CHAPTER 4

Effects on the Climate System

Chapter at a Glance

Chapter 3 examined the major controls on the climate system, including the effects of *latitude*, Earth–Sun relationships, *continentality*, atmospheric and oceanic circulation, elevation, and general local features. This chapter explains the role of other important components on the climate system. These contributors may be thought of as internal components because they affect the system already set in place by the aforementioned climate controls. The features discussed in this chapter work to influence and change the already-established climate system. Even though the oceans were mentioned in Chapter 3, they warrant further scrutiny in this regard. Because over 70 percent of Earth's surface is covered by oceans, processes occurring in the oceans play an important role in climate and climatic variations.

Ocean Circulation

Surface Currents

Atmospheric Effects Oceanic surface currents are driven by overlying winds that on the broadest scale are dictated by the great global atmospheric **subtropical anticyclones**—large semipermanent high-pressure cells that exist in each ocean basin approximately centered on the 20 to 30° parallel of latitude. These subtropical anticyclones wax and wane in strength and position seasonally, but they are always present. The clockwise circulation of the anticyclones in the northern hemisphere and the counterclockwise circulation of the systems in the southern hemisphere initiate corresponding surface water motions in the oceans. Of course, the near-surface waters are also moved by the *Coriolis effect* inducing the *Ekman spiral*, but for a large section of the oceans, near-surface waters move in a general clockwise pattern in the northern hemisphere and counterclockwise in the southern hemisphere because of these subtropical anticyclones (**Figure 4.1**). These circular flows, caused by a coupling of the atmospheric and surface oceanic circulations, are termed **gyres**.

As we saw in Chapter 3, the large-scale motions of the oceanic surface ensure that cold currents occupy the eastern sides of the ocean basins and warm currents are found along the western edges of the basins. This spatial pattern is caused by mass *advection*—lateral movement—of warm waters traveling from relatively low latitudes along the

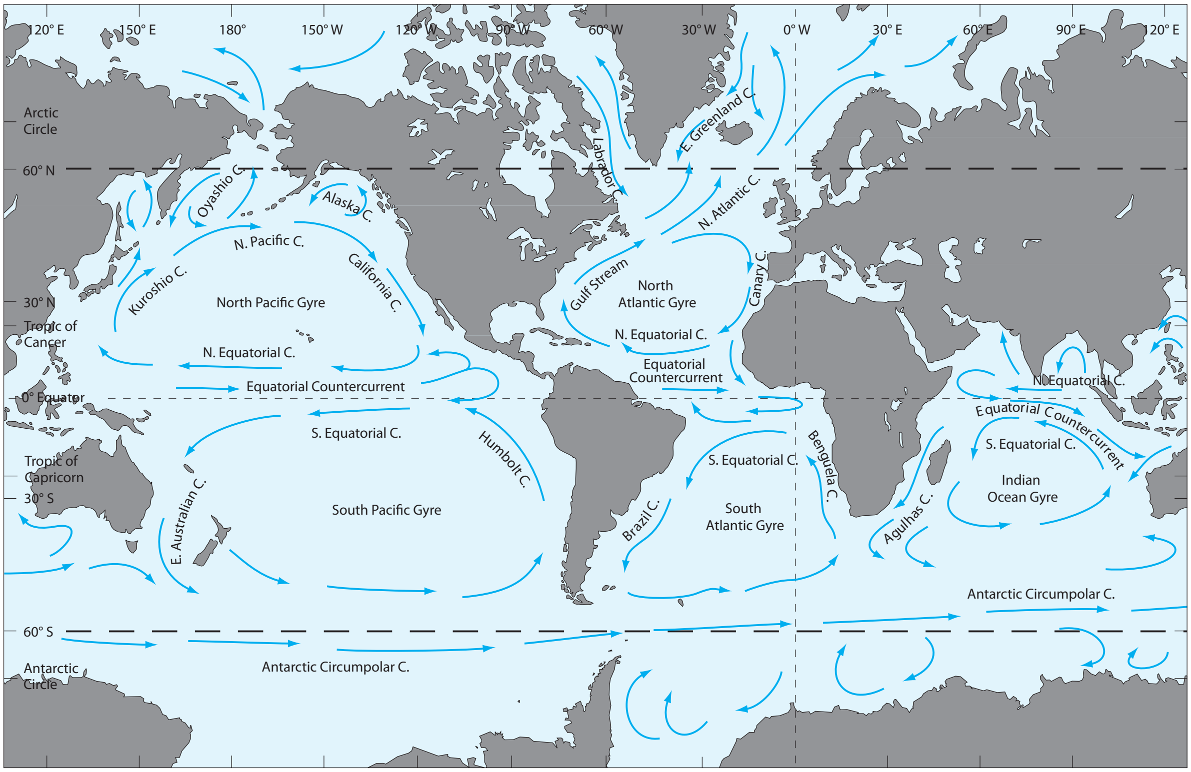


Figure 4.1 Surface currents.

western ocean edge, while cold water from the high latitudes is advected along the eastern edge, in both hemispheres. The effect is that low surface temperatures on the eastern ocean basins (with warmer air above the cold air adjacent to the cold water) tend to stabilize the atmosphere. A **stable atmosphere** is one in which vertical motions are discouraged because the colder, denser air exists below warmer, less dense air and, therefore, it tends to rise above the less dense air. Although this concept is explored in more detail in Chapter 5, we can say now that a stable atmosphere promotes net sinking motions in the atmosphere, which discourages cloud formation processes. For this reason some of the most enjoyable climates on Earth are located along the eastern ocean margins (and, therefore, the western coasts of continents) where pleasant temperatures, abundant sunshine, and little precipitation occur.

By contrast, the western ocean basins are dominated by warm waters that destabilize the overlying atmosphere. In this situation warm, moist air adjacent to the warm ocean currents becomes buoyant and rises. Such an **unstable atmosphere** is generally conducive to cloud formation and precipitation. Therefore, the western ocean basins (and the adjacent eastern coasts of continents) typically have abundant precipitation that is usually distributed fairly evenly throughout the year. During summers the subtropical and tropical midlatitude regions on the east coasts of continents become hot and humid because abundant water vapor usually exists from the *maritime effect*. In winter the effect is less pronounced, at least in the middle and subtropical latitudes, as westerly wind systems dominate the midlatitudes, promoting more continental temperatures along the eastern coasts.

Upwelling, Downwelling, and Mass Advection

Upwelling reinforces the effect of the cold currents along the eastern ocean basins. When offshore surface winds parallel a coastline for some distance, with the coastline to the left of the direction of flow in the northern hemisphere (and to the right of the flow in the southern hemisphere), the net water advection near the surface is directed away from the coastline by the Ekman spiral. Upwelling results from the Ekman spiral's deflection of surface water

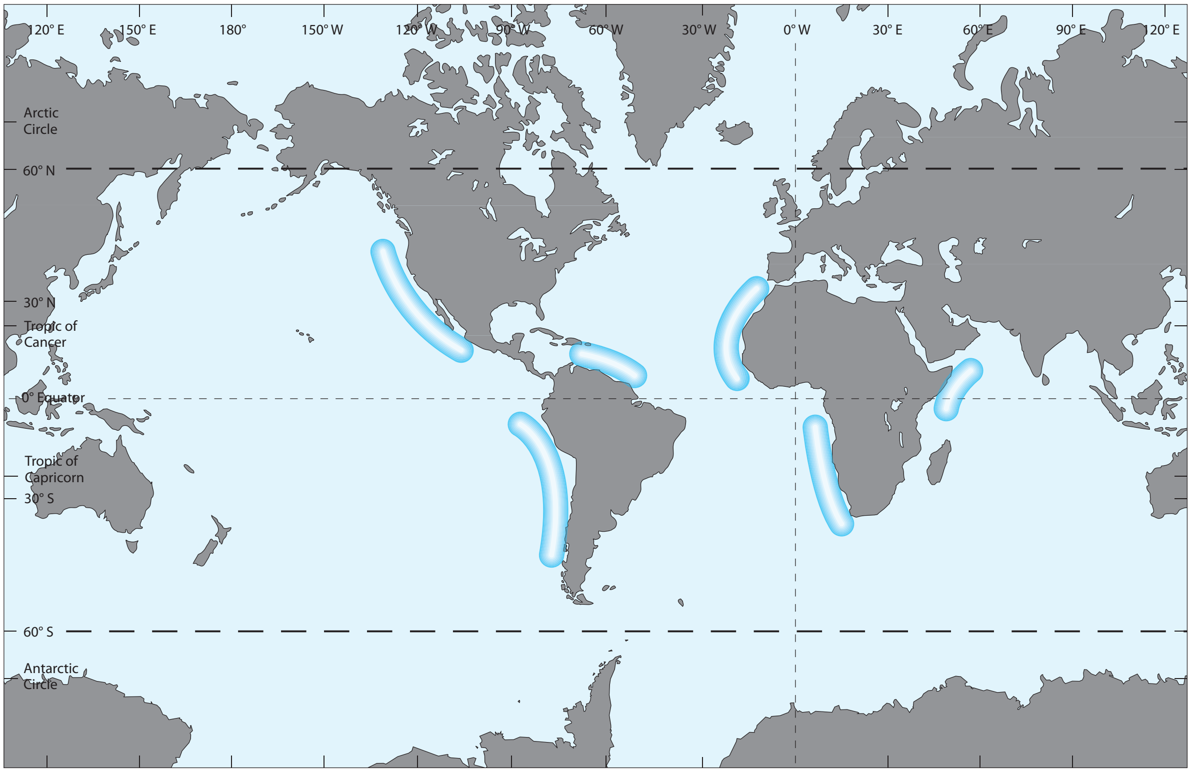


Figure 4.2 Locations where coastal upwelling is important.

to the right (in the northern hemisphere) with depth. Examples of locations around the world where upwelling is particularly effective because of the coastline shape and consistency of the winds are shown in **Figure 4.2**. Upwelling also can occur in areas where two currents diverge, allowing water from the depths to rise to replace the surface water that has been moved away laterally. Regardless of the cause of the upwelling, departing surface waters are replaced by cold deep water from beneath. In such situations an already cold surface current becomes even colder.

Perhaps the best example of upwelling is associated with the **Humboldt** (also known as the **Peru**) **Current** located off the western coast of South America (**Figure 4.3**). The South Pacific subtropical anticyclone is particularly well established and strong, because of the size of the South Pacific Ocean and the lack of interfering land masses. A very strong and persistent counterclockwise circulation results and forces very cold surface waters to move equatorward from the Antarctic. As this water parallels the South American coast, the Ekman spiral forces it westward. The upwelling results in one of the coldest ocean currents on Earth. The low surface temperatures (even at tropical latitudes) stabilize the overlying atmosphere, causing cool, dry climates to dominate the western edge of the continent. The Atacama Desert of coastal Peru and Chile is the driest desert on Earth.

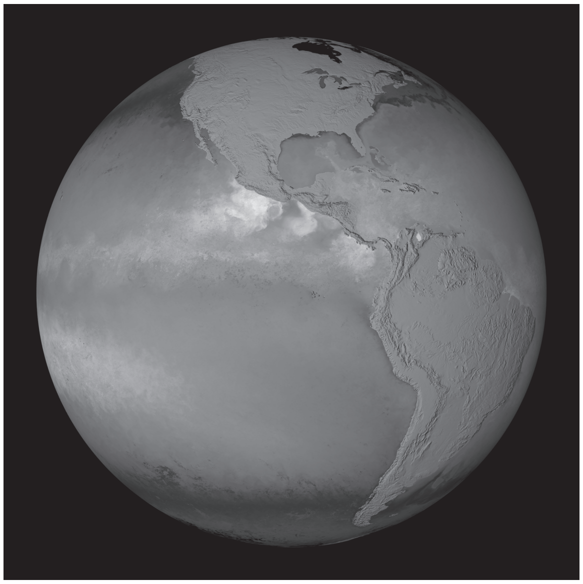


Figure 4.3 Cold water upwelling along the South American coast. (See color plate 4.3)

On the western sides of ocean basins, **downwelling** may occur—an oceanic process that is the reverse situation in which surface airflow pushes water against a coastline where it is forced to sink. In addition, in locations where two surface ocean currents converge, the pile-up of surface water can induce downwelling. Downwelling typically supports high ocean temperatures as sinking warm waters push the cold water to deeper levels. An example occurs along the equatorial western Pacific Ocean where easterly (east to west) winds push waters westward toward Indonesia. This water warms significantly along its westward journey across the tropics. On the western side of the equatorial Pacific, the water is forced to sink. The Ekman spiral does not affect the bulk of this water because the Coriolis effect does not occur along the equator. Without Coriolis deflection the current maintains its straight course. The **Maritime Continent**—the Indonesia–Philippines region—is, therefore, dominated by very high ocean surface temperatures that promote low-level atmospheric instability. Such situations support cloud formation and precipitation. Locations on the western sides of ocean currents (eastern sides of continents) in the subtropics are usually dominated by warm, wet climates.

In the North Atlantic Ocean, for example, the subtropical anticyclone forces a clockwise circulation that supports the cold water **Canary Current** off the coast of southern Europe and northern Africa, the **North Equatorial Current** near the equator, the warm *Gulf Stream* along the eastern coast of North America, and the *North Atlantic Drift* (current), which completes the northern gyre circulation. Again, the circulation regime is initiated by the atmospheric anticyclone and mimicked by the ocean in a corresponding gyre. Similar oceanic circulations occur in all other ocean basins.

Because of the deflection of the Ekman spiral, water tends to pile beneath the subtropical anticyclones in each ocean basin. As the gyre circulates, the Ekman spiral dictates that mass advection occurs 45 to 90° to the right (in the northern hemisphere) of the initial water motion. Equatorward-moving surface water, the Canary Current in this example, is forced toward the central ocean region. Water moving from east to west across the low latitudes in association with the North Equatorial Current is also forced by the Ekman spiral toward the middle of the basin. Surface waters associated with the Gulf Stream and portions of the North Atlantic Drift, which moves essentially west to east, are also forced toward the ocean center. The result is a mound of water located roughly in the middle of the North Atlantic Ocean basin near the center of the atmospheric subtropical anticyclone. The mound supports sea levels exceeding those of surrounding locations.

At the same time, gravity acts on the mound, pulling it downward toward the lower sea level on the periphery. Thus, the water within this mound is constantly affected by offsetting forces. The Coriolis effect (manifested as the Ekman spiral) pushes water inward, whereas gravity pulls water outward (downward). As the water circulates clockwise (in the northern hemisphere) along this mound, it reaches an equilibrium between the two forces. An oceanic version of **geostrophic flow** occurs when these forces are in balance (**Figure 4.4**).

An exactly opposite condition occurs for waters flowing counterclockwise (in the northern hemisphere) in association with semipermanent low atmospheric pressure regions, normally centered around 60° latitude. An oceanic depression occurs at these locations and waters swirl around the depression in geostrophic balance.

The central axes of these mounds and depressions are not perfectly centered beneath the atmospheric highs and lows but instead are offset toward the west of the centers. This is because Coriolis deflection increases with latitude, affecting the amount of water transported via the Ekman spiral along the gyre. Poleward-moving currents have increasing amounts of water advected toward the center of the basin, while equatorward-moving currents have decreasing amounts of net transport along their trajectory. The result is a pile of water with its axis offset to the west of the central ocean basin.

The effect of the offset central axis causes poleward-moving waters (i.e., on the western sides

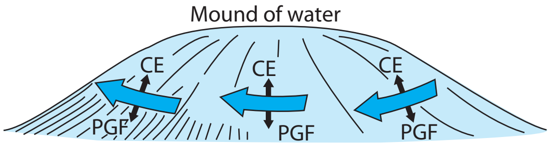


Figure 4.4 Geostrophic balance in the ocean.

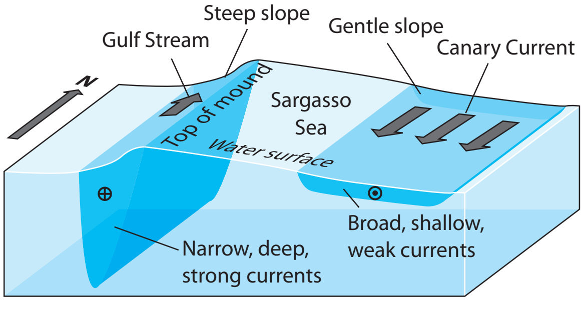
of ocean basins in both hemispheres) to pile up between the continent and the mound axis. When a moving fluid converges, as in this case, a speed change is initiated because the fluid is forced through a smaller space over a constant time period. This type of speed change may be seen when placing a finger partially over the opening of a hose. Once the opening constricts, water, under pressure, is forced to increase in velocity. In the ocean the response results in **western-boundary intensification**, a very deep and swift western ocean basin current (**Figure 4.5**). The Gulf Stream is a perfect example of western-boundary intensification, because it is a very deep, fast-moving western ocean basin current. On the opposite side of the ocean basin, the cold water current (in this case, the Canary Current) is typically very shallow and slow moving and is spread across a larger surface area. These properties affect the climates of adjacent locations.

Another way to view western-boundary intensification is relative to the slope of the sea surface. Because the central axis of the water mound is offset to the west, the corresponding slope in sea surface is steeper in that location. This results in water moving along a steeper pressure gradient, which increases the speed of water motion. On the opposite side of the ocean basin, the colder water flows over a much gentler sea surface slope, resulting in a slower rate of flow (Figure 4.5).

Deep Ocean Thermohaline Circulations

Surface currents are not the only currents that influence climate. Deep ocean currents are driven by *thermohaline circulation*, as discussed in Chapter 3. **Thermohaline currents** flow in response to temperature ("thermo") and/or salinity ("haline") characteristics through the deep ocean. Just as density differences (cold versus warm) in air drive atmospheric motions, deep ocean thermohaline differences establish net pressure gradients. The fluids of the deep ocean respond, because denser waters tend to sink beneath less dense waters. Because colder, saltier water is denser than warmer, fresher water, net downward motions occur where waters become colder and/or saltier. Warmer and/or fresher waters are more buoyant and rise. Any situation in which colder water underlies warmer water represents **stable stratification**, the oceanic equivalent to a stable atmosphere (**Figure 4.6**). Further *convection* (vertical motion) is suppressed unless another force or energy source initiates it.

Interestingly, deep ocean currents are actually driven by surface processes because seawater gains its thermohaline characteristics from surface sources. Intense solar heating in low-latitude regions warms the water surface sufficiently to decrease its density. The reduced solar input and heat loss (to the frigid atmosphere) in high-latitude regions favor a denser ocean surface because of its colder surface characteristics. Oceanic areas with



Geostrophic flow around the North Atlantic Ocean

Figure 4.5 Western-boundary intensification.

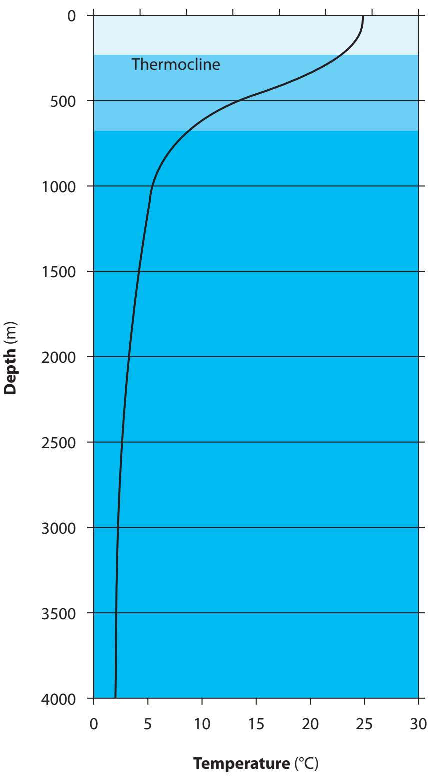


Figure 4.6 Deep-water stratification.

abundant precipitation have lower water densities because of the high input of fresh water. Likewise, oceanic areas near coastlines in humid climates typically have fresher water because of abundant input of stream discharge. By contrast, areas of the ocean that receive less precipitation than *evaporation* and/or have input only from a few small streams typically have dense, salty water. Precipitation characteristics of both the ocean and the surrounding land masses influence the density of ocean waters.

The freshest ocean waters on Earth are typically found near the equator, where high temperatures and abundant precipitation support low-density waters. High salinities usually occur near the centers of the subtropical anticyclones (30° latitude), where abundant sunshine evaporates large quantities of surface water, leaving behind salts. When these salty waters are advected to higher latitudes, the high salt content combines with lower temperatures to create the densest ocean waters. These waters sink to the deep layers of the ocean where they are forced to move along thermohaline gradients.

Source areas are locations near the surface that provide water to the ocean depths. These are located in relatively high-latitude regions of the Atlantic and Pacific Oceans (**Figure 4.7**). In the North Atlantic, deep water originates at the surface near Iceland, where it sinks and moves equatorward. The South Atlantic also acts as a source area for deep water near Antarctica and in the area east of the tip of South America. In the North Pacific, deep water sinks near the tip of the Aleutian Islands and moves equatorward. The South Pacific deep-water source area is located near 65°S latitude.

There are many deep-water thermohaline currents, but the main one in the Pacific sees deep water moving from the North Pacific southward across the equator and then looping in the extreme South Pacific back toward the equator. In the Atlantic Ocean the main body of deep water also begins in the northern hemisphere near Iceland. It travels

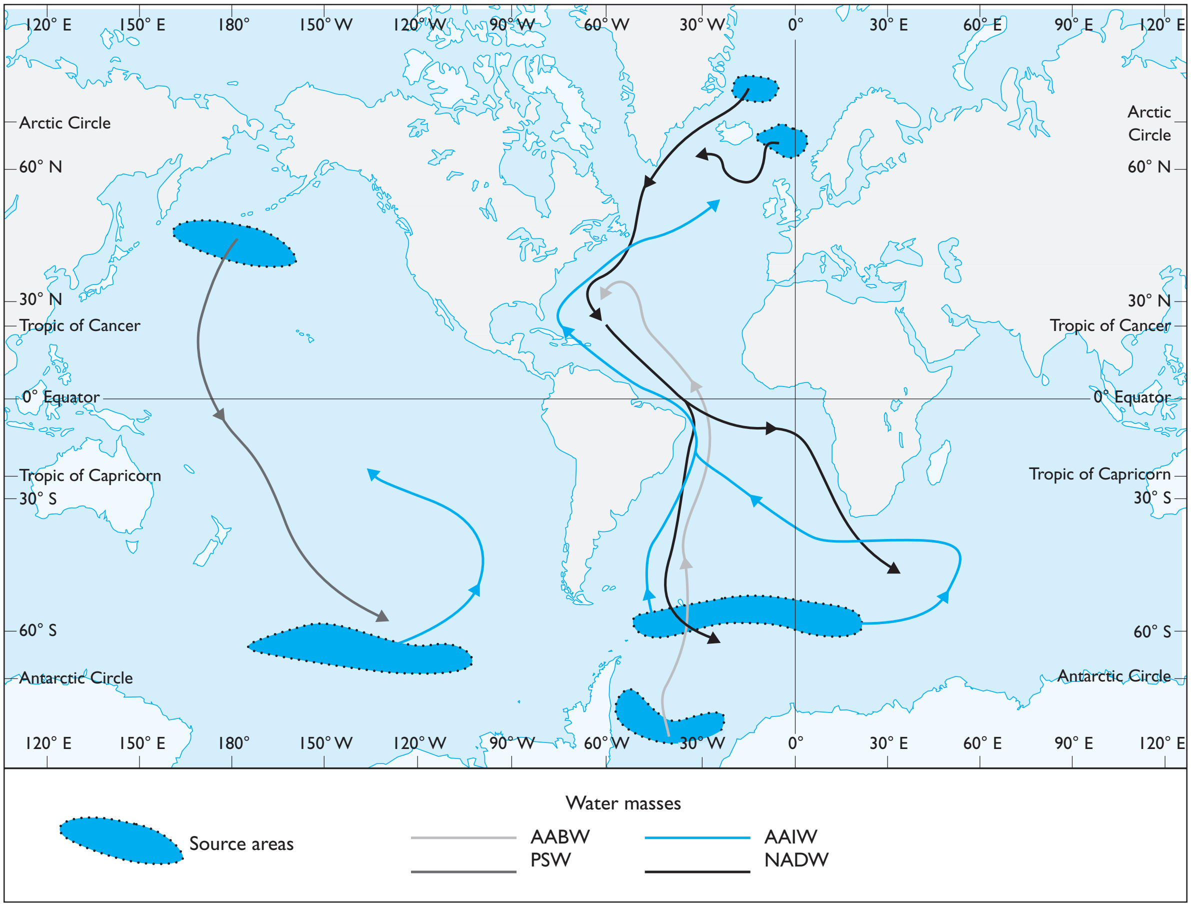


Figure 4.7 Deep ocean currents of the world. *Adapted from*: Gordon, A. L., *Lamont-Doherty Geological Observatory Report*, 1990–1991.

equatorward largely beneath the Gulf Stream, crosses the equator off the eastern coast of South America, and then continues toward Antarctica. Once in the high latitudes the deep water turns eastward before moving back toward the equator. The deep water travels northward near its opposing equatorward-flowing counterpart, before completing the loop near Iceland.

Deep waters travel at varying depths relative to each other. This makes it possible for different deep-water currents to occupy similar regions. The deepest waters in the Atlantic Ocean are those arriving from the **Antarctic Bottom Water**, the coldest ocean current, which forms near Antarctica (Figure 4.7). The **Antarctic Deep Water** moves over that layer as it flows northward and gently upward, eventually flowing beneath the current known as the **North Atlantic Deep Water**. The progression continues upward to the surface.

In the Pacific, two currents—the **Common Water**, initiated again near Antarctica, and the **Pacific Subarctic Water**—occupy the lowest layers of the ocean. These currents are overridden by **Antarctic Intermediate Water** and the **North Pacific Intermediate Water**. Surface waters override those layers. Thermohaline currents in the Indian Ocean are dominated by Common Water arriving from the region of Antarctica and Antarctic Intermediate Water.

Coexisting with these individual thermohaline currents is a massive conveyor current that connects all the ocean basins on Earth except the Arctic. Much of what is known concerning this deep-water thermohaline conveyor comes from the work of Henry Stommel. In 1958 Stommel devised the simplified model of deep ocean circulation, basing water motions on similar forces that drive western-boundary intensification. The **Stommel model** indicates that net sinking motions are initiated in the North Atlantic near Iceland (**Figure 4.8**). This water sinks to the floor of the North Atlantic as it moves equatorward. After crossing the equator the conveyor moves toward Antarctica, where Antarctic Bottom Water is added. Then, it turns eastward to move between Africa and Antarctica. The deep water continues eastward but forks into two branches, one progressing equatorward through the Indian Ocean and the other moving eastward

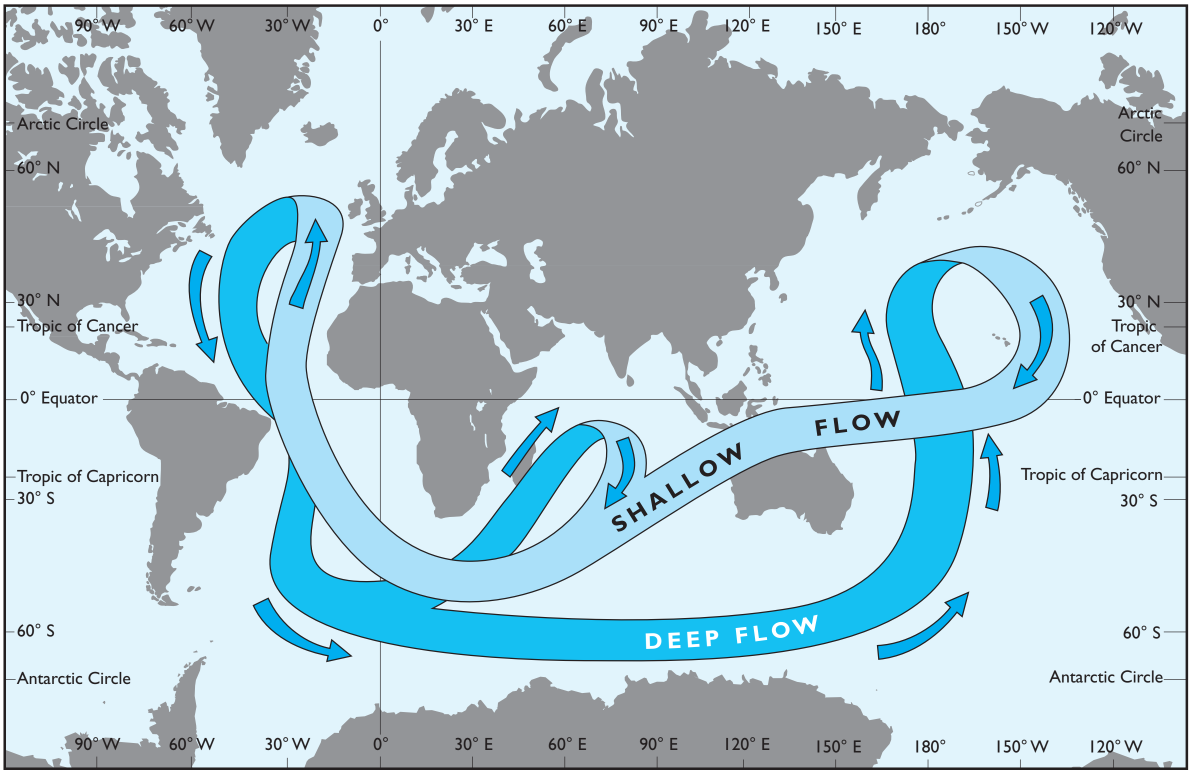


Figure 4.8 Stommel deep water conveyor model.

into the Pacific. The Indian Ocean branch rises toward the surface near the equator south of India. This water then turns southward and moves as a warmer shallow layer back toward the Atlantic. The southern deep-water branch progresses into the South Pacific before moving northward east of Australia. This water stream crosses the equator and rises in the central North Pacific. It then loops back and moves near the Maritime Continent as shallow water. This current ultimately joins the shallow water stream in the Indian Ocean. Both branches then move back around the tip of Africa and into the Atlantic, where the conveyor moves northward, ultimately sinking again near Iceland.

This deep-water conveyor is capable of transporting huge amounts of oxygen and energy from one side of the planet to the other. The oxygen provides a mechanism by which oceanic life is supported. The energy is capable of influencing climate for centuries, as signatures of past climatic variations are present in the slow-moving water itself. Reintroduction of this stored energy into the present or future atmosphere can alter climate, particularly where the conveyor approaches the surface and can transfer the energy back into the atmosphere easily. Likewise, present-day atmospheric changes, most notably **global warming**, can provide additional storage of energy in the conveyor belt and elsewhere in the oceans. This additional energy is likely to cause future changes both to the *hydrosphere* in the form of surface currents, thermohaline circulation, and conveyor belt and to other "spheres" in the climate system. The impacts are unknown.

El Niño-Southern Oscillation Events

The **El Niño-Southern Oscillation (ENSO) event** is perhaps one of the most misunderstood of all atmospheric processes. ENSO events affect global weather in a very profound way. Perhaps only Earth–Sun relationships exert more of an influence on the global climate system than ENSO.

The term **El Niño**, translated from Spanish as "the boy," originally referred to the annual warming of the equatorial ocean current off the western coast of South America during the Christmas season (**Figure 4.9**). This sea surface warming is associated with the change of seasons—the beginning of winter in the northern hemisphere and summer in the southern hemisphere. For most of the year in the tropics strong winds, known as **trade winds,** push the warm surface waters of the tropical Pacific westward, allowing upwelling of cold, deep ocean waters in the eastern tropical Pacific. As the seasonal atmospheric circulation pattern becomes established during the transition of autumn and spring, trade winds along the equator weaken, allowing the warm water in the western equatorial Pacific to migrate back toward the east. This annual migration warms the Pacific's eastern equatorial rim, typically around December.

Over the years the meaning of the term El Niño has changed from its original reference to the normal annual event described above. It is now used to refer only to the unusually extreme increases in sea surface temperatures (SSTs) occurring for several months approximately every 3 to 7 years in the central and eastern equatorial Pacific Ocean. By contrast, **La Niña**—the opposite of El Niño—refers to a strengthened "normal" situation, which typically reinforces cold water conditions in the eastern equatorial Pacific and warm water conditions in the western tropical Pacific near the Maritime Continent. In recent years the neutral situation—one in which neither El Niño nor La Niña conditions occur—has been termed **La Nada**, or "the nothing."

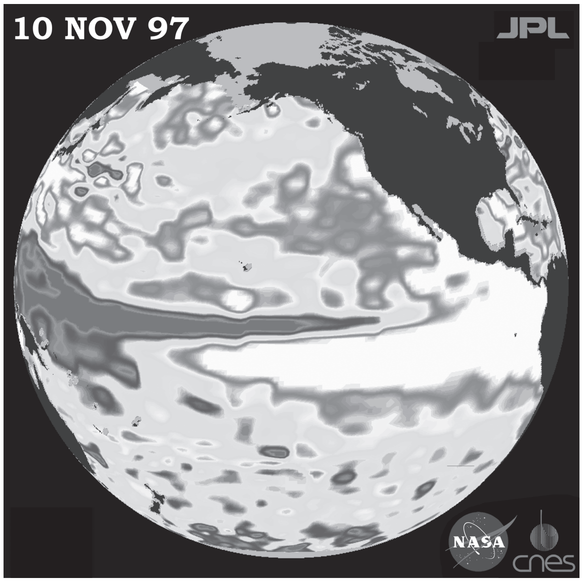


Figure 4.9 Satellite image of water temperatures in the Pacific Ocean during an El Niño event. White represents unusually warm water. (See color plate 4.9)

The **Southern Oscillation**, recognized by the climatologist Sir Gilbert Walker in the 1930s, refers to a seesaw effect of surface atmospheric pressure between the eastern and western equatorial Pacific Ocean in which higher-than-normal pressure in one of these two regions is coincident with lower-than-normal pressure in the other. Climatologist Jacob Bjerknes realized in 1969 that these pressure changes resulted from SST variations over several years in the equatorial Pacific, establishing the link between El Niño and La Niña events and the Southern Oscillation.

Today, most climatologists refer to the entire phenomenon as El Niño-Southern Oscillation, or ENSO. The variations in atmospheric pressure associated with extremes in the Southern Oscillation and the changes in the oceans during extreme phases of ENSO (El Niño or La Niña events) cause unusual global atmospheric circulation features and impacts. Because it is associated with a reversal of the typical Pacific pressure patterns rather than an intensification of them, the El Niño phase usually has wider and stronger impacts than the La Niña phase.

Walker Circulation

In 1969 Bjerknes coined the term **Walker circulation** to describe the connection between the atmospheric pressure centers in the equatorial Pacific associated with the Southern Oscillation, the SSTs, and the tropical trade winds that blow from east to west near the surface across the Pacific Ocean (and other regions of the Earth within the tropics). The Walker circulation exists to balance the normally observed pressure gradients over the tropical Pacific Ocean. The Walker circulation represents "normal" or "La Nada" atmospheric and oceanic conditions in the equatorial Pacific Ocean, characterized by high surface atmospheric pressure in the east and relatively low surface pressure in the west (**Figure 4.10**). A pressure gradient forms in an east-to-west direction at the surface with atmospheric mass (winds) working to "fill the low." Thus, surface winds normally blow strongly from the east toward the west in this region. Known as the **northeast trade winds** (or northeast trades) in the northern hemisphere and the **southeast trade winds** in the southern hemisphere, these winds comprise a major part of the global atmospheric circulation that is discussed more fully in Chapter 7.

The frictional dragging of the sea surface by these winds causes the North and South Equatorial Currents to occur along the equator, approximating the atmospheric circulation pattern, flowing from east to west in both hemispheres. The currents push the surface waters warmed by the Sun

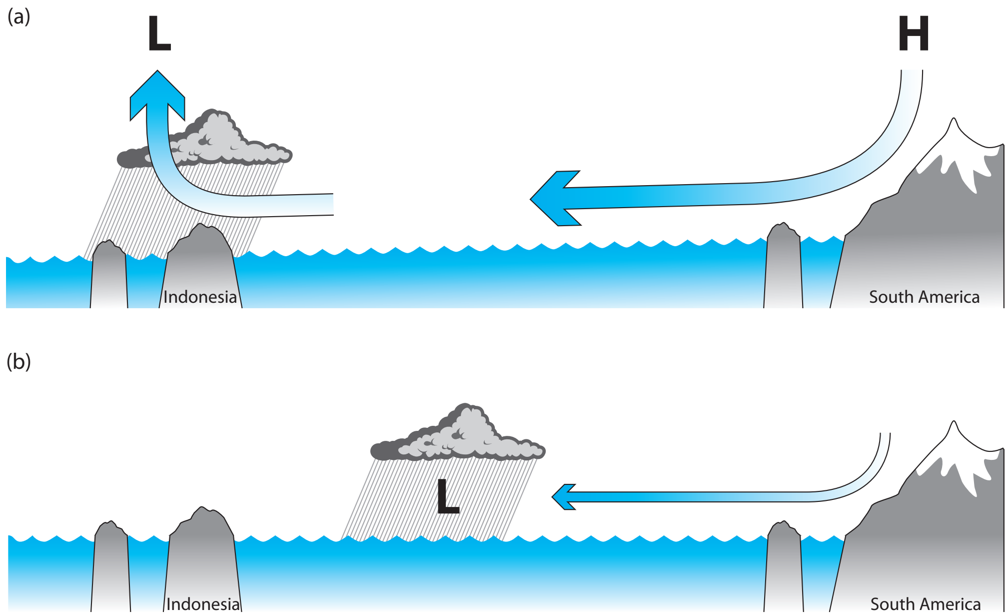


Figure 4.10 "Normal" (or La Nada) Walker circulation (a) and El Niño–related atmospheric circulation (b).

westward. This results in an accumulation of warm water in the western tropical Pacific Ocean near Australia and the Maritime Continent. Average sea level may be as much as 40 cm (16 in) higher and water temperatures 4 to 8 C° (7 to 14 F°) higher in the western tropical Pacific than at the same latitude in the eastern Pacific near South America (**Figure 4.11**). The reduced SSTs in the east are caused both by the cold surface current of the eastern South Pacific and by upwelling of colder, deep water replacing the warmer surface waters that were displaced to the west by the equatorial currents.

These "normal" or La Nada ocean temperatures control the Walker circulation along the equator. Lower SSTs in the east chill the overlying air, which in turn increases the air density, reducing its buoyancy. The sinking air causes high atmospheric pressure and usually restricts precipitation because cool air is less likely than warm air to rise vertically so that its moisture can condense and form vertical clouds. The eastern equatorial Pacific is normally dry as a result, and the extension of this dry area on the land surface is the dry Atacama Desert. Warm waters in the western tropical Pacific cause the density of overlying air to decrease. The rising air leads to lower atmospheric pressure and buoyancy that produces frequently cloudy and wet conditions over the region.

A simple index was devised to describe the atmospheric pressure variations in the tropical Pacific Ocean. **The Southern Oscillation Index (SOI)** is derived from sea level pressure differences between the eastern and western Pacific. The SOI is found by subtracting the air pressure at sea level in Darwin, Australia, from that in Tahiti. This value is often standardized statistically so that a value of zero represents La Nada, values exceeding +1 may be considered to coincide with La Niña in the ocean, and values below −1 may be considered to represent El Niño conditions. Another means of identifying El Niño and La Niña events involves monitoring SSTs in various regions of the equatorial Pacific Ocean. A temperature departure of ±1 C° away from normal conditions for 3 consecutive months constitutes a major event.

Historical Observations of ENSO

Direct information about ENSO events first came from accounts of Spanish explorers in South America during the 1500s. Indirect data sources such as tree rings, flood frequency, sediment cores, and coral reef growth suggest that anomalous weather events associated with ENSO events have been occurring for at least many thousands of years. The earliest written records of impacts believed to be related to extreme El Niño phases extend from the Chimu Dynasty (AD 1100) in the Moche Valley of Peru and indicate periodic extreme flooding, now known as **Chimu Floods**, extending as far back as 2500 BP (before present).

Most accounts are not direct observations of atmospheric or oceanic conditions but suggest indirect effects of ENSO on climate. Sources include ship logs in addition to writings by clergy members who reported unusual natural phenomena in great detail. These records became more detailed between 1600 and the mid-1800s, when South American events were chronicled in European literature. Accounts from historians, explorers, geographers, pirates, and engineers became more

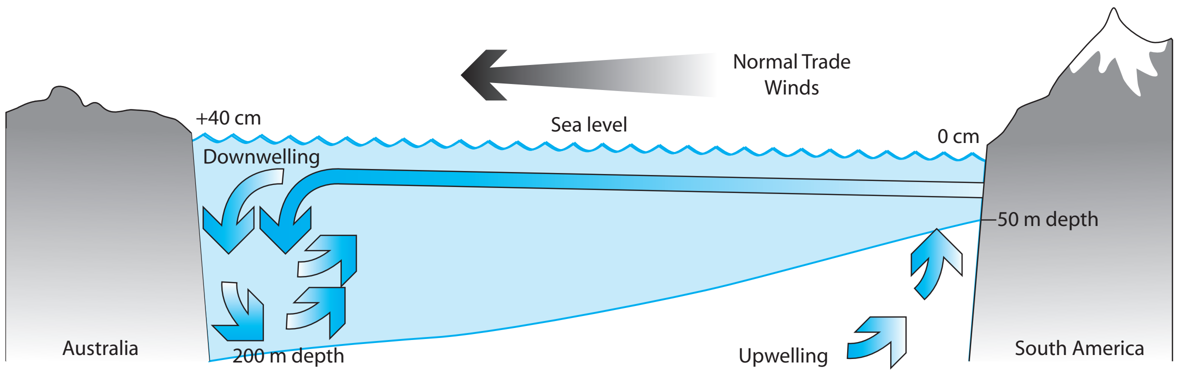


Figure 4.11 Warm water piling in the western equatorial Pacific during "normal" or La Nada conditions.

detailed toward the end of the 1800s. Identification of El Niño events took many forms. Some of these are listed in **Table 4.1**.

El Niño Characteristics

Each extreme of the ENSO cycle (El Niño and La Niña) occurs about every 3 to 7 years. An El Niño event in the ocean coincides with a reversal of the normal Walker circulation. Trade wind flow weakens or may even reverse along the equator, allowing the pool of warm water piled up in the western Pacific to flow back toward the east. Because La Nada and (especially) La Niña conditions pile warm water in the west, the ocean is simply regaining a somewhat uniform sea surface level when the trade wind flow weakens.

Table 4.1 Indirect Evidence for El Niño Events in Historical Sources

- Variations in travel times from sailing vessels
- Ship logs noting unusual weather and sea conditions
- Presence of "aguaje" or red tide, a bloom of toxic marine plankton
- Abnormally warm waters along the South American coast
- Severe and unusual weather events, such as heavy rains and flooding
- Property damage caused by floods
- Travel obstructions from washed-out roads or mudslides
- Agricultural destruction
- Increases in sea levels along the South American coast
- Mass mortality of marine sea life caused by a decrease in the upwelling of nutrients
- Death and/or departure of birds
- Reductions in productivity in coastal fisheries

As the warm water migrates eastward, the overlying atmospheric low-pressure center follows the warm water migration eastward as well. By the time the warm water pool reaches the eastern boundary of the tropical Pacific Ocean, reduced atmospheric pressures and increased precipitation are well established. At the same time, colder than normal water conditions become established in the western tropical Pacific. Higher pressures build over that area as a result, and precipitation is far below normal in the region around the Maritime Continent. El Niño, then, simply coincides with a reversal of the "normal" or "neutral" equatorial Pacific air/sea conditions set up by the Walker circulation (**Figure 4.12**).

Movement of the warm water pool from west to east during El Niño, usually taking about 4 months, appears in the form of an **equatorial Kelvin wave**—a pool of warm water moving eastward while surface waves propagate westward. The surface waves are initiated by overlying winds that continue to blow from east to west as a part of the normal trade wind flow. However, during El Niño events the trade winds are weaker than normal, which allows the warm water pool to move eastward as an equatorial Kelvin wave.

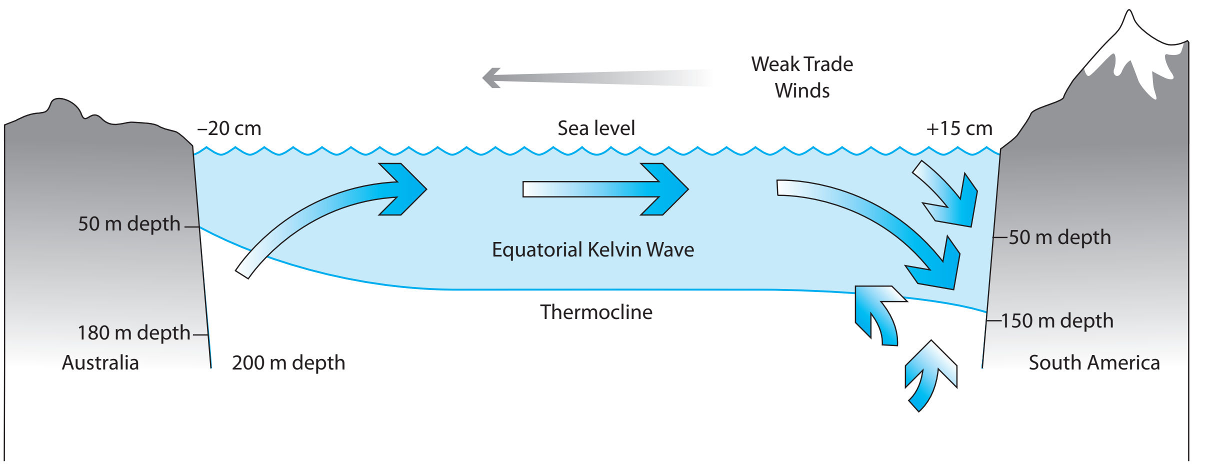


Figure 4.12 Ocean response to El Niño. Sea level values represent change from La Nada conditions.

When the warm water pool reaches the eastern boundary, it splits into three primary components. The main component is the **equatorial Rossby wave**, which sloshes back westward along the equator, typically reaching the starting point within 6 to 8 months, ending the El Niño event. Movement of the return flow in this wave is slower than the original Kelvin wave. These oceanic Rossby waves differ from Kelvin waves in that the bulk of water motion is in the same direction as the surface waves.

The remainder of the original eastward-moving equatorial Kelvin wave splits into **coastal Kelvin waves**—smaller warm water pools that migrate north and south along the North and South American coasts, displacing cold currents off the west coasts of both continents. These waves are responsible for many regional climate abnormalities.

The warm water pool in the eastern equatorial Pacific causes a downward movement of the **thermocline**—the boundary between warm surface waters and colder deep waters. Oceanic upwelling still occurs in the eastern ocean during El Niño events, but because of the deeper thermocline the cold water involved in upwelling is confined to the deeper layers. Because of these abnormally warm waters near the American coast, El Niño events are sometimes referred to as warm-ENSO events. In its entirety an El Niño event usually lasts between 10 and 14 months.

Because so much energy is transported across such a large distance regardless of the ENSO phase, disruptions to the La Nada situation have worldwide atmospheric consequences. The most direct effects occur in the tropics during the El Niño phase (**Figure 4.13**). The reversal of the usual atmospheric pressure and SST patterns during El Niño events causes atmospheric and oceanic circulation systems on the planetary scale to readjust. These anomalous circulation patterns cause seemingly chaotic weather conditions worldwide. Normally dry regions, such as western North and South America and western Australia, become much wetter than normal, while characteristically wet regions such as northeastern Brazil, eastern Australia, and the Maritime Continent

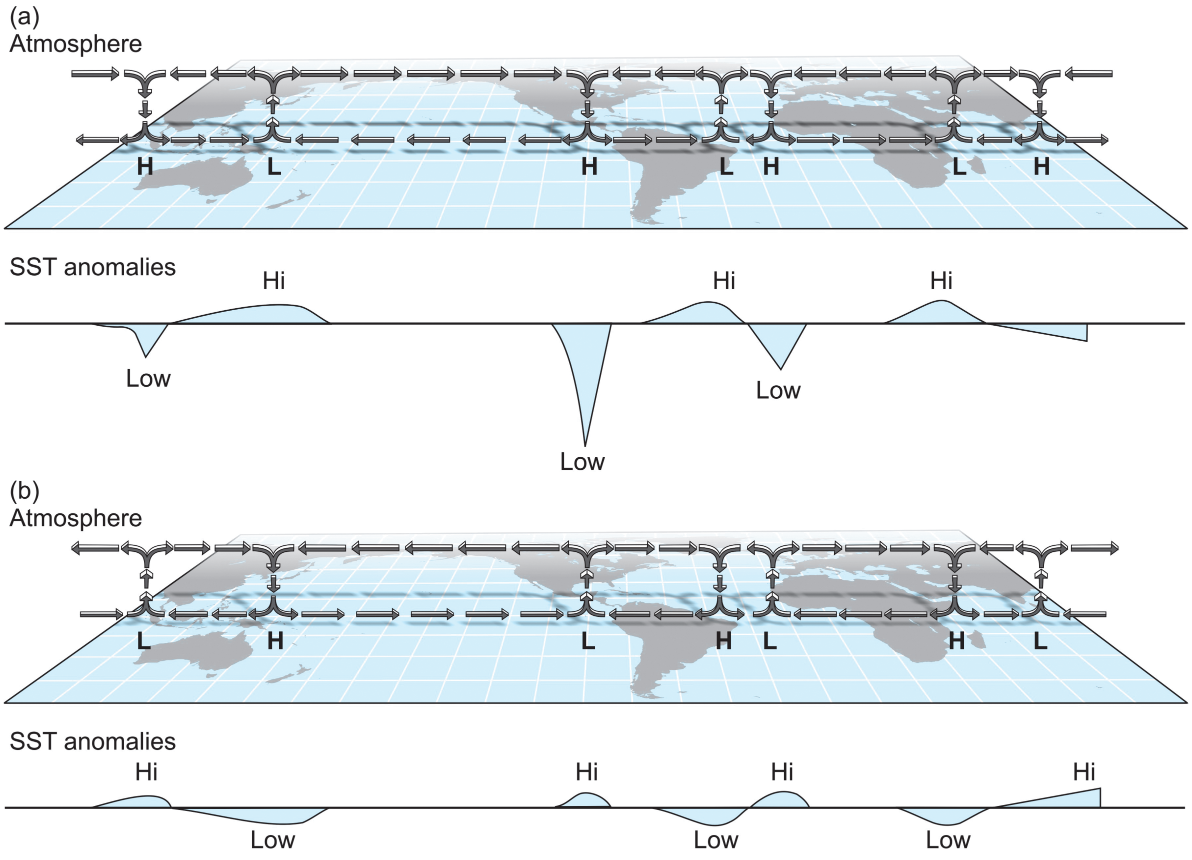


Figure 4.13 Equatorial air/ocean circulation anomalies during (a) La Nada and (b) El Niño periods.

become excessively dry. Such disruption of normal atmospheric and oceanic conditions leads to some devastating ecological and economic problems.

La Niña Characteristics

La Niña may be considered an extreme version of the "normal" or La Nada characteristics in the sense that the Walker circulation does not reverse. During this phase the trade wind flow along the equatorial Pacific Ocean becomes even stronger than normal, which increases warm water accumulation in the western equatorial Pacific and cold water upwelling in the east. This causes a deeper thermocline in the western tropical Pacific and a shallower than normal thermocline in the east (**Figure 4.14**). Sea levels respond accordingly, as the west records higher than normal sea levels and temperatures, while in the east lower than normal sea levels and temperatures occur. The enhanced cold water upwelling near the Americas has given La Niña another name in recent years—"cold-ENSO events."

Global Effects

As suggested above, the consequences of ENSO events do not stop with the equatorial Pacific Ocean. A closer inspection of Figure 4.13 reveals that the effects of warm-ENSO events carry through the downstream circulation patterns of the entire tropics. Because lower pressure builds over the western portion of South America during negative phases of the Southern Oscillation, the circulation regime of eastern South America is altered. Normally, eastern South America is dominated by low atmospheric pressure associated with the abundant heat energy and humidity from the Amazon rain forest. During the El Niño phase the western South American low disrupts the usual circulation over the eastern portion of the continent. As a result, higher than normal air pressure and subsiding airflow is initiated over tropical eastern South America, bringing drought to much of the rain forest region.

Just as the circulation is altered in South America during warm-ENSO events, the circulation regimes of other tropical locations are affected. The relatively high-pressure regime that normally prevails over southwestern Africa flips to lower atmospheric pressure and the region becomes anomalously wet. This in turn reverses the normally low pressures that occur near southeastern Africa, resulting in higher air pressures and drought near Madagascar. This induces a low-pressure region over the equatorial Indian Ocean, which is normally dominated by higher pressures, and the region becomes wetter than normal. Finally, the circulation is linked to the western side of the Walker circulation over eastern Indonesia and northeastern Australia, which experiences El Niño–induced above-normal air pressures and the drought conditions discussed previously. The effect is that the atmosphere seesaws to an opposite regime from normal.

Energy transfers during warm-ENSO events also alter temperate climates, as indicated in **Table 4.2**. Such interactions originate from increased heat energy and moisture transport from the equatorial Pacific into the midlatitudes. Much of this energy transport is accomplished by the

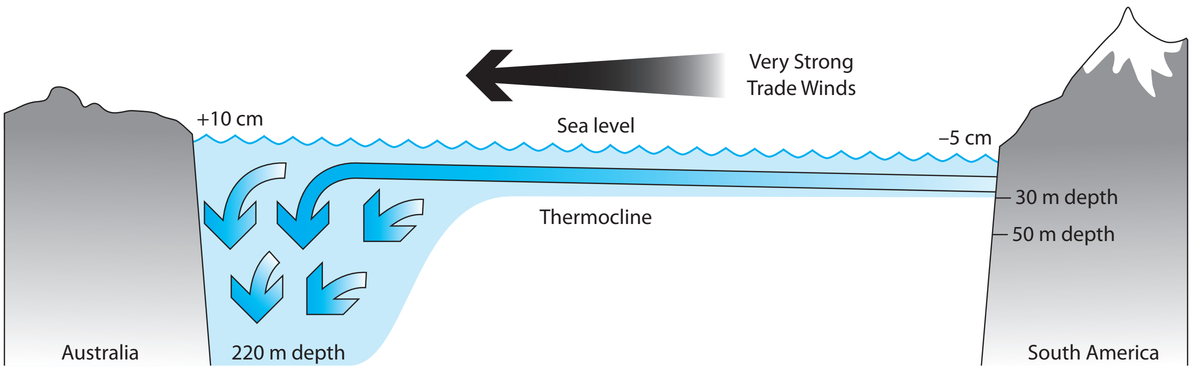


Figure 4.14 Ocean response to La Niña. Sea level values represent the change from La Nada conditions.

Table 4.2 Persistent Global Effects of El Niño

Condition	Areas Affected
Drier than normal	Maritime Continent; southeastern Africa and Madagascar; east central Africa; eastern South America (Brazil)
Wetter than normal	Central equatorial Pacific Ocean; eastern equatorial Pacific Ocean and western South America (Ecuador, Peru); southeastern South America (southern Brazil, Argentina); southeastern United States
Warmer than normal	Japan, eastern Asia (China/Manchuria); northwestern North America (southern Alaska through U.S. Pacific Northwest into central North America); eastern Canada (Labrador, Nova Scotia)

poleward-moving coastal Kelvin waves. These warm water pools displace cold currents along the west coasts of North and South America, overriding the colder, denser currents normally present in those locations. This position allows the abundant stored oceanic heat energy to be transferred easily into the atmosphere, particularly under the conditions of unusually low atmospheric pressure, initiating rising motions in the atmosphere. Such conditions are capable of providing energy for storms that then migrate across the normally dry western continental locations.

As a general rule, La Niña situations strengthen normal atmospheric circulation patterns across the tropics. A normally dry region becomes exceedingly dry; a normally wet region becomes exceedingly wet. Such conditions may have as many negative ecological and economic consequences as an El Niño event in some locations.

Extreme phases of the Southern Oscillation stress ecosystems in several ways. Large-scale animal migrations and die-outs occur in the affected regions. These factors in turn stress humans as food sources are affected and landscapes are degraded. For instance, western South America has seen widespread famine as a result of fish migrations away from the coast during warm-ENSO events. As fish move away from the coast in search of prey, birds that feed on the fish are affected. In addition, human populations are affected directly, because seafood serves as a prime source of nutrition in these coastal cultures affected by El Niño. At the same time, the Atacama region may experience heavy rains that cause widespread floods in a landscape barren of vegetation and without natural stream drainage capable of handling the sudden downbursts. Mudslides become common on hill slopes and occasionally destroy entire villages. Roads become blocked and bridges collapse. In short, widespread ruin may occur during particularly strong ENSO events.

Effects in the United States

Relationships between El Niño and the U.S. climate have been fairly well documented. Because the **jet streams**—fast currents of air in the upper troposphere—are most active during the cool season (November to March), the region sees most ENSO-related changes during that time. In particular, southern and central U.S. precipitation and southwestern U.S. temperatures appear strongly tied to warm-ENSO events. Increased energy and moisture are transported from the tropics to North America as the equatorial Kelvin wave and the smaller coastal Kelvin wave warm pools displace cold currents along North and South America. Thus, increased precipitation and storm activity are also typical effects of El Niño in much of the southern, central, and southwestern United States. The small, northward-migrating coastal Kelvin pool displaces the usual cold **California Current** off the U.S. Pacific coast, destabilizing the overlying atmosphere and causing an adjustment in the North American jet streams.

As expressed more completely in Chapter 7, the two major rivers of air in the high troposphere—the **polar front jet stream** (over midlatitude locations) and the **subtropical jet stream**—transport energy and moisture in a generally west-to-east direction. During warm-ENSO events, the **amplitude**—the north–south and south–north component of motion—of the polar front jet stream tends to increase across the United States. As we see later, jet amplitude dictates where storms form, their intensity, and direction of migration.

During the El Niño phase the polar front jet is altered from normal as a **trough**—an equatorward dip in the flow—overrides the eastern North Pacific Ocean. Midlatitude storm systems form just to the east of trough regions. The trough is accompanied by a **ridge**—a poleward shift in the jet flow—downstream (toward the east), as shown in **Figure 4.15**.

During warm-ENSO events the polar front jet may split into two distinct branches—one north, one south—over the eastern North Pacific Ocean. This situation greatly alters normal jet flow across North America and affects the climate of many associated regions. The northern branch of the polar front jet tends to remain farther to the north than the usual polar front jet and typically prevents the coldest Canadian air from penetrating southward into the United States. Thus warm-ENSO winters are usually warmer than normal in the northern United States and southern Canada. The southern branch of the polar front jet during warm-ENSO events flows across the northern Gulf of Mexico and tends to steer midlatitude storm systems into the Gulf Coast states, after allowing them to acquire moisture over the Gulf of Mexico. The subtropical jet still exists in its normal form, south of the southern branch of the polar front jet, even when the polar front jet bifurcates.

Because El Niño events can also trigger increases in jet amplitude across North America, a trough in the northern branch of the polar jet can cause colder air to infiltrate the eastern United States as far as the Gulf Coast. Northern states are not impacted with extreme events under these conditions because this cold air would have been present whether or not the dip in the jet stream existed. This trough also causes an increase in precipitation for the southern and central United States.

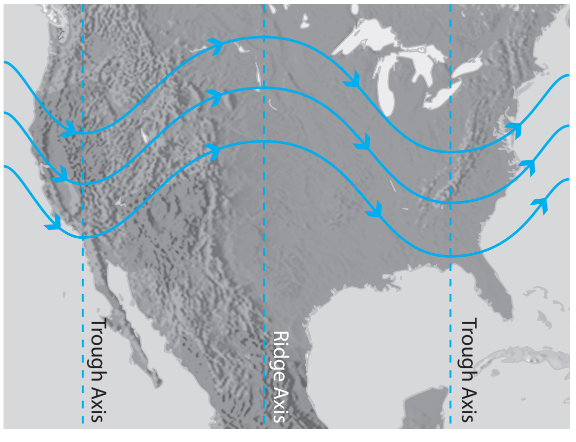


Figure 4.15 A typical ridge–trough configuration in the upper troposphere.

The northeastern United States shows a weaker relationship between El Niño and temperature and precipitation patterns. One explanation for the lack of relationship is that the polar front jet exits the continent over the Northeast regardless of jet flow amplitude. It should be noted, however, that any particular warm-ENSO event can cause drastic changes in northeastern U.S. weather. Each ENSO event changes the jet flow pattern somewhat differently, and strong El Niño events occasionally change the jet pattern substantially. The response to El Niño in the northeastern United States is usually slightly higher temperatures along with slightly drier conditions caused by a net reduction in snowfall.

Recent research indicates that cold-ENSO events have as much influence on precipitation in the southern United States as warm-ENSO events. Recent La Niña years have been accompanied by pronounced drought throughout the southern and south-central United States, even in summer, if the SOI remains positive through the summer. Additionally, cold-ENSO periods are associated with temperature increases throughout the Southwest as the polar front jet stream pushes northward over the western United States. Slight temperature increases also occur in the north-central area of the United States (Dakotas to Wisconsin). La Niña periods also see heightened Atlantic hurricane activity if the event is in force into late summer and autumn, as was evidenced by the very active 2004 and 2005 seasons. Incipient El Niño conditions in late summer and autumn 2006 and early summer 2009 were associated with a much quieter Atlantic hurricane season.

Relationship to Global Warming

Although much research has been done on ENSO events, much work is still needed. Many mechanisms thought to trigger ENSO events must be explained further. One such mechanism that has gained recent publicity is global warming. It is widely assumed that global warming is caused by human emission of pollutants known as *greenhouse gases*. The recent speculation that global warming triggers extreme ENSO events was generated by a higher incidence of intense ENSO events during recent years of high global temperatures. Since 1970 warm-ENSO events have occurred with a periodicity of about 2.8 years. This significantly exceeds the frequency of the long-term average of 4.7 years. In time, relationships between a warmer atmosphere and El Niño events may prove valid; however, the reverse may be equally true: that a higher incidence of intense warm-ENSO events may be forcing higher global temperatures. Such a realization may be substantiated given the slow response of oceans to atmospheric forcing in addition to the long-term heat storage capability of oceans.

Recent research supports a more plausible explanation for the increase in extreme ENSO events since 1970. The **Pacific Decadal Oscillation (PDO)**, an oceanic phenomenon described in more detail in Chapter 13, is directly tied to ENSO strength and frequency. The PDO is similar to the Southern Oscillation in that warm and cold phases occur over time. As the name implies, variability associated with the PDO occurs much more slowly than that associated with the Southern Oscillation. A PDO regime may last 20 to 30 years, during which one phase of the oscillation tends to dominate. By contrast, the Southern Oscillation fluctuates over periods of 3 to 7 years. During times when the Southern Oscillation and the PDO are in phase (i.e., both in a "warm phase" or in a "cold phase"), the impacts of the Southern Oscillation tend to be magnified. When the phases offset the Southern Oscillation effects tend to be dampened.

A PDO warm phase occurred from the early 1970s until the late 1990s. This situation supported frequent and strong El Niño events. Beginning in the winter of 1997 and 1998 the PDO shifted to a cold phase. This shift is believed to support and magnify the effects of La Niña over the next few decades.

Clearly, continued research on the causes and effects of extreme ENSO events becomes more important with the increasing demands made by humans upon the natural environment. Given the abnormalities in the temperature and precipitation regimes during El Niño and La Niña events, heightened understanding of these events is important for planning purposes in a wide array of environmental and societal applications.

Volcanic Activity and Climate

General Effects

As Earth's crustal plates move very slowly (at about the same rate at which your fingernails grow), volcanic activity occurs in certain locations. This volcanism contributes to both short- and long-term climatic fluctuations. In Chapter 2 we saw that the primordial atmospheric composition resulted from the *outgassing* of molten rock as the Earth cooled and the molten material hardened. This led to an atmosphere rich in N_2 and CO_2. Water vapor was also initially introduced to the atmosphere through outgassing processes. The atmosphere shed excessive water vapor in the form of precipitation, which eventually formed the oceans of today. The composition of the atmosphere is, therefore, linked to volcanic activity.

Evidence indicates that the early landscape of Earth was marked by rather frequent volcanism as the volatile Earth cooled from the surface inward. Over time, volcanic activity decreased. Still, volcanism is an important contributor to the Earth–ocean–atmosphere system. We typically do not hear about active volcanism unless a particular volcanic event directly threatens humans or the event is of such magnitude as to invite attention. Many cases of active volcanism are associated with "cracks" in the oceanic crust that are widening—midoceanic ridges—deep beneath the ocean surface, whereas others are associated with rather remote locations such as the Aleutian Island chain of Alaska. Others, such as Kilauea, Hawaii, are tourist attractions.

Volcanic activity today contributes 1.2 to 2.1×10^{11} kg (130 to 230 million tons) of CO_2 to the atmosphere each year. Volcanoes also add between 3.3 and 6.6×10^{12} kg (3.6 and 7.3 billion tons) of **sulfur dioxide (SO_2)** to the atmosphere annually. Significant amounts of water vapor are also ejected into the atmosphere. Of the gases emitted by volcanoes, the one that produces the most significant climatic signal is SO_2. The amount of CO_2 emitted by volcanic activity is low compared with the amount already present in the atmosphere. The additional amount is quickly absorbed into biomass and/or the oceans. Water, of course, exits the atmosphere very quickly as precipitation. But SO_2 presents a different problem.

SO_2 and atmospheric *aerosols* of volcanic origin can trigger either net surface cooling or warming, depending on individual eruption characteristics. SO_2 typically combines in the atmosphere with water, dust, and sunlight to produce **vog**, or volcanic smog. Vog can have both local- and planetary-scale impacts. At the local scale vog may form near the surface, where it may hinder loss of longwave radiation back to space, leading to warming. On the island of Hawaii, vog is persistent because of the continuous effusive (gentle) eruption of Kilauea since 1986. The volcano contributes about 1.8 million kg (2000 tons) of SO_2 to the local atmosphere daily.

Vog becomes a planetary-scale problem when a major explosive eruption ejects sulfur compounds into the *stratosphere*. Once there, the sulfur compounds can linger up to 4 years, in part because the stratosphere is higher than most precipitation clouds, which would rinse aerosols and SO_2 from the atmosphere. SO_2 combines with the limited amounts of water found in the stratosphere, dust particles, and sunlight to form vog. In that situation the vog is capable of producing a haze that has a rather high **albedo**—the percentage of incoming energy from the Sun that is reflected off an object. The result is that the haze directly reduces surface air temperatures.

Long-term climatic changes are not initiated by single volcanic events. Instead, volcanoes lead to significant long-term climatic changes only during prolonged periods of above-normal activity. Persistent volcanism is thought to help maintain Earth's rather steady climate state. As we saw in Chapter 2, Earth temperatures have varied by less than 15 C° (27 F°) over its 4.6 billion year history. Volcanic activity is partly responsible for this relatively delicate energy balance that maintains this range of temperatures.

Individual volcanoes are, however, capable of altering hemispheric and global climates over relatively short time periods. When volcanoes erupt, gases and solid aerosols (**particulates**) are ejected into the atmosphere. Most of the aerosols fall back to the surface over short periods of time. Particles that are sand sized or larger fall back to the surface within minutes of an eruption. Smaller aerosols are capable of being suspended in the atmosphere for much longer periods. This is especially true of dust-sized and smaller particles, which may reach the stratosphere if the volcano is high and the eruption is especially explosive. Large eruptions have an average recurrence interval of about 30 years over recorded history (**Table 4.3**).

Aerosol Indices

Two indices have been designed to estimate the amount of aerosols, especially those of volcanic origin, in the atmosphere. The **Dust Veil Index** is based on the amount of material dispersed into the atmosphere. It uses surface air temperatures and the amount of *insolation* reaching the surface, among other variables, to estimate the total amount of particulates in the atmosphere. This index is most useful in the midlatitudes because it has been calibrated in predominantly middle-latitude locations. Its major weakness is that by using temperature to estimate the Dust Veil Index it is impossible to assess the impact of volcanic activity on temperature accurately.

The **Volcanic Explosivity Index** is based only on volcanic criteria. The data used are derived from the magnitude, intensity, dispersion, and destructiveness of individual volcanic events. A scale between 1 and 8 is used for each event, with 8 being the strongest volcanic event. An event with a Volcanic Explosivity Index exceeding 4 is assumed

Table 4.3 Major Volcanic Eruptions of the Past 200 Years

Volcano	Year	Average Resulting Global Temperature Decline (C°)
Tambora	1815	0.4–0.7
Krakatau, Indonesia	1883	0.3
Santa Maria, Guatemala	1902	0.4
Katmai, Alaska	1912	0.2
Agung, Indonesia	1963	0.3
El Chichón, Mexico	1982	0.5
Mount Pinatubo, Philippines	1991	0.5

to produce emissions into the stratosphere, but atmospheric composition is not taken into account in the derivation of the Volcanic Explosivity Index.

Major Volcanic Eruptions

With the possible exception of Eyjafjallajokull in Iceland, which began erupting in Spring 2010, the most noteworthy example of a recent volcanic eruption that led to surface cooling was **Mount Pinatubo**, which erupted in the Philippines on June 15, 1991. Pinatubo's eruption blasted over 1.8×10^{10} kg (20 million tons) of SO_2 and ash into the atmosphere. The vertical column of ejected material was measured at 19 km (12 mi) high during the eruption. The resulting stratospheric SO_2 plume spread rather evenly across the globe over time, leading to an estimated global surface temperature decline of 0.5 C° (0.9 F°) for 2 years after the eruption.

The 1815 eruption of **Tambora** in Sumbawa, Indonesia is regarded as the largest in modern history, as it ejected an estimated 50 km^3 (12 mi^3) of magma and an astonishing 1.8×10^{11} kg (200 million tons) of SO_2 into the atmosphere. The eruption led to the widely regarded "year without a summer" in 1816. Snow fell in July in Boston, Massachusetts. Global surface air temperatures are believed to have decreased by 0.4 to 0.7 C° (0.7 to 1.3 F°) during the year after the eruption.

The eruption of **Krakatau** in 1883, also in Indonesia, is thought to have exceeded Tambora in explosiveness. The eruption is believed to have killed up to 40,000 people, and it ejected ash and dust as high as 12 km (7 mi) above the surface as most of Rakata Island disappeared. In total, 20 km^3 (5 mi^3) of material were ejected into the atmosphere, making Krakatau about 20 times as destructive as the Mount Saint Helens eruption. Although global temperatures apparently were not affected as significantly as by Tambora, the eruption caused spectacular sunsets for over 70 percent of the globe over a time period of 3 years.

Another notable eruption was the 1783 **Laki Fissure** eruption in Iceland, which lasted 8 months and was responsible for devastating much of the human and animal population of Iceland. It is estimated that 14 km^3 (3.4 mi^3) of basalt was ejected. In addition, over 9.1×10^{10} kg (100 million tons) of SO_2 were emitted, leading to an estimated 1 C° (1.8 F°) temperature drop for the northern hemisphere.

The most catastrophic eruption known occurred on **Mount Toba** in Sumatra approximately 71,000 years ago. This eruption was so cataclysmic that it is thought to have accelerated the onset of the last **glacial advance**. Global climates changed so much that massive extinctions and population declines occurred in many plant, animal, and human populations across the globe. In fact, the event is believed to have caused an evolutionary **bottleneck** in humans—a significant drop in population that triggers rapid genetic divergence in surviving individuals. This process occurs as significant genetic differences proliferate at a rapid rate through small populations, as opposed to being washed out of much larger populations.

Deforestation and Desertification

Humans play a role in climatic variation through a number of ways. Most **anthropogenic** (human-induced) climatic effects relate to changes in atmospheric composition through the combustion of *fossil fuels* and the manufacture of certain gases and solids. Human land-use activities also can contribute to variation and changes in the climate system. Many of these involve the processes of deforestation and desertification.

Deforestation refers to the systematic and widespread clearing of forested regions. Although most associate deforestation with tropical locations, the most widespread deforestation actually occurred in Europe and North America a few hundred years ago. Entire forests were cleared for fuel and/or building materials during the early part of the Industrial Revolution, beginning in the late 1700s. Today, the most widespread deforestation occurs in tropical rain forests, where large tracts of land are deforested to support either individual subsistence farms or grazing areas.

Because soils in the rain forest regions are leached of their nutrients by the abundant rainfall, they are not well suited to agriculture. As a result, farmers must continually move from location to location because agriculture is usually successful for only a few years before the soil's nutrients become depleted. This type of migratory farming in which forests are continually cleared, often by burning, is called **slash and burn agriculture**. This method became widespread once it was discovered that burning vegetation adds nutrients to the upper soil layers. These nutrients are capable of supporting crops for only a few extra years, after which the soils become too leached to be productive.

If very small plots of land are deforested in this manner, no long-term damage is done, because the surrounding forest is quick to recapture the "slashed and burned" plot. The problem today involves very large deforested plots of land, especially when the activity leaves only small patches of rain forest surrounded by much larger deforested areas. These small plots are not sufficient to maintain their existence, and they become more susceptible to disease and other problems with such a high percentage of the trees near the fringe of the forest. The result is that the isolated plots die off. Human activities then move farther into the forest, taking more and more trees out of existence. In many areas the rain forests have been totally decimated in this manner. Deforestation of old growth forests within the past few centuries in many locations in Central America has left only a tiny percentage of rain forest undisturbed, and total annihilation looms in the near future. Currently, the worst deforestation of tropical rain forests is occurring in South America, especially northeastern Brazil, and in Indonesia. At present rates of clear cutting, it is estimated that all rain forests will be eliminated within the next 100 to 200 years, if not sooner.

This deforestation has dire ecological consequences. Tropical rain forests represent the most diverse ecosystems on Earth's land surface. Elimination of these regions will directly lead to massive extinctions of plants and animals, many of which may be useful for medicinal and economic purposes.

Large-scale deforestation causes numerous impacts on climate. Most of the precipitation water in rain forests is generated locally through the process of **transpiration**—the constant recycling of rainwater through uptake through tree roots and out through the leaves. Tropical rain forests have been referred to as the **rain machine** for that reason. Once the trees are removed, precipitation is more likely to run downslope and leave the area. Temperatures after deforestation increase abruptly, because of the loss of shade as well as increases in **sensible energy** with concurrent decreases in *latent energy* input.

An additional climatic problem is that deforestation involves the removal of one of the planet's primary carbon *sinks*. In 1 year a single acre of trees can uptake the amount of CO_2 released by driving 26,000 miles. The discontinuation of *photosynthesis* when the trees die decreases the rate at which CO_2 can be removed from the atmosphere. This has large-scale consequences because increased atmospheric CO_2 is a primary cause of global warming. Furthermore, the burning of the trees returns CO_2 that was sequestered in the biomass to the atmosphere, directly increasing atmospheric CO_2 concentrations. Finally, photosynthesis in the tropical rain forests produces a large share of the planet's atmospheric oxygen. Obviously, elimination of the planet's "lungs" would be disastrous.

Another human land-use effect that can modify large-scale climate changes is **desertification**—the expansion of deserts into semiarid regions, largely through the impact of human activities such as ranching and overuse of water. The domestication of grazing animals has become very important in many semiarid regions of the world, where grasslands are dominant. When these activities become too concentrated, they can quickly strip a region of vegetation, deplete and contaminate water, and compact the soil, leading to a rapid drying of the landscape.

Semiarid regions typically display wide variability in the precipitation regime. Wet periods may persist for many years or decades, only to be offset by years or decades of exceedingly dry conditions. Humans typically move into the regions during wet periods and establish grazing practices. But during the dry periods that inevitably follow, they are reluctant to leave. Their continued activities quickly compound the problem, leading to further expansion of the surrounding desert.

Perhaps the most prevalent example of desertification is the **Sahel**—a region of Africa that borders the southern rim of the Sahara Desert and has undergone widespread degradation over the recent past (**Figure 4.16**). Much of the problem began in the early twentieth century, when wet conditions brought people into the region. This settlement, combined with natural population growth and the demise of transient herders in favor of more permanent herding establishments, created a situation with far too many grazing animals in the re-

Figure 4.16 Sahel region of Africa.

gion. During the 1970s widespread drought in the region caused the animals to strip far too much vegetation in a short period of time before succumbing to the drought themselves. The concurrent water and food shortages led to tragic famine and death throughout the region. The consequent impact on the landscape was rapid desertification and southern expansion of the Sahara Desert. The region has yet to recover and remains one of the primary regions of food and water shortages on the planet.

Once the desert expands into a semiarid region, it is very difficult for vegetation to reclaim the region because the local water and energy balances are disrupted. The removal of vegetation changes the color and texture of the landscape. The generally dark and rough vegetated surface is replaced by lighter and smoother surfaces, which in turn support higher albedoes, reflecting away a higher percentage of insolation. But this effect is more than compensated by a decrease in water availability after the vegetation is removed. Like a deforested landscape, an unvegetated landscape allows water to run off the surface more quickly, causing less evaporative cooling and a higher percentage of energy devoted to sensible heating rather than latent heating. The results are increased temperatures, reduced water availability, and larger sections of land being converted to desert.

Several other land cover changes affect climates, particularly at the local scale. For example, irrigation and construction of dams and reservoirs tend to alter the local water and energy budget by producing sudden, periodic, and drastic increases in water availability at the surface. Drainage of swamps tends to have the opposite impact. In all these cases, although local evaporation rates and humidity are likely to be affected, the scale is usually too small to see significant changes in local precipitation totals. And, of course, the most dramatic land cover change on the planet—urbanization—has a distinct and irrefutable global impact. That impact is discussed in detail in Chapter 12.

Cryospheric Changes

Ice on the Earth's Surface

The *cryosphere*—the region consisting of all seasonal and "permanent" ice on the planet—is both a direct consequence of and an influence on the climate system. It may exist as a part of semipermanent alpine glaciers, continental ice sheets, seasonal sea ice, and/or seasonal snowpack. During cold periods of the year, all forms of ice accumulate from precipitation and/or **deposition**—the direct conversion of atmospheric water vapor to ice, bypassing the liquid water phase.

In the case of glaciers, the bulk of the ice body remains in below-freezing temperatures throughout the year. However, a portion does exist in areas where temperatures exceed the freezing point for at least part of the year. Parts of glaciers are, therefore, continually melting. Glacial advances occur during cooler and/or wetter periods when the rate of snow/ice **accumulation** in the colder part of the glacier exceeds the rate of **ablation** (which includes melting and **sublimation**—the conversion of ice directly to water vapor, bypassing the liquid water phase) in the warmer part of the glacier. Glacial retreat occurs during times when the rate of ablation exceeds accumulation. In the case of a retreating glacier the ice merely melts or sublimates back from its most equatorward or downhill extent—the glacier does not physically move backward. A net mass balance point exists at the **equilibrium**

line—a point within the body of glacier where the rate of accumulation equals the rate of ablation. As this line moves equatorward and/or downhill, the glacier is "healthy," indicating growth, and when it retreats poleward and/or uphill, ablation exceeds accumulation for the system.

Earth has undergone several periods when most glaciers and ice sheets simultaneously advanced over many thousands of years. These glacial advances—intervals of 50,000 to 150,000 years or so—are separated by **interglacial phases**, warmer periods of approximately 8,000 to 12,000 years when net glacial retreat occurs in most glaciers. Summer temperatures generally determine whether glacial advance or retreat is occurring, because even abnormally high winter temperatures are below freezing in most glacial environments. Cool, short summers with snowy transition seasons generally provide the optimal conditions for glacial advance. Long, warm, dry summers cause the high rates of ablation coincident with interglacial phases.

Regardless of whether a glacial or interglacial phase is occurring, any time in geological history when semipermanent ice exists somewhere on Earth's surface is termed an **ice age**. We are in an ice age today, because permanent ice exists on the planet—in Antarctica, Greenland, the north polar ocean, and on the tops of the world's highest mountains at any latitude. The present ice age may have begun as many as 40 to 50 million years ago, but evidence shows that it became more intense some 1.6 million years ago. The last major glacial advance in the present ice age peaked between 12,000 and 18,000 years ago. This advance is known as the **Wisconsin Glacial Phase**, which occurred during the **Pleistocene Epoch**, a generally cold period that occurred from about 1.8 million years ago until about 10,000 years ago. Because planetary temperatures have generally increased for the last 10,000 years or so, most of the ice has been retreating poleward and/or uphill, and we are currently in the **Holocene Interglacial Phase**, an interglacial phase within the present ice age that corresponds to **Holocene Epoch**, the present epoch in geological time.

Feedbacks in the Cryosphere

A very important role in the climate system is played by the **positive feedback system**—an input that creates change to a system in such a way that triggers additional, similar changes in the system. A small snowball rolling down a hill—picking up more snow on its trek, thereby gaining *momentum* and rolling faster and faster as it gains more mass—is an effective example of a positive feedback. Another example is the suggestion planted by seeing a person in your climatology class yawn; within seconds several classmates yawn, despite the very interesting course material.

By contrast, a **negative feedback system** involves an input to the system that decreases the likelihood of further changes of the same type to the system. An example of a negative feedback system might be your study habits. If you study hard and do well on the first exam, you may then be tempted to study less and then do poorly on the second exam. But then you are likely to study harder and do better on the third exam. The net effect is that your overall grade is average. Negative feedbacks lead to stabilization of a system.

An important positive feedback in the cryosphere is caused by surface albedo changes when the ice- and snow-covered area expands or contracts. The surface of the terrestrial Earth is, for the most part, dark. Expansion of bright white continental ice sheets across continents increases hemispheric and global albedo. In such instances a larger percentage of insolation is reflected from the surface to space. As a result, a decrease in the amount of absorbed insolation occurs at the surface, triggering a reduction in temperature, which in turn supports further growth of the ice sheets.

A similar positive feedback system occurs during periods of slight warming, such as at the beginning of an interglacial phase. Slightly elevated temperatures trigger increased icepack ablation. The albedo then decreases slightly, as the darker surface beneath the ice is exposed. This in turn initiates increased absorption of insolation. The net energy gains then cause increased atmospheric temperatures, which cause further increases in ablation and further albedo decreases.

It is apparent from the discussion above that the cryosphere is intricately linked to the atmosphere over long time scales. But the cryosphere can also influence the atmosphere (and vice versa) on short time scales. For example, a region may be hit with a heavy snowfall event in autumn. In such a case the snow may effectively change the regional albedo. After the event, the surface albedo changes may cause the region to grow colder, which in turn may cause the polar jet stream to shift farther equatorward than normal, because it exists near the boundary between cold and warm air. Because the jet steers midlatitude storm systems, displacement of the jet may initiate even more snowstorms over the affected regions. In this way a positive feedback system is set up, causing even more snowpack and higher albedo rates even farther equatorward, leading to further cooling.

Given such direct relationships between the cryosphere and the atmosphere, it is important that researchers examine and understand processes involving changes in the cryosphere. Such changes may lead to feedback systems that could influence the planetary-scale atmosphere. These atmospheric changes may then cause further feedbacks in the cryosphere and the other "spheres" in the climate system.

Researchers studying regional ice packs have found that the spring melt in western Canada has occurred earlier in more recent years than before, changing by as much as a half-day per year since 1955. These findings support computer modeling studies that suggest widespread reduction in snow cover could occur over the next 50 to 100 years as concentrations of greenhouse gases such as CO_2 increase in the atmosphere. But this trend is not solely dependent on greenhouse warming, as extreme ENSO events, shifts in major circulation patterns, and other factors also play important roles.

Some researchers now estimate that the Greenland ice sheet, the largest in the northern hemisphere, could lose as much as one-half of its mass over the next thousand years, leading to an increase in global sea level of about 2.7 m (9 ft). Adjacent summer sea ice has decreased markedly over the past few decades, and some expect that within the next century the Arctic Ocean could be largely ice free. Alpine (mountain) glaciers are in active retreat worldwide, with only a few regional exceptions.

The largest single planetary ice sheet, in Antarctica, also shows signs of net ablation. In particular, temperatures over the West Antarctic Ice Sheet have increased by approximately 4 C° (7 F°) over the past half century. A decrease in adjacent sea ice extent has also resulted, and two large collapses of major ice shelves have occurred over the past decade. The East Antarctic Ice Sheet appears to have remained stable during the same time period. If all permanent continental ice were to melt, sea levels would rise by approximately 67 m (220 ft).

A common misconception is that the melting of sea ice would not affect sea level because the ice displaces the same volume of seawater as its water equivalent. However, because fresh water is less dense than saltwater, freshwater ice floats higher over the salty seawater and does not displace quite as much seawater as it would if the two had the same density. So when freshwater floating ice melts, it also increases sea level by a small amount because of an increased amount of meltwater compared with the amount of seawater originally displaced.

Both this extra water and (especially) melted continental ice would greatly affect populations, because many of the world's major cities would be inundated by the sea level increases. Fortunately, even in the worst-case scenarios, the entire cryosphere is not expected to melt completely in a short time. But the (unknown) feedback mechanisms involved would determine whether any initial warming and melting would be counteracted (a negative feedback) or accelerated (a positive feedback). Positive feedbacks would further warm the climate system, which itself could have major global consequences.

Summary

This chapter explored the effects of several phenomena in the nonatmospheric parts of the climate system on climate. Surface ocean currents derived from atmospheric circulation in turn affect the adjacent climate of affected locations. The subtropical anticyclones centered in each ocean basin play an especially important role in the strength, direction, and variability of these currents. The anticyclones and corresponding semipermanent low-pressure cells—*cyclones*—located poleward of the anticyclones support cold ocean currents in the eastern ocean basins and warm ocean currents in the western basins in each hemisphere. The Ekman spiral, combined with latitudinal differences in Coriolis deflection, causes an accumulation of water to the west of the central ocean basin, which leads to western-boundary intensification—strong, deep, warm ocean currents in the western ocean basins—and shallow, slower cold currents in the eastern basins. Deep ocean currents also influence the broad-scale climate. Deep-water motions were described for each ocean basin, with particular attention paid to the

Stommel model deep-water circulation, which stores and releases large quantities of energy into the climate system over long time periods.

El Niño–Southern Oscillation events represent the greatest single source of variability in the climate, excluding Earth-Sun-related seasonality. El Niño events occur when a warm water pool that normally occurs in the western equatorial Pacific Ocean migrates eastward during times of reduced trade wind flow. The water pool brings changes to typical atmospheric stability patterns. Specifically, clouds and precipitation occur in the normally clear, dry eastern Pacific region. Because of the immense amount of energy carried by the pool, global climatic regimes are affected. The opposite phenomenon—La Niña—is associated with the "normal" (La Nada) directions of oceanic and atmospheric flow but with increased intensities of that flow and effects.

Processes in the lithosphere and biosphere can also impact the climate system. Times of heightened volcanic activity may produce both short-term and even long-term climate variation. Human activities such as deforestation and desertification alter local to regional energy and water balances, which can ultimately affect hemispheric and global climate regimes. Finally, the cryosphere was discussed as an element of the climate system. Positive and negative feedback systems, especially in the cryosphere, are likely to dictate the severity of impacts of climatic change caused by human and natural forces.

Key Terms

Ablation
Accumulation
Advection
Aerosol
Albedo
Amplitude
Antarctic Bottom Water
Antarctic Deep Water
Antarctic Intermediate Water
Anthropogenic
Bottleneck
California Current
Canary Current
Chimu Floods
Coastal Kelvin wave
Common Water
Continentality
Convection
Coriolis effect
Cryosphere
Cyclone
Deforestation
Deposition
Desertification
Downwelling
Dust Veil Index
Ekman spiral
El Niño
El Niño-Southern Oscillation (ENSO) event
Equatorial Kelvin wave
Equatorial Rossby wave
Equilibrium line
Evaporation
Fossil fuel
Geostrophic flow
Glacial advance
Global warming
Greenhouse gas
Gulf Stream
Gyre
Holocene Epoch
Holocene Interglacial Phase
Humboldt (Peru) Current
Hydrosphere
Ice age
Insolation
Interglacial phase
Jet stream
Krakatau
La Nada
La Niña
Laki Fissure
Latent energy
Latitude
Maritime Continent
Maritime effect
Momentum
Mount Toba
Mount Pinatubo
Negative feedback system
North Atlantic Deep Water
North Atlantic Drift
North Equatorial Current
North Pacific Intermediate Water (NPIW)
Northeast trade winds
Outgassing
Pacific Decadal Oscillation
Pacific Subarctic Water
Particulates
Peru Current
Photosynthesis
Pleistocene Epoch
Polar front jet stream
Positive feedback system
Rain machine
Ridge
Sahel
Sensible energy
Sink
Slash and burn agriculture
Source area
Southeast trade winds
Southern Oscillation
Southern Oscillation Index (SOI)
Stable atmosphere
Stable stratification
Stommel model
Stratosphere
Sublimation
Subtropical anticyclone
Subtropical jet stream
Sulfur dioxide (SO_2)
Tambora
Thermocline

Thermohaline circulation
Thermohaline current
Trade winds
Transpiration
Trough
Unstable atmosphere
Upwelling
Vog
Volcanic Explosivity Index
Walker circulation
Western-boundary intensification
Wisconsin Glacial Phase

Terms in italics have appeared in at least one previous chapter.

Review Questions

1. Discuss the role of atmospheric circulation in creating and maintaining surface currents in the oceans.
2. Discuss the role of surface ocean currents on climate.
3. What is geostrophic balance in the oceans and why is it important?
4. Describe the importance of western-boundary intensification.
5. What are thermohaline currents and how and why are they maintained?
6. How are thermohaline currents tied to the atmosphere and how can these currents affect climatic variations in the future?
7. Discuss the importance of the Stommel model of deep-water motion.
8. What is the Walker circulation?
9. Describe La Nada or "neutral" conditions along the equatorial Pacific Ocean.
10. What is El Niño and how is it initiated?
11. Discuss changes in the sea surface circulation and the thermocline of the Pacific Ocean during an El Niño event.
12. Describe the changes in the overlying atmosphere during an El Niño event.
13. Discuss the global climatic significance of an El Niño event.
14. What is a La Niña event and why is it significant?
15. Discuss the role of volcanism on the primordial atmosphere.
16. Discuss the role of volcanism relative to short-term and long-term climatic change and variability.
17. Compare and contrast deforestation and desertification and their impacts on the climate system.
18. How do atmospheric changes drive processes in the cryosphere?
19. How can changes in the cryosphere lead to changes in the climate system?

Questions for Thought

1. Before 3 million years ago, there was no connection between North America and South America via the Isthmus of Panama. How do you believe the formation of the isthmus may have altered the global oceanic circulation?
2. Think of an example of a possible negative feedback mechanism that might result in a minimization of the global warming problem in the cryosphere.

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