Gulf Stream and the Brazil Current,

[2]Notice that western boundary currents are off the *eastern* coasts of adjoining continents. It's easy to be confused about this because we have a land-based perspective. From an *oceanic perspective*, however, the western side of the ocean basin is where western boundary currents reside.

which are shown in Figure 7.5, are western boundary currents. They come from equatorial regions, where water temperatures are warm, so they carry warm water to higher latitudes. Note that Figure 7.5 shows warm currents as red arrows.

Northern or Southern Boundary Currents Between 30 and 60 degrees latitude, the prevailing westerlies blow from the northwest in the Southern Hemisphere and from the southwest in the Northern Hemisphere. These winds direct ocean surface water in an easterly direction across an ocean basin [see the North Atlantic Current and the Antarctic Circumpolar Current (West Wind Drift) in Figure 7.5]. In the Northern Hemisphere, these currents comprise the northern parts of subtropical gyres and are called **northern boundary currents**; in the Southern Hemisphere, they comprise the southern parts of subtropical gyres and are called **southern boundary currents**.

Eastern Boundary Currents When currents flow back across the ocean basin, the Coriolis effect and continental barriers turn them toward the equator, creating **eastern boundary currents** of subtropical gyres along the eastern boundary of the ocean basins. Examples of eastern boundary currents include the Canary Current and the Benguela Current,[3] which are shown in Figure 7.5. They come from high-latitude regions where water temperatures are cool, so they carry cool water to lower latitudes. Note that Figure 7.5 shows cold currents as blue arrows.

EQUATORIAL COUNTERCURRENTS A large volume of water is driven westward due to the north and south equatorial currents. The Coriolis effect is minimal near the equator, so the majority of the water is not turned toward higher latitudes. Instead, the water piles up along the western margin of an ocean basin, which causes average sea level on the western side of the basin to be as much as 2 meters (6.6 feet) higher than on the eastern side. The water on the western margins then flows downhill under the influence of gravity, creating narrow **equatorial countercurrents** that flow to the east counter to and between the adjoining equatorial currents.

Figure 7.5 shows that an equatorial countercurrent is particularly apparent in the Pacific Ocean. This is because of the large equatorial region that exists in the Pacific Ocean and because of a dome of equatorial water that becomes trapped in the island-filled embayment between Australia and Asia. Continual influx of water from equatorial currents builds the dome and creates an eastward countercurrent that stretches across the Pacific toward South America. The equatorial countercurrent in the Atlantic Ocean, on the other hand, is not nearly as well defined because of the shapes of the adjoining continents, which limit the equatorial area that exists in the Atlantic Ocean. The presence of an equatorial countercurrent in the Indian Ocean is strongly influenced by the monsoons, which will be discussed later in this chapter.

SUBPOLAR GYRES Northern or southern boundary currents that flow eastward as a result of the prevailing westerlies eventually move into subpolar latitudes (about 60 degrees north or south latitude). Here, they are driven in a westerly direction by the polar easterlies, producing **subpolar gyres** that rotate opposite the adjacent subtropical gyres. Subpolar gyres are smaller and fewer than subtropical gyres. Two examples include the subpolar gyre in the Atlantic Ocean between Greenland and Europe (named the *Viking Gyre* in honor of the Viking voyages during the Middle Ages) and in the Weddell Sea off Antarctica (Figure 7.5).

KEY CONCEPT

The principal ocean surface current pattern consists of subtropical and subpolar gyres that are large, circular-moving loops of water powered by the major wind belts of the world.

[3]Currents are often named for a prominent geographic location near where they pass. For instance, the Canary Current passes the Canary Islands, and the Benguela Current is named for the Benguela Province in Angola, Africa.

Other Factors Affecting Ocean Surface Circulation

Several other factors influence circulation patterns in subtropical gyres, including Ekman spiral and Ekman transport, geostrophic currents, and western intensification of subtropical gyres.

EKMAN SPIRAL AND EKMAN TRANSPORT During the voyage of the *Fram* (Web Box 7.1), Norwegian explorer Fridtjof Nansen observed that Arctic Ocean ice moved 20 to 40 degrees to the right of the wind blowing across its surface (Figure 7.6). Not only ice but surface waters in the Northern Hemisphere were also observed to move to the right of the wind direction; in the Southern Hemisphere, surface waters move to the *left* of the wind direction. Why does surface water move in a direction different than the wind? **V. Walfrid Ekman** (1874–1954), a Swedish physicist, developed a circulation model in 1905 called the **Ekman spiral** (Figure 7.7) that explains Nansen's observations as a balance between frictional effects in the ocean and the Coriolis effect.

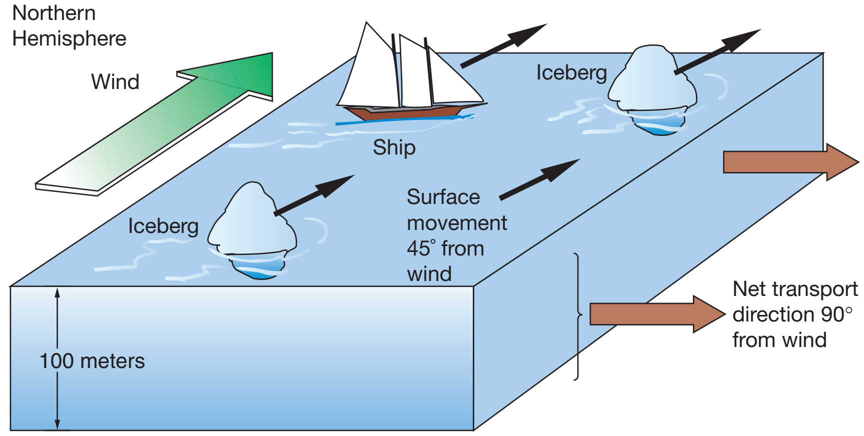
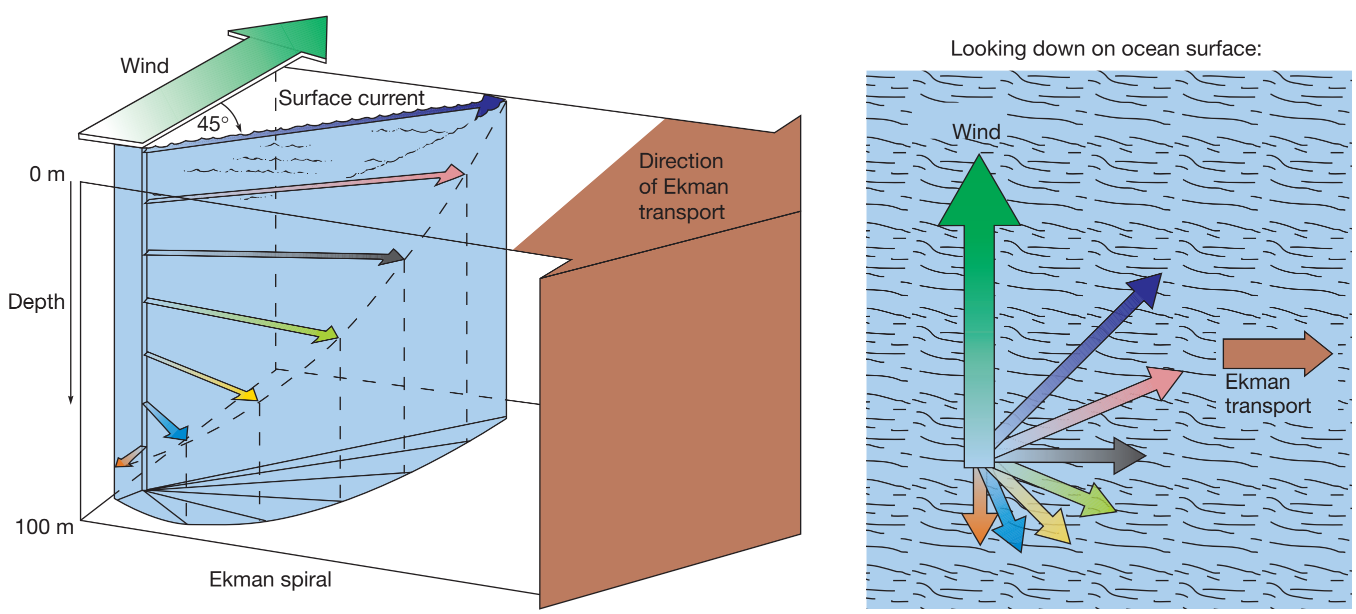


FIGURE 7.6 Transport of floating objects. Fridtjof Nansen first noticed that floating objects, such as icebergs and ships, were carried to the right of the wind direction in the Northern Hemisphere.

Ekman Spiral and Coastal Upwelling/ Downwelling

The Ekman spiral describes the speed and direction of flow of surface waters at various depths. Ekman's model assumes that a uniform column of water is set in motion by wind blowing across its surface. Because of the Coriolis effect, the immediate surface water moves in a direction 45 degrees to the right of the wind (in the Northern Hemisphere). The surface water moves as a thin "layer" on top of deeper layers of water. As the surface layer moves, other layers beneath it are set in motion, thus passing the energy of the wind down through the water column just like how a deck of cards can be fanned out by pressing on and rotating only the top card.

Current speed decreases with increasing depth, however, and the Coriolis effect increases curvature to the right (like a spiral). Thus, each successive layer of water is set in motion at a progressively slower velocity, and in a direction progressively to the right of the one above it. At some depth, a layer of water may move in a direction *exactly opposite from the wind direction that initiated it!* If the water is deep enough, friction will consume the energy imparted by the wind and no motion will occur below that depth. Although it depends on wind speed and latitude, this stillness normally occurs at a depth of about 100 meters (330 feet).



(a) (b)

FIGURE 7.7 Ekman spiral. Perspective view **(a)** and top view **(b)** of Ekman spiral and Ekman transport. Wind drives surface water in a direction 45 degrees to the right of the wind in the Northern Hemisphere. Deeper water continues to deflect to the right and moves at a slower speed with increased depth, causing the Ekman spiral. Ekman transport, which is the average water movement for the entire column, is at a right angle (90 degrees) to the wind direction.

STUDENTS SOMETIMES ASK . . .

What does an Ekman spiral look like at the surface? Is it strong enough to disturb ships?

The Ekman spiral creates different layers of surface water that move in slightly different directions at slightly different speeds. It is too weak to create eddies or whirlpools (vortexes) at the surface and so presents no danger to ships. In fact, the Ekman spiral is unnoticeable at the surface. It can be observed, however, by lowering oceanographic equipment over the side of a vessel. At various depths, the equipment can be observed to drift at various angles from the wind direction according to the Ekman spiral.

Figure 7.7 shows the spiral nature of this movement with increasing depth from the ocean's surface. The length of each arrow in Figure 7.7 is proportional to the velocity of the individual layer, and the direction of each arrow indicates the direction it moves.[4] Under ideal conditions, therefore, the surface layer should move at an angle of 45 degrees from the direction of the wind. All the layers combine, however, to create a net water movement that is 90 degrees from the direction of the wind. This average movement, called **Ekman transport**, is 90 degrees to the *right* in the Northern Hemisphere and 90 degrees to the *left* in the Southern Hemisphere.

"Ideal" conditions rarely exist in the ocean, so the actual movement of surface currents deviates slightly from the angles shown in Figure 7.7. Generally, surface currents move at an angle somewhat less than 45 degrees from the direction of the wind and Ekman transport in the open ocean is typically about 70 degrees from the wind direction. In shallow coastal waters, Ekman transport may be very nearly the same direction as the wind.

GEOSTROPHIC CURRENTS Ekman transport deflects surface water to the right in the Northern Hemisphere, so a clockwise rotation develops within an ocean basin and produces a **Subtropical Convergence** of water in the middle of the gyre, causing water literally to pile up in the center of the subtropical gyre. Thus, there is a hill of water within all subtropical gyres that is as much as 2 meters (6.6 feet) high.

Surface water in a Subtropical Convergence tends to flow downhill in response to gravity. The Coriolis effect opposes gravity, however, deflecting the water to the right in a curved path (Figure 7.8a) into the hill again. When these two factors balance, the net effect is a **geostrophic** *(geo* = earth*, strophio* = turn*)* **current** that moves in a circular path around the hill and is shown in Figure 7.8a as the *path of ideal geostrophic flow*.[5] Friction between water molecules, however, causes the water to move gradually down the slope of the hill as it flows around it. This is the path of *actual geostrophic flow* labeled in Figure 7.8a.

If you reexamine the satellite image of sea surface elevation in Figure 7.2, you'll see that the hills of water within the subtropical gyres of the Atlantic Ocean are clearly visible. The hill in the North Pacific is visible as well, but the elevation of the equatorial Pacific is not as low as expected because the map shows conditions during a moderate El Niño event,[6] so there is a well-developed warm and anomalously high equatorial countercurrent. Figure 7.2 also shows very little distinction between the North and South Pacific gyres. Moreover, the South Pacific (Heyerdahl) Gyre hill is less pronounced than in other gyres, mostly because it covers such a large area; it lacks confinement by continental barriers along its western margin; and because of interference by numerous islands (really the tops of tall sea floor mountains). The South Indian Ocean hill is rather well developed in the figure, although its northeastern boundary stands high because of the influx of warm Pacific Ocean water through the East Indies islands.

WESTERN INTENSIFICATION OF SUBTROPICAL GYRES Figure 7.8a shows that the apex (top) of the hill formed within a rotating gyre is closer to the western boundary than the center of the gyre. As a result, the western boundary currents of the subtropical gyres are faster, narrower, and deeper than their eastern boundary current counterparts. For example, the Kuroshio Current (a western boundary current) of the North Pacific (Turtle) Gyre is up to 15 times faster, 20 times narrower, and five times as deep as the California Current (an eastern boundary current). This phenomenon is called **western intensification**, and

[4]The name Ekman *spiral* refers to the spiral observed by connecting the tips of the arrows shown in Figure 7.7.

[5]The term *geostrophic* for these currents is appropriate, since the currents behave as they do because of Earth's rotation.

[6]El Niño events are discussed later in this chapter, under "Pacific Ocean Circulation."

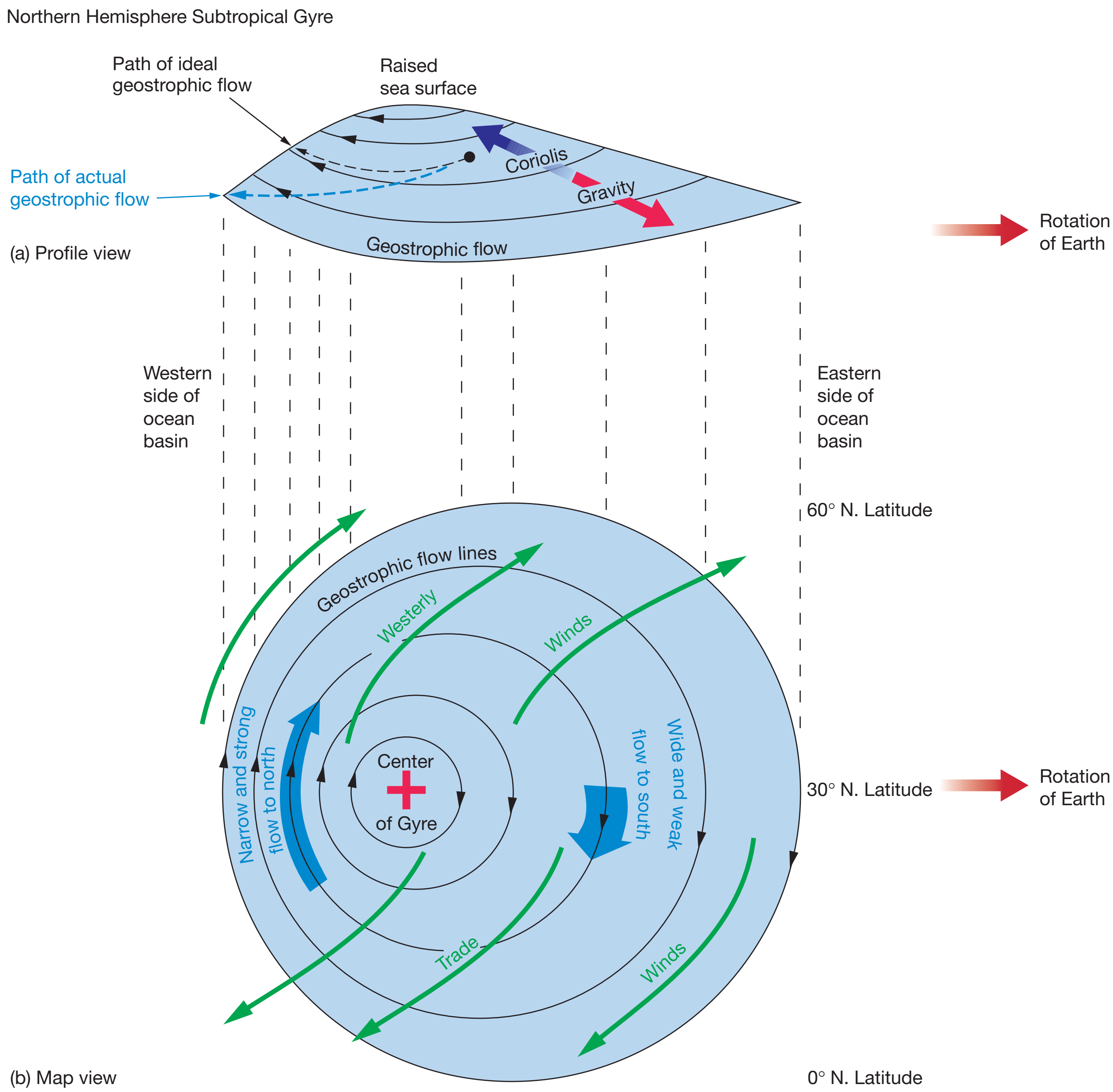


FIGURE 7.8 Geostrophic current and western intensification. **(a)** A cross-sectional view of a subtropical gyre showing how water literally piles up in the center, forming a hill up to 2 meters (6.6 feet) high. Gravity and the Coriolis effect balance to create an ideal geostrophic current that flows in equilibrium around the hill. However, friction makes the current gradually run downslope (*actual geostrophic flow*). **(b)** A map view of the same subtropical gyre, showing that the flow pattern is restricted (lines are closer together) on the western side of the gyre, resulting in western intensification.

currents affected by this phenomenon are said to be *western intensified*. Note that the western boundary currents of *all* subtropical gyres are western intensified, *even in the Southern Hemisphere*.

A number of factors cause western intensification, including the Coriolis effect. The Coriolis effect increases toward the poles, so eastward-flowing high-latitude water turns toward the equator more strongly than westward-flowing equatorial water turns toward higher latitudes. This causes a wide, slow, and shallow flow of water toward the equator across most of each subtropical gyre, leaving only a narrow band through which the poleward flow can occur along the western margin of the ocean basin. If a constant volume of water rotates around the apex of the hill in Figure 7.8b, then the velocity of the water along the western margin will be much greater than the velocity around the eastern side.[7] In Figure 7.8b, the lines are close

[7]A good analogy for this phenomenon is a funnel: In the narrow end of a funnel, the flow rates are speeded up (such as in western intensified currents) in the wide end, the flow rates are sluggish (such as in eastern boundary currents).

TABLE 7.2 CHARACTERISTICS OF WESTERN AND EASTERN BOUNDARY CURRENTS OF SUBTROPICAL GYRES

Current type	Examples	Width	Depth	Speed	Transport volume (millions of cubic meters per second[a])	Comments
Western boundary current	Gulf Stream, Brazil Current, Kuroshio Current	*Narrow:* usually less than 100 kilometers (60 miles)	*Deep:* to depths of 2 kilometers (1.2 miles)	*Fast:* hundreds of kilometers per day	*Large:* as much as 100 Sv[a]	Waters derived from low latitudes and are warm; little or no upwelling
Eastern boundary current	Canary Current, Benguela Current, California Current	*Wide:* up to 1000 kilometers (600 miles)	*Shallow:* to depths of 0.5 kilometer (0.3 mile)	*Slow:* tens of kilometers per day	*Small:* typically 10 to 15 Sv[a]	Waters derived from middle latitudes and are cool; coastal upwelling common

[a] One million cubic meters per second is a flow rate equal to one Sverdrup (Sv).

KEY CONCEPT

Western intensification is a result of Earth's rotation and causes the western boundary current of all subtropical gyres to be fast, narrow, and deep.

together along the western margin, indicating the faster flow. The end result is a high-speed western boundary current that flows along the hill's steeper westward slope and a slow drift of water toward the equator along the more gradual eastern slope. Table 7.2 summarizes the differences between western and eastern boundary currents of subtropical gyres.

Ocean Currents and Climate

Ocean surface currents directly influence the climate of adjoining landmasses. For instance, warm ocean currents warm the nearby air. This warm air can hold a large amount of water vapor, which puts more moisture (high humidity) in the atmosphere. When this warm, moist air travels over a continent, it releases its water vapor in the form of precipitation. Continental margins that have warm ocean currents offshore (Figure 7.9, *red arrows*) typically have a humid climate. The presence of a warm current off the East Coast of the United States helps explain why the area experiences such high humidity, especially in the summer.

Conversely, cold ocean currents cool the nearby air, which is more likely to have low water vapor content. When the cool, dry air travels over a continent, it results in very little precipitation. Continental margins that have cool ocean currents offshore (Figure 7.9, *blue arrows*) typically have a dry climate. The presence of a cold current off California is part of the reason why the climate is so arid there.

7.3 What Causes Upwelling and Downwelling?

Upwelling is the vertical movement of cold, deep, nutrient-rich water to the surface; **downwelling** is the vertical movement of surface water to deeper parts of the ocean. Upwelling hoists chilled water to the surface. This cold water, rich in

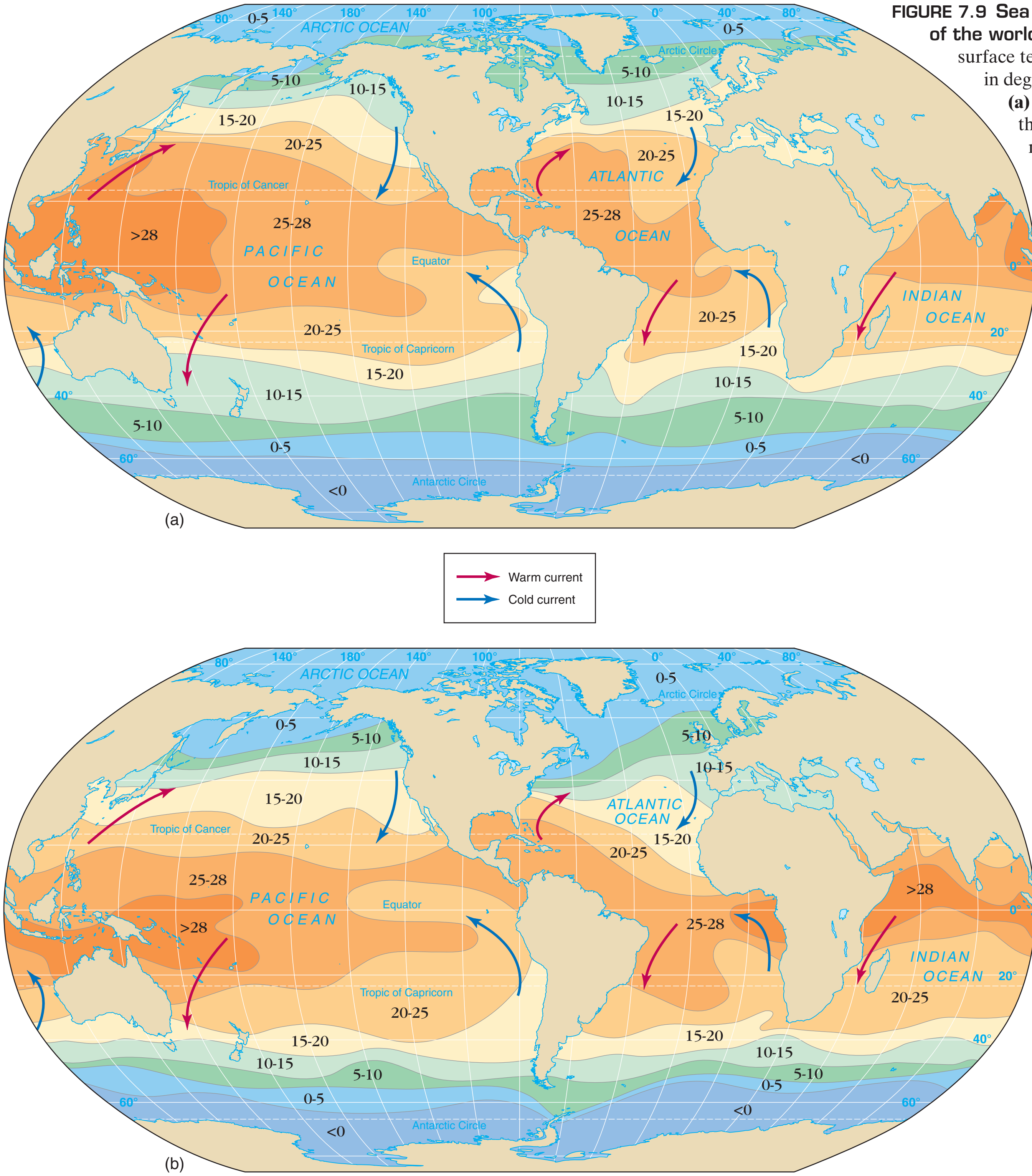


FIGURE 7.9 Sea surface temperature of the world ocean. Average sea surface temperature distribution in degrees centigrade for August **(a)** and for February **(b)**. Note that temperatures migrate north–south with the seasons. Red arrows indicate warm surface currents; blue arrows indicate cool surface currents.

nutrients, creates high **productivity** (an abundance of microscopic algae), which establishes the base of the food web and, in turn, supports incredible numbers of larger marine life like fish and whales. Downwelling, on the other hand, is associated with much lower amounts of surface productivity but carries necessary dissolved oxygen to those organisms living on the deep-sea floor.

Upwelling and downwelling provide important mixing mechanisms between surface and deep waters and are accomplished by a variety of methods.

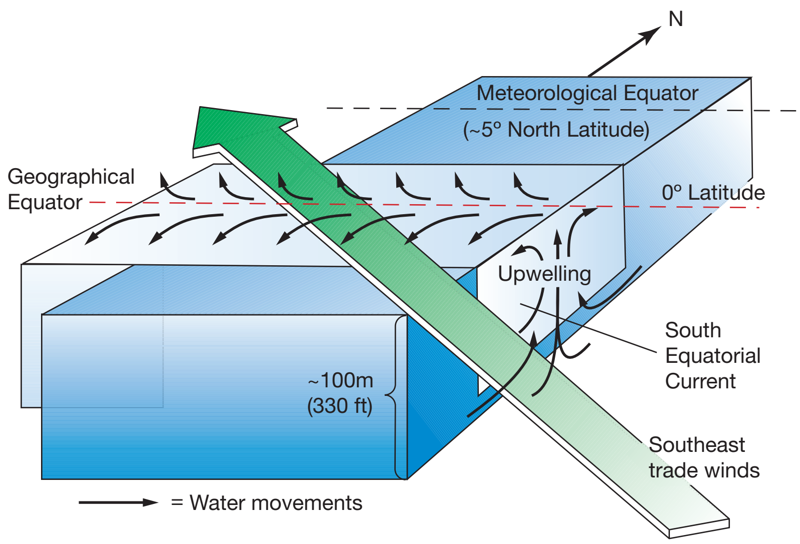


FIGURE 7.10 Equatorial upwelling. As the southeast trade winds pass over the geographical equator to the meteorological equator, they cause water within the South Equatorial Current north of the equator to veer to the right (northward) and water south of the equator to veer to the left (southward). Thus, surface water diverges, which causes equatorial upwelling.

Diverging Surface Water

Current divergence occurs when surface waters move *away from* an area on the ocean's surface, such as along the equator. As shown in Figure 7.10, the South Equatorial Current occupies the area along the *geographical equator* (most notably in the Pacific Ocean; see Figure 7.5), while the *meteorological equator* (where the doldrums exist) typically occurs a few degrees of latitude to the north. As the southeast trade winds blow across this region, Ekman transport causes surface water north of the equator to veer to the right (northward) and water south of the equator to veer to the left (southward). The net result is a divergence of surface currents along the geographical equator, which causes upwelling of cold, nutrient-rich water. Because this type of upwelling is common along the equator—especially in the Pacific—it is called **equatorial upwelling**, and it creates areas of high productivity that are some of the most prolific fishing grounds in the world.

Converging Surface Water

Current convergence occurs when surface waters move *toward* each other. In the North Atlantic Ocean, for instance, the Gulf Stream, the Labrador Current, and the East Greenland Current all come together in the same vicinity. When currents converge, water stacks up and has no place to go but downward. The surface water slowly sinks in a process called downwelling (Figure 7.11). Unlike upwelling, areas of downwelling are not associated with prolific marine life because the necessary nutrients are not continuously replenished from the cold, deep, nutrient-rich water below the surface. Consequently, downwelling areas have low productivity.

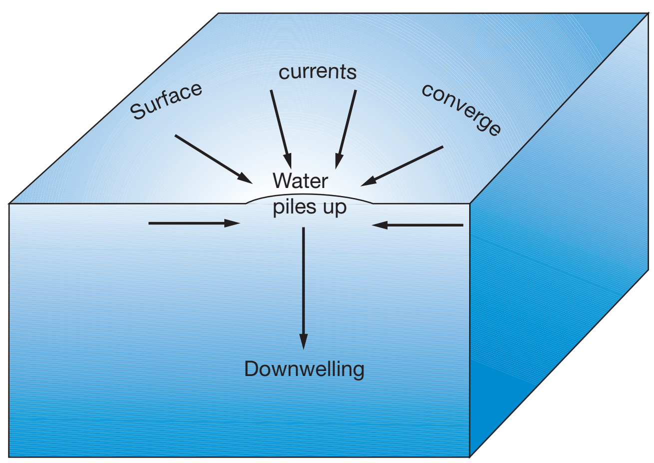


FIGURE 7.11 Downwelling caused by convergence of surface currents. Where surface currents converge, water piles up and slowly sinks downward, creating downwelling.

Coastal Upwelling and Downwelling

Coastal winds can cause upwelling or downwelling due to Ekman transport. Figure 7.12 shows a coastal region along the west coast of a continent in the Northern Hemisphere with winds moving parallel to the coast. If the winds are from the north (Figure 7.12a), Ekman transport moves the coastal water to the right of the wind direction, causing the water to flow *away from* the shoreline. Water rises from below to replace the water moving away from shore in a process called **coastal upwelling**. Areas where coastal upwelling occurs, such as the West Coast of the United States, are characterized by high concentrations of nutrients, resulting in high biological productivity and rich marine life. This coastal upwelling also creates low water temperatures in areas such as San Francisco, providing a natural form of air conditioning (and much cool weather and fog) in the summer.

If the winds are from the south, Figure 7.12b shows that Ekman transport still moves the coastal water to the right of the wind direction but, in this case, the water flows *toward* the shoreline. The water stacks up along the shoreline and has nowhere to go but down, in a process called **coastal downwelling**. Areas where coastal downwelling occurs have low productivity and a lack of marine life. If the winds reverse, areas that are typically associated with coastal downwelling can experience upwelling.

A similar situation exists for coastal winds and upwelling/downwelling in the Southern Hemisphere, except that Ekman transport is to the *left* of the wind direction.

Other Causes of Upwelling

Figure 7.13 shows how upwelling can be created by offshore winds, sea floor obstructions, or a sharp bend in a coastline. Upwelling also occurs in high-latitude regions, where there is no pycnocline (a layer of rapidly changing density). The

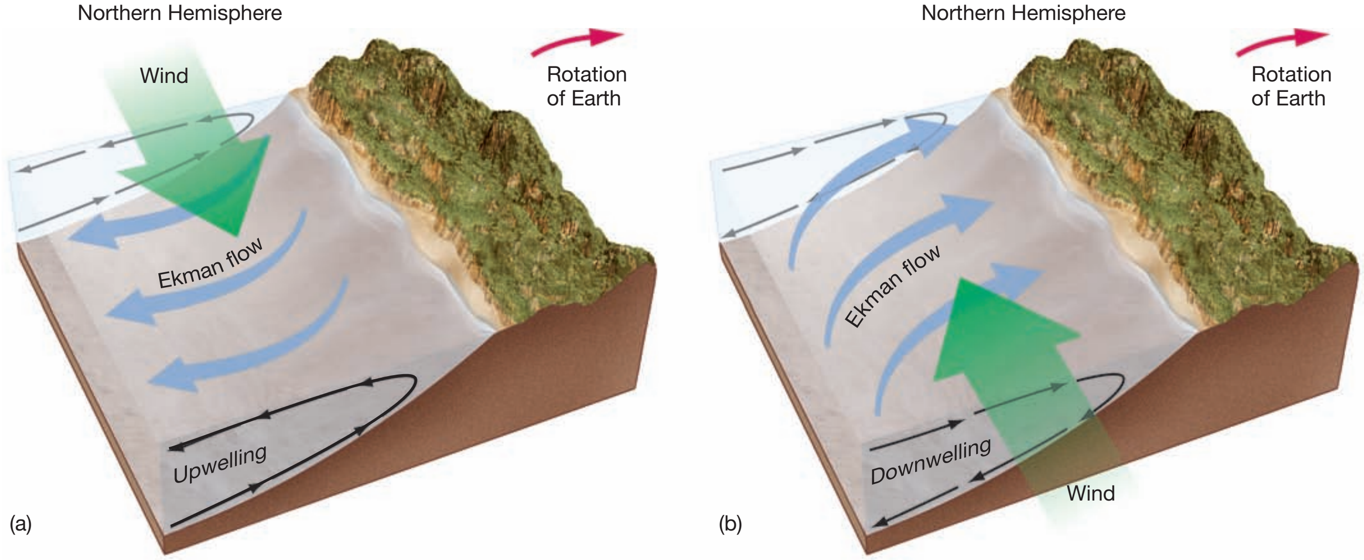


FIGURE 7.12 Coastal upwelling and downwelling. **(a)** Where northerly coastal winds blow parallel to a west coast in the Northern Hemisphere, Ekman transport carries surface water to the *right* of the wind direction and away from a continent. Upwelling of deeper water replaces the surface water that has moved away from the coast. **(b)** A reversal of the wind direction still causes Ekman transport to the right but results in water piling up against the shore, producing downwelling. A similar situation exists for coastal winds and upwelling/downwelling in the Southern Hemisphere, except that Ekman transport is to the *left* of the wind direction.

KEY CONCEPT

Upwelling and downwelling cause vertical mixing between surface and deep water. Upwelling brings cold, deep, nutrient-rich water to the surface, which results in high productivity.

absence of a pycnocline allows significant vertical mixing between high-density cold surface water and high-density cold deep water below. Thus, both upwelling and downwelling are common in high latitudes.

7.4 What Are the Main Surface Circulation Patterns in Each Ocean?

The pattern of surface currents varies from ocean to ocean depending upon the geometry of the ocean basin, the pattern of major wind belts, seasonal factors, and other periodic changes.

Antarctic Circulation

Antarctic circulation is dominated by the movement of water masses in the southern Atlantic, Indian, and Pacific Oceans south of about 50 degrees south latitude.

ANTARCTIC CIRCUMPOLAR CURRENT The main current in Antarctic waters is the **Antarctic Circumpolar Current**, which is also called the **West Wind Drift** or the *Penguin Gyre*. This current encircles

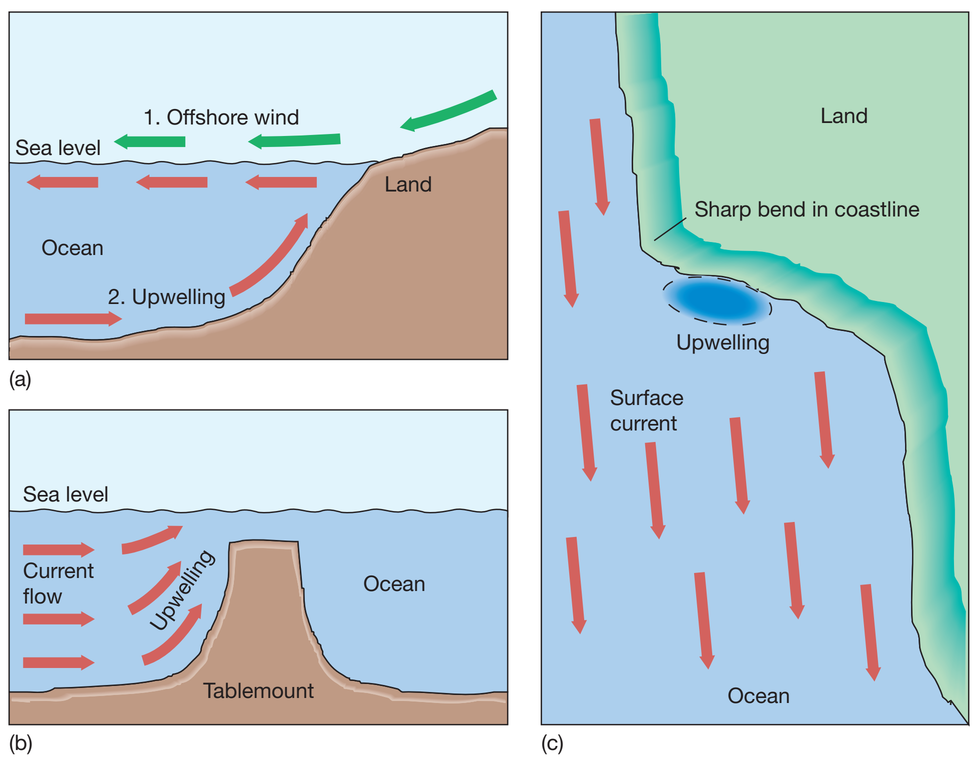


FIGURE 7.13 Other types of upwelling. Upwelling can be caused by **(a)** offshore winds; **(b)** a sea floor obstruction, in this case, a tablemount; **(c)** a sharp bend in coastal geometry.

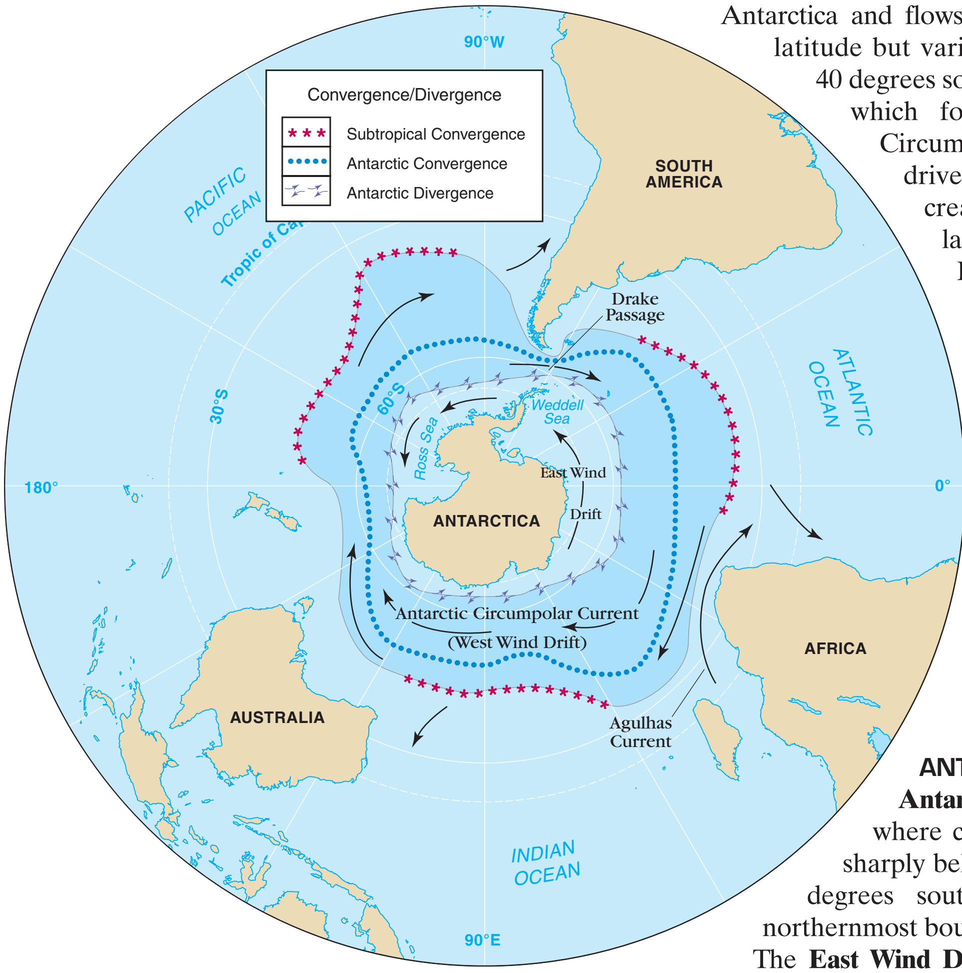


FIGURE 7.14 South polar view of Earth showing Antarctic surface circulation. The East Wind Drift is driven by the polar easterlies and flows around Antarctica from the east. The Antarctic Circumpolar Current (West Wind Drift) flows around Antarctica from the west but is further from the continent and is a result of the strong prevailing westerlies. The Antarctic Convergence and Antarctic Divergence are caused by interactions at the boundaries of these two currents.

Antarctica and flows from west to east at approximately 50 degrees south latitude but varies between 40 and 65 degrees south latitude. At about 40 degrees south latitude is the *Subtropical Convergence* (Figure 7.14), which forms the northernmost boundary of the Antarctic Circumpolar Current. The Antarctic Circumpolar Current is driven by the powerful prevailing westerly wind belt, which creates winds so strong that these Southern Hemisphere latitudes have been called the "Roaring Forties," "Furious Fifties," and "Screaming Sixties."

The Antarctic Circumpolar Current is the only current that completely circumscribes Earth and is allowed to do so because of the lack of land at high southern latitudes. It meets its greatest restriction as it passes through the *Drake Passage* [named for the famed English sea captain and ocean explorer Sir Francis Drake (1540–1596)] between the Antarctic Peninsula and the southern islands of South America, which is about 1000 kilometers (600 miles) wide. Although the current is not speedy [its maximum surface velocity is about 2.75 kilometers (1.65 miles) per hour], it transports more water (an average of about 130 million cubic meters per second[8]) than any other surface current.

ANTARCTIC CONVERGENCE AND DIVERGENCE The **Antarctic Convergence** (Figure 7.14) or *Antarctic Polar Front* is where colder, denser, Antarctic waters converge with (and sink sharply below) warmer, less dense sub-Antarctic waters at about 50 degrees south latitude. The Antarctic Convergence marks the northernmost boundary of the Southern or Antarctic Ocean.

The **East Wind Drift**, a surface current propelled by the polar easterlies, moves from an easterly direction around the margin of the Antarctic continent. The East Wind Drift is most extensively developed to the east of the Antarctic Peninsula in the Weddell Sea region and in the area of the Ross Sea (Figure 7.14). As the East Wind Drift and the Antarctic Circumpolar Current flow around Antarctica in opposite directions, they create a surface divergence. Recall that the Coriolis effect deflects moving masses to the left in the Southern Hemisphere, so the East Wind Drift is deflected toward the continent and the Antarctic Circumpolar Current is deflected away from it. This creates a divergence of currents along a boundary called the **Antarctic Divergence**. The Antarctic Divergence has abundant marine life in the Southern Hemisphere summer because of the mixing of these two currents, which supplies nutrient-rich water to the surface through upwelling.

Atlantic Ocean Circulation

Figure 7.15 shows Atlantic Ocean surface circulation, which consists of two large subtropical gyres: the North Atlantic (Columbus) Gyre and the South Atlantic (Navigator) Gyre.

THE NORTH AND SOUTH ATLANTIC SUBTROPICAL GYRES The **North Atlantic Subtropical Gyre** (Columbus Gyre) rotates clockwise and the **South Atlantic Subtropical Gyre** (Navigator Gyre) rotates counterclockwise, due to the combined

[8]One million cubic meters per second is a useful flow rate for describing ocean currents, so it has become a standard unit, named the **Sverdrup (Sv)**, after Norwegian meteorologist and physical oceanographer Harald Sverdrup (1888–1957).

effects of the trade winds, the prevailing westerlies, and the Coriolis effect. Figure 7.15 shows that each gyre consists of a poleward-moving warm current (*red*) and an equatorward-moving cold "return" current (*blue*). The two gyres are partially offset by the shapes of the surrounding continents, and the **Atlantic Equatorial Countercurrent** moves in between them.

In the South Atlantic (Navigator) Gyre, the **South Equatorial Current** reaches its greatest strength just below the equator, where it encounters the coast of Brazil and splits in two. Part of the South Equatorial Current moves off along the northeastern coast of South America toward the Caribbean Sea and the North Atlantic. The rest is turned southward as the **Brazil Current**, which ultimately merges with the Antarctic Circumpolar Current (West Wind Drift) and moves eastward across the South Atlantic. The Brazil Current is much smaller than its Northern Hemisphere counterpart, the Gulf Stream, due to the splitting of the South Equatorial Current. The **Benguela Current**, slow moving and cold, flows toward the equator along Africa's western coast, completing the gyre.

Outside the gyre, the *Falkland Current* (Figure 7.15), which is also called the *Malvinas Current*, moves a significant amount of cold water along the coast of Argentina as far north as 25 to 30 degrees south latitude, wedging its way between the continent and the southbound Brazil Current.

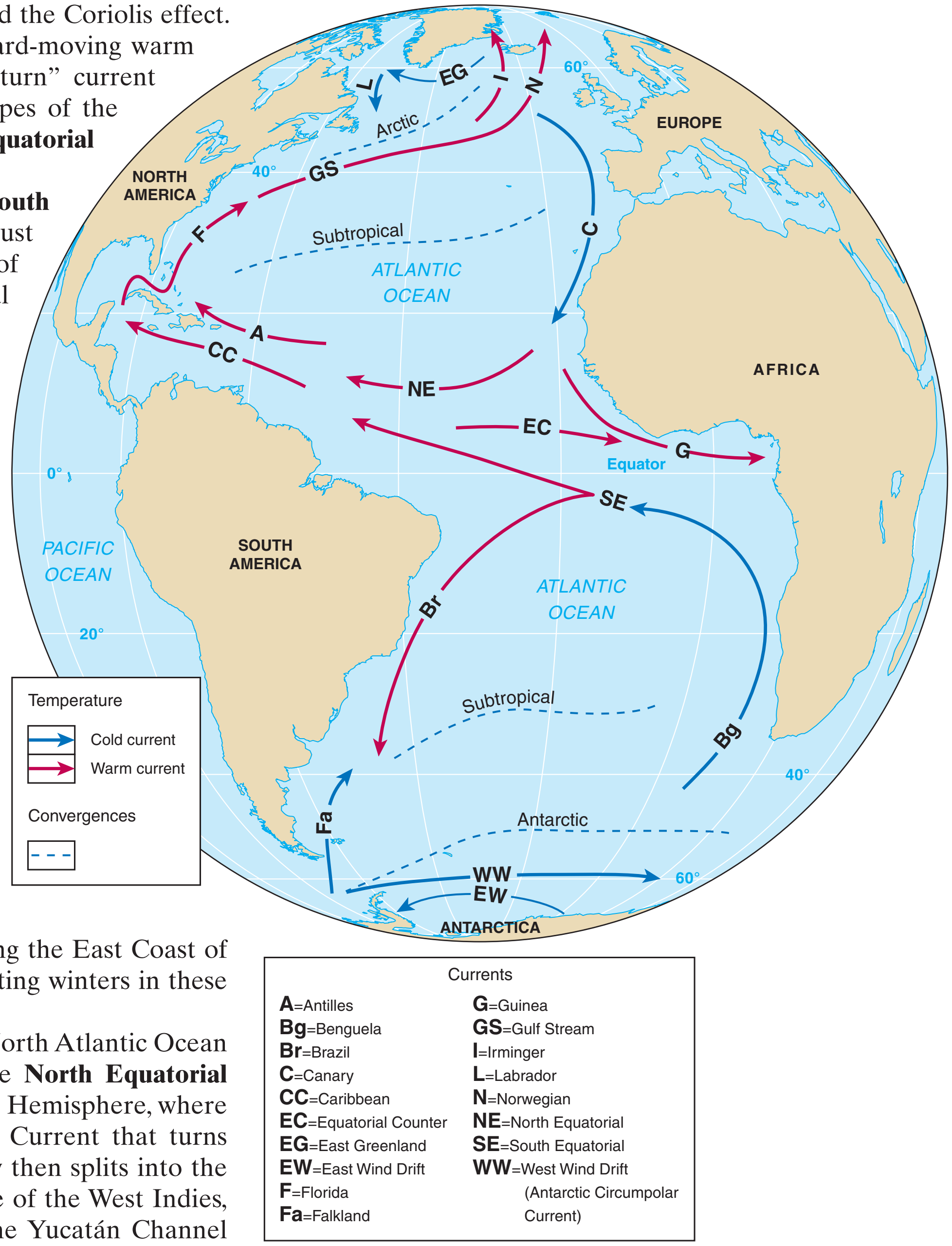


FIGURE 7.15 Atlantic Ocean surface currents. Atlantic Ocean surface circulation is composed primarily of two subtropical gyres.

THE GULF STREAM The **Gulf Stream** is the best studied of all ocean currents. It moves northward along the East Coast of the United States, warming coastal states and moderating winters in these and northern European regions.

Figure 7.16 shows the network of currents in the North Atlantic Ocean that contribute to the flow of the Gulf Stream. The **North Equatorial Current** moves parallel to the equator in the Northern Hemisphere, where it is joined by the portion of the South Equatorial Current that turns northward along the South American coast. This flow then splits into the **Antilles Current**, which passes along the Atlantic side of the West Indies, and the **Caribbean Current**, which passes through the Yucatán Channel into the Gulf of Mexico. These masses reconverge as the **Florida Current**.

The Florida Current flows close to shore over the continental shelf at a rate that at times exceeds 35 Sverdrups. As it moves off North Carolina's Cape Hatteras and flows across the deep ocean in a northeasterly direction, it is called the Gulf Stream. The Gulf Stream is a western boundary current, so it is subject to western intensification. Thus, it is only 50 to 75 kilometers (31 to 47 miles) wide, but it reaches depths of 1.5 kilometers (1 mile) and speeds from 3 to 10 kilometers (2 to 6 miles) per hour, making it the fastest current in the world ocean.

The western boundary of the Gulf Stream is usually abrupt, but it periodically migrates closer to and farther away from the shore. Its eastern boundary is very difficult to identify because it is usually masked by meandering water masses that change their position continuously.

The Sargasso Sea The Gulf Stream gradually merges eastward with the water of the **Sargasso Sea**. The Sargasso Sea is the water that circulates around the rotation center of the North Atlantic gyre. The Sargasso Sea can be thought of as the stagnant eddy of the North Atlantic (Columbus) Gyre. Its name is derived

7.2 HISTORICAL FEATURE

BENJAMIN FRANKLIN: THE WORLD'S MOST FAMOUS PHYSICAL OCEANOGRAPHER

Benjamin Franklin (Figure 7B, *inset*) is well known as a scientist, inventor, economist, statesman, diplomat, writer, poet, international celebrity, and one of the founding fathers of the United States. He even held the position of deputy postmaster general of the colonies from 1753 to 1774. Remarkably, he also became known as one of the first physical oceanographers because he contributed greatly to the understanding of the Gulf Stream, a North Atlantic Ocean surface current. Why would a postmaster general be interested in an ocean current?

Franklin became interested in North Atlantic Ocean circulation patterns because he needed to explain why mail ships coming from Europe to New England took about two weeks less time when they took a longer, more southerly route than when they took a more direct, northerly route. In about 1769 or 1770, Franklin mentioned this dilemma to his cousin, a Nantucket sea captain named Timothy Folger. Folger told Franklin that a strong current with which the mail ships were unfamiliar was impeding their journey because it flowed against them. The whaling ships were familiar with the current because they often hunted whales along its boundaries. The whalers often met the mail ships within the current and told their crews they would make swifter progress if they avoided the current. The British captains of the mail ships, however, would not accept advice from simple American fishers, so they continued to make slow progress within the current. If the winds were light, their ships were actually carried *backward*!

Folger sketched the current on a map for Franklin, including directions for avoiding it by taking a more southerly route when sailing from Europe to North America. Franklin then asked other ship captains for information concerning the movement of surface waters in the North Atlantic Ocean. Franklin inferred that there was a significant current moving northward along the eastern coast of the United States, which then headed east across the North Atlantic. He concluded that this current was responsible for aiding the progress of ships traveling through the North Atlantic to Europe and slowing ships traveling in the reverse direction. He subsequently measured the temperature of the current himself and first published a map of the current in 1777 based on these observations and distributed it to the captains of the mail ships (who initially ignored it). This strong current is named the *Gulf Stream* because it carries warm water from the Gulf of Mexico and because it is narrow and well defined—similar to a stream, but in the ocean.

In 1969, six scientists studied the Gulf Stream aboard a submersible vessel that was allowed to float for a month underwater wherever the current took her. During the vessel's 2640-kilometer (1650-mile) journey, the scientists observed and measured the properties of and cataloged life forms within the Gulf Stream. Appropriately enough, the vessel was named the *Ben Franklin*.

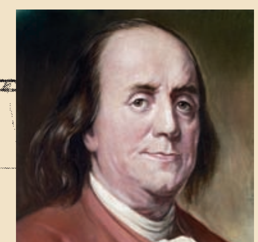


FIGURE 7B **A chart of the Gulf Stream (1786) based on sketches by Ben Franklin (*inset*).**

from a type of floating marine alga called *Sargassum* (*sargassum* = grapes) that abounds on its surface.

The transport rate of the Gulf Stream off Chesapeake Bay is about 100 Sverdrups,[9] which suggests that a large volume of water from the Sargasso Sea has combined with the Florida Current to produce the Gulf Stream. By the time

[9]The Gulf Stream's flow of 100 Sverdrups equates to a volume of about 100 major league sport stadiums passing by the southeast U.S. coast *each second* and is more than 100 times greater than the combined flow of *all* the world's rivers!

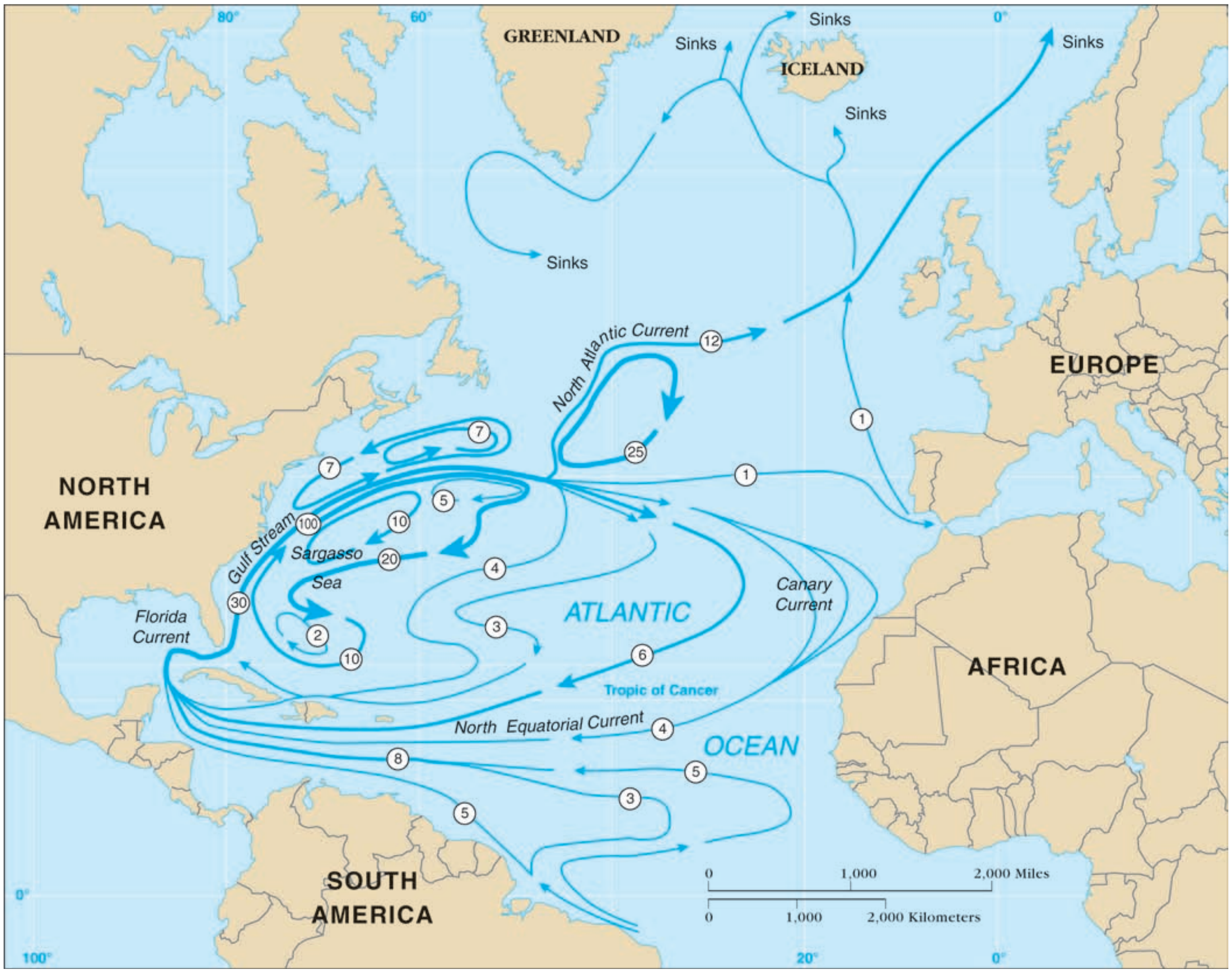


FIGURE 7.16 North Atlantic Ocean circulation. The North Atlantic (Columbus) Gyre, showing average flow rates in *Sverdrups* (1 Sverdrup = 1 million cubic meters per second). The four major currents include the western intensified Gulf Stream, the North Atlantic Current, the Canary Current, and the North Equatorial Current. Some water splits off in the North Atlantic, where it becomes cold and dense, so it sinks. The Sargasso Sea occupies the stagnant eddy in the middle of the subtropical gyre.

the Gulf Stream nears Newfoundland, however, the transport rate is only 40 Sverdrups, which suggests that a large volume of water has returned to the diffuse flow of the Sargasso Sea.

Warm- and Cold-Core Rings The mechanisms that produce the dramatic loss of water as the Gulf Stream moves northward are yet to be determined. Meanders, however, may cause much of it. *Meanders* (*Menderes* = a river in Turkey that has a very sinuous course) are snakelike bends in the current that often disconnect from the Gulf Stream and form large rotating masses of water called *vortexes* (*vortexes* = to turn), which are more commonly known as *eddies* or *rings*. Figure 7.17 shows several of these rings, which are noticeable near the center of each image. The figure also shows that meanders along the north boundary of the Gulf Stream pinch off and trap warm Sargasso Sea water in eddies that rotate clockwise, creating **warm-core rings** (*yellow*) surrounded by cooler (*blue and green*) water. These warm rings contain shallow, bowl-shaped masses of warm water about 1 kilometer (0.6 mile) deep, with diameters of about

STUDENTS SOMETIMES ASK . . .

Is the Gulf Stream rich in life?

The Gulf Stream *itself* isn't rich in life, but its *boundaries* often are. The oceanic areas that have abundant marine life are typically associated with cool water—either in high-latitude regions, or in any region where upwelling occurs. These areas are constantly resupplied with oxygen- and nutrient-rich water, which results in high productivity. Warm-water areas develop a prominent thermocline that isolates the surface water from colder, nutrient-rich water below. Nutrients used up in warm waters tend not to be resupplied. The Gulf Stream, which is a western intensified, warm-water current, is therefore associated with low productivity and an absence of marine life. New England fishers knew about the Gulf Stream (Box 7.2) because they sought their catch along the *sides* of the current, where mixing and upwelling occur.

Actually, all western intensified currents are warm and are associated with low productivities. The Kuroshio Current in the North Pacific Ocean, for example, is named for its conspicuous absence of marine life. In Japanese, *Kuroshio* means "black current," in reference to its clear, lifeless waters.

100 kilometers (60 miles). Warm-core rings remove large volumes of water as they disconnect from the Gulf Stream.

Cold nearshore water spins off to the south of the Gulf Stream as counterclockwise-rotating **cold-core rings** (*green*) surrounded by warmer (*yellow* and *red-orange*) water (Figure 7.17). The cold rings consist of spinning cone-shaped masses of cold water that extend over 3.5 kilometers (2.2 miles) deep. These rings may exceed 500 kilometers (310 miles) in diameter at the surface. The diameter of the cone increases with depth and sometimes reaches all the way to the sea floor, where cones have a tremendous impact on sea floor sediment. Cold rings move southwest at speeds of 3 to 7 kilometers (2 to 4 miles) per day toward Cape Hatteras, where they often rejoin the Gulf Stream.

Both warm- and cold-core rings maintain not only unique temperature characteristics, but also unique biological populations. Studies of rings have found they are isolated habitats for either warm-water organisms in a cold ocean or, conversely, cold-water organisms in a warmer ocean. The organisms can survive as long as the ring does; in some cases, rings have been documented to last as long as two years. In addition, cold-core rings are typically associated with high nutrient levels and an abundance of marine life while warm-core rings are zones of downwelling that lack nutrients and are deficient in marine life.

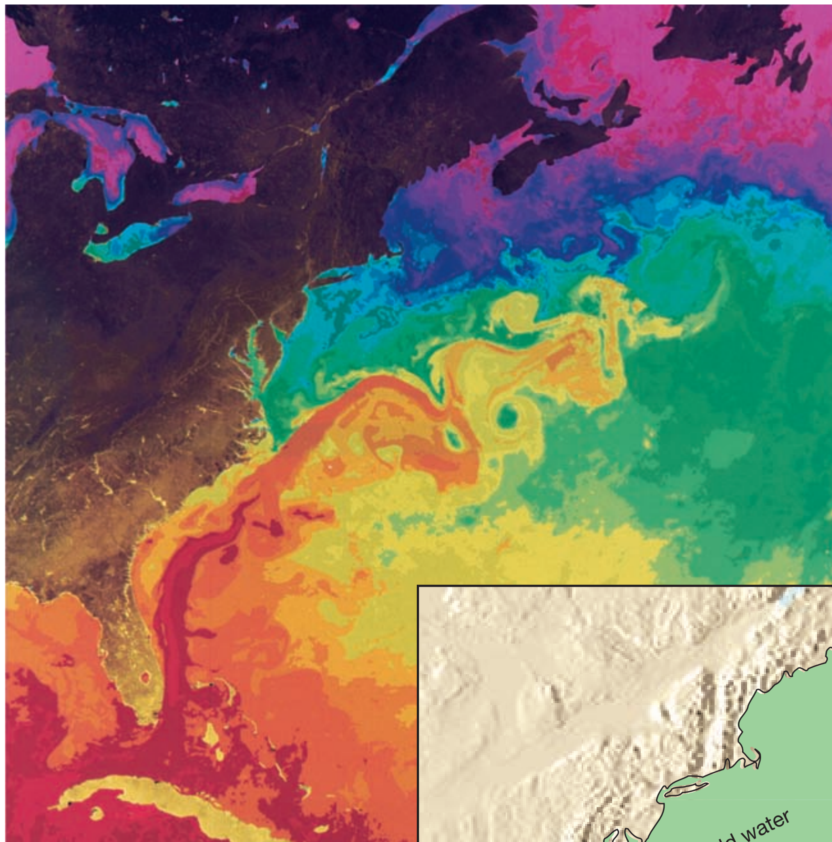
OTHER NORTH ATLANTIC CURRENTS Southeast of Newfoundland, the Gulf Stream continues in an easterly direction across the North Atlantic (Figure 7.16). Here the Gulf Stream breaks into numerous branches, many of which become cold and dense enough to sink beneath the surface. As shown in Figure 7.15, one major branch combines the cold water of the **Labrador Current** with the warm Gulf Stream, producing abundant fog in the North Atlantic. This branch eventually breaks into the **Irminger Current**, which flows along Iceland's west coast, and the **Norwegian Current**, which moves northward along Norway's coast. The other major branch crosses the North Atlantic as the **North Atlantic Current** (also called the *North Atlantic Drift*, emphasizing its sluggish nature), which turns southward to become the cool **Canary Current**. The Canary Current is a broad, diffuse southward flow that eventually joins the North Equatorial Current, thus completing the gyre.

CLIMATIC EFFECTS OF NORTH ATLANTIC CURRENTS The warming effects of the Gulf Stream are far ranging. The Gulf Stream not only moderates temperatures along the East Coast of the United States but also in northern Europe (in conjunction with heat transferred by the atmosphere). Thus, the temperatures across the Atlantic at different latitudes are much higher in Europe than in North America because of the effects of heat transfer from the Gulf Stream to Europe. For example, Spain and Portugal have warm climates, even though they are at the same latitude as the New England states, which are known for severe winters. The warming that northern Europe experiences because of the Gulf Stream is as much as 9°C (20°F), which is enough to keep high-latitude Baltic ports ice free throughout the year.

The warming effects of western boundary currents in the North Atlantic Ocean can be seen on the average sea surface temperature map for February shown in Figure 7.9b. Off the east coast of North America from latitudes 20 degrees north (the latitude of Cuba) to 40 degrees north (the latitude of Philadelphia), for example, there is a 20°C (36°F) difference in sea surface temperatures. On the eastern side of the North Atlantic, on the other hand, there is only a 5°C (9°F) difference in temperature between the same latitudes, indicating the moderating effect of the Gulf Stream.

The average sea surface temperature map for August (see Figure 7.9a) also shows how the North Atlantic and Norwegian Currents (branches of the Gulf Stream) warm northwestern Europe compared with the same latitudes along the

North American coast. On the western side of the North Atlantic, the southward-flowing Labrador Current—which is cold and often contains icebergs from western Greenland—keeps Canadian coastal waters much cooler. During the Northern Hemisphere winter (Figure 7.9b), North Africa's coastal waters are cooled by the southward-flowing Canary Current and are much cooler than waters near Florida and the Gulf of Mexico.



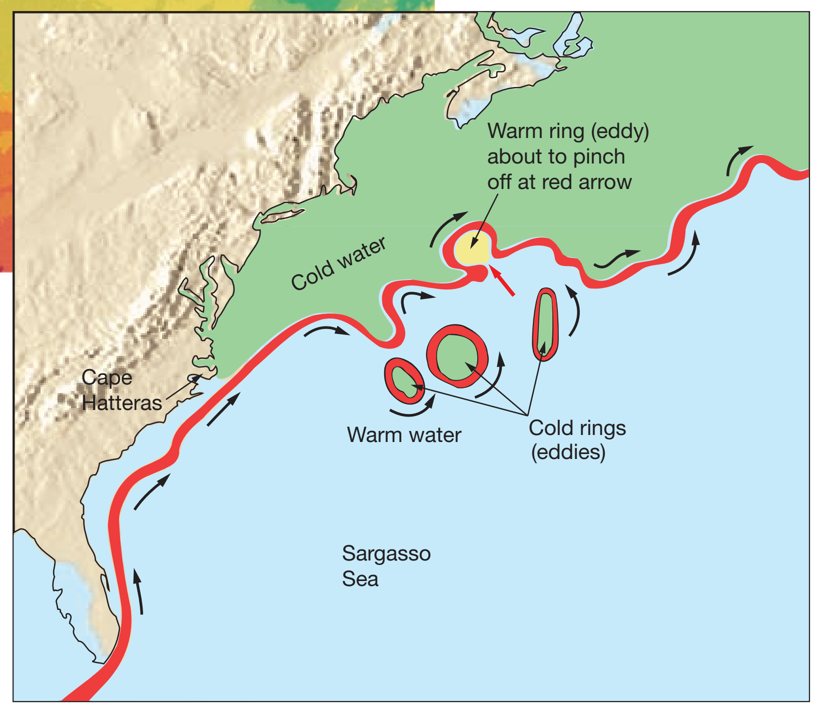


FIGURE 7.17 The Gulf Stream and sea surface temperatures. A NOAA satellite false-color image of sea surface temperature (*upper*) and a schematic diagram of the same area (*lower*). The warm waters of the Gulf stream are shown in red and orange; colder waters are shown in green, blue, and purple. As the Gulf stream meanders northward, some of its meanders pinch off and form either warm-core or cold-core rings.

Indian Ocean Circulation

Because of the shape and position of India, the Indian Ocean exists mostly in the Southern Hemisphere. From November to March, equatorial circulation in the Indian Ocean is similar to that in the Atlantic Ocean, with two westward-flowing equatorial currents (North and South Equatorial Currents) separated by an eastward-flowing Equatorial Countercurrent. As compared to circulation in the Atlantic, however, the Equatorial Countercurrent in the Indian Ocean lies in a more southerly position because most of the Indian Ocean lies in the Southern Hemisphere. The shape of the Indian Ocean basin and its proximity to the high mountains of Asia cause it to experience strong seasonal changes.

MONSOONS The winds of the northern Indian Ocean have a seasonal pattern called **monsoon** (*mausim* = season) winds. During winter, air over the Asian mainland rapidly cools, creating high atmospheric pressure, which causes the wind to blow from southwest Asia off the continent and out over the ocean (Figure 7.18a, *green arrows*). These northeast trade winds are called the *northeast monsoon*. During this season, there is little precipitation because the air associated with the high pressure over land is so dry.

During summer, the winds reverse. Because of the lower heat capacity of rocks and soil compared with water, the Asian mainland warms faster than the adjacent ocean, creating low atmospheric pressure over the continent. As a result, the winds blow strongly from the Indian Ocean onto the Asian landmass (Figure 7.18b, *green arrows*), giving rise to the *southwest monsoon*, which may be thought of as a continuation of the southeast trade winds across the equator. During this season, there is heavy precipitation on land because the air brought in from the Indian Ocean is warm and full of moisture.

Not only does this seasonal cycle affect weather patterns on land, it also affects surface current circulation in the Indian Ocean. In fact, the northern Indian Ocean is the only place in the world where reversing seasonal winds

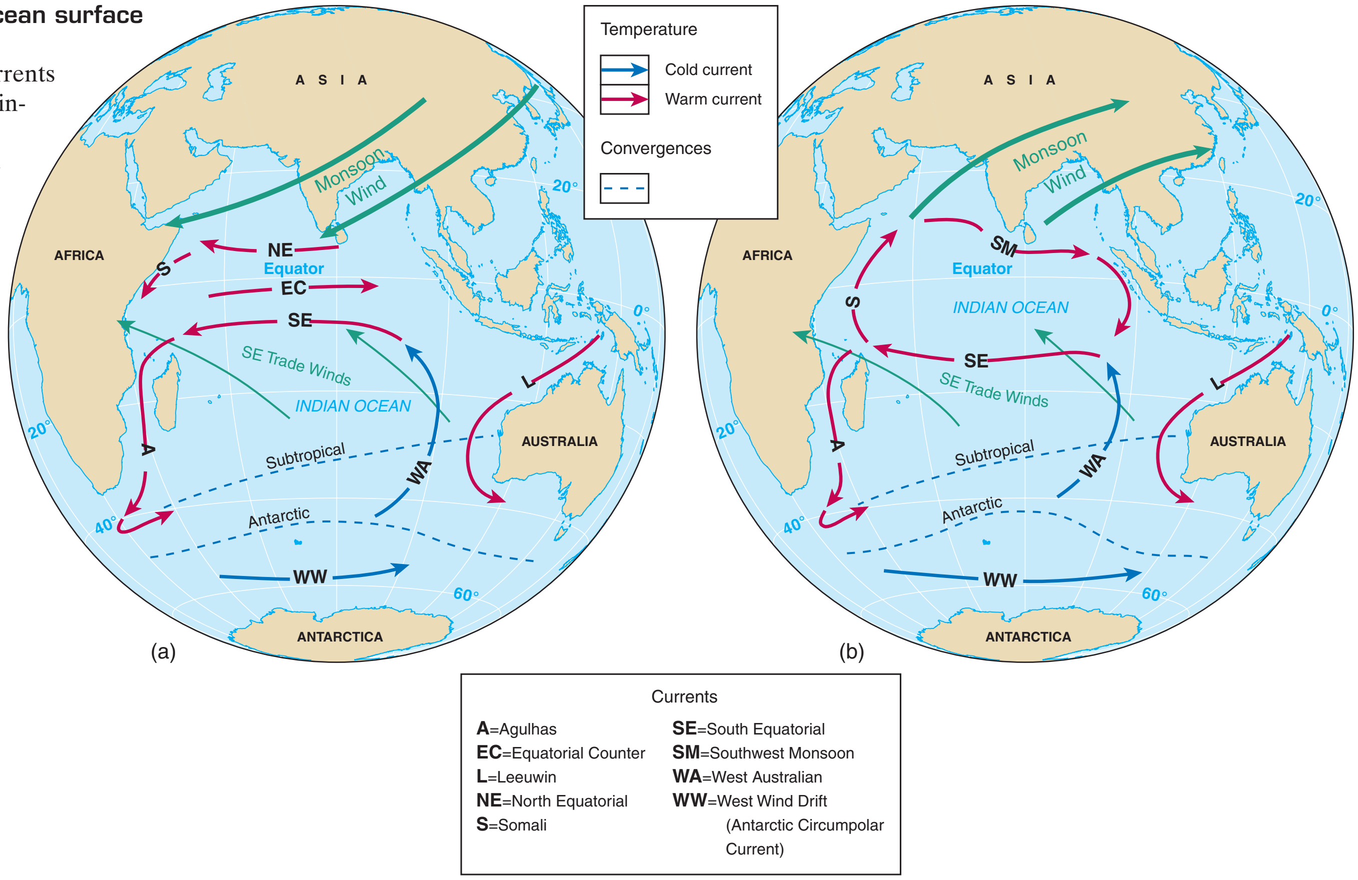


FIGURE 7.18 Indian Ocean surface currents and the monsoons. Surface currents in the Indian Ocean are influenced by the seasonal monsoons. **(a)** Northeast monsoon, which occurs during winter. **(b)** Southwest monsoon, which occurs during summer.

actually cause major ocean surface currents to switch direction. During the wintertime northwest monsoon (Figure 7.18a), offshore winds cause the North Equatorial Current to flow from east to west and its extension, the **Somali Current**, flows south along the coast of Africa. An *Equatorial Countercurrent* is also established. During the summertime southwest monsoon (Figure 7.18b), the winds reverse, causing the North Equatorial Current to be replaced by the *Southwest Monsoon Current*, which flows in the opposite direction. The winds cause the Somali Current to reverse as well, which flows rapidly northward with velocities approaching 4 kilometers (2.5 miles) per hour and feeds the Southwest Monsoon Current. By October, the northeast trade winds are reestablished and the North Equatorial Current reappears (Figure 7.18a).

The movement of winds during the summertime southwest monsoon also affects sea surface temperatures, which cool near the Arabian Peninsula because of upwelling as water is drawn away from shore. This cool water also supports large populations of phytoplankton during the summer southwest monsoon (Figure 7.19). Studies of productivity in the Indian Ocean show that upwelling has increased in recent years due to stronger winds caused by warming of the Eurasian landmass, resulting in higher than normal summer productivity in the Arabian Sea.

INDIAN OCEAN SUBTROPICAL GYRE Surface circulation in the southern Indian Ocean (the **Indian Ocean Subtropical Gyre**, or *Majid Gyre*) is similar to subtropical gyres observed in other southern oceans. When the northeast trade winds blow, the South Equatorial Current provides water for the Equatorial Countercurrent and the **Agulhas Current**,[10] which flows southward along Africa's east coast and joins the Antarctic Circumpolar Current (West Wind Drift). The *Agulhas Retroflection* is

[10]The Agulhas Current is named for Cape Agulhas, which is the southernmost tip of Africa.

created when the Agulhas Current makes an abrupt turn as it meets the strong Antarctic Circumpolar Current (see the chapter-opening satellite image). Turning northward out of the Antarctic Circumpolar Current is the **West Australian Current**, an eastern boundary current that merges with the South Equatorial Current, completing the gyre.

LEEUWIN CURRENT Eastern boundary currents in other subtropical gyres are cold drifts toward the equator that produce arid coastal climates [that is, they receive less than 25 centimeters (10 inches) of rain per year]. In the southern Indian Ocean, however, the **Leeuwin Current** displaces the West Australian Current offshore. The Leeuwin Current is driven southward along the Australian coast from the warm-water dome piled up in the East Indies by the Pacific equatorial currents.

The Leeuwin Current produces a mild climate in southwestern Australia, which receives about 125 centimeters (50 inches) of rain per year. During El Niño events, however, the Leeuwin Current weakens, so the cold Western Australian Current brings drought instead.

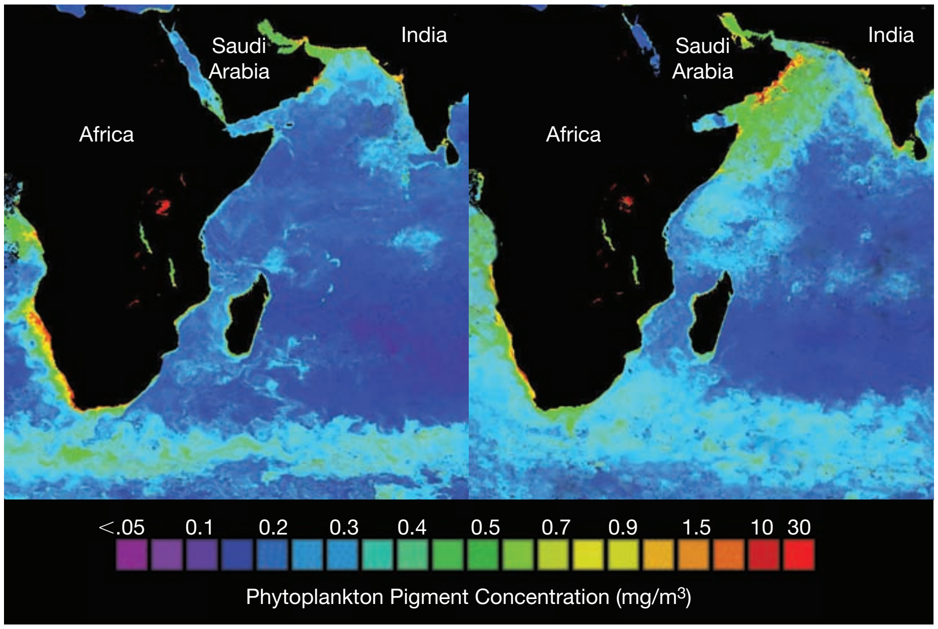


FIGURE 7.19 Seasonal variations in phytoplankton concentration in the Indian Ocean. Paired satellite images showing oceanic phytoplankton pigment, where orange and red colors indicate higher amounts phytoplankton and thus higher biological productivity. **(a)** During the northeast (winter) monsoon, lack of upwelling conditions result in low concentrations of phytoplankton along the coast of Saudi Arabia. **(b)** During the southwest (summer) monsoon, strong winds generate upwelling of nutrient-rich waters, leading to an increase in the concentration of phytoplankton along the coast of Saudi Arabia.

Pacific Ocean Circulation

Two large subtropical gyres dominate the circulation pattern in the Pacific Ocean, resulting in surface water movement and climatic effects similar to those found in the Atlantic. However, the Equatorial Countercurrent is much better developed in the Pacific Ocean than in the Atlantic (Figure 7.20), largely because the Pacific Ocean basin is larger and more unobstructed than the Atlantic Ocean.

NORMAL CONDITIONS "Normal" conditions in the Pacific Ocean are a bit of a misnomer because they are experienced so infrequently. As we'll see, various atmospheric and oceanic disturbances dominate conditions in the Pacific. Still, "normal" conditions provide a baseline from which to measure these disturbances.

North Pacific Subtropical Gyre Figure 7.20 shows that the **North Pacific Subtropical Gyre** (*Turtle Gyre*) includes the North Equatorial Current, which flows westward into the western intensified **Kuroshio Current**[11] near Asia. The warm waters of the Kuroshio Current make Japan's climate warmer than would be expected for its latitude. This current flows into the **North Pacific Current**, which connects to the cool-water **California Current**. The California Current flows south along the coast of California to complete the loop. Some North Pacific Current water also flows to the north and merges into the **Alaskan Current** in the Gulf of Alaska.

South Pacific Subtropical Gyre Figure 7.20 also shows how the **South Pacific Subtropical Gyre** (*Heyerdahl Gyre*) includes the South Equatorial Current, which flows westward into the western intensified **East Australian Current**.[12] From there, it joins the Antarctic Circumpolar Current (West Wind Drift) and

[11]Kuroshio is pronounced "kuhr-ROH-shee-oh." Because of its proximity to Japan, the Kuroshio Current is also called the *Japan Current*.

[12]Note that the western intensified East Australian Current was named because it lies off the *east coast* of Australia, even though it occupies a position along the *western* margin of the Pacific Ocean basin.

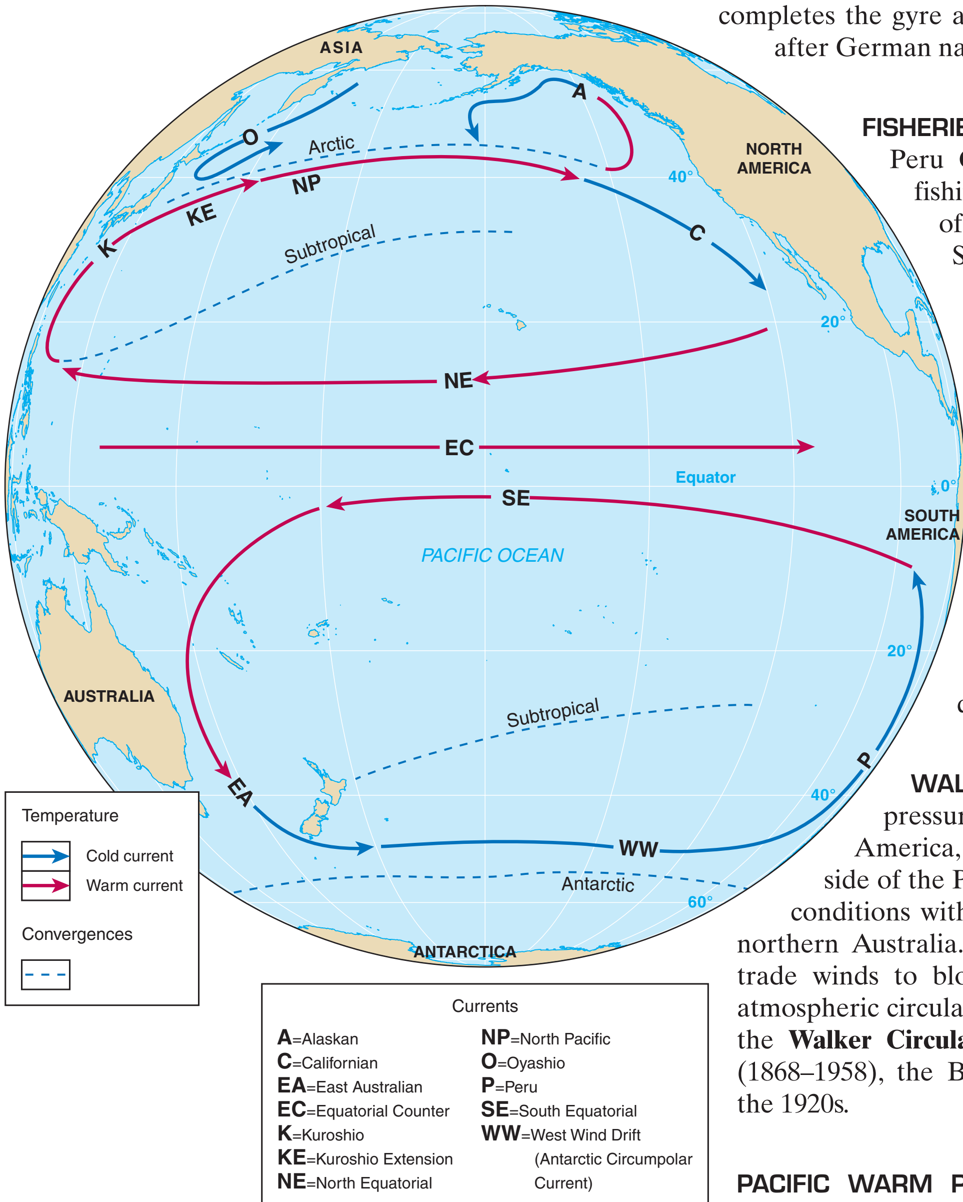


FIGURE 7.20 Pacific Ocean surface currents. Circulation in the Pacific Ocean consists of two large subtropical gyres similar to those in the Atlantic Ocean. However, the equatorial countercurrent is more strongly developed in the Pacific than in smaller ocean basins.

completes the gyre as the **Peru Current** (also called the *Humboldt Current*, after German naturalist Friedrich Heinrich Alexander von Humboldt).

FISHERIES AND THE PERU CURRENT The cool waters of the Peru Current have historically been one of Earth's richest fishing grounds. What conditions produce such an abundance of fish? Figure 7.21a shows that along the west coast of South America, coastal winds create Ekman transport that moves water away from shore, causing upwelling of cool, nutrient-rich water. This upwelling increases productivity and results in an abundance of marine life, including small silver-colored fish called *anchovetas* (anchovies) that become particularly plentiful near Peru and Ecuador. Anchovies provide a food source for many larger marine organisms and also supply Peru's commercial fishing industry, which was established in the 1950s. Anchovies had been so abundant in the waters off South America that by 1970 Peru was the largest producer of fish from the sea in the world, with a peak production of 12.3 million metric tons (13.5 million short tons), accounting for about one-quarter of *all* fish from the sea worldwide.

WALKER CIRCULATION Figure 7.21a shows that high pressure and sinking air dominate the coastal region of South America, resulting in clear, fair, and dry weather. On the other side of the Pacific, a low-pressure region and rising air create cloudy conditions with plentiful precipitation in Indonesia, New Guinea, and northern Australia. This pressure difference causes the strong southeast trade winds to blow across the equatorial South Pacific. The resulting atmospheric circulation cell in the equatorial South Pacific Ocean is named the **Walker Circulation Cell** (*green arrows*) after Sir Gilbert T. Walker (1868–1958), the British meteorologist who first described the effect in the 1920s.

PACIFIC WARM POOL The southeast trade winds set ocean water in motion, which also moves across the Pacific toward the west. The water warms as it flows in the equatorial region and creates a wedge of warm water on the western side of the Pacific Ocean, called the **Pacific warm pool** (see Figure 7.9). Due to the movement of equatorial currents to the west, the Pacific warm pool is thicker along the western side of the Pacific than along the eastern side. The *thermocline* beneath the warm pool in the western equatorial Pacific occurs below 100 meters (330 feet) depth. In the eastern Pacific, however, the thermocline is within 30 meters (100 feet) of the surface. The difference in depth of the thermocline can be seen by the sloping boundary between the warm surface water and the cold deep water in Figure 7.21a.

EL NIÑO–SOUTHERN OSCILLATION (ENSO) CONDITIONS Historically, Peru's residents knew that every few years, a current of warm water reduced the population of anchovies in coastal waters. The decrease in anchovies caused a dramatic decline not only in the fishing industry, but also in marine life such as sea birds and seals that depended on anchovies for food. The warm current also brought about changes in the weather—usually intense rainfall—and even brought such interesting items as floating coconuts from tropical islands near the

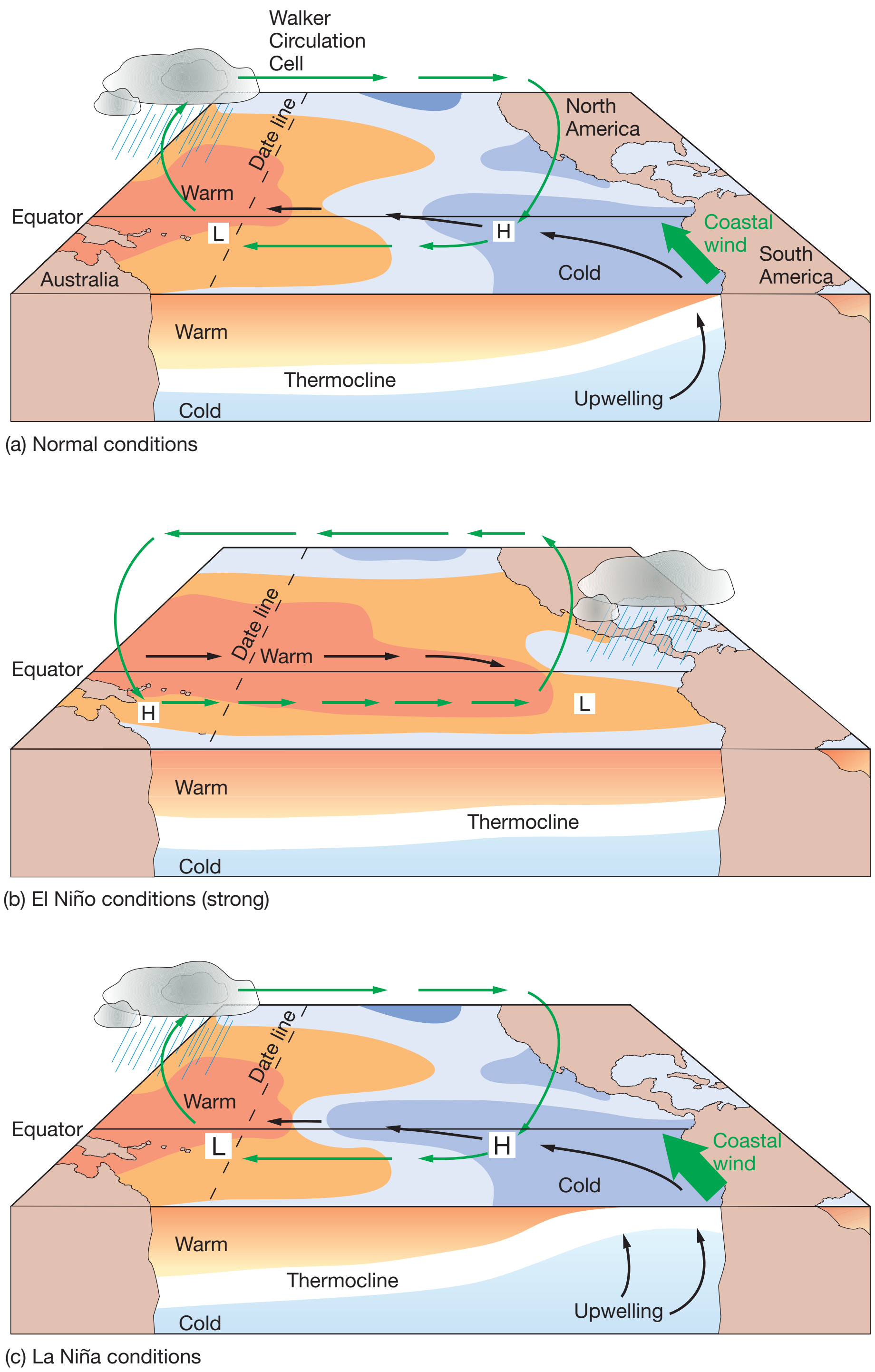


FIGURE 7.21 Normal, El Niño, and La Niña conditions. Perspective views of oceanic and atmospheric conditions in the equatorial Pacific Ocean. **(a)** Normal conditions. **(b)** El Niño (ENSO warm phase) conditions. **(c)** La Niña (ENSO cool phase) conditions.

web animation
El Niño and La Niña

WEB VIDEO
El Niño

equator. At first, these events were called *años de abundancia* (years of abundance) because the additional rainfall dramatically increased plant growth on the normally arid land. What was once thought of as a joyous event, however, soon became associated with the ecological and economic disaster that is now a well-known consequence of the phenomenon.

This warm-water current usually occurred around Christmas and thus was given the name **El Niño**, Spanish for "the child," in reference to baby Jesus. In the 1920s, Walker was the first to recognize that an east–west atmospheric pressure seesaw accompanied the warm current and he called the phenomenon the **Southern Oscillation**. Today, the combined oceanic and atmospheric effects are

STUDENTS SOMETIMES ASK . . .

The amount of anchovies produced by Peru is impressive! Besides a topping for pizza, what are some other uses of anchovies?

Anchovies are an ingredient in certain dishes, hors d'oeuvres, sauces, and salad dressing, and they are also used as bait by fishers. Historically, however, most of the *anchoveta* caught in Peruvian waters were exported and used as fishmeal (consisting of ground anchovies). The fishmeal, in turn, was used largely in pet food and as a high-protein chicken feed. As unbelievable as it may seem, El Niños affected the price of eggs! Prior to the collapse of the Peruvian *anchoveta* fishing industry in 1972–1973, El Niño events significantly reduced the availability of *anchovetas*. This drastically cut the export of anchovies from Peru, causing U.S. farmers to pursue more expensive options for chicken feed. Thus, egg prices typically increased.

The collapse of the *anchoveta* fishing industry in Peru was triggered by the 1972–1973 El Niño event but was caused by chronic overfishing in prior years (see Web Box 13.2). Interestingly, the shortage of fishmeal after 1972–1973 led to an increased demand for soyameal, an alternative source of high-quality protein. Increased demand for soyameal increased the price of soy commodities, thereby encouraging U.S. farmers to plant soybeans instead of wheat. Reduced production of wheat, in turn, caused a major global food crisis—all triggered by an El Niño event.

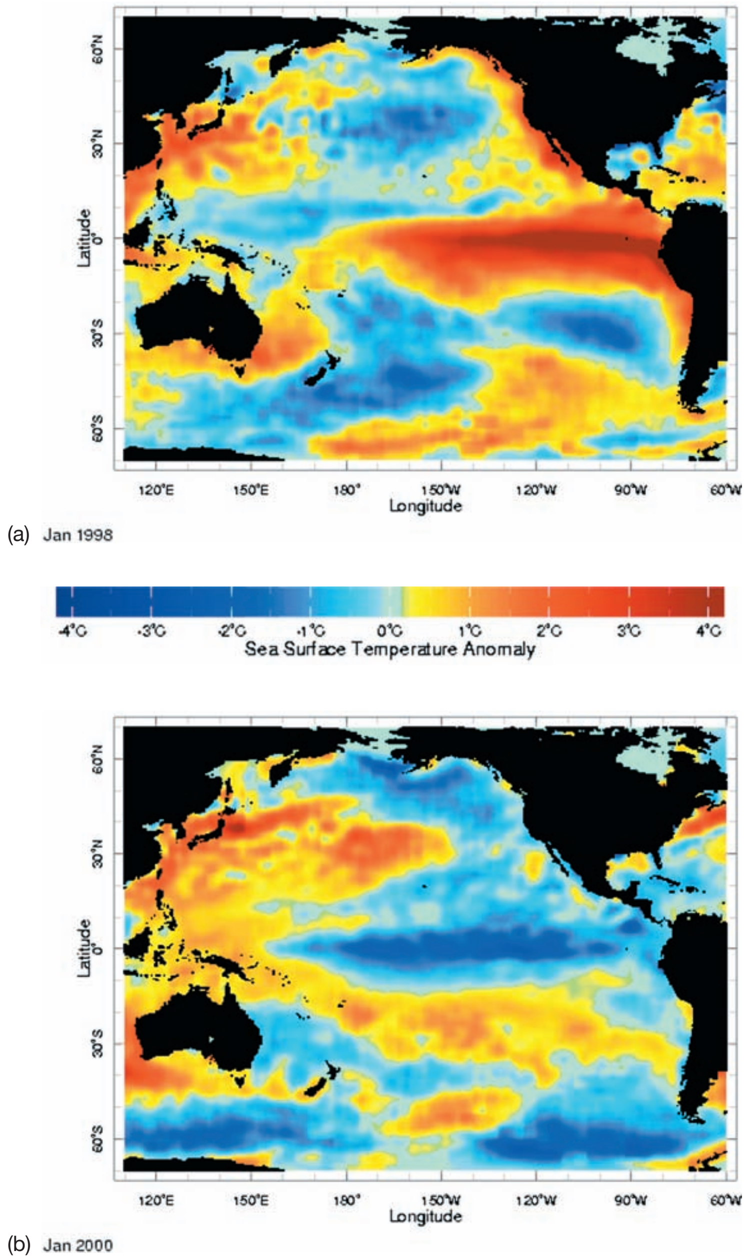


FIGURE 7.22 Sea surface temperature anomaly maps. Maps showing sea surface temperature anomalies, which represent departures from normal conditions. Red colors indicate water warmer than normal and blue colors represent water cooler than normal. **(a)** Map of the Pacific Ocean in January 1998, showing the anomalous warming during the 1997–1998 El Niño. **(b)** Map of the same area in January 2000, showing cooling in the equatorial Pacific related to La Niña.

called **El Niño–Southern Oscillation (ENSO)**, which periodically alternate between warm and cold phases and cause dramatic environmental changes.

ENSO Warm Phase (El Niño) Figure 7.21b shows the atmospheric and oceanic conditions during an ENSO warm phase, which is known as El Niño. The high pressure along the coast of South America weakens, reducing the difference between the high- and low-pressure regions of the Walker Circulation Cell. This, in turn, causes the southeast trade winds to diminish. In very strong El Niño events, the trade winds actually blow in the *reverse* direction.

Without the trade winds, the Pacific Warm Pool that has built up on the western side of the Pacific begins to flow back across the ocean toward South America. Aided by an increase in the flow of the Equatorial Countercurrent, the Pacific Warm Pool creates a band of warm water that stretches across the equatorial Pacific Ocean (Figure 7.22a). The warm water usually begins to move in September of an El Niño year and reaches South America by December or January. During strong to very strong El Niños, the water temperature off Peru can be up to 10°C (18°F) higher than normal. In addition, the average sea level can increase as much as 20 centimeters (8 inches), simply due to thermal expansion of the warm water along the coast.

As the warm water increases sea surface temperatures across the equatorial Pacific, temperature-sensitive corals are decimated in Tahiti, the Galápagos, and other tropical Pacific islands. In addition, many other organisms are affected by the warm water (see Web Box 13.2). Once the warm water reaches South America, it moves north and south along the west coast of the Americas, increasing average sea level and the number of tropical hurricanes formed in the eastern Pacific.

The flow of warm water across the Pacific also causes the sloped thermocline boundary between warm surface waters and the cooler waters below to flatten out and become more horizontal (Figure 7.21b). Near Peru, upwelling brings warmer, nutrient-depleted water to the surface instead of cold, nutrient-rich water. In fact, *downwelling* can sometimes occur as the warm water stacks up along coastal South America. Productivity diminishes and most types of marine life in the area are dramatically reduced.

As the warm water moves to the east across the Pacific, the low-pressure zone also migrates. In a strong to very strong El Niño event, the low pressure can move across the entire Pacific and remain over South America. The low pressure substantially increases precipitation along coastal South America. Conversely, high pressure replaces the Indonesian low, bringing dry conditions or, in strong to very strong El Niño events, drought conditions to Indonesia and northern Australia.

ENSO Cool Phase (La Niña) In some instances, conditions opposite of El Niño prevail in the equatorial South Pacific; these events are known as ENSO cool phase or **La Niña** (Spanish for "the female child"). Figure 7.21c shows La Niña conditions, which are similar to normal conditions but more intensified because there is a larger pressure difference across the Pacific Ocean. This larger pressure difference creates stronger Walker Circulation and stronger trade winds, which in turn cause more upwelling, a shallower thermocline in the eastern Pacific, and a band of cooler than normal water that stretches across the equatorial South Pacific (Figure 7.22b).

La Niña conditions commonly occur following an El Niño. For instance, the 1997–1998 El Niño was followed by several years of persistent La Niña conditions. The alternating pattern of El Niño–La Niña conditions since 1950 is shown by the multivariate **ENSO index** (Figure 7.23), which is calculated using a weighted average of atmospheric and oceanic factors including atmospheric pressure, winds,

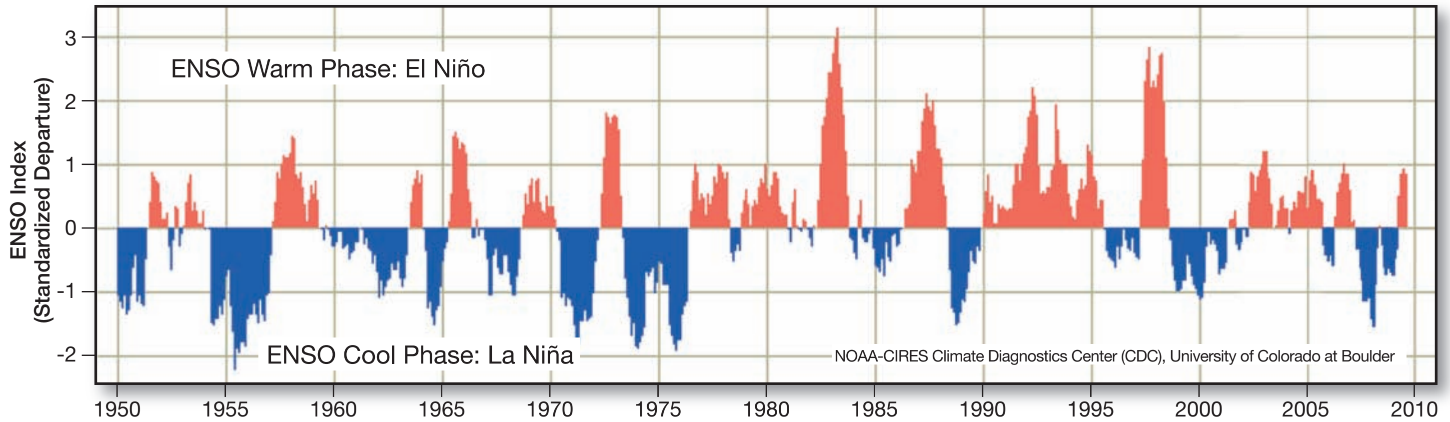


FIGURE 7.23 Multivariate ENSO Index 1950–Present. The multivariate ENSO index is calculated using a variety of atmospheric and oceanic factors. ENSO index values greater than zero (*red areas*) indicate El Niño conditions while ENSO index values less than zero (*blue areas*) indicate La Niña conditions. The greater the value is from zero, the stronger the corresponding El Niño or La Niña. Updates are available at http://www.cdc.noaa.gov/people/klaus.wolter/MEI/.

and sea surface temperatures. Positive ENSO index numbers indicate El Niño conditions, whereas negative numbers reflect La Niña conditions. Normal conditions are indicated by a value near zero, and the greater the index value differs from zero (either negative or positive), the stronger the respective condition.

Table 7.3 compares atmospheric and oceanic conditions during normal, El Niño, and La Niña conditions.

TABLE 7.3 COMPARISON OF ATMOSPHERIC AND OCEANIC CONDITIONS DURING NORMAL, EL NIÑO, AND LA NIÑA CONDITIONS

	Normal	El Niño	La Niña
Atmospheric pressure	High over South America; low over Indonesia	High over Indonesia; low over South America	More powerful high over South America; more powerful low over Indonesia
Winds	Strong, steady southeast trade winds	Southeast trade winds weaken and can even reverse	Stronger southeast trade winds
Atmospheric circulation	Normal Walker Circulation	Severely weakened or reversed Walker Circulation	Intensified Walker Circulation
Atmospheric conditions/ weather	Dry, clear weather in South America; humid and rainy weather in Indonesia	Flooding in South America; drought in Indonesia	Can cause drought in South America; flooding in Indonesia
Ocean surface currents	Strong South Equatorial Current	Weakened South Equatorial Current; stronger Equatorial Countercurrent	South Equatorial Current becomes stronger
Coastal upwelling and abundance of marine life	Strong coastal upwelling off South America due to coastal winds; abundant marine life	Coastal winds stop so coastal upwelling off South America ceases; downwelling can occur; lack of marine life	Stronger than normal coastal winds, so intensified coastal upwelling off South America; more abundant marine life
Sea surface temperature	Warm off Indonesia (Pacific Warm Pool); cold off South America (due to upwelling)	Pacific Warm Pool moves to the east and brings warm water to South America; remains warm off Indonesia	Increased upwelling off South America makes for more cold water that spreads farther to the west
Sea surface elevation	Higher off Indonesia, lower off South America	Evens out across the Pacific Ocean as Pacific Warm Pool moves east	Even higher off Indonesia, and even lower off South America
Thermocline	Very close to the surface off South America; deep off Australia	Lowers (deepens) off South America, causing thermocline to even out across the Pacific Ocean	Raised closer to the surface off South America; deepens off Australia

How Often Do El Niño Events Occur? Records of sea surface temperatures over the past 100 years reveal that throughout the 20th century, El Niño conditions occur on average about every 2 to 10 years, but in a highly irregular pattern. In some decades, for instance, there has been an El Niño event every few years, while in others there may have been only one. Figure 7.23 shows the pattern since 1950, revealing that the equatorial Pacific fluctuates between El Niño and La Niña conditions, with only a few years that could be considered "normal" conditions (represented by an ENSO index value close to zero). Typically, El Niño events last for 12 to 18 months and are followed by La Niña conditions that usually exist for a similar length of time. However, some El Niño or La Niña conditions can last for several years.

Recently recovered sediments from a South American lake provide a continuous 10,000-year record of the frequency of El Niño events. The sediments indicate that between 10,000 and 7000 years ago, no more than five strong El Niños occurred each century. The frequency of El Niños then increased, peaking at about 1200 years ago (and coinciding with the early Middle Ages in Europe), when they occurred every three years or so. If the pattern observed in the lake sediments continues, researchers predict that there should be an increase in El Niños in the early part of the 22nd century.

El Niño events—especially severe ones—may occur more frequently as a result of increased global warming. For instance, the two most severe El Niño events in the 20th century occurred in 1982–1983 and 1997–1998. Presumably, increased ocean temperatures could trigger more frequent and more severe El Niños. However, this pattern could also be a part of a long-term natural climate cycle. Recently, oceanographers have recognized a phenomenon called the **Pacific Decadal Oscillation (PDO)**, which lasts 20 to 30 years and appears to influence Pacific sea surface temperatures. Analysis of satellite data suggests that the Pacific Ocean has been in the warm phase of the PDO from 1977 to 1999 and that it is now in its cool phase, which may suppress the initiation of El Niño events during the next few decades.

Effects of El Niños and La Niñas Mild El Niño events influence only the equatorial South Pacific Ocean while strong to very strong El Niño events can influence worldwide weather. Typically, stronger El Niños alter the atmospheric jet stream and produce unusual weather in most parts of the globe. Sometimes the weather is drier than normal; at other times, it is wetter. The weather may also be warmer or cooler than normal. It is still difficult to predict exactly how a particular El Niño will affect any region's weather.

Figure 7.24 shows how very strong El Niño events can result in flooding, erosion, droughts, fires, tropical storms, and effects on marine life worldwide. These weather perturbations also affect the production of corn, cotton, and coffee. More locally, the satellite images in Figure 7.25 show that sea surface temperatures off western North America are significantly higher during an El Niño year.

Even though severe El Niños are typically associated with vast amounts of destruction, they can be beneficial in some areas. Tropical hurricane formation, for instance, is generally suppressed in the Atlantic Ocean, some desert regions receive much-needed rain, and organisms adapted to warm-water conditions thrive in the Pacific.

La Niña events are associated with sea surface temperatures and weather phenomena opposite to those of El Niño. Indian Ocean monsoons, for instance, are typically drier than usual in El Niño years but wetter than usual in La Niña years.

Examples from Recent El Niños Recent El Niños provide an indication of the variability of the effects of El Niño events. For instance, in the winter of 1976, a moderate El Niño event coincided with northern California's worst drought of the 20th century, showing that El Niño events don't always bring torrential rains to the western United States. During that same winter, the eastern United States experienced record cold temperatures.

STUDENTS SOMETIMES ASK . . .

Do El Niño events occur in other ocean basins?

Yes, the Atlantic and Indian Oceans both experience events similar to the Pacific's El Niño. These events are not nearly as strong, however, nor do they influence worldwide weather phenomena to the same extent as those that occur in the equatorial Pacific Ocean. The great width of the Pacific Ocean in equatorial latitudes is the main reason that El Niño events occur more strongly in the Pacific.

In the Atlantic Ocean, this phenomenon is related to the North Atlantic Oscillation (NAO), which is a periodic change in atmospheric pressure between Iceland and the Azores Islands. This pressure difference determines the strength of the prevailing westerlies in the North Atlantic, which in turn affects ocean surface currents there. The Atlantic Ocean periodically experiences NAO events, which sometimes cause intense cold in the northeast United States, unusual weather in Europe, and heavy rainfall along the normally arid coast of southwest Africa.

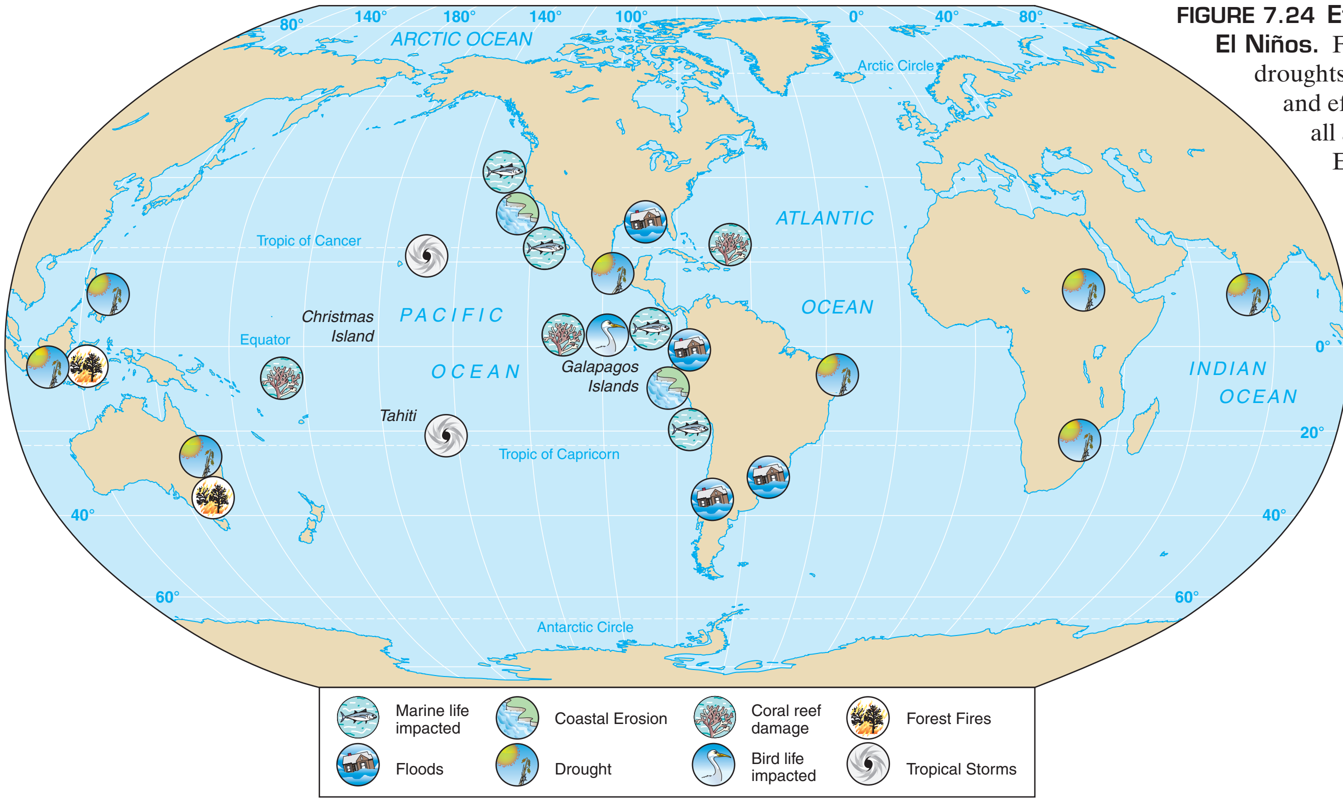


FIGURE 7.24 Effects of severe El Niños. Flooding, erosion, droughts, fires, tropical storms, and effects on marine life are all associated with severe El Niño events.

THE 1982–1983 EL NIÑO The 1982–1983 El Niño is the strongest ever recorded, causing far-ranging effects around the globe. Not only was there anomalous warming in the tropical Pacific, but the warm water also spread along the west coast of North America, influencing sea surface temperatures as far north as Alaska. Sea level was higher than normal (due to thermal expansion of the water), which, when high surf was experienced, caused damage to coastal structures and increased coastal erosion. In addition, the jet stream swung much farther south than normal across the United States, bringing a series of powerful storms that resulted in three times normal rainfall across the southwestern United States. The increased rainfall caused severe flooding and landslides as well as higher than normal snowfall in the Rocky Mountains. Alaska and western Canada had a relatively warm winter, and the eastern United States had its mildest winter in 25 years.

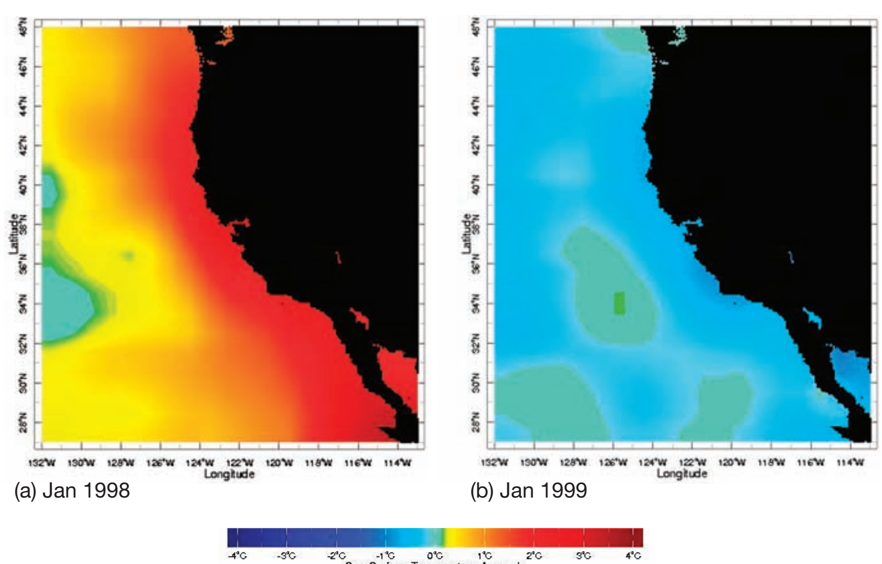


FIGURE 7.25 Sea surface temperatures off western North America during El Niño and La Niña. Satellite-derived sea surface temperature anomaly maps (in °C) along the west coast of North America. Red color represents water that is warmer than normal; blue color represents water that is colder than normal. **(a)** Sea surface temperature anomaly map for January 1998, an El Niño year. **(b)** Sea surface temperature anomaly map of the same region a year later (January 1999), during a La Niña event.

The full strength of El Niño was experienced in western South America. Normally arid Peru was drenched with more than 3 meters (10 feet) of rain, causing extreme flooding and landslides. Sea surface temperatures were so high for so long that temperature-sensitive coral reefs across the equatorial Pacific were decimated. Marine mammals and sea birds, which depend on the food normally available in the highly productive waters along the west coast of South America, went elsewhere or died. In the Galápagos Islands, for example, over half of the island's fur seals and sea lions died of starvation during the 1982–1983 El Niño.

French Polynesia had not experienced a hurricane in 75 years; in 1983, it endured six. The Hawaiian Island of Kauai also experienced a rare hurricane. Meanwhile, in Europe, severe cold weather prevailed. Worldwide, droughts occurred in Australia, Indonesia, China, India, Africa, and Central America. In all, more than 2000 deaths and at least $10 billion in property damage ($2.5 billion in the United States) were attributed to the 1982–1983 El Niño event.

THE 1997–1998 EL NIÑO The 1997–1998 El Niño event began several months earlier than normal and peaked in January 1998. The amount of Southern Oscillation and sea surface warming in the equatorial Pacific was initially as strong as the 1982–1983 El Niño, which caused a great deal of concern. However, the 1997–1998 El Niño weakened in the last few months of 1997 before reintensifying in early 1998. The impact of the 1997–1998 El Niño was felt mostly in the tropical Pacific, where surface water temperatures in the eastern Pacific averaged more than 4°C (7°F) warmer than normal, and, in some locations, reached up to 9°C (16°F) above normal (see Figure 7.22a). High pressure in the western Pacific brought drought conditions that caused wildfires to burn out of control in Indonesia. Also, the warmer than normal water along the west coast of Central and North America increased the number of hurricanes off Mexico.

In the United States, the 1997–1998 El Niño caused killer tornadoes in the Southeast, massive blizzards in the upper Midwest, and flooding in the Ohio River Valley. Most of California received twice the normal rainfall, which caused flooding and landslides in many parts of the state. The lower Midwest, the Pacific Northwest, and the eastern seaboard, on the other hand, had relatively mild weather. In all, the 1997–1998 El Niño caused 2100 deaths and $33 billion in property damage worldwide.

Predicting El Niño Events The 1982–1983 El Niño event was not predicted, nor was it recognized until it was near its peak. Because it affected weather worldwide and caused such extensive damage, the **Tropical Ocean–Global Atmosphere (TOGA)** program was initiated in 1985 to study how El Niño events develop. The goal of the TOGA program was to monitor the equatorial South Pacific Ocean during El Niño events to enable scientists to model and predict future El Niño events. The 10-year program studied the ocean from research vessels, analyzed surface and subsurface data from radio-transmitting sensor buoys, monitored oceanic phenomena by satellite, and developed computer models.

These models have made it possible to predict El Niño events since 1987 as much as one year in advance. After the completion of TOGA, the **Tropical Atmosphere and Ocean (TAO)** project (sponsored by the United States, Canada, Australia, and Japan) has continued to monitor the equatorial Pacific Ocean with a series of 70 moored buoys, providing real-time information about the conditions of the tropical Pacific that is available on the Internet. Although monitoring has improved, the causes of El Niño events are still not fully understood.

KEY CONCEPT

El Niño is a combined oceanic–atmospheric phenomenon that occurs periodically in the tropical Pacific Ocean, bringing warm water to the east. La Niña describes conditions opposite of El Niño.

7.5 What Deep-Ocean Currents Exist?

Deep currents occur in the deep zone below the pycnocline, so they influence about 90% of all ocean water. Density differences create deep currents. Although these density differences are usually small, they are large enough to cause denser waters to sink. Deep-water currents move larger volumes of water and are much slower than surface currents. Typical speeds of deep currents range from 10 to 20 kilometers (6 to 12 miles) per year. Thus, it takes a deep current an *entire year* to travel the same distance that a western intensified surface current can move in *one hour*.

Because the density variations that cause deep ocean circulation are caused by differences in temperature and salinity, deep-ocean circulation is also referred to as **thermohaline** (*thermo* = heat, *haline* = salt) **circulation**.

Origin of Thermohaline Circulation

Recall from Chapter 5 that an increase in seawater density can be caused by a *decrease* in temperature or an *increase* in salinity. Temperature, though, has the greater influence on density. Density changes due to salinity are important only in very high latitudes, where water temperature remains low and relatively constant.

Most water involved in deep-ocean currents (thermohaline circulation) originates in high latitudes *at the surface*. In these regions, surface water becomes cold and its salinity increases as sea ice forms. When this surface water becomes dense enough, it sinks, initiating deep-ocean currents. Once this water sinks, it is removed from the physical processes that increased its density in the first place, so its temperature and salinity remain largely unchanged for the duration it spends in the deep ocean. Thus, a **temperature–salinity (T–S) diagram** can be used to identify deep-water masses based on their characteristic temperature, salinity, and resulting density. Figure 7.26 shows a T–S diagram for the North Atlantic Ocean.

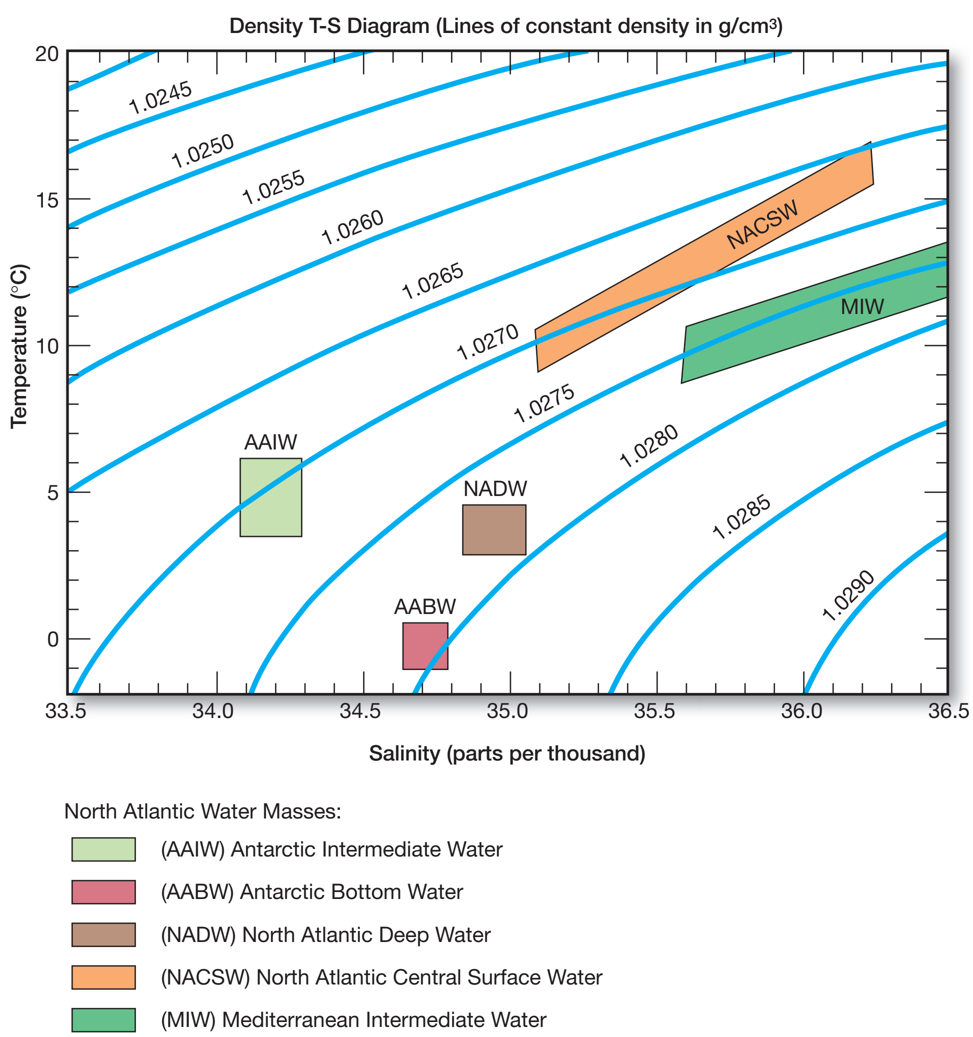
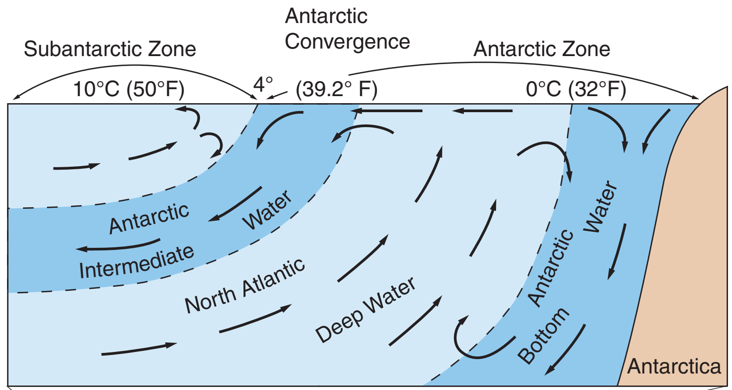
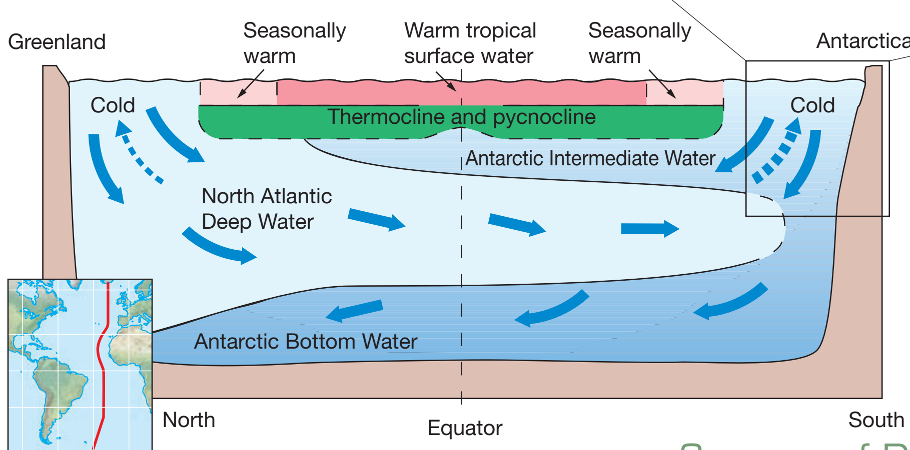


FIGURE 7.26 Temperature–salinity (T–S) diagram. A density T–S diagram for the North Atlantic Ocean. Lines of constant density are in grams/cm^3. After various deep-water masses sink below the surface, they can be identified based on their characteristic temperature, salinity, and resulting density.

FIGURE 7.27 Atlantic Ocean subsurface water masses. Schematic diagram of the various water masses in the Atlantic Ocean. Similar but less distinct layering based on density occurs in the Pacific and Indian Oceans as well. Upwelling and downwelling occur in the North Atlantic and near Antarctica (*inset*), creating deep-water masses.





As these surface-water masses become dense and are sinking (downwelling) in high-latitude areas, deep-water masses are also rising to the surface (upwelling). Because the water temperature in high-latitude regions is the same at the surface as it is down below, the water column is isothermal, there is no thermocline or associated pycnocline (see Chapter 5), and upwelling and downwelling can easily be accomplished.

Sources of Deep Water

In southern subpolar latitudes, huge masses of deep water form beneath sea ice along the margins of the Antarctic continent. Here, rapid winter freezing produces very cold, high-density water that sinks down the continental slope of Antarctica and becomes **Antarctic Bottom Water**, the densest water in the open ocean (Figure 7.27). Antarctic Bottom Water slowly sinks beneath the surface and spreads into all the world's ocean basins, eventually returning to the surface perhaps 1000 years later.

In the northern subpolar latitudes, large masses of deep water form in the Norwegian Sea. From there, the deep water flows as a subsurface current into the North Atlantic, where it becomes part of the **North Atlantic Deep Water**. North Atlantic Deep Water also comes from the margins of the Irminger Sea off southeastern Greenland, the Labrador Sea, and the dense, salty Mediterranean Sea. Like Antarctic Bottom Water, North Atlantic Deep Water spreads throughout the ocean basins. It is less dense, however, so it layers on top of the Antarctic Bottom Water (Figure 7.27).

Surface-water masses converge within the subtropical gyres and in the Arctic and Antarctic. Subtropical Convergences do not produce deep water, however, because the density of warm surface waters is too low for them to sink. Major sinking does occur, however, along the **Arctic Convergence** and Antarctic Convergence (Figure 7.27, *inset*). The deep-water mass formed from sinking at the Antarctic Convergence is called the **Antarctic Intermediate Water** mass (Figure 7.27), which remains one of world's most poorly studied water masses.

Figure 7.27 also shows that the highest density water is found along the ocean bottom, with less-dense water above. In low-latitude regions, the boundary between the warm surface water and the deeper cold water is marked by a prominent thermocline and corresponding pycnocline that prevent vertical mixing. There is no pycnocline in high-latitude regions, so substantial vertical mixing (upwelling and downwelling) occurs.

This same general pattern of layering based on density occurs in the Pacific and Indian Oceans as well. They have no source of Northern Hemisphere deep water, however, so they lack a deep-water mass. In the northern Pacific Ocean, the low salinity of surface waters prevents them from sinking into the deep ocean. In the northern Indian Ocean, surface waters are too warm to sink. **Oceanic Common Water**, which is created when Antarctic Bottom Water and North Atlantic Deep Water mix, lines the bottoms of these basins.

Worldwide Deep-Water Circulation

For every liter of water that sinks from the surface into the deep ocean, a liter of deep water must return to the surface somewhere else. However, it is difficult to identify specifically *where* this vertical flow to the surface is occurring. It is generally believed that it occurs as a gradual, uniform upwelling throughout the ocean basins and that it may be somewhat greater in low-latitude regions, where surface temperatures are higher. Alternatively, recent research on turbulent mixing rates between deep-ocean and surface waters in the Southern Ocean suggests that deep water traveling across rugged bottom topography is a major factor in producing the upwelling that returns deep water toward the surface.

CONVEYER-BELT CIRCULATION An integrated model combining deep thermohaline circulation and surface currents is shown in Figure 7.28. Because the overall circulation pattern resembles a large conveyer belt, the model is called **conveyer-belt circulation**. Beginning in the North Atlantic, surface water carries heat to high latitudes via the Gulf Stream. During the cold winter months, this heat is transferred to the overlying atmosphere, warming northern Europe.

Cooling in the North Atlantic increases the density of this surface water to the point where it sinks to the bottom and flows southward, initiating the lower limb of the "conveyor." Here, seawater flows downward at a rate equal to 100 Amazon Rivers and begins its long journey into the deep basins of all the world's oceans. This limb extends all the way to the southern tip of Africa, where it joins the deep water that encircles Antarctica. The deep water that

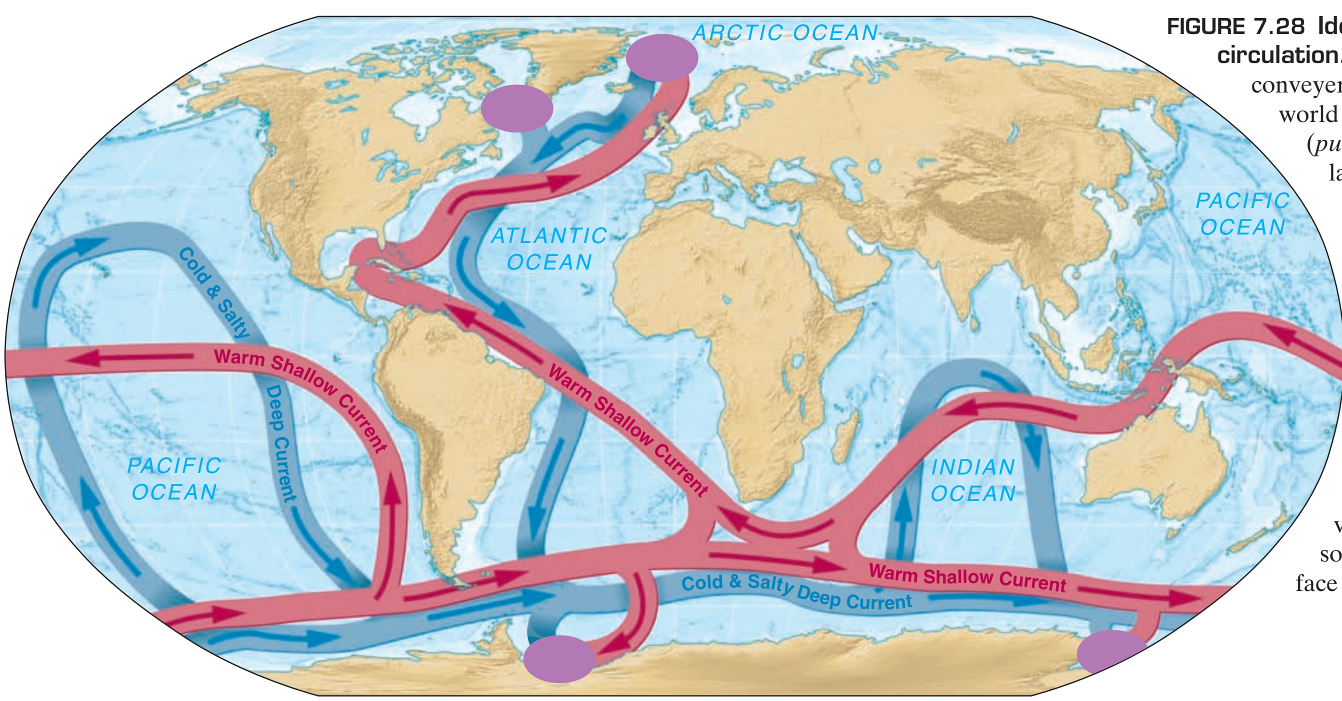


FIGURE 7.28 Idealized conveyer-belt circulation. Schematic map of conveyer-belt circulation of the world ocean. Source areas (*purple dots*) exist in high-latitude regions where surface water cools and becomes high density. These source areas feed the flow of deep, high density waters (*blue lines*), which flow into all of the oceans. This water slowly ascends throughout the oceans and completes the conveyer by returning to the source areas as warm surface currents (*red lines*).

encircles Antarctica includes deep water that descends along the margins of the Antarctic continent. This mixture of deep waters flows northward into the deep Pacific and Indian Ocean basins, where it eventually surfaces and completes the conveyer belt by flowing west and then north again into the North Atlantic Ocean.

DISSOLVED OXYGEN IN DEEP WATER Cold water can dissolve more oxygen than warm water. Thus, deep-water circulation brings dense, cold, oxygen-enriched water from the surface to the deep ocean. During its time in the deep ocean, deep water becomes enriched in nutrients as well, due to decomposition of dead organisms and the lack of organisms using nutrients there.

At various times in the geologic past, warmer water probably constituted a larger proportion of deep oceanic waters. As a result, the oceans had a lower oxygen concentration than today because warm water cannot hold as much oxygen. Moreover, the oxygen content of the oceans has probably fluctuated widely throughout time.

If high-latitude surface waters did not sink and eventually return from the deep sea to the surface, the distribution of life in the sea would be considerably different. There would be very little life in the deep ocean, for instance, because there would be no oxygen for organisms to breathe. In addition, life in surface waters might be significantly reduced without the circulation of deep water that brings nutrients to the surface.

KEY CONCEPT

Thermohaline circulation describes the movement of deep currents, which are created at the surface in high latitudes where they become cold and dense, so they sink.

7.6 Can Power From Currents Be Harnessed as a Source of Energy?

The movement of ocean currents has often been considered to be capable of providing a source of renewable, clean energy similar to wind farms (see Chapter 6) but underwater. In fact, currents carry much more energy than winds because water has about 800 times the density of air, so currents have the potential to generate even more power than wind farms do.

One location that has received much consideration as a site for harnessing power from ocean currents is the Florida–Gulf Stream Current System, which is a fast, western intensified surface current that runs along the East Coast of the United States. In fact, researchers have determined that at least 2000 megawatts[13] of electricity could be recovered from this ocean current system along the southeast coast of Florida alone.

Various devices that have been proposed to extract the energy in ocean currents all involve some sort of mechanism for converting the movement of water into electrical energy. For example, a series of underwater turbines similar to windmills could be placed within a current and anchored to the ocean floor (Figure 7.29). The turbines can swivel on their anchors to face oncoming currents, so this system is also useful in locations where strong reversing tidal flows occur. Such a system of six turbines has been successfully tested in the East River near New York City. Once this system is expanded to its capacity of 300 turbines, it will have the ability to generate about 10 megawatts of electricity. However, systems such as these are expensive, difficult to maintain, and can be dangerous to ship traffic. In addition, placing any moving machinery into the marine environment is problematic because seawater tends to corrode most materials. Still, similar turbine systems powered by currents are in use in Strangford Lough, Ireland, and are planned for offshore South Korea.

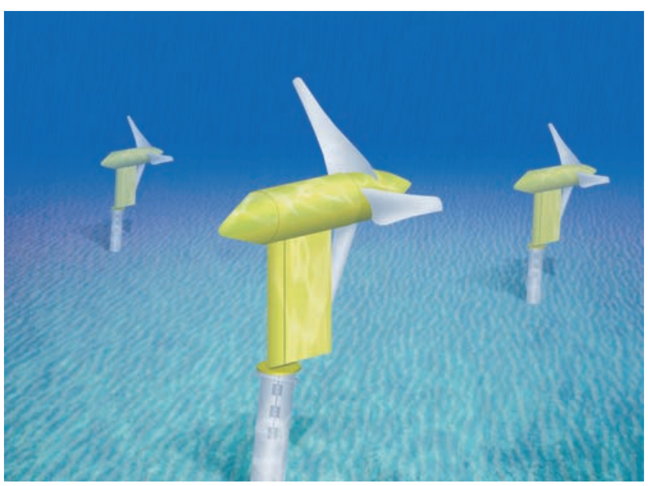


FIGURE 7.29 Power from ocean currents. A prototype of an ocean current power system, which uses a field of underwater turbines anchored to the ocean floor. As currents flow past the turbines, they turn the rotors and generate electricity. The turbines can swivel on their anchors to face oncoming currents, so this system is also useful in locations where strong tidal flows occur.

[13]Each megawatt of electricity is enough to serve the energy needs of about 800 average U.S. homes.

Chapter in Review

- *Ocean currents are masses of water that flow* from one place to another and can be divided into *surface currents that are wind driven and deep currents that are density driven*. Currents can be measured directly or indirectly.
- *Surface currents occur within and above the pycnocline*. They consist of circular-moving loops of water called gyres, set in motion by the major wind belts of the world. They are modified by the positions of the continents, the Coriolis effect, and other factors. There are *five major subtropical gyres in the world*, which rotate *clockwise in the Northern Hemisphere* and *counterclockwise in the Southern Hemisphere*. Water is pushed toward the center of the gyres, forming low "hills" of water.
- The *Ekman spiral* influences shallow surface water and is *caused by winds and the Coriolis effect*. The average net flow of water affected by the Ekman spiral causes the water to move at *90-degree angles to the wind direction*. At the center of a gyre, the Coriolis effect deflects the water so that it tends to move into the hill, whereas gravity moves the water down the hill. When gravity and the Coriolis effect balance, a *geostrophic current* flowing parallel to the contours of the hill is established.
- *The apex (top) of the hill is located to the west of the geographical center of the gyre* due to Earth's rotation. A phenomenon called *western intensification* occurs in which *western boundary currents of subtropical gyres are faster, narrower, and deeper* than their eastern boundary counterparts.
- *Upwelling and downwelling help vertically mix deep and surface waters*. Upwelling—the movement of *cold, deep, nutrient-rich water to the surface*—stimulates biologic productivity and creates a large amount of marine life. Upwelling and downwelling can occur in a variety of ways.
- *Antarctic circulation is dominated by a single large current, the Antarctic Circumpolar Current* (West Wind Drift), which flows in a clockwise direction around Antarctica and is driven by the Southern Hemisphere's prevailing westerly winds. Between the Antarctic Circumpolar Current and the Antarctic continent is a current called the *East Wind Drift*, which is powered by the polar easterly winds. The two currents flow in opposite directions, so the Coriolis effect deflects them away from each other, creating the *Antarctic Divergence*, an area of abundant marine life due to upwelling and current mixing.
- *The North Atlantic (Columbus) Gyre and the South Atlantic (Navigator) Gyre dominate circulation in the Atlantic Ocean*. A poorly developed equatorial countercurrent separates these two subtropical gyres. The highest velocity and best studied ocean current is the *Gulf Stream*, which carries warm water along the southeastern U.S. Atlantic coast. Meanders of the Gulf Stream produce *warm- and cold-core rings*. The warming effects of the Gulf Stream extend along its route and reach as far away as northern Europe.
- *The Indian Ocean consists of one gyre, the Indian Ocean (Majid) Gyre*, which exists mostly in the Southern Hemisphere. The *monsoon wind system*, which changes direction with the seasons, dominates circulation in the Indian Ocean. The monsoons blow from the northeast in the winter and from the southwest in the summer.
- *Circulation in the Pacific Ocean consists of two subtropical gyres: the North Pacific (Turtle) Gyre and the South Pacific (Heyerdahl) Gyre*, which are separated by a well-developed equatorial countercurrent.
- *A periodic disruption of normal sea surface and atmospheric circulation patterns in the Pacific Ocean is called El Niño–Southern Oscillation (ENSO)*. The *warm phase of ENSO (El Niño)* is associated with the eastward movement of the Pacific warm pool, halting or reversal of the trade winds, a rise in sea level along the equator, a decrease in productivity along the west coast of South America, and, in very strong El Niños, worldwide changes in weather. El Niños fluctuate with the *cool phase of ENSO (La Niña conditions)*, which are associated with cooler than normal water in the eastern tropical Pacific.
- *Deep currents occur below the pycnocline*. They affect much larger amounts of ocean water and move much more slowly than surface currents. Changes in temperature and/or salinity at the surface create slight increases in density, which set deep currents in motion. Deep currents, therefore, are called *thermohaline circulation*.
- *The deep ocean is layered based on density. Antarctic Bottom Water*, the densest deep-water mass in the oceans, forms near Antarctica and sinks along the continental shelf into the South Atlantic Ocean. Farther north, at the Antarctic Convergence, the low-salinity *Antarctic Intermediate Water* sinks to an intermediate depth dictated by its density. Sandwiched between these two masses is the *North Atlantic Deep Water*, which has high nutrient levels after hundreds of years in the deep ocean. Layering in the Pacific and Indian oceans is similar, except there is no source of Northern Hemisphere deep water.
- *Worldwide circulation models that include both surface and deep currents resemble a conveyer belt*. Deep currents carry oxygen into the deep ocean, which is extremely important for life on the planet.
- *Ocean currents can be harnessed as a source of power.* Although there is vast potential for developing this clean, renewable resource, significant problems must be overcome to make this a practical source of energy.

Key Terms

El Niño–Southern Oscillation (ENSO) (p. 218)
ENSO index (p. 218)
Equatorial countercurrent (p. 200)
Equatorial current (p. 199)
Equatorial upwelling (p. 206)
Florida Current (p. 209)
Franklin, Benjamin (p. 201)
Geostrophic current (p. 202)
Gulf Stream (p. 209)
Gyre (p. 198)
Indian Ocean Subtropical Gyre (p. 214)
Irminger Current (p. 212)
Kuroshio Current (p. 215)
La Niña (p. 218)
Labrador Current (p. 212)
Leeuwin Current (p. 215)
Monsoon (p. 213)
North Atlantic Current (p. 212)
North Atlantic Deep Water (p. 224)
North Atlantic Subtropical Gyre (p. 208)
North Equatorial Current (p. 209)
North Pacific Current (p. 215)
North Pacific Subtropical Gyre (p. 215)
Northern boundary current (p. 200)
Norwegian Current (p. 212)
Ocean current (p. 193)
Oceanic Common Water (p. 225)
Pacific Decadal Oscillation (PDO) (p. 220)
Pacific warm pool (p. 216)
Peru Current (p. 216)
Productivity (p. 205)
Sargasso Sea (p. 209)
Somali Current (p. 214)
South Atlantic Subtropical Gyre (p. 208)
South Equatorial Current (p. 209)
South Pacific Subtropical Gyre (p. 215)
Southern boundary current (p. 200)
Southern Oscillation (p. 217)
Subpolar gyre (p. 200)
Subtropical Convergence (p. 202)
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Surface current (p. 193)
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Temperature–salinity (T–S) diagram (p. 223)
Thermohaline circulation (p. 223)
Tropical Atmosphere and Ocean (TAO) (p. 222)
Tropical Ocean–Global Atmosphere (TOGA) (p. 222)
Upwelling (p. 204)
Walker Circulation Cell (p. 216)
Warm-core ring (p. 211)
West Australian Current (p. 215)
West Wind Drift (p. 207)
Western boundary current (p. 199)
Western intensification (p. 202)

Review Questions

1. Compare the forces that are directly responsible for creating horizontal and deep vertical circulation in the oceans. What is the ultimate source of energy that drives both circulation systems?

2. Describe the different ways in which currents are measured.

3. What atmospheric pressure is associated with the centers of subtropical gyres? With subpolar gyres? Explain why the subtropical gyres in the Northern Hemisphere move in a clockwise fashion while the subpolar gyres rotate in a counterclockwise pattern.

4. Describe the voyage of the *Fram* and how it helped prove that there was no continent beneath the Arctic ice pack.

5. What causes the apex of the geostrophic "hills" to be offset to the west of the center of the ocean gyre systems?

6. Draw or describe several different oceanographic conditions that produce upwelling.

7. Observing the flow of Atlantic Ocean currents in Figure 7.15, offer an explanation as to why the Brazil Current has a much lower velocity and volume transport than the Gulf Stream.

8. Why did Benjamin Franklin want to know about the surface current pattern in the North Atlantic Ocean?

9. Explain why Gulf Stream eddies that develop northeast of the Gulf Stream rotate clockwise and have warm-water cores, whereas those that develop to the southwest rotate counterclockwise and have cold-water cores.

10. Describe changes in atmospheric pressure, precipitation, winds, and ocean surface currents during the two monsoon seasons of the Indian Ocean.

11. Describe changes in atmospheric and oceanographic phenomena that occur during El Niño/La Niña events, including changes in atmospheric pressure, winds, Walker Circulation, weather, equatorial surface currents, coastal upwelling/downwelling and the abundance of marine life, sea surface temperature and the Pacific warm pool, sea surface elevation, and position of the thermocline.

12. How often do El Niño events occur? Using Figure 7.23, determine how many years since 1950 have been El Niño years. Has the pattern of El Niño events occurred at regular intervals?

13. How is La Niña different from El Niño? Describe the pattern of La Niña events in relation to El Niños since 1950 (see Figure 7.23).

14. Describe the global effects of severe El Niños.

15. Discuss the origin of thermohaline vertical circulation. Why do deep currents form only in high-latitude regions?

16. Name the two major deep-water masses and give the locations of their formation at the ocean's surface.

17. The Antarctic Intermediate Water can be identified throughout much of the South Atlantic based on its temperature, salinity, and dissolved oxygen content. Why is it colder and less salty—and contain more oxygen—than the surface-water mass above it and the North Atlantic Deep Water below it?

Critical Thinking Exercises

1. What would the pattern of ocean surface currents look like if there were no continents on Earth?

2. On a base map of the world, plot and label the major currents involved in the surface circulation gyres of the oceans. Use colors to represent warm versus cool currents and indicate which currents are western intensified. On an overlay, superimpose the major wind belts of the world on the gyres and describe the relationship between wind belts and currents.

3. Diagram and discuss how Ekman transport produces the "hill" of water within subtropical gyres that causes geostrophic current flow. As a starting place on the diagram, use the wind belts (the trade winds and the prevailing westerlies).

4. During flood stage, the largest river in the world—the mighty Amazon River—dumps 200,000 cubic meters of water into the Atlantic Ocean each second. Compare its flow rate with the volume of water transported by the West Wind Drift and the Gulf Stream. How many times larger than the Amazon is each of these two ocean currents?

Oceanography on the Web

Visit the *Essentials of Oceanography* Online Study Guide for Internet resources, including chapter-specific quizzes to test your understanding and Web links to further your exploration of the topics in this chapter.

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