Learning Outcomes

After studying the information in this chapter students should be able to:

1. *describe* and *sketch* the motion of water in the Ekman layer,
2. *diagram* the formation of surface current gyres,
3. *locate* the major surface currents on a map of the oceans,
4. *explain* the process of western intensification,
5. *relate* patterns of surface convergence and divergence with downwelling and upwelling, and
6. *sketch* the gross structure of combined wind-driven and thermohaline circulation in the oceans.

Earth is surrounded by two great oceans: an ocean of air and an ocean of water. Both are in constant motion, driven by the energy of the Sun and the gravity of Earth. Their motions are linked; the winds give energy to the sea surface and the currents are the result. The currents carry heat from one location to another, altering Earth's surface temperature patterns and modifying the air above. The interaction between the atmosphere and the ocean is dynamic; as one system drives the other, the driven system acts to alter the properties of the driving system.

In this chapter, we explore the formation of the ocean's surface currents. We follow these currents as they flow, merge, and move away from each other. We examine both horizontal and vertical circulation, inspect the coupling of these water motions, and consider the ways in which they are linked to the overall interaction between the atmosphere and the ocean.

9.1 Surface Currents

When the winds blow over the oceans, they set the surface water in motion, driving the large-scale surface currents in nearly constant patterns. The density of water is about 1000 times greater than the density of air, and once in motion, the mass of the moving water is so great that its inertia keeps it flowing. The currents flow more in response to the average atmospheric circulation than to the daily weather and its short-term changes; however, the major currents do shift slightly in response to seasonal changes in the winds. The currents are further modified by interactions between the currents and along zones of converging and diverging water. The major surface currents have been called the rivers of the sea; they have no banks to contain them, but they maintain their average course.

Because the frictional coupling between the ocean water and Earth's surface is small, the moving water is deflected by the Coriolis effect in the same way that moving air is deflected (see chapter 7). But because water moves more slowly than air, it takes longer to move water the same distance as air. During this longer time period, Earth rotates farther out from under the water than from under the wind. Therefore, the slower-moving water appears to be deflected to a greater degree than the overlying air. The surface-current acted upon by the Coriolis effect is deflected to the right of the driving wind direction in the Northern Hemisphere and to the left in the Southern Hemisphere. In the open sea, the surface flow is deflected at a 45° angle from the wind direction, as shown in figure 9.1.

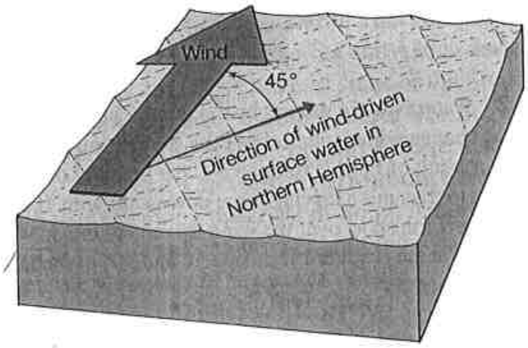

Figure 9.1 A wind-driven surface current moves at an angle of 45° to the direction of the wind; this angle is to the right in the Northern Hemisphere and to the left in the Southern Hemisphere.

The Ekman Spiral and Ekman Transport

Wind-driven surface water sets the water immediately below it in motion. But because of low-friction coupling in the water, this next deeper layer moves more slowly than the surface layer and is deflected to the right (Northern Hemisphere) or left (Southern Hemisphere) of the surface-layer direction. The same is true for the next layer down and the next. The result is a spiral in which each deeper layer moves more slowly and with a greater angle of deflection to the surface flow. This current spiral is called the **Ekman spiral,** after the physicist V. Walfrid Ekman, who developed its mathematical relationship. The spiral extends to a depth of approximately 100–150 m (330–500 ft), where the much reduced current will be moving in the opposite direction to the surface current. Over the depth of the spiral, the average flow of the water set in motion by the wind, or the net flow **(Ekman transport),** moves 90° to the right or left of the surface wind, depending on the hemisphere (fig. 9.2). This relationship is in contrast to the surface water, which moves at an angle of 45° to the wind direction.

Ocean Gyres

Refer to figure 9.3 as you read the description of surface currents in the major oceans. In the Northern Hemisphere, the wind-driven

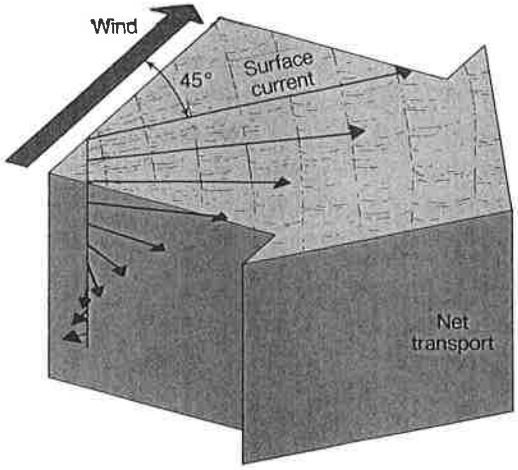

Figure 9.2 Water is set in motion by the wind. The direction and speed of flow change with depth to form the Ekman spiral. This change with depth is a result of Earth's rotation and the inability of water, due to low friction, to transmit a driving force downward with 100% efficiency. The net transport over the wind-driven column is 90° to the right of the wind in the Northern Hemisphere and 90° to the left in the Southern Hemisphere.

Ekman transport under the westerlies moves 90° to the right of the westerlies, away from an ocean's western shore or boundary, and along the 40°–50°N latitudes until it reaches its eastern shore or boundary. The Ekman transport under the trade winds moves 90° to the right of the trades, away from an ocean's eastern boundary, and along the 10°–20° latitudes until the current reaches the western boundary of the ocean. When Northern Hemisphere water moving with the trade winds accumulates at the land boundary on the west side of an ocean, the water flows north to the latitude of the westerlies and then eastward across the ocean. Water accumulating on the east side of a northern ocean flows south, toward the region from which the water moves westward under the trade winds. In Southern Hemisphere oceans, the east-west wind-driven Ekman transport is deflected 90° to the left of the trade winds and the westerlies. Water accumulating on the eastern side of a Southern Hemisphere ocean moves north, and water on the western side of a southern ocean moves south.

The Ekman transport causes an accumulation of water at the center of the circular flow pattern that results in an elevated convergence. As the elevation builds, the wind-driven surface flow moves more closely in line with the driving winds, and the surface current circulates around the convergence zone. In each hemisphere, this pattern produces continuous flow and a series of interconnecting surface currents moving in a circular path centered on 30° latitude. The rotation is clockwise in the Northern Hemisphere and counterclockwise in the Southern Hemisphere. These large, circular-motion, wind-driven current systems are known as **gyres.** In the more southern latitudes, there is no land between the Atlantic, Pacific, and Indian Oceans; here, the surface currents, driven by the westerlies, continue around Earth in a circumpolar flow around Antarctica.

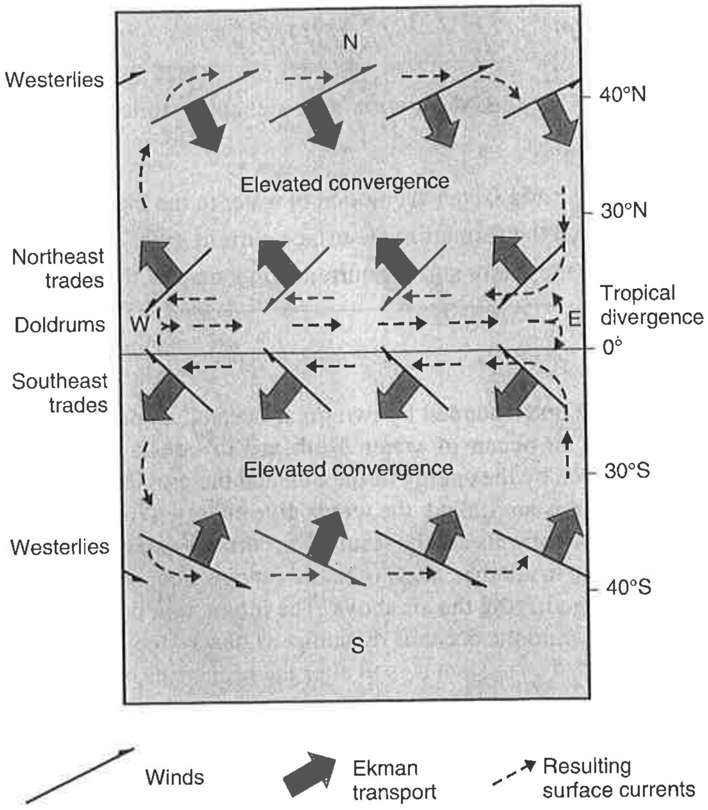

Figure 9.3 Wind-driven transport and resulting surface currents in an ocean bounded by land to the east and to the west. The currents form large oceanic gyres that rotate clockwise in the Northern Hemisphere and counterclockwise in the Southern Hemisphere.

Geostrophic Flow

If Ekman transport is applied to oceans with eastern and western land boundaries, a portion of the wind-driven surface water is deflected toward the center of each of the large, circular current gyres just described (fig. 9.3). A convergent lens of surface water is elevated more than 1 m (3 ft) above the equilibrium sea level, and this lens depresses the underlying denser water.

The thickness of the surface lens is about 1000 times greater than the elevation of the lens above sea level. This is because the difference in density between the surface water and the deeper water is only about 1/1000 of the density difference between air and water at the sea surface. The surface slope of the mound increases as deflected water moves inward until the outward pressure driving the water away from the gyre center equals the Coriolis effect, acting to deflect the moving water into the raised central mound. At this balance point, **geostrophic flow** is said to exist, and no further deflection of the moving water occurs. Instead, the currents flow smoothly around the gyre parallel to its elevation contours. See figure 9.4 for a diagram of this process. Using the subsurface water-density distribution to describe the extent of the depression of the deeper water, oceanographers are able to calculate the elevation and slope of the sea surface and so calculate the velocity, volume transport, and depth of the currents present in the geostrophic flow around the mound. It is also possible to measure the topography of the sea surface using satellites

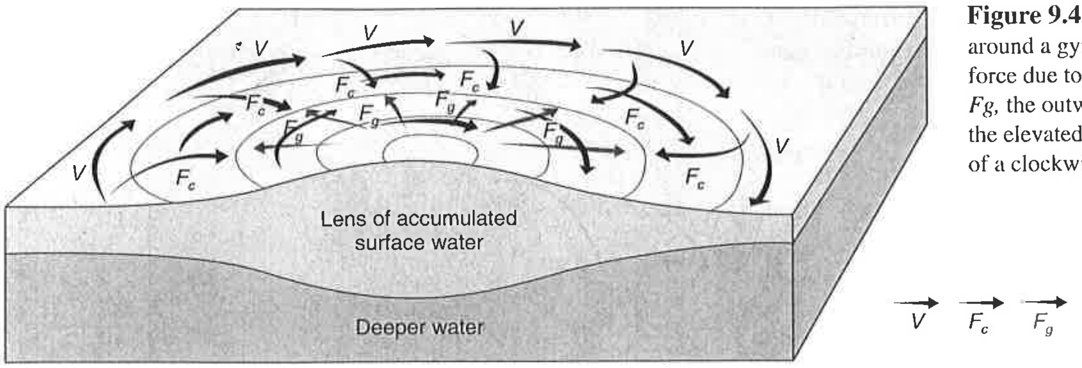

Figure 9.4 Geostrophic flow (*V*) exists around a gyre when *Fc,* the inward deflection force due to the Coriolis effect, is balanced by *Fg,* the outward-acting pressure force created by the elevated water and gravity. This example is of a clockwise gyre in the Northern Hemisphere.

and to calculate the geostrophic flow that maintains the topography. The region of the Sargasso Sea in the North Atlantic Ocean is the classic example of a gyre in geostrophic balance; it is discussed following the Atlantic currents in section 9.2.

9.2 Wind-Driven Ocean Currents

The currents that make up the large oceanic gyre systems and other major currents have been given names and descriptions based on their average positions. These are presented here ocean by ocean and can be followed on figure 9.5. As you follow these current paths, review their associations with the large gyre systems and their overlying wind belts.

Pacific Ocean Currents

In the North Pacific Ocean, the northeast trade winds push the water toward the west and northwest; this is the **North Equatorial Current.** The westerlies create the **North Pacific Current,** or **North Pacific Drift,** moving from west to east. Note that the trade winds move the water away from Central and South America and pile it up against Asia, while the westerlies move the water away from Asia and push it against the west coast of North America. The water that accumulates in one area must flow toward areas from which the water has been removed. This movement forms two currents: the **California Current,** moving from north to south along the western coast of North America, and the **Kuroshio Current,** moving from south to north along the east coast of Japan. The Kuroshio and California Currents are not wind-driven currents; they provide continuity of flow and complete a circular motion centered around 30°N latitude. This circular, clockwise flow of water is called the North Pacific gyre. Other major North Pacific currents include the **Oyashio Current,** driven by the polar easterlies, and the **Alaska Current,** fed by water from the North Pacific Current and moving in a counterclockwise gyre in the Gulf of Alaska. Little exchange of water occurs through the Bering Strait between the North Pacific and the Arctic Ocean; no current exists that is comparable to the Atlantic Ocean's Norwegian Current, which moves warm water to the Arctic Ocean.

In the South Pacific Ocean, the southeast trade winds move the water to the left of the wind and westward, forming the **South Equatorial Current.** The westerly winds push the water to the east; at these southern latitudes, the surface current so formed can move almost continuously around Earth. This current is the **Wes Wind Drift.** The tips of South America and Africa deflect a portion of this flow northward on the east sides of the South Pacific and South Atlantic Oceans. As in the North Pacific, continuity currents form between the South Equatorial Current and the Wes Wind Drift. The **Peru Current,** or **Humbolt Current,** flows from south to north along the coast of South America, while the **East Australia Current** can be seen moving weakly from north to south on the west side of the ocean. These four currents form the counterclockwise South Pacific gyre.

The North Pacific and South Pacific gyres form on either side of 5°N because the meteorological equator or doldrums belt is displaced northward from the geographic equator (0°), owing to the unequal heating of the Northern and Southern Hemispheres. Also between the North and South Equatorial Currents, in the zone o the doldrums is a current moving in the opposite direction, from west to east. This is a continuity current known as the **Equatorial Countercurrent,** which helps to return accumulated surface water eastward across the Pacific. Under the South Equatoria Current is a subsurface current flowing from west to east called the **Cromwell Current.** This cold-water continuity current also returns water accumulated in the western Pacific.

Atlantic Ocean Currents

The North Atlantic westerly winds move the water eastward a the **North Atlantic Current,** or **North Atlantic Drift.** The northeast trade winds push the water to the west, forming the **North Equatorial Current.** The north-south continuity current are the **Gulf Stream,** flowing northward along the coast o North America, and the **Canary Current,** moving to the south on the eastern side of the North Atlantic. The Gulf Stream is fed by the **Florida Current** and the North Equatorial Current. The North Atlantic gyre rotates clockwise. The polar easterlies provide the driving force for the **Labrador** and **East Greenland Currents,** which balance water flowing into the Arctic Ocean from the **Norwegian Current.**

In the South Atlantic, the westerlies continue the West Wind Drift. The southeast trade winds move the water to the west, bu the bulge of Brazil deflects part of the **South Equatorial Curren northward into the Caribbean Sea and eventually in**to the Gulf o Mexico, where it exits as the Florida Current and joins the Gul Stream. A portion of the South Equatorial Current moves south of the Brazilian bulge along the western side of the South Atlantic

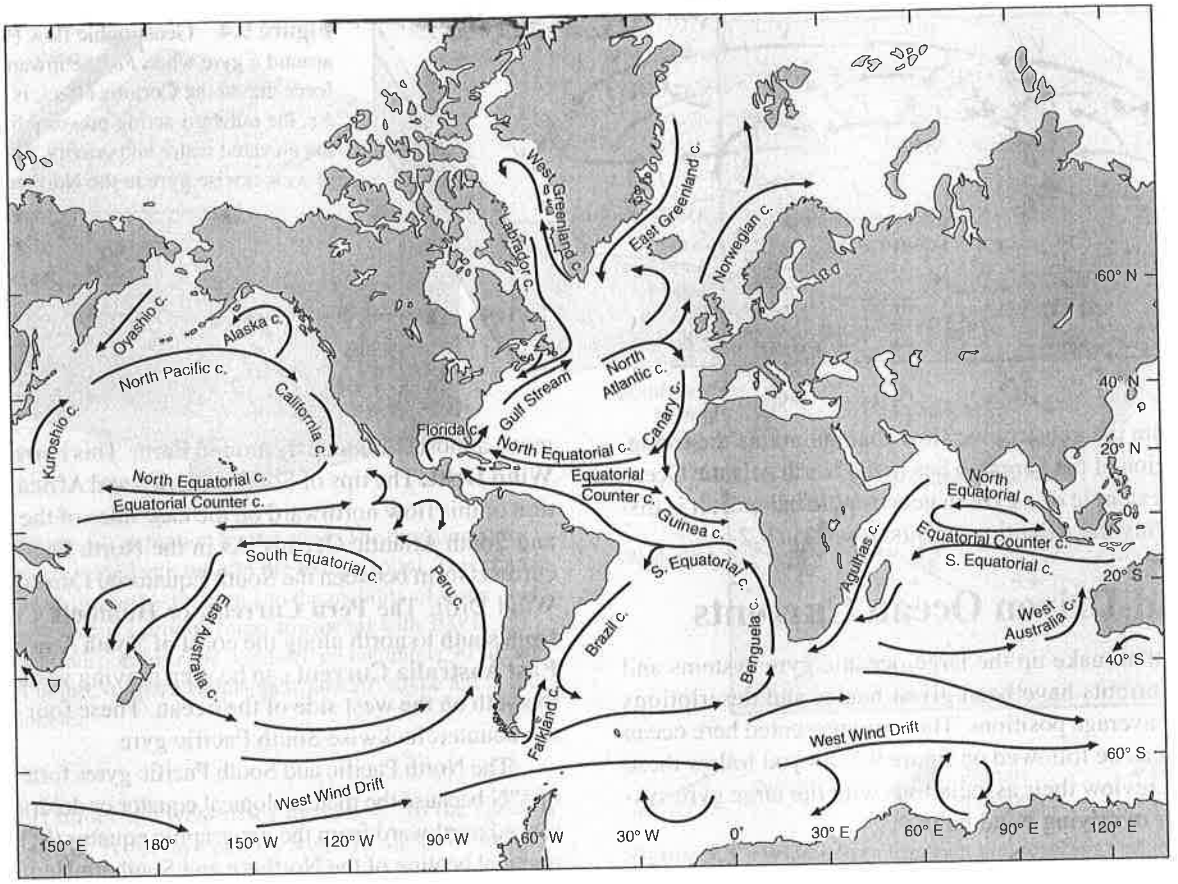

Figure 9.5 The long-term average flow of the major surface currents of the oceans.

to form the **Brazil Current.** The **Benguela Current** moves northward along the African coast. The South Atlantic gyre is complete, and it rotates counterclockwise.

Because much of the South Equatorial Current is deflected across the equator, the Equatorial Countercurrent appears only weakly in the eastern portion of the mid-Atlantic. The northward movement of South Atlantic surface water across the equator results in a net flow of surface water from the Southern Hemisphere to the Northern Hemisphere. This flow is balanced by a flow of water at depth from the Northern Hemisphere to the Southern Hemisphere. This deep-water return flow is the North Atlantic deep water, discussed in chapter 8. Again, the equatorial currents are displaced northward, although not as markedly as in the Pacific Ocean.

The Sargasso Sea marks the middle of an ocean gyre. It is located in the central North Atlantic Ocean, and its boundaries are the Gulf Stream on the west, the North Atlantic Current to the north, the Canary Current on the east, and the North Equatorial Current to the south. The circular motion of the gyre currents isolates a lens of clear, warm, downwelling water 1000 m (3000 ft) deep. The region is famous for the floating mats of *Sargassum,* a brown seaweed, stretching across its surface. The extent of the floating seaweed frightened early sailors, who told stories of ships imprisoned by the weed and sea monsters lurking below the surface. Except for the floating *Sargassum,* with its rich and specialized ecological community, the clear water is nearly a biological desert.

Indian Ocean Currents

The Indian Ocean is mainly a Southern Hemisphere ocean. The southeast trade winds push the water to the west, creating the **South Equatorial Current.** The Southern Hemisphere westerlies still move the water eastward in the West Wind Drift. The gyre is completed by the **West Australia Current** moving northward and the **Agulhas Current** moving southward along the east coast of Africa. Because this is a Southern Hemisphere ocean, the currents are deflected left of the wind direction, and the gyre rotates counterclockwise. The northeast trade winds in winter drive the **North Equatorial Current** to the west, and the **Equatorial Countercurrent** returns water eastward toward Australia. Again, these equatorial currents are displaced approximately 5°N. With the coming of the wet monsoon season and its west winds, these currents are reduced. The strong seasonal monsoon effect controls the surface flow of the Northern Hemisphere portion of the Indian Ocean. In the summer, the winds blow the surface water eastward, and in the winter, they blow it westward. This strong seasonal shift is unlike anything found in the Atlantic or the Pacific Ocean.

Arctic Ocean Currents

The relentless drift of water and ice in the Arctic Ocean moves in a large clockwise gyre driven by the polar easterly winds. This gyre is centered not on the North Pole, as early explorers

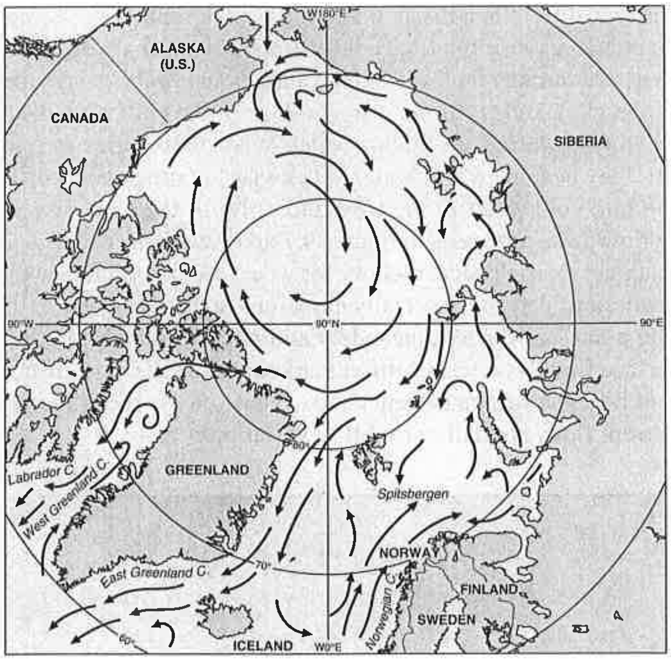

Figure 9.6 The circulation in the Arctic Ocean is driven by the polar easterlies, which produce a large, clockwise gyre. Water enters the Arctic Ocean from the North Atlantic by way of the Norwegian Current and exits to the Atlantic by the East Greenland Current and the Labrador Current.

expected, but is offset over the Canadian basin at 150°W and 80°N (fig. 9.6). Although the currents and the winds move the ice slowly at 0.1 knot (2 mi/day), Arctic explorers trying to reach the North Pole found that they traveled south with the drifting ice and water at speeds almost equal to their difficult progress north.

The Arctic Ocean is supplied from the North Atlantic by the Norwegian Current; some of this flow enters west of Spitsbergen, but most flows along the coast of Norway and moves eastward along the Siberian coast into the Chukchi Sea. A small inflow of water entering the Arctic through the Bering Strait brings water from the Bering Sea to join the eastward flow along Siberia and the large Arctic gyre. The western side of the gyre crosses the center of the Arctic Ocean to split north of Greenland. Here, the larger flow forms the East Greenland Current flowing south and taking Arctic Ocean water into the North Atlantic. The lesser flow moves along the west side of Greenland to join the Labrador Current and move south along the Canadian coast.

Outflow from Siberian rivers is caught in the eastward flow of water and ice along Siberia. Eventually, this discharge joins the gyre, distributing sediments and pollutants throughout the Arctic (see the box in chapter 8 titled "Arctic Ocean Studies").

9.3 Current Flow

Current Speed

Wind-driven open-ocean surface currents move at speeds that are about 1/100 of the wind speed measured 10 m (30 ft) above the sea surface. The water moves between 0.25 and 1.0 knot, or 0.1–0.5 m (0.3–1.5 ft) per second. Currents flow faster when a large volume of water is forced to flow through a narrow gap. For example, the North and part of the South Atlantic Equatorial Currents flow into the Caribbean Sea, then into the Gulf of Mexico, and finally exit to the North Atlantic as the Florida Current through the narrow gap between Florida and Cuba. The Florida Current's speed may exceed 3 knots, or 1.5 m (5 ft) per second. Once into the Atlantic Ocean this current turns north and becomes the Gulf Stream.

The flow is distributed over the width and depth of the current. When the cross-sectional area of the current expands, the current slows down; when the cross-sectional area decreases, the current speeds up. Speed of flow may not be directly related to surface wind speed but can be affected by the depth and width of the current as determined by land barriers, by the presence of another current, or by the rotation of Earth, as explained in the "Western Intensification" section of this chapter.

Current Volume Transport

Major ocean currents transport enormous volumes of water. A convenient unit to report transport volume is the Sverdrup (Sv) (named after Harald Sverdrup, a leading oceanographer of the last century and former Director of the Scripps Institution of Oceanography). A Sverdrup equals 1 million cubic meters ($\sim 3.5 \times 10^7$ ft^3) per second. The transport rate of fresh water in all of the world's rivers into the ocean is about 1 Sv. Transport rates of ocean currents are difficult to measure accurately and can vary by both location in the current and time of the year. The Gulf Stream transports about 30 Sv passing through the Strait of Florida as the Florida Current. This increases steadily as it moves north along the coast until it transports about 80 Sv near Cape Hatteras. The transport of the Gulf Stream continues to increase downstream of Cape Hatteras at a rate of 8 Sv every 100 km, reaching a maximum transport of about 150 Sv at 55°W. The downstream increase in transport between Cape Hatteras and 55°W is thought to be caused by increased velocities in the deep waters of the Gulf Stream. The current transports a maximum amount of water in the fall and a minimum in the spring.

Western Intensification

In the North Atlantic and North Pacific, the currents flowing on the western side of each ocean tend to be much stronger, deeper, and narrower in cross section than the currents on the eastern side. This phenomenon is known as the **western intensification** of currents. The Gulf Stream and Kuroshio Currents are faster and narrower than the Canary and California Currents, although both the eastern and western boundary currents transport about the same amount of water to preserve continuity of flow around the gyres. Western intensification of currents traveling from low to high latitudes is related to (1) the eastward turning of Earth, (2) the increase in the Coriolis effect with increasing latitude, (3) the changing strength and direction of the east-west wind field (trade winds and westerlies) with latitude, and (4) the friction between land masses and ocean water currents. These factors cause a compression of the currents on the western side of the oceans, where water is moving from lower to higher latitudes. This compression requires that the current speed increase to transport the water circulating about the gyre. On the eastern side of the gyre, where currents are moving from higher to lower latitudes, the currents are stretched in the east-west direction. Here, the current's speed is reduced, but it still transports the required volume of water. The changing speed of flow around the gyre causes the Coriolis effect to vary. Where the current speed is high, the Coriolis effect is large, and a steeper surface slope is required to create a geostrophic flow balance.

Fast-flowing, western-boundary currents move warm equatorial surface water to higher latitudes. Both the Gulf Stream and the Kuroshio Current bring heat from equatorial latitudes to moderate the climates of Japan and northern Asia (in the case of the Kuroshio) and the British Isles and northern Europe (in the case of the Gulf Stream, via the North Atlantic and Norwegian Currents). Western intensification is obscured in the South Pacific and South Atlantic, because both Africa and South America deflect portions of the West Wind Drift and create strong currents on the eastern side of these oceans. The deflection of water from the Atlantic's South Equatorial Current to the Northern Hemisphere removes water from the South Atlantic gyre and strengthens the Gulf Stream. The flow of surface water from the Pacific to the Indian Ocean through the islands of Indonesia also helps to prevent the development of strongly flowing currents on the west side of Southern Hemisphere oceans.

9.4 Eddies

When a narrow, fast-moving current moves into or through slower-moving water, the force of its flow displaces the quieter water and captures additional water as it does so. The current oscillates and develops waves along its boundary that are known as meanders. These meanders break off to form **eddies,** or pockets of water moving with a circular motion; eddies take with them energy of motion from the main flow and gradually dissipate this energy through friction. Eddies also act to mix and blend water.

As the Gulf Stream moves away from the North American coast, it is likely to develop a meandering path. The western edge of the Gulf Stream develops oscillations, and the indentations are filled by cold water from the Labrador Current side. When these indentations pinch off, they become counterclockwise-rotating, cold-water eddies that are displaced eastward through the Gulf Stream and into the warm-water core of the gyre. Bulges at the western edge of the Gulf Stream are filled with warm Gulf Stream water. When these bulges are cut off, they become warm-water, clockwise-rotating eddies drifting into cold water to the west and north of the Gulf Stream. Follow these processes in figures 9.7 and 9.8. These eddies may maintain their physical identity for weeks as they wander about the oceans; they are especially numerous in the area north of the Sargasso Sea. Current meanders and eddy formation produce surface flow patterns that differ markedly from the uniform current flows shown on current charts. These charts show average current flow, not daily or weekly variations.

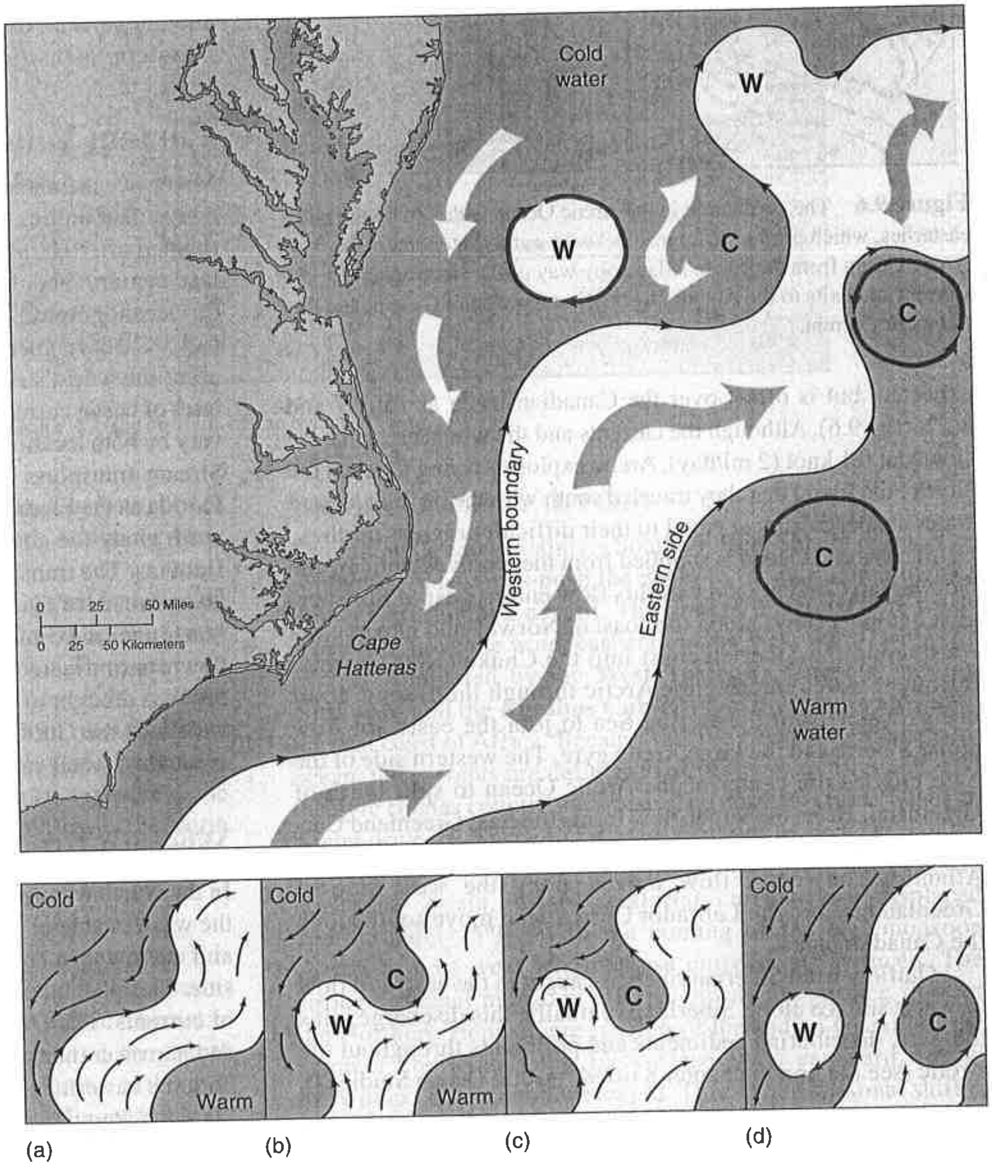

Figure 9.7 The western boundary of the Gulf Stream is defined by sharp changes in current velocity and direction. Meanders form at this boundary after the Gulf Stream leaves the U.S. coast at Cape Hatteras. The amplitude of the meanders increases as they move downstream (a and b). In time, the current flow pinches off the meander (c). The current boundary re-forms, and isolated rotating cells of warm water (*W*) wander into the cold water, while cells of cold water (*C*) drift through the Gulf Stream into the warm water (d).

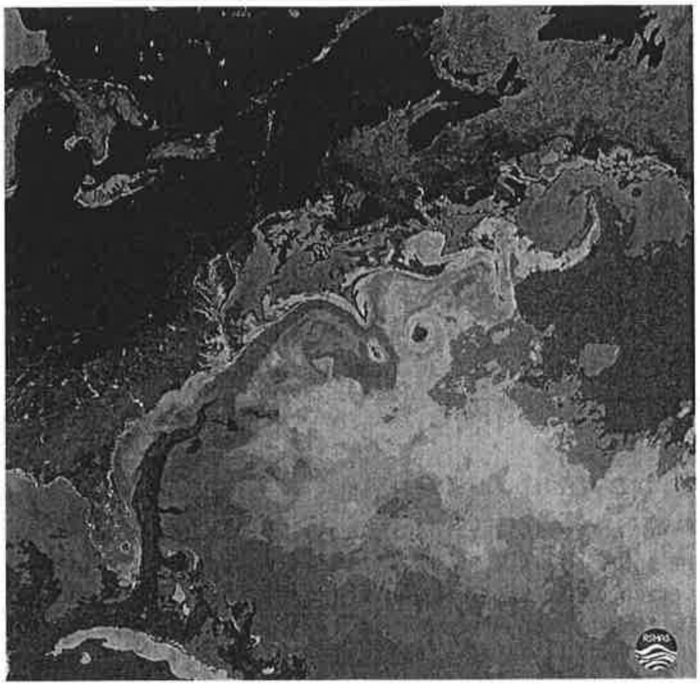

Figure 9.8 A composite satellite image of the sea surface reveals the warm (*orange* and *yellow*) and cold (*green* and *blue*) eddies that form along the Gulf Stream. (*Reddish blue* areas at the top are the coldest waters.) These eddies may stir the water column right down to the ocean floor, kicking up blizzards of sediment.

Figure 9.9 Space shuttle view. Sunlight reflected off the Mediterranean reveals spiral eddies; their effects on climate are being monitored. Dimensions of this image are 500 km × 500 km (310 mi × 310 mi).

Large and small eddies generated by horizontal flows or currents exist in all parts of the oceans; these eddies are of varying sizes, ranging from 10 to several hundred kilometers in diameter. Each eddy contains water with specific chemical and physical properties and maintains its identity and rotational inertia as it wanders through the oceans. Eddies may appear at the sea surface or be embedded in waters at any depth.

Eddies rotate in a clockwise or counterclockwise direction. They stir the ocean until they gradually dissipate because of fluid friction, losing their chemical and thermal identity and their energy of motion. By testing the water properties of an eddy, oceanographers are able to determine the eddy's place of origin. Small surface eddies encountered 800 km (500 mi) southeast of Cape Hatteras in the North Atlantic have been found with water properties of the eastern Atlantic near Gibraltar, more than 4000 km (2500 mi) away. Eddies from the Strait of Gibraltar are formed in the salty water of the Mediterranean as it sinks and spreads out into the Atlantic 500–1000 m (1600–3300 ft) down; these eddies have been nicknamed "Meddies." Deep-water eddies near Cape Hatteras may come from the eastern and western Atlantic, the Caribbean, or Iceland. Researchers estimate that some of these eddies are several years old; age determination is based on drift rates, distance from source, and biological consumption of oxygen.

The rotational water speed in the large eddies that form at the western boundary of the Gulf Stream is about 0.51 m/s (1 knot), but because of the water's density, the force of the flow is similar to that generated by a 35-knot wind. The diameter of the eddies may be as much as 325 km (200 mi), and their effect may reach to the sea floor. At the sea floor, the rotation rate is zero; therefore, a few meters above the bottom the speed of rotation diminishes very rapidly, and considerable turbulence is generated as the energy of the eddy is dissipated. These eddies are similar in many ways to the winds rotating about atmospheric pressure cells, and they are sometimes called abyssal storms. As the eddies wander through the oceans, they stir up bottom sediments, producing ripples and sand waves in their wakes; they also mix the water, creating homogeneous water properties over large areas. Eventually, the eddies lose their energy to turbulence and blend into the surrounding water.

Eddies constantly form, migrate, and dissipate at all depths. Eddy motion is superimposed on the mean flow of the oceans. To understand the role of eddies in mixing the oceans, we need more data and better tracking of eddy size, position, and rate of dissipation. Satellites are important tools for detecting surface eddies because they can precisely measure temperature, increased elevation, and light reflection of the sea surface (fig. 9.9). Deep-water eddies are monitored by using instruments designed to float at a mid-depth density layer. The instruments are caught up in the eddies, moving with them and sending out acoustic signals that are monitored through the sofar channel. In this way, the rate of deep-water eddy formation, the numbers of major eddies, their movements, and their life spans can be observed.