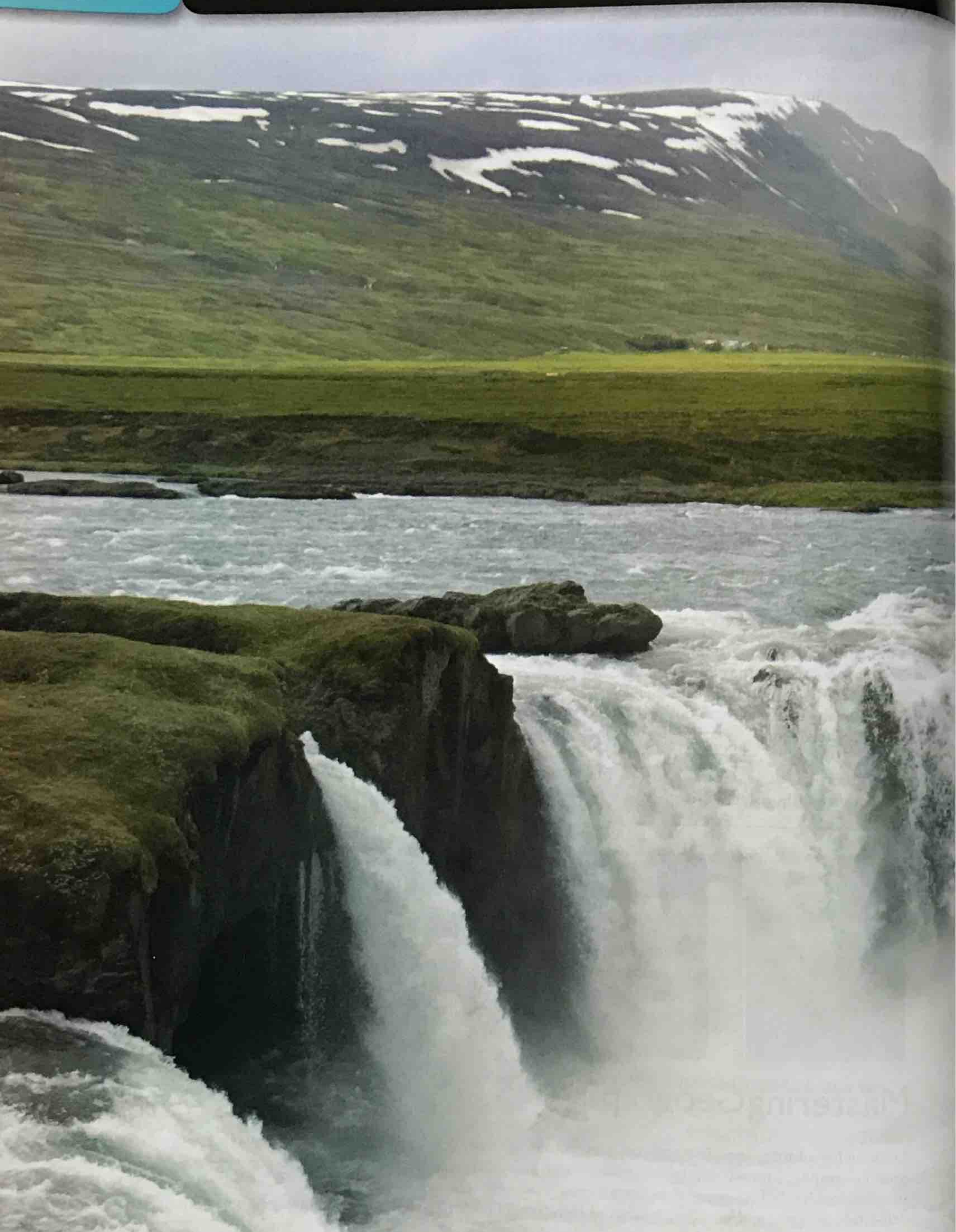
Chapter 9

THE HYDROSPHERE



THE HYDROSPHERE IS AT ONCE THE MOST PERVASIVE AND the least well defined of the four "spheres" of Earth's physical environment. It includes the surface water in oceans, lakes, rivers, and swamps; all underground water; frozen water in the form of ice, snow, and high-cloud crystals; water vapor in the atmosphere; and the moisture temporarily stored in plants and animals.

The hydrosphere overlaps significantly with the other three spheres. Liquid water, ice, and even water vapor occur in the soil and rocks of the lithosphere. Water vapor and cloud particles composed of liquid water and ice are important constituents of the lower portion of the atmosphere, and water is a critical component of every living organism of the biosphere. Life is impossible without water; every living thing depends on it. Watery solutions in living organisms dissolve or disperse nutrients for nourishment. Most waste products are carried away in solutions. Indeed, the total mass of every living thing is more than half water, the proportion ranging from about 60 percent for some animals to more than 95 percent for some plants.

It is through water, then, that the interrelationships of the four spheres are most conspicuous and pervasive. In Chapter 6 we introduced many of the physical properties of water and the roles of water in weather and climate. In this chapter, we examine the geography of water more broadly and explore one of the most important of all Earth systems.

As you study this chapter, think about these key questions:

- **How does the *hydrologic cycle* involve movement of water between the four "spheres" of Earth?**
- **What are the four oceans of Earth, and what factors influence characteristics of ocean water, such as salinity?**
- **How are the causes of tides different from the causes of surface ocean currents?**
- **What are the main components of the *cryosphere*?**
- **How and why do natural lakes and human made reservoirs change over time?**
- **What factors influence the quantity and availability of *groundwater*?**

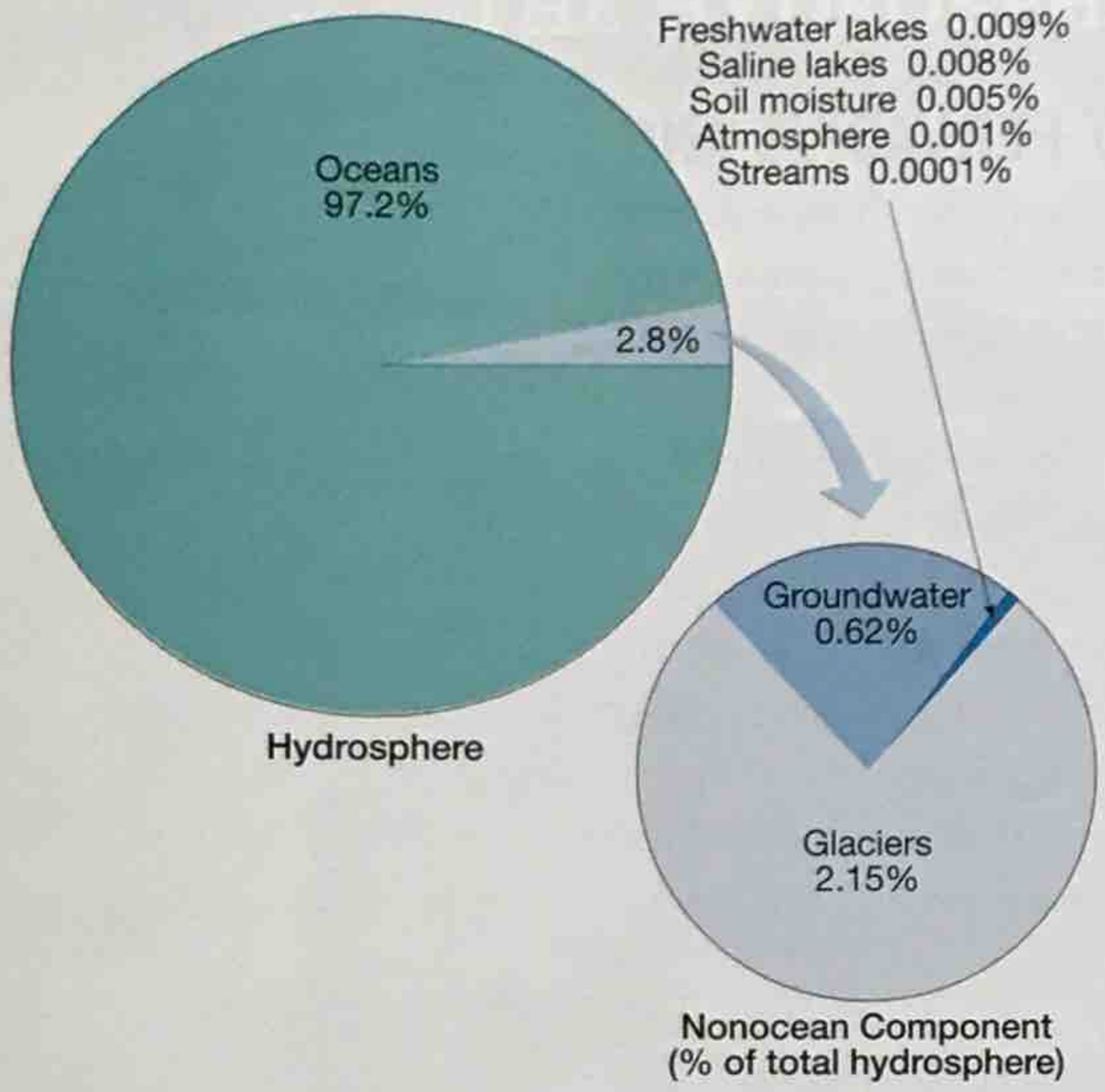
THE HYDROLOGIC CYCLE

We begin this chapter with a more detailed look at the movement of water—in all its forms—through the hydrosphere. Water, essential to life and finite in amount, is distributed very unevenly on, in, and above Earth. The great bulk of all moisture, more than 99 percent, is in "storage"—in oceans, lakes, and streams, locked up as glacial ice, or held in rocks below Earth's surface (Figure 9-1). Water frozen as ice in glaciers and continental ice sheets represents about three-fourths of all of the freshwater on the planet.

Animation
Hydrologic Cycle

Seeing Geographically

Goðafoss, or "waterfall of the gods," along the river Skjlfandafljt, in north central Iceland. What different forms of water can you see in this image? How are these forms of water connected through Earth's systems?



▲ **Figure 9-1** Moisture inventory of Earth. More than 97 percent of all water is contained in the oceans.

The proportional amount of moisture in these various storage reservoirs is relatively constant over thousands of years. Only during an ice age is there a notable change in these components: as we will see in Chapter 19 during periods of glaciation, the volume of the oceans becomes smaller as the ice sheets grow and the level of atmospheric water vapor diminishes; then during deglaciation, the ice melts, the volume of the oceans increases as the meltwater flows into them, and there is an increase in atmospheric water vapor.

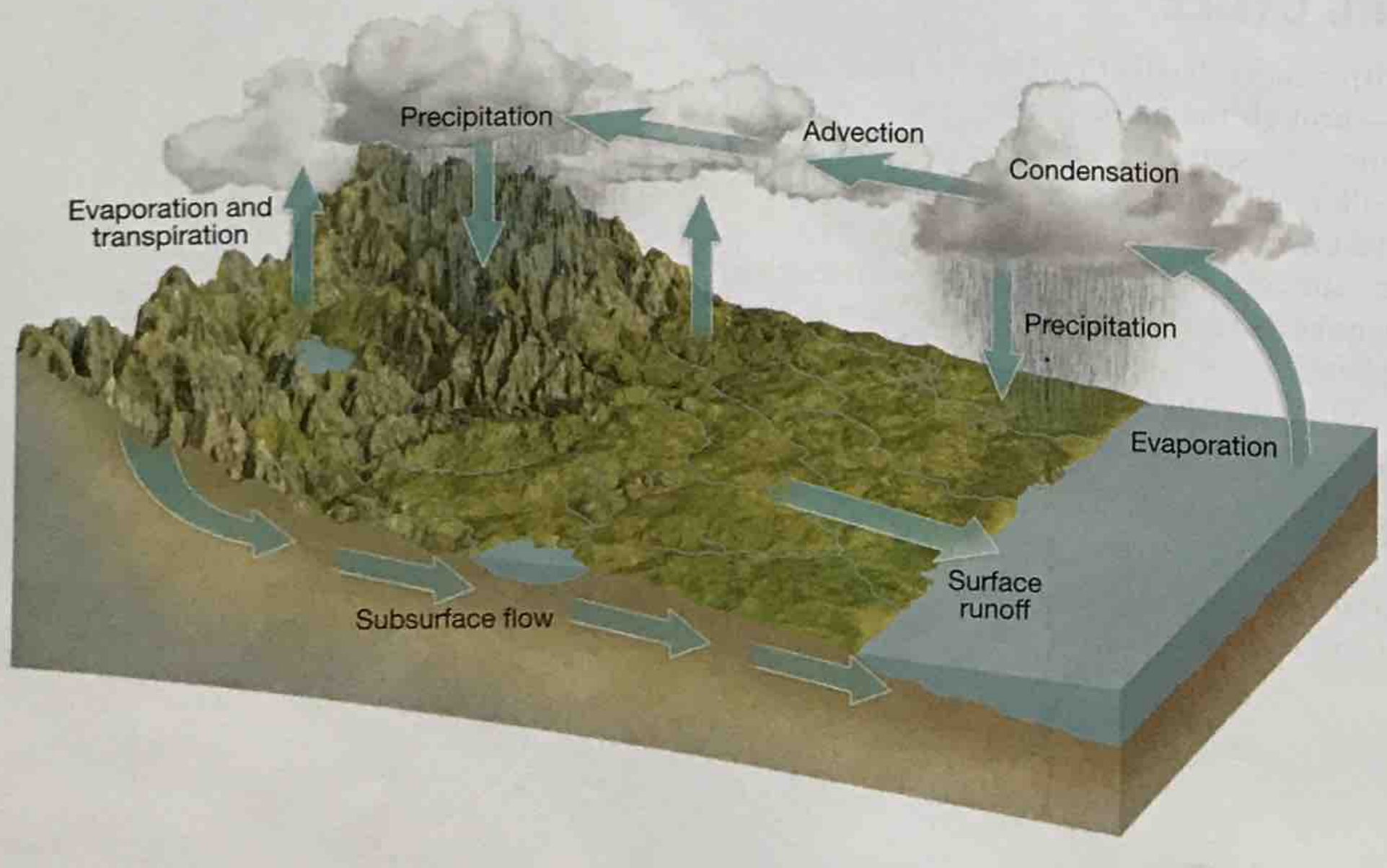
Video
Hydrologic Cycle

The remaining small fraction—less than 1 percent—of Earth's total moisture is involved in an almost continuous sequence of movement and change, the effects of which are absolutely critical to life on this planet. This tiny portion of Earth's water supply moves from one storage area to another—from ocean to air, from air to ground, and so on—in the **hydrologic cycle**. We first introduced the hydrologic cycle in Chapter 6. In this chapter, we examine the complexities of this cycle in detail.

The hydrologic cycle can be viewed as a series of storage areas interconnected by various transfer processes, in which there is a ceaseless interchange of moisture in terms of both its geographic location and its physical state (Figure 9-2). Liquid water on Earth's surface evaporates to become water vapor in the atmosphere. That vapor then condenses and precipitates, either as liquid water or as ice, back onto the surface. This precipitated water then runs off into storage areas and later evaporates into the atmosphere once again. Because this is a closed, circular system, we can begin the discussion at any point. It is perhaps clearest to start with the movement of moisture from Earth's surface into the atmosphere.

Surface-to-Air Water Movement

Most of the moisture that enters the atmosphere from Earth's surface does so through *evaporation* (transpiration from plants is the source of the remainder). The oceans, of course, are the principal source of water for evaporation. They occupy 71 percent of Earth's surface, have unlimited moisture available for evaporation, and are extensive in low latitudes, where considerable



◀ **Figure 9-2** The hydrologic cycle. The two major components are evaporation from surface to air and precipitation from air to surface. Other important elements of the cycle include transpiration of moisture from vegetation to atmosphere, surface runoff and subsurface flow of water from land to sea, condensation of water vapor to form clouds from which precipitation may fall, and advection of moisture from one place to another.

TABLE 9-1 Moisture Balance of Continents and Oceans

	Total of World Surface Area	Total of World Precipitation Received	Total of World Water Vapor From Surface
Oceans	71%	78%	86%
Continents	29%	22%	14%

warmth and wind movement facilitate evaporation. As a result, an estimated 86 percent of all evaporated moisture is derived from ocean surfaces (Table 9-1). The 14 percent that comes from land surfaces includes the twin processes of evaporation and transpiration, referred to as *evapotranspiration*.

Water vapor from evaporation remains in the atmosphere a relatively short time—usually only a few hours or days. During that interval, however, it may move a considerable distance, either vertically through convection or horizontally through advection driven by wind.

Air-to-Surface Water Movement

Sooner or later, water vapor in the atmosphere condenses to liquid water or sublimates to ice to form cloud particles. As we saw in Chapter 6, under the proper circumstances clouds may drop precipitation in the form of rain, snow, sleet, or hail. As Table 9-1 shows, 78 percent of this precipitation falls into the oceans and 22 percent falls onto land.

Over several years, total worldwide precipitation is approximately equal to total worldwide evaporation/transpiration. Although precipitation and evaporation/transpiration balance in time, they do not balance in place: evaporation exceeds precipitation over the oceans, whereas the opposite is true over the continents. This imbalance is explained by the advection of moist maritime air onto land areas, so that there is less moisture available for precipitation over the ocean. Except for coastal spray and storm waves, the only route by which moisture moves from sea to land is via the atmosphere.

Movement On and Beneath Earth's Surface

Looking at Table 9-1, you see 8 percent more water is leaving the ocean than precipitating back into it. The "surplus" precipitation over the continents is effectively returned to the ocean through surface **runoff**, water draining off the land and back into the sea in streams.

The 78 percent of total global precipitation that falls on the ocean is simply incorporated immediately into the water already there; the 22 percent that falls on land goes through a more complicated series of events. Rain falling on a land surface collects in lakes, runs off if the surface is a slope, or infiltrates the ground. Any water that pools on the surface eventually either evaporates or sinks into the ground, runoff water eventually ends up in the ocean, and infiltrated water is either stored temporarily as soil moisture or percolates farther down to become part of the underground water supply.

Much of the soil moisture eventually evaporates or transpires back into the atmosphere, and much of the underground water eventually reappears at the surface via springs. Then sooner or later, and in one way or another, most of the water that reaches the surface evaporates again, and the rest is incorporated into streams and rivers and becomes runoff flowing into the oceans. This runoff water from continents to oceans amounts to 8 percent of all moisture circulating in the global hydrologic cycle. It is this runoff that balances the excess of precipitation over evaporation taking place on the continents and that keeps the oceans from drying up and the land from flooding.

Learning Check 9-1 **Is the amount of precipitation and evapotranspiration over the continents the same? Explain. (Answer on p. AK-3)**

Residence Times

Although the hydrologic cycle is a closed system with an essentially finite total capacity, there is enormous variation in *residence times* for individual molecules of water as they move through different parts of the cycle. For example, a particular molecule of water may be stored in oceans and deep lakes, or as glacial ice, for thousands of years without moving through the cycle, and one trapped in rocks buried deep beneath Earth's surface may be excluded from the cycle for thousands or even millions of years.

However, whatever water is moving through the cycle is in almost continuous motion (Figure 9-3). Runoff water can

◀ **Figure 9-3** Oregon's Mount Hood and Lake Trillium with morning fog. Moisture constantly moves through the hydrologic cycle through evaporation, condensation, precipitation, and runoff.

travel hundreds of kilometers to the sea in only a few days, and moisture evaporated into the atmosphere may remain there for only a few minutes or hours before it is precipitated back to Earth. Indeed, at any given moment, the atmosphere contains only a few days' potential precipitation.

Energy Transfer in the Hydrologic Cycle

As we've seen, the hydrologic cycle is powered by the Sun. Recall from our discussion of Earth's energy cycle in Chapters 4 and 6 that water vapor represents not only a reservoir of moisture for precipitation, but a reservoir of energy as well. The latent heat "stored" in water vapor is released during condensation—acting as the fuel of storms such as hurricanes—and serving as one way that energy is transferred from the tropics toward the poles.

THE OCEANS

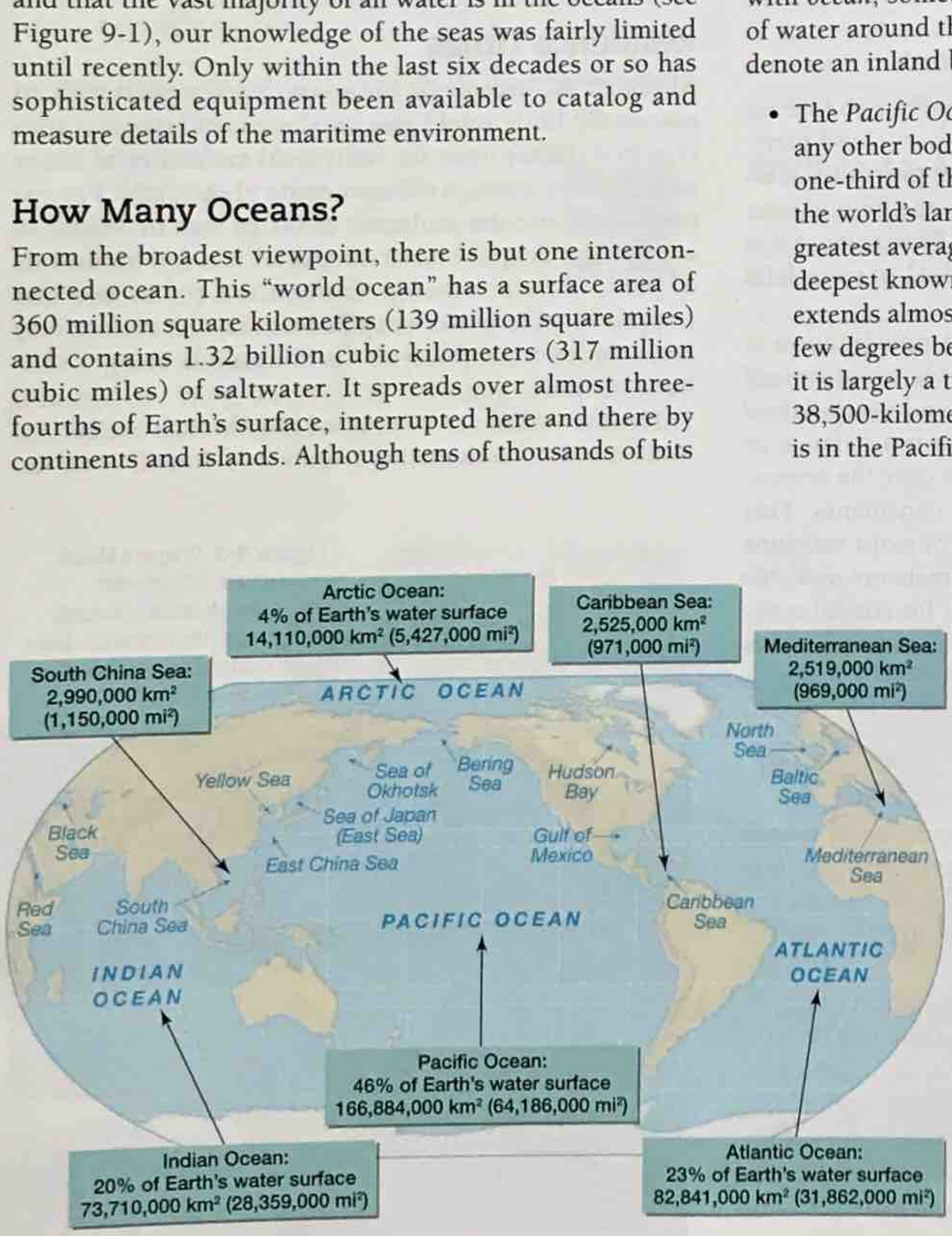
Despite the facts that most of Earth's surface is oceanic and that the vast majority of all water is in the oceans (see Figure 9-1), our knowledge of the seas was fairly limited until recently. Only within the last six decades or so has sophisticated equipment been available to catalog and measure details of the maritime environment.

How Many Oceans?

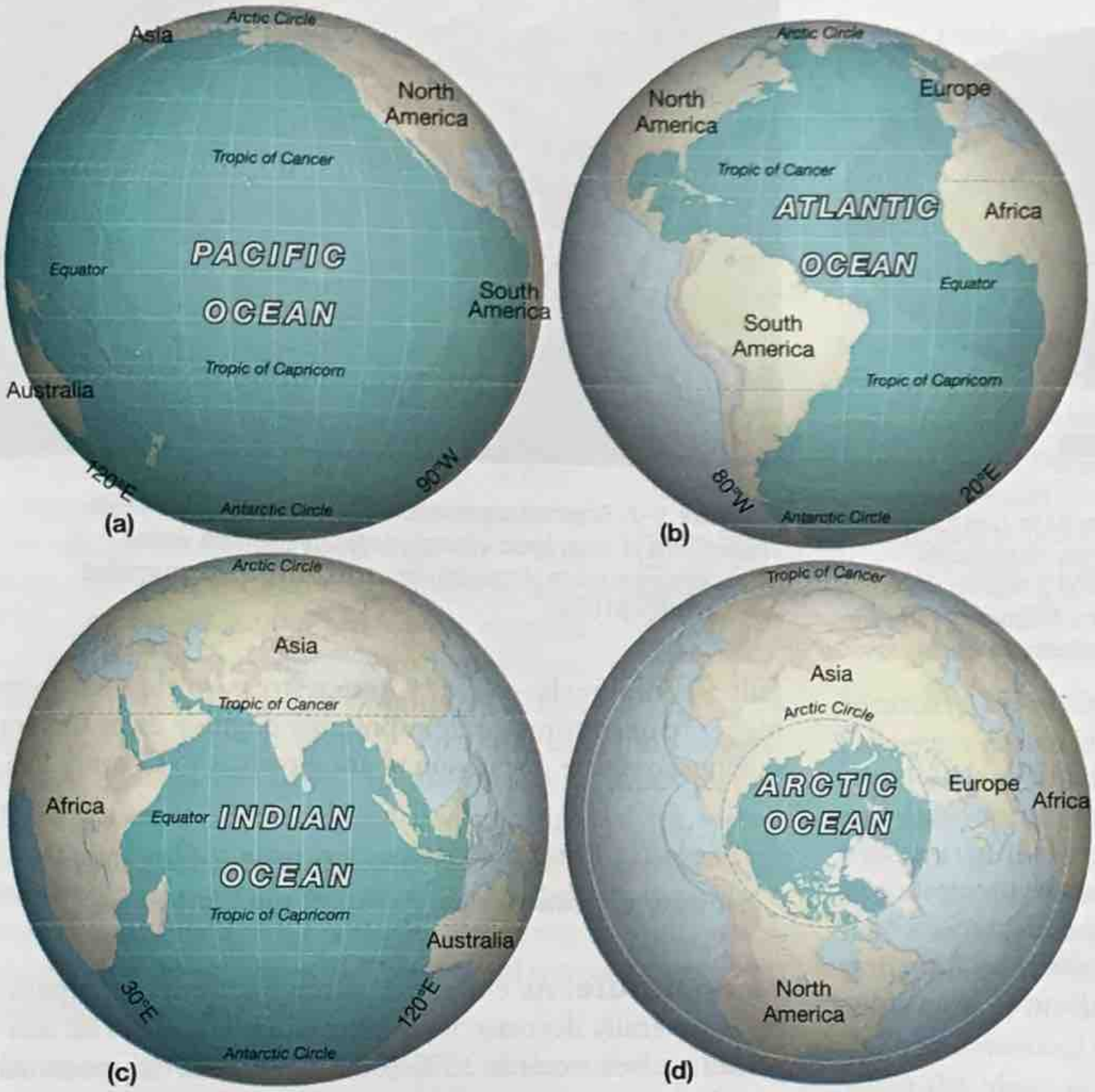
From the broadest viewpoint, there is but one interconnected ocean. This "world ocean" has a surface area of 360 million square kilometers (139 million square miles) and contains 1.32 billion cubic kilometers (317 million cubic miles) of saltwater. It spreads over almost three-fourths of Earth's surface, interrupted here and there by continents and islands. Although tens of thousands of bits of land protrude above the blue waters, the world ocean is so vast that half a dozen continent-sized portions of it are totally devoid of islands, without a single piece of land breaking the surface of the water. It is one or more of these large expanses of water we are usually referring to when we use the term *ocean*.

In generally accepted usage, the world ocean is divided into four principal parts—the Pacific, Atlantic, Indian, and Arctic Oceans (Figure 9-4). Some people refer to the waters around Antarctica as the *Antarctic Ocean* or the *Great Southern Ocean*, but this distinction is not universally accepted. The boundaries of the four oceans are not everywhere precise, and around some of their margins are partly landlocked smaller bodies of water called *seas*, *gulfs*, *bays*, and other related terms. Most of these smaller bodies can be considered as portions of one of the major oceans, although a few are so narrowly connected (Black Sea, Mediterranean Sea, Hudson Bay) to a named ocean as to deserve separate consideration, as Figure 9-4 shows. This nomenclature is further clouded by the term *sea*, which is used sometimes synonymously with *ocean*, sometimes to denote a specific smaller body of water around the edge of an ocean, and occasionally to denote an inland body of water.

- The *Pacific Ocean* (Figure 9-5a) is twice as large as any other body of water on Earth. It occupies about one-third of the total area of Earth, more than all the world's land surfaces combined. It contains the greatest average depth of any ocean as well as the deepest known oceanic trenches. Although the Pacific extends almost to the Arctic Circle in the north and a few degrees beyond the Antarctic Circle in the south, it is largely a tropical ocean. Almost one-half of the 38,500-kilometer (24,000-mile) length of the equator is in the Pacific. The character of this ocean often



◀ **Figure 9-4** The four principal oceans and major seas of the world.



◀ **Figure 9-5** The four major parts of the world ocean: (a) the Pacific Ocean, (b) the Atlantic Ocean, (c) the Indian Ocean, (d) the Arctic Ocean.

belies its tranquil name, for it houses some of the most disastrous of all storms (typhoons) and, as we'll see in Chapter 14, its rim is called the "Ring of Fire" because of its many volcanoes and earthquakes.

- The *Atlantic Ocean* is slightly less than half the size of the Pacific (Figure 9-5b). Its north–south extent is roughly the same as that of the Pacific, but its east–west spread is only about half as great. Its average depth is a little less than that of the Pacific.
- The *Indian Ocean* (Figure 9-5c) is a little smaller than the Atlantic, and its average depth is slightly less than that of the Atlantic. Nine-tenths of its area is south of the equator.
- The *Arctic Ocean* (Figure 9-5d) is much smaller and shallower than the other three and is mostly covered with ice. It is connected to the Pacific by a relatively narrow passageway between Alaska and Siberia, but it has a broad and indefinite connection with the Atlantic between North America and Europe.

Learning Check 9-2 **Why is it difficult to designate distinct boundaries between the oceans of the world?**

Characteristics of Ocean Waters

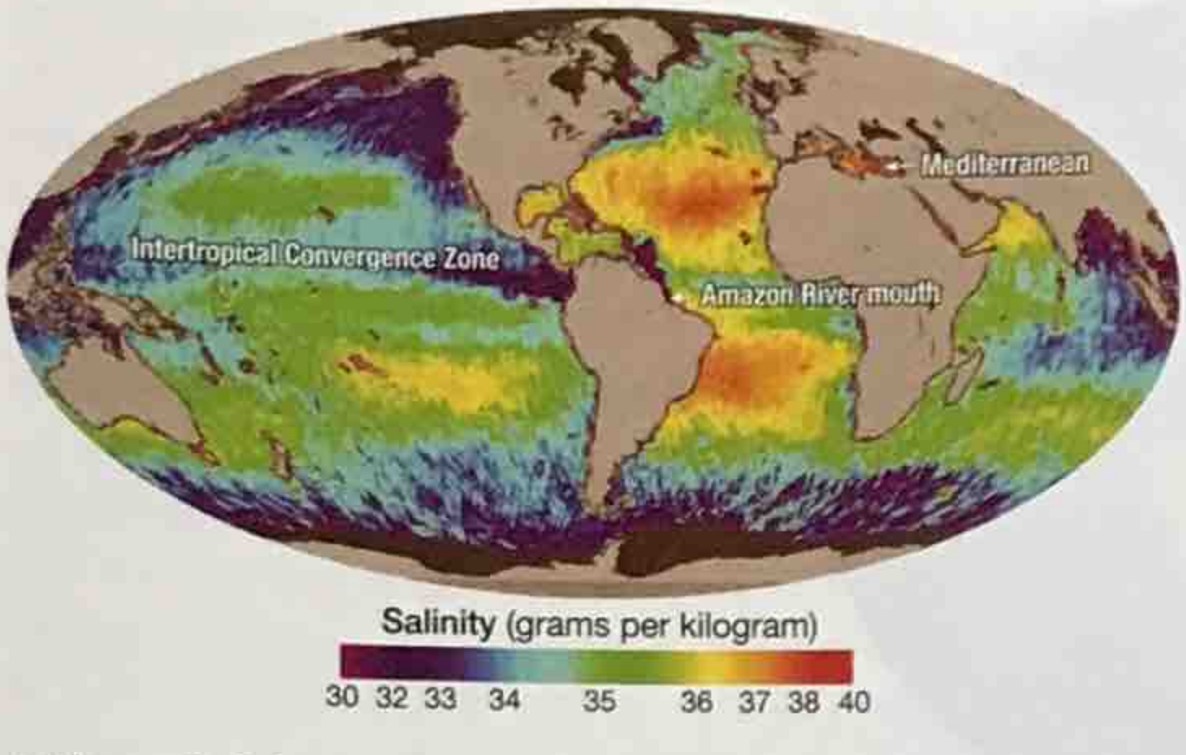
Wherever they are found, the waters of the world ocean have many similar characteristics, but they also show significant differences from place to place. The differences are particularly notable in the surface layers, down to a depth of about 100 meters (about 350 feet).

Chemical Composition: Almost all known elements are found to some extent in seawater, but by far the most important are sodium (Na) and chlorine (Cl), which form sodium chloride (NaCl)—the common salt we know as "table salt." In the language of chemistry, "salts" are substances that result when a *base* neutralizes an *acid*. For instance, sodium chloride is formed when the base sodium hydroxide (NaOH) neutralizes hydrochloric acid (HCl).

The **salinity** of seawater is a measure of the concentration of dissolved salts, which are mostly sodium chloride but also include salts containing magnesium, sulfur, calcium, and potassium. The average salinity of seawater is about 35 parts per thousand, or 3.5 percent of total mass.

The geographic distribution of surface salinity varies (Figure 9-6). At any given location on the ocean surface, the salinity depends on how much evaporation is taking place and how much freshwater (primarily from rainfall and stream discharge) is being added. Where the evaporation rate is high, so is salinity; where the inflow of freshwater is high, salinity is low.

Typically the lowest salinities are found where rainfall is heavy and near the mouths of major rivers. Salinity is highest in partly landlocked seas in dry, hot regions because here the evaporation rate is high and stream discharge is minimal. As a general pattern, salinity is low



▲ **Figure 9-6** Average salinity of oceans from May 27 to June 2, 2012. Lowest salinity (violet and blue areas) is found in areas of freshwater runoff, such as the mouths of rivers, and where rainfall is high (as in the ITCZ); highest salinity (red and yellow) is found where evaporation rates are highest. The data were gathered by NASA's Aquarius instrument onboard Argentina's *Satélite de Aplicaiones Cientificas.*

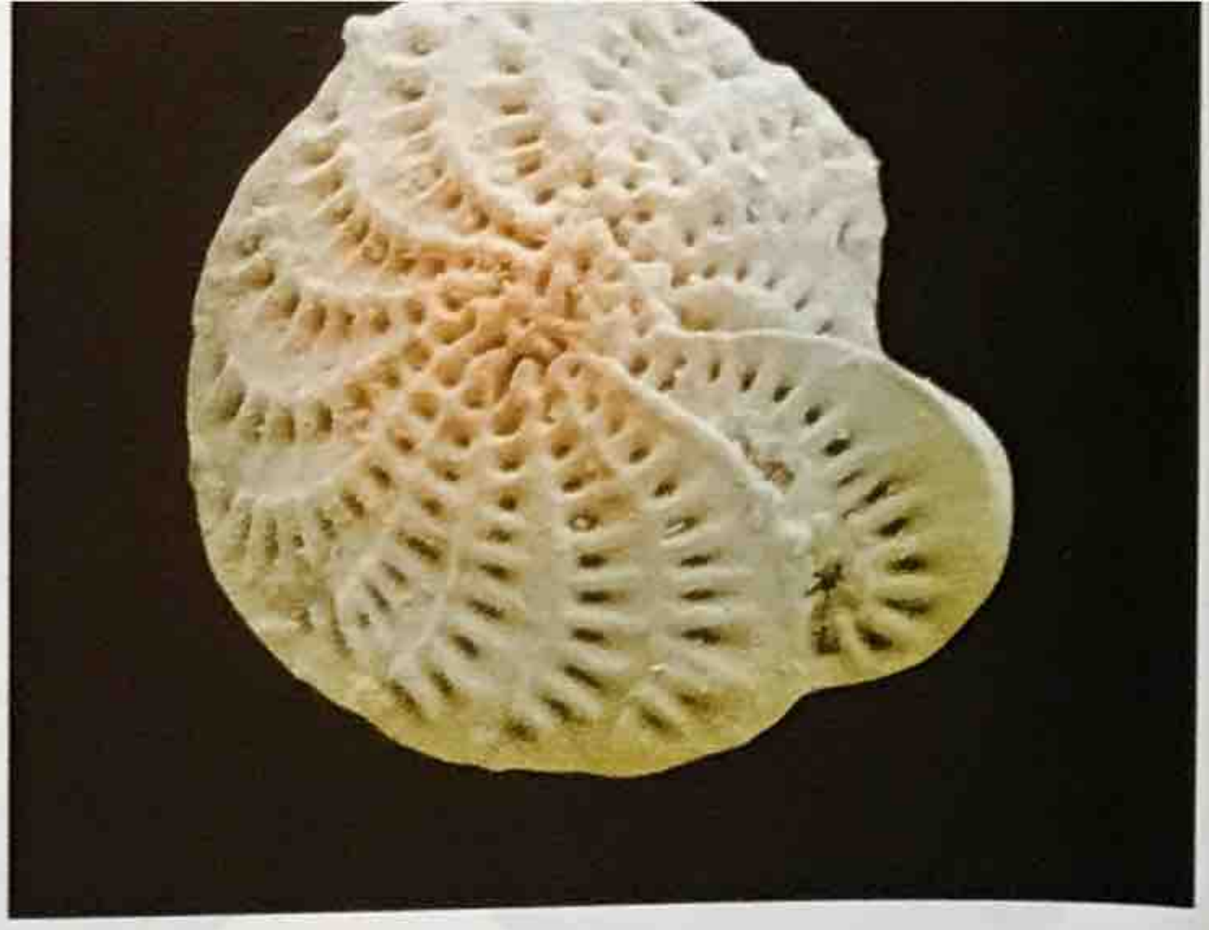
in equatorial regions because of heavy rainfall, cloudiness, and humidity, all of which inhibit evaporation, and also because of considerable river discharge. Salinity rises to a general maximum in the subtropics, where precipitation is low and evaporation extensive, and decreases to a general minimum in the polar regions, where evaporation is minimal and there is considerable inflow of freshwater from rivers and ice caps.

Increasing Acidity: The oceans absorb carbon dioxide from the atmosphere. Perhaps one-third of the excess CO_2 released into the air each year by human activity is absorbed by the oceans. When CO_2 is taken in by the ocean, it forms *carbonic acid* (H_2CO_3), a weak acid. Research now suggests that as a result of the great quantities of CO_2 absorbed since the beginning of the industrial revolution, the ocean is becoming more acidic.

Currently, ocean water is slightly alkaline, with a pH of 8.1 (see "Acid Rain" in Chapter 6 for a description of the pH scale). Although still alkaline, this value is estimated to be about 0.1 lower—in other words more acidic—than it was in the preindustrial era. Given the current rate of fossil fuel use and continued absorption of CO_2 by the oceans, the pH of ocean water could drop to 7.7 by the end of this century.

The consequences of a slightly more acidic ocean are not completely known, but it is likely that it will affect the growth of organisms such as coral polyps and microscopic creatures such as *foraminifera* (Figure 9-7) that build their shells or exoskeletons from calcium carbonate ($CaCO_3$) extracted from seawater. As the oceans become more acidic, there are fewer calcium ions in seawater and so the growth of calcium carbonate shells is inhibited. It is not clear if these creatures will be able to adapt to the changing chemistry of the ocean.

Because foraminifera are at the bottom of the oceanic food web, among the potentially important consequences of a decline in their numbers would be the loss of food for a number of fish, such as mackerel and salmon. If the increased acidity of the oceans reduces the growth of coral



▲ **Figure 9-7** Scanning electron microscope image of *Elphidium crispum*, one of many kinds of single-celled foraminifera whose exoskeletons are made of calcium carbonate, shown here magnified approximately 80 times.

polyps, coral reefs—already under stress worldwide from higher temperatures—might possibly degrade even further (a more complete discussion of coral reefs is in Chapter 20).

Learning Check 9-3 **How and why does the salinity of seawater vary around the world?**

Temperature: As expected, surface seawater temperatures generally decrease with increasing latitude. The temperature often exceeds 26°C (80°F) in equatorial locations and decreases to –2°C (28°F), the average freezing point for seawater, in Arctic and Antarctic seas. (Dissolved salts lower the freezing point of the water from the 0°C [32°F] of pure water.) The western sides of oceans are nearly always warmer than the eastern margins because of the movement of major ocean currents (see Figure 4-26 in Chapter 4). This pattern of warmer western parts is due to the contrasting effects of poleward-moving warm currents on the west side of ocean basins and equatorward-moving cool currents on the east side of ocean basins.

Density: Seawater density varies with temperature, degree of salinity, and depth. High temperature produces low density, and high salinity produces high density. Deep water has high density because of low temperature and because of the pressure of the overlying water.

Surface layers of seawater tend to contract and sink in cold regions, whereas in warmer areas deeper waters tend to rise to the surface. Surface currents also affect this situation, particularly by producing an upwelling of colder, denser water in some localities. As we will see later in this chapter, differences in density are partially responsible for a vast, slow circulation of deep ocean water.

MOVEMENT OF OCEAN WATERS

The liquidity of the ocean permits it to be in continuous motion, and this motion can be grouped under three headings: tides, currents, and waves. The movement of almost

anything over the surface—the wind, a boat, a swimmer—can set the water surface into motion, and so the ocean surface is almost always ridged with swells and waves. Disturbances of the ocean floor can also trigger significant movements in the water (see Chapter 20 for a discussion of *tsunami*). Currents may entail considerable displacement of water, particularly horizontally, but also vertically and obliquely. The gravitational attraction of the Moon and Sun causes the greatest movements of all: the tides.

Tides

Animation
Tides

On the shores of the world ocean, almost everywhere, sea level fluctuates regularly. For about six hours each day, the water rises, and then for about six hours it falls. These rhythmic oscillations have continued unabated, day and night, winter and summer, for eons. **Tides** are essentially bulges in the sea surface in some places that are compensated by lower areas or "sinks" in the surface at other places. Thus, tides are primarily vertical motions of the water. In shallow-water areas around the margins of the oceans, however, the vertical oscillations of the tides may produce significant horizontal water movements as well, when tides cause ocean water to advance and retreat along gently sloping coastal plains.

Causes of Tides: Every object in the universe exerts an attractive gravitational force on every other object. Thus, Earth exerts an attractive force on the Moon, and the Moon exerts an attractive force on Earth. The same is true for Earth and the Sun. It is the gravitational attraction between the Moon and Earth, and between the Sun and Earth, that cause tides.

The strength of the force of gravity is inversely proportional to the square of the distance between the two bodies, and so, because the Sun is 150,000,000 kilometers (93,000,000 miles) from Earth and the Moon is 385,000 kilometers (239,000 miles), the Moon produces a greater percentage of Earth's tides than does the Sun. The *lunar tides* are about twice as strong as the *solar tides*. To keep things simple, let us first discuss lunar tides alone, ignoring solar tides for the moment.

Gravitational attraction pulls ocean water toward the Moon. There is more gravitational attraction on the side of Earth facing the Moon (the side closest to the Moon) than on the opposite side of Earth. The difference in force slightly elongates the shape of the global ocean, so that two bulges of ocean water develop—one on the side of Earth facing the Moon and the other on the opposite side of Earth. As Earth rotates, coastlines move into and out of these bulges, producing simultaneous high tides on the opposite sides of Earth and low tides halfway between.

As Earth rotates eastward, the tidal progression appears to move westward. The tides rise and fall twice in the interval between two "rising" Moons, an interval that is about 50 minutes longer than a 24-hour day. The combination of Earth's rotation and the Moon's revolution around Earth means that Earth makes about 12° more than a full rotation between each rising of the Moon. Thus, two complete tidal cycles have a duration of about 24 hours and 50 minutes. This means that on all oceanic coastlines there are normally two high tides and two low tides about every 25 hours.

The magnitude of tidal fluctuation is quite variable in time and place, but the sequence of the cycle is generally similar everywhere. From its lowest point, the water rises gradually for about 6 hours and 13 minutes, so that there is an actual movement of water toward the coast in what is called a **flood tide**. At the end of the flooding period, the maximum water level, *high tide*, is reached. Soon the water level begins to drop, and for the next 6 hours and 13 minutes there is a gradual movement of water away from the coast, a movement called an **ebb tide**. When the minimum water level (*low tide*) is reached, the cycle begins again.

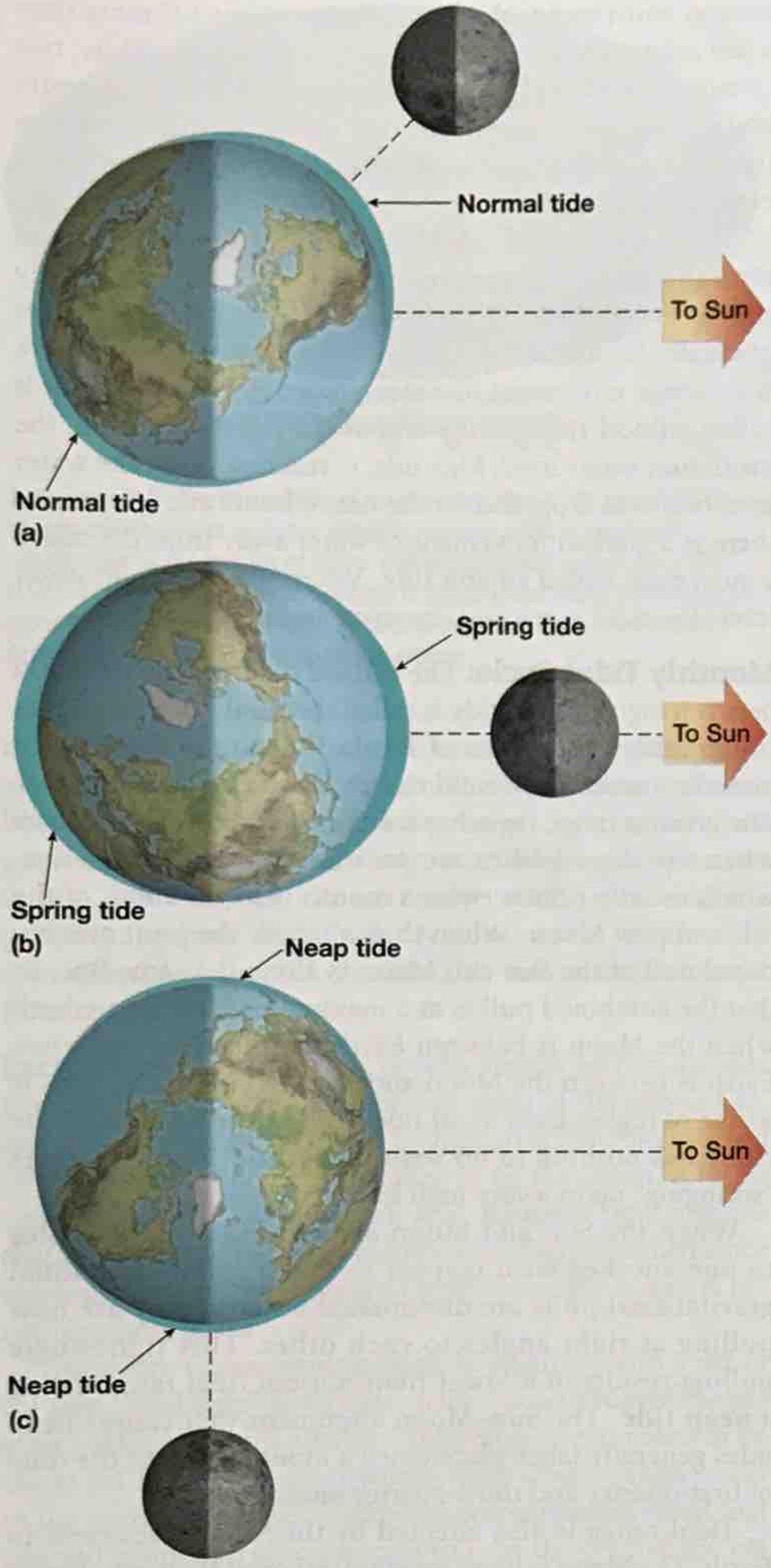
Monthly Tidal Cycle: The vertical difference in elevation between high and low tide is called the **tidal range**. Changes in the relative positions of Earth, Moon, and Sun induce periodic variations in tidal ranges, as shown in Figure 9-8. The greatest range (in other words, the highest tide) occurs when the three bodies are positioned in a straight line, which usually occurs twice a month near the times of the full and new Moon. When thus aligned, the joint gravitational pull of the Sun and Moon is along the same line, so that the combined pull is at a maximum. This is true both when the Moon is between Earth and the Sun and when Earth is between the Moon and Sun. In either case, this is a time of higher than usual tides, called **spring tides**. (The name has nothing to do with the season; think of water "springing" up to a very high level.)

When the Sun and Moon are located at right angles to one another with respect to Earth, their individual gravitational pulls are diminished because they are now pulling at right angles to each other. This right-angle pulling results in a lower than normal tidal range called a **neap tide**. The Sun–Moon alignment that causes neap tides generally takes place twice a month at about the time of first-quarter and third-quarter moons.

Tidal range is also affected by the Moon's nearness to Earth. The Moon follows an elliptical orbit in its revolution around Earth, the nearest point (called *perigee*) is about 50,000 kilometers (31,200 miles), or 12 percent, closer than the farthest point (*apogee*). During perigee, tidal ranges are greater than during apogee.

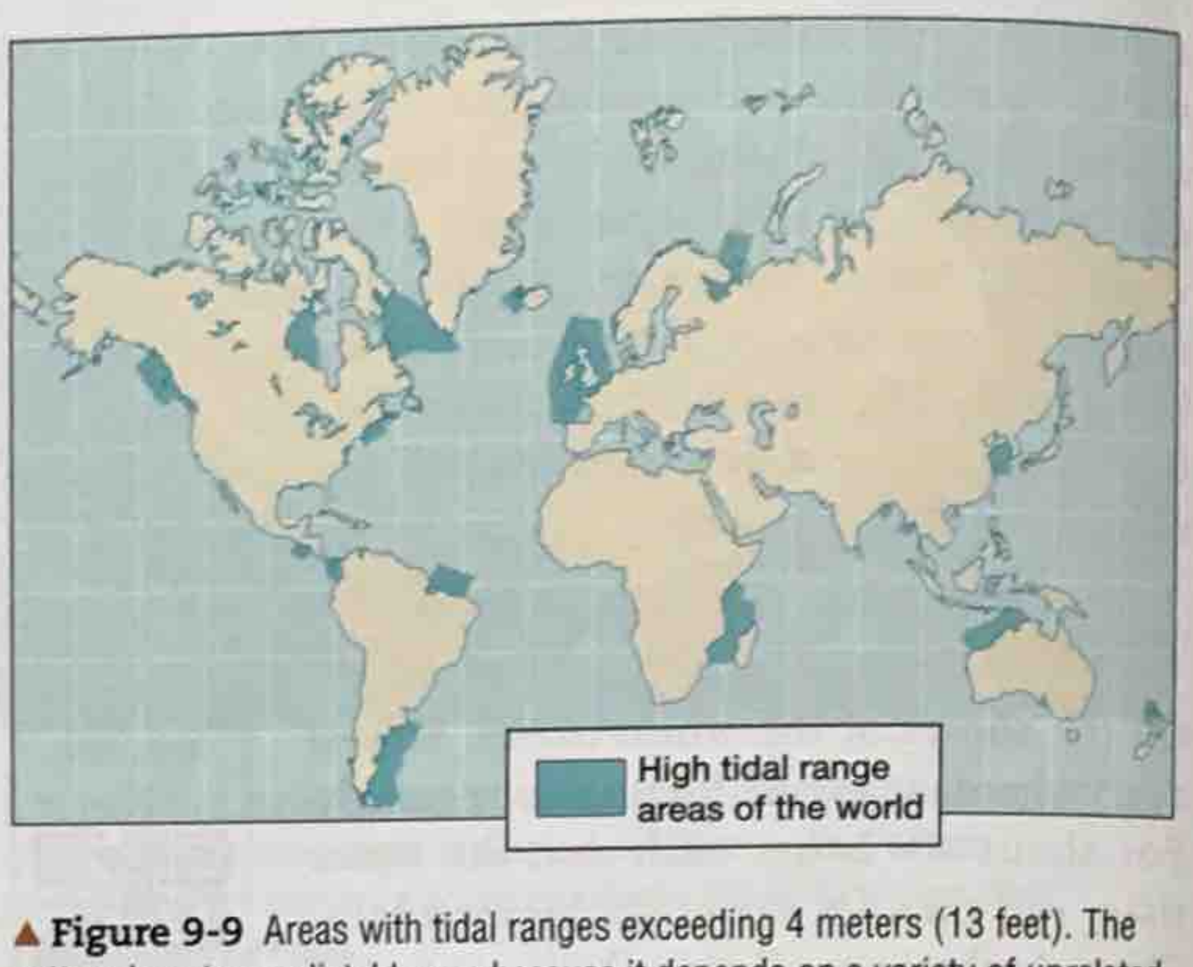
Learning Check 9-4 **Describe the positions of the Sun, Moon, and Earth that produce the highest high tides and the lowest low tides.**

Global Variations in Tidal Range: Tidal range fluctuates all over the world at the same times of the month. There are, however, enormous variations in range along different coastlines (Figure 9-9). Midocean islands may experience tides of only 1 meter (3 feet) or less, whereas continental seacoasts have greater tidal ranges, because the amplitude is



▲ **Figure 9-8** The monthly tidal cycle. The juxtaposition of the Sun, Moon, and Earth accounts for variations in Earth's tidal range. (a) When the Moon and Sun are neither aligned nor at right angles to each other, we have normal levels of high tides on both sides of Earth. (b) When the Sun, Earth, and Moon are positioned along the same line, *spring tides* (the highest high tides) are produced. (c) When the line joining Earth and the Moon forms a right angle with the line joining Earth and the Sun, *neap tides* (the lowest high tides) result.

greatly influenced by the shape of the coastline and the configuration of the sea bottom beneath coastal waters. Along most coasts, there is a moderate tidal range of 1.5 to 3 meters (5 to 10 feet). Some partly landlocked seas, such as the Mediterranean, have almost negligible tides. Other places, such as the northwestern coast of Australia, experience enormous tides of 10 meters (35 feet) or so.



▲ **Figure 9-9** Areas with tidal ranges exceeding 4 meters (13 feet). The pattern is not a predictable one because it depends on a variety of unrelated factors, particularly shoreline and sea bottom configuration.

The greatest tidal range in the world is found at the upper end of the Bay of Fundy in eastern Canada (Figure 9-10), where a 15-meter (50-foot) water-level fluctuation twice a day is not uncommon, and a wall of seawater—called a **tidal bore**—several centimeters to more than a meter in height rushes up the Petitcodiac River in New Brunswick for many kilometers.

Tidal variation is exceedingly small in inland bodies of water. Even the largest lakes usually experience a tidal rise and fall of no more than 5 centimeters (2 inches). Effectively, then, tides are important only in the world ocean, and they are normally noticeable only around its shorelines.

Ocean Currents

Animation
Ocean Circulation Patterns—Subtropical Gyres

As we learned in Chapter 4, the world ocean contains a variety of currents that shift vast quantities of water both horizontally and vertically. Surface currents are caused primarily by wind flow, whereas other currents are set in motion by contrasts in temperature and salinity. All currents may be influenced by the size and shape of the particular ocean, the configuration and depth of the sea bottom, and the Coriolis effect. Some currents involve subsidence of surface waters downward; other vertical flows bring an upwelling of deeper water to the surface.

Geographically speaking, the most prominent currents are the major horizontal flows that make up the general circulation of the various oceans. The dominant surface currents introduced in Chapter 4 are generally referred to as *subtropical gyres* (see Figure 4-26). They are set up by the action of the dominant surface wind systems in the tropics and midlatitudes: the trade winds and the westerlies.

Ocean currents not only can transport floating debris, both natural and human-produced, across large expanses of ocean, but they also can concentrate trash in several

(a)

(b)

▲ **Figure 9-10** (a) The world's maximum tides are in the Bay of Fundy, where ocean water moves long distances up many of the coastal rivers twice a day. (b) A tidal bore moving up the Petitcodiac River in New Brunswick, Canada.

areas of the Pacific Ocean—see the box, "People and the Environment: The Great Pacific Garbage Patch."

Deep Ocean Circulation: In addition to the major surface ocean currents, there is an important system of deep ocean circulation as well. This circulation of deep ocean water occurs because of differences in water density that arise from differences in salinity and temperature. For this reason, this water movement is sometimes referred to as **thermohaline circulation**. Ocean water will become denser, and thus sink, if its salinity increases or its temperature decreases. This happens predominantly in high-latitude ocean areas where the water is cold and salinity increases when sea ice develops (the dissolved salts are not taken up in the ice when water freezes, so the salinity of the remaining water increases).

Animation
Ocean Circulation Patterns—Global Conveyor-Belt Circulation

The combination of deep ocean water movement through thermohaline circulation, along with influences from surface ocean currents, establishes an overall **global conveyer-belt circulation** pattern (Figure 9-11). Beginning in the North Atlantic, cold, dense water sinks and slowly flows deep below the surface to the south, where it eventually joins the eastward moving deep, cold, high salinity water circulating around Antarctica. Some of this deep water eventually flows north into the Indian and Pacific Oceans, where it rises to form a shallow, warm current that flows back to the North Atlantic Ocean, where it sinks and begins its long journey once again. These deep ocean currents might travel only 15 kilometers (9 miles) in a year—thus requiring many centuries to complete a single circuit.

The global conveyor-belt circulation does not have as immediate an effect on weather and climate as do the subtropical gyres and other surface currents discussed in Chapter 4. Nonetheless, this circulation plays a role in energy transfer around the globe—and therefore long-term climate patterns. Recent research suggests that a connection exists between the global conveyer-belt circulation and global climate. For example, if global climate becomes warmer, the freshwater runoff from the melting of Greenland's glaciers could form a pool of lower density water in the North Atlantic; this lower-density surface water could disrupt the downwelling of water in the North Atlantic, altering the redistribution of heat—and so climate—around the world.

Learning Check 9-5 **Explain what causes the movement of water in the global conveyor-belt circulation.**

Waves

To the casual observer, the most conspicuous motion of the ocean is provided by waves. Most of the sea surface is in a

The Great Pacific Garbage Patch

▶ Jennifer Rahn, Samford University, Birmingham, Alabama

Characteristics that make plastic items useful to consumers—their strength and durability—also make them a problem in marine environments. Each year more than 90 billion kilograms (200 billion pounds) of plastic is produced worldwide, and about 10 percent of this ends up in the ocean. The trash tends to accumulate in areas where winds and currents are weak in the center of the ocean current *subtropical gyres* (see Figure 4-26)—especially in the area of the subtropical high (Figure 9-A).

Some of the trash sinks but most of it floats in the upper 10 meters (30 feet) of the ocean (Figure 9-B). Estimates of the size of the floating trash patch now in the Pacific Ocean vary from the size of Texas to twice the size of Texas. It contains approximately 3.2 billion kilograms (3.5 million tons) of trash, and 80 percent of it is plastic. In the last few years, this floating mass of trash has received a vast amount of media attention and is now known as the *Great Pacific Garbage Patch*. A 2012 study based on research by Scripps Institution of Oceanography estimates that the trash accumulating in the patch has increased by 100 times in just the last four decades.

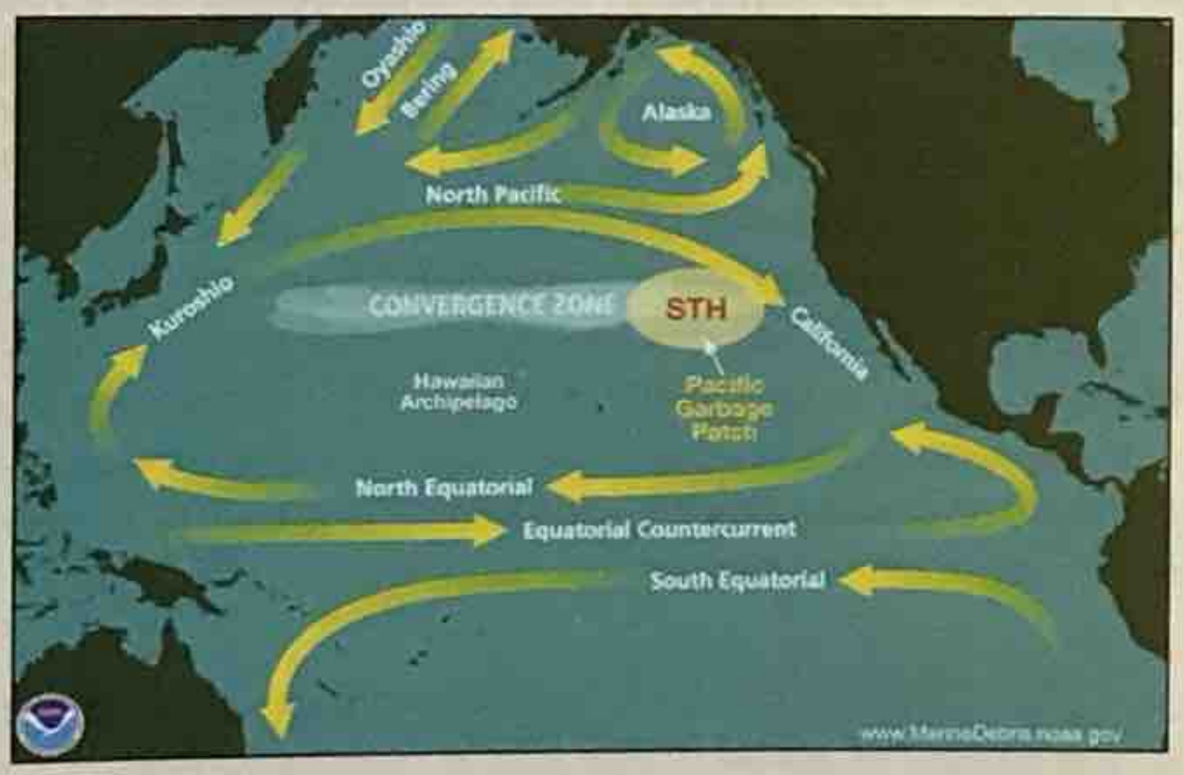
Loction of Pacific Garbage Patch: The Great Pacific Garbage Patch actually consists of two main regions of ever-growing garbage accumulation. The eastern garbage patch—the first to gain attention—floats between Hawai'i and California, generally in the location of the subtropical high. The western garbage patch extends east of Japan to the western archipelago of the Hawaiian Islands, within what is called the *North Pacific Subtropical Convergence Zone*. These patches of garbage and flotsam in the Pacific (and evidently other ocean basins as well) are not new; they have always been there. What is new is that now most of it is nonbiodegradable plastic—formerly it was debris such as wood, glass bottles, and fishing floats.

Hazards to Marine Life: A variety of environmental hazards are associated with the Great Pacific Garbage Patch. Plastic sea trash often floats at the surface and includes bottle caps, bags, and wrappers. Marine animals often mistake the floating plastic for food. To sea turtles or birds, a plastic bag floating in the water looks like a jellyfish—one of their favorite foods. However, they have no way of digesting plastic. Animals that eat too much plastic die because they cannot pass it—it fills their stomachs and they starve to death.

Marine animals can also become entangled in plastic bags or the plastic rings that hold canned drinks; unable to eat, they starve to death. More than 267 marine species have been harmed by the debris, and about 100,000 whales, seals, turtles, birds, dolphins, and other marine animals are killed each year by plastic–induced asphyxiation, strangulation, contamination, and entanglement.

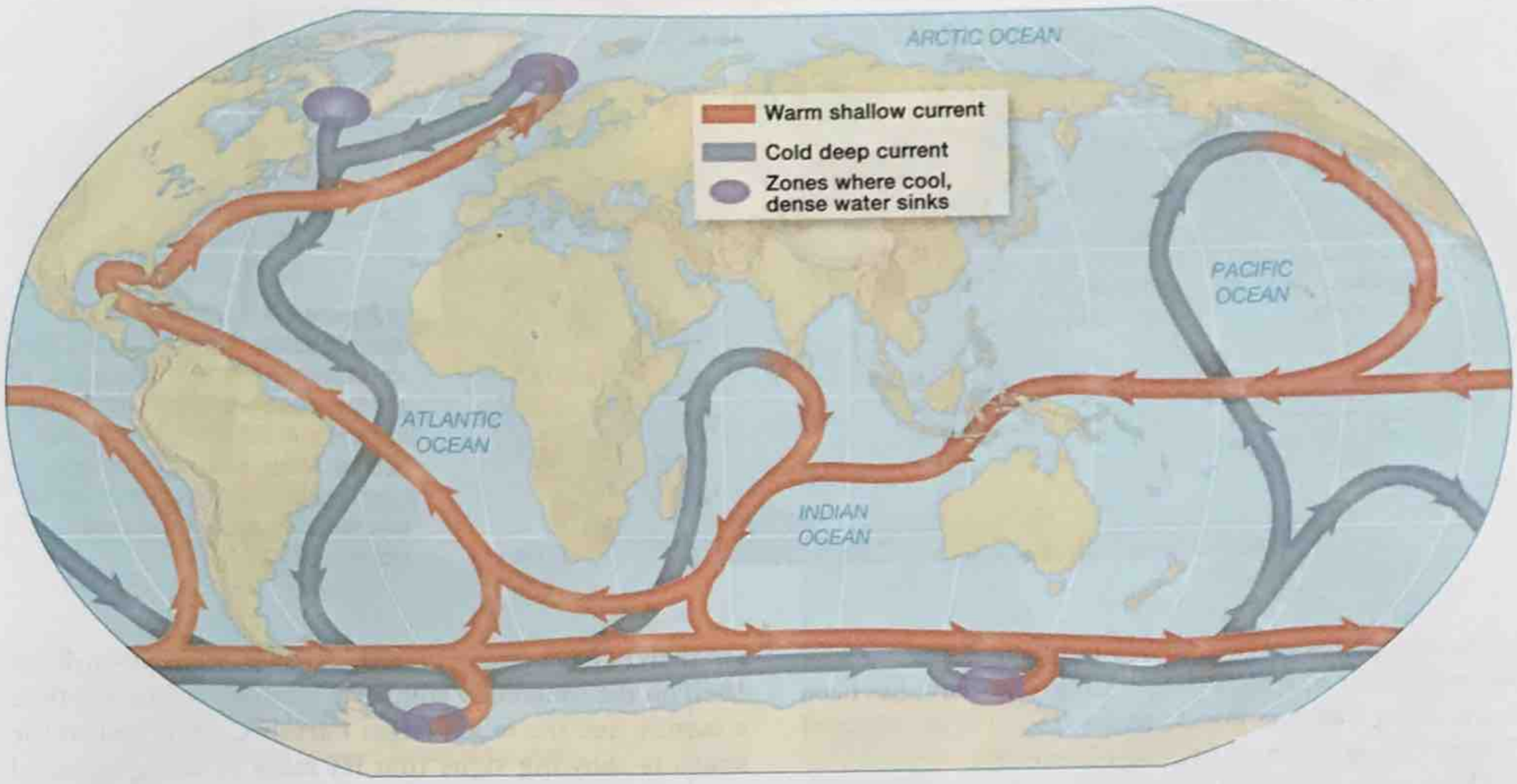
Instead of biodegrading, most plastic slowly breaks up by photodegrading into smaller and smaller pieces. Fish mistakenly consume these small plastic particles, thinking they are plankton, their main food source. In the Great Pacific Garbage Patch there is now six times more plastic than plankton. The small particles of plastic ingested by the small fish have many toxic qualities. In the Great Pacific Garbage Patch toxic chemical levels in fish have been as high as a million times the concentration in the surrounding water. The chemicals in the plastic break down and enter the system of the fish, and these toxins are concentrated in the top of the food chain where they may be consumed by whales, dolphins—and humans. As people eat the large fish (tuna, shark, king mackerel, marlin and swordfish, to name a few), they are receiving concentrated doses of these toxins because the effects of the pollutants increase as they advance up the food chain.

Debris from 2011 Japanese Tsunami: By the spring of 2012, debris washed offshore by the great March 2011 tsunami in Japan (see Chapter 20) was beginning to come ashore on the opposite side of the Pacific—for example, a 20-meter (66-foot) dock arrived on an Oregon beach in June 2012. One computer model suggests that much of the tsunami debris will be incorporated into the Great Pacific Garbage Patch by 2016.



▲ **Figure 9-A** Map showing the location of the Great Pacific Garbage Patch. In addition to the garbage patch generally located in the area of the subtropical high (STH), garbage also accumulates in the western portion of the North Pacific Subtropical Convergence Zone.

▲ **Figure 9-B** Floating debris in the Great Pacific Garbage Patch. Credit: Scripps Institution of Oceanography, UC San Diego



▲ **Figure 9-11** Idealized global conveyor-belt circulation. In the North Atlantic Ocean cool, dense water sinks and moves south as a deep subsurface flow. It joins cold, deep water near Antarctica, eventually moving into the Indian and North Pacific Ocean where the water rises slowly, eventually flowing back into the North Atlantic where it again sinks. The violet ovals show major locations where cool, dense surface water feeds the flow of deep water. One circuit may take many hundreds of years to complete.

state of constant agitation, with wave crests and troughs bobbing up and down most of the time. Moreover, around the margin of the ocean, waves of one size or another lap, break, or pound on the shore in endless procession.

Most of this movement is like "running in place" from the water's point of view, with little forward progress. Waves in the open ocean are mostly just shapes, and the movement of a wave across the sea surface is a movement of form rather than of substance or, to say the same thing another way, of energy rather than matter. Individual water particles make only small oscillating movements. Only when a wave "breaks" does any significant shifting of water take place. Waves are discussed in detail in Chapter 20.

PERMANENT ICE—THE CRYOSPHERE

Second only to the world ocean as a storage reservoir for moisture is the solid portion of the hydrosphere—the ice of the world, or *cryosphere*—as we learn from a glance back at Figure 9-1. Although minuscule in comparison with the amount of water in the oceans, the moisture content of ice at any given time is more than twice as large as the combined total of all other types of storage (groundwater, surface waters, soil moisture, atmospheric moisture, and biological water).

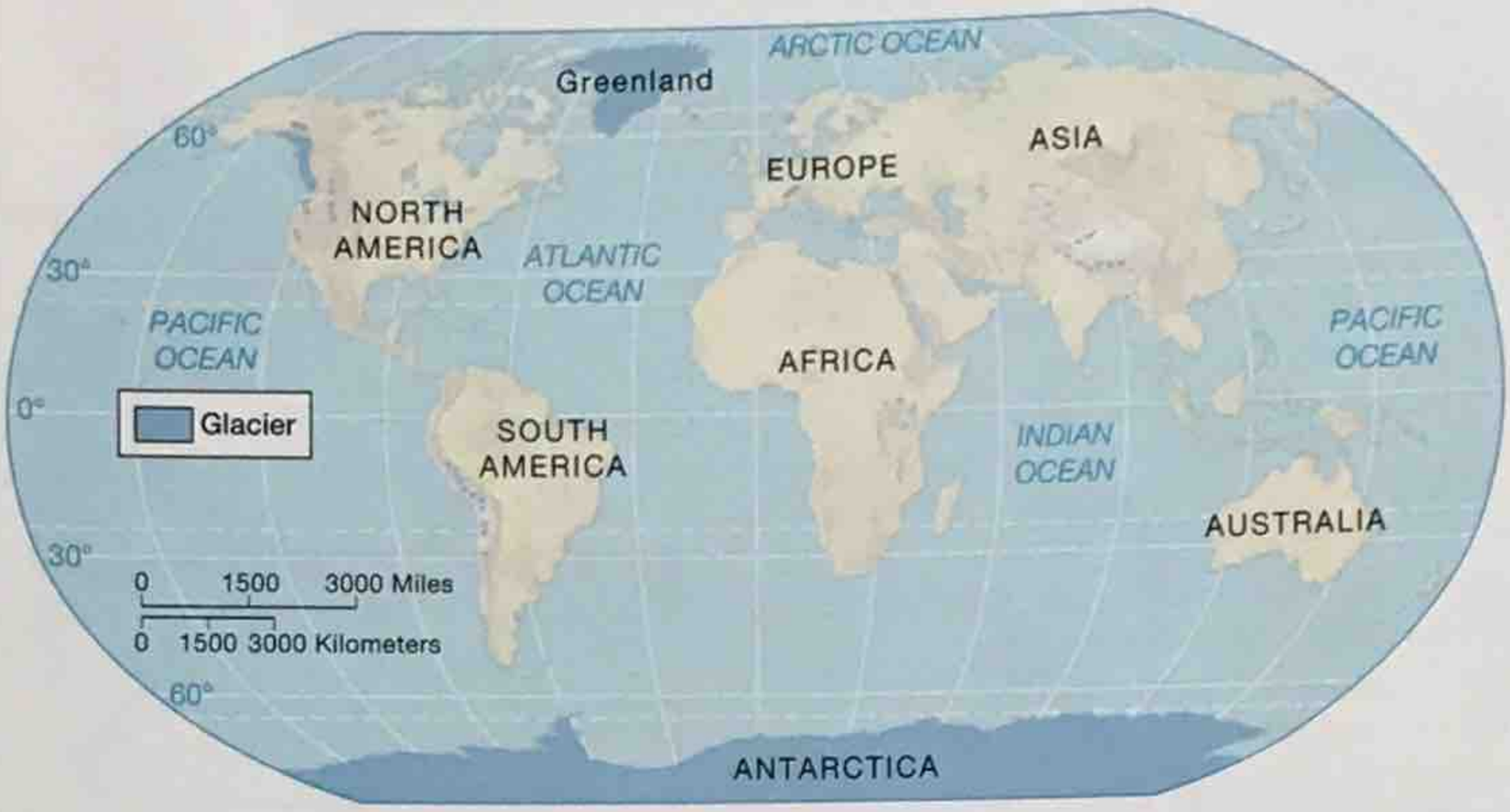
The ice portion of the hydrosphere is divided between ice on land and ice floating in the ocean, with the land portion being the larger. Ice on land is found as mountain glaciers, ice sheets, and ice caps, all of which are studied in Chapter 19. Approximately 10 percent of the land surface of Earth is covered by ice (Figure 9-12). It is estimated that enough water is locked up in this ice to feed all the rivers of the world at their present rate of flow for nearly 900 years.

Oceanic ice has various names, depending on size:

- **Ice pack**: An extensive and cohesive mass of floating ice.
- **Ice shelf**: A massive portion of a continental ice sheet that projects out over the sea.
- **Ice floe**: A large, flattish mass of ice that breaks off from larger ice bodies and floats independently.
- **Iceberg**: A chunk of floating ice that breaks off from an ice shelf or glacier. Because ice has a lower density than that of liquid water, only about 14 percent of the mass of an iceberg is exposed above the water, with about 86 percent below (the exact ratio varies slightly; Figure 9-13).

Despite the fact that some oceanic ice freezes directly from seawater, all forms of oceanic ice are composed almost entirely of freshwater because the salts present in the seawater in its liquid state are not incorporated into ice crystals when that water freezes.

The largest ice pack covers most of the surface of the Arctic Ocean (Figure 9-14); on the other side of the globe, an ice pack fringes most of the Antarctic continent (Figure 9-15). Both of these packs become greatly enlarged during their respective winters, their areas are essentially

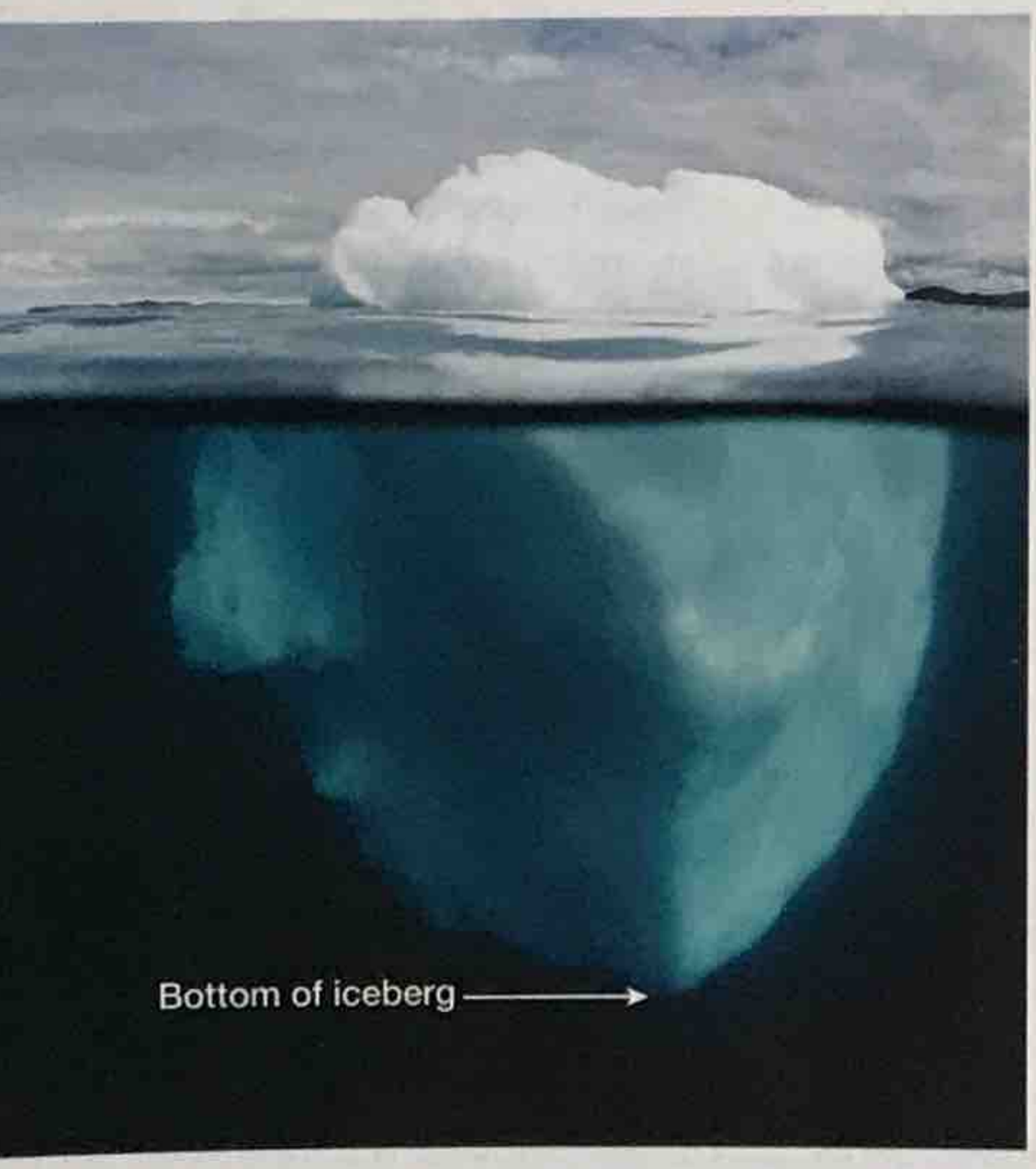


◀ **Figure 9-12** Glacial ice covers about 10 percent of Earth's surface. This ice is confined primarily to Antarctica and Greenland, with small amounts also found at high altitudes in the Canadian Rockies, Andes, Alps, and Himalayas. (The apparent size of glaciers on the continents is exaggerated to show locations.)

doubled by increased freezing around their margins. As we saw in Chapter 8, sea ice in the Arctic especially has been diminishing over the last 35 years (see "Focus: Signs of Climate Change in the Arctic" in Chapter 8).

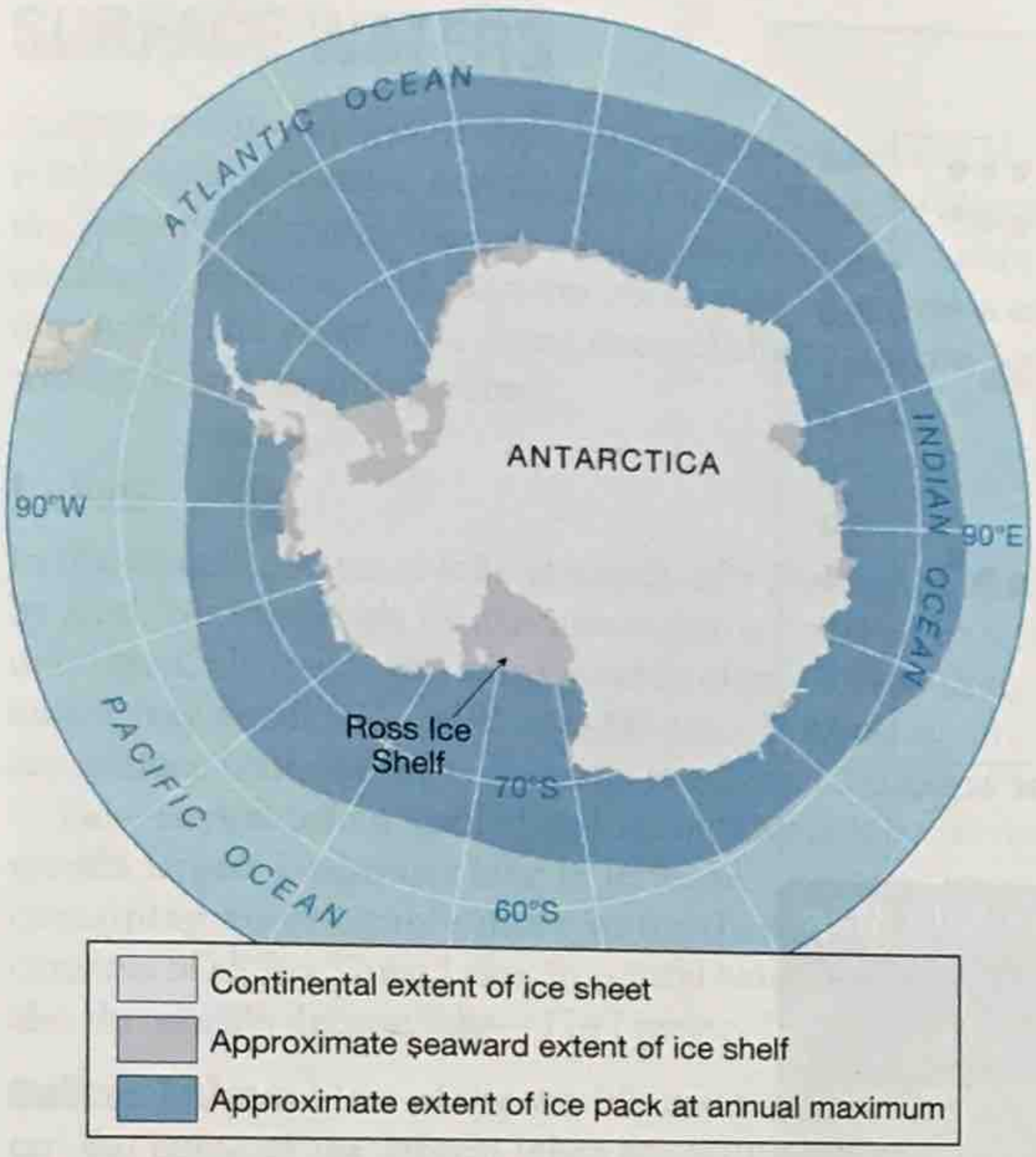
There are a few small ice shelves in the Arctic, mostly around Greenland, but several gigantic shelves are attached to the Antarctic ice sheet, most notably the Ross Ice Shelf of some 100,000 square kilometers (40,000 square miles). Some Antarctic ice floes are enormous; the largest ever observed was 10 times as large as the state of Rhode Island.

Over the last two decades, because of increasing temperatures, formerly stable ice shelves in Antarctica have broken apart. Since the early 1990s as much as 8000 square kilometers (over 3000 square miles) of Antarctic ice shelves have disintegrated. In 2002, the Larsen-B Ice Shelf on the Antarctic Peninsula disintegrated in less than a month, and the much larger Larsen-C shelf just to the south is showing signs that its mass is being reduced because of increasing water temperatures below it. In 2008, the Wilkins Ice Shelf in Antarctica also began to

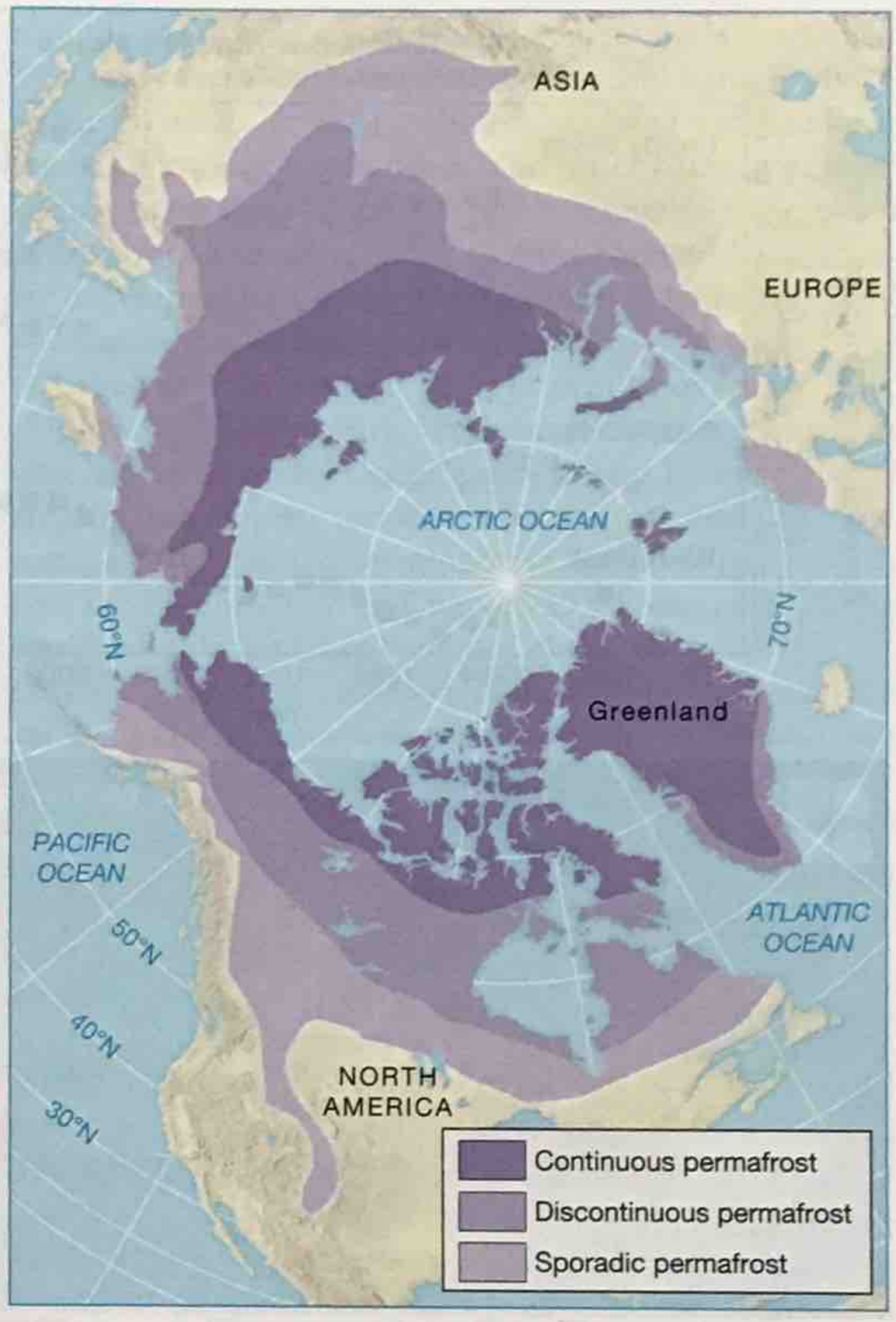


▲ **Figure 9-13** Most of an iceberg is underwater, as shown here in the waters of Disko Bay, Greenland.

▲ **Figure 9-14** The largest ice pack on Earth covers most of the Arctic Ocean, making that body of water essentially unnavigable. Powerful icebreaker ships allow passage from the Atlantic to the Pacific via this northern route, the fabled "Northwest Passage" of early European explorers. Over the last 35 years the Arctic summer ice pack has diminished by more than 40 percent from its twentieth-century long-term average shown here, and so the Northwest Passage may well become a reality in the future.



▲ **Figure 9-15** Maximum extent of ice in Antarctica. The ice sheet covers land, and the ice shelf and ice pack are oceanic ice. As is true in the Arctic, over the last three decades the extent of sea ice around Antarctica has diminished from its earlier twentieth-century long-term average shown here.



▲ **Figure 9-16** Extent of permafrost in the Northern Hemisphere. All the high-latitude land areas and some of the adjacent midlatitude land areas are underlain by permafrost. Climate change is slowly reducing the extent of permafrost.

disintegrate. (See Chapter 19 for further discussion of changes in glaciers and ice sheets around the world.)

Learning Check 9-6 **Where is most of the ice in the cryosphere found?**

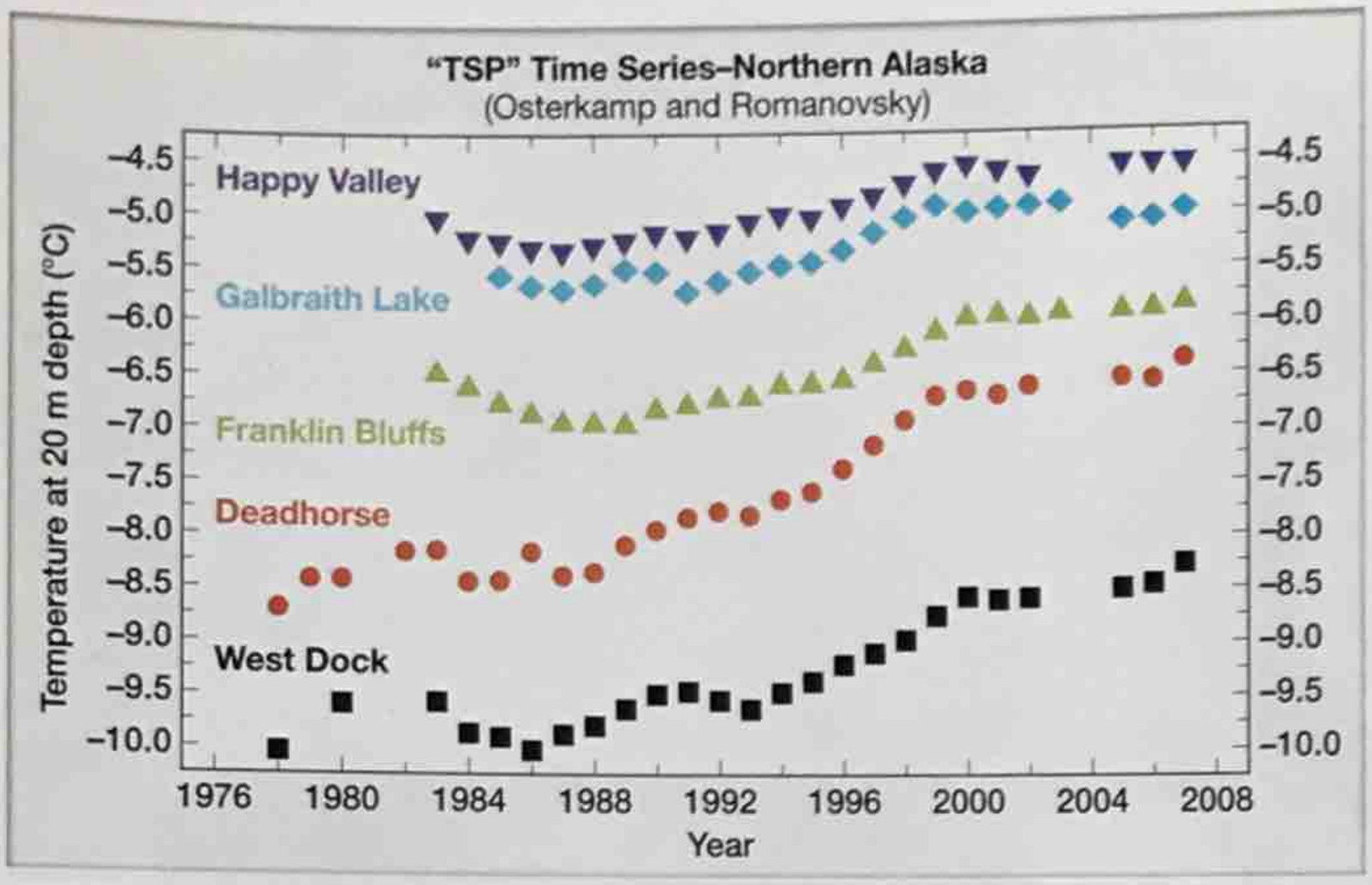
Permafrost

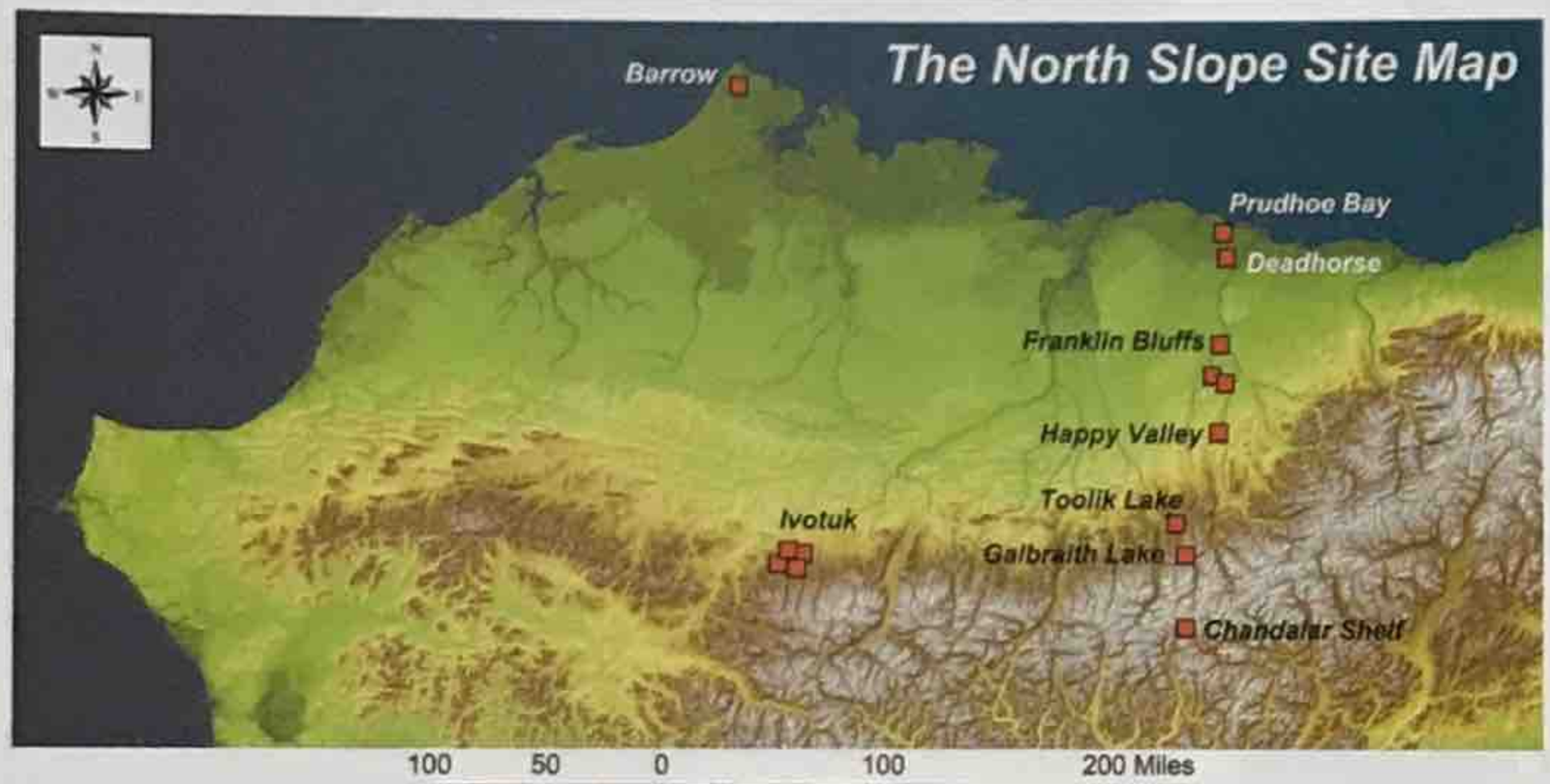
A relatively small proportion of the world's ice occurs beneath the land surface as ground ice. This type of ice occurs only in areas where the temperature is continuously below the freezing point, and so it is restricted to high-latitude and high-elevation regions (Figure 9-16). Most permanent ground ice is **permafrost**, which is permanently frozen subsoil. It is widespread in northern Canada, Alaska, and Siberia and found in small patches in many high mountain areas. Some ground ice is aggregated as veins of frozen water, but most of it develops as ice crystals in the spaces between soil particles.

Thawing of Permafrost: In locations such as the region around the city of Fairbanks in central Alaska, permafrost is widespread just below the surface. During the summer, only the upper 30 to 100 centimeters (12 to 40 inches) of soil thaws in what is called the *active layer*; below that is a layer of permanently frozen ground perhaps 50 meters (165 feet) thick. Much of the permafrost found in the high latitude areas of the world has been frozen for at least the last few thousands of years, but as a response to higher average temperatures, it is beginning to thaw. In just the last 35 years, a warming trend has been observed, bringing the ground temperature in some areas above the melting point of the permafrost. Deep in the permafrost layer where ground still remains frozen, temperatures are rising also (Figure 9-17).

For people accustomed to living in temperate environments, it might seem that having the ground thaw would not be a problem, but such is not the case. As the ground thaws, buildings, roads, pipelines, and airport runways are increasingly destabilized, and transportation and business are likely to be disrupted as a consequence (Figure 9-18). In areas with poor surface drainage, the degradation of permafrost can lead to what is called *wet thermokarst* conditions, where the surface subsides and the ground becomes oversaturated with water. In some cases, unpaved roads become impassible. In the last three decades, the number of days that the Alaska Department of Natural Resources permits oil exploration activity in areas of tundra has been cut in half due to the increasingly soft ground.

Along the Beaufort Sea, rising temperatures are thawing permafrost in the coastal bluffs and contributing to more



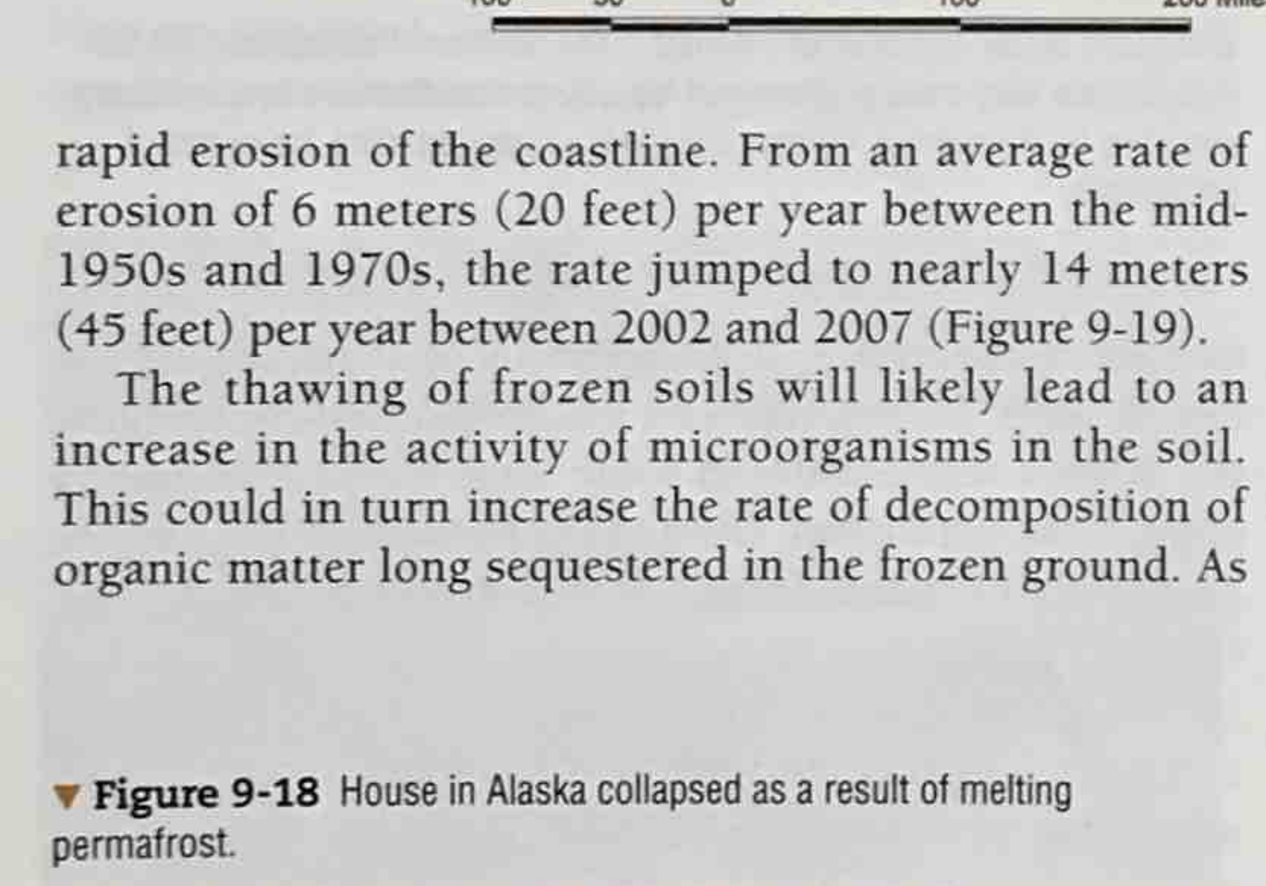


◀ **Figure 9-17** Changes in permafrost temperature at a depth of 20 meters (65 feet) from 1976 to 2008 in Alaska. Sites ranged from the Brooks Range to the North Slope.

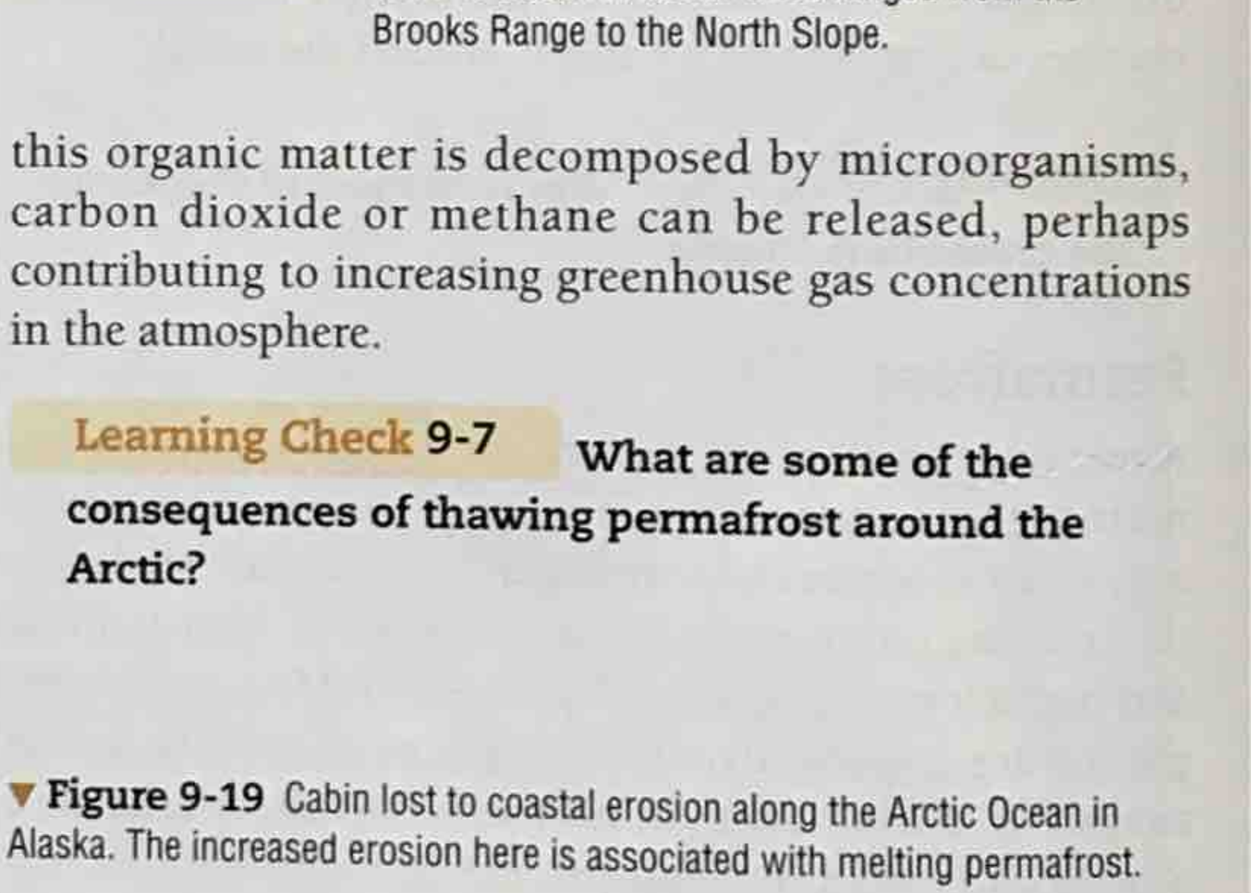
rapid erosion of the coastline. From an average rate of erosion of 6 meters (20 feet) per year between the mid-1950s and 1970s, the rate jumped to nearly 14 meters (45 feet) per year between 2002 and 2007 (Figure 9-19).

The thawing of frozen soils will likely lead to an increase in the activity of microorganisms in the soil. This could in turn increase the rate of decomposition of organic matter long sequestered in the frozen ground. As this organic matter is decomposed by microorganisms, carbon dioxide or methane can be released, perhaps contributing to increasing greenhouse gas concentrations in the atmosphere.

Learning Check 9-7 **What are some of the consequences of thawing permafrost around the Arctic?**



▼ **Figure 9-18** House in Alaska collapsed as a result of melting permafrost.



▼ **Figure 9-19** Cabin lost to coastal erosion along the Arctic Ocean in Alaska. The increased erosion here is associated with melting permafrost.

SURFACE WATERS

Surface waters represent only about 0.02 percent of the world's total moisture supply (see Figure 9-1), but from the human viewpoint they are of incalculable value. Lakes, wetlands, swamps, and marshes abound in many parts of the world, and all but the driest parts of the continents are seamed by rivers and streams.

Lakes

In the simplest terms, a **lake** is a body of water surrounded by land. No minimum or maximum size is attached to this definition, although the word *pond* is often used to designate a very small lake. Well over 90 percent of the nonfrozen surface water of the continents is contained in lakes.

Lake Baykal (often spelled Baikal) in Siberia is by far the world's largest freshwater lake in terms of volume of water, containing considerably more water than the combined contents of all five Great Lakes in central North America. It is also the world's deepest lake—1742 meters (5715 feet) deep.

Saline Lakes: Most of the world's lakes contain freshwater, but some of the largest lakes are saline. Indeed, more than 40 percent of the lake water of the planet is salty, with the lake we call the Caspian Sea containing more than three-quarters of the total volume of the world's nonoceanic saline water. (In contrast, Utah's famous Great Salt Lake contains less than 1/2500 the volume of the Caspian.) Any lake that has no natural drainage outlet, either as a surface stream or as a sustained subsurface flow, will become saline.

Most small salt lakes and some large ones are *ephemeral*, which means that they contain water only sporadically and are dry much of the time because they are in dry regions with insufficient inflow to maintain them on a permanent basis. We will discuss ephemeral lakes in desert regions in greater detail in Chapter 18.

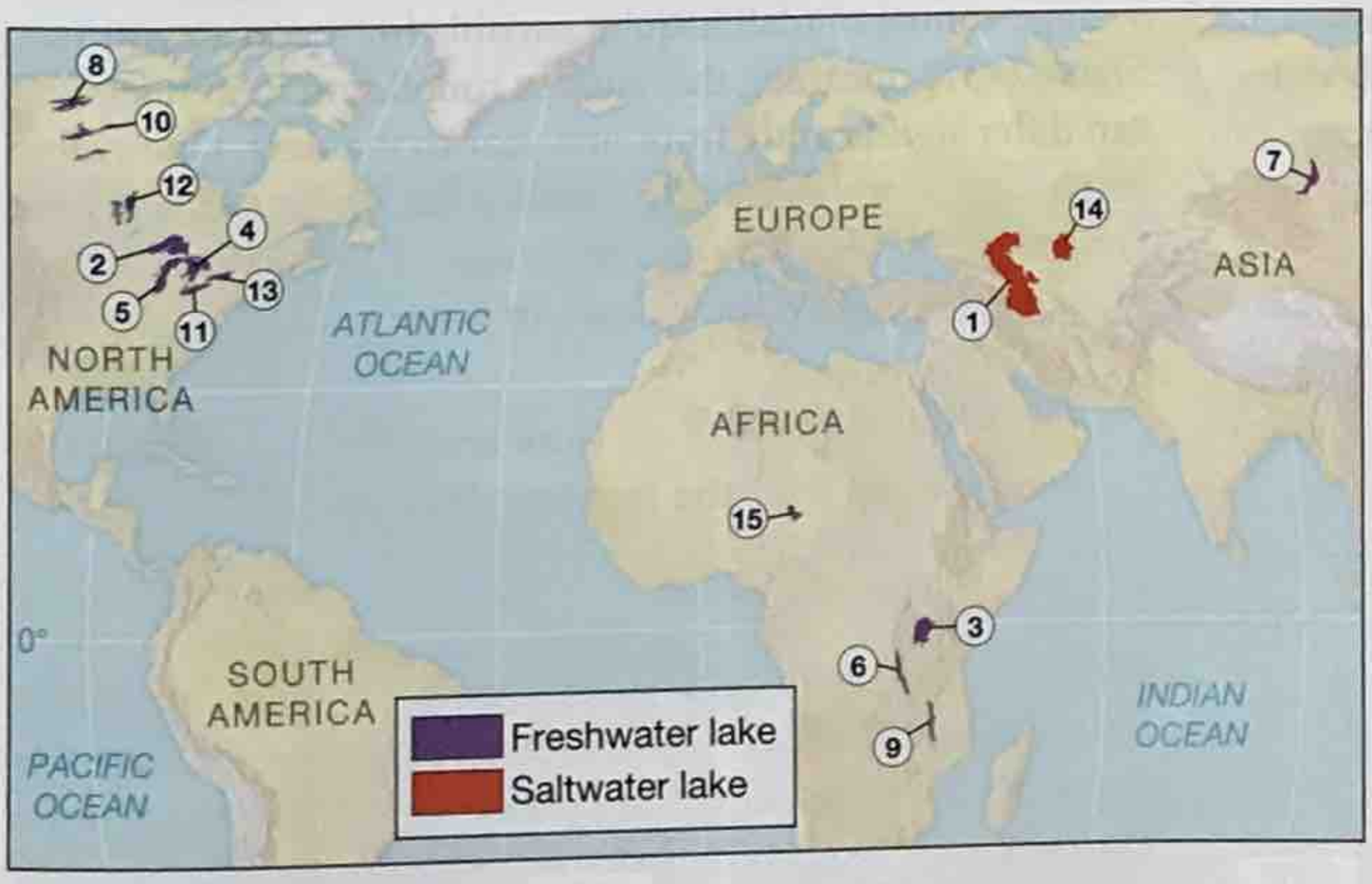
Formation of Lakes: Most lakes are fed and drained by streams, but lake origin is usually due to other factors. Two conditions are necessary for the formation and continued existence of a lake: (1) some sort of natural basin having a restricted outlet, and (2) sufficient inflow of water to keep the basin at least partly filled. The water balance of most lakes is maintained by surface inflow, sometimes combined with springs and seeps below the lake surface. A few lakes are fed entirely by springs. Most freshwater lakes have only one stream that serves as a drainage outlet.

Lakes are distributed very unevenly over the land (Figure 9-20). They are very common in regions that were glaciated in the recent geologic past because glacial erosion and deposition deranged the normal drainage patterns and created innumerable basins (Figure 9-21; also see Figure 19-28 in Chapter 19). Some parts of the world notable for lakes were not glaciated, however. For example, the remarkable series of large lakes in eastern and central Africa was created by faulting as Earth's crust spread apart tectonically (for example, see Figure 14-14 in Chapter 14); and the many thousands of small lakes in Florida were formed by sinkhole collapse when rainwater dissolved calcium carbonate from the limestone bedrock (for example, see Figure 17-9 in Chapter 17).

Most lakes are relatively temporary features of the landscape. Few have been in existence for more than a few thousand years, a time interval that is momentary in the grand scale of geologic time. Inflowing streams bring sediment to fill lakes up; outflowing streams cut channels progressively deeper to drain them; and as the lake becomes shallower, a continuous increase in plant growth accelerates the infilling (a process discussed in Chapter 10). Thus, the destiny of most lakes is to disappear naturally.

Human Alteration of Natural Lakes: Human activity also plays a part in the disappearance of lakes. For example, the diversion of streams flowing into California's Mono Lake (to the east of Yosemite National Park) has reduced its volume by one-half since the 1940s.

More dramatically, the Aral Sea was once the world's fourth-largest lake in terms of surface area, but beginning



World's Largest Lakes by Surface Area

		Square km	Square mi
(1)	Caspian Sea	372,450	143,250
(2)	Lake Superior	82,420	31,700
(3)	Lake Victoria	69,400	26,700
(4)	Lake Huron	59,800	23,000
(5)	Lake Michigan	58,000	22,300
(6)	Lake Tanganyika	33,000	12,650
(7)	Lake Baikal	31,700	12,200
(8)	Great Bear Lake	31,500	12,100
(9)	Lake Nyasa (L. Malawi)	30,000	11,550
(10)	Great Slave Lake	29,400	11,300
(11)	Lake Erie	25,700	9900
(12)	Lake Winnipeg	23,500	9100
(13)	Lake Ontario	19,500	7500
(14)	Aral Sea	*	*
(15)	Lake Chad	*	*

* Greatly reduced in size from that shown here

▲ **Figure 9-20** The largest lakes of the world, ranked by surface area.

◀ **Figure 9-21** Glaciation is responsible for the formation of Convict Lake in California.

in the 1960s, irrigation projects designed to boost agricultural production in Soviet Central Asia cut off much of the water flowing into the lake. The sea is now only about 10 percent of its original size (Figure 9-22). The once viable commercial fishing industry is gone, and winds now carry away a cloud of choking clay and salt dust lifted from the exposed lake bottom. The sea has split into several pieces. A new dam on the Syr Darya River is allowing the northern remnant of the Aral Sea to recover slightly, but the southern remnants are likely to remain dry.

In some cases, both human and natural changes are responsible for the loss of a lake. Fifty years ago, Lake Chad was one of the largest lakes in Africa, but ongoing drought has reduced it to about 5 percent of its original size (Figure 9-23). Nearly all of the lake's water comes from the Chari River flowing into the lake from the south. The lake is shallow and surrounded by an extensive wetlands area—once the second largest in Africa. Because the lake is shallow, it responds quite quickly to changes in inflow. Although water diversion projects along the Chari River have contributed to the reduction of Lake Chad, climate change in the region is likely responsible for much of its ongoing decline.

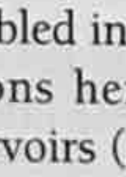
Reservoirs: One of the most notable things people have done to alter the natural landscape is to produce artificial lakes, or *reservoirs*. Such lakes have been created largely by the construction of dams, ranging from small earth mounds heaped across a gully to immense concrete structures blocking the world's major rivers (Figure 9-24). Some reservoirs are as large as medium-sized natural lakes.

Reservoirs are constructed for a number of different reasons, including controlling floods, ensuring a stable agricultural or municipal water supply, and for the generation of hydroelectric power—frequently for all of these reasons. The creation of artificial lakes has had immense ecological and economic consequences, not all of them foreseen at the time of construction (Figure 9-25). In addition to the obvious loss of the land that has been inundated by the waters of the reservoir, downstream ecosystems may be altered by restricted stream flows; and in some locations rapid sedimentation may restrict the useful life of a reservoir. In Chapter 16, we will consider the implications of flood control through the use of dams and river levees.

In the arid southwest of the United States—part of the so-called "Sunbelt" of the country—population growth has been especially rapid over the last two decades (Las Vegas more than doubled in population between 1990 and 2010). The populations here have depended on a network of dams and reservoirs (and, as discussed later in this chapter, groundwater pumping) for drinking water and agriculture. Recall from Chapter 6 that precipitation in regions of low average annual rainfall is quite variable from year to year (see Figure 6-37), meaning that surface runoff into local reservoirs can differ significantly from one year to the next. One visible consequence of this varying runoff is the "bathtub rings" seen around many reservoirs—a few years of lower-than-average rainfall causes a large drawdown in water level.

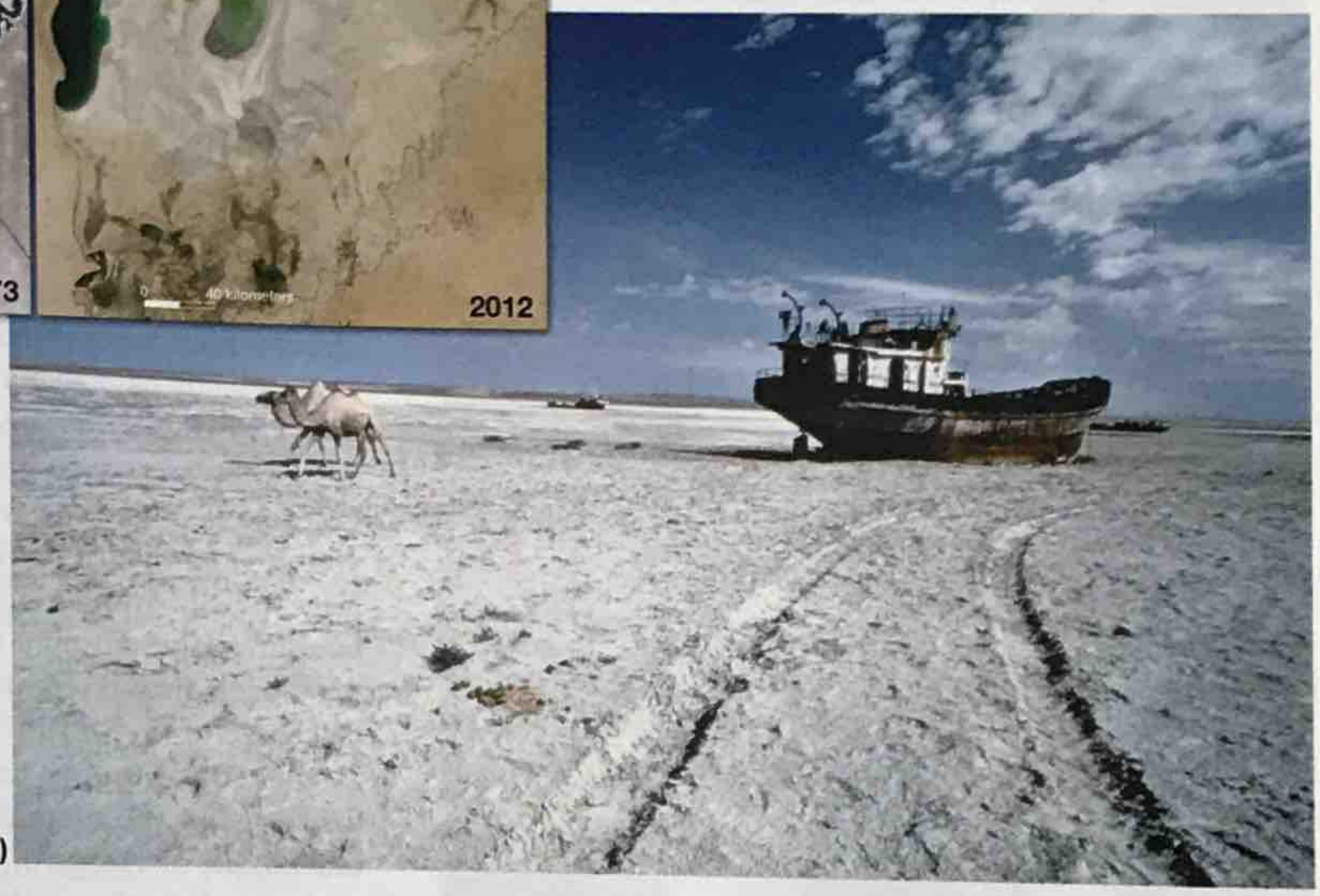
Learning Check **9-8** **How and why has the Aral Sea changed over the last few decades?**

Wetlands



Closely related to lakes but less numerous and containing a much smaller volume of water are **wetlands**—broadly defined as land areas where saturation with water is the overriding factor that influences soil development and plant and animal communities. As we will see in Chapter 11,

(a)

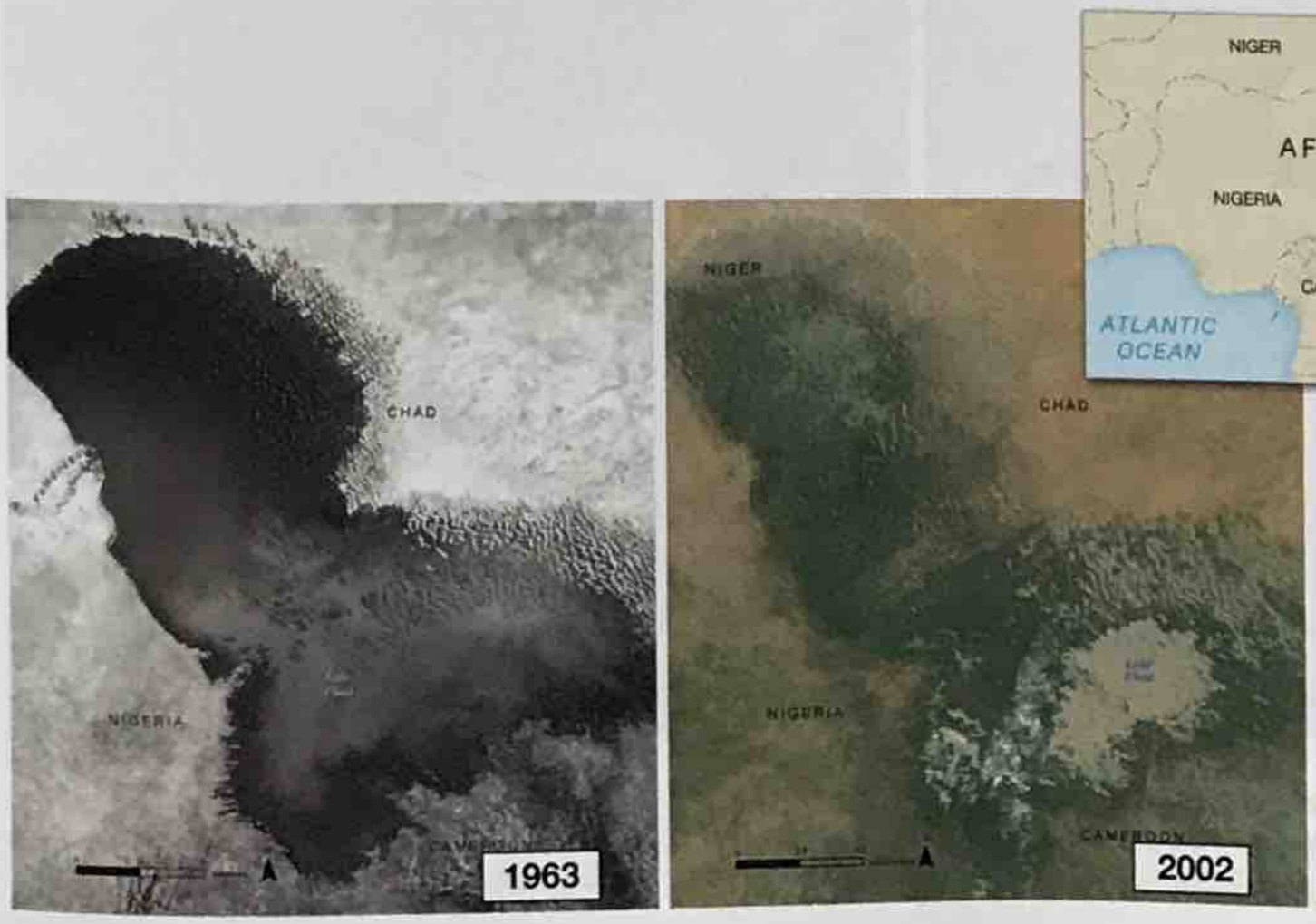


(b)

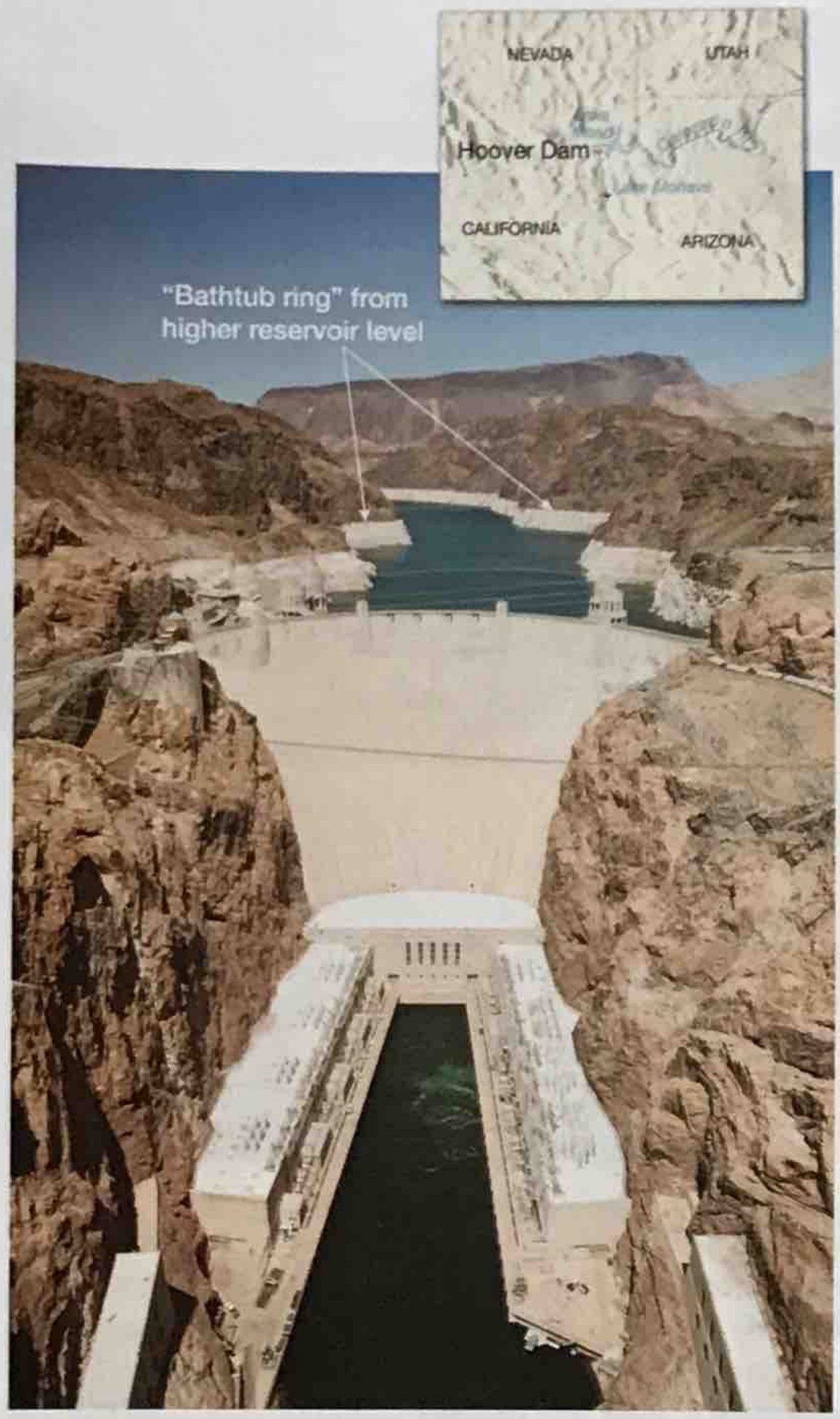
▲ **Figure 9-22** In 1960, the Aral Sea was the world's fourth-largest lake. However, as irrigation needs have forced farmers to drain more and more water from the rivers feeding the Aral, its size has decreased by 90 percent in the last 40 years. (a) The Aral Sea in 1973 (left) and in 2012 (right). (b) Where fish once swam, camels now wander over the floor of the "sea." If present trends continue, the Aral may cease to exist.

wetland areas play important roles in not only local ecosystems as sources of food and nutrients, but are keys to the water quality of many lakes, streams, and coastal waters by acting as "filters" for surface runoff. Further, as we saw in Chapter 7, coastal saltwater wetlands can act as buffers, reducing the immediate impact of hurricane storm surges.

Swamps and Marshes: Swamps and marshes are flattish places that are submerged in water at least part of the time but are shallow enough to permit the growth of water-tolerant plants (Figure 9-26). The conceptual distinction between the terms is that a **swamp** has a plant growth that is dominantly trees, whereas a **marsh** is



◀ **Figure 9-23** Lake Chad in 1963 and 2002.



▲ **Figure 9-24** Hoover Dam and Lake Mead on the Colorado River. The "bathtub ring" around the margin of the reservoir marks the water level when Lake Mead is at full capacity.

vegetated primarily with grasses and rushes. Both are usually associated with coastal plains, broad river valleys, or recently glaciated areas. Sometimes they represent an intermediate stage in the infilling of a lake.

Rivers and Streams

Although containing only a small proportion of the world's water at any given time, rivers and streams are an extremely dynamic component of the hydrologic cycle. (Although the terms are basically interchangeable, in common usage a *stream* is smaller than a *river*; geographers, however, call any flowing water a "stream," no matter what its size.) Streams provide the means by which the land surface drains and by which water, sediment, and dissolved chemicals are moved ever seaward. The occurrence of rivers and streams is closely, but not absolutely, related to precipitation patterns. Humid lands have many rivers and streams, most of which flow year-round; dry lands have fewer, almost all of which are ephemeral (which means they are dry most of the time).

Table 9-2 lists the world's largest rivers by discharge volume and length, while Figure 9-27 shows the world's largest river drainage basins (a *drainage basin* is all the land area drained by a river and its tributaries). A mere two dozen great rivers produce one-half of the total stream discharge of the world. The mighty Amazon yields nearly 20 percent of the world total, more than five times the discharge of the second-ranking river, the Congo River. Indeed, the discharge of the Amazon is three times as great as the total combined discharge of all rivers in the United States. The Mississippi is North America's largest river by far, with a drainage basin that encompasses about 40 percent of the total area of the 48 conterminous states and a flow that amounts to about one-third of the total discharge from all other rivers of the country.

We will explore the ways in which streams shape the landscape of the continents in Chapter 16.

▲ **Figure 9-25** The Three Gorges Dam and reservoir on the Yangtze River in China. The Landsat satellite image on the left was taken in 1987 before the dam was constructed; the image on the right was taken in 2009 after the reservoir behind the 2300-meter-wide dam was nearly full. As many as 1 million people will be displaced by the 600-kilometer-long reservoir.

▲ **Figure 9-26** Marshes are particularly numerous along the poorly drained South Atlantic and Gulf of Mexico coasts of the United States.

GROUNDWATER

Beneath the land surface is another important component of the hydrosphere—underground water. As Figure 9-1 shows, the total amount of underground water is many times that contained in lakes and streams. Moreover, underground water is much more widely distributed than surface water. Whereas lakes and rivers are found only in restricted locations, underground water is almost ubiquitous, occurring beneath the land surface throughout the world. Its quantity is sometimes limited, its quality is sometimes poor, and its occurrence is sometimes at great depth, but almost anywhere on Earth one can dig deep enough and find water. Strictly speaking, the term **groundwater** refers to underground water in the subsurface zone where the pore spaces are completely filled with water (the *zone of saturation*), but the term is often used broadly to refer to all underground water.

More than half of the world's underground water is found within 800 meters (about half a mile) of the surface. Below that depth, the amount of water generally decreases gradually and erratically. Although water has been found at depths below 10 kilometers (6 miles), it is almost immobilized because the pressure exerted by overlying rocks is so great and openings are so few and small.

Movement and Storage of Underground Water

Almost all underground water comes originally from above. Its source is precipitation that either percolates directly into the soil or eventually seeps downward from lakes and streams.

Porosity: Once the moisture gets underground, any one of several things can happen to it depending largely on the nature of the soil and rocks it infiltrates. The quantity of water that can be held in subsurface material (rock or soil) depends on the **porosity** of the material, which is the percentage of the total volume of the material that consists

TABLE 9-2 The World's Largest Rivers by Discharge and Length

Name	Rank by Discharge Volume	Rank by Length	Approximate Discharge (cubic meters per second)	Approximate Length (kilometers)	Approximate Drainage Area (square kilometers)	Continent
Amazon	1	2	210,000	6400	5,800,000	South America
Congo	2	9	40,000	4700	4,000,000	Africa
Ganges-Brahmaputra	3	23	39,000	2900	1,730,000	Eurasia
Yangtze	4	3	21,000	6300	1,900,000	Eurasia
Paranà-La Plata	5	8	19,000	4900	2,200,000	South America
Yenisey	6	5	17,000	5550	2,600,000	Eurasia
Mississippi-Missouri	7	4	17,000	6000	3,200,000	North America
Orinoco	8	27	17,000	2700	880,000	South America
Nile	25	1	5000	6650	2,870,000	Africa

Note: Estimates of river lengths and discharges are approximate; the relative rankings of some rivers vary from one data source to another.

▲ **Figure 9-27** The world's largest drainage basins are scattered over the four largest continents in all latitudes.

of voids (pore spaces or cracks) that can fill with water. The more porous a material is, the greater the amount of open space it contains and the more water it can hold.

Permeability: Porosity is not the only factor affecting underground water flow. If water is to move through rock or soil, the pores must be connected to one another and be large enough for the water to move through them. The ability to transmit underground water (as opposed to just hold it) is termed **permeability**, and this property of subsurface matter is determined by the size of pores and by their degree of interconnectedness. The water moves by twisting and turning through these small, interconnected openings. The smaller and less connected the pore spaces, the less permeable the material and the slower the water moves.

The rate at which water moves through rock depends on both porosity and permeability. For example, clay is usually of high porosity because it has a great many *interstices* (openings) among the minute flakes that make up the clay, but it generally has low permeability because the interstices are so tiny that the force of molecular attraction binds the water to the clay flakes and holds it in place. Thus, clay is typically very porous but relatively impermeable and consequently can trap large amounts of water and keep it from draining.

Aquifers: Underground water is stored in, and moves slowly through, moderately to highly permeable rocks called **aquifers** (from the Latin, *aqua*, "water," and *ferre*, "to bear"). The rate of movement of the water varies with the situation. In some aquifers, the flow rate is only a few centimeters a day; in others, it may be several hundred meters per day. A "rapid" rate of flow would be 12 to 15 meters (40 to 50 feet) per day.

Impermeable materials composed of components such as clay or very dense unfractured rock, which hinder or prevent water movement, are called **aquicludes** (Figure 9-28).

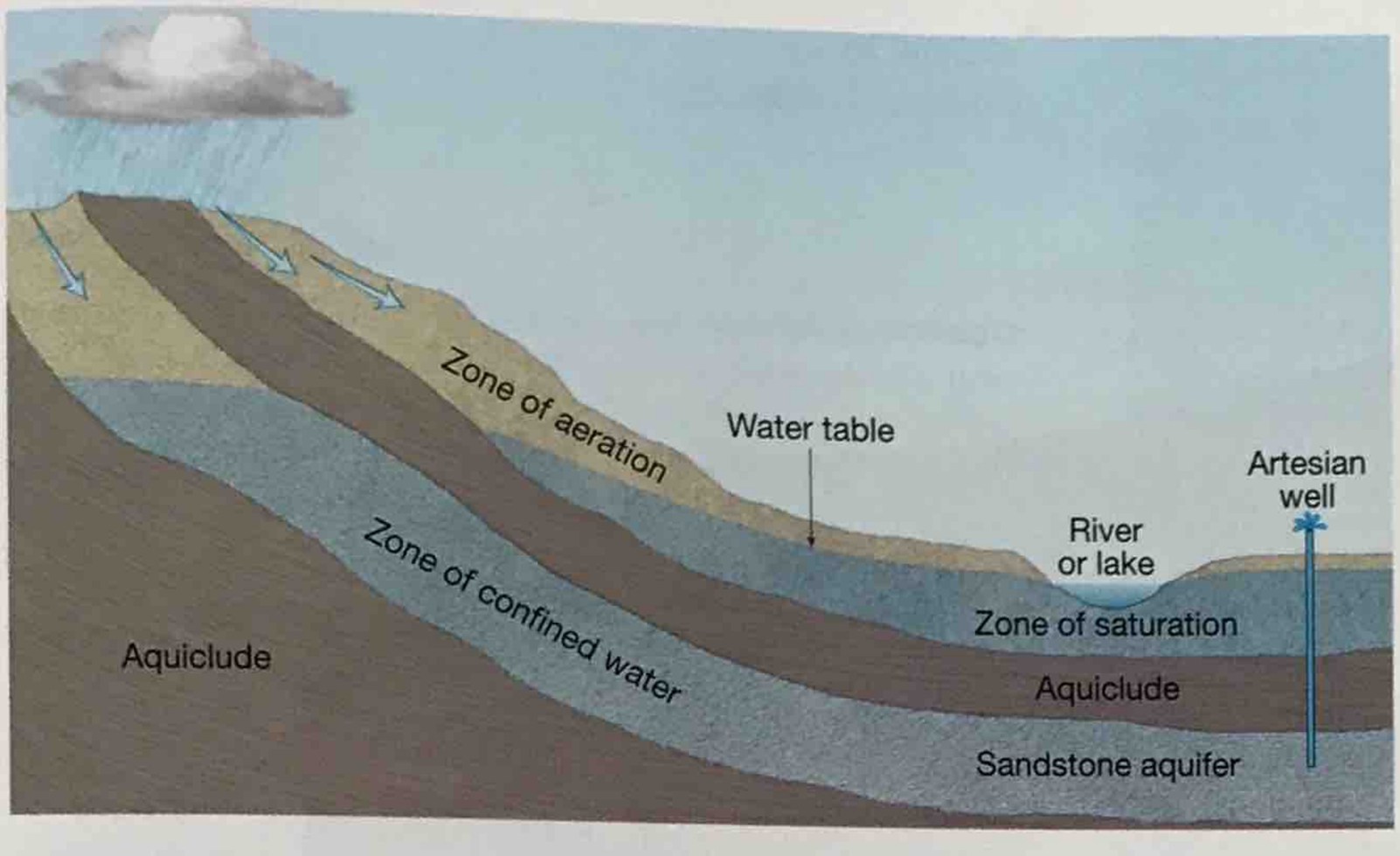
The general distribution of underground water can probably best be understood by visualizing a vertical subsurface cross section. Usually at least three and often four hydrologic zones are arranged one below another. From top to bottom, these layers are called the *zone of aeration*, the *zone of saturation*, the *zone of confined water*, and the *waterless zone*.

Zone of Aeration

Animation
The Water Table

The topmost band, the **zone of aeration**, is a mixture of solids, water, and air. Its depth can be quite variable, from a few centimeters to hundreds of meters. The interstices in this zone are filled partly with water and partly with air. The amount of water fluctuates considerably with time. After a rain, the pore spaces may be saturated with water, but the water may drain away rapidly. Some of the water evaporates, but much is absorbed by plants, which later return it to the atmosphere by transpiration. Water that molecular attraction cannot hold seeps downward into the next zone.

Learning Check 9-9 **What is an *aquifer*?**



◀ **Figure 9-28** An aquifer is a rock structure that is permeable and/or porous enough to hold water, whereas an aquiclude has a structure that is too dense to allow water to penetrate it.

Zone of Saturation

Immediately below the zone of aeration is the **zone of saturation**, in which all pore spaces in the soil and cracks in the rocks are fully saturated with water. The moisture in this zone is properly called *groundwater*. Groundwater seeps slowly through the ground following the pull of gravity and guided by rock structure.

The top of the saturated zone is referred to as the **water table**. The orientation and slope of the water table usually conform roughly to the slope of the land surface above, nearly always approaching closer to the surface in valley bottoms and being more distant from it beneath a ridge or hill. Where the water table intersects Earth's surface, water flows out, forming a spring. A lake, swamp, marsh, or permanent stream is almost always an indication that the water table reaches the surface there. In humid regions, the water table is higher than in arid regions, which means that the zone of saturation is nearer the surface in humid regions. Some desert areas have no saturated zone at all.

Sometimes a localized zone of saturation develops above an aquiclude, and this configuration forms a *perched water table*.

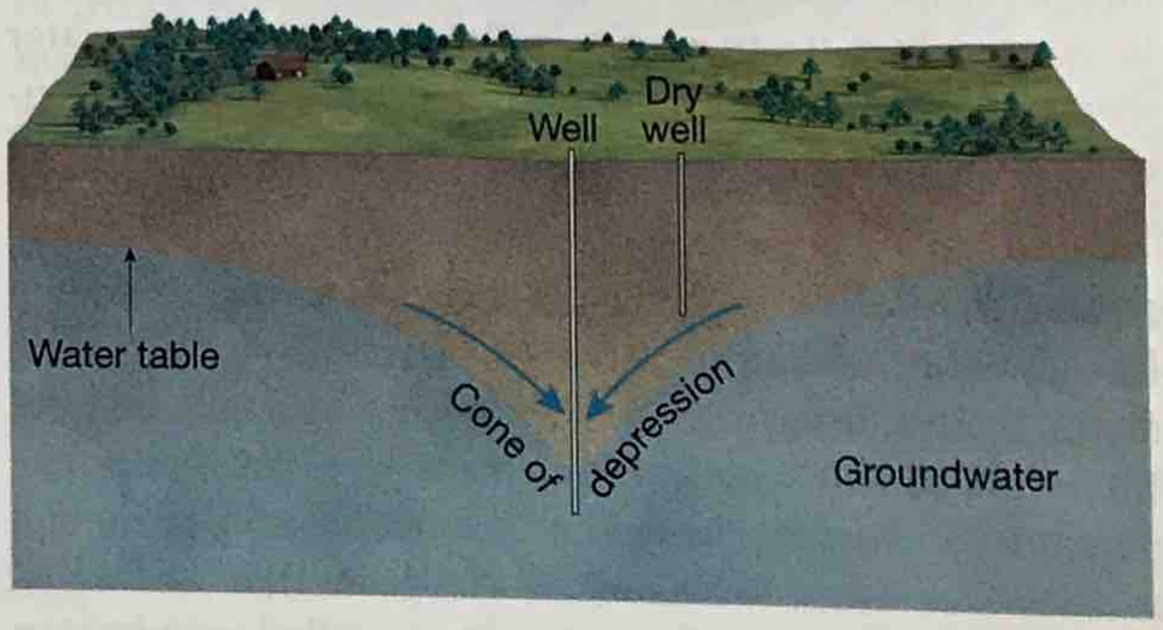
Cones of Depression: A well dug into the zone of saturation fills with water up to the level of the water table. When water is taken from the well faster than it can flow in from the saturated rock, the water table drops in the immediate vicinity of the well in the approximate shape of an inverted cone. This striking feature is called a **cone of depression** (Figure 9-29). If many wells are withdrawing water faster than it is being replenished naturally, the water table may be significantly depressed over a large area, causing shallower wells to go dry.

Animation
Groundwater Cone of Depression

Water percolates slowly through the saturated zone. Gravity supplies much of the energy for groundwater percolation, leading it from areas where the water table is high toward areas where it is lower—that is, toward surface streams or lakes. Percolation flow is not always downward, however. Often the flow follows a curving path and then turns upward (against the force of gravity) to enter the stream or lake from below. This trajectory is possible because saturated-zone water at any given height is under greater pressure beneath a hill than beneath a stream valley. Thus, the water moves toward points where the pressure is least.

The lower limit of the zone of saturation is marked by the absence of pore spaces and therefore the absence of water. This boundary may be a single layer of impermeable rock, or it may simply be that the increasing depth has created so much pressure that no pore spaces exist in any rocks at that level.

Learning Check 9-10 **How does a *cone of depression* form and how does it affect an aquifer?**



▲ **Figure 9-29** If water is withdrawn from a well faster than it can be replenished, a cone of depression will develop. This can effectively lower the water table over a large area. Nearby shallow wells may run dry because they lie above the lowered water table.

many arid or semiarid regions that are poor in surface water or groundwater, thus providing a critical resource for these dry lands.

Waterless Zone

At some depth below the surface, the overlying pressure on the rock is so great that there are effectively no pore spaces—and so the rock here cannot hold or transmit groundwater. This *waterless zone* generally begins several kilometers beneath the land surface.

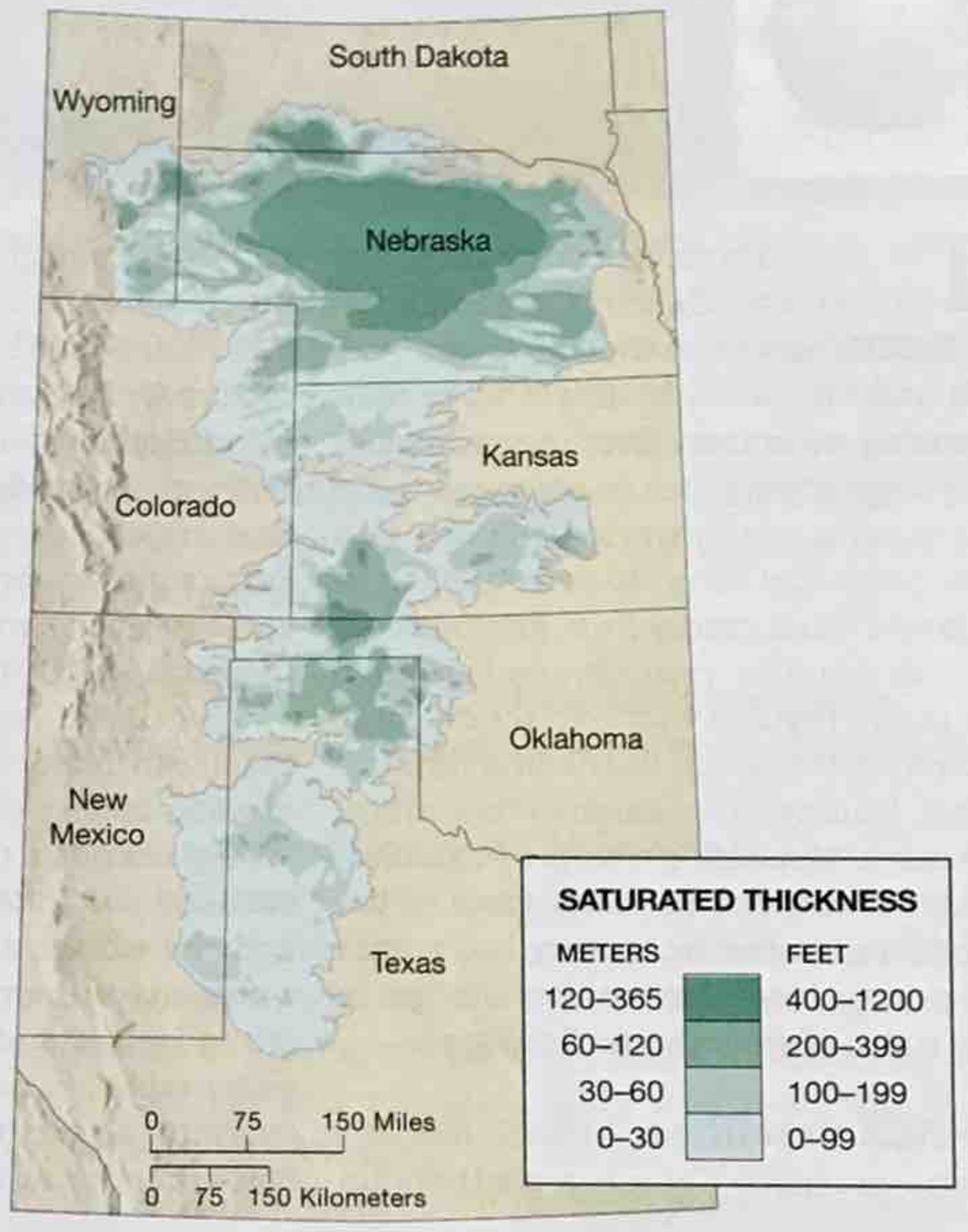
Groundwater Mining

In most parts of the world where groundwater occurs, it has been accumulating for a long time. Rainfall and snowmelt seep and percolate downward into aquifers, where the water may be stored for decades or centuries or millennia. Only in recent years have most of these aquifers been discovered and tapped by humans. They represent valuable sources of water that can supplement surface water resources. Underground water has been particularly utilized by farmers to irrigate in areas that contain insufficient surface water.

The accumulation of underground water is tediously slow. Its use by humans, however, can be distressingly rapid. In many parts of the U.S. Southwest, for example, the recharge (replenishment) rate averages only 0.5 centimeter (0.2 inch) per year, but it is not uncommon for a well to pump 75 centimeters (30 inches) per year. Thus, yearly pumpage is equivalent to 150 years' recharge. This rate of groundwater use can be likened to mining because a finite resource is being removed with no hope of replenishment. For this reason, the water in some aquifers is referred to as "fossil water." Almost everywhere in the world that underground water is being utilized on a large scale, the water table is dropping steadily and often precipitously.

In addition to depleting the water supply, groundwater mining causes a variety of problems. In some places, the compaction of sediments that takes place when groundwater is extracted faster than it is recharged leads to subsidence of the surface. For example, in the southern part of California's Central Valley, groundwater pumping resulted in 8.5 meters (about 29 feet) of subsidence in the mid-twentieth century. During the 1990s, groundwater pumping in the Las Vegas Valley of Nevada produced as much as 20 centimeters (8 inches) of subsidence. Because populations in many parts of the world are becoming more dependent on groundwater, monitoring the state of this vital resource is becoming ever more critical—see the box, "Focus: Monitoring Groundwater Resources from Space."

The Ogallala Aquifer: A classic example of groundwater mining is seen in the southern and central parts of the Great Plains, where the largest U.S. aquifer, the Ogallala or High Plains Aquifer, underlies 585,000 square kilometers (225,000 square miles) of eight states. The Ogallala formation consists of a series of limey and sandy layers that



▲ **Figure 9-32** The Ogallala or High Plains Aquifer. Darker areas indicate greater thickness of the water-bearing strata.

function as a gigantic underground reservoir ranging in thickness from a few centimeters in parts of Texas to more than 300 meters (1000 feet) under the Nebraska Sandhills (Figure 9-32). Water has been accumulating in this aquifer for some 30,000 years. At the midpoint of the twentieth century, it was estimated to contain 1.4 billion acre-feet (1.7 quadrillion liters or 456 trillion gallons) of water, an amount roughly equivalent to the volume of one of the larger Great Lakes.

Farmers began to tap the Ogallala in the early 1930s. Before the end of that decade, the water table was already dropping. After World War II, the development of high-capacity pumps, sophisticated sprinklers, and other technological innovations encouraged the rapid expansion of irrigation based on Ogallala water. Water use in the region has almost quintupled since 1950. The results of this accelerated usage have been spectacular. Above ground, there has been a rapid spread of high-yield farming into areas never before cultivated (especially in Nebraska) and a phenomenal increase in irrigated crops in all eight Ogallala states. Beneath the surface, however, the water table is sinking ever deeper—dropping as much as 30 meters (100 feet) over large areas (Figure 9-33). Farmers who once obtained water from 15-meter (50-foot) wells now must bore to 45 or 75 meters (150 or 250 feet), and as the price of energy increases, the cost of pumping increases operating expenses enormously and so extraction has dropped slightly over the last few years. Some 170,000 wells tapped the Ogallala in the 1970s, but thousands of those have now been abandoned.

FOCUS

Monitoring Groundwater Resources from Space

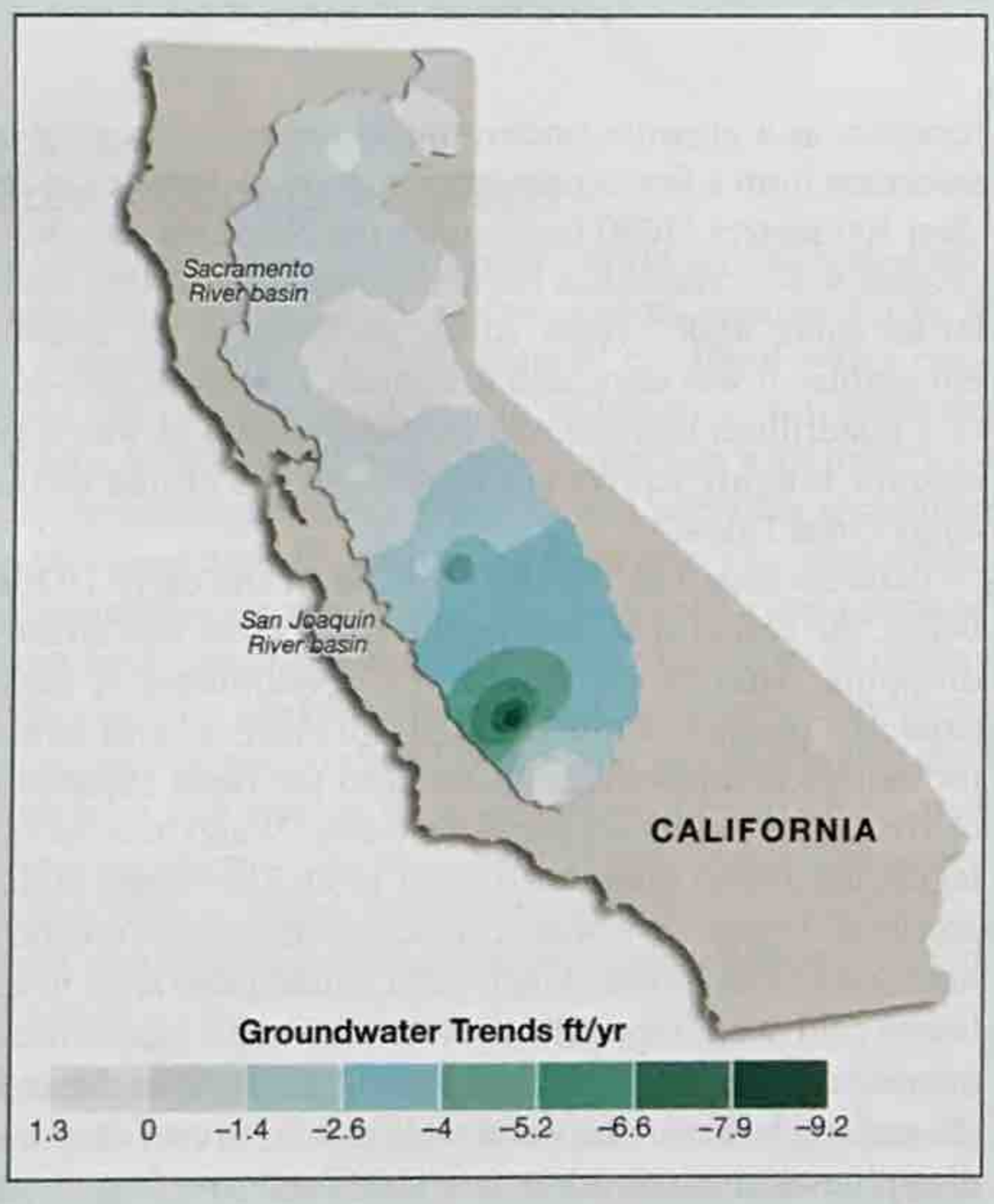
The United Nations Educational, Scientific and Cultural Organization (UNESCO) estimates that 2.5 billion people around the world obtain all of their drinking water from groundwater, including large populations in some relatively poor parts of the world. UNESCO also estimates that about 40 percent of all irrigation water comes from groundwater. The demand for groundwater is so high in many regions that extraction rates currently far exceed the natural recharge rates, leading to depletion of this critical resource. Monitoring changes in groundwater is difficult in many parts of the world. Innovative technology, however, is allowing scientists to monitor changes in the status of groundwater from space.

GRACE Satellites: In 2002, the German Aerospace Center in partnership with NASA launched a pair of polar orbiting satellites that circle the planet about 220 kilometers (137 miles) apart. Called the *Gravity Recovery and Climate Experiment* (GRACE), the satellites measure tiny differences in the distance between them that are caused by slight variations in Earth's gravity field. These local differences in gravity are caused by differences in the mass of Earth below.

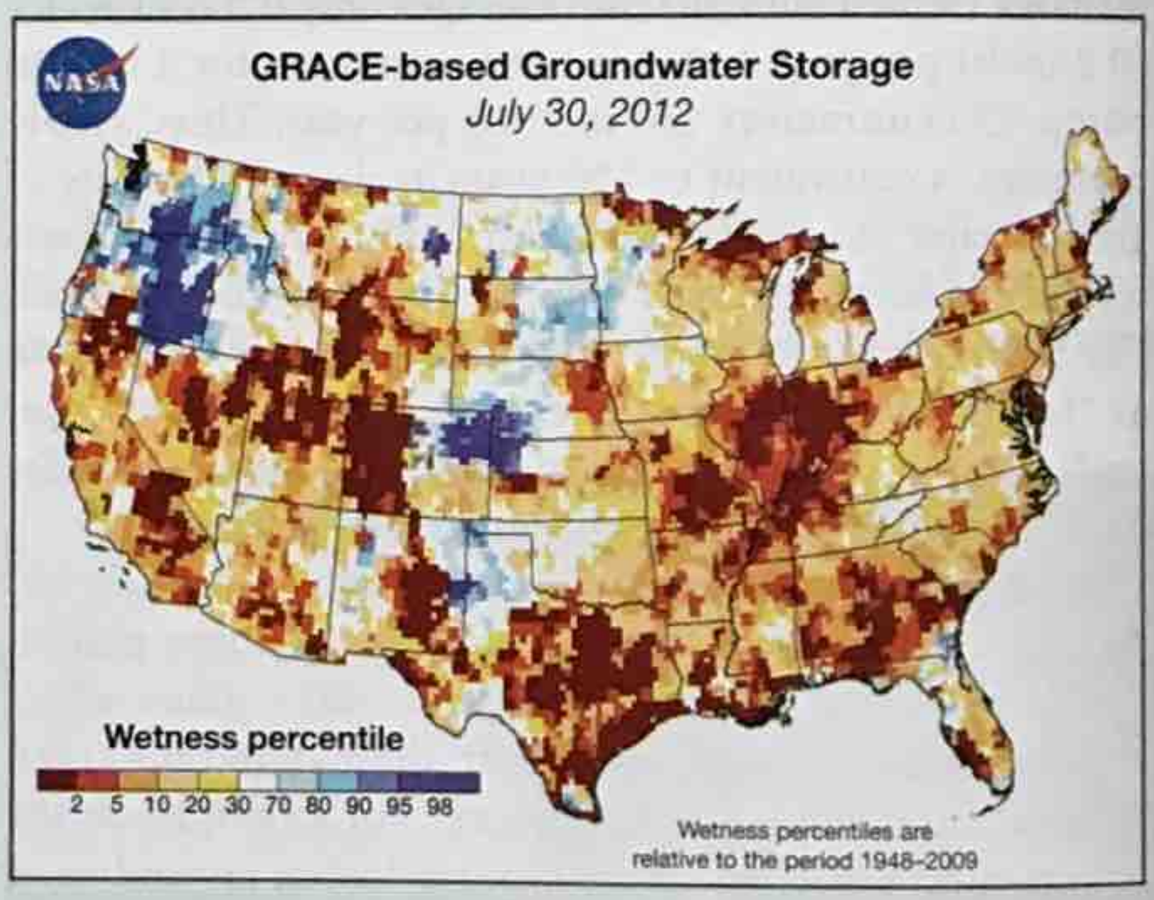
The GRACE system is so sensitive that it can detect differences in the mass of water and ice on and within Earth, allowing scientists to track changes in the exchange of water between ice sheets and the ocean, and between groundwater and the surface. The depletion of groundwater and the lowering of the water table of aquifers can result from overpumping as well as from declines that occur during droughts.

For example, data show that between October 2003 and March 2009, aquifers in California's Central Valley, the state's primary agricultural region, lost more than 30 cubic kilometers of water—enough water to nearly fill Lake Mead (Figure 9-C).

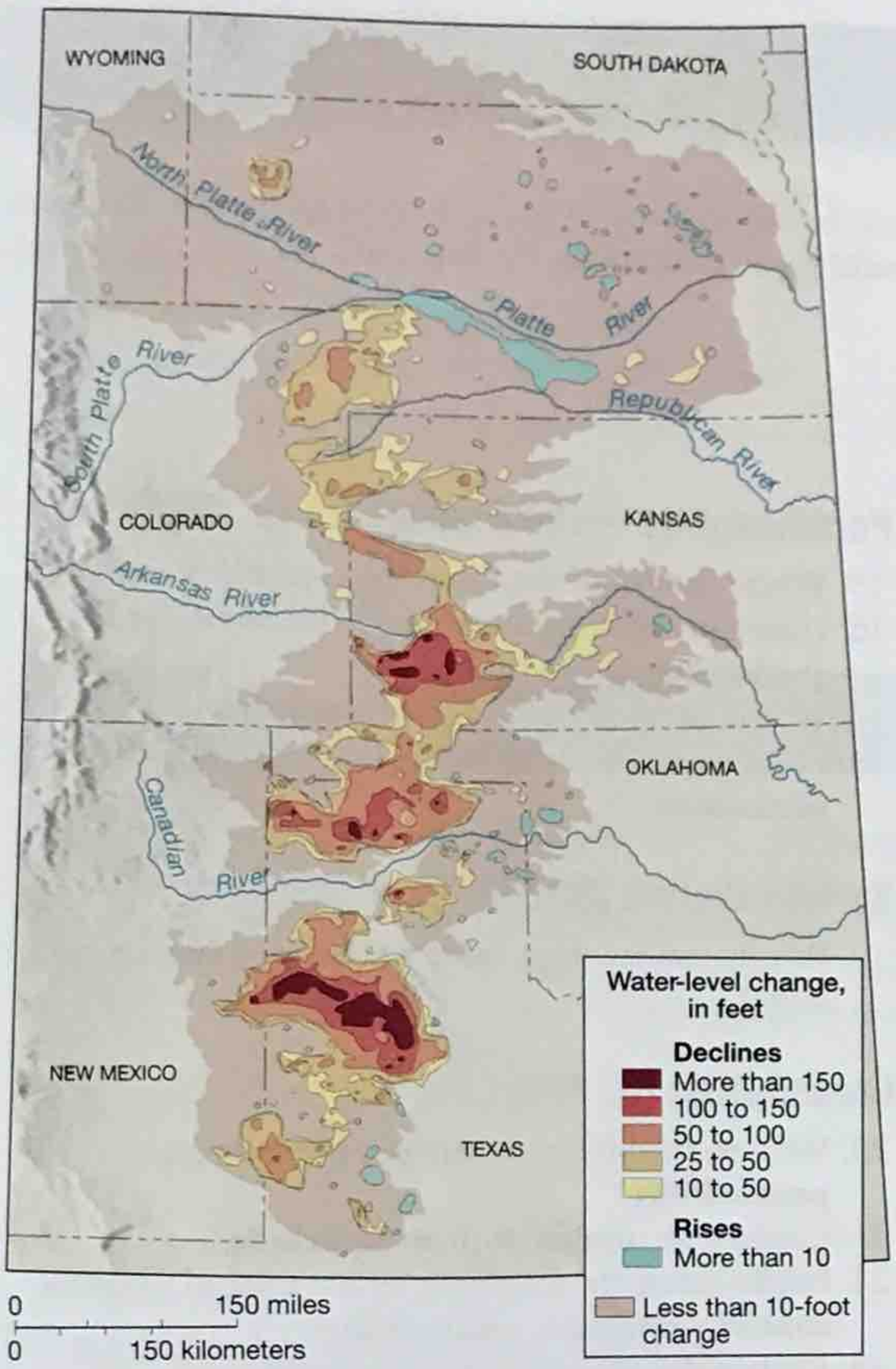
GRACE data is also used on an experimental basis to measure short-term differences in soil moisture and groundwater levels caused by weather variations such as droughts. For example, Figure 9-D shows the wetness percentile of groundwater storage in July 2012 relative to the average of wetness from 1948 to 2009; the decline in groundwater associated with the 2011–2012 drought in the southwestern United States and the upper Mississippi basin is clearly shown.



▲ **Figure 9-C** Observed change in groundwater level trend between October 2003 and March 2009 based on GRACE satellite data. Areas shown in dark blue and green experienced water table declines of 0.8 to 2.4 meters (2.7 to 7.9 feet) per year.



▲ **Figure 9-D** Estimated wetness percentiles of groundwater storage on July 30, 2012, compared with the average moisture content of the ground between 1948 and 2009, based on GRACE satellite data. The dark maroon areas show the extreme dryness of the ground during the 2012 drought.



▲ **Figure 9-33** Water table change in the Ogallala Aquifer from the early twentieth century through 2009. Increases in the water table occurred in places where surface water irrigation has been extensive.

Some farmers have been shifting to crops that require less water. Others are adopting water- and energy-conserving measures that range from a simple decision to irrigate less frequently to the installation of sophisticated machinery that uses water in the most efficient fashion (Figure 9-34). Many farmers have faced or will soon face the prospect of abandoning irrigation entirely. During the next four decades, it is estimated that 2 million hectares (5 million acres) now irrigated will revert to dry-land production. Other farmers concentrate on high-value crops before it is too late, hoping to make a large profit and then get out of farming.

Learning Check 9-11 **How has groundwater mining affected the Ogallala Aquifer since the 1930s?**

Water conservation is further complicated by the obvious fact that groundwater is no respecter of property boundaries. A farmer who is very conservative in his or her water use must face the reality that less careful neighbors are pumping from the same aquifer and that their recklessness may seriously diminish the water available to everyone.

The situation varies from place to place. The Nebraska Sandhills have the most favorable conditions. The aquifer is deepest there, previous water use was minimal, and there is a relatively rapid recharge rate. Indeed, for the 13-county area that makes up the bulk of the Sandhills, withdrawal averages only about 10 percent of recharge, a remarkable situation. In contrast, the 13 counties of southwestern Kansas have a withdrawal rate more than 20 times the recharge rate—a clearly unsustainable situation.

▼ **Figure 9-34** Fields using center pivot irrigation in northern Texas, near Dimitt.

Chapter 9 LEARNING REVIEW

After studying this chapter, you should be able to answer the following questions. Key terms from each text section are shown in **bold type**. Definitions for key terms are also found in the glossary at the back of the book.

KEY TERMS AND CONCEPTS

The Hydrologic Cycle (*p. 253*)

1. Where is most of the world's freshwater found?
2. Explain the role of evaporation in the **hydrologic cycle**.
3. What is the relationship between transpiration and evaporation?
4. Describe the roles of advection and **runoff** in the hydrologic cycle.

The Oceans (*p. 256*)

5. Is the Pacific Ocean significantly different from other oceans? Explain.
6. Why does **salinity** vary in different parts of the world ocean?
7. Why are the oceans becoming slightly more acidic?

Movement of Ocean Waters (*p. 258*)

8. Why do most oceanic areas experience two high **tides** and two low tides each day?
9. What is meant by the **tidal range** of a coastal location?
10. Distinguish between **flood tide** and **ebb tide**.
11. Describe and explain **spring tides** and **neap tides**.
12. What is a **tidal bore**?
13. What is **thermohaline circulation**?
14. Explain the **global conveyor–belt circulation**.

Permanent Ice—The Cryosphere (*p. 263*)

15. Where is most of the ice in the cryosphere found?
16. Distinguish among an **ice pack**, **ice shelf**, **ice floe**, and **iceberg**.
17. Why does all sea ice consist of freshwater?
18. Describe the characteristics and global distribution of **permafrost**.

Surface Waters (*p. 267*)

19. Distinguish among a **lake**, **wetlands**, a **swamp**, and a **marsh**.

Groundwater (*p. 271*)

20. What is the difference between **porosity** and **permeability**?
21. Contrast an **aquifer** with an **aquiclude**.
22. Briefly define the following terms: **zone of aeration**, **zone of saturation**, **groundwater**.
23. Explain the concept of a **water table**.
24. Describe and explain the cause of a **cone of depression**.
25. Under what circumstances can a **zone of confined water** develop?
26. What is meant by the **piezometric surface**?
27. Distinguish between an **artesian well** and a subartesian well.

STUDY QUESTIONS

1. In what part of the hydrologic cycle is water most likely to stay for a very short time? A very long time? Why?
2. "How many oceans are there?" Why is this a difficult question to answer?
3. How can an increase in the acidity of ocean water affect corals and other ocean creatures with calcite skeletons?
4. What are some of the consequences of melting permafrost?
5. Explain why and how the Aral Sea has changed in recent decades.
6. Why are most lakes considered to be "temporary" features of the landscape?
7. Why is the water from some aquifers referred to as fossil water?
8. How has groundwater mining affected the Ogallala Aquifer since the 1930s?

EXERCISES

1. If a floating iceberg has a surface area of 100 square meters and is 10 meters high, what is the total volume of ice including both the exposed portion above water and the portion below the water? _____ cubic meters
2. If the natural recharge rate of an aquifer is 1 centimeter per year, but the rate of groundwater pumping is 15 centimeters per year, how far will the water table drop in 10 years? _____ centimeters
3. Assuming a natural recharge rate of 0.5 centimeters per year, if groundwater pumping lowers the water table by 50 centimeters, how many years of "fossil water" have been extracted? _____ years

Seeing Geographically

Look again at the photograph of the waterfall in Iceland at the beginning of the chapter (p. 252). Which components of the hydrologic cycle can you observe here? Find Iceland on a map of the North Atlantic Ocean or the world map on the inside cover of this book. Where do you think is the source of most of the water vapor that condenses and falls as precipitation here? Why do you say that?

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