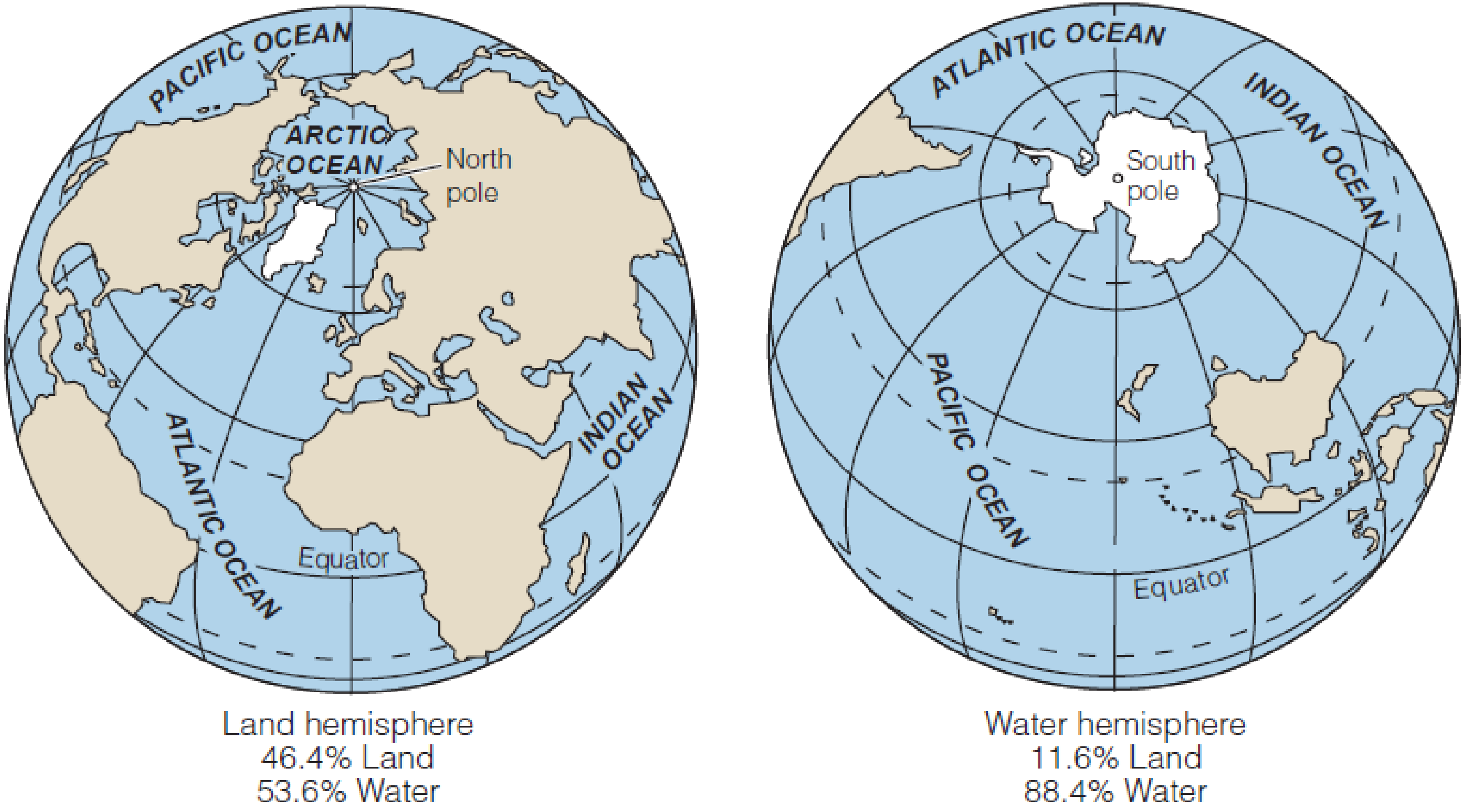
Earth System Processes (ES1201)

The Circulation of the Oceans
(Spring 2025 by Gaurav Shukla)

Book: ***The Earth System*** **by L.R. Kump, J.F. Kasting and R.G. Crane**

FIGURE 10.2 Ocean and land
The unequal distribution of land and ocean can be seen if we view Earth from above Britain and above New Zealand. In the first view, land covers nearly half the hemisphere, whereas in the other nearly 90 percent of the hemisphere is water.



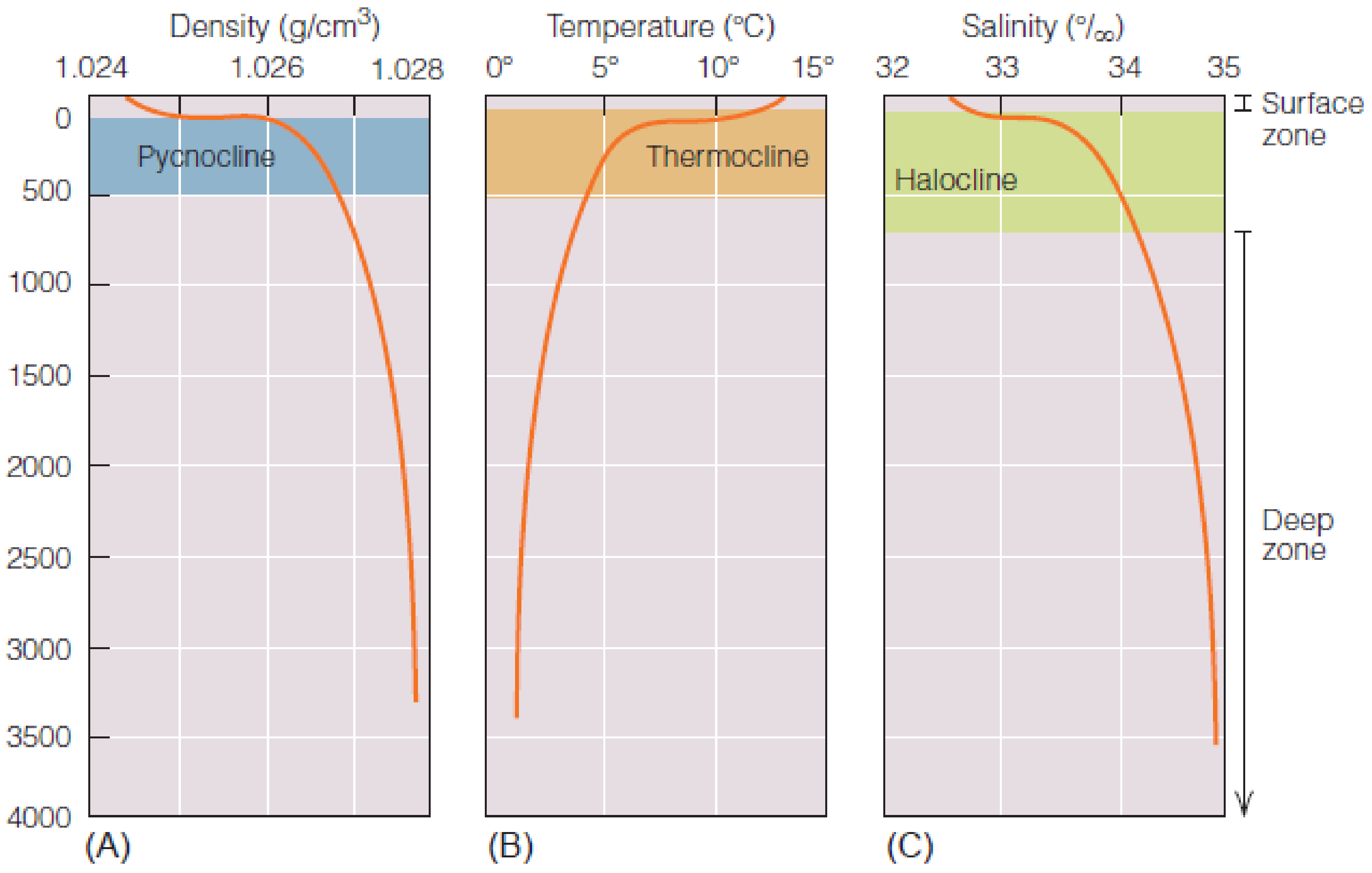
Ocean Circulation

- The oceans are vertically stratified with denser water at the bottoms of the major ocean basins and less dense water near the surface.

- The density is controlled by temperature and the salt content (*salinity*) of the water.

- The deep ocean water is separated from the surface layer of the ocean by a transition zone with sharply defined density, temperature, and salinity gradients.

FIGURE 10.6 Depth zones in the ocean
Below the surface zone there is a zone in which the ocean-water properties experience a significant change with increasing depth. This zone is variously known as the *pycnocline* (A), a zone in which density increases with depth; the *thermocline* (B), a zone in which temperature decreases with depth; and the *halocline* (C), a zone in which salinity increases with depth. Still lower lays the *deep zone*, where water is dense as a result of low temperature and high salinity.



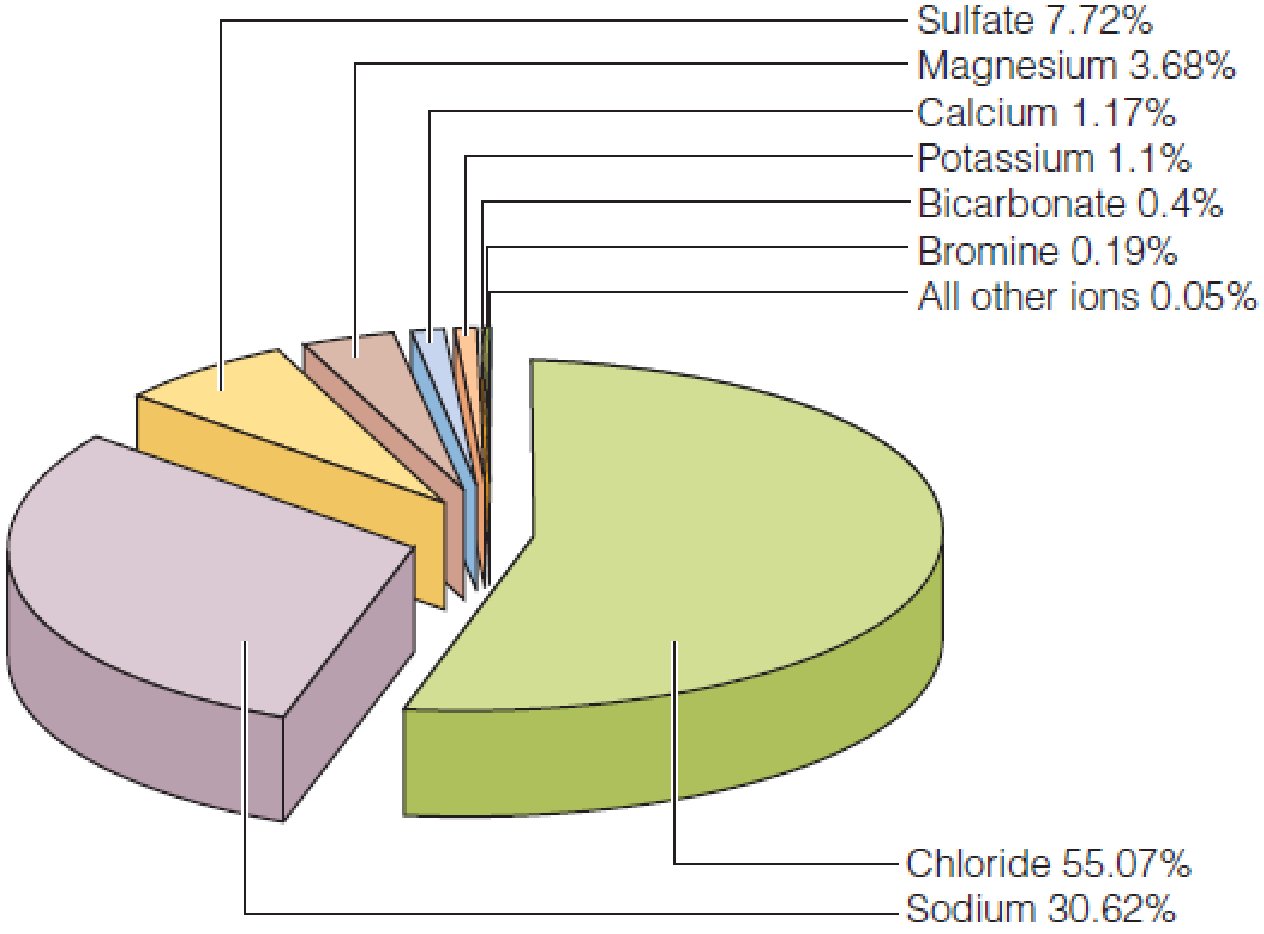


FIGURE 10.3 Principal ions in seawater
More than 99.9 percent of the salinity of seawater is due to eight ions, the two most important of which (Na^+ and Cl^-) are the constituents of common salt.

Ocean Circulation

Surface Circulation:

- The wind patterns of atmospheric circulations are responsible for the ocean surface circulation and the formation of major ocean currents.

- The movement of the wind over the ocean causes the friction at the surface. As a result, the wind drags the ocean surface with it as it blows and sets a pattern of surface ocean wind-drift currents.

- These surface currents are also affected by Coriolis force.

Controls on Ocean Salinity

- Evaporation, which removes fresh water and leaves the remaining water saltier.

- Precipitation of rain and snow, which adds fresh water, thereby diluting the seawater and making it less salty.

- Inflow of fresh and salty water.

- Freezing of sea ice because when seawater freezes, salts are excluded from the ice (crystals) leaving the unfrozen seawater saltier.

Structure of the Oceans

- Unlike the surface-ocean circulation, deep-ocean circulation is driven by differences in water density, which are caused by temperature and salinity variation.

- Salinity is defined as the salt content of a water mass and usually expressed in parts per thousand or part per mil (‰).

- The average salinity of the world's oceans is approximately 35‰. Local variations are caused by evaporation, precipitation, sea ice formation, and river runoff.

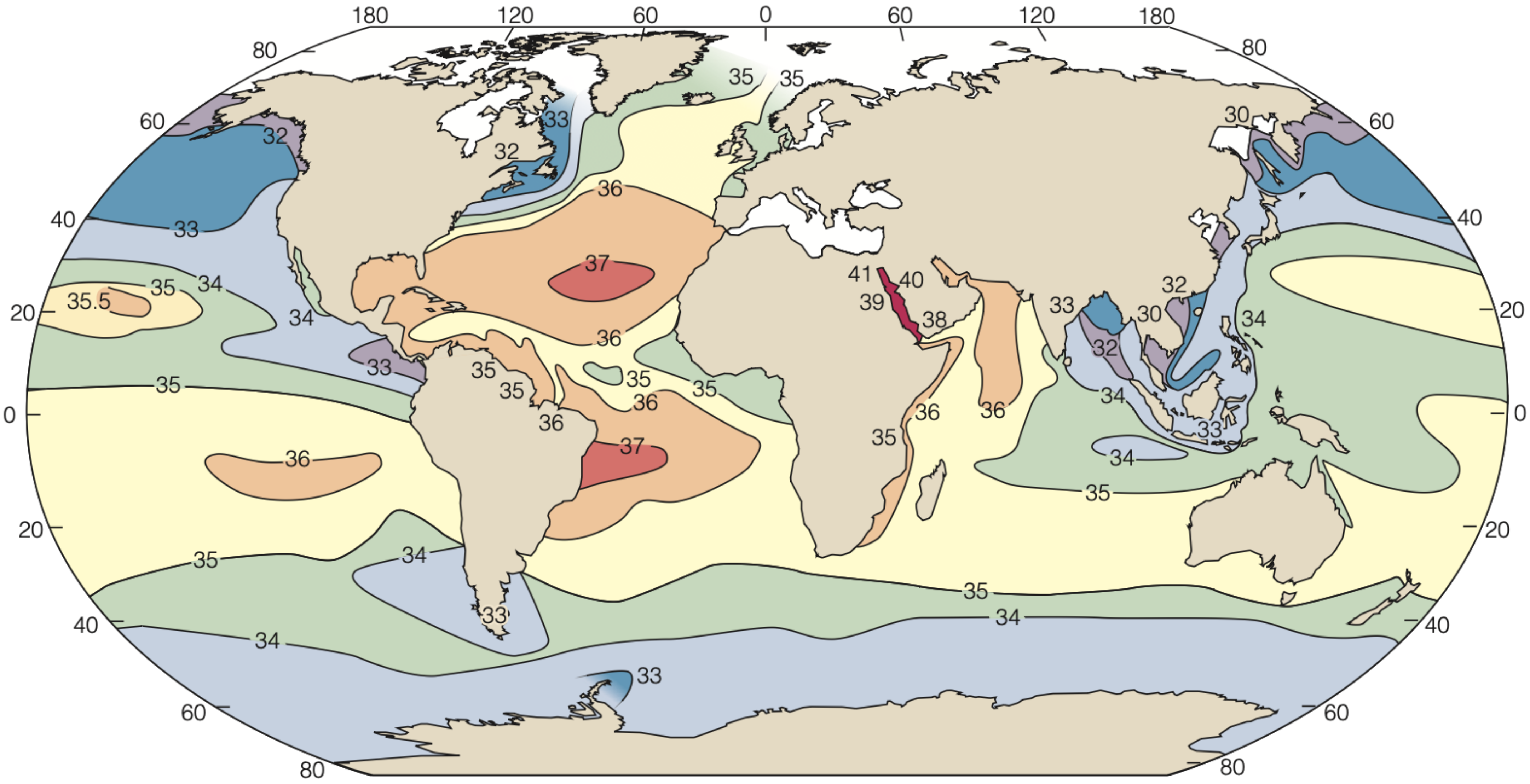
Structure of the Oceans

- The salts contained in seawater are largely the result of the breakdown of crustal rocks, or *weathering* and erosion. It is estimated that the rivers carry the salt produced through weathering and erosion and deliver to ocean approximately $\mathbf{2.5 \times 10^{12} - 4 \times 10^{12}}$ **kg every year**.

- However, salt is also removed form ocean by formation of evaporite deposits, biological shells, and sea spray. Salt is also removed through chemical reaction between seawater and newly formed volcanic rocks on the sea floor.

Overall, the rate removal of salt from the oceans equals the rate of input, when averaged over <u>geological time scales</u>.

FIGURE 10.4 Ocean salinity
High salinity values are found in tropical and subtropical water where evaporation exceeds precipitation. The highest salinity has been measured in enclosed seas like the Persian Gulf, the Red Sea, and the Mediterranean Sea. Salinity values (shown here in per mil, or ‰) generally decrease poleward, but low values also are found off the mouths of large rivers.



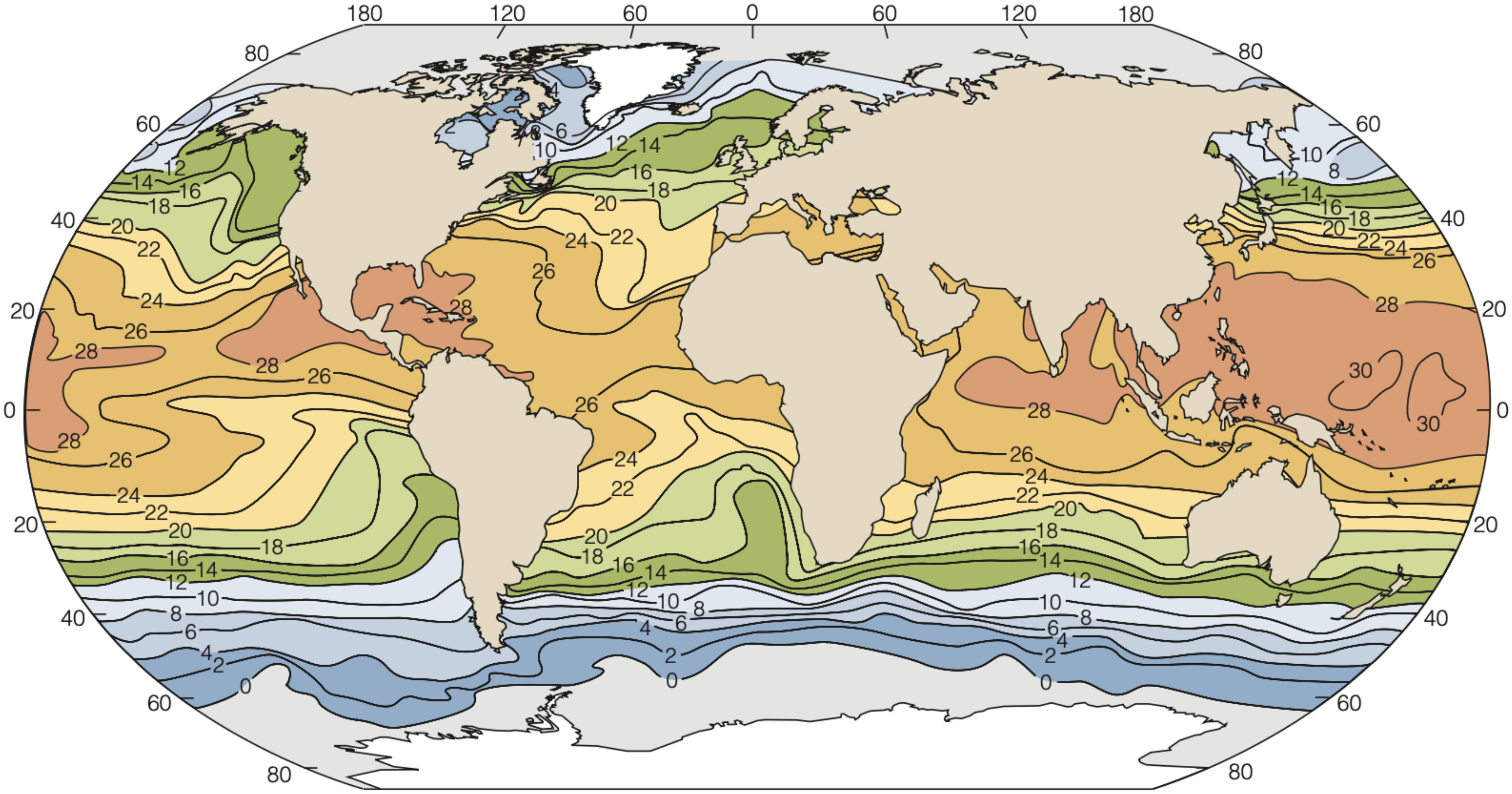


FIGURE 10.5 Sea-surface temperatures
This map shows typical sea-surface temperatures (in °C) in the world ocean during August. The warmest temperatures (≥28°C) are found in the tropical Indian and Pacific oceans. Temperatures decrease poleward from this zone, reaching values close to freezing in the north and south polar seas.

FIGURE 10.6 Depth zones in the ocean
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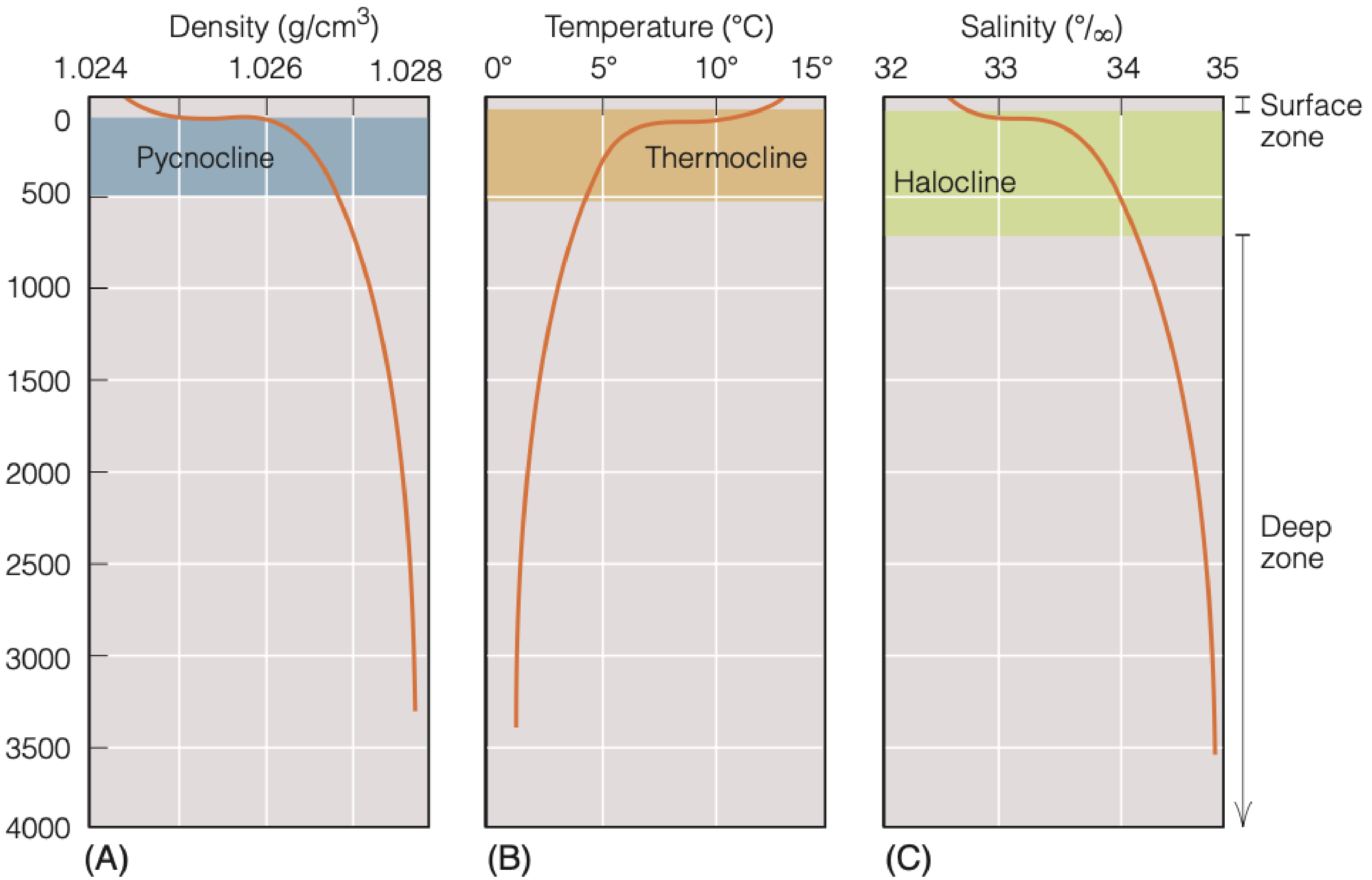


Ocean Circulation

Deep Ocean Circulation:

- The deep ocean water moves as a response to density gradient.
- The movement is largely independent of the surface circulation
- However, both (surface and deep ocean) circulations contribute to the redistribution of available energy in the Earth system though over a very different time scale.
- These circulations play a major role in the distribution of nutrient supplies in the oceans.

Unlike the atmospheric circulations in the troposphere, the surface ocean does not circulate as a direct response to the surface heating. The surface temperature influences the atmospheric circulation, and the resulting pattern of global winds determine the circulation of the upper ocean.

Surface Ocean Circulation

The major surface-ocean currents

- The surface currents form a large circular pattern (ocean gyre).
- In northern hemisphere (clockwise circulation)
- In southern hemisphere (anticlockwise circulation)

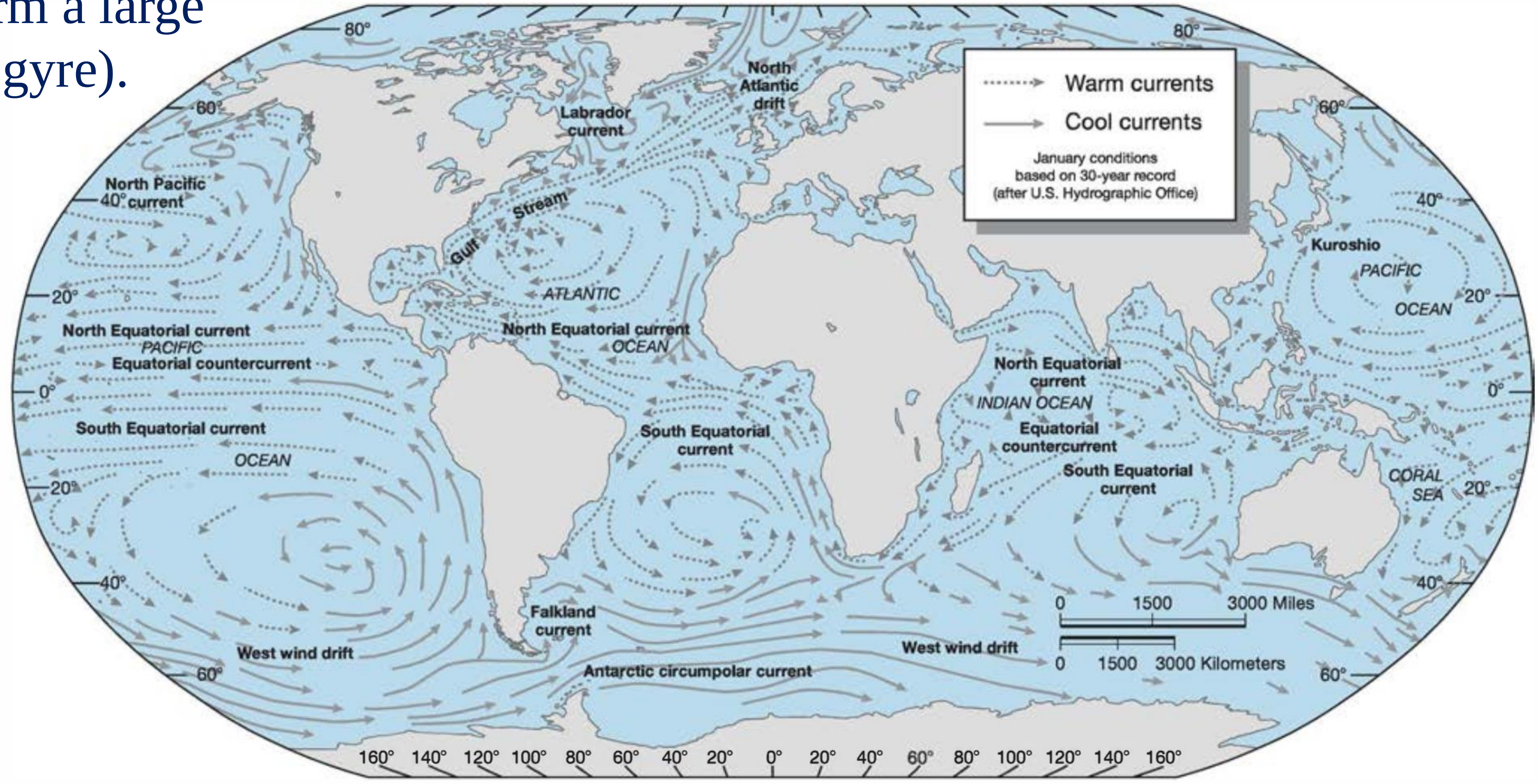


FIGURE 5-2 The major surface-ocean currents. (*Source:* From R. W. Christopherson, *Geosystems: An Introduction to Physical Geography*, 3/e, 1997. Reprinted by permission of Prentice Hall, Upper Saddle River, N.J.)

Surface Ocean Circulation

Schematic Model for Surface Circulation of the Oceans

To understand the different features of the ocean surface circulation shown in Figure 5.2, let us explore a simplified schematic model (Figure 5.1):

- Trade winds in the subtropical zones (0 – 30° N&S) and westerlies in the midlatitude (30° – 60° N&S) sets the pattern of the ocean surface wind-drift current.

- Coriolis force deflect the surface current **rightward/leftward** to the initial movement in the **northern/southern** hemisphere.

- Observations show that the deflection due to Coriolis effect is approximately 20° – 25° from the wind direction.

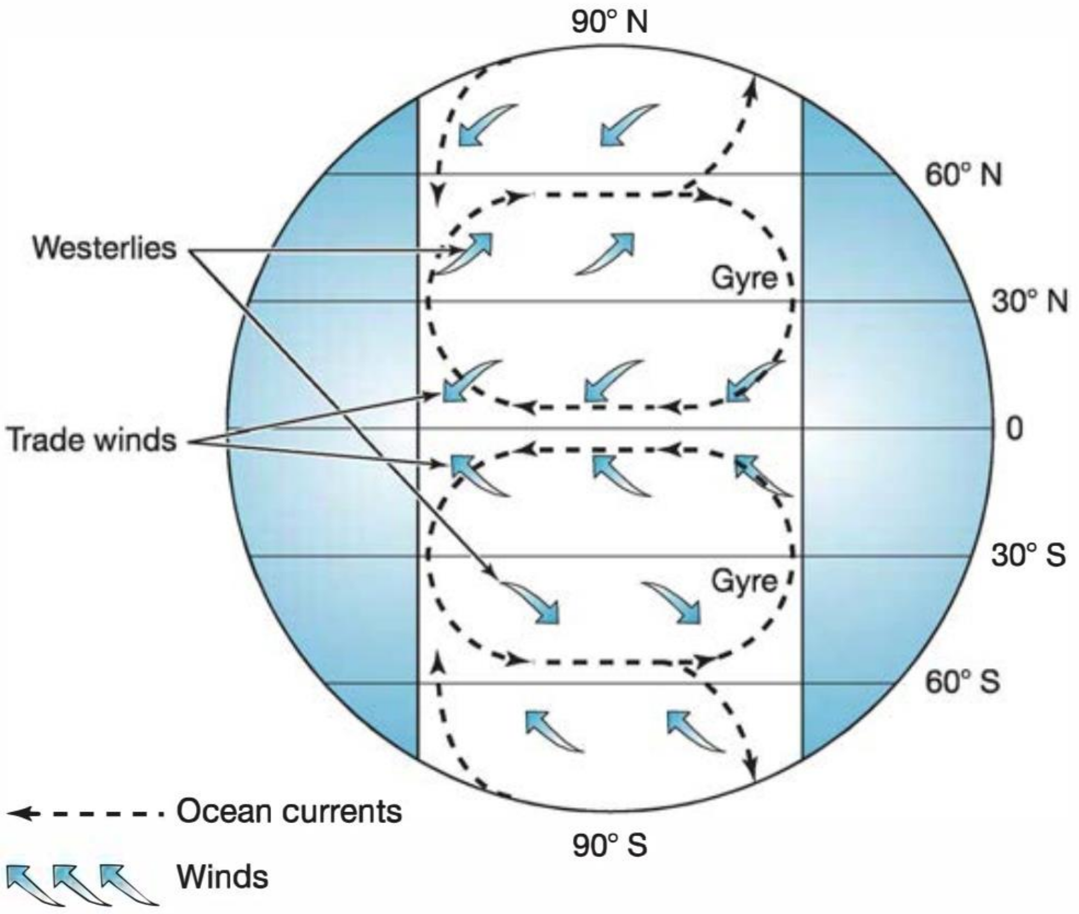


FIGURE 5-1 A simplified view of the surface-ocean circulation.

Surface Ocean Circulation

Schematic Model for Surface Circulation of the Oceans (Contd.)

- Trade winds produce westward-flowing currents in the tropics. After reaching the western continental boundary, they get deflected norward and southward. Then they come under the influence of westerlies, which cause the currents to flow eastward in the midlatitudes.

- When these eastward currents reach eastern continental boundary, they get deflected poleward and equatorward.

- Water that flow toward equator again comes under the influence of the trade winds and are blown westward completing the large circular path called **gyre**.

Surface Ocean Circulation

Schematic Model for Surface Circulation of the Oceans (Contd.)

- The circulation of these gyres is **clockwise/anticlockwise** in **norther/southern** hemisphere.
- The real circulation pattern (Figure 5.2) differs from this schematic model (Figure 5.1) due various factors such as: distribution of land and water, vorticity etc. We will discuss them soon.

Surface Ocean Circulation

Ekman Spiral and Ekman Transport

- Fridtjof Nansen, a Norwegian oceanographer, during an expedition across the arctic ocean noted that his ship, which got frozen into the ice, drifted (along with the ice) not in the wind direction but at 20° – 40° to the right of the wind path.

- Based on the observation, Vagn Walfrid Ekman, a Swedish physicist, derived mathematical equation taking into account surface wind motion, friction between wind and ocean surface, and the Coriolis force and came up with the theory of Ekman spiral.

Surface Ocean Circulation

Ekman Spiral and Ekman Transport

- Due to friction between wind and water surface, a fraction of the kinetic energy of the air is transferred to the top layer of the water.

- As that (surface) layer moves, it drags the layer just below it. Now this layer (second from the surface) drags the layer below it (third from the surface), and so on.

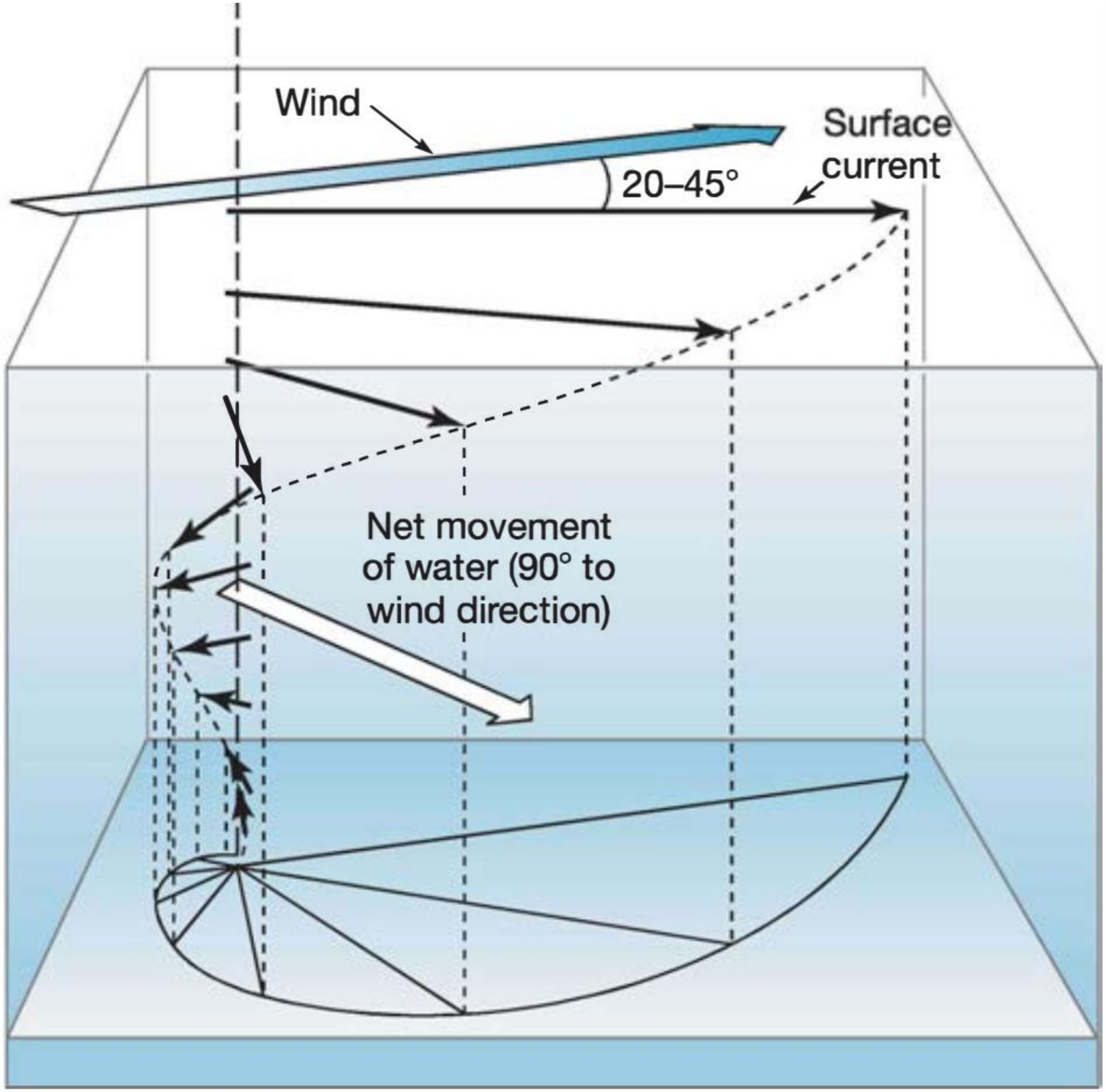
- The water appears to move as many thin, coupled layers, and the kinetic energy is transferred down the water column.

- However, friction causes the dissipation of energy in the form of heat.

Surface Ocean Circulation

Ekman Spiral and Ekman Transport

- So, each layer moves more slowly than the layer above. At some depth below the surface, the effects of the wind-induced movement disappear.
- Each layer is subjected to Coriolis force. Once a layer starts to move, the water is deflected to the right/left of the path of the layer above in the northern/southern hemisphere.
- The deeper the layer, greater is the deflection with respect to surface layer.
- This spiralling pattern is known as **Ekman spiral**.



Surface Ocean Circulation

Implications of Ekman Spiral

Ekman’s theory predicts that:

- The surface current will flow approximately at **~45°** to the surface-wind path.
- At particular depth (~100 m), *Ekman depth*, the flow will be opposite to the surface current.
- At Ekman depth (~100 m), the flow will be considerably reduced in the speed.
- The net movement of water column is at a **right angle (90°) to the wind direction**. This basically is the addition of the movements of all the individual layers of the water in the spiral. This net movement of the water is known as **Ekman transport**.

Surface Ocean Circulation

Implications of Ekman Spiral

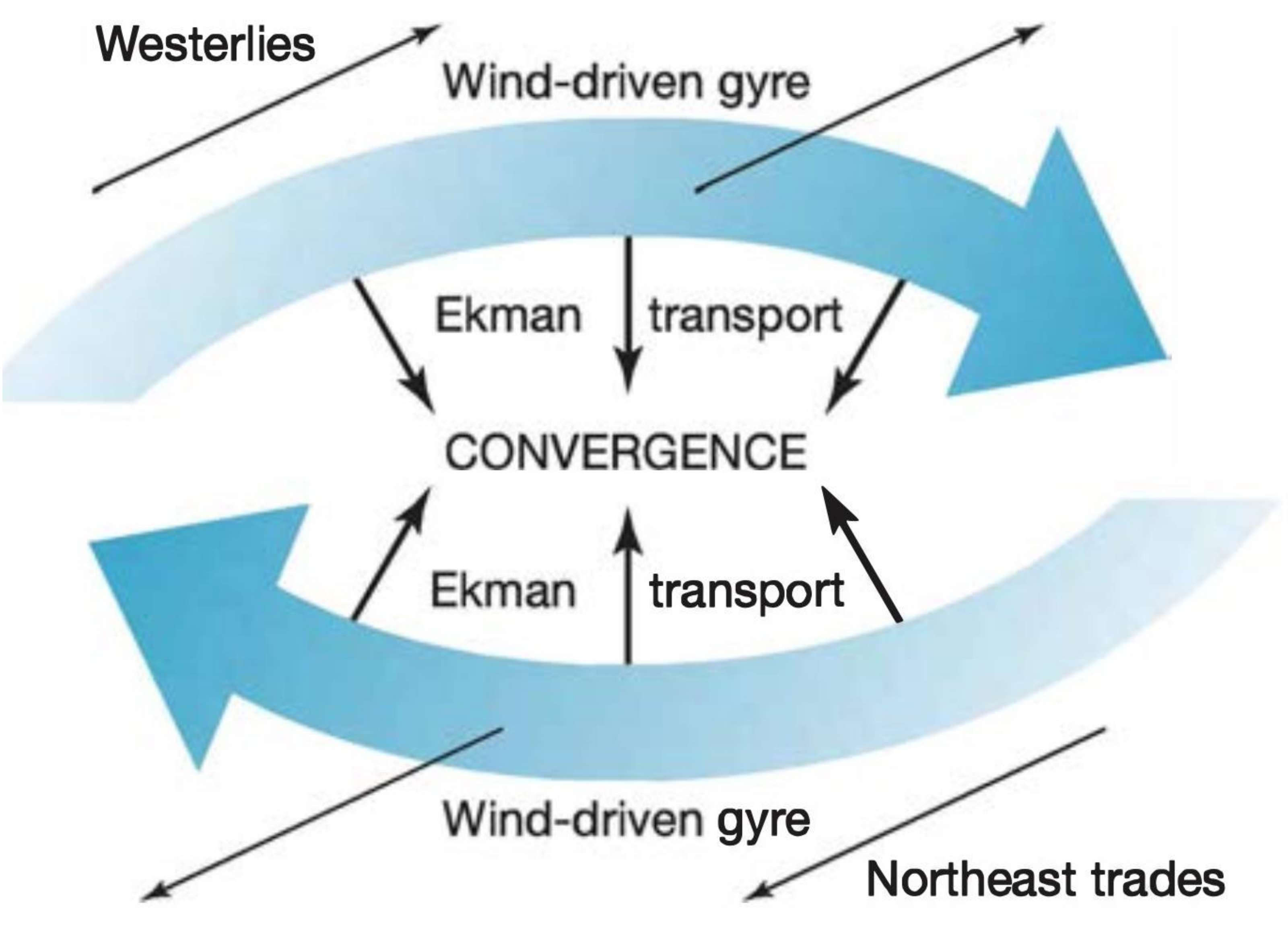
Consequence of Ekman Transport:

- Ekman transport will push the water into the center of the gyre (convergence).

- Ekman transport is also responsible for upwelling and downwelling in the ocean, responsible for the distribution of energy and nutrient supplies in the ocean.

Surface Ocean Circulation

Implications of Ekman Spiral (Convergence)

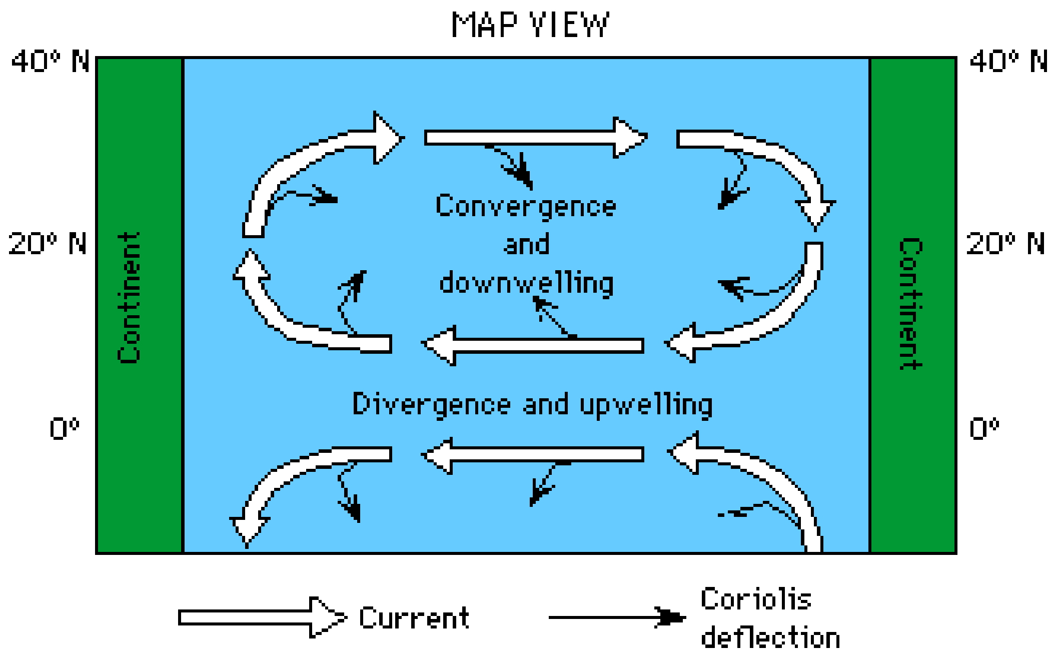


Surface Ocean Circulation

Convergence and Divergence

- At centre of the gyre water converges due to Ekman transport. The accumulated water sink in a process known as **downwelling**.

- Near the equator, divergence occurs and the warm divergent water is replaced by **upwelling** cool and nutrient rich water



(b) In the open oceans, the Coriolis effect induces a radial inflow of water at the center of circulation gyres. This inflow produces convergence and downwelling. Along the equator, the Coriolis effect in the Northern and Southern hemispheres deflects water to the right and left, respectively. This current divergence causes equatorial upwelling.

https://www.ldeo.columbia.edu/edu/dees/ees/dorothy/slides/condiv.gif

Surface Ocean Circulation

Convergence and Divergence

Coastal Upwelling and Downwelling

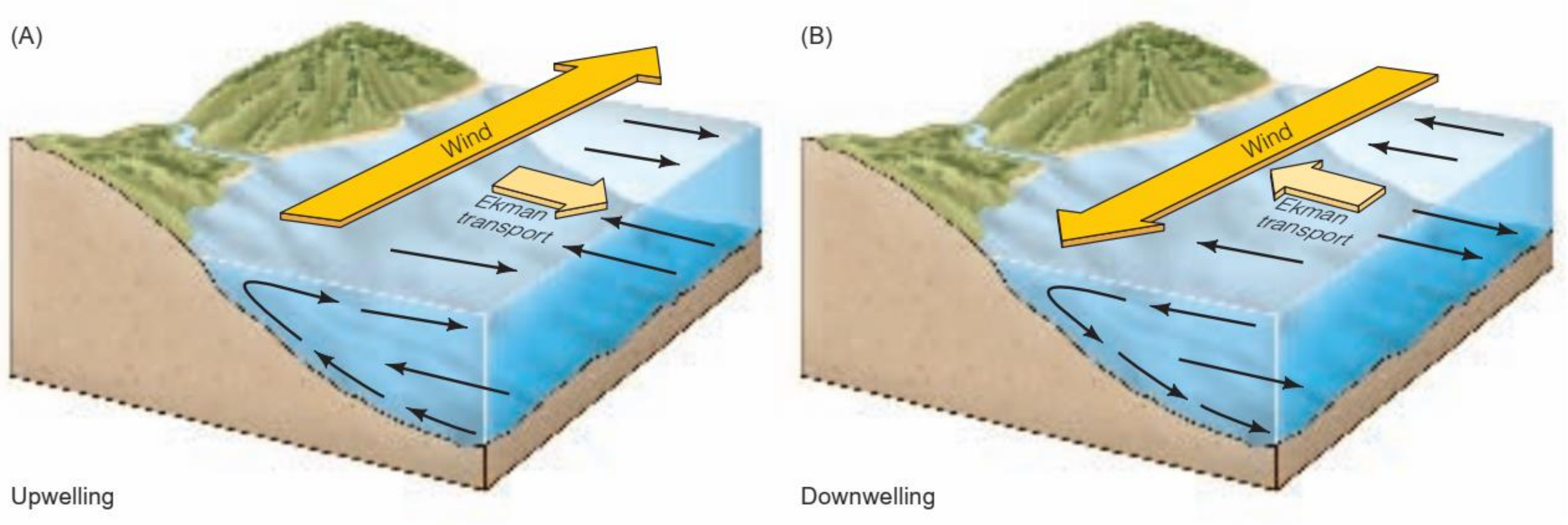


FIGURE 10.10 Upwelling and downwelling
Winds blowing parallel to a coast exert a drag on the surface water, forcing it away from (A) or toward the land (B), depending on wind direction. If the net Ekman transport is away from the land, rising deeper water replaces the surface water moving offshore, which produces upwelling. If the net Ekman transport is toward the shore, the surface water thickens and sinks, which produces downwelling.

Surface Ocean Circulation

Convergence and Divergence

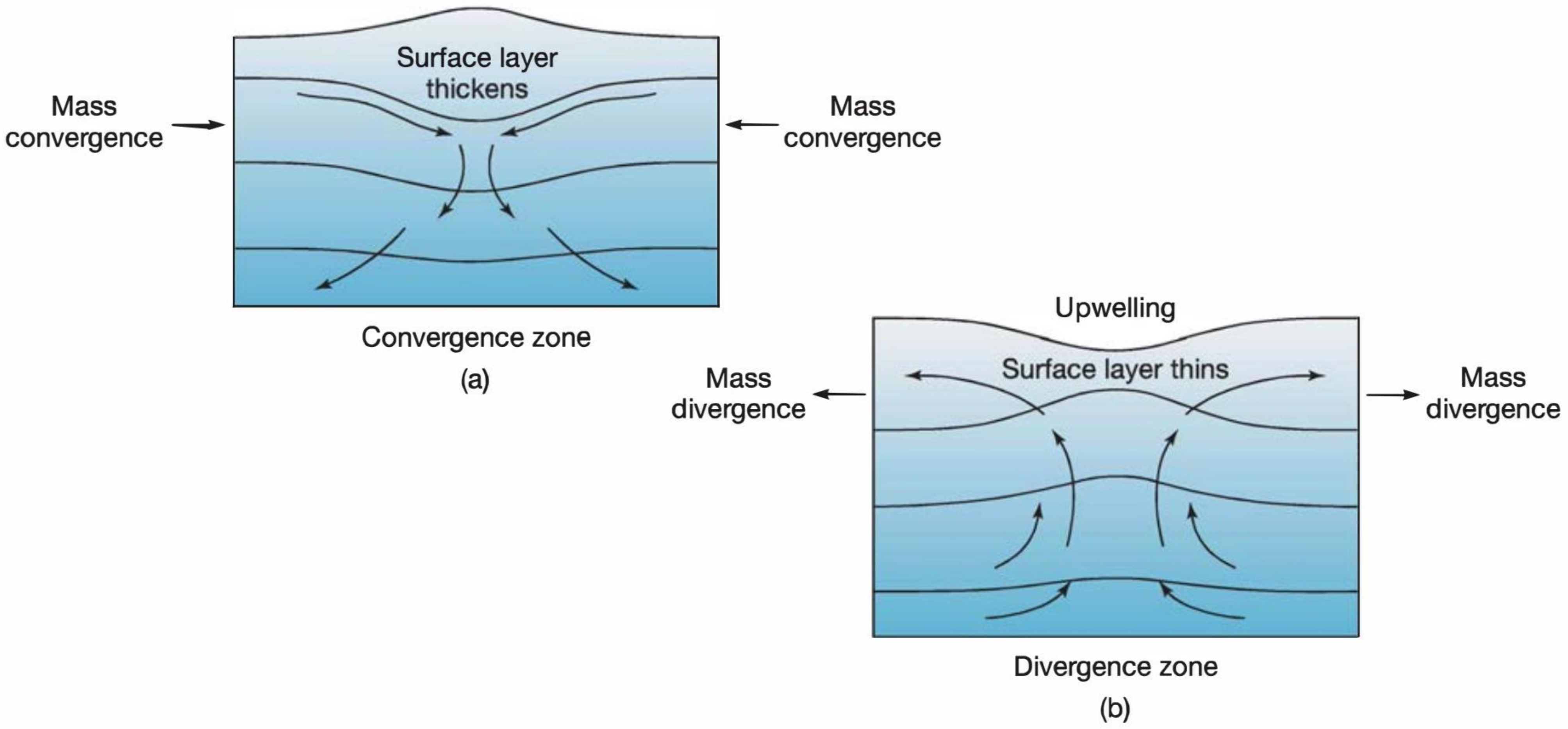


FIGURE 5-4 Schematic representation of zones of convergence and divergence. (a) Surface water accumulates in convergence zones, increasing the surface elevation (very exaggerated in the diagram) and thickening the surface layer. (b) The opposite happens in divergence zones—there is a decrease in surface elevation, and the surface layer thins.

Surface Ocean Circulation

Geostrophic Flow

- Areas of convergence and divergence produce slight variation in sea-surface elevation (order of few meter over 10^2 to 10^5 km) across the ocean basin.

- These slight elevation gradients are sufficient to cause downslope force on the water due to gravity.

- As the water flows, it is deflected toward right/left in the northern/southern hemisphere due to Coriolis force. Eventually, this Coriolis force balances the pressure gradient force acting down the slope due to gravity.

Surface Ocean Circulation

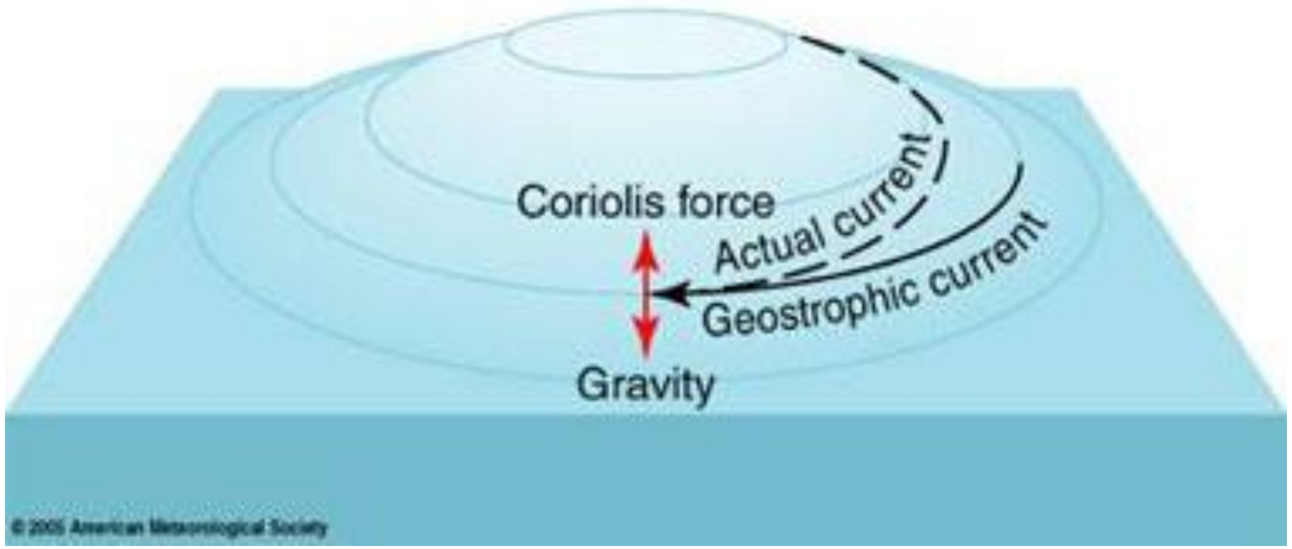
Geostrophic Flow

- As a result, water flows in a circular pattern around the gyre that is approximately parallel to the ocean slope (isobars). This flow is called **geostrophic flow**, which flows around the gyre clockwise/anticlockwise in the northern/southern hemisphere.

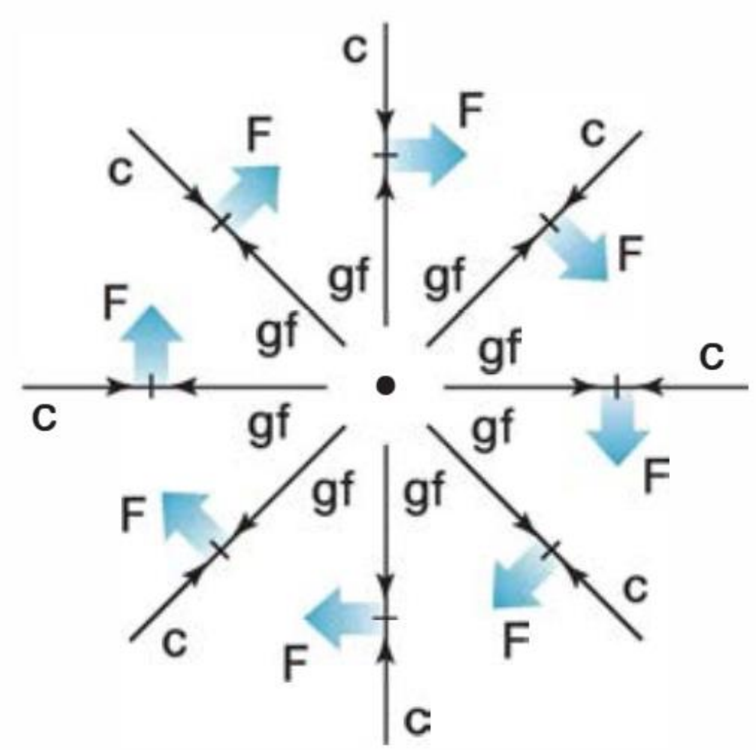
- In practice, the flow is little less than 90° to the slope, so in fact water tends to spiral inward as it moves around the gyre and the convergence in the gyre results downwelling.

Surface Ocean Circulation

Geostrophic Flow



Ekman transport from the wind-driven currents causes water to pile up in the central region of a subtropical gyre from all sides, producing a broad mound of water. Surface water begins flowing downhill. A balance develops between the Coriolis force and the force arising from the horizontal water pressure gradient such that surface currents flow parallel to the contours of elevation of sea level. This current is known as geostrophic flow.



Clockwise gyre resulting from geostrophic flow.

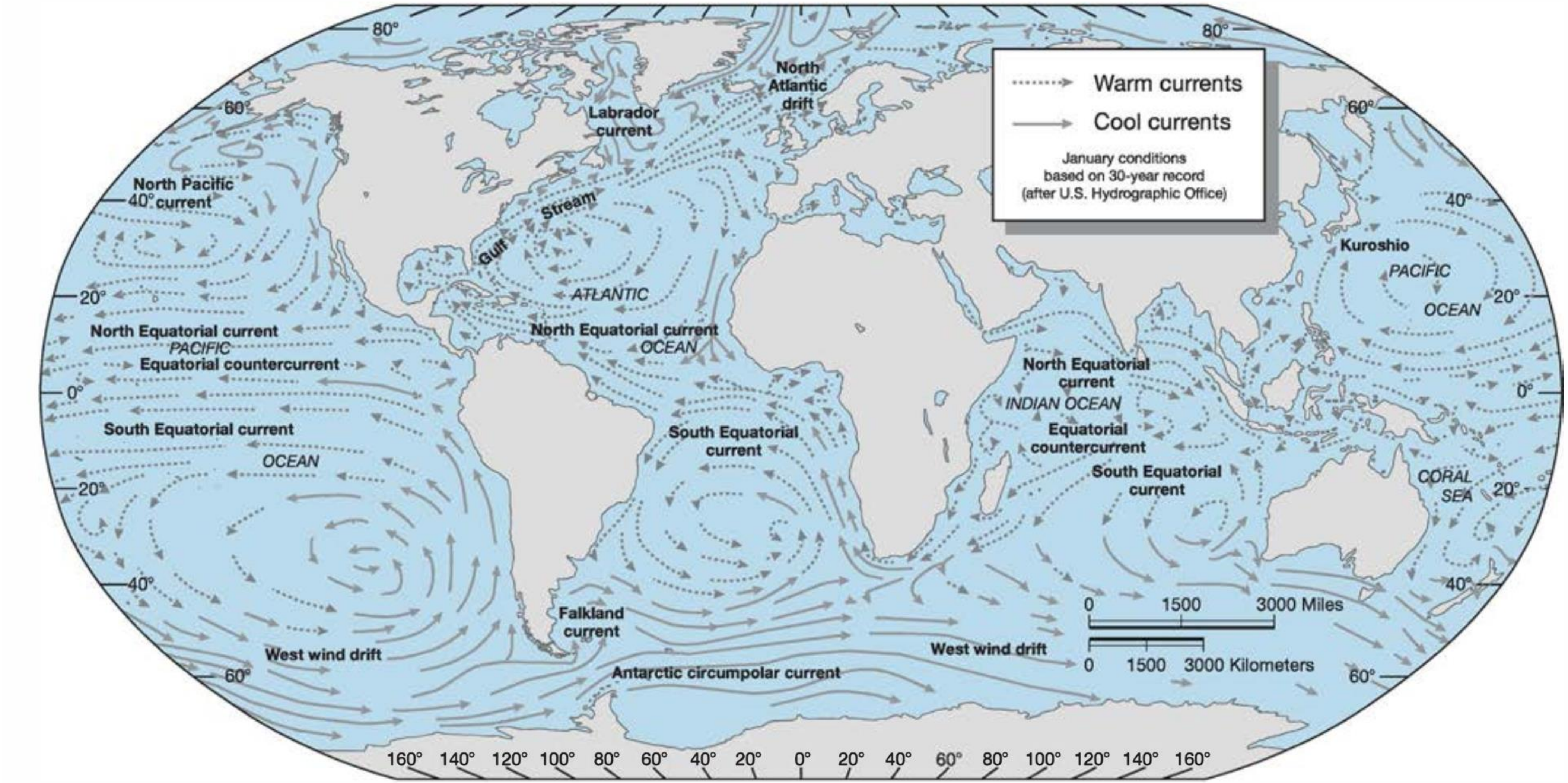


FIGURE 5-2 The major surface-ocean currents. (*Source:* From R. W. Christopherson, *Geosystems: An Introduction to Physical Geography,* 3/e, 1997. Reprinted by permission of Prentice Hall, Upper Saddle River, N.J.)

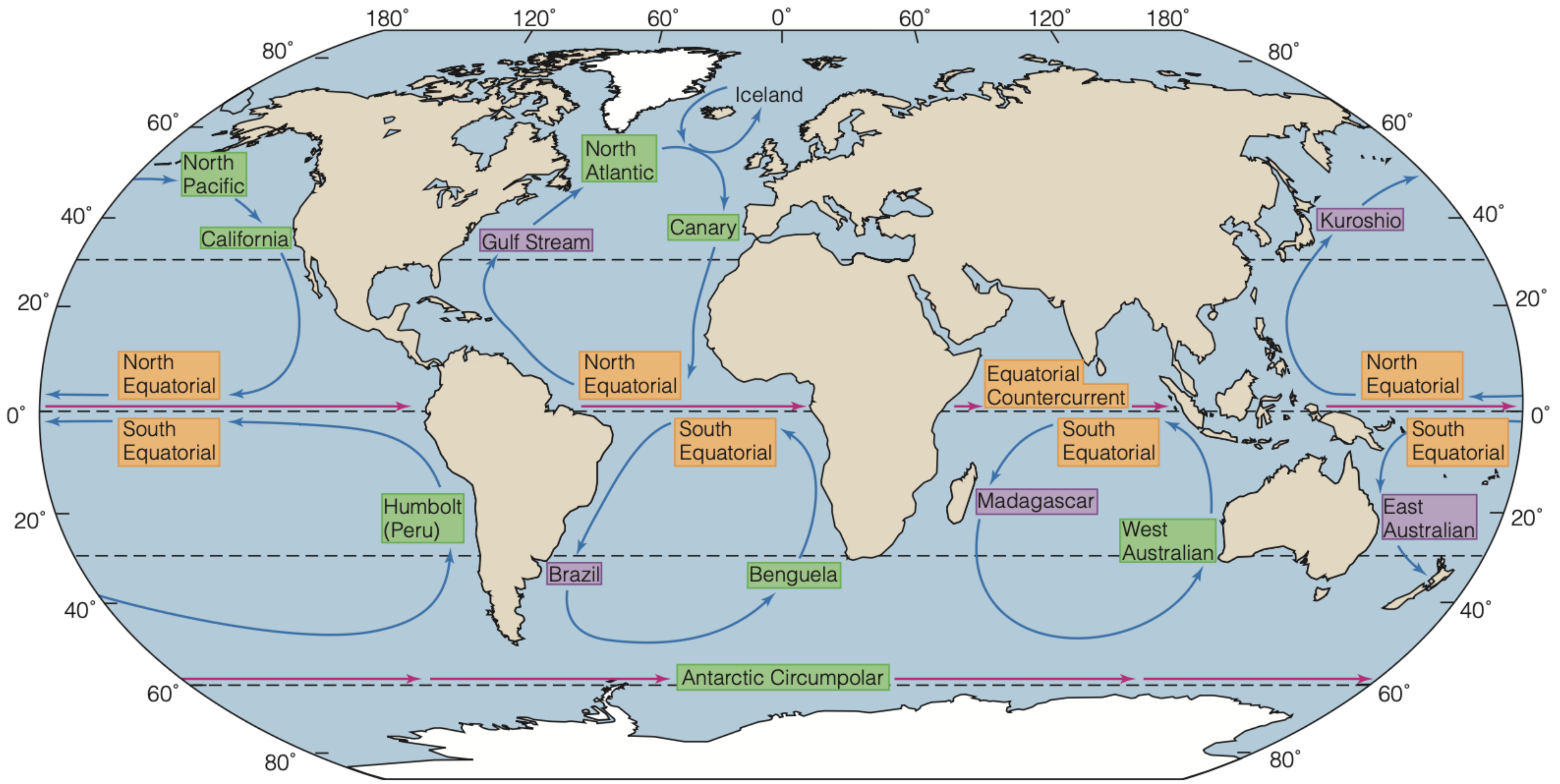
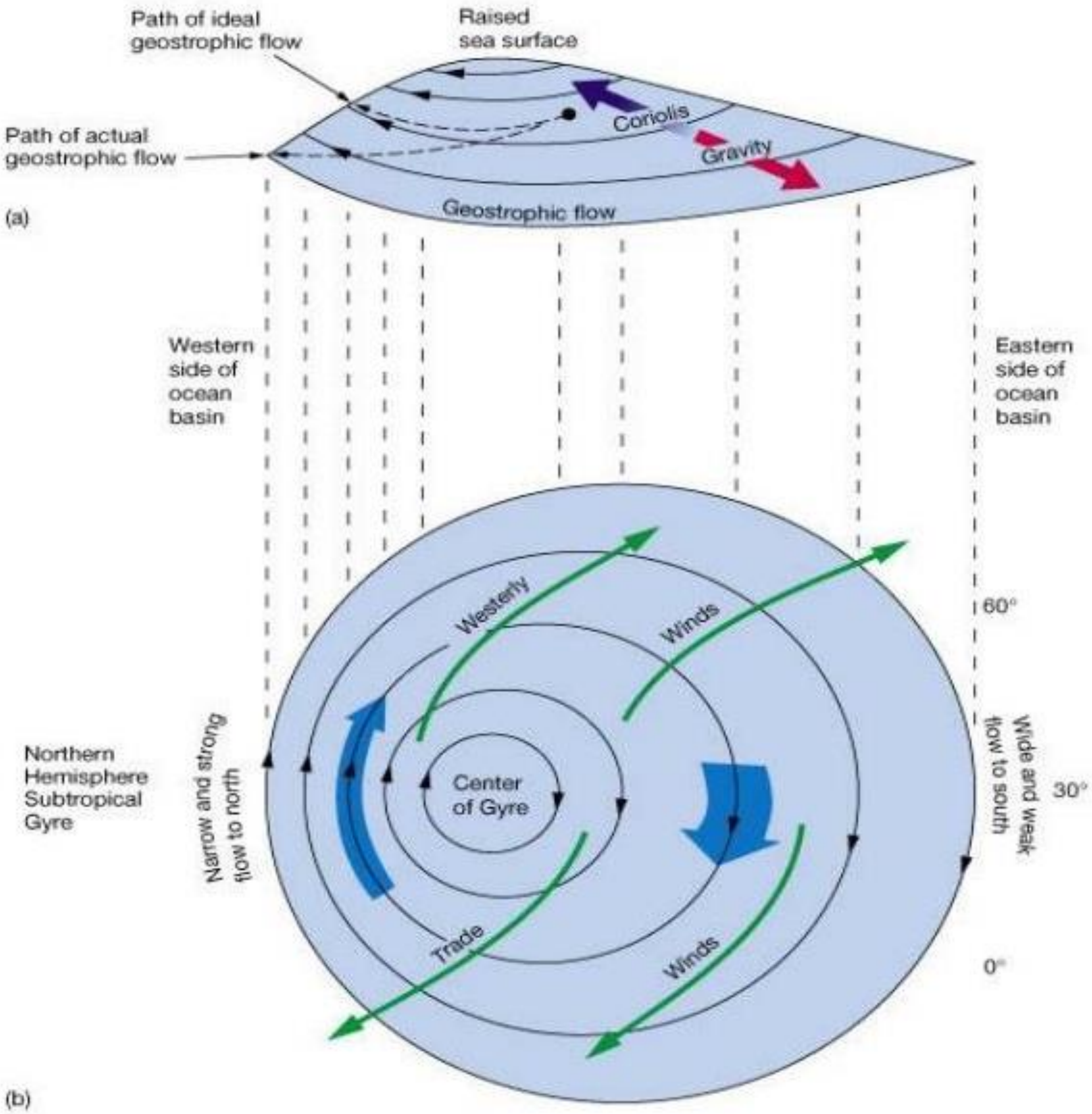


FIGURE 10.11 Surface ocean currents
Surface ocean currents form a distinctive pattern, curving to the right (clockwise) in the northern hemisphere and to the left (counterclockwise) in the southern hemisphere. The westward flow of warm, tropical water (the Equatorial currents) in the Atlantic, Pacific, and Indian oceans is interrupted by continents, which deflect the water poleward. The flow then turns away from the poles to define the middle-latitude margins of the five great midocean gyres: two in the Atlantic, two in the Pacific, and one in the Indian Ocean. Blue arrows show cold currents, and red arrows show warm currents.

Surface Ocean Circulation

Geostrophic Flow



Surface Ocean Circulation

Boundary Currents

We can see from pattern of the major surface ocean currents that:

- Gyres are not symmetrical.

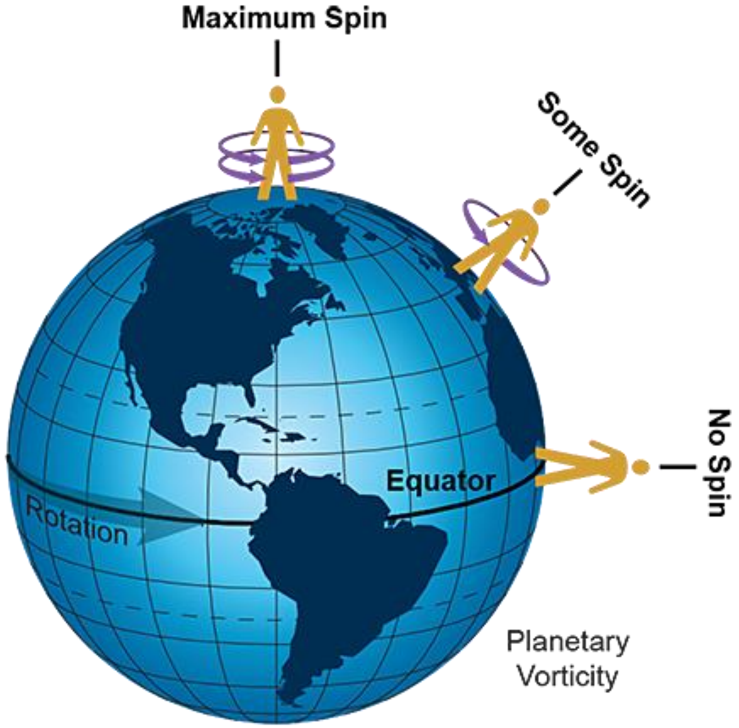
- The flow in the western part of the gyre is confined to a narrow path with fast-flowing current (*western boundary current*), whereas the eastern part is much more diffuse, spread over much larger area and with much-reduced current speeds (*eastern boundary current*).

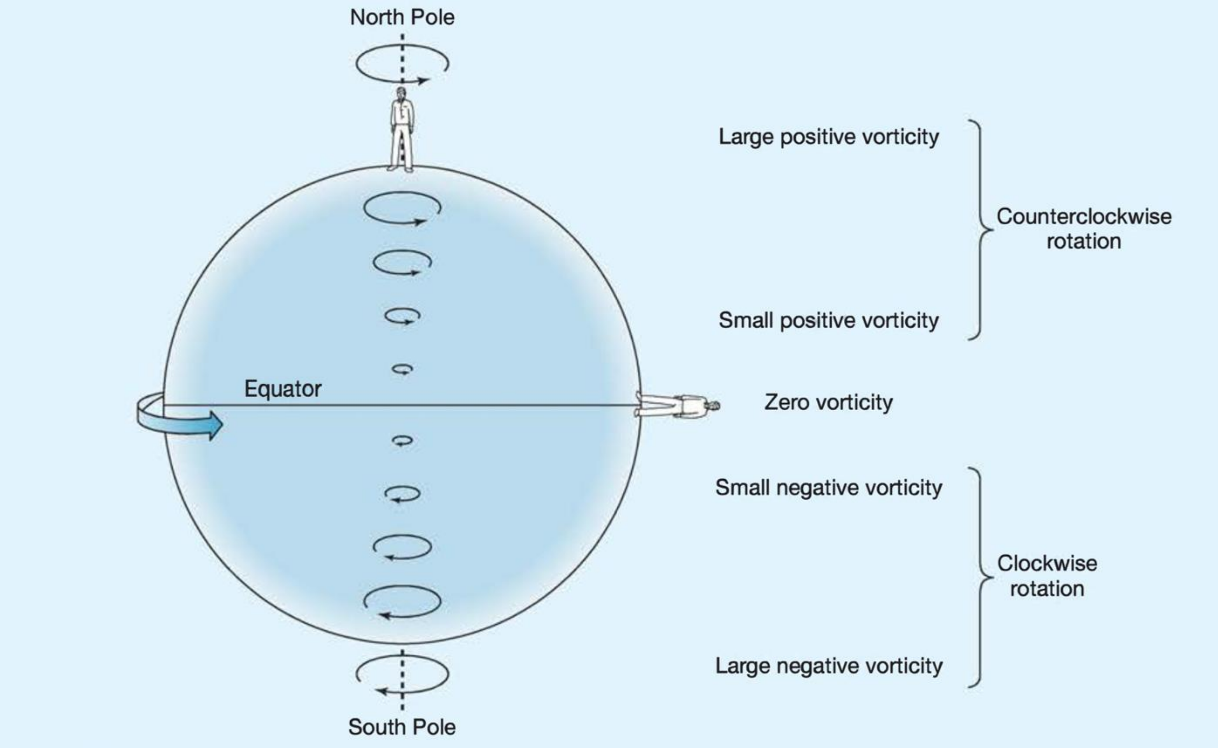
- To understand these features, we need to study the ***vorticity***, a tendency of a fluid to rotate. A tendency to rotate anticlockwise is referred to as a *positive vorticity*, whereas tendency for clockwise rotation is *negative vorticity*.

Surface Ocean Circulation

Planetary Vorticity

The Earth’s rotation produces planetary vorticity, which is maximum at pole and zero at the equator.



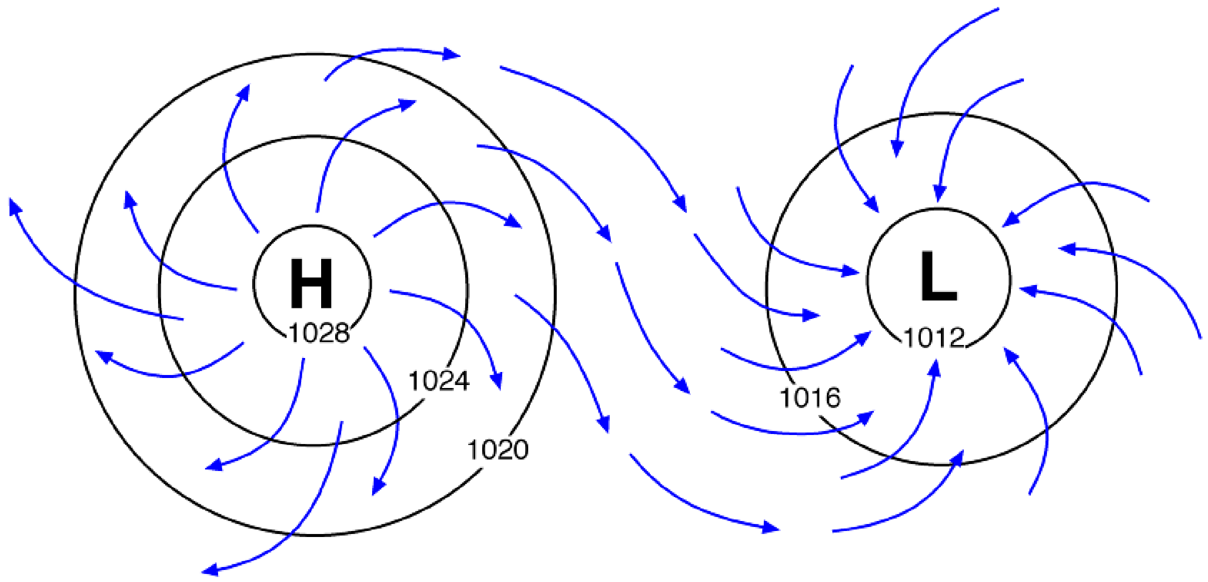


BOX FIGURE 5-1 Planetary vorticity, increasing from zero at the equator to a maximum at the poles. (*Source:* Open University, *Ocean Circulation*, New York: Pegamon Press, 1989.)

Surface Ocean Circulation

Relative Vorticity

- Relative vorticity when surface waters are driven by cyclonic (low-pressure) and anticyclonic (high-pressure) circulations in the atmosphere.

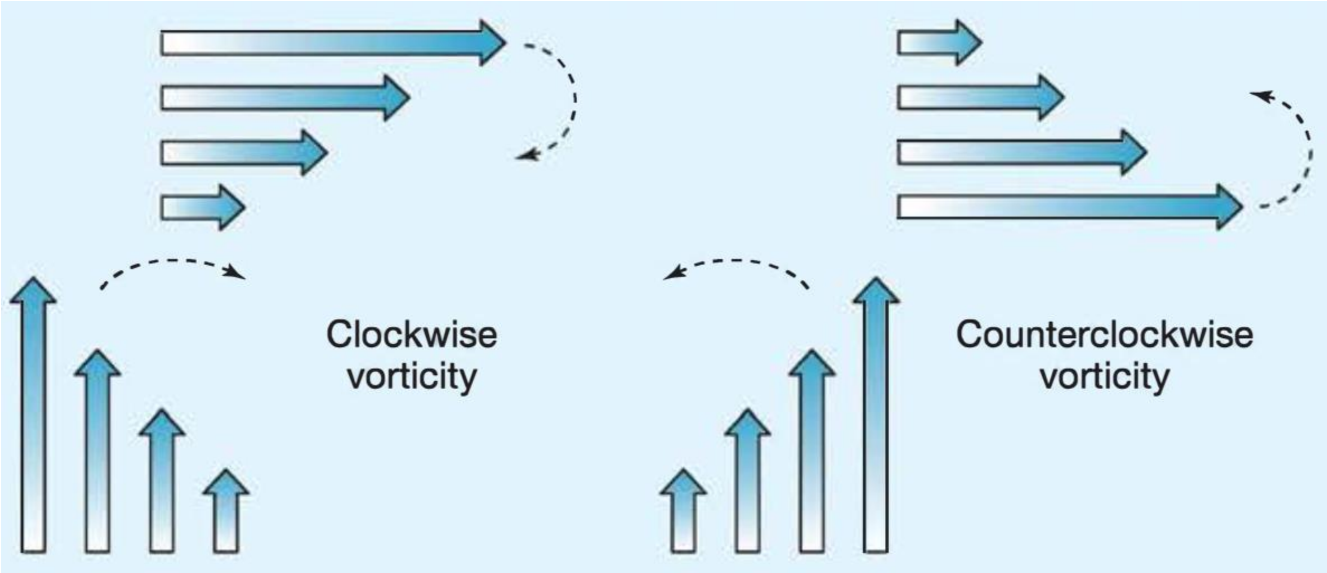


High pressure (producing clockwise, anticyclonic) and low pressure (counterclockwise, cyclonic) centers producing relative negative and positive vorticity.

Surface Ocean Circulation

Relative Vorticity

- Relative vorticity could also caused by *current shear*, in which the speed of the current changes across the current.



Schematic diagram of current shear producing negative (clockwise) and positive (counterclockwise) relative vorticity.

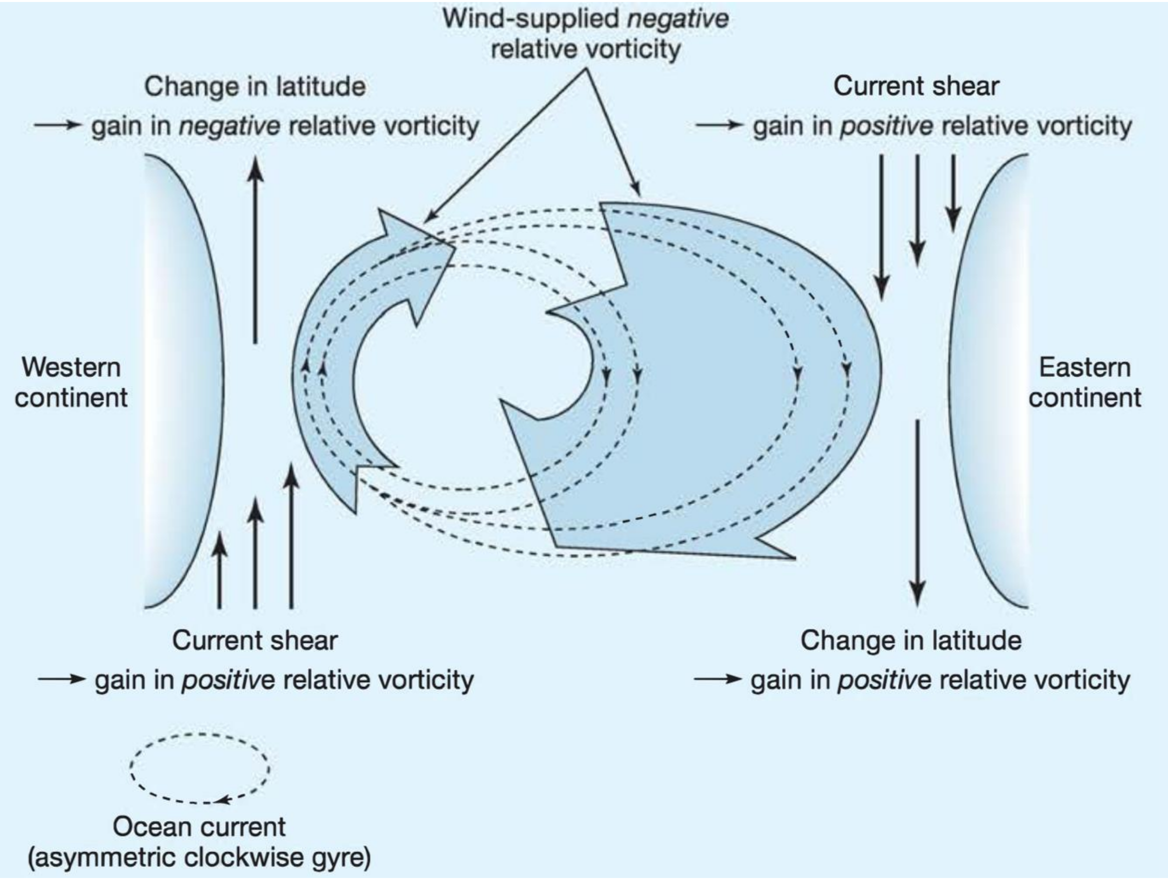
Surface Ocean Circulation

Boundary Currents

The *absolute vorticity*, a conserved quantity, experienced by a body of water is the sum of the planetary and relative vorticity. Vorticity conservation leads to asymmetric nature of gyres.

At the eastern boundary current:

- Wind driven eastward flow is supplied with negative relative vorticity.
- Current shear at the eastern boundary produces positive relative vorticity (tendency for anticlockwise rotation).
- The southward movement of the water at the eastern boundary decreases the positive planetary vorticity.
- Since the absolute vorticity is conserved, this decrease in planetary vorticity has to be balanced by a decrease in relative negative vorticity (or gain in positive relative vorticity). For that, current slows down and diffused.



Effect of vorticity on the asymmetric nature of gyre (clockwise) in northern hemisphere.

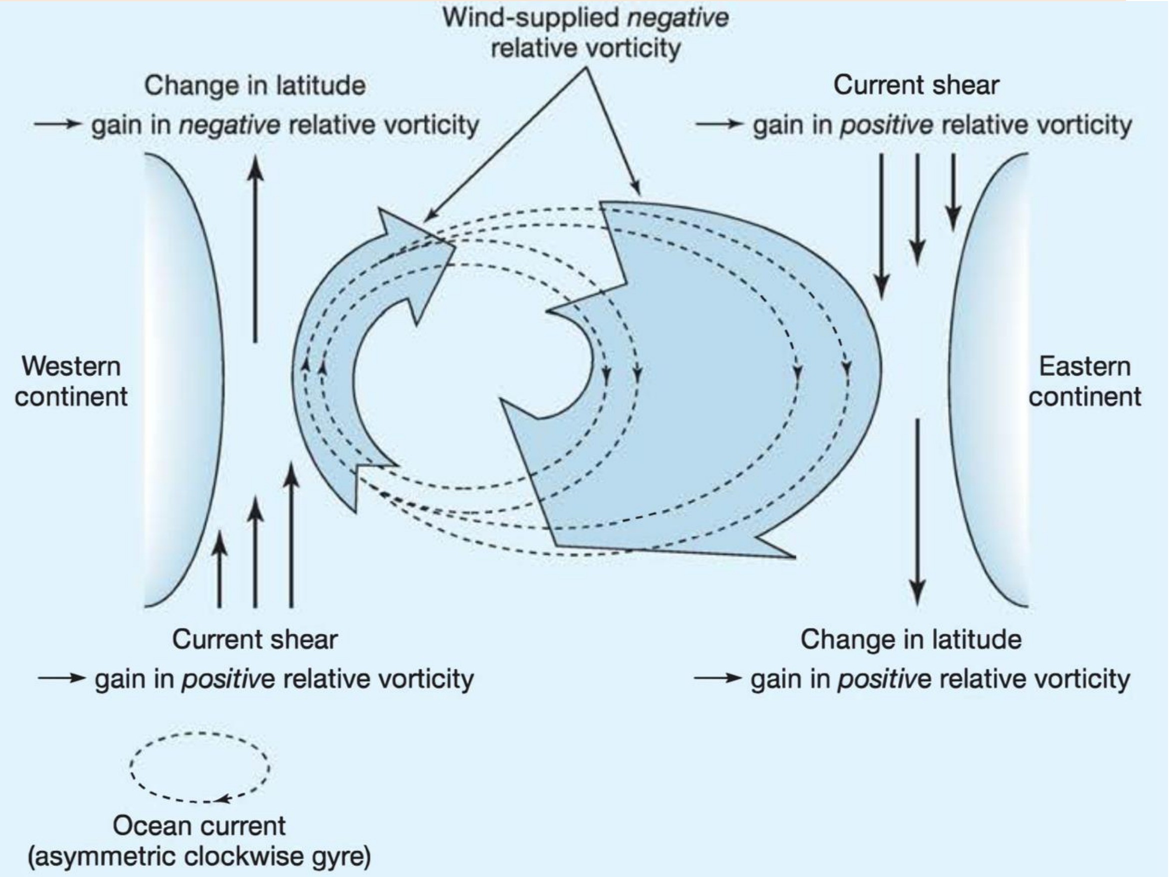
Surface Ocean Circulation

Boundary Currents

The *absolute vorticity*, a conserved quantity, experienced by a body of water is the sum of the planetary and relative vorticity. Vorticity conservation leads to asymmetric nature of gyres.

At the western boundary current:

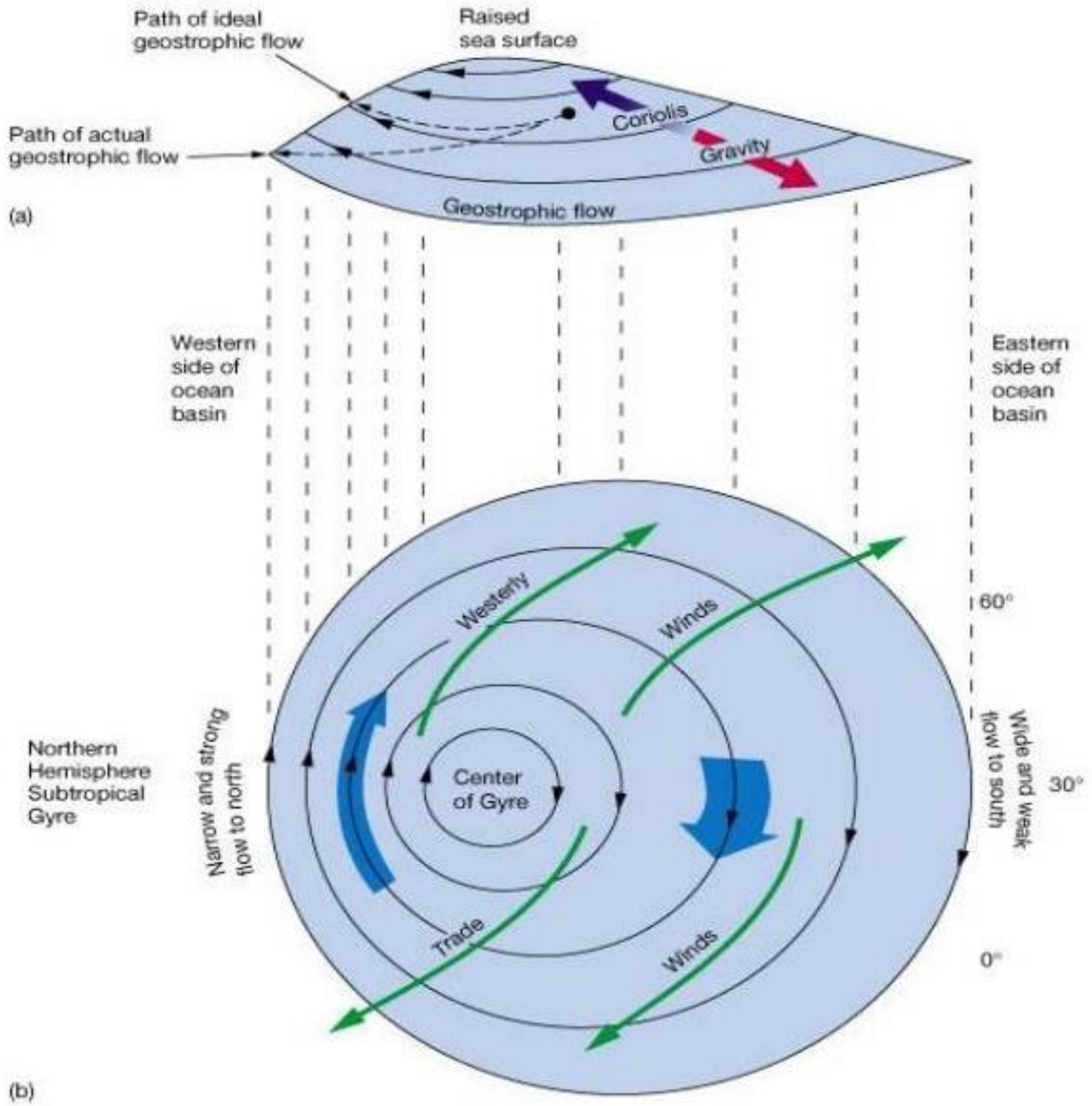
- Current shear again produces positive relative vorticity.
- The poleward movement increase the positive planetary vorticity.
- Therefore, to balance this, faster and narrower flow is enforced at the western boundary current.



Effect of vorticity on the asymmetric nature of gyre (clockwise) in northern hemisphere.

Surface Ocean Circulation

Geostrophic Flow



Vorticity is expressed as

$$\vec{\omega} = \vec{\nabla} \times \vec{v}$$

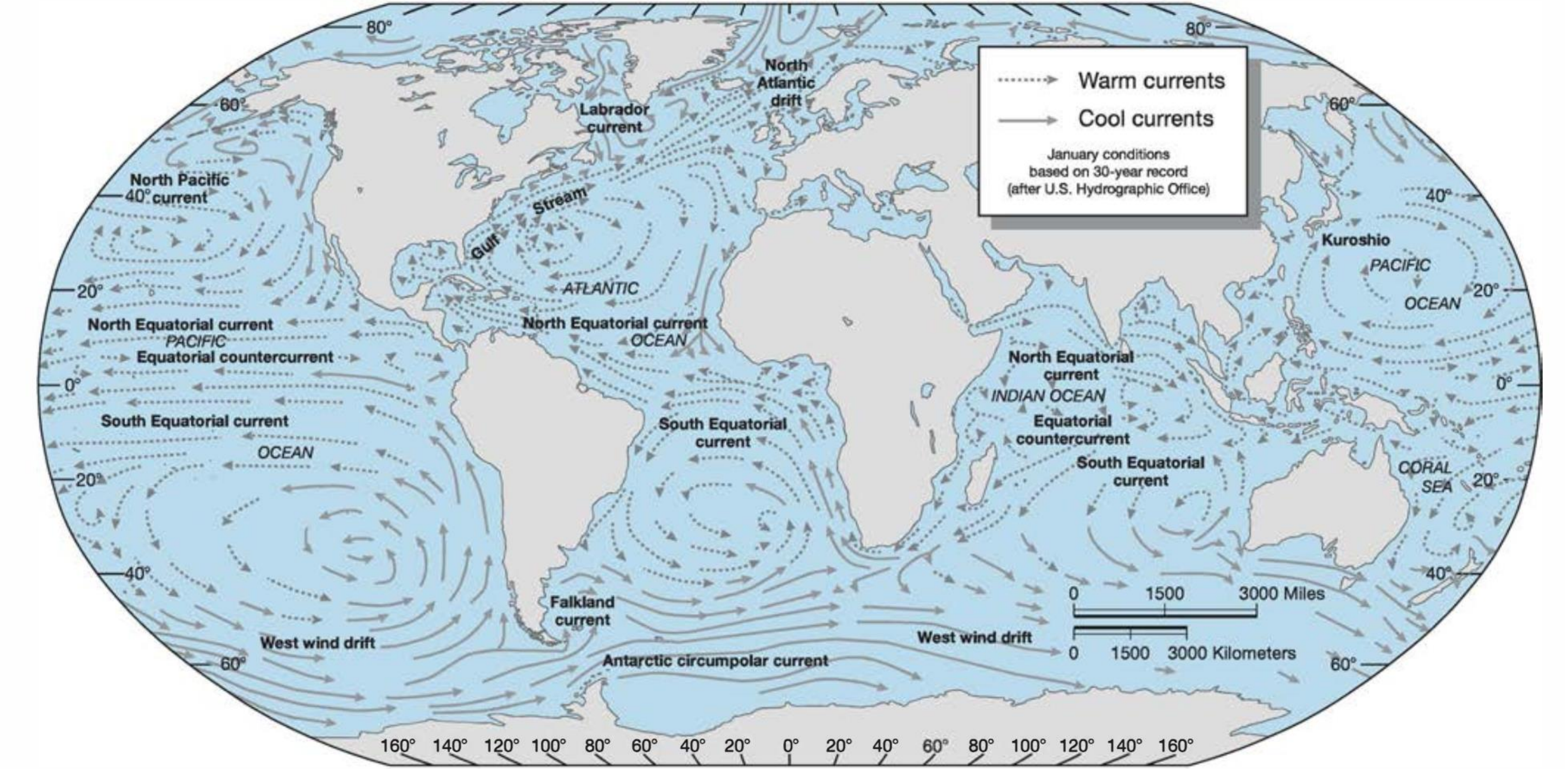
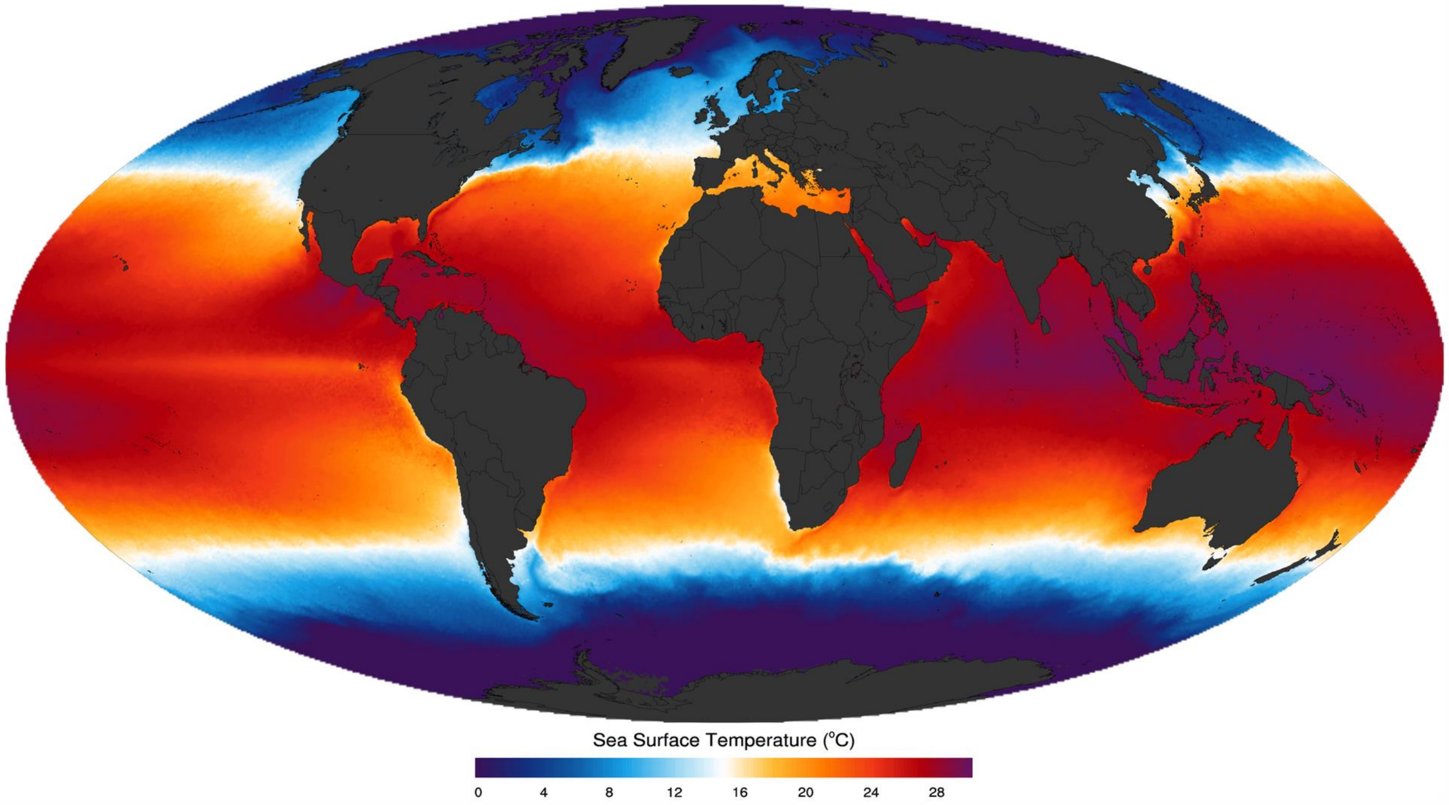


FIGURE 5-2 The major surface-ocean currents. (*Source:* From R. W. Christopherson, *Geosystems: An Introduction to Physical Geography,* 3/e, 1997. Reprinted by permission of Prentice Hall, Upper Saddle River, N.J.)

Surface Ocean Circulation

Ocean Circulation and Sea-Surface Temperature (SST)



2003–2011 SST based on [MODIS](#) Aqua data

https://en.wikipedia.org/wiki/Sea_surface_temperature#/media/File:MODIS_sst.png

Surface Ocean Circulation

Ocean Circulation and Sea-Surface Temperature (SST)

- Along with the atmospheric circulations, ocean circulation pattern has a significant impact on the redistribution of energy around the globe and on regional temperature.
- The equatorial currents are deflected poleward carrying **warmer** water to middle and high latitude.
- When these currents are further deflected northward and southward by eastern landmass, the water moving poleward is warmer than the polar ocean, whereas the water moving equatorward is colder than the tropical ocean.
- Nowadays, sea-surface temperatures (SST) are determined using weather satellites.
- SSTs averaged between 2003-2011 are shown in Figure. There are reginal variations in SSTs: El Niño-Southern Oscillation events.

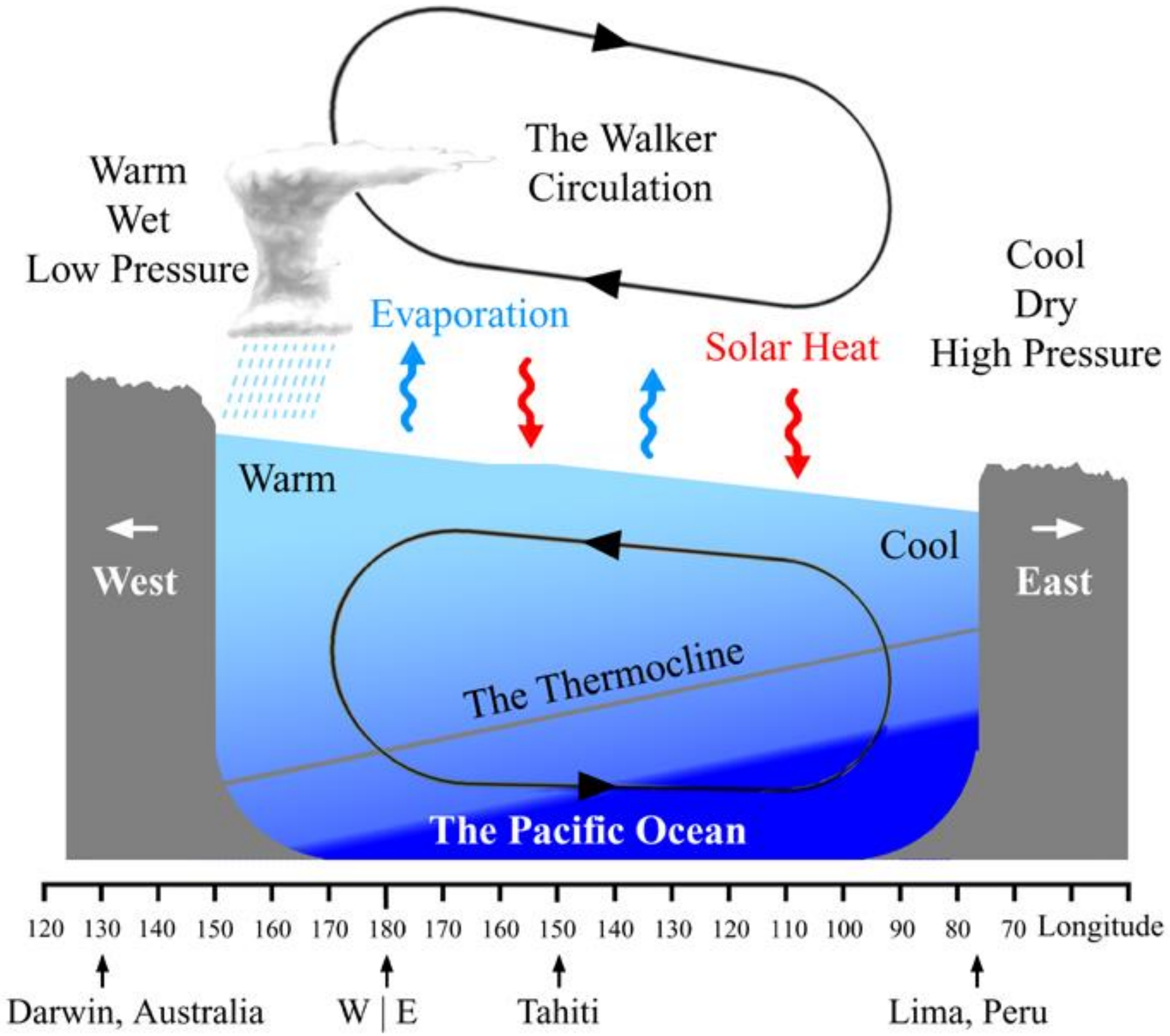
Surface Ocean Circulation

El Niño-Southern Oscillation (ENSO) events

- El Niño events are periodic oscillation in the sea-level pressure (also referred as the Southern Oscillation) and SSTs across the equatorial pacific.
- El Niño event occurs usually in every 2-7 years.
- These events give rise to significant climate anomalies over much of tropics and midlatitudes.

Surface Ocean Circulation

El Niño-Southern Oscillation (ENSO) events



Surface Ocean Circulation

El Niño-Southern Oscillation (ENSO) events

- As we can see from SST data, the western equatorial pacific, the region which encompasses Australia and Indonesia, has the highest temperature on globe and so is the site of intense atmospheric convection.

- The rising air diverges at the high altitude and flows eastward and westward also along with the northward and southward (Remember: this northward and southward flow is the part of Hadley cells).

Surface Ocean Circulation

El Niño-Southern Oscillation (ENSO) events

- The eastward-moving air crosses the Pacific, where it subsides off the west coast of South America. The circulation is completed by an easterly flow at the surface. This equatorial east-west circulation is also know as **Walker circulation**.

- The persistent easterly wind at the surface in the Pacific ocean produces a westward flowing current, which results in the accumulation of warm surface water in the western pacific.

Surface Ocean Circulation

El Niño-Southern Oscillation (ENSO) events

- This east-to-west movement of water thickens the warm surface layer in the west and thins it in the east. The thinning of the surface layer allows the upwelling of the colder, nutrient rich water from the below, which promotes high levels of biological productivity and large fish population (Coastal Peru: Among the richest fishing ground in the world)

- This pattern represent the *normal or neutral* scenario (Figure (b) in the next slide).

Surface Ocean Circulation

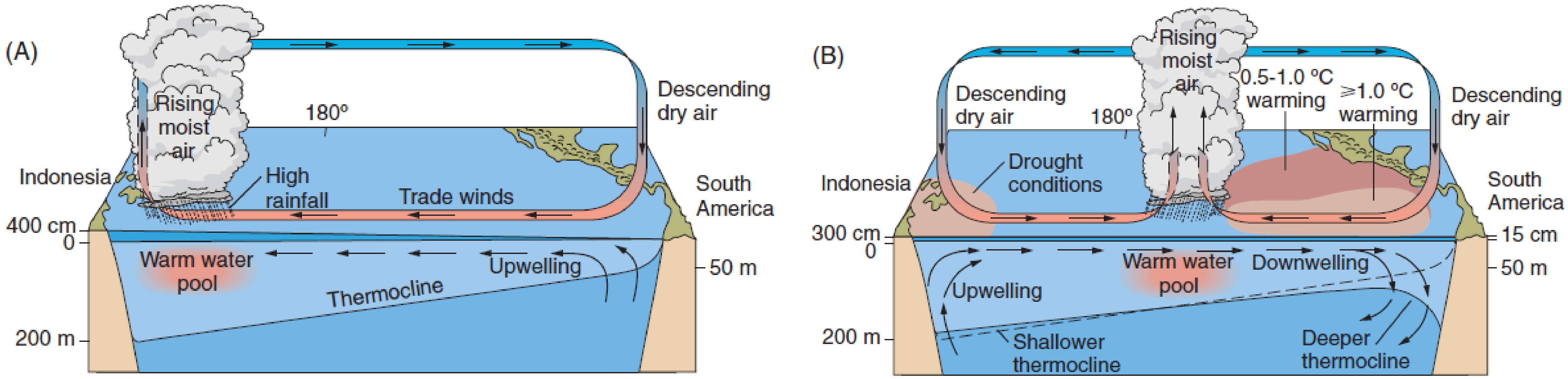
El Niño-Southern Oscillation (ENSO) events

- For some reason (not know for certain yet but global warming is one of the strong candidate), if there is a **decline in the strength of the easterly winds (El Niño conditions),** then the piled-up warm water in the western Pacific cannot be restrained and it comes sloshing back across the ocean (*Kelvin* wave).

- This process shifts the high sea-surface temperatures (SSTs) from western to central pacific., which completely changes the atmospheric circulation. *It also shuts off the upwelling the eastern Pacific, which drastically reduces the biological productivity*.

Surface Ocean Circulation

El Niño-Southern Oscillation (ENSO) events

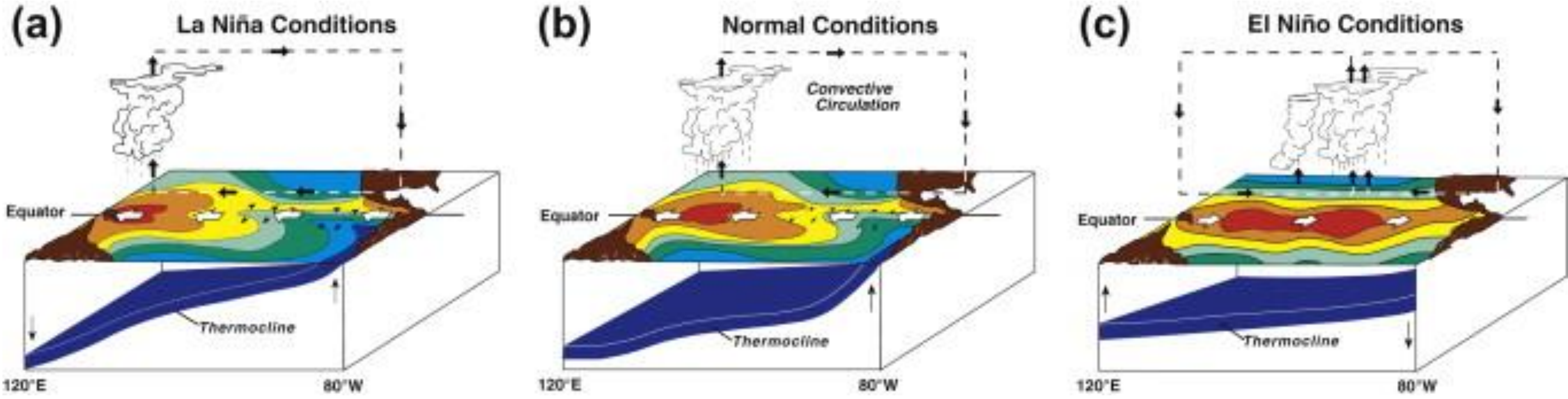


Normal conditions in the tropical Pacific

El Niño conditions in the tropical Pacific

Surface Ocean Circulation

El Niño-Southern Oscillation (ENSO) events



https://www.sciencedirect.com/topics/earth-and-planetary-sciences/walker-circulation

Surface Ocean Circulation

El Niño-Southern Oscillation (ENSO) events

- In some years, the Walker circulation get strengthened resulting in stronger displacement of warm surface water from eastern to Western pacific.

- This leads to strong upwelling in the eastern Pacific and biological productivity enhancement.

- Western warm pool is shifted to far western boundary.

- These conditions are referred to as **La Niña**.

Surface Ocean Circulation

Southern Oscillation Index

- Weakening and strengthening of the trade winds lead to oscillation of the surface pressure between western and eastern Pacific.

- As we see, in non-ENSO (*normal* or *neutral*) year, there is low pressure at the surface of Australia and Indonesia and high pressure at the surface of in the central and eastern Pacific.

- ENSO (El Niño) year, this pattern reverses. **The pressure difference between eastern and western of the tropical Pacific is termed as Southern Oscillation Index (SOI)**.

- Strong positive values of SOI indicate La Niña conditions and strong negative values indicate El Niño conditions.

Surface Ocean Circulation

El Niño-Southern Oscillation (ENSO) events

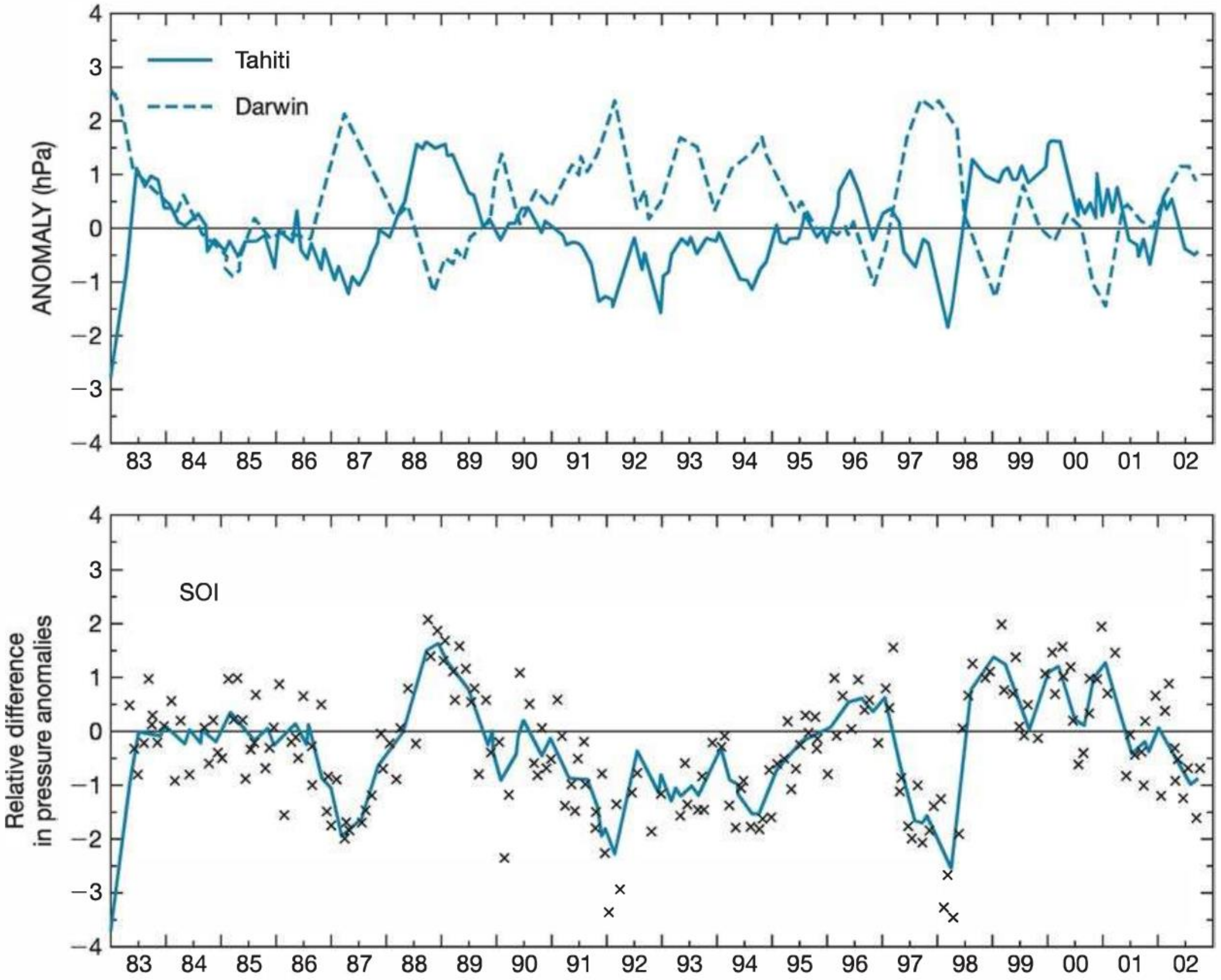


FIGURE 5-11 (a) The sea-level pressures at Tahiti and Darwin, Australia, and (b) the Southern Oscillation Index (SOI). The SOI is computed from the sea-level pressure differences. Negative values of the SOI indicate warm (El Niño) events. Note the strengths of the 1982–1983 and 1997–1998 events. (*Source:* NOAA Climate Prediction Center http://www.cpc.ncep.noaa.gov/data/indices/).

Surface Ocean Circulation

Climate Impacts of ENSO

- The most dramatic impact of ENSO events are seen in the rainfall pattern.

- In non-ENSO years, summertime convection and rainfall occur over Australia and Indonesia. In contrast, there are dry conditions (subsidence) west of the Andes.

- However, in ENSO years, the dominant convective region shifts toward central Pacific and convection and rainfall over Australia and Indonesia diminish. This leads to drought in Australia, Indonesia, and southeast Africa and anomalously high rainfall in the central Pacific and on the western slopes of the Andes in Ecuador and Peru.

- Peatland fires in Indonesia are enhanced due to dry conditions. As a result, large amount of organically stored CO_2 is released degrading the air quality severely.

- You may read https://www.unep.org/news-and-stories/story/how-countries-can-tackle-devastating-peatland-wildfires

Surface Ocean Circulation

Climate Impacts of ENSO

- In ENSO years, upwelling shuts off in the eastern pacific (coast of Peru) leading to a massive loss of fish production.

- ENSO events also have some effect on the monsoon circulation over India. Resulting in increased rain over southern India and reduced rainfall over northern India and Himalayas.

- ENSO evens impact the overall atmospheric circulation having it consequences in regions other than tropics also.

Deep Ocean Circulation

Thermohaline Circulation

- Deep-ocean circulation depends on temperature and salinity, so it is referred to as **thermohaline circulation.**

- Thermohaline circulation begins with the bottom-water formation, dense (cold and/or salty) water, at the high latitudes. The bottom water constitutes the densest water produced in the ocean.

- Near the poles, the surface waters are cooled below the freezing point and when it freezes it forms a layer of sea ice several meters thick that floats on the surface of the polar oceans.

Deep Ocean Circulation

Thermohaline Circulation

- Freezing results in the exclusion of the most of the salt because salt does not fit into the crystal structure of the ice.

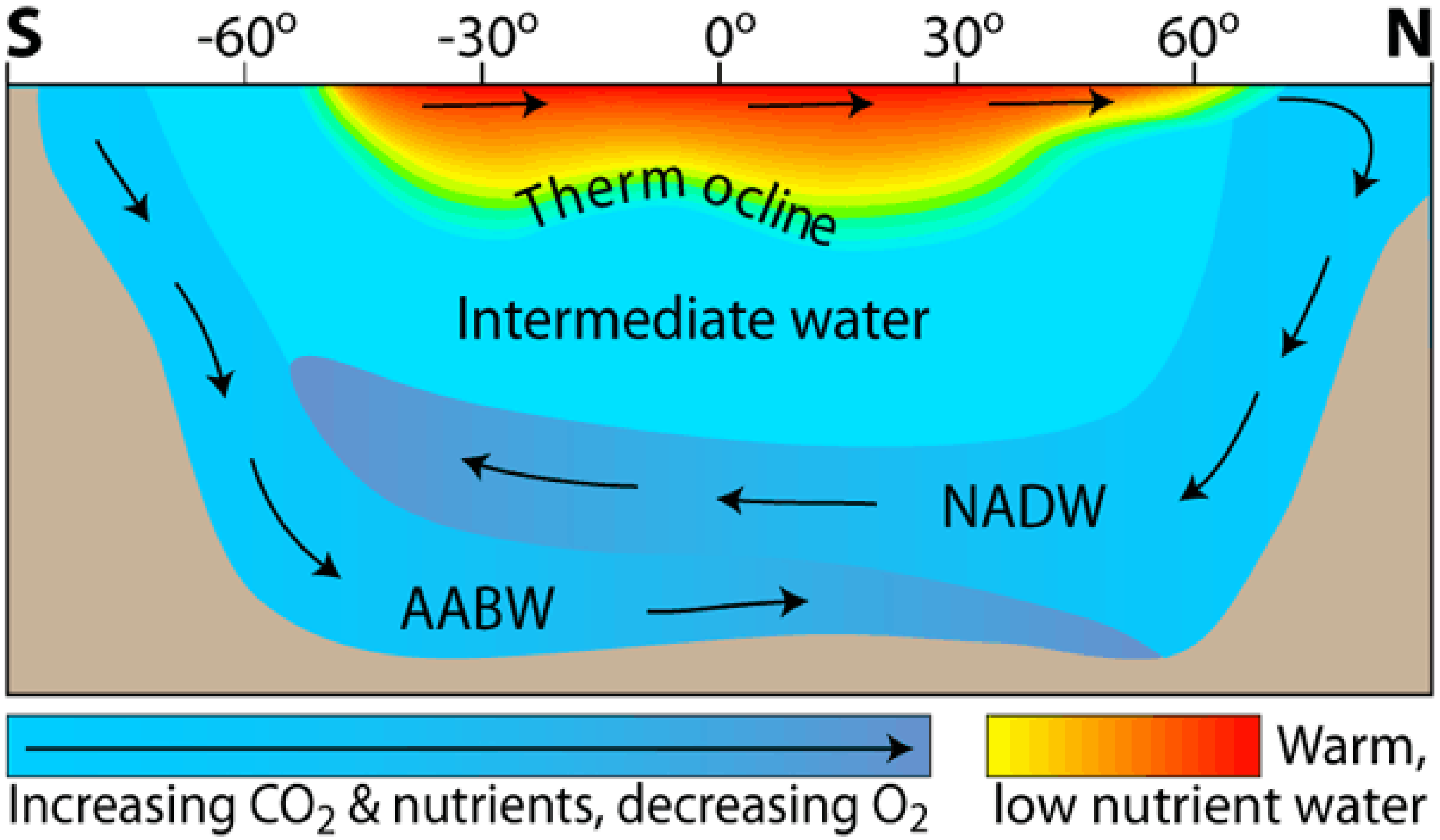
- Water just beneath the sea ice becomes saltier and an underlayer of very cold, high saline water forms.

- The combination of low temperatures and high salinity results in a very dense water that sinks and flows down the slope of the basin and spreads toward the equator as the bottom layer of the water in the deep-ocean basin. This leads to mixing with existing bottom water and upwelling in other regions.

Deep Ocean Circulation

Thermohaline Circulation

- **Antarctic Bottom Water (AABW)** forms in the Weddell Sea off Antarctica and flows northward as the deepest layer in all three major ocean basins: Atlantic, Pacific, and Indian Ocean. It can go up to 45° N in North Atlantic and 50 ° N in the North Pacific.

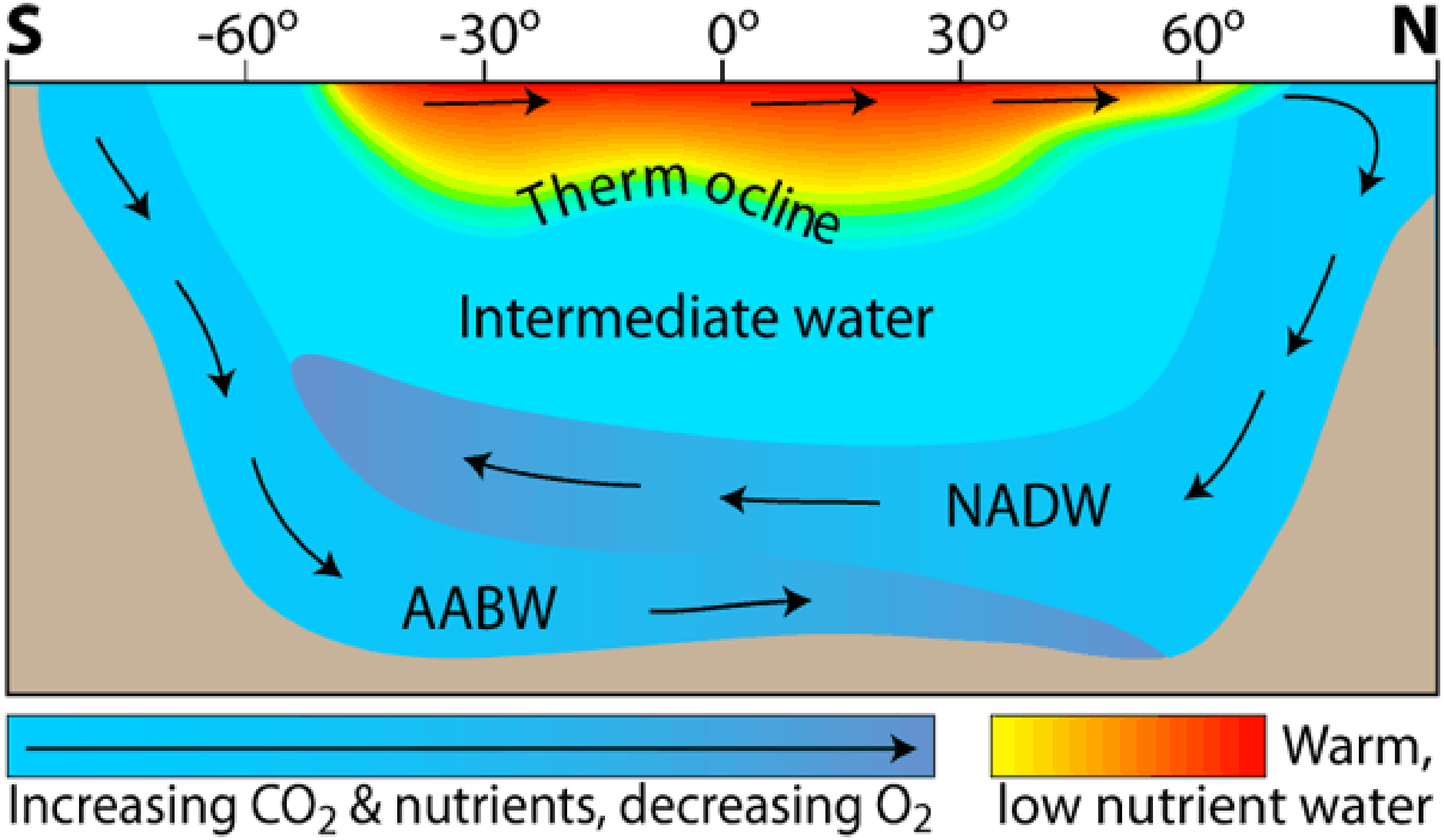


Deep Ocean Circulation

Thermohaline Circulation

- **North Atlantic Deep Water (NADW)** forms in the Arctic Ocean off the coast of Greenland and flows south at the depth into western North Atlantic and joins AABW.

- The sinking water at the high latitude is replaced by poleward flowing warm water. The sinking of water is also compensated by upwelling (Notice the biological productivity and marine life in eastern boundary region.



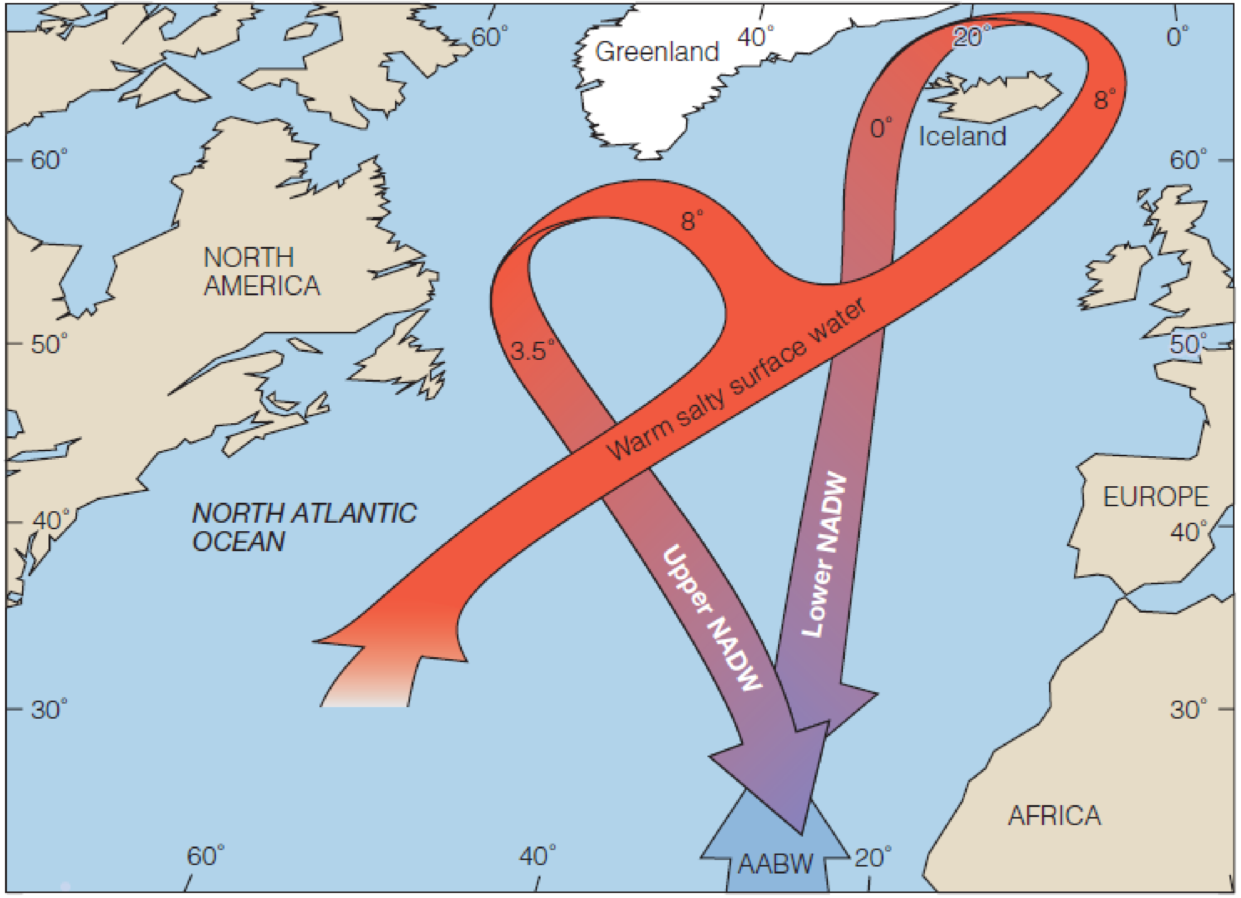


FIGURE 10.13 North Atlantic Deep Water
North Atlantic Deep Water (NADW) forms when the warm, salty water of the Gulf Stream/North Atlantic Current cools, becomes increasingly saline due to evaporation, and plunges downward to the ocean floor. The densest water then spills over the Greenland–Scotland ridge and flows southward as Lower NADW. Less dense water forming between Greenland and North America moves southeastward as Upper NADW and overrides denser Lower NADW. Because both water masses are less dense than northward-flowing Antarctic Bottom Water (AABW), they pass over it on their southward journey (as shown in a side view in Fig. 10.12).

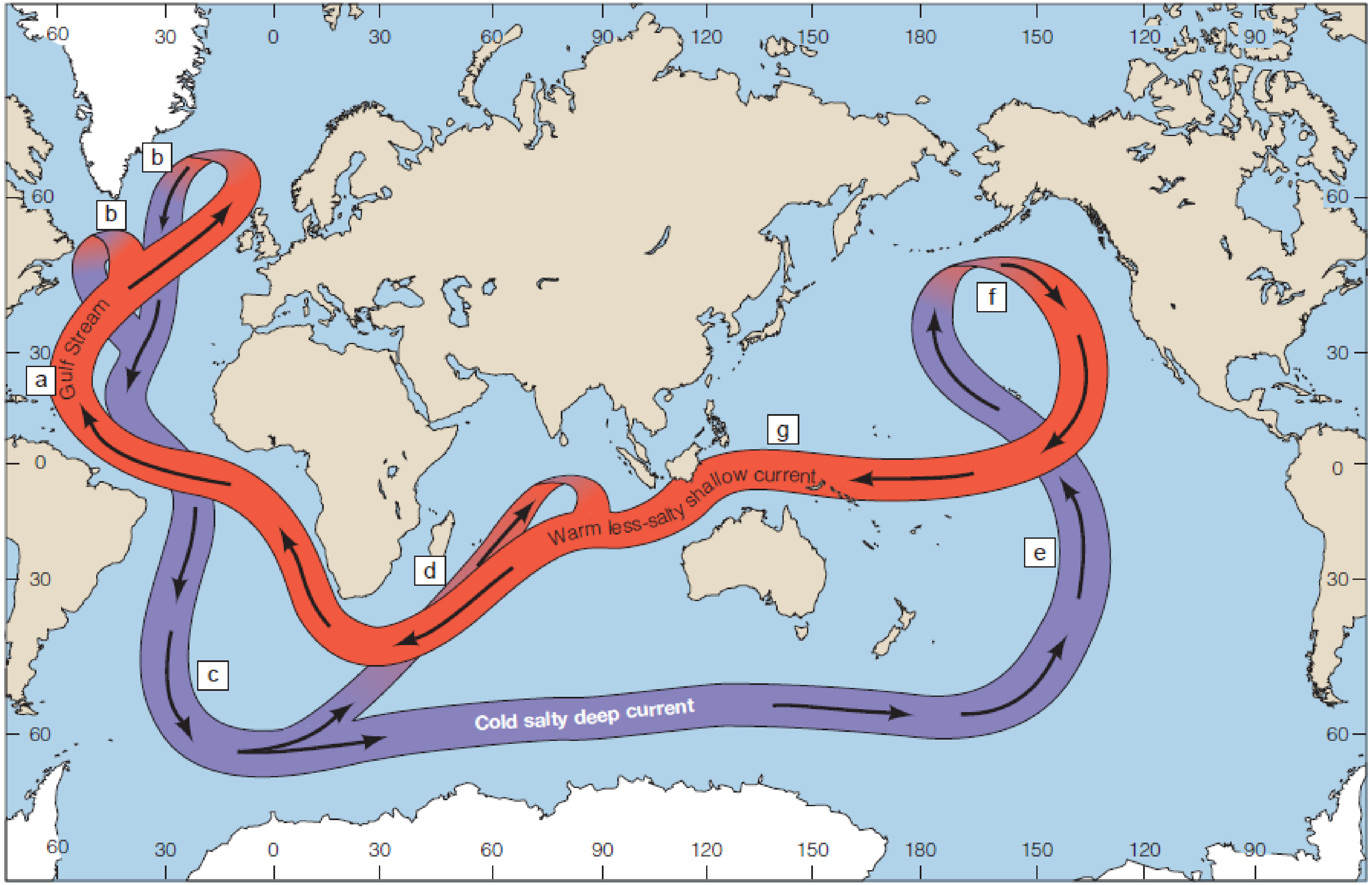


FIGURE 10.14 **The thermohaline circulation**
The major thermohaline circulation cells that make up the global ocean conveyor system are driven by the density of ocean water, which is in turn driven by the exchange of heat and moisture between the atmosphere and ocean. Warm water brought in by the Gulf Stream (*a*) cools and sinks at a number of sites in the North Atlantic (*b*). The North Atlantic Deep Water (NADW) spreads slowly along the ocean floor to the South Atlantic (*c*), eventually to enter both the Indian (*d*) and Pacific (*e*) oceans before slowly upwelling (*f*) and entering shallower parts of the thermohaline circulation cells. Meanwhile, Antarctic Bottom Water (AABW) forms adjacent to Antarctica (near *c*) and flows northward in fresher, colder circulation cells beneath warmer, more saline water in the South Atlantic (see Fig. 10.12) and South Pacific. Surface water warmed by solar energy flows into the western Pacific and Atlantic basins (*g*) to close the loop of the great global thermohaline cells.

Deep Ocean Circulation

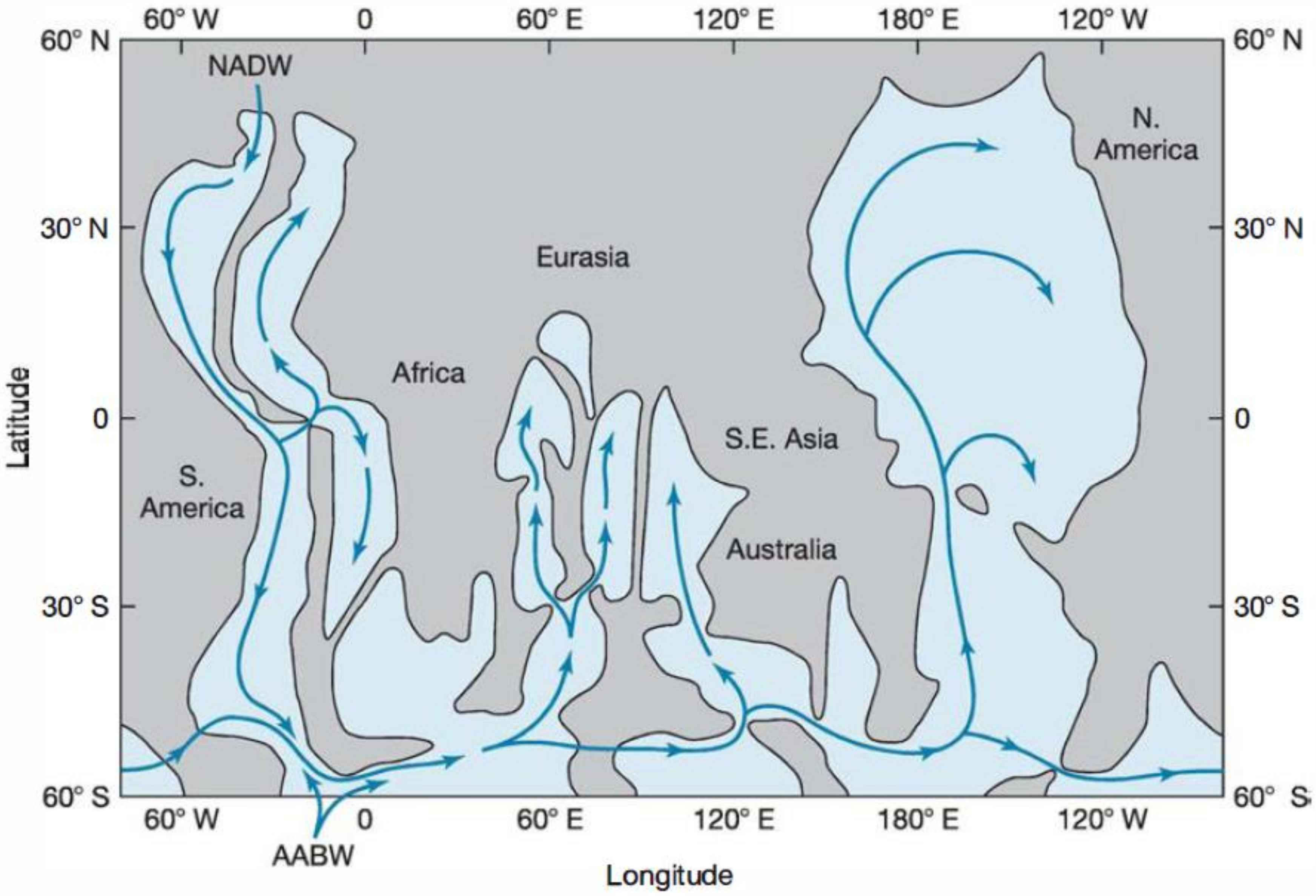


FIGURE 5-17 Flow pattern of the North Atlantic Deep Water and the Antarctic Bottom Water. This diagram represents the flow at a depth of 4000 m; the strange-looking continent/ocean configuration is what we would obtain if the oceans were drained to this depth. (*Source:* W. S. Broecker and T.-S. Peng, *Tracers in the Sea*, New York: Eldigio Press, 1982, Figure 1-12.)

Deep Ocean Circulation

Thermohaline Circulation

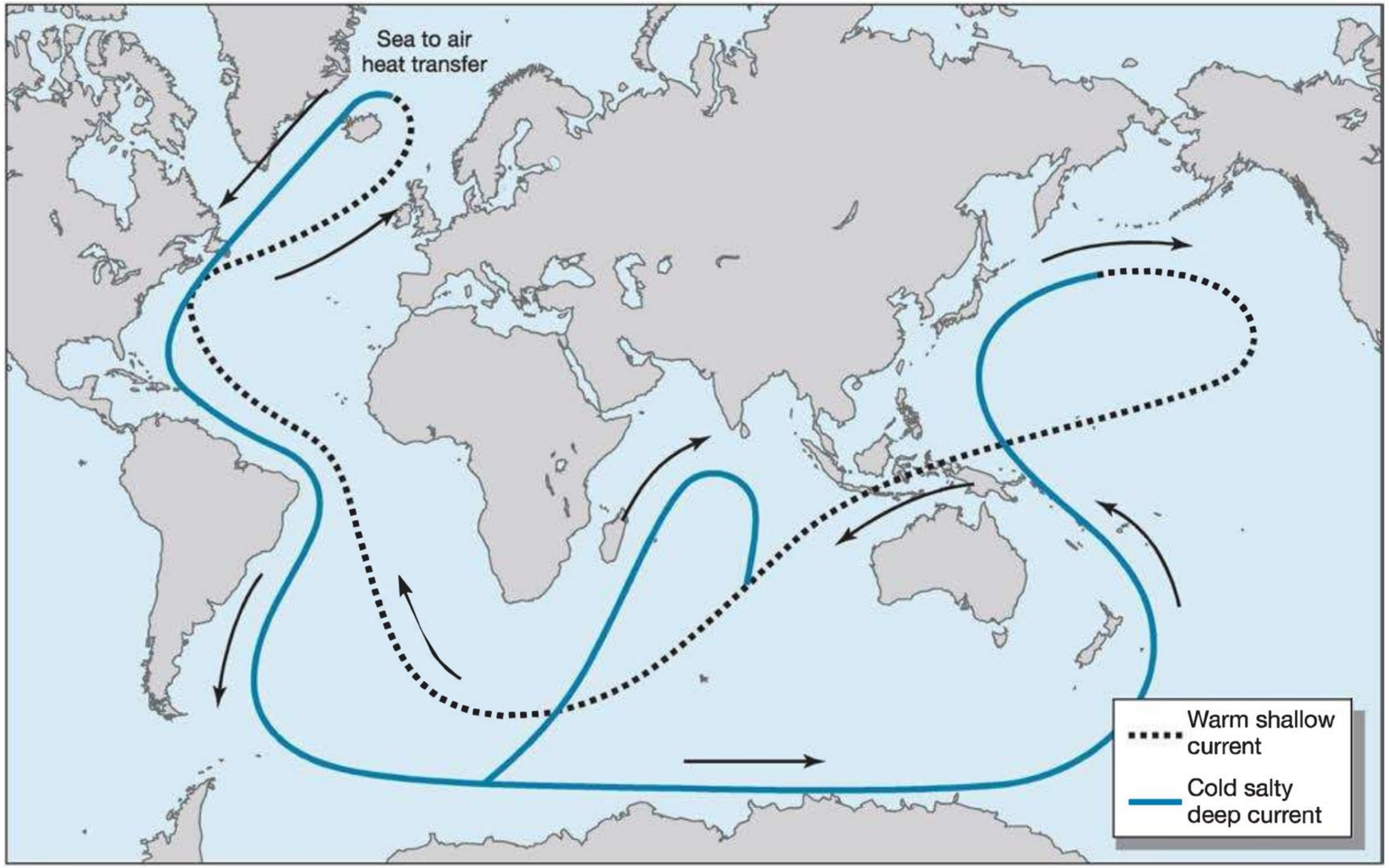


FIGURE 5-19 An idealized map of the deep-water flow (solid lines) and the returning surface circulation (dashed lines). This circulation has been described as a global conveyor belt. The deep water flows out of the North Atlantic, mixing with warmer water to the south. It is recooled by mixing with the cold surface water that subsides around Antarctica. Joining with the Antarctic Bottom Water, it flows around Antarctica in the Antarctic Circumpolar Current. Branches then flow back into the Atlantic as well as the Pacific and Indian oceans, where upwelling brings the cold waters to the surface. The water eventually returns via the surface currents to the North Atlantic to complete the circulation. (*Source:* From W. K. Hamblin and E. H. Christiansen, *Earth's Dynamic Systems*, 8/e, 1998. Reprinted by permission of Prentice Hall, Upper Saddle River, N.J.)

You may also look at this video: https://gpm.nasa.gov/education/videos/thermohaline-circulation-great-ocean-conveyor-belt

- It is roughly estimated that Antarctic bottom water (ABW) will reemerge at the surface in Indian ocean after ~335 years and in Pacific ocean after ~595 years.

- The average residence time for entire deep ocean is ~500 years.

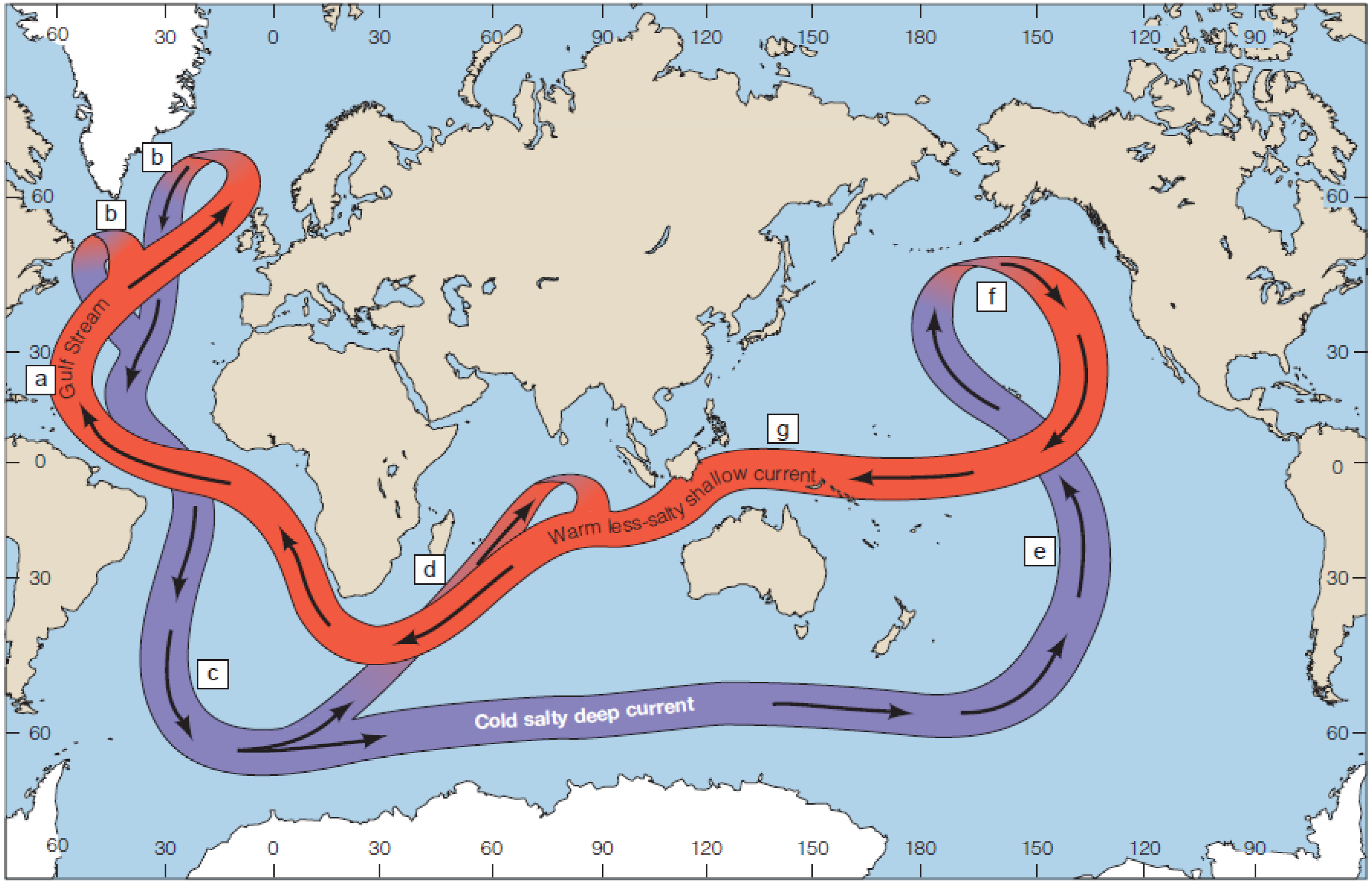


FIGURE 10.14 The thermohaline circulation

The major thermohaline circulation cells that make up the global ocean conveyor system are driven by the density of ocean water, which is in turn driven by the exchange of heat and moisture between the atmosphere and ocean. Warm water brought in by the Gulf Stream (*a*) cools and sinks at a number of sites in the North Atlantic (*b*). The North Atlantic Deep Water (NADW) spreads slowly along the ocean floor to the South Atlantic (*c*), eventually to enter both the Indian (*d*) and Pacific (*e*) oceans before slowly upwelling (*f*) and entering shallower parts of the thermohaline circulation cells. Meanwhile, Antarctic Bottom Water (AABW) forms adjacent to Antarctica (near *c*) and flows northward in fresher, colder circulation cells beneath warmer, more saline water in the South Atlantic (see Fig. 10.12) and South Pacific. Surface water warmed by solar energy flows into the western Pacific and Atlantic basins (*g*) to close the loop of the great global thermohaline cells.