9 The Atmosphere-Ocean System

Earth's outer fluid spheres operate as an enormous interconnected system of moving air and water that creates and controls the hydrologic system and the entire planet's climate. Every day we find our activities affected by the ceaseless movement of the atmosphere and oceans, as well as its constantly changing temperature and water vapor content. A moment in this highly variable system is captured in this panorama that looks out over the water in the Gulf of Mexico from Cancun, Mexico. Here you see the Sun (the ultimate energy source for the atmosphere-ocean system), clouds formed as a result of evaporation of water from the sea, and evidence of winds moving the turbulent atmosphere and making waves in the ocean.

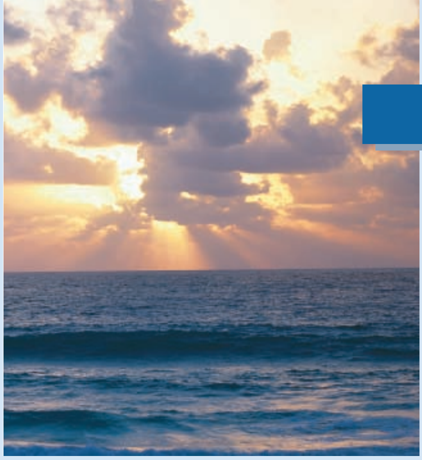
In the longer term, we look forward to the march of the seasons. They repeatedly bring alternating warmth and cold and drive the annual cycle of life. On an even longer scale, however, we are probably completely unaware of variations in our overall climate. But, despite our ignorance, climate change over hundreds or thousands of years is just as

relentless as any daily change in weather. Detecting a change in the climate is a daunting task, given the large daily, seasonal, and even annual variations in temperature and precipitation and the lack of good weather records before the 1800s. Moreover, natural events such as volcanic eruptions can cause short-term climate change.

Nonetheless, the record of climate change is extremely clear on the face of Planet Earth. Its sediments, rocks, and even its landscapes record the sometimes dramatic—but often slow and ponderous—changes in climate.

Climate significantly affects almost all geologic systems, discussed in detail in subsequent chapters, because climate is the fundamental control on the operation of the hydrologic system. Tremendous river systems, the slow circulation of great ocean currents and endless crashing waves, the massive ice cap on Antarctica, the vast deserts, and even the soil in which we grow our food, all owe their existence to climatic controls. Consequently, climate profoundly affects all forms of life. In turn, we humans now can affect climate by altering Earth's surface and by introducing pollutants, such as carbon dioxide, into the atmosphere.

In this chapter, we focus on the two most important components of Earth's climate system: the oceans and atmosphere. To understand this system, you must have a basic understanding of the origin, composition, structure, and flow patterns of air and seawater. We close the chapter with a few notes on how humans affect the climate.



MAJOR CONCEPTS

1. Earth's climate system is driven by solar heat and the interactions of the oceans, the atmosphere, and their circulation patterns.
2. The atmosphere is the envelope of gases that surrounds Earth. It consists mostly of nitrogen and oxygen. Latitudinal variations in humidity and temperature are caused by the uneven distribution of solar radiation, and therefore heat, on Earth's surface.
3. Earth's ocean consists of liquid water, capped at the poles with sea ice. A strong vertical temperature gradient in ocean waters creates a thin, warm surface layer and a thick mass of cold deep water. The most important dissolved constituents in seawater are salt (NaCl) and calcium carbonate ($CaCO_3$).
4. Circulation of the oceans is driven by the wind, by seawater density differences (caused by variations in salinity and temperature), and by coastal upwelling. A global circulation pattern involving surface and deep waters mixes the entire ocean.
5. Global climate change can be caused by changes in solar radiation intensity, by volcanism, by the development of new mountain belts, by changes in the composition of the atmosphere (especially its carbon dioxide content), and to some extent by the tectonic position of the continents.
6. Concerns about global warming are based on increases in atmospheric carbon dioxide caused by our burning fossil fuels.

COMPOSITION AND STRUCTURE OF THE ATMOSPHERE

Among the planets of the Solar System, Earth's atmosphere is unique because it is rich in nitrogen and oxygen. Temperature variations divide it into several layers; the most important layer for geologic development of the surface is the troposphere.

Seen from space, the brilliant white swirling clouds of Earth's atmosphere are perhaps its most conspicuous feature. Although this tenuous envelope of gas is an insignificantly small fraction of the planet's mass (less than 0.01%), it is tremendously important because it is an extremely dynamic, open system. The atmosphere moves easily and rapidly and reacts chemically with surface materials. As a result, the atmosphere plays a part in the evolution of most features of the landscape.

The atmosphere transports heat energy from the tropics to the polar regions and moderates the far greater temperature extremes that would otherwise exist. Water from the oceans is evaporated and carried over the continents by wind. Above the land, it may precipitate to form rivers, glaciers, and systems of groundwater. Over vast desert areas, the flow of the wind drives the movement of sand. Winds also supply the energy that drives ocean surface currents, which transport heat, salt, and nutrients in addition to water. The wind drives the waves that modify our shorelines. Chemical reaction of the atmosphere with minerals drives weathering processes and creates soils and ore deposits. Consequently, an understanding of the composition and flow of the atmosphere is fundamental to understanding many of Earth's geologic systems.

What makes Earth's atmosphere unique?

Composition of the Atmosphere

Earth's atmosphere consists mainly of only a few gases. Just three constituents—oxygen, nitrogen, and argon—make up 99.9% of the atmosphere (Table 9.1). Earth's atmosphere is unique compared with the atmospheres of the eight other planets in our solar system (Figure 9.1). Ours is the only atmosphere with large amounts of oxygen. Oxygen is extremely important because it is necessary for most forms of animal life. Moreover, atmospheric oxygen is constantly reacting with minerals that originally formed deep inside Earth to make new minerals in equilibrium with the atmosphere. These reactions are one of the reasons for the continuing change at Earth's surface.

The major gases, along with the inert gases (helium, neon, and krypton), are all found in nearly constant proportions. But other constituents, most notably water, have concentrations that vary from place to place and from time to time. Water vapor **(humidity)** can vary from a bone-dry 0.01% to an extremely humid 3% of the atmosphere. Short-term variations in water content are hallmarks of an active hydrologic system. Another constituent—carbon dioxide—varies on a much longer time scale. Today it has an abundance of about 0.03%. Over the last few decades, carbon dioxide has been increasing in abundance because it is produced by the burning of fossil fuels.

The major atmospheric gases are nearly transparent to incoming solar radiation, and they do little to affect the heat balance at Earth's surface. However, some minor gases absorb certain wavelengths of light and thus help to heat the atmosphere. In fact, without these absorbent gases, Earth's surface temperature would be 30°C lower than it is today. Earth would be a frozen wasteland. The most important gases for the absorption of solar energy make up less than 1% of the atmosphere. In order of importance, they are water vapor, carbon dioxide, ozone, methane, and various nitrous oxides. Because the amount of carbon dioxide is increasing, this variation carries important implications for Earth's future climates.

TABLE 9.1 Composition of Earth's Atmosphere

Component	Chemical Formula	Concentration (volume)
Nitrogen	N_2	78.0%
Oxygen	O_2	21.0%
Argon	Ar	0.9%
Carbon dioxide	CO_2	353 ppm
Neon	Ne	18 ppm
Helium	He	5 ppm
Methane	CH_4	2 ppm
Krypton	Kr	1 ppm
Water vapor	H_2O	Variable

Compiled from D. L. Hartmann.

Thermal Structure of the Atmosphere

The most widely recognized climate variable is temperature. Almost all of the heat in the atmosphere and oceans originates from nuclear fusion in the distant Sun (Figure 9.2). This energy is transmitted 150 million kilometers to Earth by radiation and heats our planet's surface. The global average temperature of the air just above the surface is 15°C (59°F). However, the range of surface temperatures across the globe is rather wide (–90° to 58°C). Temperature also changes vertically above Earth's surface (Figure 9.3) and divides the atmosphere into several layers.

What causes the atmosphere to divide into more or less distinct layers?

The Troposphere. In the lowermost layer of the atmosphere, the temperature decreases with altitude at a rate of about 6.5°C per kilometer. In other words, if you climb 1000 m up the side of a mountain, it will be 6.5°C cooler than it was at the bottom. In reality, the rate of temperature change varies from place to place and even from season to season.

We live in this lowermost layer, called the **troposphere.** It is marked by turbulent movement of the air (wind) and wide variations in humidity and temperature. It is the zone where all the phenomena related to weather occur. From a geologic viewpoint, the most significant part of the atmosphere is the troposphere. This layer, or zone, contains about 80% of the atmosphere's mass and practically all of its water vapor and clouds. It is the zone in which evaporation, condensation, and precipitation occur, in which storm systems develop, and in which decay of solid surface rock takes place.

The Stratosphere. In the layer above the troposphere, the temperature change reverses and temperatures increase with altitude (Figure 9.3). This layer is known as the **stratosphere.** Temperatures increase to nearly the same level as at the surface, apparently because solar energy is absorbed by molecules of **ozone** (O_3) that are concentrated in the stratosphere. Because of this reversal of the temperature gradient, the lower two layers of the atmosphere do not readily mix. Consequently, gases and particulates move through the troposphere rapidly but only slowly across the boundary into the stratosphere. Once in the stratosphere, small particles may

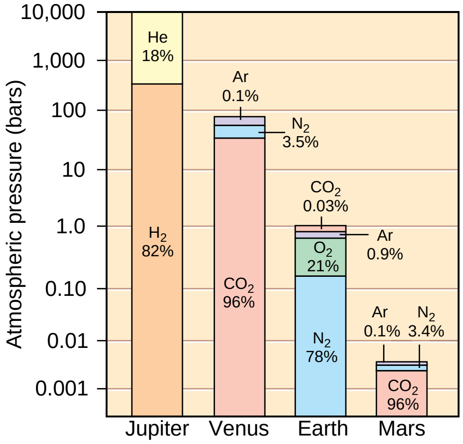


FIGURE 9.1 Earth's atmosphere is dramatically different in its composition and pressure from those of other planets. It is dominated by nitrogen and oxygen, whereas the atmospheres of other inner planets (Mars and Venus) are mostly carbon dioxide. The much larger outer planets, such as Jupiter, have thick atmospheres of hydrogen and helium.

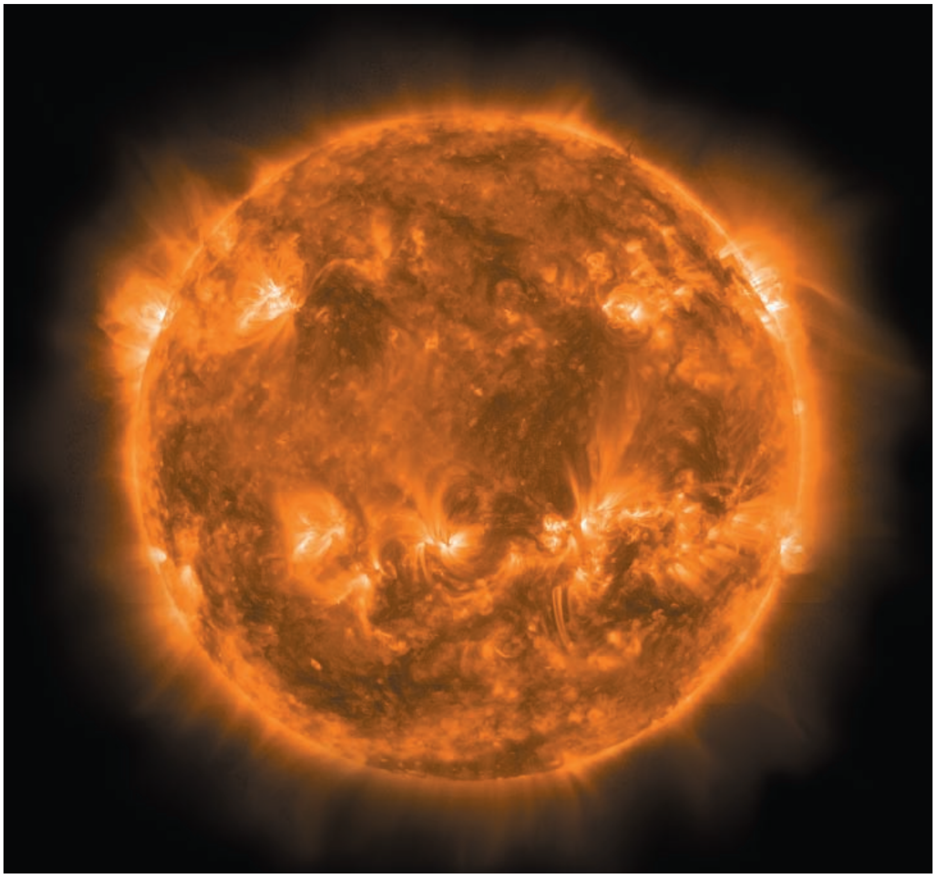


FIGURE 9.2 **The Sun** is a seething mass of hydrogen and helium where energy is formed by nuclear fusion. Some of this energy is transmitted by electromagnetic radiation to Earth, where it drives the circulation of the atmosphere and the ocean. This image was constructed from radiation characteristic of a temperature of about 1 million degrees Celsius *(Courtesy of the TRACE Project, Lockheed Martin Solar and Astrophysics Laboratory, and NASA)*

remain suspended for a very long time. No rain occurs in the stratosphere to remove particles that reach this height. Moreover, the stratosphere is quiet, and turbulence is uncommon. Because the density of the air in the stratosphere decreases with height, the stratosphere does not mix readily and it is stratified, or layered.

Although only a minor constituent in the atmosphere, ozone gas plays several important roles. Most of the ozone is concentrated in the stratosphere, where it forms the **ozone layer.** In addition to warming the stratosphere, ozone in the upper atmosphere also absorbs harmful ultraviolet (UV) radiation from the Sun. Thus, it forms a radiation shield for many kinds of plants and animals, including humans. Excessive ultraviolet radiation has been linked to skin cancer.

Which layer of the atmosphere has the greatest turbulent motion?

Unlike the other gases in the atmosphere, ozone is not released from the planet's interior, nor is it created by plants on the surface. Instead, stratospheric ozone is produced when sunlight breaks the bonds in an O_2 molecule to form atomic oxygen (O), which then reacts with another O_2 molecule to form O_3. Ozone concentrations reach a maximum of about 10 ppm (parts per million) at altitudes of 20 to 25 km. That is a very low concentration for any gas, but it is sufficient to create the "ozone shield."

Lower in the atmosphere, ozone plays a completely different role and is created by entirely different mechanisms. Ozone in the troposphere, a pungent gas, is strongly reactive and oxidizing. As a result, it is corrosive and constitutes a health hazard near the surface, where it is an important pollutant.

The Upper Layers of the Atmosphere. Above the stratosphere, the temperature decreases again in what is called the **mesosphere,** or "middle sphere" (coincidentally, the same term applied to the middle of Earth's interior). At an altitude of about 90 km, the temperature change reverses again to form the **thermosphere.** Here the temperature increases as ultraviolet energy from the Sun is absorbed by the molecules in the atmosphere (Figure 9.3). In fact, the gases

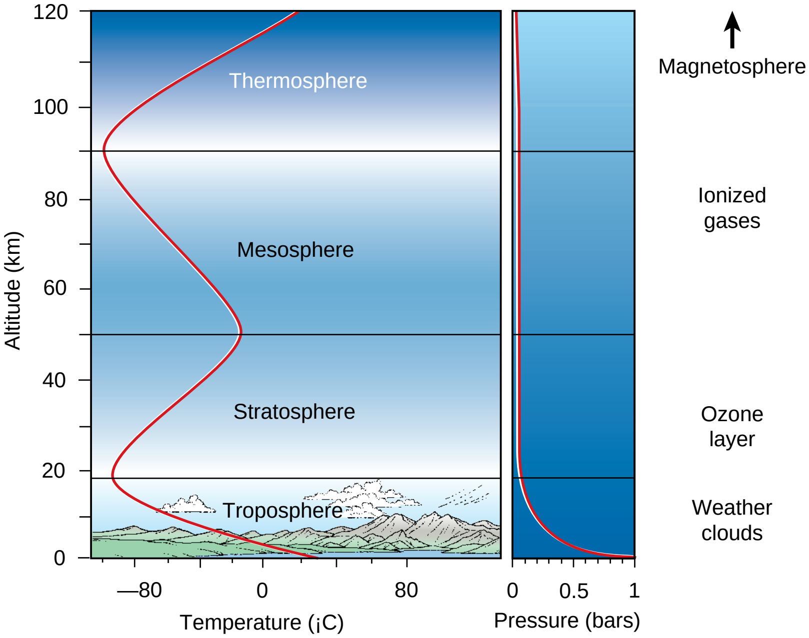


FIGURE 9.3 The main layers of Earth's atmosphere are defined according to their temperature gradients (left). Earth's weather systems develop in the troposphere. This profile shows mean temperatures at 15° N. The atmospheric pressure decreases regularly with height (right).

become so warm that some molecular bonds are broken and charged ions of oxygen and nitrogen form.

Beyond the atmosphere is the **magnetosphere,** a tear-drop shaped zone where electrically charged particles streaming from the Sun are trapped by Earth's magnetic field. This part of the atmosphere is another powerful shield against damaging radiation that comes from outer space.

Atmospheric Pressure

The air about us seems so tenuous as to be almost weightless. In fact, the density of air at sea level is only about 1/800 the density of liquid water. Nonetheless, these air molecules exert a pressure that is just over 1 bar at sea level (1 bar = 1 kg/cm^2 or 14.7 $lb/in.^2$) at sea level. Perhaps you have seen what happens to a sealed aluminum can when the air inside is pumped out; the can collapses, crushed under the weight of the overlying air. Our own bodies are the same way; were it not for internal fluid pressures, we would be crushed flat.

Atmosphere Layers

Atmospheric pressure is greatest at sea level and drops rapidly with increasing altitude (Figure 9.3). At an elevation of about 5.6 km, atmospheric pressure is about 0.5 bar, and half of all the gas molecules in the atmosphere lie below this level. The atmospheric pressure is cut in half again for each additional increase of 5.6 km in altitude. At an elevation of 8.8 km, the height of Mount Everest, the air is so "thin" that it is difficult for a human to get enough oxygen in each breath to survive. At 80 km above the surface, the pressure is only about 10^{-6} bars. Nonetheless, at 500 km above the surface, there is still a trace of an atmosphere, although it is extremely tenuous.

Atmospheric Water Vapor

What part of the atmosphere contains the greatest amount of water vapor?

One of the most important variables in the atmosphere is its water vapor content (Figure 9.4). Water is removed from the ocean by evaporation and rapidly carried aloft as water vapor in the turbulent troposphere. The amount of water that passes through the atmosphere each day is staggering. Water vapor is also important because it has a warming influence on the atmosphere—the so-called **greenhouse effect.** Moreover, the water vapor that condenses to form clouds controls the amount of solar energy that is reflected away from Earth, for clouds are highly reflective.

It is important to realize that cold air can hold much less water vapor than warm

FIGURE 9.4 **Water vapor** is a minor but extremely important part of Earth's atmosphere. This global view of the water vapor (white) was constructed by images taken in infrared light and reveals the relative concentrations of water vapor and its transport paths in the atmosphere. You can see that water is almost everywhere in the atmosphere, but that high concentrations occur in swirling storm systems. *(Courtesy NASA-Goddard Space Flight Center, Scientific Visualization Studio)*

air. As a result, the percentage of water vapor in the atmosphere at the poles is almost 10 times less than at the equator. Likewise, the water vapor high in the atmosphere is much less than near the surface.

Precipitation

Precipitation occurs when the air becomes oversaturated with water vapor. Oversaturation occurs when vapor is no longer the stable form of water but must be joined by liquid as well. The vapor condenses to form small droplets of liquid water (or ice), which fall to the surface. Precipitation is generally caused by cooling of the air (see Figure 3.5). Commonly air masses cool as they rise into the colder upper troposphere. Ascending air may be caused by winds that force air over high mountains or by the buoyancy of plumes of warm air. The distribution of precipitation on Earth's surface is shown in Figure 9.5. Most precipitation occurs along the equator. The least precipitation falls in the deserts north and south of the equator and also in the polar zones.

ENERGY AND MOTION OF THE ATMOSPHERE

Motion of the atmosphere is driven by the uneven distribution of solar energy. Solar heating is greatest in equatorial regions and causes water in the oceans to evaporate and the moist air to rise. The warm, humid air forms a belt of equatorial clouds and heavy rainfall. It is bordered in the middle latitudes by high-pressure zones that are cloud-free and contain dry descending air. Temperate and polar zones are marked by separately convecting masses of air.

Solar Radiation and Heat Balance

Much of the Sun's radiation that reaches Earth is reflected immediately back into space. Fully 30% of the energy is reflected from bright areas such as clouds, oceans,

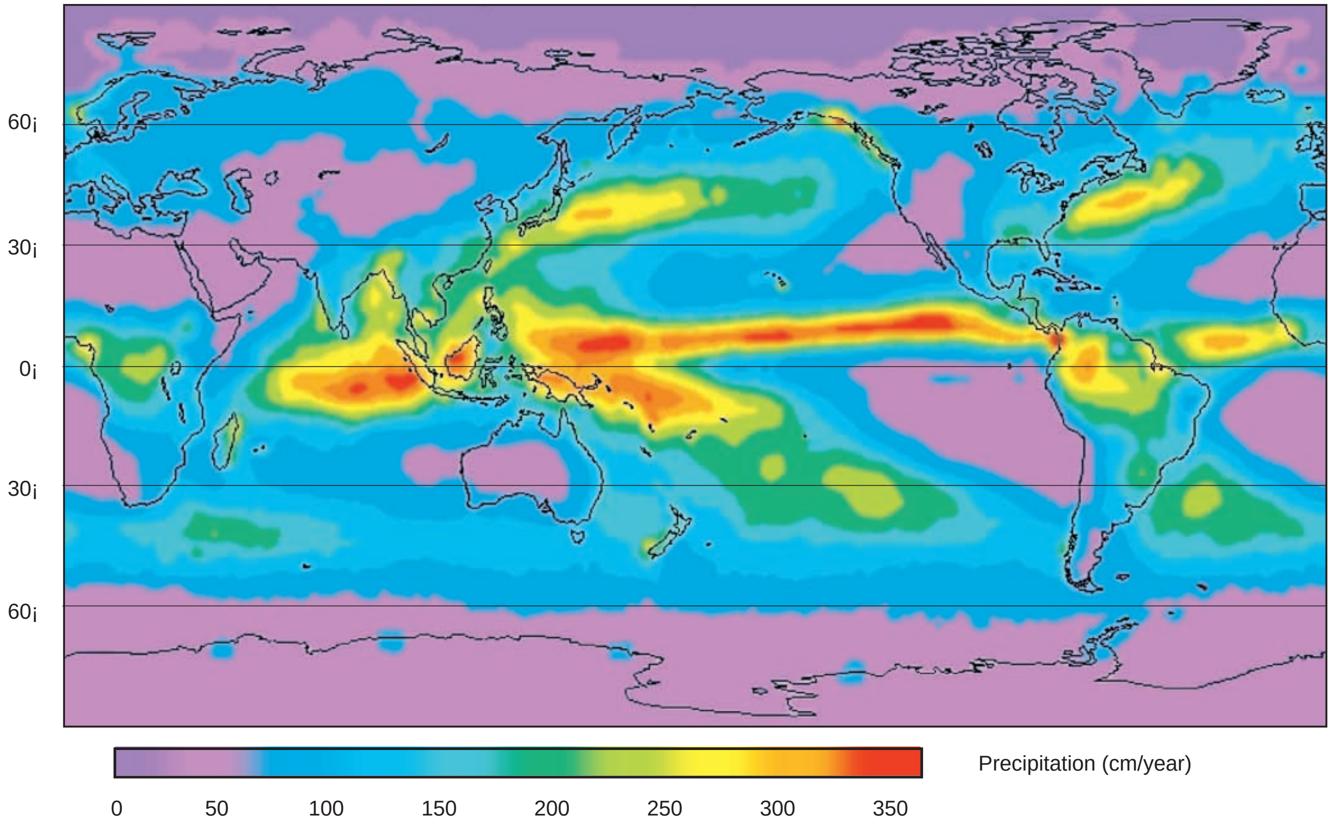


FIGURE 9.5 Precipitation is greatest near the equator, where warm, moisture-laden air rises, then cools at high altitude, and becomes supersaturated with water that falls as rain. This phenomenon causes the tropical rain forests. Dry regions lie in subtropical belts north and south of the equator, because here dry air descends, becomes heated, and can then absorb more water vapor. Such conditions cause evaporation to predominate over precipitation and a desert climate to exist. *(Data from Global Precipitation Climatology Project, NOAA)*

ice fields, and snow-covered plains. The solar energy that is not reflected is absorbed by the atmosphere and by the surface. As the surface warms, it radiates heat back toward space and warms the lower atmosphere in the process.

What is the fundamental control of climate?

It has long been known that the amount of solar radiation absorbed by Earth decreases with the distance from the equator. This variation causes the pronounced temperature difference between the warm equatorial regions and the frigid polar regions. Measurements of the average surface temperature clearly show this global pattern (Figure 9.6).

The strikingly systematic temperature pattern north and south of the equator is the result of several factors. First, because Earth is a sphere, the angle at which the Sun's rays hit its surface varies from nearly vertical at the equator to nearly horizontal at the poles (Figure 9.7). Consequently, much less energy is received per square kilometer at the poles because the same amount of incoming radiation is spread over a larger area because of the angle. The same energy is concentrated in a much smaller area at the equator.

Earth's Orbit

In addition, in the polar regions, the low-angle Sun's rays travel through a much greater thickness of atmosphere, where more absorption and reflection occur. The result is a reduction in the energy received at the poles.

Still another critical factor affecting the heat distribution at Earth's surface is the length of the day. Because Earth's spin axis is tilted at an angle of 23.5° with respect to the plane of its orbit, the length of the day varies with the seasons. During the winter, the days are shorter because the spin axis is tilted away from the Sun. In the extreme polar regions, no sunlight falls on the surface for weeks. Thus, little solar heating occurs. During the summer at the poles, the "midnight Sun" does not set because the spin axis is now leaning toward the Sun. Nonetheless, the sunlight falls on the surface at such a low angle that little heating occurs.

Why is heat distributed unevenly across Earth's surface?

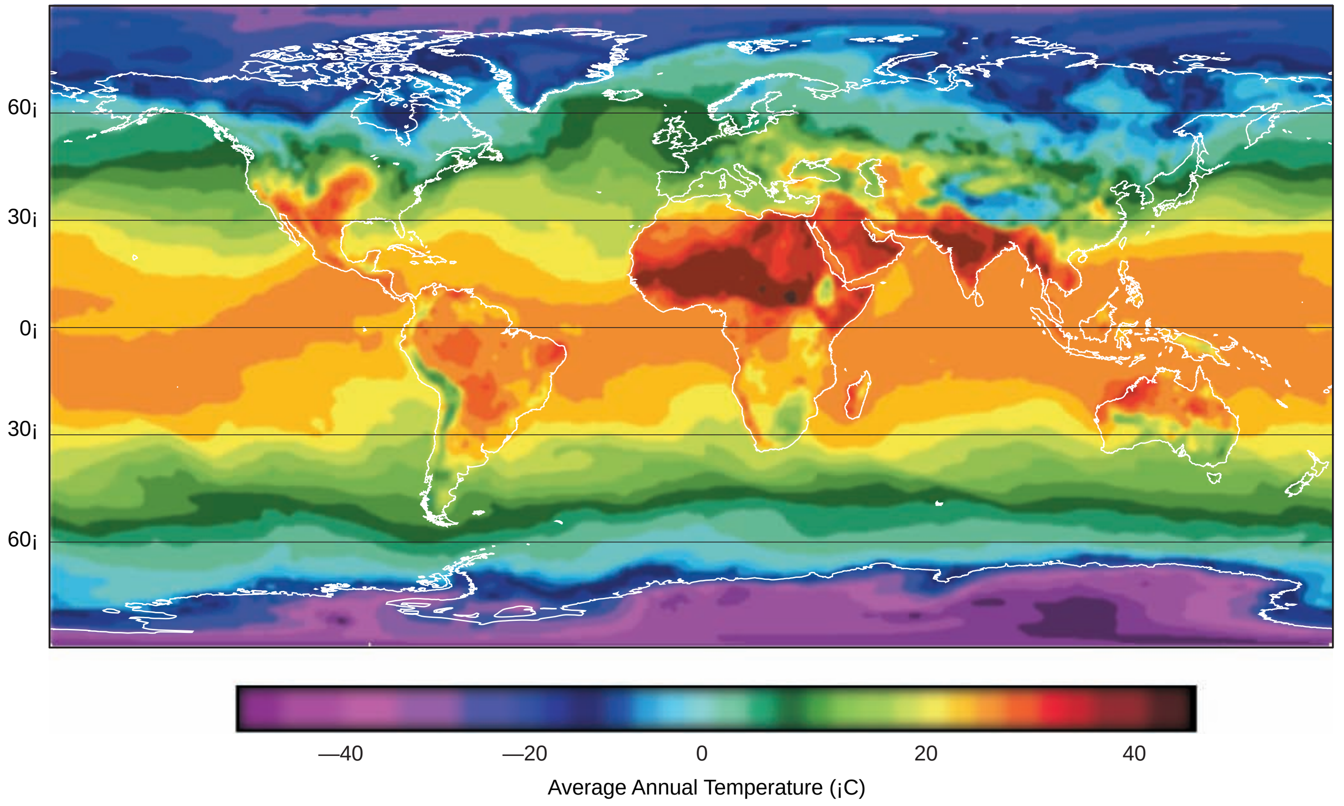


FIGURE 9.6 The mean surface temperature for June 1988 as obtained from National Oceanic and Atmospheric Administration weather satellites. Temperature increases from purple to blue to yellow to red. *(Courtesy of GLOBE Program, Goddard Space Flight Center, NASA)*

In contrast at the equator, the Sun's rays strike the surface at a high angle, sunlight passes through less atmosphere, and the hours of sunlight change much less with the seasons. Consequently, the equatorial regions are efficiently heated.

Global Circulation of the Atmosphere

Recall from Chapter 2 that we said: Systems not in equilibrium tend to change in a direction to reach equilibrium. The global circulation of the atmosphere is an attempt to reach equilibrium by equalizing the temperature differences at the poles and equator. The resulting flow pattern of the atmosphere is critically important

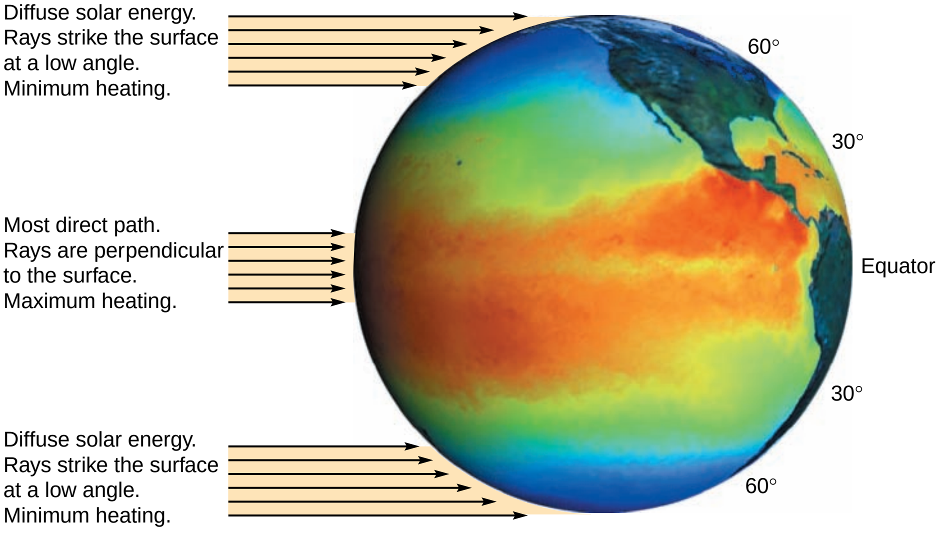


FIGURE 9.7 The Sun's energy is unevenly distributed across the surface of the nearly spherical Earth. The amount of solar energy per unit area varies with the angle at which the Sun's rays strike Earth's surface. At low latitudes, near the equator, the Sun's rays are nearly perpendicular and much more heat is received per unit area. At higher latitudes, where the angle is smaller, the same amount of energy is spread over a larger elliptical area and warms the surface less. Moreover, sunlight must travel through a much greater thickness of atmosphere near the poles than at the equator. This greater thickness also diminishes the amount of heat that reaches the surface.

for Earth's climates. It also drives the wind, which helps drive the circulation of the oceans as well as the atmosphere and, thus, the hydrologic system as a whole.

You have felt the wind blow, but you might not have noticed its systematic nature. Even from space, seeing that the atmosphere is in constant motion is easy; the circulation patterns are dramatically revealed by the shape and orientation of the clouds (page 50) and the distribution of water vapor (Figure 9.4). At first glance, these circulation patterns may appear confused, but upon close examination, we find that they are well organized. If we smooth out the details of local weather systems, the global atmospheric circulation becomes apparent. For example, there is considerable symmetry in the flow patterns of the Northern and Southern Hemispheres.

What are the main patterns of the atmosphere's global circulation?

The general circulation of the troposphere is depicted in Figure 9.8. If the circulation were due solely to solar heating, hot air would rise at the equator and flow toward the poles. As this air cooled, it would sink at the poles and then return to the equator by flowing across the surface. All surface winds would simply flow straight from the poles to the equator.

Atmospheric Circulation

However, winds on the spinning Earth are deflected by the planet's rotation. This **Coriolis effect** is an illustration of Newton's first law of motion: A body in motion keeps its speed and direction unless acted on by an outside force. This inertial force divides atmospheric circulation into several latitudinal zones. Thus, the atmosphere flows in three separate loops, as shown in Figure 9.8. The tropical, temperate, and polar cells are spiraling convection cells that stretch around the planet.

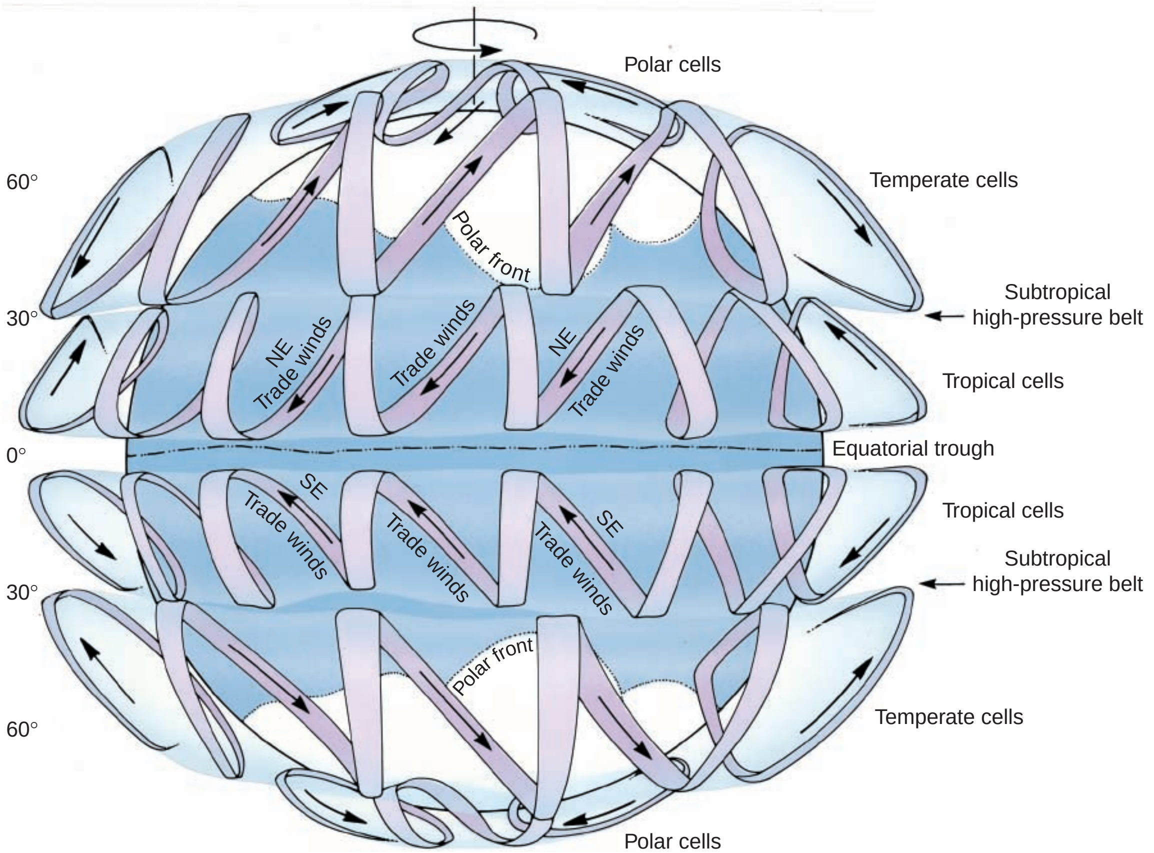


FIGURE 9.8 **Atmospheric circulation** and prevailing wind patterns are generated by the uneven distribution of solar radiation in combination with Earth's rotation. In the equatorial regions, air is intensely heated; the heating reduces its density, and the air rises. At higher altitudes, this air cools, becomes denser, and descends, forming the subtropical high-pressure belts (deserts) on either side of the equator. Near the surface, this air then moves back toward the equator to complete the cycle, causing trade winds. In the Northern Hemisphere, this air is deflected by Earth's rotation to flow southwestward. (In the Southern Hemisphere, flow is northwestward.) Temperate cells form a complementary spiral, creating strong west-to-east winds. Cold polar air tends to wedge itself toward the lower latitudes and forms polar fronts.

The Global Patterns of Water Movement

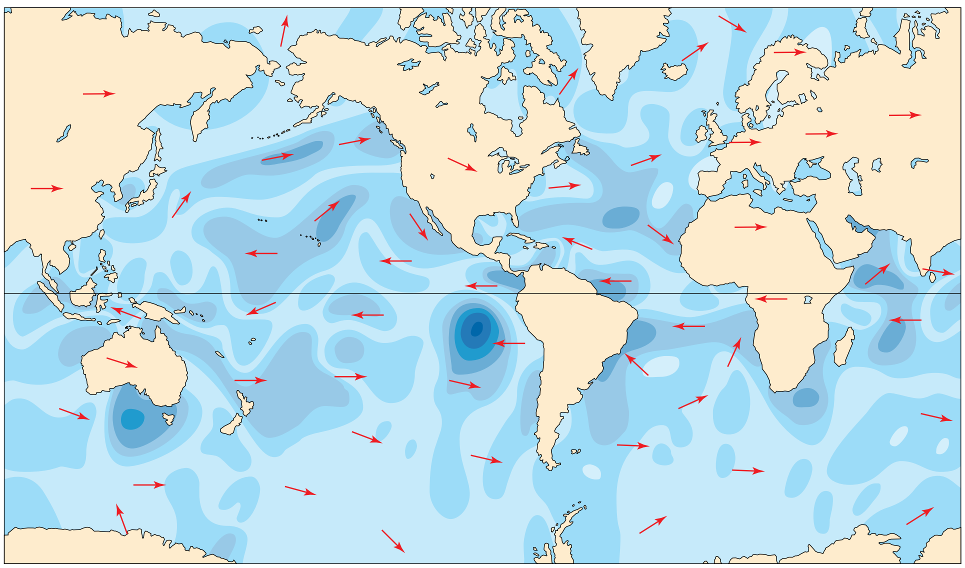
Once you can visualize temperature variations across the globe and the flow of the atmosphere, you can also understand many facets of water movement in the hydrologic system. Combine the atmospheric pattern with two simple rules and we can explain the global transport patterns for water in the hydrologic system: (1) Evaporation rate increases with temperature; (2) Warm air holds more water vapor than cold air. Consequently, evaporation is high near Earth's equator and low at the poles (Figure 9.9).

A Circulation Model. Over the equatorial oceans, hot, moist air rises because of the low density of the warm air. As it rises and cools, the moisture condenses. This condensation produces intense tropical rains, which fuel the growth of tropical rain forests in South America, Africa, and Indonesia. The Coriolis effect deflects surface winds in this climate zone, creating the trade winds that converge toward the equator (Figure 9.8).

As the rain is removed over the tropical regions, the rising air becomes much drier. At the top of the troposphere, the air splits into two convection paths, some flowing northward and some southward (Figure 9.8). As the dry air flows poleward, it cools and becomes denser until it begins to descend toward the surface. This dry air reaches the surface at about 30° north and south of the equator (Figure 9.8). As the dry, cool air descends, it warms, and its capacity to hold and absorb water vapor increases. As a result, evaporation exceeds precipitation (Figure 9.9). This is a very important factor in the movement of water in the hydrologic system. Very little rain falls from this dry air. The low precipitation and high evaporation rates combine to cause the subtropical belts of deserts centered between 15° and 30° latitude (Figure 9.5). These deserts form a fundamental climatic zone on our planet.

Why are there deserts in the mid-latitudes and polar regions?

Large temperate convection cells mark Earth's mid-latitudes between 30° and about 50°. In the Northern Hemisphere, the Coriolis force deflects the north-flowing air to the right to create the prevailing westerly winds of this zone.



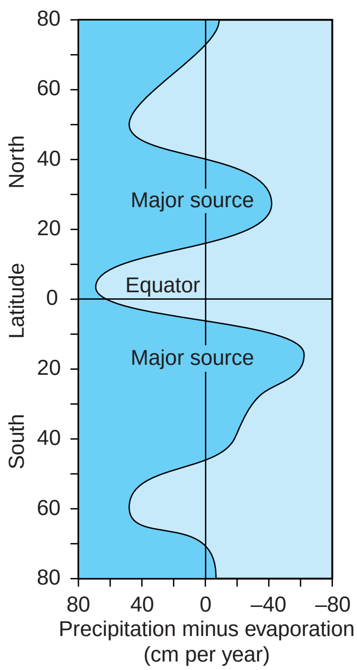


FIGURE 9.9 **Evaporation creates major sources** of water for the hydrologic system. Darkest areas are where evaporation exceeds precipitation, moving great volumes of moisture into the air. These areas are the main sources of water for the global hydrologic system. Light areas are where precipitation dominates, returning water from the atmosphere to the surface. Arrows show the direction of water movement in the atmosphere as caused by prevailing winds. The graph on the right shows that the two major sources of water for the hydrologic system are the oceans between 10° and 40° north and south of the equator. The equatorial oceans and the high-latitude oceans do not supply significant water to the global system. (*Modified from J. P. Peixit and M. A. Kettani*)

Consequently, most storm systems sweep from west to east in the temperate zone, as you probably have observed on weather maps for the United States. Mild, moist winds blow frequent cyclonic storm systems to the western sides of the continents. Precipitation is higher than in the desert zones, and temperatures are moderate. (Note that the directional patterns are reversed in the Southern Hemisphere.)

The polar front is another important element of mid-latitude climates (Figure 9.8). Here warmer air masses from the temperate cell rise over cold air masses that convect separately in the polar regions. Near the surface, the air turns back toward the equator, completing the circulation of the temperate cell. A zone of unstable air, storm activity, and abundant precipitation is created at the polar front. When the warm, moist air flowing from the south cools, it drops its moisture as rain or snow. The irregular shifting position of the polar front is an important variable in weather conditions on the continents. A very fast-moving stream of cold air—the polar **jet stream**—marks the boundary between the two air masses.

The polar air that moves toward the equator becomes warm and rises and at high altitude flows northward to the pole. On its way to the pole, it cools and eventually sinks to complete the polar cell. Here, transport of water is limited because of low evaporation rates over the oceans—many of them are ice-covered—and because of the small amount of water vapor carried in cold air.

Evaporation-Precipitation Balance. One of the major factors influencing the patterns of water movement on a global scale is the balance between evaporation and precipitation. The curve in Figure 9.9 shows where annual evaporation exceeds precipitation (on the right) and areas where precipitation exceeds evaporation (on the left). Where precipitation exceeds evaporation, a net loss of water occurs from the atmosphere. These areas are therefore not the major sources for the water that falls on the continents. Instead, the major sources of moisture are areas of the ocean where evaporation exceeds precipitation.

If you study Figure 9.9, you will see that the flow of water from the oceans to the atmosphere is almost symmetrical with respect to the equator. Near the equator, there is a comparatively narrow zone where precipitation exceeds evaporation. Flanking this tropical zone are two broad areas where evaporation exceeds precipitation. These zones are the most important sources of water in the entire hydrologic system. Water is literally pumped from the ocean in these regions and carried to adjacent continents, where it is eventually precipitated.

Rainfall Sources for River Flow. The terrestrial branch of the hydrologic system is an extension of the atmospheric branch. Regions of excess evaporation are the major sources for water for Earth's major river systems. By careful analysis of Figure 9.9, you can find the major sources of water for Earth's large river systems (see Figure 12.38). Areas of intense evaporation in the western Atlantic are the major sources for the Amazon River. Prevailing winds (arrows) blowing westward carry the water vapor over the continent. The source for the Mississippi River is evaporation in the eastern Pacific, where prevailing winds carry the water vapor eastward. The Indian Ocean is a major source for the water in the rivers of southeast Asia, including the Indus, Ganges, Mekong, and Yangtze.

Why are the world's largest river systems in the tropics?

In contrast, the area of intense evaporation west of South America is not a major source of continental water. Prevailing winds carry the vapor into the central Pacific, where the water precipitates as rain and falls back into the oceans. Likewise, the water vapor from the source south of Australia is carried eastward over the South Pacific. Indeed, more than 90% of the water that evaporates from the ocean returns directly to the ocean as rain without falling on a continent.

Areas on land where evaporation exceeds precipitation are the world's major deserts (Sahara, Arabian, and Australian, for example; see Figure 9.20). Here, few rivers flow during the entire year.

COMPOSITION AND STRUCTURE OF THE OCEANS

Oceans are the great reservoirs of water in the hydrologic system and affect essentially every phase of Earth's dynamics. There are two principal layers of oceanic water: (1) a thin upper layer of warm, well-stirred water and (2) a thick mass of deeper, colder water that is relatively calm and slow-moving.

The importance of the oceans is hard to exaggerate. They influence practically every phase of Earth's dynamics. Consider a few facts about the oceans. Most of Earth's water resides in the seas, which cover 70% of the surface and contain about 97% of Earth's water. Some scientists compare the ocean to a huge boiler in which water is constantly changing from liquid to vapor and cycling through the hydrologic system. Indeed, the oceans are the major source of the water vapor that eventually precipitates onto the continents as snow or rain. The great capacity of the oceans to store heat moderates seasonal temperature changes and slows the rate of long-term climate change. Together with the atmosphere, the oceans help moderate temperature differences from the equator to the poles. Because gases can dissolve in seawater, the oceans play a major role in the composition of the atmosphere. Some of these dissolved gases eventually precipitate to form carbonate minerals in limestones. Seawater cycles through the oceanic crust, transforming hot, dry rock into wet, cold rock during seafloor metamorphism. Finally, the oceans were the womb and the cradle of life. Every element of the biosphere is directly or indirectly tied to the ocean. Everywhere you look, even in the heart of a large continent far from the seashore, you can see and feel the effects of the ocean.

Composition of Seawater

The oceans are not pure water, as you can easily taste. They contain many different kinds of dissolved salts, the importance of which is far-reaching. The major dissolved constituent of seawater is common table salt (sodium chloride or NaCl). The waters of the open ocean have about 30 g of dissolved salt per kg of water. Other dissolved constituents add up to another 5 g per kg (Table 9.2).

What path does cold polar water follow to get to the equator?

Salinity is a measure of all of the dissolved salts in seawater. It varies with the amount of freshwater input from rivers or melting glaciers and with the rate of evaporation. In subtropical regions, the salinity of surface water is high because intense evaporation leaves the water rich in salts that cannot evaporate. At high latitudes where the temperature is lower, the evaporation rate is much lower and fresh rainwater makes the surface waters low in salinity.

However, there is little variation in salinity with depth in the ocean. Salinity is greater just below a surface layer of sea ice; the ice rejects the dissolved constituents, thus enriching them in the liquid beneath the floating ice. Highly saline waters are denser than fresher waters. These differences in salinity, along with temperature, help drive the circulation and flow of seawater, which is critical for daily weather patterns, climate control, and the movement of nutrients in the ocean.

The ocean plays another important role because it controls the composition of the atmosphere by exchanging gases, especially carbon dioxide. In turn, some dissolved carbon is removed by the precipitation of calcium carbonate—in the shells of living creatures, for example. Some dissolved carbon is converted to organic carbon and deposited in marine shales.

TABLE 9.2 Major Dissolved Components in Earth's Ocean

Component	Chemical Formula	Concentration (g/kg)
Chloride	Cl^-	19.4
Sodium	Na^+	10.8
Magnesium	Mg^+	1.3
Sulfate	SO_4^{2-}	2.7
Calcium	Ca^{2+}	0.4
Potassium	K^+	0.4
Bicarbonate	HCO_3^-	0.1

Compiled from D. L. Hartmann

Thermal Structure of the Oceans

Water has one of the highest heat capacities of any substance. Consequently, the waters in the ocean have a tremendous capacity to store, transport, and release heat. Because of this fact, ocean temperature is important, and it powerfully affects Earth's weather and climates.

The average temperature of the global ocean is 3.6°C, but it varies widely. For example, ocean temperature generally decreases with depth (Figure 9.10). Near the surface, seawater is nearly the same temperature as the atmosphere. At great depths, the temperature is very nearly freezing, regardless of latitude on the globe. Consequently, the difference in temperature between the surface and the bottom water is small at the poles, and the temperature gradient is low.

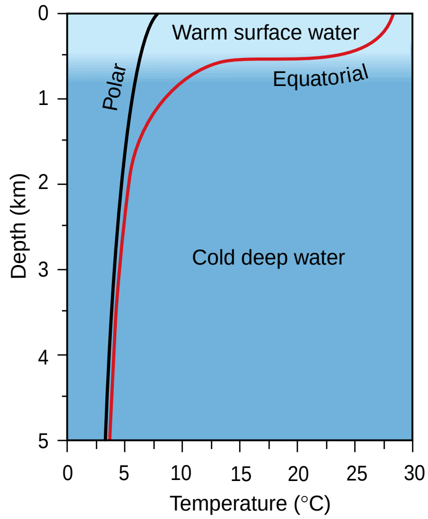


FIGURE 9.10 **Ocean temperatures** vary with depth and with latitude. In most cases, the ocean is stratified into warm surface water and cooler (and therefore denser) deep water. Except in polar regions, ocean water becomes markedly cooler with depth. Surface waters are warmest near the equator, but the temperature at 1 km depth varies little with latitude. Mixing is vigorous only in the surface layer.

Surface Water. The ocean is layered because of temperature differences, just as the atmosphere is. The ocean has only two important layers (Figure 9.10). A thin upper layer **(surface water)** is generally warm and has a lower density, and a thick mass of cold water below has a higher density. The upper 100 m or so of the oceans are well mixed, stirred by winds, waves, and surface currents. This surface water communicates extensively with the atmosphere, freely exchanging constituents such as water vapor and carbon dioxide, and is relatively warm and oxygen-rich. In this surface layer, temperature and composition change very little with depth. It is a zone of turbulent mixing and, in this sense, is comparable to the troposphere.

Deep Water. Below the surface layer, the temperature rapidly drops through a transition zone to the cold **deep water** of the oceans. Deep water has an almost uniform temperature that changes very little north or south of the equator (Figure 9.10). This zone is very thick and contains most of the ocean water. Deep water moves very slowly. Moreover, the density difference between the two layers makes it very difficult for the dense cold water below to rise and mix with the lower-density warm surface layers. Thus, the stratification of the ocean is very stable. Deep water mixes slowly with the surface layer and is almost completely isolated from the atmosphere.

Why are the ocean waters layered?

Sea Ice. Over large regions of the polar oceans, the temperature is so low that solid ice is the stable form of water. Sea ice plays a pivotal role in Earth's climate by increasing the amount of solar energy that is reflected back into space. Ice reflects much more solar energy than does the darker seawater. At any time, this **sea ice** covers as much as 15% of Earth's surface. The extent of ice changes with the season, growing to cover more of the ocean in the winter and shrinking to expose liquid during the summer (Figure 9.11). However, even in the present relatively warm climate, sea ice never completely disappears from the Arctic Ocean or from the fringes of the Antarctic continent. Sea ice is permanently present on about 7% of the ocean.

Sea ice is thin, usually no more than 4 m thick, because it is a good insulator that floats on top of the warmer water below. Fresh water freezes at 0°C, but seawater freezes at about –2°C, because of the salt it contains. The layer of sea ice grows thicker as ice crystallizes from the underlying water. It may also become thicker if snow falls onto the top of the ice sheet. Moreover, while sea ice crystallizes, distinctly dense and salty water forms beneath it as a complement to the salt-free ice. When the ice melts again in the spring, the fresh water from the ice dilutes the salty seawater.

Sea Ice Variation

The average thickness of sea ice in the Arctic Ocean is 3 to 4 m; around Antarctica the ice is thinner, averaging about 1 to 2 m thick. Sea ice is quite smooth on a regional scale, but it is typically broken into a series of smaller blocks, or floes, of varying thickness (Figure 9.12). The ice is repeatedly fractured by its movement, which exposes seawater that then freezes between the ice floes. Where plates of sea ice are driven together by winds or ocean currents, compressive deformation features—pressure ridges—form, and the ice can become as much as 10 m thick below these ridges.

If it is so cold in the polar regions, why don't the oceans freeze completely?

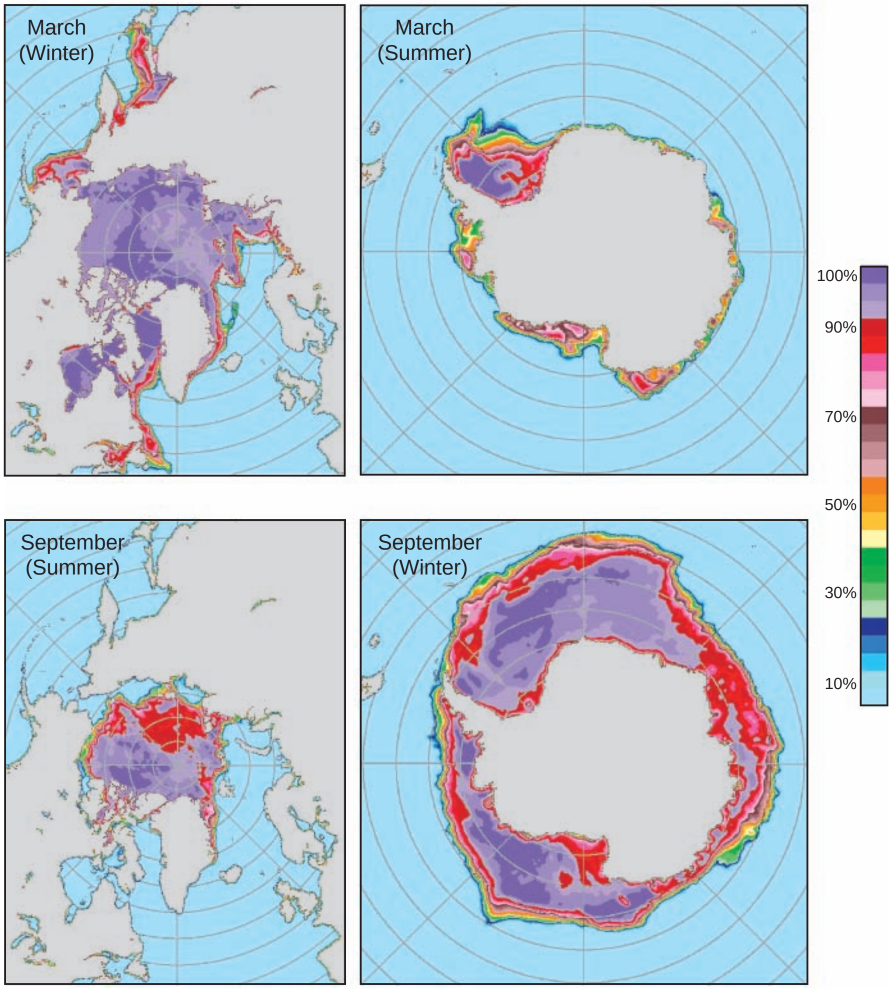


FIGURE 9.11 The extent of sea ice waxes and wanes with the seasons. The shading shows the percentage of area covered by ice. In the Northern Hemisphere, sea ice is at a maximum in March (at winter's end) and then declines through the summer (September). In the Southern Hemisphere, the variations in sea ice are similar, but at opposite times of the year, because the seasons are reversed. As sea ice declines in the north, it is expanding in the south, and vice versa. *(Courtesy of J. C. Comiso, NASA Goddard Space Flight Center)*

ENERGY AND MOTION OF THE OCEANS

The warm surface layer of the ocean is moved principally by wind-generated currents that form circular patterns. The deep oceans circulate because of changes in density caused by salinity and temperature. Global oceanic circulation carries cold surface water deep into the North Atlantic, around Africa, and into the Indian and Pacific oceans. Surface currents then return the water to the North Atlantic.

No part of the ocean is completely still, although movement of water in the abyssal deep is extremely slow—the ocean is a sluggish beast by comparison with the atmosphere. The circulation of the oceans is one of the major factors in developing Earth's climate. The deep and shallow waters of the oceans circulate by distinctive mechanisms and at different rates. However, the surface and deep-water circulation are connected to form a global circulation system for seawater. Here again, the concept of a natural system attempting to reach equilibrium with its changing environment (temperature, salinity, wind pressure) is the critical motive force.

Wind-Driven Circulation of Surface Waters

Surface currents have been known and measured since ancient times and were extensively exploited by early navigators (Figure 9.13). Movement in the surface

FIGURE 9.12 **Sea ice** covers as much as 10% of the sea surface today. It slows the loss of heat from the oceans and reflects sunlight. Both effect Earth's climate. Note how the cracks in the ice have frozen over here in the Ross Sea, Antarctica. *(Kim Westerskov/Tony Stone Images)*

layer is driven primarily by the wind. In turn, the prevailing winds are caused by the uneven heating of Earth's surface. Circulation of surface waters might be best understood by considering the Pacific Ocean, which is bordered by continents on the east and west (Figure 9.13). Strong equatorial currents (North and South Equatorial Currents) are pushed westward by the trade winds. As the currents encounter the western land masses (Asia and Australia), some of the water is deflected northward and some southward to form two large ring-shaped currents. Helped by the Coriolis force, the flow is clockwise in the Northern Hemisphere and counterclockwise in the Southern Hemisphere. Other rings form at each pole and orbit in the opposite direction.

What determines the direction of surface currents?

Surface currents in other areas of the world ocean are more complex than in the Pacific because of the shapes and arrangements of land masses and the configuration of the ocean floor, but the basic pattern is still obvious (Figure 9.13). Large circular patterns dominate surface currents in the Atlantic, Pacific, and Indian oceans. Note that each circular current flow has a strong, narrow, poleward current on its west side and a weaker current on its east side. The most pronounced of these strong western-margin currents in the Northern Hemisphere are the Gulf Stream in the Atlantic and the Kuroshio current in the Pacific. Because these currents carry water from the south to the north, they are much warmer than the surrounding waters. The speed of these surface currents may exceed 2 m/sec. The return eastern-margin flow from the mid-latitudes to the equator is much slower and occurs over a broader area. Western boundary currents also occur in the Southern Hemisphere along the shores of South America and Africa. These currents are not as strong as those in the Northern Hemisphere.

The northward-flowing Gulf Stream is part of this global pattern. It is obvious as a warm anomaly in the North Atlantic (Figure 9.14). As it flows northward, it mixes with colder waters in turbulent swirls, or eddies, and eventually loses its identity. The warm waters carried by the Gulf Stream are very important for moderating the climate of northern Europe. The eastern Atlantic Ocean is much warmer at the surface than the western Atlantic. Consequently, western European winters are milder than their counterparts in eastern North America at the same

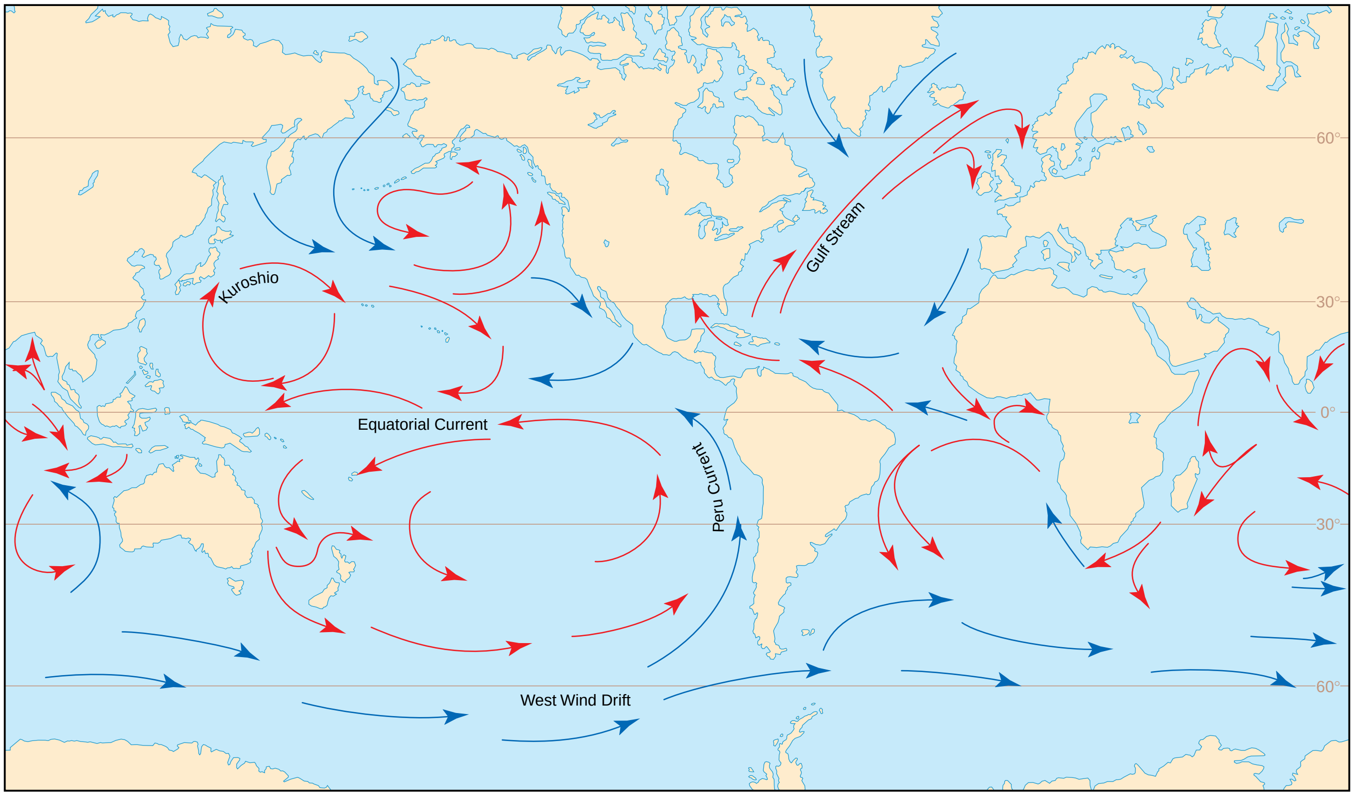


FIGURE 9.13 **Surface currents of the oceans** are driven by prevailing winds, which are in turn caused by the uneven heating of Earth's surface illustrated in Figure 9.6. Most of the currents have crudely circular patterns. Warm (red) and cold (blue) currents are shown.

latitude. Compare the climates of New York City and Lisbon, Portugal—two cities found at the same latitude but on opposite sides of the Atlantic. Some of the heat carried by the Gulf Stream is picked up by the Norwegian Current and carried even farther into polar regions.

Cold surface currents flow toward the equator along the eastern Pacific Ocean—the California Current along North America and the Peru Current off South America (Figure 9.13). These cool waters lower the air temperature along their shorelines, compared with continental regions at similar latitudes.

Density-Driven Circulation of the Deep Ocean

What causes the deep ocean water to move?

At great depth, the oceans are not directly affected by the winds. Instead, the slow circulation of water in the deep ocean is caused instead by changes in water density. The major causes of this density variation in seawater are its temperature and salinity. This slow but vastly important movement is called **thermohaline circulation** (in Greek, *therme* is heat and *hals* is salt or sea). The movement is so slow that measuring it is difficult. Nevertheless, the patterns have been deduced from the distribution of minor dissolved constituents, principally salt and dissolved gases such as oxygen, and by careful measurement of water temperature at depth. The decay of the naturally formed radioactive isotope of carbon (^{14}C) also can be used to estimate the flow velocities for these density currents.

From these measurements, we infer that water from the surface sinks to great depths in the polar oceans (Figure 9.15). For example, cold, high-salinity water forms beneath the sea ice around Antarctica. This dense Antarctic water drops to the seafloor and then slowly flows along the base of the Atlantic Ocean, eventually reaching as far north as 40° N (Figure 9.15). Another large mass of cold deep water is formed in the North Atlantic, where frigid air cools surface waters. The water sinks and flows southward above the even denser Antarctic bottom water. This water rises back to the surface near 60° S. Cold water formed in mid-latitudes

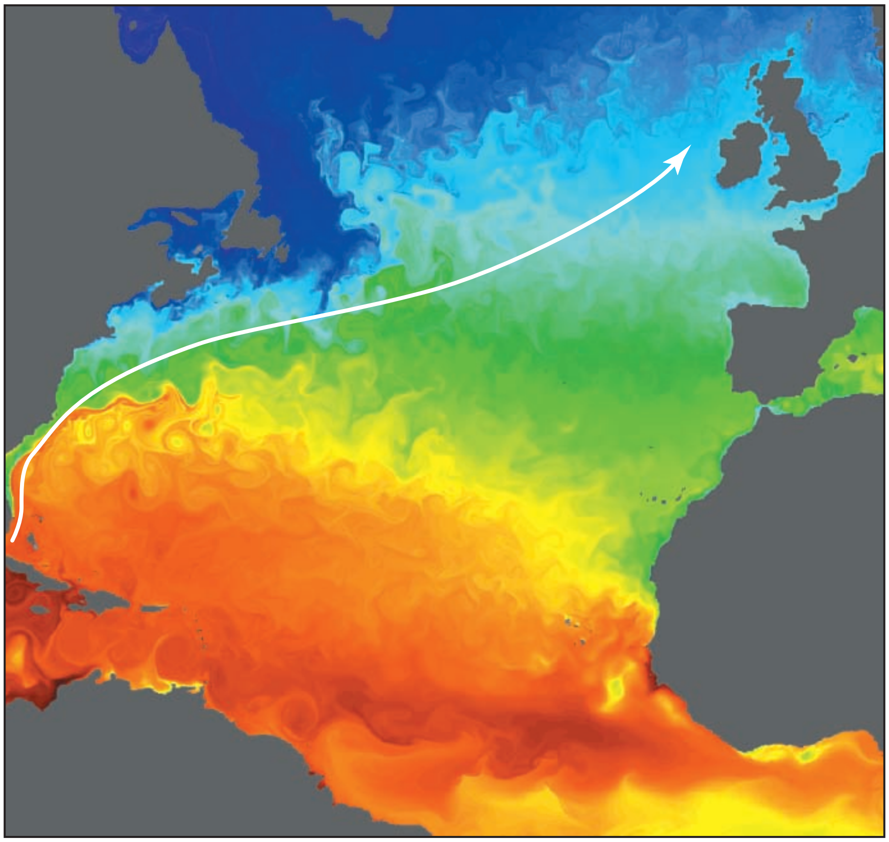


FIGURE 9.14 **The Gulf Stream** is a warm north-flowing current in the North Atlantic. It is revealed in this computer model where reds are warm waters; blues and violets are cooler. Note the warm waters flow from the Gulf of Mexico along the Atlantic coast northward to the cool Arctic waters. The large swirls are eddies in the Gulf Stream. *(Courtesy of the Advanced Computing Laboratory, Los Alamos National Laboratory)*

of the Southern Hemisphere wedges itself between the warm surface water and the North Atlantic deep water.

It takes about 1000 years for a complete cycle of surface water to become deep water and then surface water again. Most chemical and thermal properties of the oceans should not change rapidly because of this slow movement of deep ocean water. Thus, the oceans act to slow the rate of climate change. The transport of heat by the slowly moving waters of the oceans is one of the major factors in controlling Earth's climate.

Deep-ocean waters are generally rich in dissolved nutrients. They have spent considerable time at depth, where falling detritus can be dissolved and where no organisms exist to consume the nutrients because of the low amount of light. Where deep-ocean water wells upward into sun-drenched shallow waters, these nutrients become important for the marine food chain.

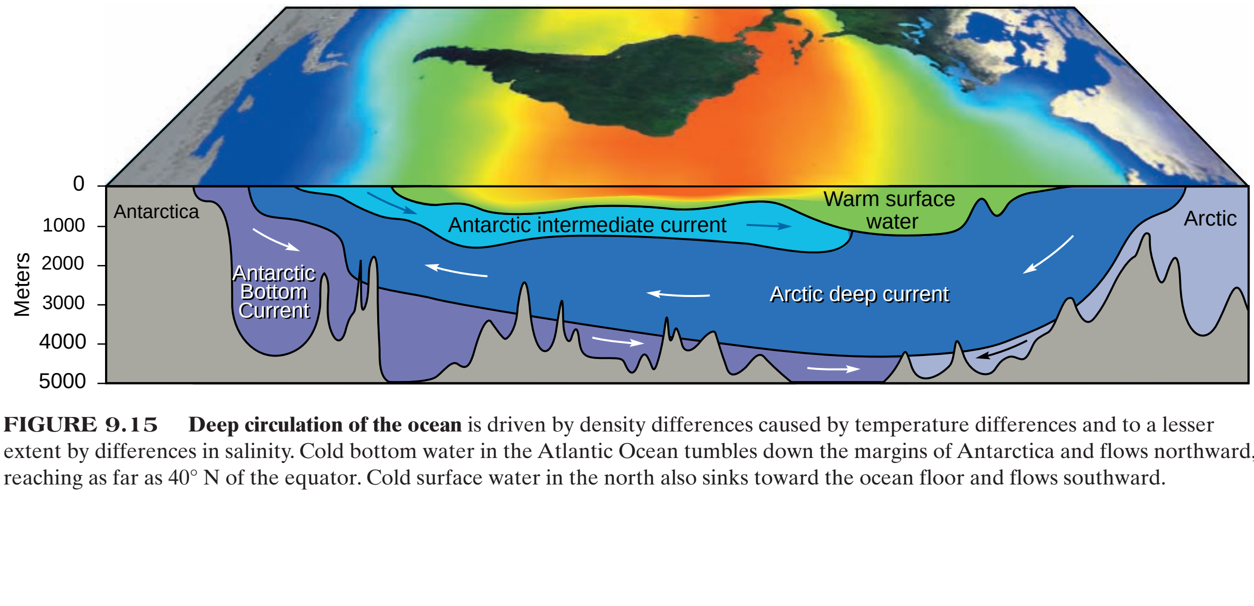


FIGURE 9.15 **Deep circulation of the ocean** is driven by density differences caused by temperature differences and to a lesser extent by differences in salinity. Cold bottom water in the Atlantic Ocean tumbles down the margins of Antarctica and flows northward, reaching as far as 40° N of the equator. Cold surface water in the north also sinks toward the ocean floor and flows southward.

Coastal Upwelling

Along the shorelines of many continents, strong **coastal upwelling** of deep-ocean water is an important part of ocean circulation. Because of the Coriolis effect, winds blowing toward the equator and along a coast cause seawater to move to the right of the wind direction in the Northern Hemisphere and to the left of the wind direction in the Southern Hemisphere (Figure 9.16). For appropriately oriented coasts, this movement of surface water away from the shore causes cold deep water to flow upward to take its place. This deep water is rich in nutrients and nourishes rich blooms of plankton, which in turn are food for a wide variety of sea animals. Some of the ocean's richest fisheries are found in these waters. Upwellings off the California coast and the western coasts of South America and Africa are excellent examples of this phenomenon. Ancient upwellings have created important deposits of phosphates (used for fertilizer) and organic materials that have contributed to the formation of oil.

El Niño

A temporary change in surface currents can have an extreme impact on coastal upwelling. For example, occasionally the normally strong trade winds weaken. Their weakening allows warm currents to approach the western shore of South America, where surface waters are normally cold. This phenomenon, called **El Niño** (The Child) because it occurs around Christmas, disrupts the upwelling of cold nutrient-rich water (Figure 9.17). Consequently, the phytoplankton population diminishes and the fish population almost disappears. Bird populations diminish, and fishermen are put out of work. Large El Niño disturbances also change precipitation patterns worldwide, causing flooding in North and South America and drought in areas as distant as India, Indonesia, and Australia.

What is El Niño and why is it important in oceanic circulation?

Global Pattern of Oceanic Circulation

The waters of the entire ocean are mixed slowly but surely because of the wind-driven circulation of the shallow ocean, coastal upwelling, and the density-driven circulation that involves the deep ocean. All of these phenomena are shown in Figure 9.18. As ocean waters move by surface flow, by sinking, or by rising, other waters must move in to take their place. The surface flow is easy to observe and therefore is better understood, but the deep-water flow is much harder to decipher. Thus, the simple picture we elaborate below is based partly on observation and partly on theoretical models.

To visualize the global flow of the ocean, let us trace the long, slow journey of a parcel of water starting in the North Atlantic (Figure 9.19). As this water equilibrates with the cold air, it also becomes cold and dense and sinks as much as 2 km

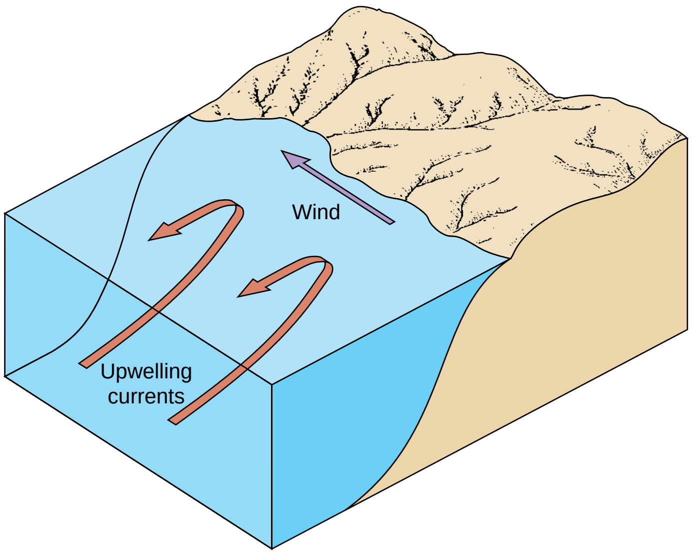
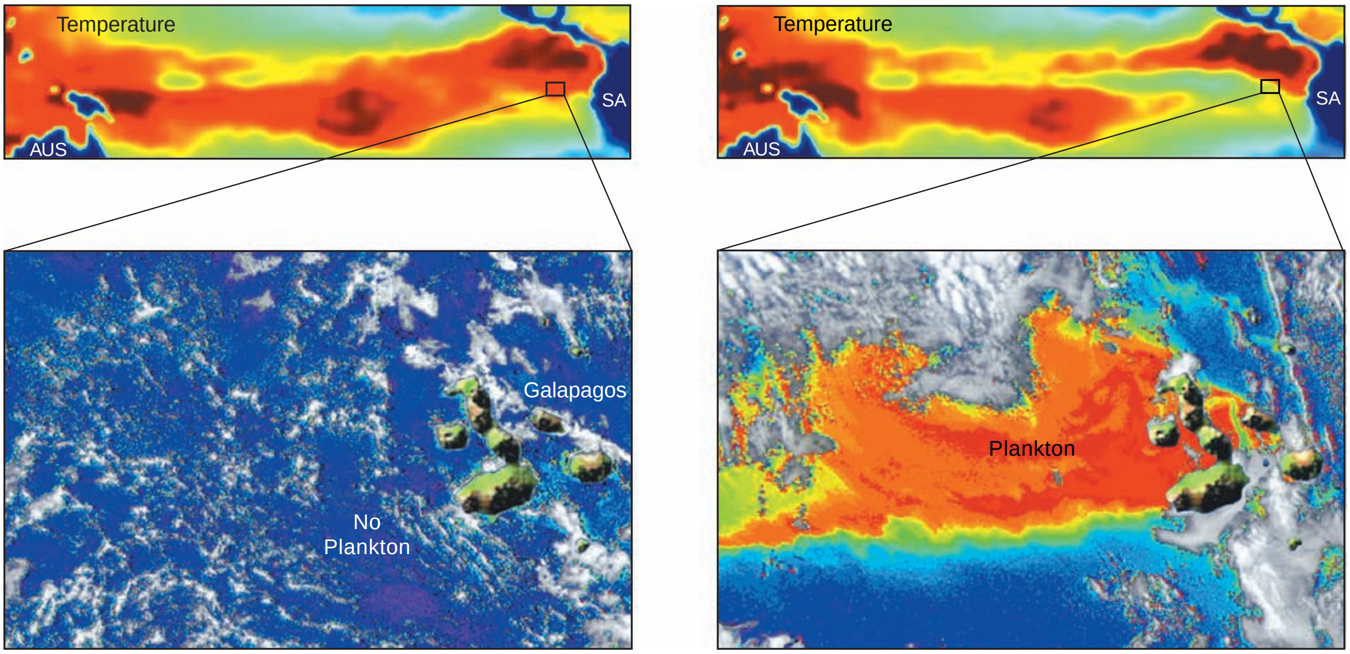


FIGURE 9.16 Upwelling ocean waters are common along the margins of the continents. In the Southern Hemisphere, coastal upwelling occurs in response to winds that blow northward. As a result, the Coriolis force drives surface water away from the shore. In response, deep waters upwell and bring nutrient-rich waters to the surface. This upwelling nourishes plankton and other organisms that feed on it.



(A) Warm water (red in the upper map) accumulates against the western shore of South America (SA), inhibits deep upwelling, and reduces the amount of phytoplankton (red in the lower map) in the Pacific Ocean.

(B) As conditions return to normal, colder surface waters (green in upper map) return near shore of South America, upwelling resumes, and phytoplankton grows across the equatorial Pacific and especially near the western shore of the Galapagos Islands.

FIGURE 9.17 **El Niño** marks an anomalous buildup of warm water along the west coast of South America. This shuts off upwelling, nutrient-rich deep waters and stifles phytoplankton production. *(NASA-Goddard Space Flight Center, Sea WIFS Project, Science Visualization Studio)*

to the ocean floor. Once cold water fills the deep basin there, it surmounts the Iceland Ridge and plunges southward as an intense bottom current on the western side of the North Atlantic. Salty, dense, but warm water spills from the Mediterranean and mixes with the North Atlantic Deep Water. At any instant, the rate of water flowing along the floor of the Atlantic is estimated to be 80 times the volume of the Amazon River.

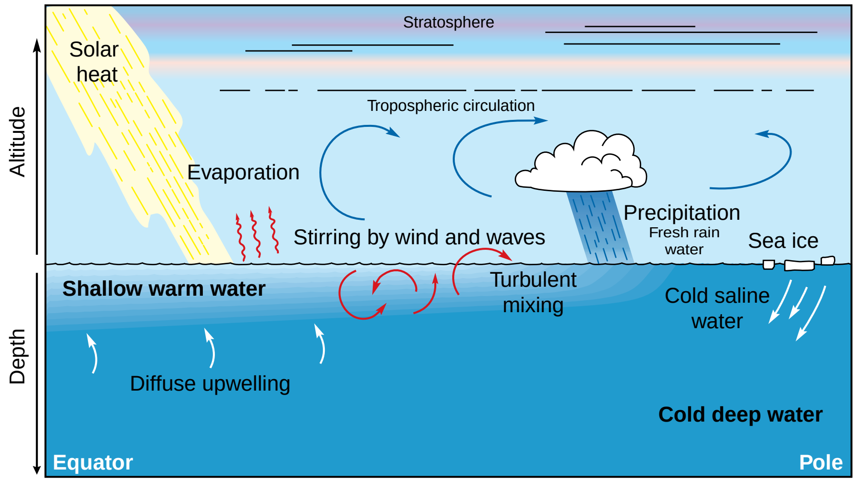


FIGURE 9.18 **The ocean and atmosphere form a simple system** of interacting water and air, but many processes are involved in the flow and mixing. Variation in solar heating causes winds, which drive the surface circulation of the ocean. Density-driven circulation vertically mixes the shallow and deep layers of the ocean. These density variations are caused by differences in temperature or salinity. Only the upper oceanic layer is well mixed by turbulence. Mixing with deep water is much less efficient and occurs mainly by the sinking of cold polar waters into the deep ocean. Diffuse upwelling throughout the ocean basins and coastal upwellings return deep water to the surface. *(Modified from D. L. Hartmann)*

STATE OF THE ART *Earth From Space: Satellite Eyes*

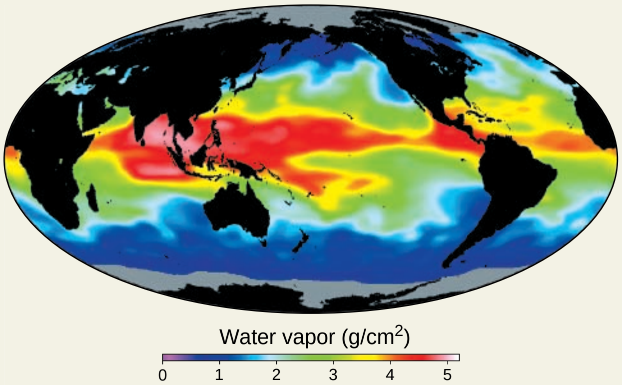
A multitude of satellites orbiting far above Earth's surface are equipped with a diverse array of sensors. One of the most straightforward applications is to take digital photographs of the surface in many different wavelengths and at different scales. The highest resolution satellite images available today show objects just only 1 or 2 m across. Figures 2.2 and 14.21 are two examples of satellite photographs.

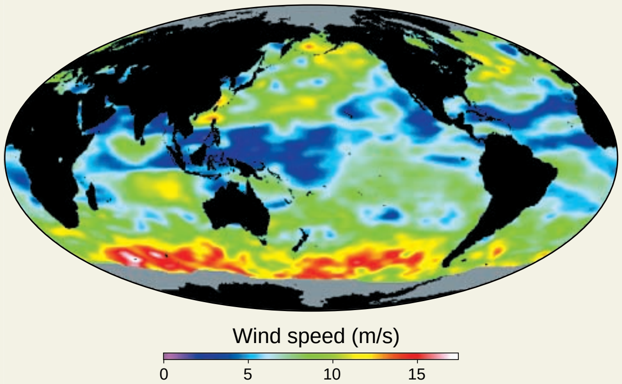
Some of these satellites are in orbits that allow them to see the entire surface of Earth each and every day. As a result, they become monitors of the daily changes in Earth's hydrosphere and atmosphere—the fundamental components of our changing global climate. Movies showing motion of the hydrologic system can be made from these time-lapse images. Imagine the huge numbers of observation stations that would be needed to replace the global coverage provided by one of these satellites in a single day. Short- and long-range weather forecasts rely heavily on information derived from these satellites.

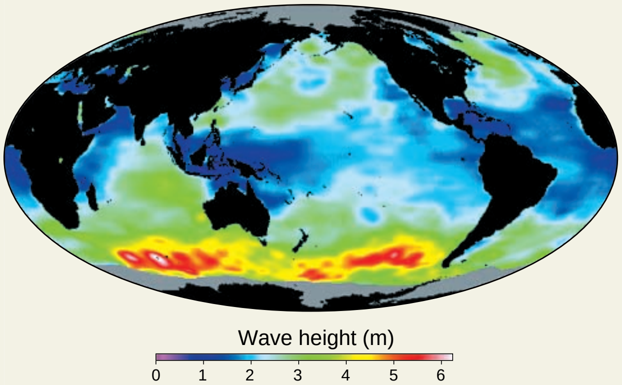
Sensors on satellites such as the TOPEX/Poseidon and Terra satellites measure the amount of water vapor in the atmosphere, wind speeds, or even wave height (to right). The map at the bottom of the page shows the elevation of the sea surface caused by differential heating and the effects of winds. Elsewhere in this book, you have seen global maps made from satellite data of precipitation (Figure 9.5), temperature (Figure 9.6), vegetation (Figure 1.3) and even the amount of ozone in the atmosphere (Figure 9.22).

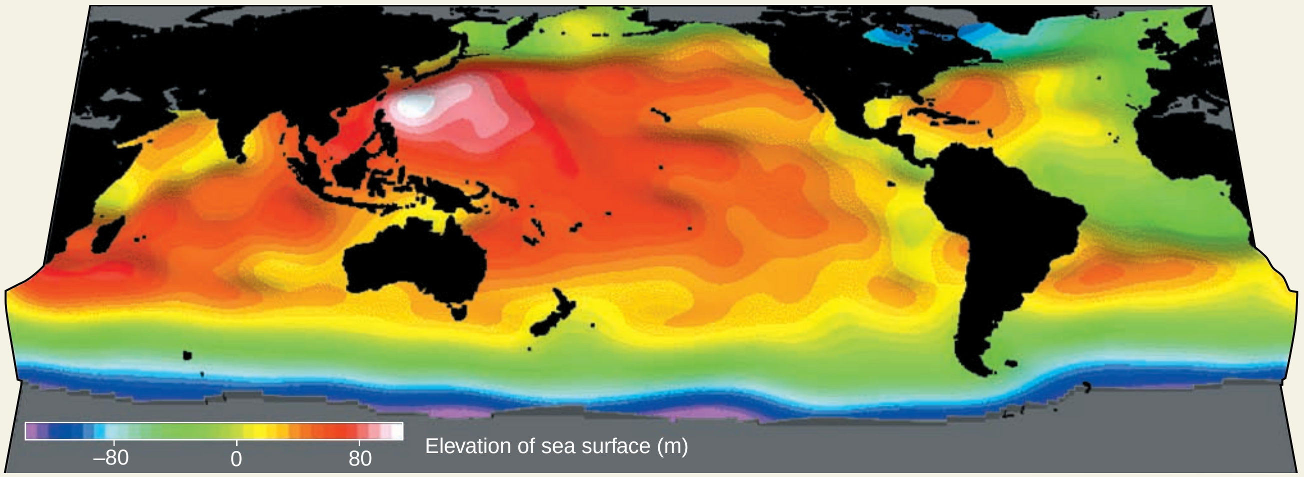
Other satellites measure sulfur or other components in the air that emanate from volcanoes. Some are equipped with lasers for measuring the elevation of the surface below or with radar to construct images or topographic maps of the terrain beneath a dense forest canopy or through clouds (Figure 12.37 and p. 18).

Satellites have literally become our eyes in the sky. These dramatic images have immensely changed our view of Earth and helped us see it as one global system.









(Courtesy of NASA/Jet Propulsion Laboratory/California Institute of Technology)

This deep current continues southward until it meets a strong northward- and eastward-flowing current of Antarctic Bottom Water in the South Atlantic. The two currents appear to merge and the water flows eastward into the deep Indian Ocean and ultimately northward into the deep Pacific Ocean. The water that originated in the North Atlantic has now been removed from contact with the atmosphere for several hundred years.

How long does it take for North Atlantic Deep Water to make one complete circuit through the oceans?

In the Pacific, much of this deep water warms as it moves toward the equator and slowly buoys to the surface. There it mixes with surface waters and begins a return flow to the Atlantic. But now, much of the journey is at the surface of the ocean. Wind-driven surface currents sweep it through the maze of Indonesian islands and into the Indian Ocean and then southward around Africa. The surface currents along the southern shore of Africa produce broad, spinning eddies that eventually feed the water into the Atlantic.

Beyond this area, northward transport is hindered by strong surface currents parallel to the equator (Figure 9.13); gigantic swirling eddies eventually spin much of the water across the equator and into the North Atlantic. Water is then swept northwestward across the Atlantic to near the Caribbean where, if caught in the Gulf Stream, it finally returns to the North Atlantic.

Of course, this long flow path is not like a pipe, conducting every molecule of water along the same path. As deep water traverses the ocean floor, there is very slow diffuse upwelling. More intense and localized upwelling of deep water also occurs along shorelines. Some water in the Pacific takes a shortcut to the North Atlantic by flowing through the Bering Sea, into the Arctic Ocean, and then southward (Figure 9.19).

The formation of North Atlantic deep water may have important implications for the global climate. Changes in the flow pattern, perhaps induced by shifting continents and swelling ridges, may have caused some of the climate change that led to the ice ages. In the future, greenhouse warming may also affect the rate at which North Atlantic deep water is formed. This effect could change oceanic circulation and have complicated global effects on precipitation.

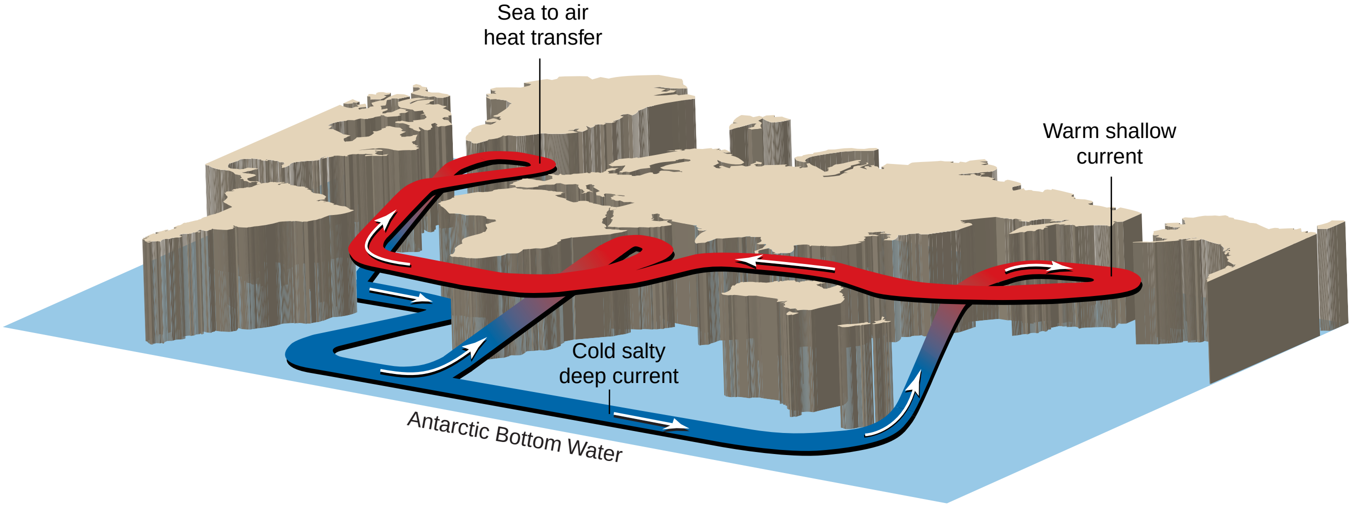


FIGURE 9.19 **The global pattern of ocean circulation** can be likened to a huge conveyor belt that carries surface water to great depths and then back again. Deep-water circulation (blue arrows) originates in the North Atlantic by the sinking of cold surface waters north of Iceland. This water flows southward at depth along the western side of the ocean basin and into the South Atlantic Ocean. Along the shores of Antarctica, it is joined by more cold sinking water and then flows eastward into the deep basins of the Indian and Pacific oceans. Diffuse upwelling in all of the oceans returns some of this water to the surface. In addition, a warm surface current from the Pacific (red arrows) may return water to the North Atlantic. *(Modified from NOAA)*

CLIMATE ZONES

Earth's climates vary with latitude. From equator to each pole, there are four fundamental climate zones: hot and wet (tropical), hot and dry (desert), moderately warm to cool and humid (temperate), and cold and dry (polar).

Climate is tremendously important in geologic processes that shape Earth's surface. As we have seen, sedimentary rocks form in immediate contact with and because of movement of the ocean or the atmosphere. These sediments record many details of ancient climates. In addition, the rates and styles of many surface processes are affected by climate. As a consequence, it is important to understand a few of the major climate zones.

Because of the systematic differences in the amount of solar radiation on the surface, combined with variations in the amount of precipitation, several major climatic zones surround the globe at different latitudes (Figure 9.20). One might expect these zones to be consistent around the globe, depending only on the radiation received from the Sun. However, local climate variations are widespread, resulting from secondary agents, such as mountain rain shadows, cold or warm surface currents, and elevation.

Tropical Climates. Moisture-laden warm air flows toward the equator from both hemispheres, as you saw in Figure 9.8. In these **tropical climates** (Figure 9.20), the annual average temperature exceeds 20°C. Precipitation rates as high as 2 m/yr are not uncommon in these regions, but much rain usually falls in a wet summer season. Tropical cyclones bring much of this moisture to the continents.

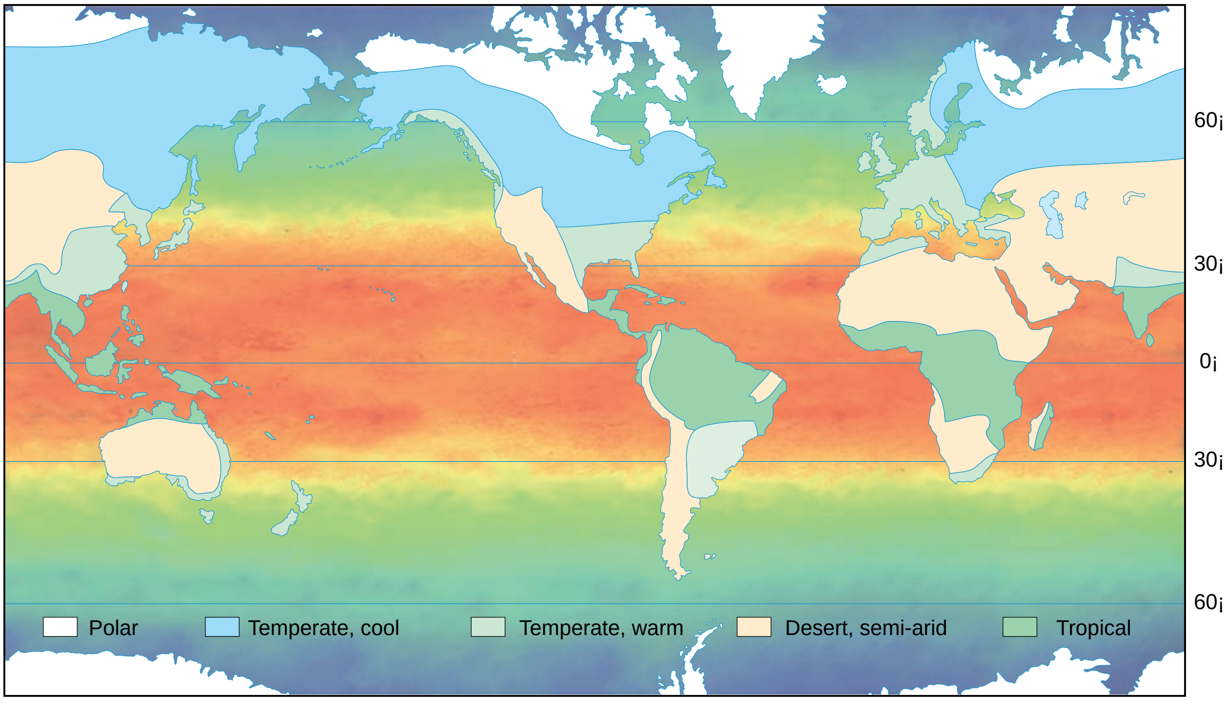


FIGURE 9.20 **A world climate map** shows the systematic variations in temperature and precipitation across the globe. Four distinctive climates have important geologic implications. Near the equators lie the *tropical climates* with their high temperatures and precipitation, much of it falling from tropical cyclones. The world's great deserts lie in broad bands of *desert climate* north and south of the tropics. *Temperate climates* dominate the mid-latitudes. Nearer the poles, cold *polar climates* with varying amounts of precipitation are characteristic. Temperature in the ocean range from systematically warm (red) near the equator to cold (blue) at the poles.

These climatic conditions are often recorded by distinctive rock types. For example, rain forests developed in the tropics may produce such lush vegetation that coal deposits form from the accumulation of dead plants. Moreover, large tropical rivers produce large deltas at their mouths. Elsewhere, thick red soils form as rocks are decomposed by deep weathering caused by the high temperatures and abundant precipitation. Nutrients are leached from the soil by the abundant precipitation.

Desert Climates. Where the precipitation is less than the evaporation rate, **desert climates** develop. Globally this situation occurs in the subtropical high-pressure zones, causing the great deserts of North Africa and the Middle East (Figures 9.8 and 9.20). Prevailing easterly winds and the high mountains of western North America are responsible for the deserts in that region. Small deserts can be produced locally in the rain shadows of high mountain belts.

Can global climate zones develop perpendicular to the equator?

Temperatures and precipitation rates vary greatly in the world's deserts. Portions of the Sahara in North Africa have an average summer high temperature of 38°C, a winter low of 16°C, and an annual precipitation of only about 2 cm/yr. Some deserts are cooler, and rain may not fall for decades. For example, the Atacama Desert of Chile has a summer average high of only 20°C and a winter minimum of 13°C. Although the Atacama is cooler than the Sahara, the average annual precipitation is extremely low—only 0.2 cm/yr.

Geologic processes in deserts include the deposition of evaporites and the development of large sand seas. Large rivers are rare, and closed river basins with no outlets to the sea are common. Decomposition of rock by weathering is slow because of a lack of water.

Temperate Climates. In regions of **temperate climates,** between latitudes of about 35° and 60° both north and south of the equator, annual temperatures range from less than 0° to 25°C (Figure 9.20). Precipitation falls throughout the year. These regions are generally too cold to support coral reefs in the oceans or rich vegetation on the continents. However, large rivers form and deposit sediment. Rich soils are created by weathering, and temperatures are high enough for intensive agricultural development.

Polar Climates. In the region north and south of about 60°, temperatures are so low that water is frozen solid during much of the year (Figure 9.20). On the continents in these **polar climates,** the average temperature is less than 10°C all year and is below freezing for most of the year. Moreover, because of atmospheric circulation patterns, precipitation is also low (Figure 9.5). In terms of lower amounts of rainfall, these are polar deserts, and wind-blown sand occurs in many areas.

The differences between geologic processes in polar regions and in other climatic zones of the world can be explained by the presence of ice. Glaciers may form and devour continental landscapes that elsewhere are dominated by stream valleys. Beyond the reach of glaciers, seasonally frozen ground may overlie a layer of permanently frozen soil and enhance the downslope movement of material. Weathering is minimal in polar regions, and vegetation is sparse. Polar oceans are far too cold to support organic reefs and are often covered by sea ice.

At times in geologic history, polar climates have expanded much farther southward. Conversely, long periods of warmth have caused polar climates to collapse. Such global changes in climate are the focus of the next section.

CLIMATE CHANGE

Climate change on a continent can be caused by its slow tectonic movement through climate zones. Alternatively, the climate may change on a global scale. Heating by the greenhouse effect is one of many important factors that cause global climate change.

What causes climate change?

Nothing is as constant as change. This cliché applies to all of Earth's dynamic systems, but especially to the climate system. Climate fluctuations are nothing new. The general features of past climate change are clear in many sedimentary rock records. Past climate changes have run the gamut from minor changes in precipitation over a local area to dramatic changes that engulfed the entire planet. Future climate changes are just as inevitable, but they are very difficult to predict. Forecasting climate change requires understanding of Earth's vast climate web and its myriad interacting elements, which weave together in a complex and often chaotic fashion. We cannot isolate one piece of the system from the rest. Predictions of future change may improve when we better understand past changes in Earth's long climate history.

The amount of temperature change necessary to alter the climate significantly is not large. In fact, huge temperature changes have not occurred on Earth. Even its oldest rocks include metamorphosed sedimentary rocks, demonstrating that Earth had cooled enough for liquid water to exist continuously since at least four billion years ago. Apparently, the surface temperature has remained between water's freezing and boiling points for a very long time. This nearly constant temperature range on Earth's surface is indeed a remarkable fact.

Just as remarkable, perhaps, is how much change is wrought by small variations in the global temperature. From geologic and geochemical evidence, it has been suggested that temperatures during the last ice age, which reached their lowest point about 20,000 years ago, were only about 3°C to 5°C lower than today's balmy average of 20°C. Yet this small change was sufficient to create ice sheets that covered much of the Northern Hemisphere with a layer of ice 3 km thick.

In the past, two types of climate change often had dramatic geological and biological results: (1) regional climate change due to continents moving into different climate zones and (2) global climate change.

Continental Drift and Climate Change

Because the continents are carried about by the slow movements of the lithosphere, they commonly move from one climate zone to another. As a result, important changes in the climate at a single location can occur over a long span of time. For example, consider the climate zones that would be encountered by a continent drifting slowly from the southern polar regions to the north (Figure 9.21). At the South Pole, the continent would likely be covered with glacial ice, producing glacial deposits and destroying river systems. As the continent moved northward into the temperate zone, the glacial deposits would be succeeded by deposits from large rivers or shallow seas, depending on sea level.

Continued movement northward would bring the continent into the subtropical high-pressure belt marked by deserts. Stream sediments would be overlain by deposits of evaporites and wind-blown sand. Continuing movement into the tropics would bring greater precipitation, and therefore large river deposits interlayered with coal might lie atop the desert sands. Shallow marine deposits in this region would include coral reefs. With continued northward movement, this sequence would reverse, with tropical deposits on the bottom, progressively overlain by desert sands, then temperate river deposits that were capped by glacial

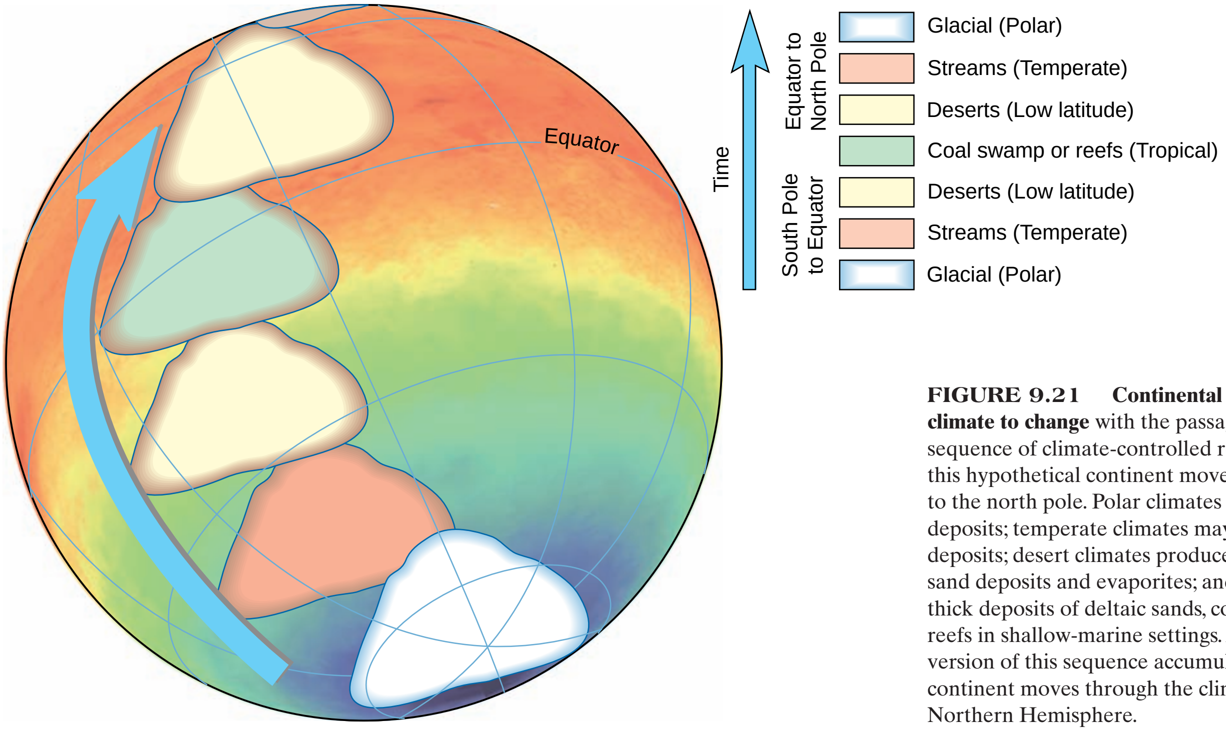


FIGURE 9.21 Continental drift causes local climate to change with the passage of time. A sequence of climate-controlled rocks develops as this hypothetical continent moves from the south to the north pole. Polar climates produce glacial deposits; temperate climates may produce river deposits; desert climates produce wind-blown sand deposits and evaporites; and tropics yield thick deposits of deltaic sands, coals, or coral reefs in shallow-marine settings. A reverse version of this sequence accumulates as the continent moves through the climate zones of the Northern Hemisphere.

deposits. This hypothetical trip would have taken about 400 million years at typical plate velocities.

Obviously, such a simple succession of rocks is unlikely to form because plate tectonics rarely carries a continent continuously in a north-south direction. Moreover, plate collisions and mountain-building events would alter the simple sequence. However, the most important conclusion from this simple model is that profound change can occur in one area simply by shifting the continent through different climate zones. Climate—and the rock record it produces—changes continuously. Despite the evidence for climate change in this theoretical example, Earth's global climate remained unchanged.

Global Climate Change

Global climate change is caused by fundamental change in one of the major climatic factors and must be clearly distinguished from the movement of a continent from one climate zone to another. Instead, global climate change involves the expansion and contraction of entire climatic zones across Earth's surface. For example, during the past ice ages, polar climates extended as far south as the northern tier of the United States and into central Europe, about 1000 kilometers or so. In the geologic past, temperate climates were found far to the north of their present positions. Obviously, global climate change and continental drift occur simultaneously, and separating their effects is not an easy task.

The most important global climate parameter is temperature. Consequently, the major controls on climate change are changes that affect the global temperature or its distribution on the surface. These include the energy output of the Sun, the composition of Earth's atmosphere, the reflectivity of Earth and its atmosphere, the ocean circulation patterns as continents move, blocking of sunlight by particles in the atmosphere, or even changes in Earth's spin or orbit. (Some of these global changes are discussed in more detail in Chapter 14, where we discuss the cause of the ice ages.) Because these temperature factors are constantly changing, climate at one spot may change as a climate zone shrinks or expands.

The Ozone Hole

Changes in the atmosphere-ocean system also may be induced by human activities. There are now so many people—approaching 6 billion—and our activities are so pervasive that humans have become an important part of the physical and chemical evolution of the entire planet. The changes we have made are not limited to the construction of buildings, dams, and highways, or to the destruction of natural vegetation in forests and plains. We are also changing the composition of the atmosphere in ways that may affect the global climate and even our own fate as a species.

Ozone Hole

The recent history of the atmosphere-ocean system involves the chemical changes caused by humans. Both the atmosphere and the ocean are becoming polluted with the products and by-products of our modern industrial and agricultural practices. For example, the chlorinated fluorocarbons (CFCs, used as refrigerants) attack and destroy ozone molecules in the stratosphere. Even the tiny amounts of CFCs released have modified the ozone balance and decreased the amount of ozone and increased the area of the depleted zone to create an **ozone hole** over both poles. Figure 9.22 shows the ozone hole over Antarctica. The ozone hole comes and goes with the seasons and is deepest in the winter when ozone production is naturally at a minimum. The destruction of stratospheric ozone increases the amount of ultraviolet radiation (a carcinogen at high dosages) that reaches the surface (Figure 9.22).

Another prominent side effect of atmospheric pollution, **greenhouse heating**, is highlighted in the *GeoLogic* essay on the next page. Will Earth return to the greenhouse conditions of the Cretaceous period when temperate climates extended as far north as Alaska? How will the production of food and other biological resources be affected by this impending climate shift? Will a natural

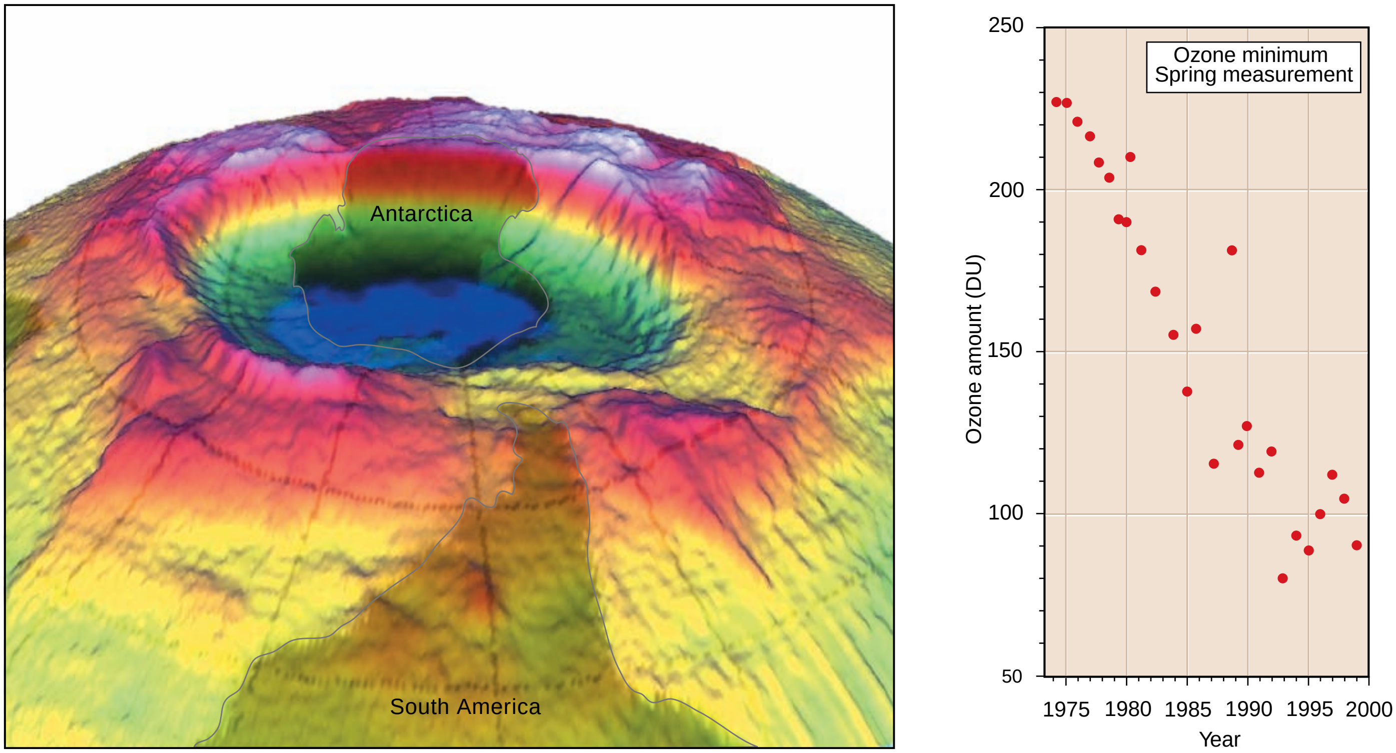


FIGURE 9.22 **The hole in the ozone layer** over Antarctica develops each winter and is deepest in the early spring (September). The "hole" is a decline in the abundance of ozone in this upper atmospheric layer. The depletion is caused by the reaction of ozone with human-made chemicals such as chlorinated fluorocarbons (CFCs) used in air conditioners and formerly as propellants in aerosol cans. Measurements of ozone (in concentration called *Dobson units*) can be made by satellites orbiting Earth and show that the depth of the ozone hole is not increasing as fast as it once was. *(Courtesy of NASA Goddard Space Flight Center, Scientific Visualization Studio)*

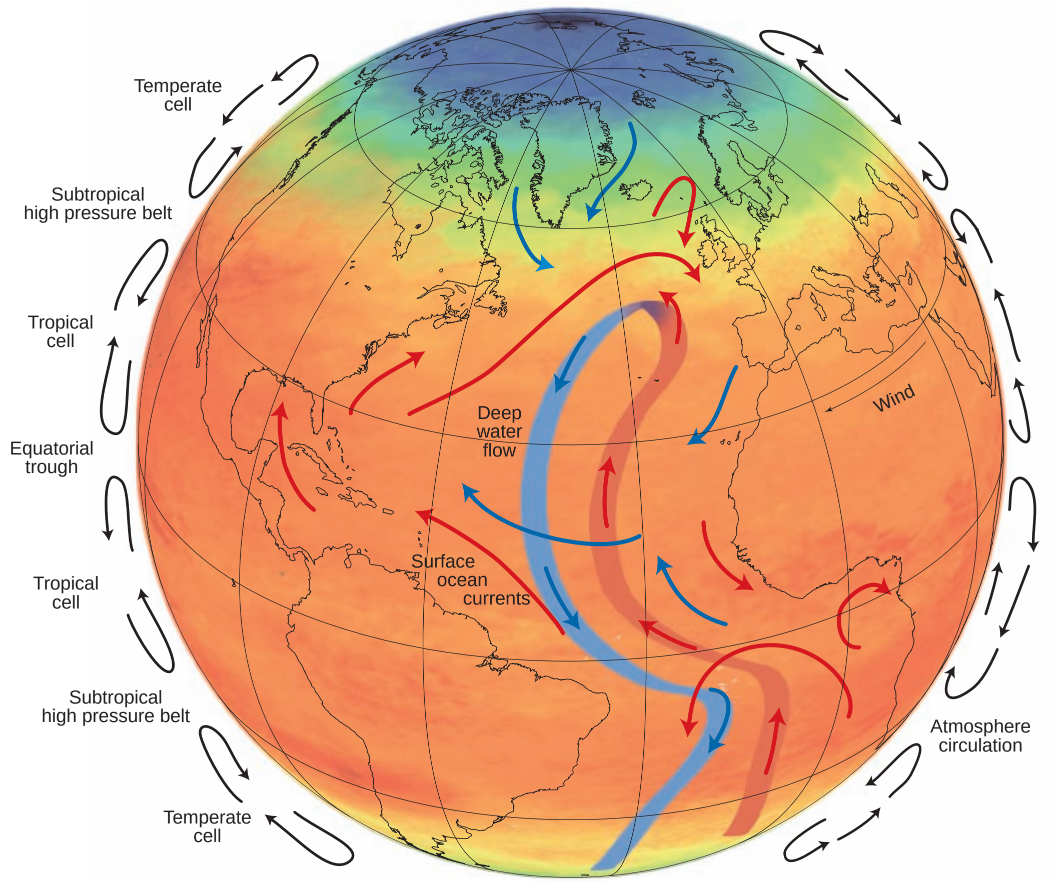


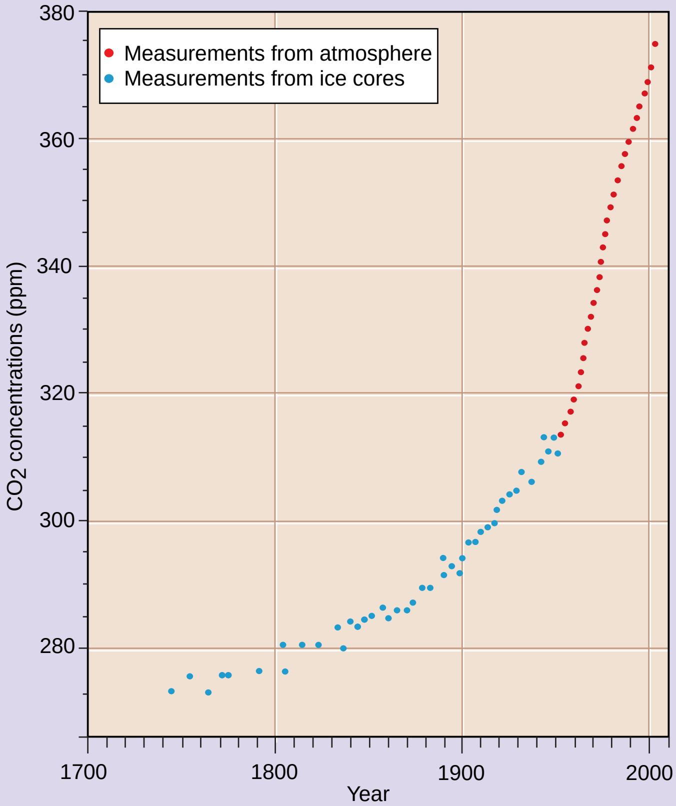
FIGURE 9.23 **Earth's climate system** is based on energy delivered by the Sun and spread unequally around the surface. This, in conjunction with variations in buoyancy and gravity-driven flow, creates vast circulation paths in atmosphere and in the ocean. In turn, these moderate the temperature differences around the planet and shape the biosphere.

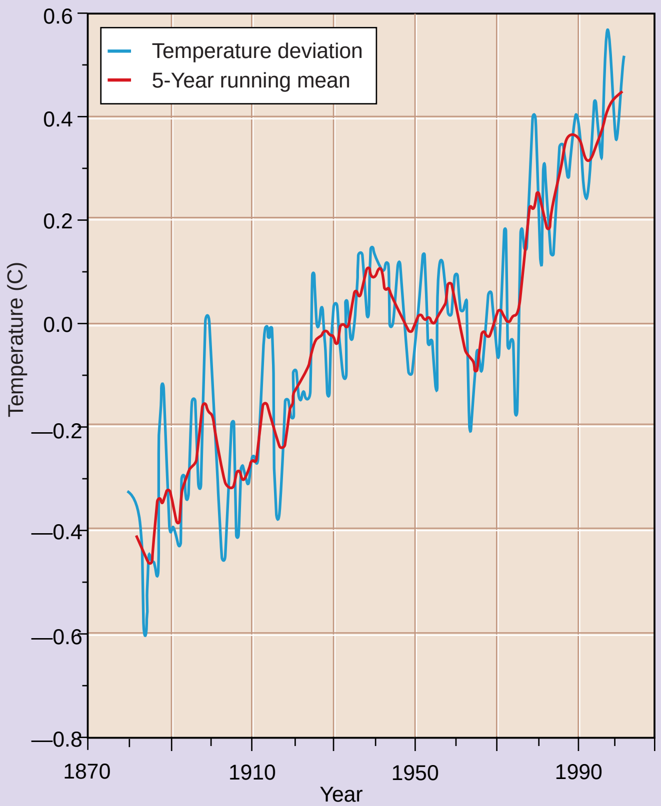
return to glacial conditions dampen the effects of the carbon dioxide increase? Only time will tell.

At this point, it is worth looking back over the atmosphere-ocean system in its entirety (Figure 9.23). The global climate system is based on energy delivered by the Sun and spread unequally on the surface. Because heat is concentrated at the equator and diffuse at the poles, a planet-wide circulation system is established in the atmosphere. Winds set up by the flow of the atmosphere drive the circulation of shallow ocean water, interference is supplied by the continents. Deep circulation of seawater is driven by density differences caused by heating and salt content. In turn, the movement of the waters in the ocean moderate the temperature differences around the globe. The climate zones are the ultimate result of these variations and have had an obvious impact on all aspects of the hydrologic system and its interaction with the lithosphere. Their role in the evolution of life and especially humans cannot be underestimated.

Greenhouse Heating

GeoLogic The Greenhouse Effect





Global climate change caused by human activities is a major political and scientific issue in the modern world. Claims and counterclaims abound in the political debate about the reality of an increase in abundance of greenhouse gases in the atmosphere, about the source of the greenhouse gases in the atmosphere, and about a global temperature increase. From a scientific point of view, the facts are less contentious.

Observations

1. Carbon dioxide in the atmosphere absorbs heat radiated from the surface and traps it in the troposphere. We have already described how certain gases absorb radiation at specific wavelengths depending upon the atoms in the molecule and the nature of the bonds that hold the atoms together. Gases that absorb energy and thus increase the atmosphere's temperature are called **greenhouse gases**.
2. Carbon dioxide concentrations have been increasing since about 1800 as shown in the graph. The first evidence came from direct measurements of the atmosphere's composition. Since 1958, regular sampling has shown that the concentration of carbon dioxide has increased from about 315 ppm to 360 ppm. Moreover, by carefully extracting bubbles of gas trapped in glacial ice, we have extended our carbon dioxide measurements back several hundred years. In the 1700s, the carbon dioxide content of the atmosphere was fairly constant at about 275 ppm, but it has increased to about 360 ppm over the last 250 years.
3. Coal, oil, gasoline (all fossil fuels) burn to release carbon dioxide as a by-product.
4. The increased carbon dioxide is coming from fossil fuels, not volcanoes or other natural sources. This is revealed by the isotopic composition of the carbon in the air.
5. The use of fossil fuels increased dramatically since the early 1800s because the population increased and because of the industrial revolution.
6. There is a scientific consensus that the global temperature has increased by about 0.8°C over the past 100 years.

Interpretations

This is a classic case of trying to determine the relationships between two correlated observations (increasing carbon dioxide and increasing temperature). Does one cause the other? If so, which is cause and which is effect? Or are they completely unrelated and their correlation is simply coincidental? In this case, most atmospheric scientists have concluded that the two factors are actually related to one another because the effect (temperature increase) is in the direction predicted by the change in the causative factor (increase in carbon dioxide). It is still not absolutely certain that the temperature increase is caused solely by greenhouse heating, but it is an obvious candidate.

KEY TERMS

coastal upwelling (p. 236)
Coriolis effect (p. 227)
deep water (p. 231)
desert climate (p. 241)
El Niño (p. 236)
greenhouse effect (p. 223)
greenhouse heating (p. 244)
greenhouse gas (p. 246)
humidity (p. 221)
jet stream (p. 229)
magnetosphere (p. 223)
mesosphere (p. 222)
ozone (p. 221)
ozone hole (p. 244)
ozone layer (p. 222)
polar climate (p. 241)
precipitation (p. 224)
salinity (p. 230)
sea ice (p. 231)
stratosphere (p. 221)
surface water (p. 231)
temperate climate (p. 241)
thermohaline circulation (p. 234)
thermosphere (p. 222)
tropical climate (p. 240)
troposphere (p. 221)

REVIEW QUESTIONS

1. Explain how weather and climate are different.
2. What causes the layering of Earth's atmosphere?
3. Why does the temperature gradient in the atmosphere reverse at the boundary between the troposphere and the stratosphere?
4. Describe the general temperature variations across Earth's surface. What causes these pronounced latitudinal changes in temperature?
5. Venus's cloudy atmosphere reflects away so much solar energy that its surface receives less than Earth. What then causes the very high (470°C) surface temperature on Venus?
6. Why does the pressure of the atmosphere decrease at high elevations?
7. Describe the global flow patterns of the atmosphere.
8. Why are the tropical rain forests found along the equator? Why does a band of deserts encircle Earth at 30° north and south of the equator?
9. Outline the role ozone plays in the atmosphere.
10. How is ozone formed in the stratosphere? What causes its destruction?
11. Outline the two major driving forces for ocean circulation.
12. Why is there so little mixing between the waters of the deep ocean and the waters in its surface layers?
13. Where is ocean water densest? What causes the density variations?
14. Why would the development of a warm surface layer associated with the El Niño event off the coast of South America inhibit coastal upwelling?
15. What are the major constituents of seawater? What is the origin of the dissolved ions?
16. Do you think Earth's climate has always been the way it is today? What evidence supports your conclusion?
17. What could cause the climate to change?
18. How is Earth's atmosphere different from any other in our solar system? What would you conclude if you discovered a planet with an oxygen-rich atmosphere?
19. What are the potential human-caused changes in Earth's climate system?
20. Why are wind velocities and wave heights so strongly correlated in the maps on page 238?

ADDITIONAL READINGS

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MULTIMEDIA TOOLS

Earth's Dynamic Systems Website
The Companion Website at **www.prenhall.com/hamblin** provides you with an on-line study guide and additional resources for each chapter, including:

- On-line Quizzes (Chapter Review, Visualizing Geology, Quick Review, Vocabulary Flash Cards) with instant feedback
- Quantitative Problems
- Critical Thinking Exercises
- Web Resources

Earth's Dynamic Systems CD
Examine the CD that came with your text. It is designed to help you visualize and thus understand the concepts in this chapter. It includes:

- Animations of crystallization of liquids
- Video clips of volcanic eruptions
- Slide shows with examples of igneous rocks
- A direct link to the Companion Website