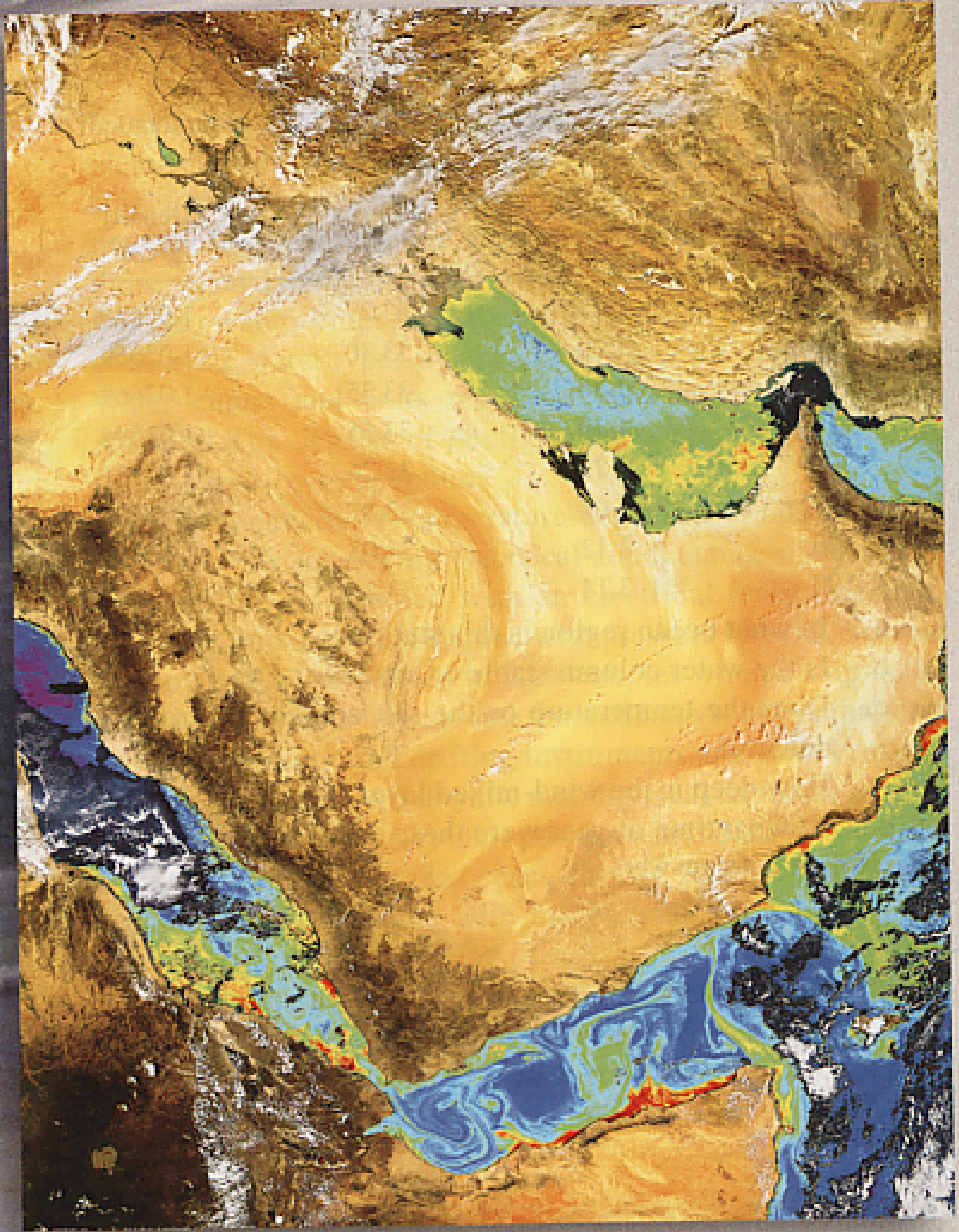
Chapter 9



Between Yemen and Somalia, the waters of the Gulf of Aden swirl in topographically squared off eddies which, in this SeaWIFS image, are made visible by the chlorophyll-bearing phytoplankton that they carry. This image was collected on November 1, 2003.

The Surface Currents

Chapter Outline

9.1 Surface Currents 219
9.2 Wind-Driven Ocean Currents 221
9.3 Current Flow 223
9.4 Eddies 224
9.5 Convergence and Divergence 226
9.6 Changing Circulation Patterns 228
Box: *Ocean Drifters 231*
9.7 Measuring the Currents 234
9.8 Practical Considerations: Energy from the Currents 236
Summary 237
Key Terms 237
Study Questions 237

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.

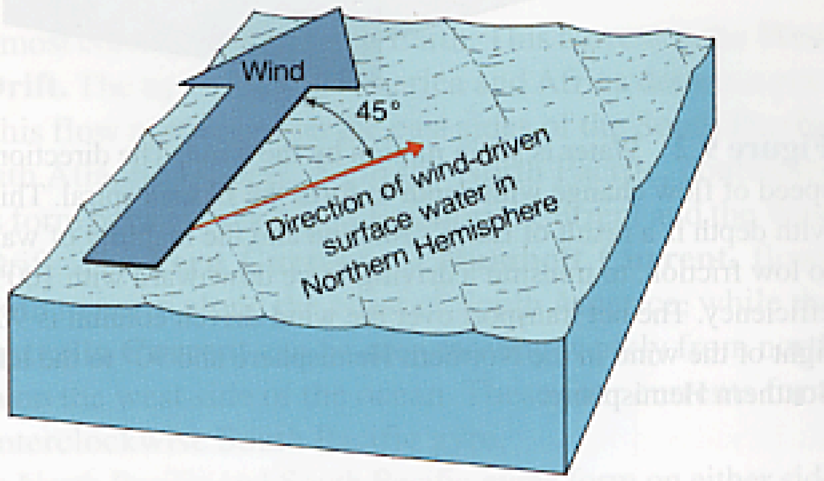


Figure 9.1 A wind-driven surface current moves at an angle of 45° to the direction of the wind; this angle is to the right in the Northern Hemisphere and to the left in the Southern Hemisphere.

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

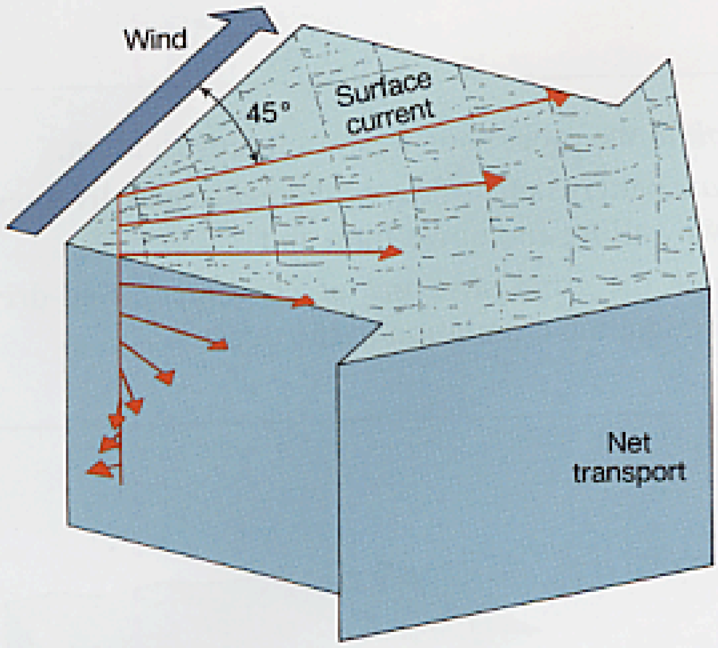


Figure 9.2 Water is set in motion by the wind. The direction and speed of flow change with depth to form the Ekman spiral. This change with depth is a result of Earth's rotation and the inability of water, due to low friction, to transmit a driving force downward with 100% efficiency. The net transport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

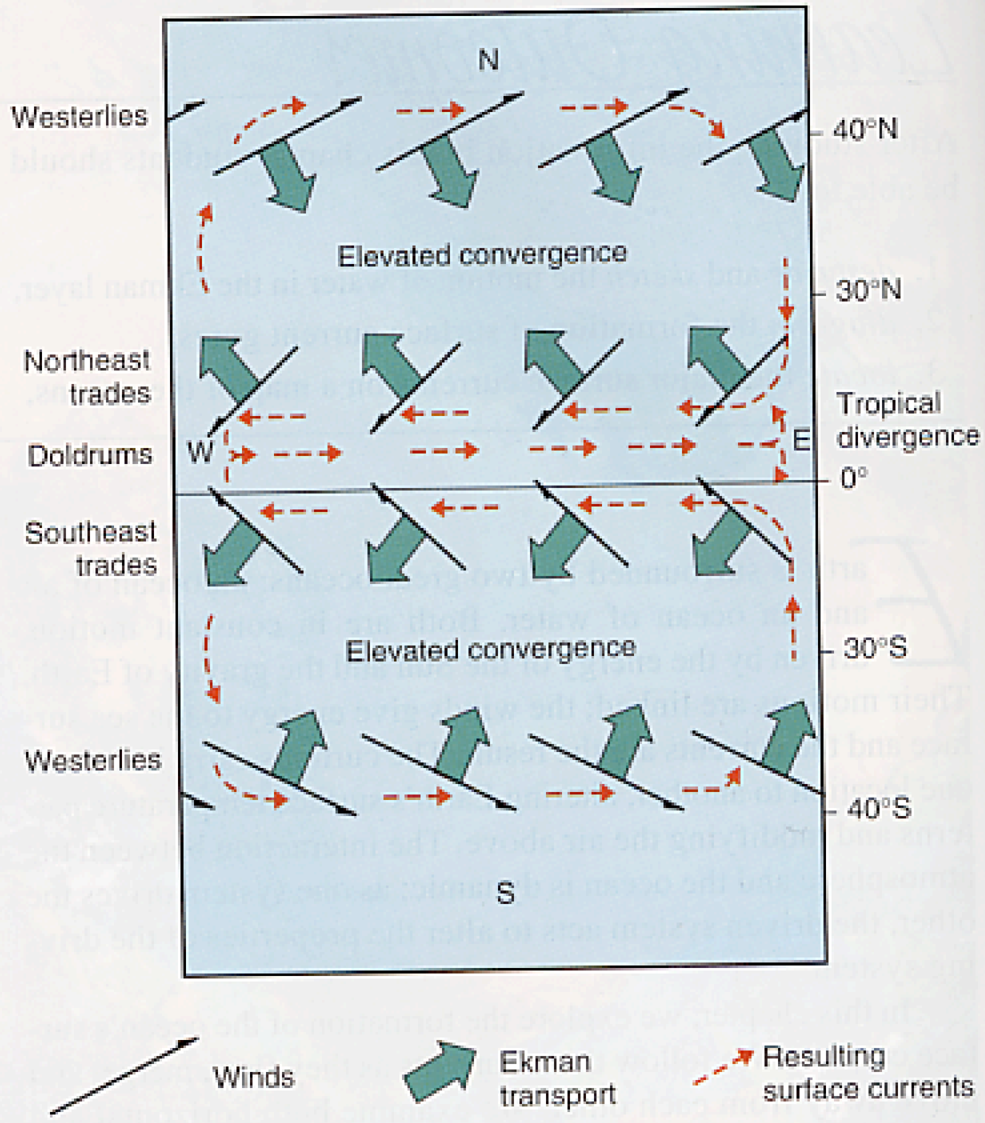


Figure 9.3 Wind-driven transport and resulting surface currents in an ocean bounded by land to the east and to the west. The currents form large oceanic gyres that rotate clockwise in the Northern Hemisphere and counterclockwise in the Southern Hemisphere.

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.

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

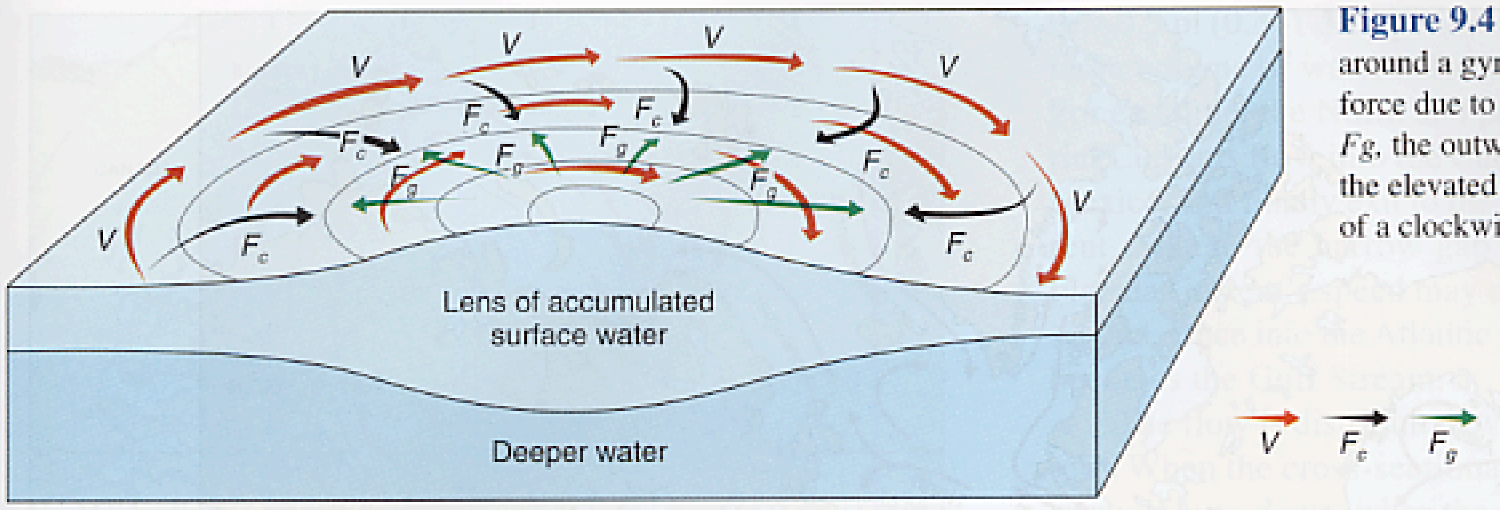


Figure 9.4 Geostrophic flow (V) exists around a gyre when Fc, the inward deflection force due to the Coriolis effect, is balanced by Fg, the outward-acting pressure force created by the elevated water and gravity. This example is of a clockwise gyre in the Northern Hemisphere.

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 **West 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 West 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 of 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 Equatorial 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 as 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 currents are the **Gulf Stream,** flowing northward along the coast of 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, but the bulge of Brazil deflects part of the **South Equatorial Current** northward into the Caribbean Sea and eventually into the Gulf of Mexico, where it exits as the Florida Current and joins the Gulf Stream. A portion of the South Equatorial Current moves south of the Brazilian bulge along the western side of the South Atlantic

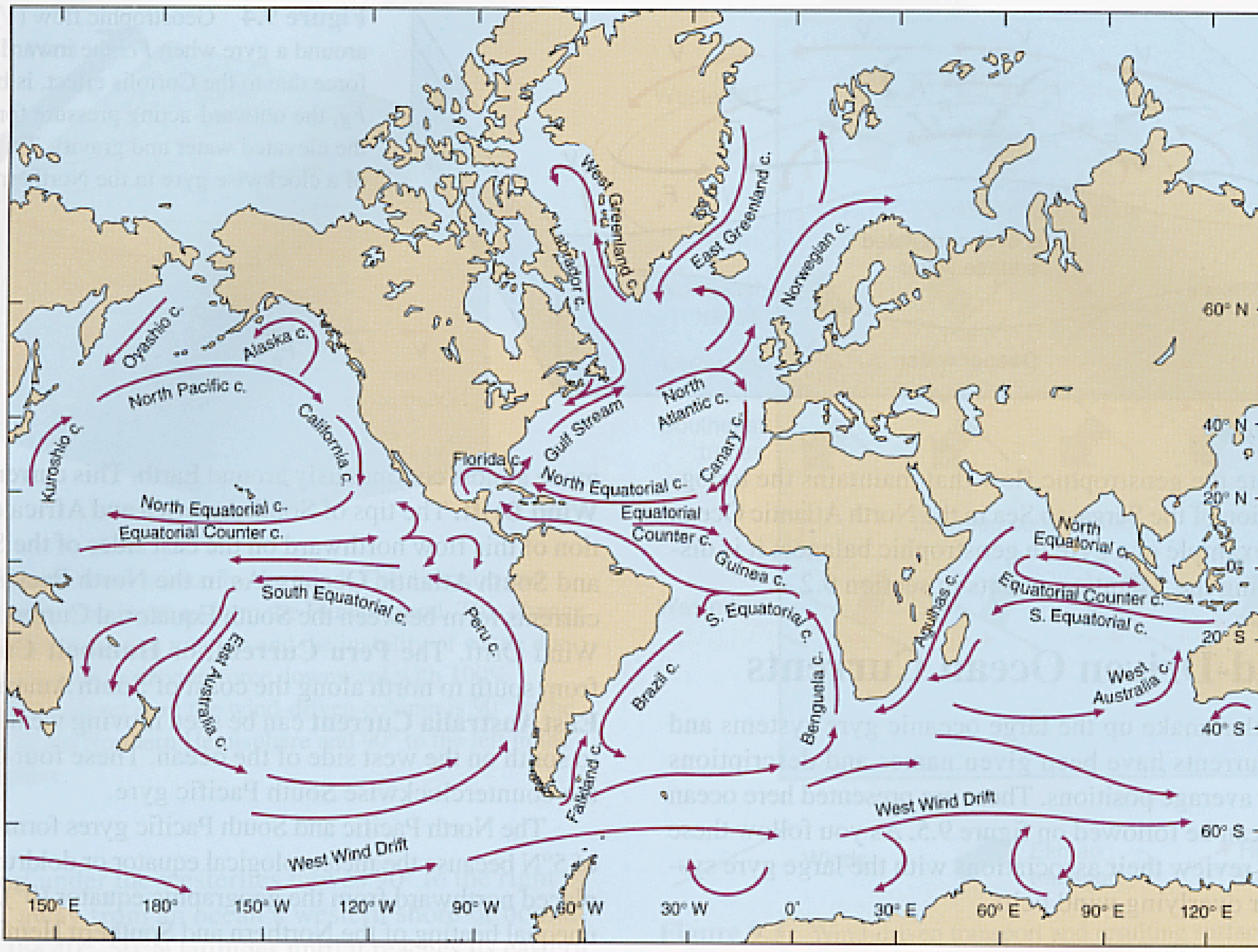


Figure 9.5 The long-term average flow of the major surface currents of the oceans.

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

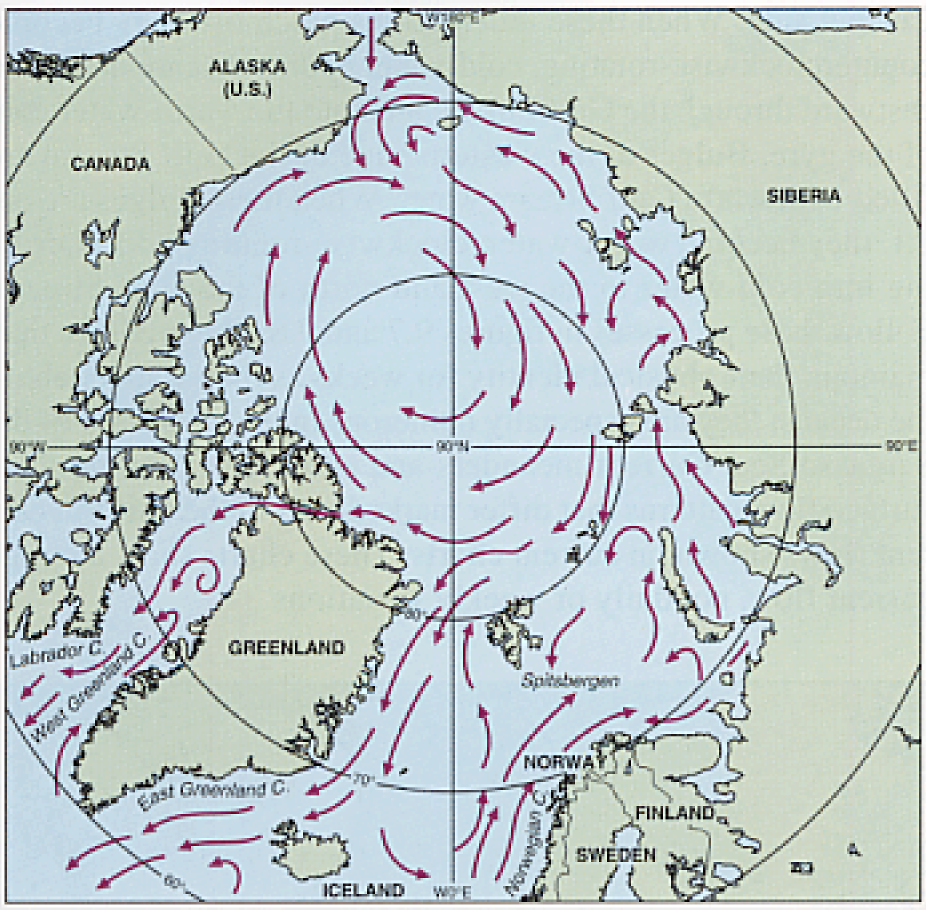


Figure 9.6 The circulation in the Arctic Ocean is driven by the polar easterlies, which produce a large, clockwise gyre. Water enters the Arctic Ocean from the North Atlantic by way of the Norwegian Current and exits to the Atlantic by the East Greenland Current and the Labrador Current.

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.

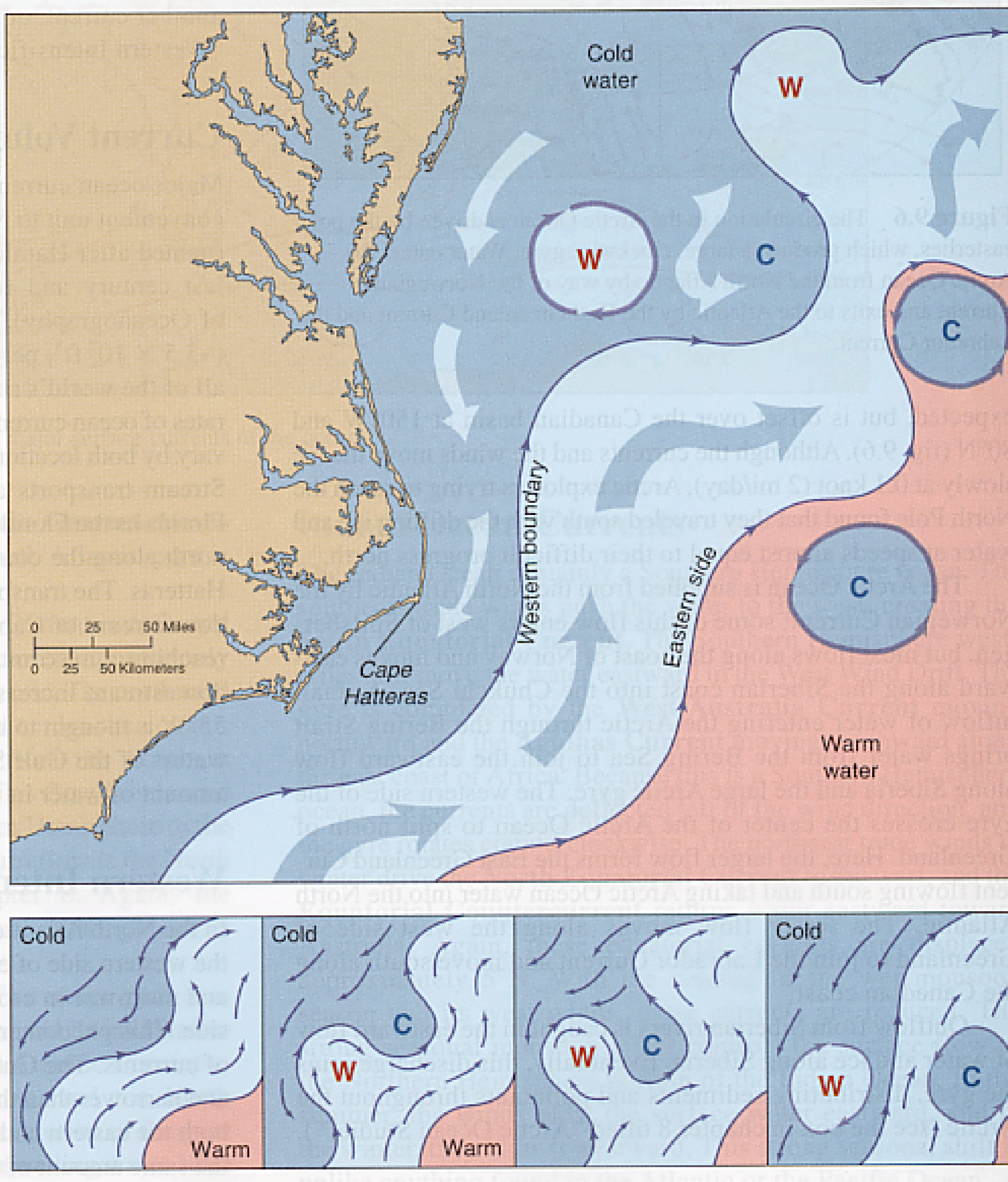


Figure 9.7 The western boundary of the Gulf Stream is defined by sharp changes in current velocity and direction. Meanders form at this boundary after the Gulf Stream leaves the U.S. coast at Cape Hatteras. The amplitude of the meanders increases as they move downstream (a and b). In time, the current 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).

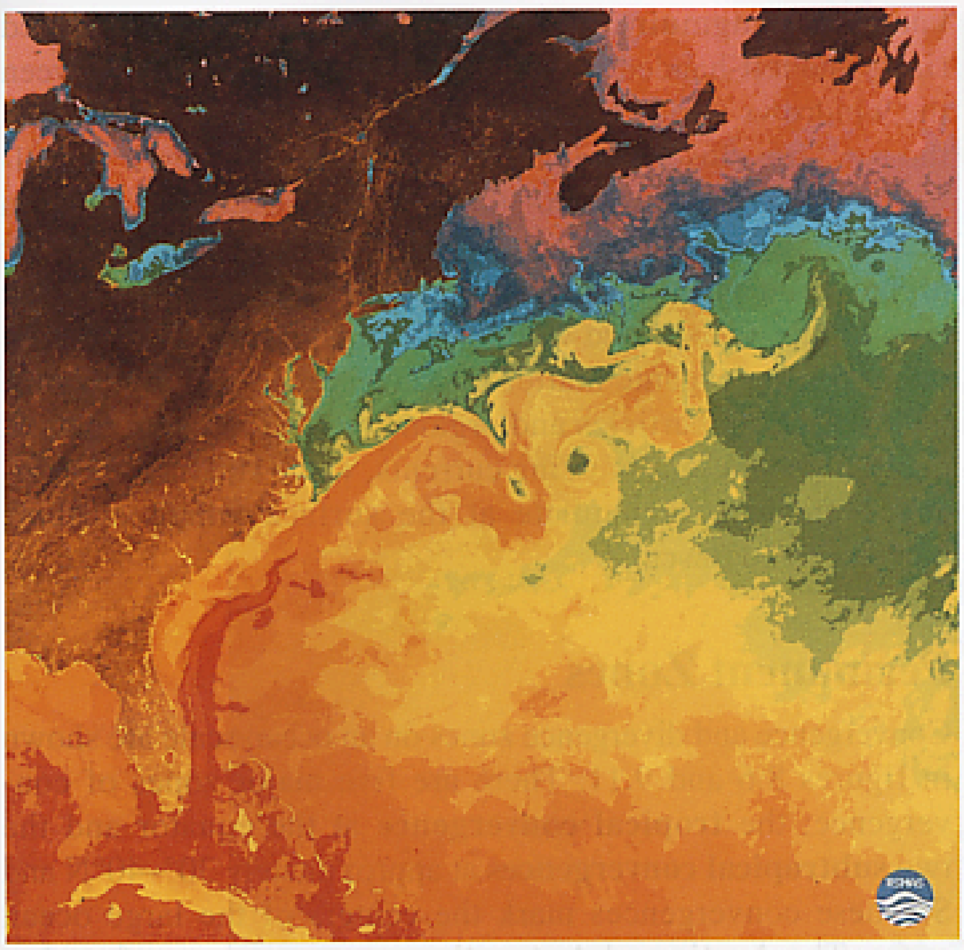


Figure 9.8 A composite satellite image of the sea surface reveals the warm (*orange* and *yellow*) and cold (*green* and *blue*) eddies that form along the Gulf Stream. (*Reddish blue* areas at the top are the coldest waters.) These eddies may stir the water column right down to the ocean floor, kicking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

9.5 Convergence and Divergence

Changes in density and the accompanying concepts of upwelling, downwelling, convergence, divergence, and continuity of flow were introduced in section 8.2 of chapter 8. The convergence and divergence zones discussed in this chapter are the product of wind-driven surface currents that produce large-scale areas of convergence and divergence at the sea surface. For example, convergence zones are at the centers of the large oceanic gyres, and when wind-driven surface currents collide or are forced against landmasses, they produce convergences. When surface currents move away from each other or away from a landmass, they produce a surface divergence. Upwellings and downwellings of this type are nearly permanent but do react to seasonal changes in Earth's surface winds.

Langmuir Cells

A strong wind blowing across the sea surface often causes streaks of foam and surface debris that are seen trailing off in the direction the wind is blowing. These streaks are called windrows and may be 100 m (330 ft) in length. Windrows mark the convergence zones of shallow circulation cells known as **Langmuir cells.** These cells are composed of paired right- and left-handed helixes (fig. 9.10). The spacing between the windrows varies between 5 and 50 m (16 and 160 ft), and the rows are closer together if the thermocline depth is shallow. The vertical extent of these Langmuir cells is 4–10 m (12–30 ft). The distance between rows becomes larger at higher wind speeds. Langmuir cells are not long-lasting but help to mix the surface waters and organize the distribution of suspended organic matter in convergence and divergence zones. Sinking particles and organisms tend to congregate at depth in the regions of rising currents, while floating particles and organisms accumulate at the surface where currents converge and descend.

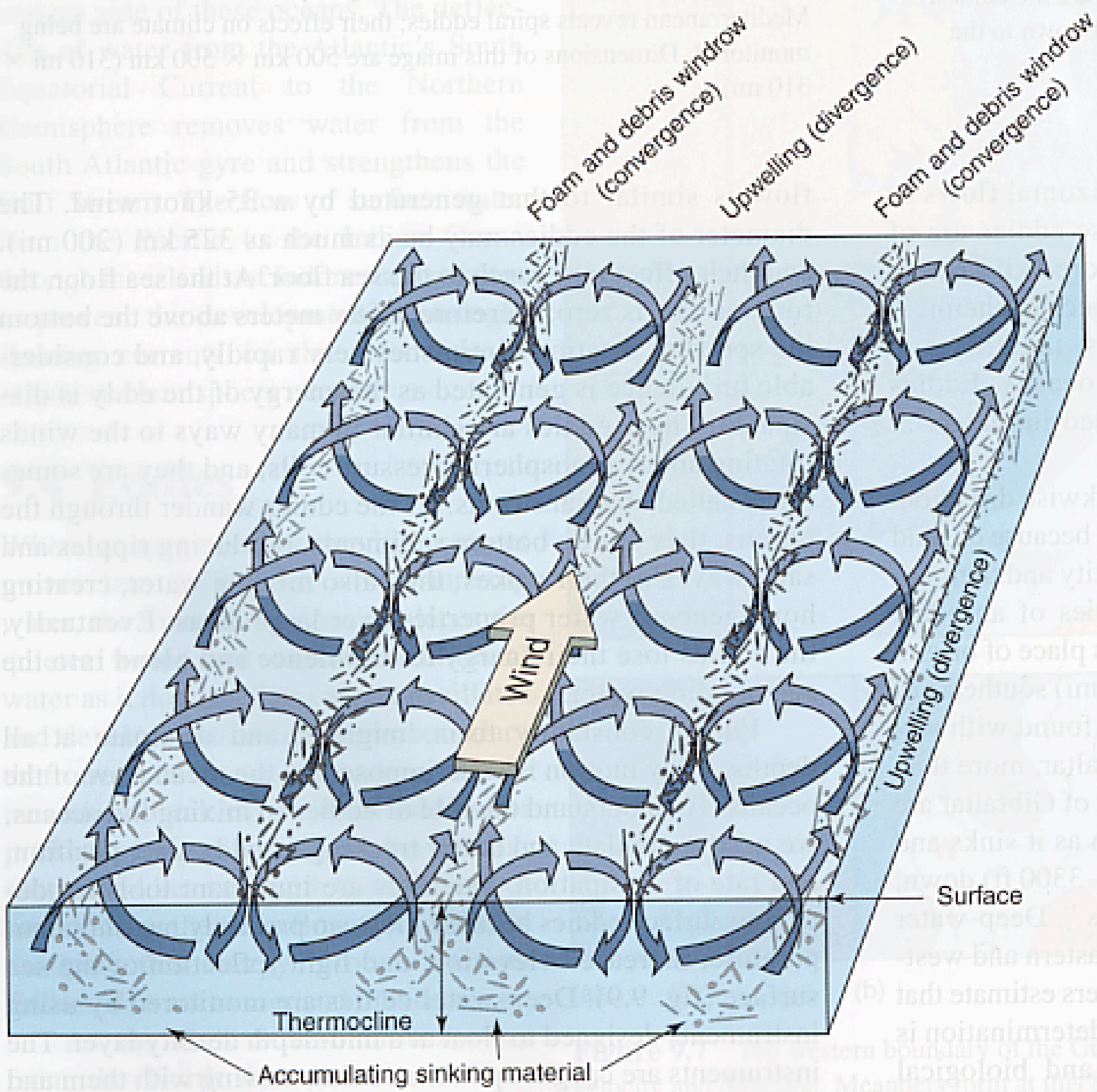


Figure 9.10 Langmuir cells are helixes of near-surface, wind-driven water motion. The cells extend downwind to form windrows of surface debris along convergences. At the same time, sinking materials are swept into zones of upwelling water.

Permanent Zones

Convergence and divergence zones on an ocean scale are shown in figures 8.6 and 9.11. There are five major zones of convergence: the **tropical convergence** at the equator and the two **subtropical convergences** at approximately 30°–40°N and S. These convergences mark the centers of the large ocean gyres. The **Arctic** and **Antarctic convergences** are found at about 50°N and S. Surface convergence zones are regions of downwelling. These areas are low in nutrients and biological productivity. There are three major divergence zones: the two **tropical divergences** and the **Antarctic divergence.** Upwelling associated with divergences delivers nutrients to the surface waters to supply the food chains that support the anchovy and tropical tuna fisheries and the richly productive waters of Antarctica.

In coastal areas where trade winds move the surface waters away from the western side of continents, upwelling occurs nearly continuously throughout the year. For example, the trade winds drive upwellings off the west coasts of Africa and South America that are very productive and yield large fish catches.

Seasonal Zones

Off the west coast of North America, downwelling and upwelling occur seasonally as the Northern Hemisphere temperate wind pattern changes from southerly in winter to northerly in summer. The downwelling and upwelling occur because of the change in direction of Ekman transport (fig. 9.12). Remember that the wind-driven Ekman transport moves at an angle of 90° to the right or left of the wind direction, depending on the hemisphere.

Along this coast, the average wind blows from the north in the summer, and

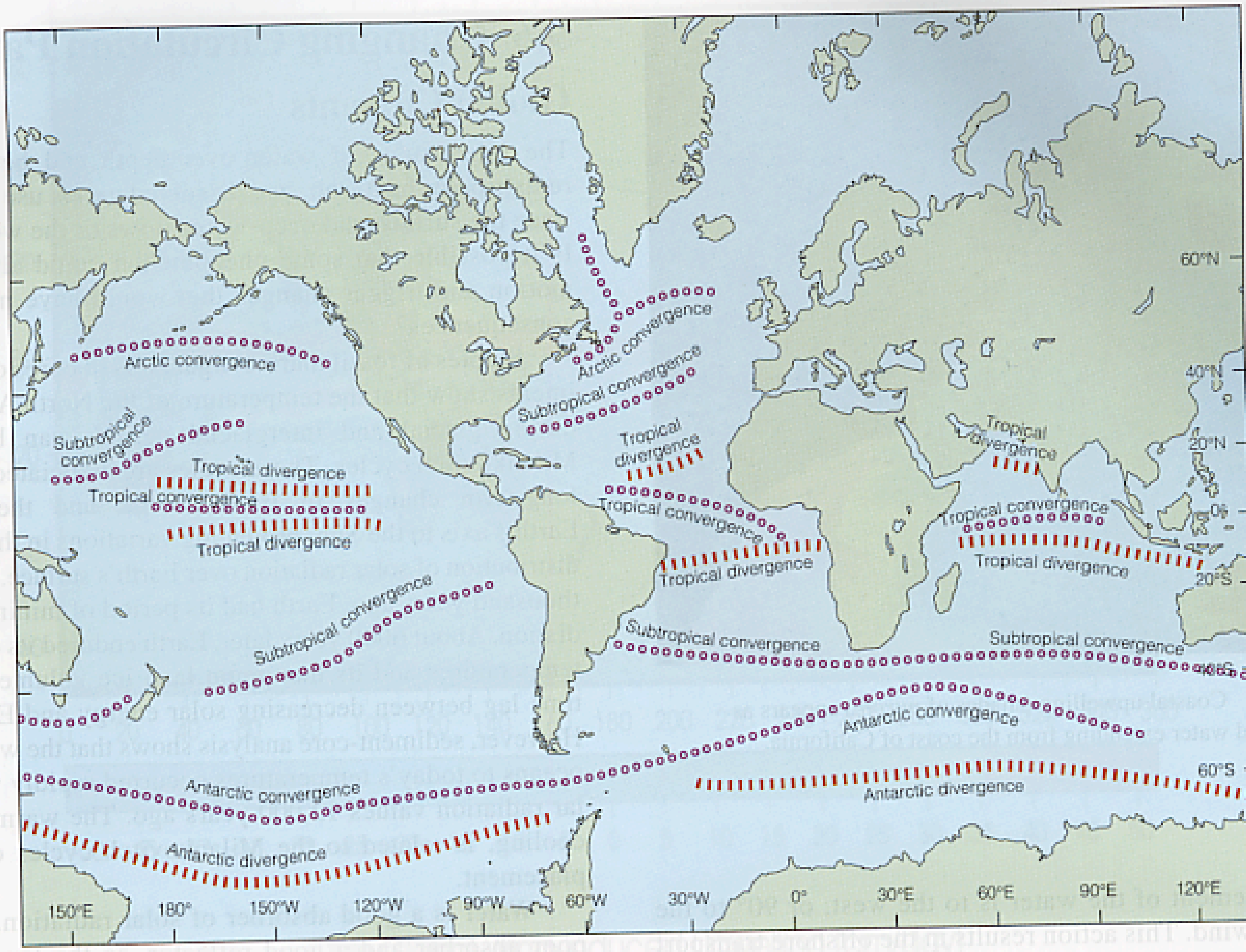


Figure 9.11 The principal zones of open-ocean surface convergence and divergence associated with wind-driven and thermohaline circulation.

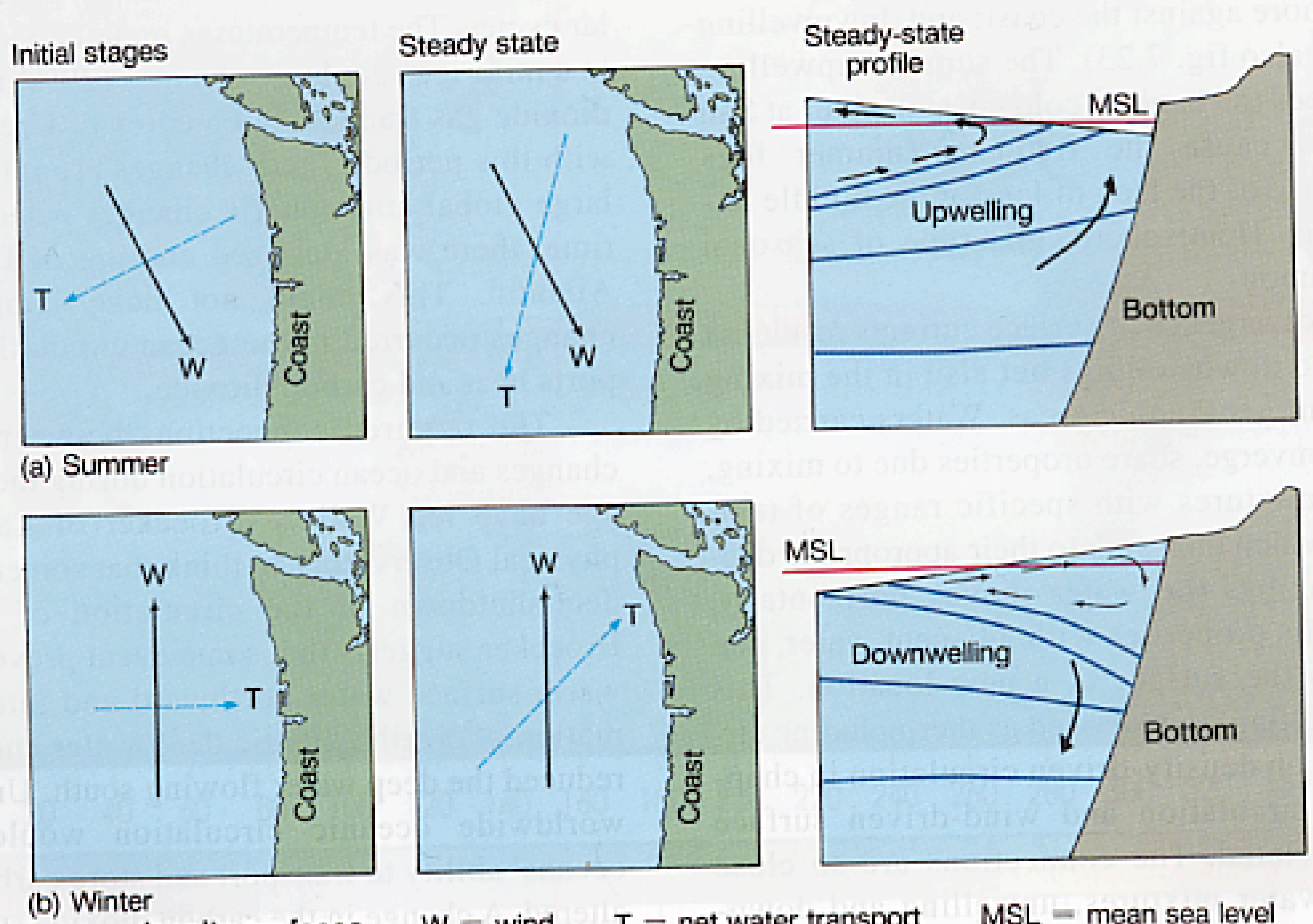


Figure 9.12 Initially, the Ekman transport is 90° to the right of the wind along the northwest coast of North America. As water is transported (a) away from the shore in summer or (b) toward the shore in winter, a sea surface slope is produced. This slope creates a gravitational force that alters the direction of the Ekman transport to produce a geostrophic balance and a new steady-state direction.

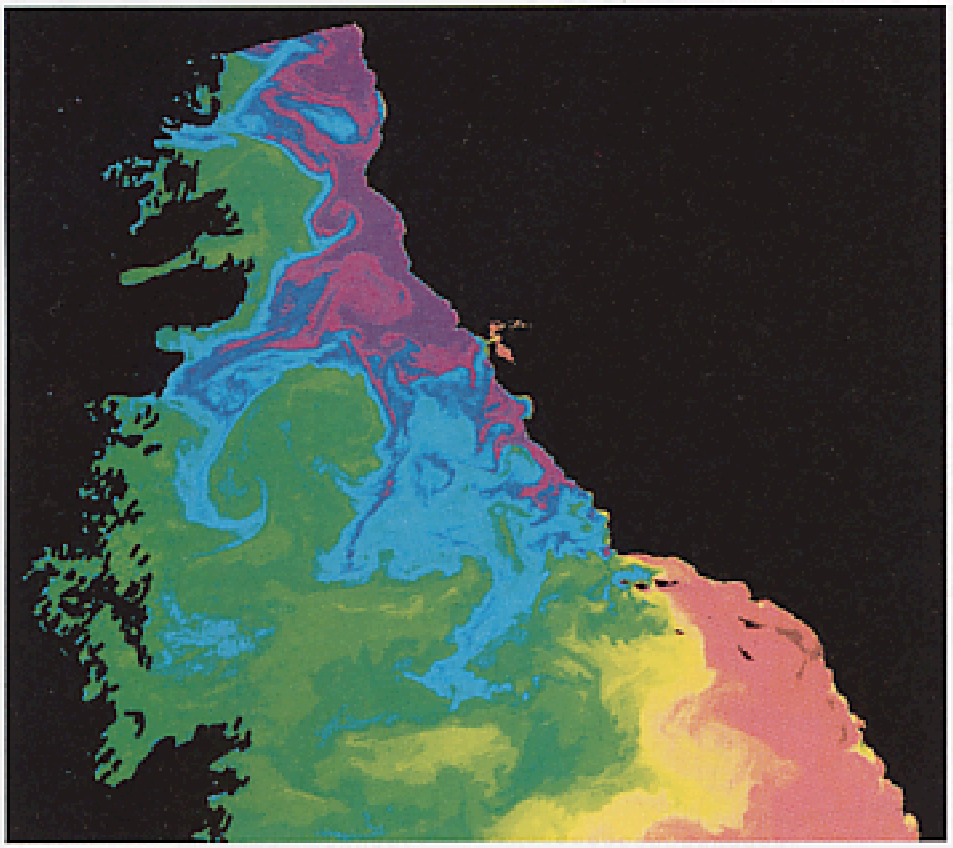


Figure 9.13 Coastal upwelling (shades of *purple*) appears as patches of cold water extending from the coast of California.

the net movement of the water is to the west, or 90° to the right of the wind. This action results in the offshore transport of the surface water and the upwelling of deeper water along the coast to replace it. The upwelling zone is evident from central California to Vancouver Island (fig. 9.13). In winter, the winds blow from the south; the wind-driven surface waters move to the east, onshore against the coast; and downwelling occurs (fig. 9.14; see also fig. 7.23). The summer upwelling pattern is what produces the band of cold coastal water at San Francisco that helps cause the frequent summer fogs (see chapter 5). Because of the lack of land at the middle latitudes in the Southern Hemisphere, this type of seasonal upwelling is less common.

Convergence and divergence of surface currents result not only in upwellings and downwellings but also in the mixing of water from different geographic areas. Waters carried by the surface currents converge, share properties due to mixing, and form new water mixtures with specific ranges of temperature and salinity, which then sink to their appropriate density levels. After sinking, the water moves horizontally, blending and sharing its properties with adjacent water, and eventually, it rises to the surface at a new location. This process, known as caballing, is discussed as thermohaline circulation in the section on density-driven circulation in chapter 8. Thermohaline circulation and wind-driven surface currents are closely related. The connections are so close among formation of water mixtures, upwelling and downwelling, and convergence and divergence that it is difficult to assign a priority of importance to one process over another. Changes in these flows and events that might cause such changes are discussed in section 9.6.

9.6 Changing Circulation Patterns

Global Currents

The interchange of water over depth and between oceans redistributes heat, salt, and dissolved gases; use figure 9.15 to trace the surface and deep-water flows of the world's oceans. Is it possible that some phenomenon could alter this water motion and trigger changes that would have major climatic consequences?

Studies of fossil marine organisms in cores of marine sediments show that the temperature of the North Atlantic Ocean during glacial and interglacial periods can be related to Milankovitch cycles. These cycles are associated with regular long-term changes in Earth's orbit and the relation of Earth's axis to the Sun, producing variations in the amount and distribution of solar radiation over Earth's surface. Twenty-three thousand years ago, Earth had its period of minimum solar radiation. About 6000 years later, Earth endured its coldest ocean temperatures and its maximum land ice volumes. Notice the time lag between decreasing solar energy and Earth cooling. However, sediment-core analysis shows that the warming of the oceans to today's temperatures occurred rapidly with high solar radiation values 12,000 years ago. The warming, like the cooling, is related to the Milankovitch cycles of Earth-Sun placement.

Water is a good absorber of solar radiation, but ice is a poor absorber and a good reflector, so the land ice melted slowly as the oceans warmed rapidly. Eleven thousand years ago, the surface temperatures of the water in the North Atlantic and the air temperatures in northern Europe decreased suddenly; the sudden decrease was unrelated to the long-term solar cycles. The temperatures remained low for about 700 years in a mini-ice age; large changes (20%) in atmospheric carbon dioxide gas trapped in ice cores of Greenland are associated with this period. These changes are interpreted to mean that large global atmospheric changes occurred, and at the same time, there was localized cooling of Europe and the North Atlantic. This could not have happened unless major changes occurred in the ocean circulation system that transports heat and carbon dioxide.

The required connections between global atmospheric changes and ocean circulation during the time of this mini-ice age have led Wallace Broecker of Lamont Doherty Geophysical Observatory to think that something triggered a sudden shutdown of the circulation of the North Atlantic. Broecker suggests that some event prevented the transport of warm surface water northward and interfered with the formation of North Atlantic deep water and in so doing greatly reduced the deep water flowing south. Under such conditions, worldwide oceanic circulation would change, and the oceans' ability to transport and store carbon dioxide would be altered. A change in the carbon dioxide storage capacity of the oceans requires a corresponding change in atmospheric carbon dioxide levels.

Broecker has proposed that the trigger for such an episode was a sudden change in the location where meltwater from the

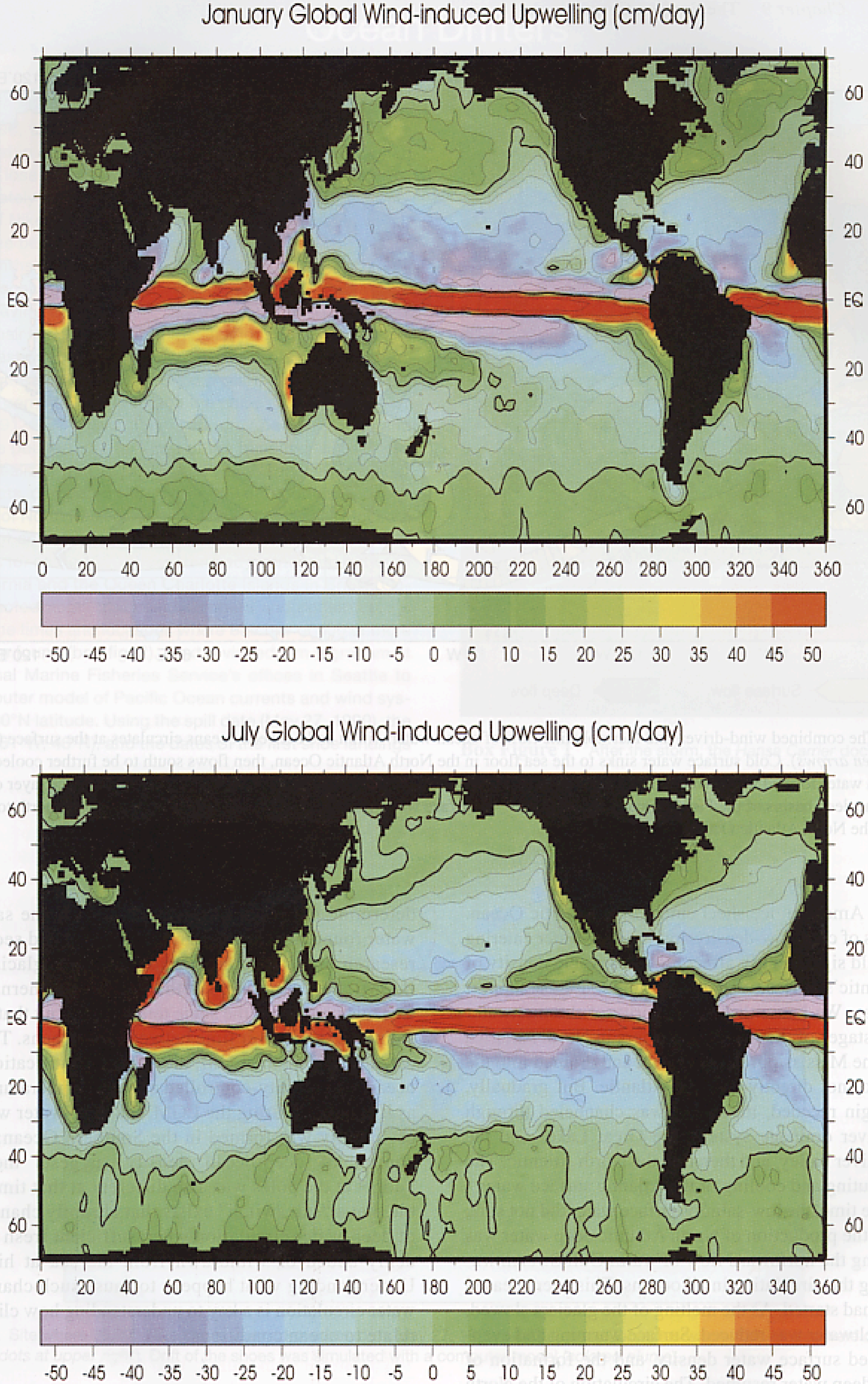


Figure 9.14 Surface winds produce surface divergences and convergences that create areas of upwelling and downwelling. Average surface wind stress values were used to produce this model of global upwelling and downwelling for January (a) and July (b). Negative values indicate downwelling. Speed of vertical motion is given in centimeters per day.

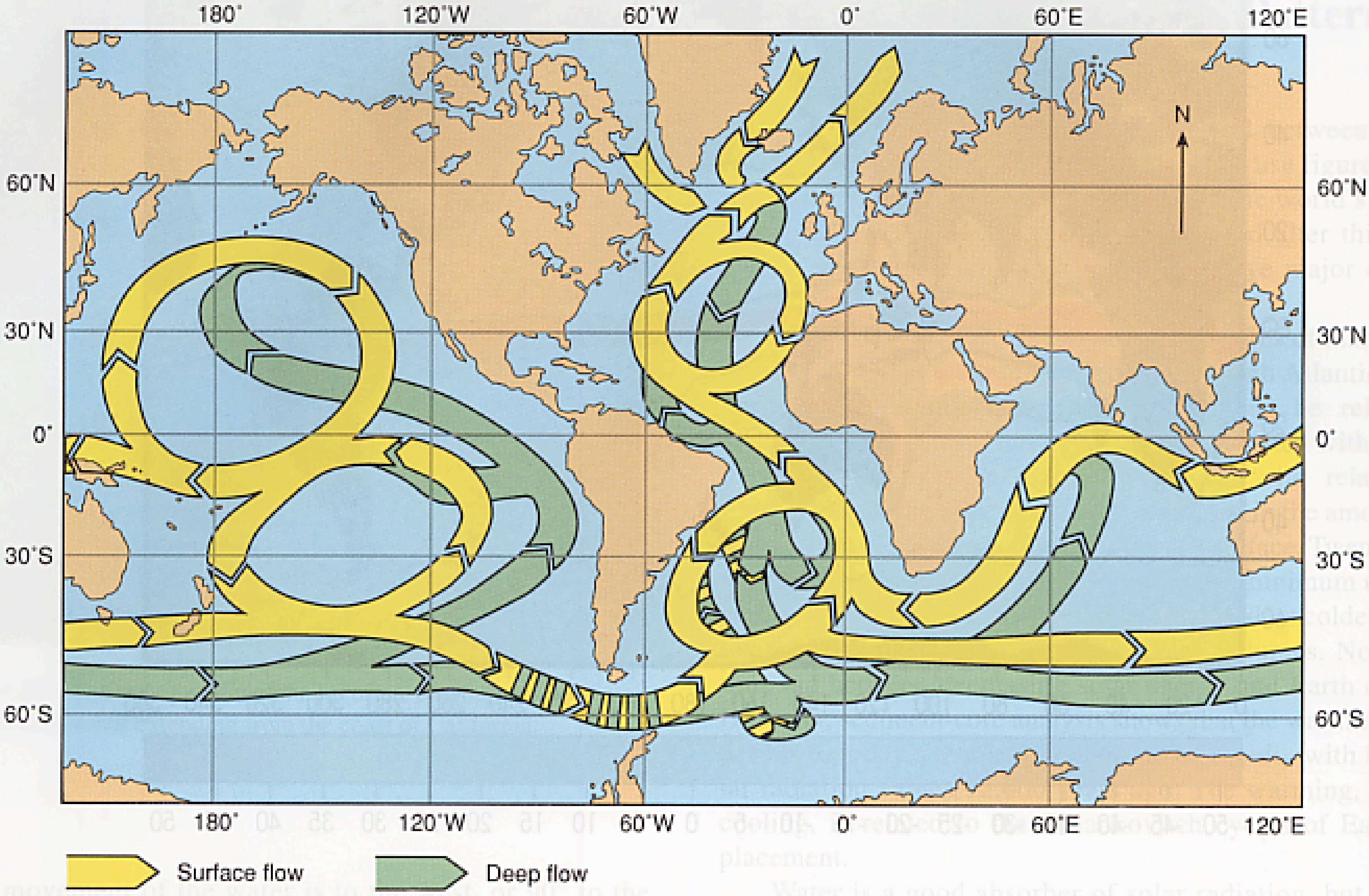


Figure 9.15 The combined wind-driven and thermohaline flow of ocean water within and between oceans circulates at the surface (*yellow arrows*) and at depth (*green arrows*). Cold surface water sinks to the sea floor in the North Atlantic Ocean, then flows south to be further cooled by the Antarctic Bottom water formed in the Weddell Sea. This deep water moves eastward around Antarctica, feeding into the surface layer of the Indian Ocean and into the deep basins of the Pacific Ocean. A return flow of surface water from the Pacific and Indian Oceans moves north to replace the surface water in the North Atlantic Ocean.

receding North American ice sheet entered the Atlantic Ocean. Large quantities of cold, low-density, low-salinity water entering the oceans would significantly affect the salinity and density of the North Atlantic's surface waters. Geologic studies support Broecker's ideas. We know that the majority of the meltwater from the early stages of the receding glaciers in North America converged on the Mississippi River system and drained into the Gulf of Mexico, not directly into the Atlantic. But gradually, as the ice margin receded, meltwater was channeled through the Hudson River drainage system, the Great Lakes and the St. Lawrence River valley, and then into the North Atlantic. The result was a diluting and cooling of the Atlantic surface water.

At the same time, the low-salinity surface water did not sink, and, therefore, the production of North Atlantic deep water was slowed, reducing the northward flow of warm Gulf Stream water and affecting the circulation in all oceans. This event ceased as rapidly as it had started. As the melting of the glaciers slowed, the influx of meltwater was reduced. Surface warming and evaporation increased surface water density, and the formation of North Atlantic deep water resumed. The circulation of the North Atlantic began a rapid recovery.

Sediment cores obtained by the Ocean Drilling Program have allowed measurements of (1) oxygen isotopes to determine the water temperature and (2) the salt content of water found between the grains of age-dated sediments. This research indicates that during the last glacial maximum (LGM), the deep waters of the Pacific, Southern, and Atlantic Oceans were about the same temperature but that variations in salinity existed over time between the oceans. This data indicate that during the LGM, the density stratification in the deep ocean was salinity-controlled and not temperature-controlled, as it is today. During the LGM, the deep water with the greatest salinity was formed in the Southern Ocean; this salinity control of deep-ocean density suggests the freshwater budget at the poles was also different at that time. It is possible that a "salt switch" exists that abruptly changes the mode of deep-water circulation when sufficient fresh water is suddenly added or withdrawn from the sea at high latitudes. Understanding what happens to cause such changes in deep-water circulation is a key to understanding how climate changes relate to ocean conditions.

North Pacific Oscillations

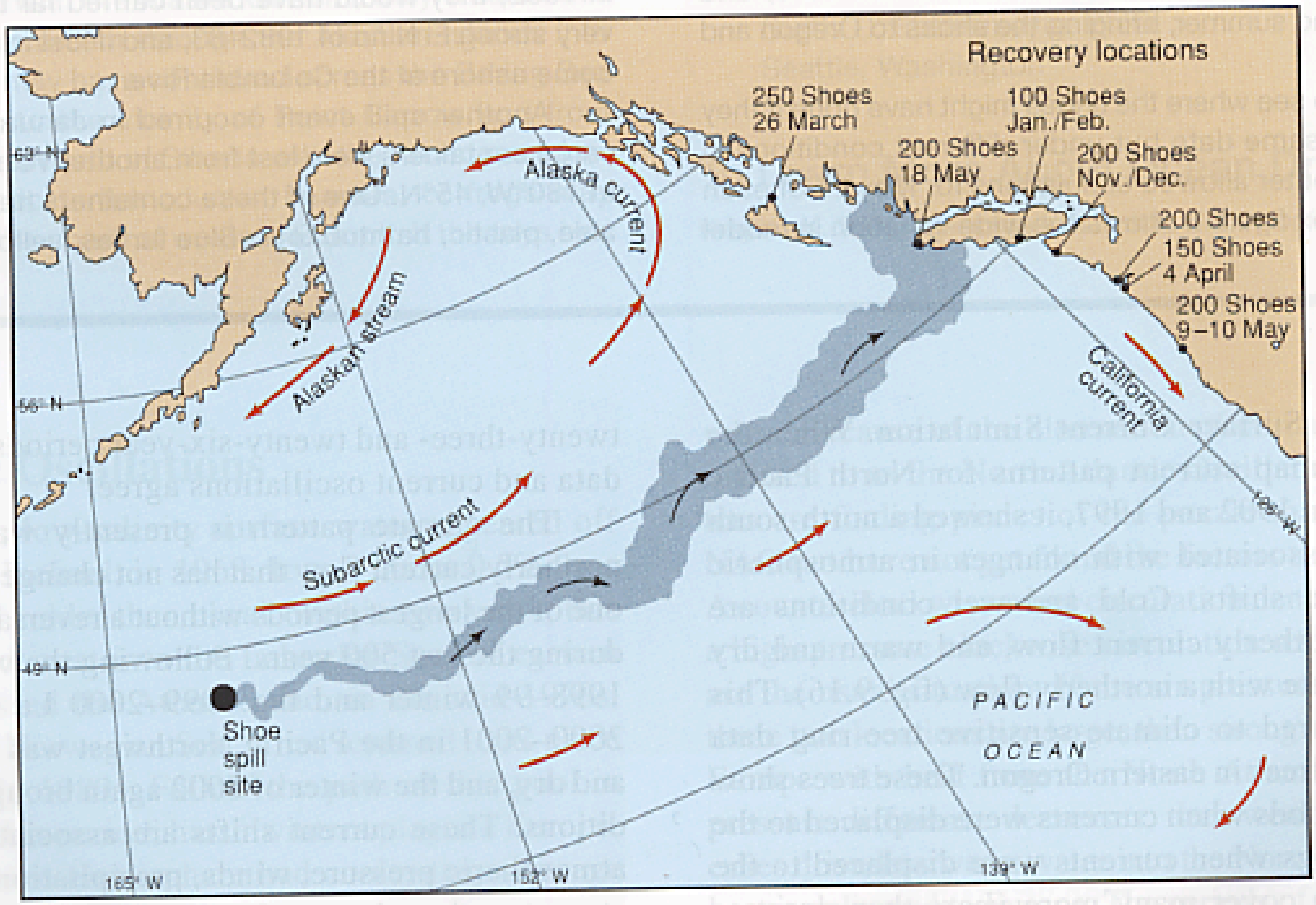
W. James Ingraham, Jr., an oceanographer at NOAA's Seattle laboratory, has developed a North Pacific Current model, or

Ocean Drifters

In May 1990, a severe storm in the North Pacific caused the container ship *Hansa Carrier,* en route from Korea to the United States, to lose overboard twenty-one deck-cargo containers, each approximately 40 ft long (box fig. 1). Among the items lost were 39,466 pairs of Nike brand athletic shoes, and these began washing up along the beaches of Washington, Oregon, and British Columbia six months to a year later. Although the shoes had been drifting in the ocean for almost a year, they were wearable after washing and having the barnacles and the oil removed. However, the shoes of a pair had not been tied together for shipping, and pairs did not come ashore together. As beach residents recovered the shoes (some with a retail value of $100 a pair), swap meets were held in coastal communities to match the pairs.

In May 1991, I was having lunch with my parents, Gene and Paul, and Gene pointed out the news of the beached Nikes. I was intrigued and realized that 78,932 shoes was a very large number of drifting objects, compared with the 33,869 drift bottles used in a 1956–59 study of North Pacific currents. I contacted Steve McLeod, an Oregon artist and shoe collector who had information on locations and dates for some 1600 shoes that had been found between northern California and the Queen Charlotte Islands in British Columbia. I contacted additional beachcombers and constructed a map showing the times and locations where batches of 100 or more shoes had been found (box fig. 2). Next, I visited Jim Ingraham at NOAA's National Marine Fisheries Service's offices in Seattle to study his computer model of Pacific Ocean currents and wind systems north of 30°N latitude. Using the spill date (May 27, 1990), the spill location (161°W; 48°N), and the dates of the first shoe landings

Box Figure 1 After the storm, the *Hansa Carrier* docked in Seattle.

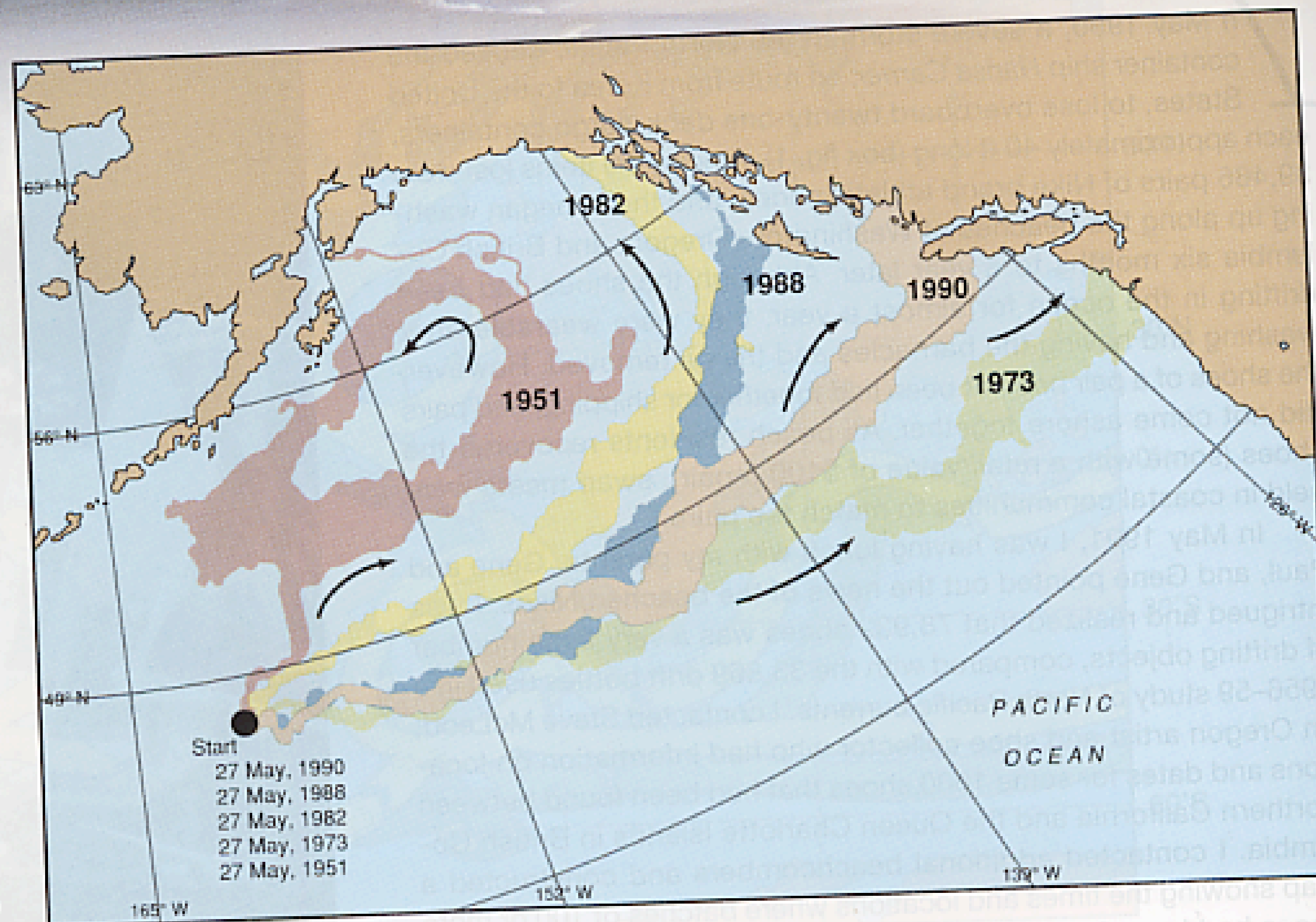


Box Figure 2 Site where 80,000 Nike shoes washed overboard on May 27, 1990, and dates and locations where 1300 shoes were discovered by beachcombers (*dots at upper right*). Drift of the shoes was simulated with a computer model (*colored plume*).

(continued)

on Vancouver Island and Washington beaches between Thanksgiving and Christmas 1990, I found that the shoe drift rates agreed with the computer model's predicted currents.

News of Jim's and my interest in the shoe spill reached an Oregon news reporter, and the story was then picked up by the Associated Press, resulting in a quick dissemination of the news nationwide. Readers sent letters describing their own shoe finds, and even reports of single shoes were valuable because we found that each shoe had within it a Nike purchase order number that could be traced to a specific cargo container. We were able to determine from these numbers that only four of the five containers broke open so that only 61,820 shoes were left afloat.



Box Figure 3 Projected drift tracks for the sneakers for the years 1951, 1973, 1982, 1988, and 1990, based on computer modeling of ocean currents and weather.

The computer model and previous experiments with satellite-tracked drifters showed that there would have been little scattering of the shoes as the ocean currents carried them eastward and approximately 1500 miles from the spill site to shore, but the shoes were found scattered from California to northern British Columbia. The north-south scattering is related to coastal currents that flowed northward in winter, carrying the shoes to the Queen Charlotte Islands, and southward in spring and summer, bringing the shoes to Oregon and California.

I was interested to see where the shoes might have gone if they had been lost on the same date but under different conditions in other years. The computer allowed simulations for May 27 of each year from 1946–91. Box figure 3 shows the wide variation in model predicted drift routes. If the shoes had been lost in 1951, they would have traveled in the loop of the Alaska Current. If they had been lost in 1982, they would have been carried far to the north during the very strong El Niño of 1982–83, and if lost in 1973, they would have come ashore at the Columbia River.

Another spill event occurred in January 1992, when twelve cargo containers were lost from another vessel in the North Pacific at 180°W, 45°N. One of these containers held 29,000 small, floatable, plastic, bathtub toys. Blue turtles, yellow ducks, red beavers,

North Pacific Ocean Surface Current Simulation. When the model was used to map current patterns for North Pacific surface water between 1902 and 1997, it showed a north-south current oscillation associated with changes in atmospheric pressure and climate shifts. Cold and wet conditions are associated with a southerly current flow, and warm and dry conditions predominate with a northerly flow (fig. 9.16). This evidence was compared to climate-sensitive tree-ring data from western juniper trees in eastern Oregon. These trees show wide rings during periods when currents were displaced to the north and narrow rings when currents were displaced to the south. Tree-ring data cover many more years than oceanographic and meteorological data, and from the tree rings, it is calculated that thirty-four north-south oscillations have occurred since the time of Columbus. The most common time period between fast and slow growth is seventeen years, with twenty-three- and twenty-six-year periods common. Tree-ring data and current oscillations agree.

The climate pattern is presently warm and dry with a northerly current flow that has not changed since 1967. This is one of the longest periods without a reversal that has been found during the last 500 years. Following the wet conditions of the 1998–99 winter and the 1999–2000 La Niña, the winter of 2000–2001 in the Pacific Northwest was exceptionally warm and dry, and the winter of 2002 again brought wet El Niño conditions. These current shifts are associated with changes in atmospheric pressure, winds, precipitation, and water temperature; together, they are known as the Pacific Decadal Oscillation, or PDO. Because the PDO affects coastal surface temperatures from California to Alaska, it is thought to affect the survival of fish stocks of the area, especially salmon. Commercial fishing is discussed further in chapter 17.

turned south, they might have merged with the Kuroshio Current and been carried past the location where they were spilled.

Two thousand five hundred cases of hockey gloves (34,300 gloves) were lost from a container ship in the North Pacific after a December 1994 fire. In August 1995, a fishing vessel found seven gloves 800 miles west of the Oregon coast, and by January 1996, the barnacle-covered gloves began to arrive on Washington beaches. The most northerly glove sighting came from Prince William Sound, Alaska, in August 1996. The gloves are expected to follow the tub toys along the coast of Alaska and into the Arctic. More than 4 million Lego pieces lost off the English coast in 1997 are expected to be distributed along Northern Hemisphere shores by 2020.

And one more time, as it is said, what goes around comes around. On December 15, 2002, a ship carrying cargo containers on its way from Los Angeles to Tacoma, Washington, ran into 25-ft seas off Cape Mendocino in northern California. The vessel rolled and several cargo containers fell overboard. A cargo container of 33,000 Nike athletic shoes was among those lost, and by mid-January 2003, the shoes were coming ashore along the Washington coast. Riding the Davidson Current northward, the shoes had traveled about 833 km (450 nautical miles). Once again, the pairs of shoes were not tied together, and notices were posted in the search for mates.

Curtis C. Ebbesmeyer, Ph.D.
Seattle, Washington

Box Figure 4 Shoes and toys after their rescue from Pacific cargo spills.

and green frogs began arriving on beaches near Sitka, Alaska, in November 1992. Advertisements asking for news of toy strandings were placed in local newspapers and the Canadian lighthouse keepers' newsletter. Beachcombers reported a total of about 400 of these toys (box fig. 4).

None of the toys was found south of 55°N latitude, suggesting that once the toys reached the vicinity of Sitka, they drifted to the north. This time, the computer model showed that if the toys had continued to float with the Alaska Current, they would have moved with the Alaska stream through the Aleutian Islands into the Bering Sea. Some may have continued across the Bering Sea into the Arctic Ocean to the vicinity of Point Barrow and from there would have drifted north of Siberia with the Arctic pack ice. Eventually, some plastic turtles, ducks, beavers, or frogs may have come to rest on the coast of western Europe. If the toys had

To Learn More About Ocean Drifters

Krajick, K. 2001. Message in a Bottle. *Smithsonian* 32 (4): 36–47.

North Atlantic Oscillations

A large pool of cold, low-salinity surface water appeared off Greenland, north of Iceland, in 1968. It was about 0.5‰ less salty and 1° and 2°C colder than usual. Within two years, this cool pool had moved west into the Labrador Sea off eastern Canada; then it crossed the Atlantic and, in the mid-1970s, moved north into the Norwegian Sea. It had returned to its place of origin by the early 1980s. Follow the path of this pool in figure 9.17. During this period, harsh winters plagued Europe, and the entire Northern Hemisphere had cooler-than-average temperatures for more than ten years.

Recent studies have further investigated the North Atlantic, seeking to improve our ability to predict climate. The new analysis shows pools of warm and cool surface water that circle the North Atlantic; the pools seem to have life spans of four to ten years. Because of the alternation of climatic conditions, this is referred to as the North Atlantic Oscillation (NAO). Investigators are finding pieces of the puzzle that are associated with NAO but have not yet found the factors that control the system. A counterclockwise wind circulation centered over Iceland and a high-pressure clockwise circulation residing near the Azores are the usual situation. If the air-pressure differences between these two locations are large, then strong westerly winds supply Europe with heat from the North Atlantic Current. If the air-pressure difference decreases, then weaker-than-normal westerlies drive less warm water into the Norwegian Current and less heat is delivered to Europe. The periods of 1950–71 and 1976–80 were recognized as prolonged cool periods for Europe. The winds may also drive cold, low-salinity water from the Arctic into the area where North Atlantic deep water is formed. The influx of this water may cause a small-scale reduction in the

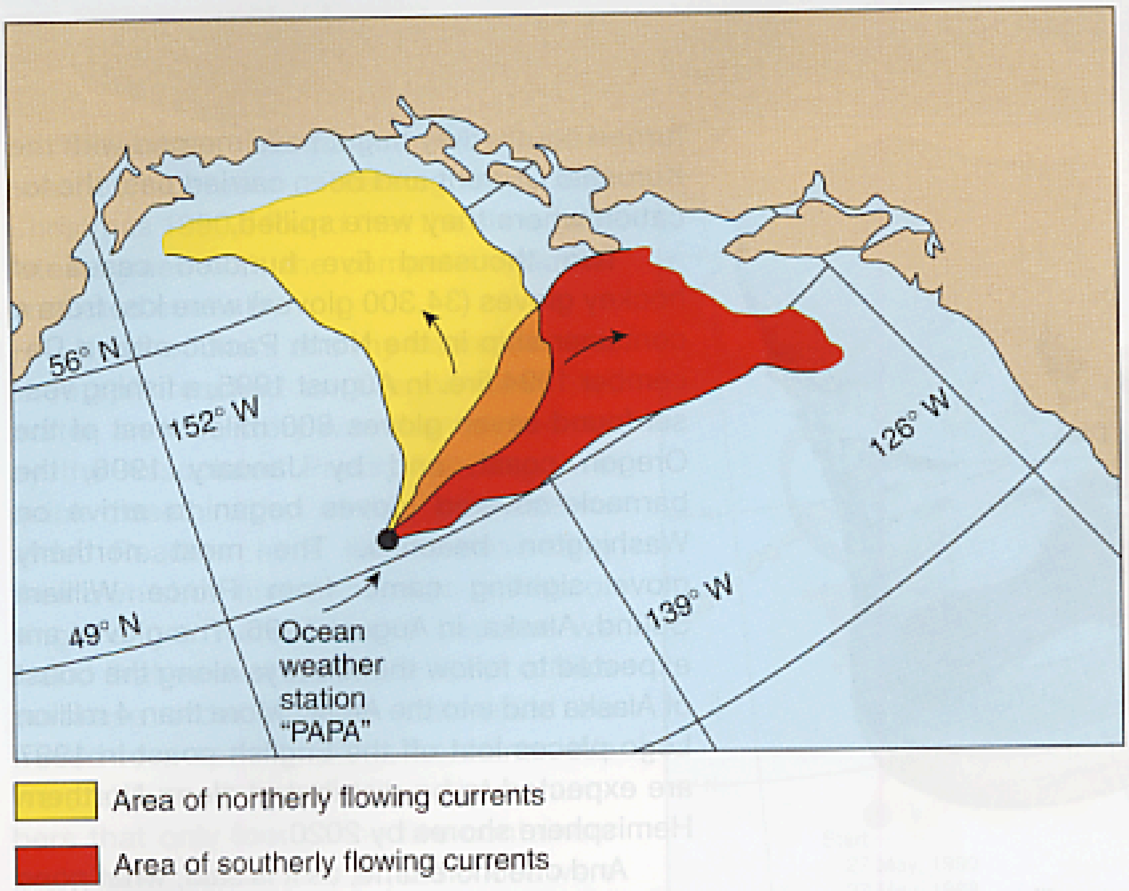


Figure 9.16 North-south current shifts in the Northeast Pacific are associated with changes in atmospheric pressure, winds, precipitation, and water temperature. This phenomenon is known as the Pacific Decadal Oscillation (PDO).

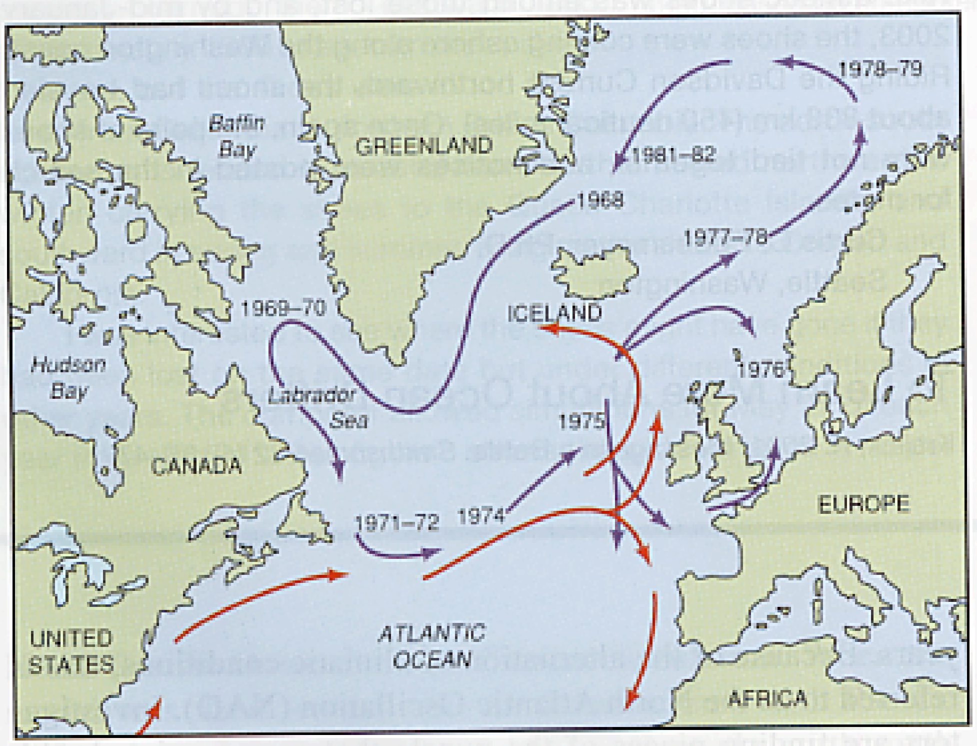


Figure 9.17 *Purple arrows* follow the path of the North Atlantic cool pool. *Red arrows* show warm-water flow from the Gulf Stream.

formation of North Atlantic deep water and an accompanying reduction of warm surface water moving northward. How much freshening is required to change ocean circulation? This question is unanswered, but if the current melting of Arctic sea ice continues, more information may soon be available.

Natural cycles operate at a variety of time scales and magnitudes, and they interact and react in ways we do not fully comprehend. In the enormously complex interactions that they are observing, oceanographers and meteorologists are beginning to identify the strands that united the ocean-atmosphere and the world current systems. Scientists use mathematical equations assembled into a model to describe interactions between the oceans and the atmosphere. Supercomputers are needed to make the millions of calculations that a model requires to predict changes in environmental conditions over a given time period. This process is repeated many times to predict conditions. Models are verified and tuned by adjusting the equations so that the predicted model changes closely agree with changes that have been observed in the past. Modeling is nearly as much an art as a science. Sometimes predictions work; sometimes they don't. It depends on how well the model has been conceived, how much data are available, and the capability of the computers to process the data. The model may be constructed to approximate the whole ocean-atmosphere system or to apply only to part of Earth. Eventually, long-term predictions concerning the oceans and the atmosphere will become possible; how we use such information and whether it will benefit ocean resources are not yet clear.

9.7 Measuring the Currents

Direct measurements of currents fall into two groups: (1) those that follow a parcel of the moving water and (2) those that measure the speed and direction of the water as it passes a fixed point. Moving waters may be followed with buoys designed to float at predetermined depths. These buoys signal their positions acoustically to a research vessel or shore station; their paths are followed and their speed and displacement due to the current are calculated. Autonomous profilers such as the Argo drifter (see fig. 8.14) also measure currents. Surface water may be labeled with buoys or with dye that can be photographed from the air. Buoy positions may also be tracked by satellites using GPS. A series of pictures or position fixes may be used to calculate the speed and direction of a current from the buoys' drift rates. Buoys can be instrumented to measure other water properties such as temperature and salinity (fig. 9.18).

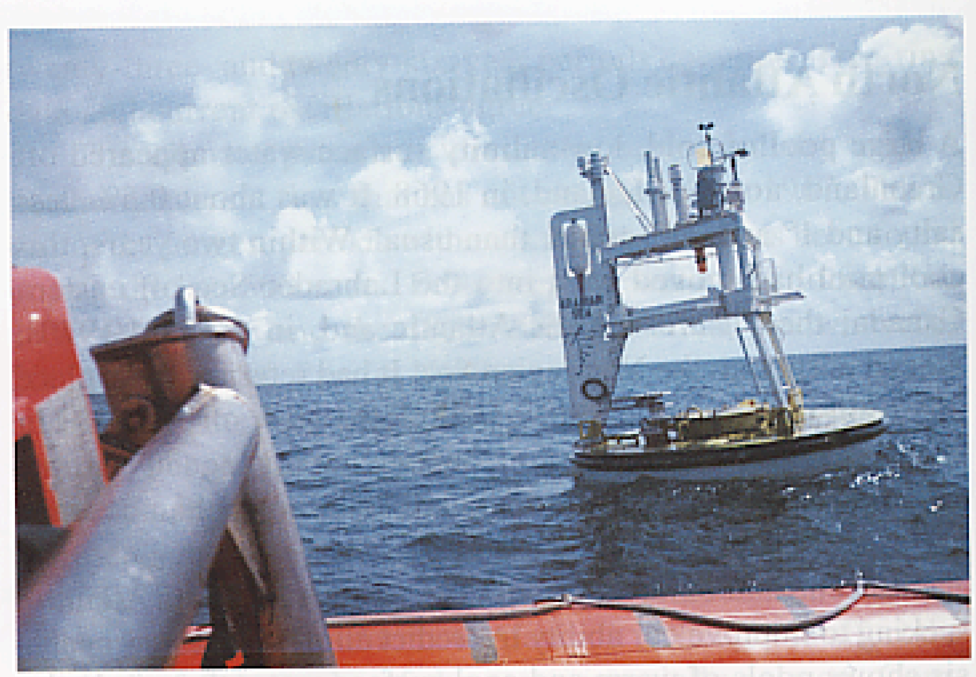
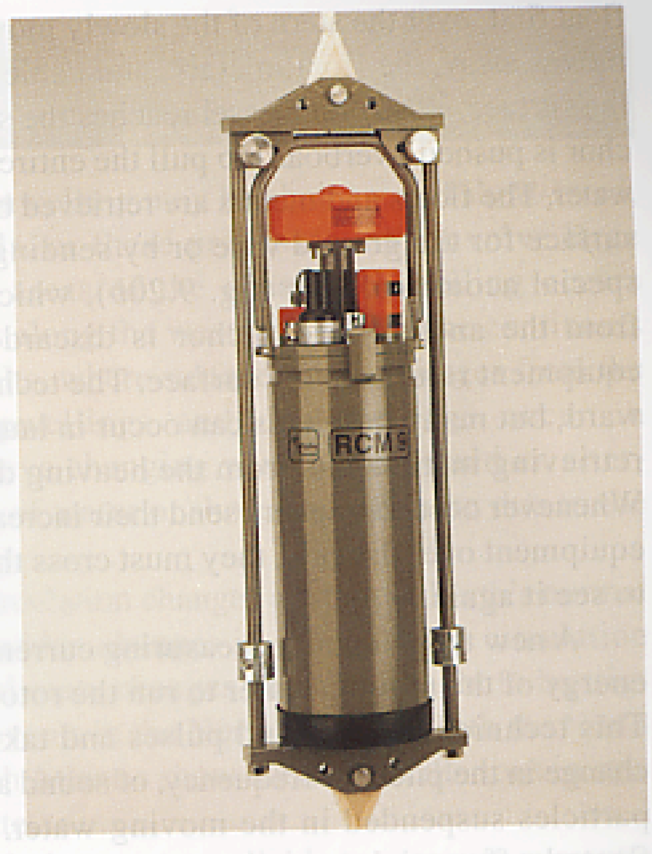


Figure 9.18 Retrieving an oceanographic research buoy in the Arabian Sea (northwest Indian Ocean). This buoy is equipped with weather, radiation, and water property sensors.


(a)



(b)

Figure 9.19 (a) An internally recording Aanderaa current meter. The vane orients the meter to the current while the rotor determines current speed. (b) A Doppler current meter sends out sound pulses in four directions. The frequency shift of the returning echoes allows the detection of the current. These meters are also equipped with salinity-temperature-depth sensors as well as instruments for measuring water turbidity and oxygen. The data may be stored internally and collected at another time.

A variation of this technique uses **drift bottles.** Thousands of sealed bottles, each containing a postcard, are released at a known position. When the bottles are washed ashore, the finders are requested to record the time and location of the find and return the card. In this case, only the release point, the recovery points, and the elapsed time are known; the actual path of motion is assumed. See the box titled "Ocean Drifters."

Sensors used to measure current speed and direction at fixed locations are called **current meters.** The current meters used by oceanographers over the last twenty years include a rotor to measure speed and a vane to measure direction of flow (fig. 9.19*a*). If the current meter is lowered from a stationary vessel, the measurements can be returned to the ship by a cable or stored by the meter for reading upon retrieval. If the current meter is attached to an independent, bottom-moored buoy system, the signals can be transmitted to the ship as radio signals or stored on tape in the meter, to be removed when the buoy and meter are retrieved.

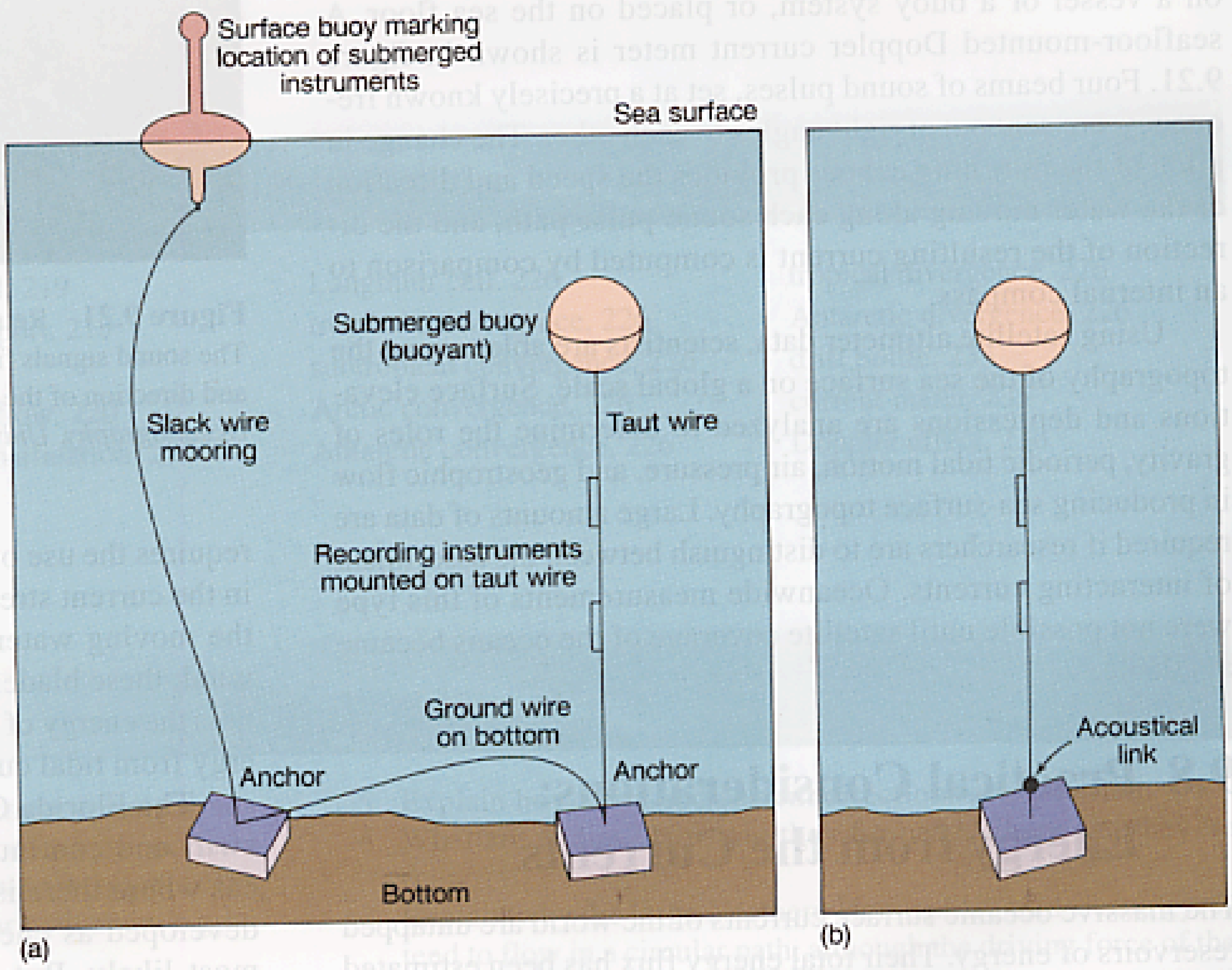


Figure 9.20 Taut-wire moorage. (a) Recovery is accomplished by retrieving the surface buoy and hauling in the wire. If the surface buoy is lost, it is possible to grapple for the ground wire. (b) In this system, a sound signal disconnects the anchor, and the equipment floats to the surface.

To measure a current at a location, a current meter must not move. Although a vessel can be moored in shallow water so that it does not move, it is very difficult, if not impossible, to moor a ship or surface platform in the open sea so that it will not move and thus move the current meter. The solution is to attach the current meter to a buoy system that is entirely submerged and not affected by winds or waves. See figure 9.20 for a diagram of this taut-wire moorage system. The string of anchors, current meters, wire, and floats is preassembled on deck and is launched, surface float first, over the stern of the slowly moving ship. As the ship moves away, the float, meters, and cable are stretched out on the surface. When the vessel reaches the sampling site, the anchor is pushed overboard to pull the entire string down into the water. The floats and meters are retrieved by grappling from the surface for the ground wire or by sending a sound signal to a special acoustical link (fig. 9.20*b*), which detaches the wire from the anchor. The anchor is discarded, and the buoyed equipment returns to the surface. The technique is straightforward, but many problems can occur in launching, finding, and retrieving instruments from the heaving deck of a ship at sea. Whenever oceanographers send their increasingly sophisticated equipment over the side, they must cross their fingers and hope to see it again.

A new technique for measuring currents does not need the energy of the moving water to run the rotor of a current meter. This technique uses sound pulses and takes advantage of the change in the pitch, or frequency, of sound as it is reflected from particles suspended in the moving water. When sound is reflected off particles moving toward the meter, the pitch increases; when the sound is reflected off particles moving away from the meter, the pitch decreases. This is the **Doppler effect;** the same effect increases the pitch of the horn or siren of an approaching vehicle and decreases the pitch as the vehicle passes and moves away. To use this effect, the sound source is mounted on a vessel or a buoy system, or placed on the sea floor. A seafloor-mounted Doppler current meter is shown in figure 9.21. Four beams of sound pulses, set at a precisely known frequency, are sent out at right angles to each other. The change in pitch of the returning echoes provides the speed and direction of the water moving along each sound pulse path, and the direction of the resulting current is computed by comparison to an internal compass.

Using satellite altimeter data, scientists are able to map the topography of the sea surface on a global scale. Surface elevations and depressions are analyzed to determine the roles of gravity, periodic tidal motion, air pressure, and geostrophic flow in producing sea-surface topography. Large amounts of data are required if researchers are to distinguish between the assortment of interacting currents. Oceanwide measurements of this type were not possible until satellite coverage of the oceans became available.

Figure 9.21 Retrieving a Doppler current meter from the sea floor. The sound signals from the meter are analyzed to determine the speed and direction of the current. *Courtesy of Mark Holmes, School of Oceanography, University of Washington.*

9.8 Practical Considerations: Energy from the Currents

The massive oceanic surface currents of the world are untapped reservoirs of energy. Their total energy flux has been estimated at 2.8×10^{14} (280 trillion) watt-hours. Because of their link to winds and surface heating processes, the ocean currents are considered as indirect sources of solar energy. If the total energy of a current was removed by conversion to electrical power, that current would cease to exist; but only a small portion of any ocean current's energy can be harnessed, owing to the current's size. Harnessing the energy from these open-ocean currents requires the use of turbine-driven generators anchored in place in the current stream. Large turbine blades would be driven by the moving water, just as windmill blades are moved by the wind; these blades could be used to turn generators and to harness the energy of the water flow. (See also the discussion on energy from tidal currents in chapter 11.)

The Florida Current and the Gulf Stream are reasonably swift and continuous currents moving close to shore in areas where there is a demand for power. If ocean currents are developed as energy sources, these currents are among the most likely. But most of the wind-driven oceanic currents generally move too slowly and are found too far from where the power is needed. In addition, the impact on other uses of the sea—transport, fishing, recreation—needs to be considered. The cost of constructing, mooring, and maintaining current-driven power-generating devices in the open sea makes them noncompetitive with other sources of power at this time.

Summary

Winds push the surface water 45° to the right of their direction in the Northern Hemisphere and 45° to the left in the Southern Hemisphere. Wind moves the water in layers that are deflected by the Coriolis effect to form the Ekman spiral; net flow over the depth of the spiral is deflected 90°. Geostrophic flow is produced when the force of gravity balances the Coriolis effect. Large surface gyres are observed in each ocean. Northern Hemisphere gyres rotate clockwise, and Southern Hemisphere gyres rotate counterclockwise. The currents of the northern Indian Ocean change with the seasonal monsoons.

Large oceanic current systems have names and descriptions based on their average locations. The water transport and speed of a current are affected by the current's cross-sectional area, by other currents, by westward intensification, and by wind speed. Eddies are formed at the surface when a fast-moving current develops waves along its boundary that break off from the parent current. Eddies occur at all depths, wander long distances, and gradually lose their identity.

Downwelling is produced by converging surface currents, and upwelling is produced by diverging surface currents. Upwelling and downwelling may be shallow and short-lived, as in Langmuir cells, or these processes may involve large volumes and large areas of the oceans. Upwelling occurs nearly continuously along the western sides of the continents in the trade-wind belts, where surface water diverges from the coast. Seasonal upwellings and downwellings occur in coastal areas that have changing wind patterns and an alternating coastal flow of water onshore and offshore due to the Ekman transport.

Cyclic global circulation changes are part of Earth's normal dynamic system. Sudden changes in global ocean circulation may lead to major climate changes and are thought to be triggered by localized events in the North Atlantic. Both the North Pacific and the North Atlantic show decadal oscillations in current flow and climate.

A variety of techniques are available to measure currents: by following the water, by measuring the water's speed and direction as it moves past a fixed point, or by using changes in the frequency of sound.

Deriving energy from the oceanic current flows is not practical at the present time.

Key Terms

All key terms from this chapter can be viewed by term, or by definition when studied as flashcards on this book's website at www.mhhe.com/sverdrup10e.

Ekman spiral, 219
Ekman transport, 219
gyre, 220
geostrophic flow, 220
western intensification, 223
eddy, 224
Langmuir cell, 226
tropical convergence, 226
subtropical convergence, 226
Arctic convergence, 226
Antarctic convergence, 226
tropical divergence, 226
Antarctic divergence, 226
drift bottle, 235
current meter, 235
Doppler effect, 236

Study Questions

1. According to the net transport of the Ekman spiral, wind-driven water is directed toward the center of a large oceanic current gyre. Why does the current not flow to the gyre's center but instead flows in a clockwise circular path about a gyre in the Northern Hemisphere?
2. How is wind-driven Ekman transport related to coastal upwelling and downwelling?
3. On a map of the world, plot the oceanographic equator, the six major wind belts, the current system of each ocean, and the main areas of surface convergence and divergence.
4. Why does a flow of water that is constant in volume transport per time increase its speed when it passes through a narrow opening?
5. Explain how wind and current directions are specified.
6. What are eddies? How are they formed? Where can they be found?
7. Explain why the large Northern Hemisphere mid-ocean gyres tend to flow in a circular path, although the driving force of the winds is to the east on the higher-latitude side of the gyre and to the west on the lower-latitude side.
8. Explain why surface convergences are located at the centers of the large subtropical gyres in both the northern and southern Atlantic and Pacific Oceans.
9. Explain why upwellings on the lee side of continents at subtropical latitudes function continuously while upwelling on the west side of North America is seasonal.