CHAPTER 9: OCEAN CIRCULATION

Chapter 9: Ocean Circulation

Learning Objectives

After reading this chapter you should:

- know the major ocean surface currents of the world (i.e. the gyres) and how they are created
- know the features of the Gulf Stream, including the formation of warm and cold core rings
- understand the causes and effects of the Ekman spiral
- understand geostrophic flow, and how it helps keep the gyres flowing even when wind dies down.
- understand why gyre currents are more intense on the western side of the oceans – i.e. western intensification
- know what causes upwelling and downwelling, and the impacts of these events on primary production
- know the locations of some of the major upwelling regions on Earth
- understand the causes and effects of ENSO events
- understand Langmuir cells
- understand the processes that drive thermohaline circulation
- understand how T-S diagrams work
- know the major global sites of deep water formation
- be familiar with the major global water masses
- understand how deep water circulates throughout the world ocean

Ocean waters are constantly in motion, from ocean-scale surface currents, to density-driven vertical turnover, to small rotating eddies. Oceanographers have an array of sophisticated tools to measure ocean currents, but from time to time, fortuitous accidents can also aid our understanding of ocean circulation. A great example is the case of the container ship *Ever Laurel*, which was on its way from Hong Kong to Tacoma, Washington, in January 1992, when 12 containers were washed overboard in a storm in the middle of the Pacific. One of the containers contained over 28,000 plastic bath toys, which were released into the ocean as the container hit the water. Ten months later, the bath toys began washing ashore, first near Sitka, Alaska, then elsewhere along the Alaskan coast, and by 1996, in Washington. Over the next two decades, some toys traveled as far as the Pacific coasts of South America and Australia, while others were found in the Arctic ice, and some even made it through the Arctic into the North Atlantic, washing up in Newfoundland and Scotland (Figure 9.1). There are still a few thousand of the toys floating around in the central North Pacific, and the paths taken by all of these toys have allowed oceanographers to study the movements of large-scale ocean surface currents.

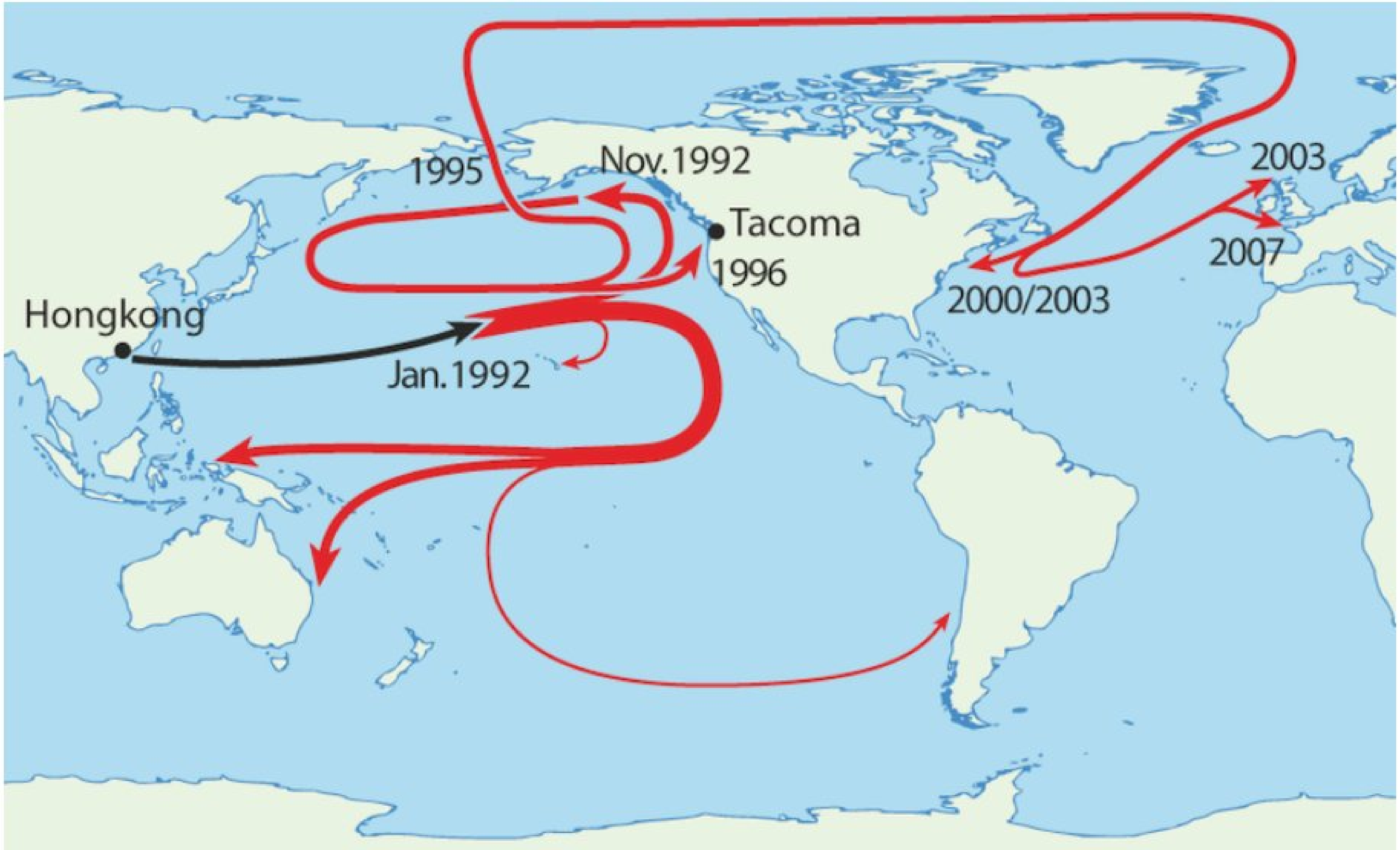


Figure 9.1 *Paths taken by the floating toys lost from the Ever Laurel in 1992, showing the years in which toys were found in different locations (NordNordWest [CC BY-SA 3.0] via Wikimedia Commons).*

9.1 Surface Gyres

In the previous chapter the major wind patterns on Earth were derived. It is these prevailing winds that blow across the water surface to create the major ocean surface currents. However, only about 2% of the wind energy is actually transferred to the water, so a 50 knot wind only creates a 1 knot current. Furthermore, wind-driven surface currents only affect the top 100-200m of water, meaning surface currents only involve about 10% of the world's ocean water. In section 9.8 we will examine deep, thermohaline circulation, which impacts around 90% of the ocean water.

Surface currents generally move in the same direction as the winds that created them. However, because of Coriolis deflection, the surface currents are offset approximately 45^o relative to the wind direction; 45^o to the right in the Northern Hemisphere, and 45^o to the left in the Southern Hemisphere. This creates a general circulation pattern where in both hemispheres, surface currents flow east to west between the equator and 30^o latitude, west to east between 30^o and 60^o, and east to west between 60^o and the poles (Figure 9.1.1).

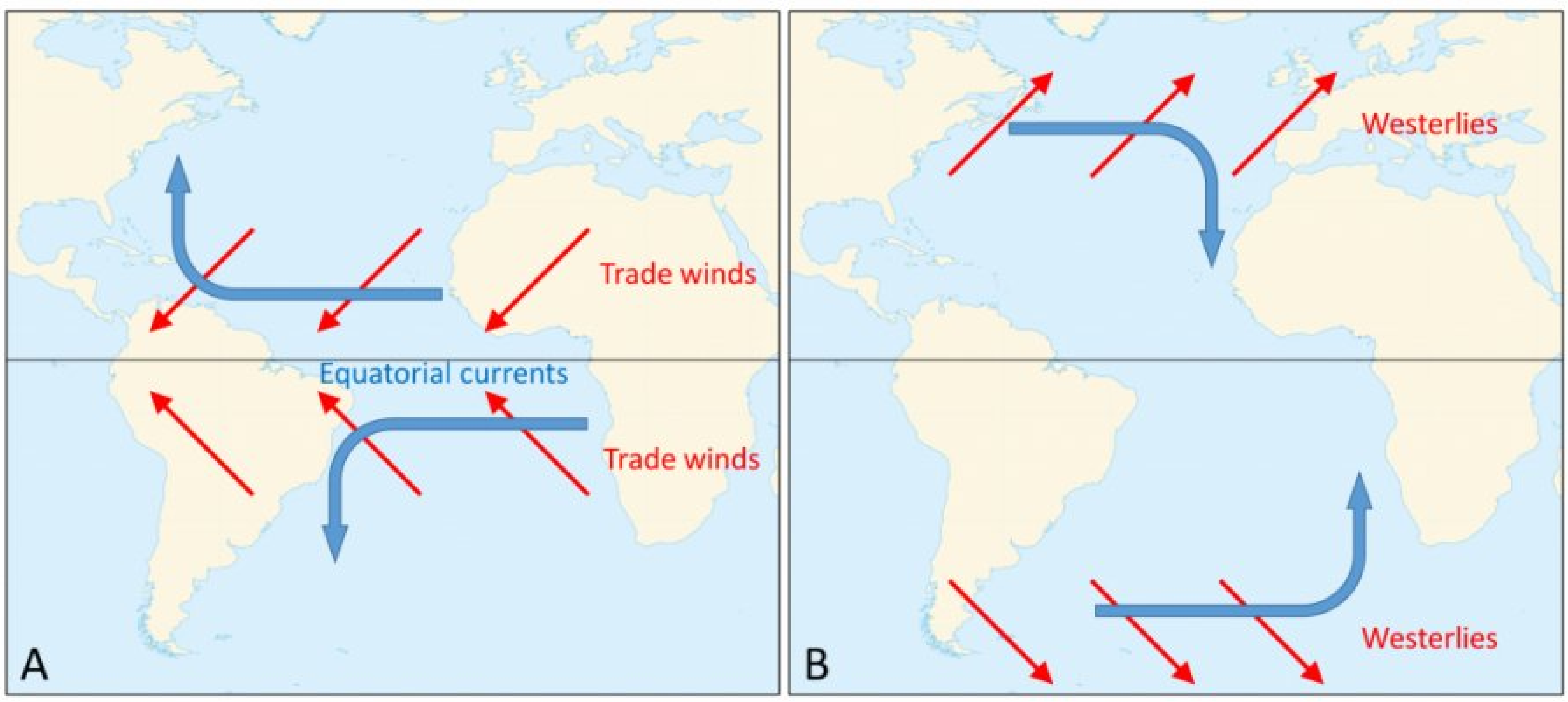


Figure 9.1.1 *Generalized surface currents in the Atlantic Ocean. A) Surface water moving at 45^o relative to the trade winds create the westward flowing equatorial currents. B) Between 30-60^o latitude, the westerlies form eastward flowing surface currents (PW, map by Catrin (Own work, Using GMT) [CC BY-SA 3.0], via Wikimedia Commons).*

The trade winds create the equatorial currents that flow east to west along the equator; the North Equatorial and South Equatorial currents. If there were no continents, these surface currents would travel all the way around the Earth, parallel to the equator. However, the presence of the continents prevents this unimpeded flow. When these equatorial currents reach the continents, they are diverted and deflected away from the equator by the Coriolis Effect; deflection to the right in the Northern Hemisphere and to the left in the Southern Hemisphere. These currents then become western boundary currents; currents that run along the western side of the ocean basin (i.e. the east coasts of the continents). Since these currents come from the equator, they are warm water currents, bringing warm water to the higher latitudes and distributing heat throughout the ocean.

At the same time, between 30-60^o latitude the westerlies move surface water towards the east. The Coriolis Effect and the presence of the continents deflect the currents towards the equator, creating eastern boundary currents (on the eastern side of the ocean basins). These currents come from high latitude areas, so they deliver cold water to the lower latitudes. Together, these currents combine to create large-scale circular patterns of surface circulation called **gyres**. In the Northern Hemisphere the gyres rotate to the right (clockwise), while in the Southern Hemisphere the gyres rotate to the left (counterclockwise).

There are five major gyres in the oceans; the North Atlantic, South Atlantic, North Pacific, South Pacific, and Indian (Figure 9.1.2). The North Pacific gyre is composed of the North Equatorial Current on its southern boundary, which turns into the Kuroshio Current (a.k.a. the Japan Current) bringing warm water north towards Japan. The Kuroshio flows into the North Pacific Current which moves east towards North America, where it becomes the California Current to complete the gyre. The North Atlantic gyre is formed by the North Equatorial Current flowing into the Gulf Stream along the east coast of the United States. The Gulf Stream merges into the North Atlantic Current to move water towards Europe, which then becomes the Canary Current as it moves south to join the North Equatorial Current.

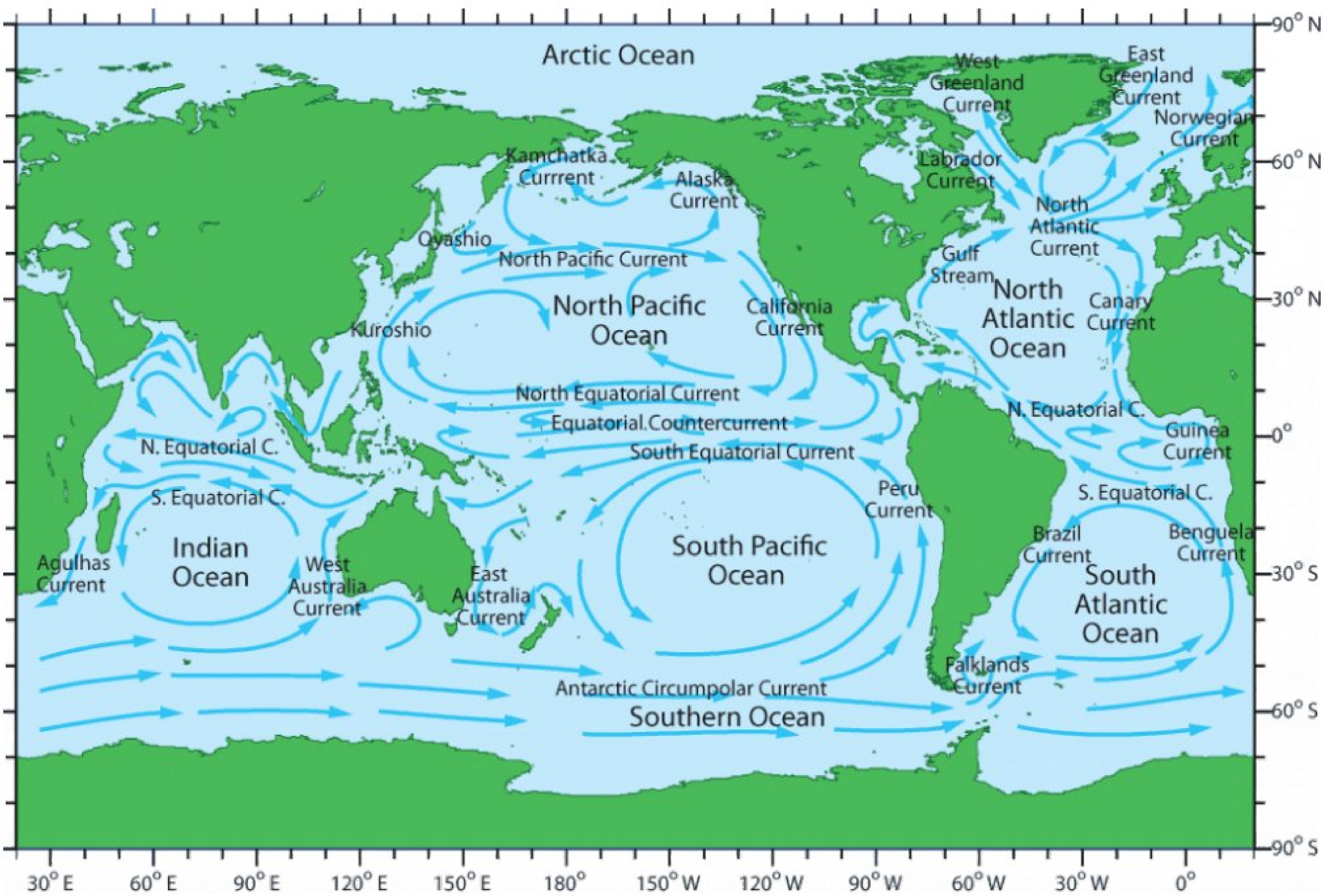


Figure 9.1.2 *The major global surface currents (http://www.seos-project.eu/modules/oceancurrents/oceancurrents-c02-p01.html, Source: NOC; CC BY-NC-SA 2.0).*

Near Antarctica the circulation is somewhat different. Because there is little in the way of continental land masses between 50-60° south, the surface current created by the westerly winds can make its way completely around the Earth, creating the Antarctic Circumpolar Current (ACC) or West Wind Drift (WWD) that flows from west to east (Figure 9.1.2). The Antarctic Circumpolar Current is the only current that connects all of the major ocean basins, and in terms of the amount of water that it transports, it is the largest surface current on Earth. Above 60° latitude the prevailing winds are the polar easterlies, which create a current flowing from east to west along the edge of the Antarctic continent, the East Wind Drift or the Antarctic Coastal Current.

The Antarctic Circumpolar Current creates the southern boundary for all of the Southern Hemisphere gyres. In the South Pacific gyre the ACC becomes the Peru Current (also known as the Humboldt Current) moving up the west coast of South America, before joining the South Equatorial Current. The South Equatorial Current flows southwards as the East Australia Current, before completing the gyre with the ACC. The South Atlantic gyre is composed of the South Equatorial Current, the Brazil Current, the ACC, and the Benguela Current. Finally, the currents making up the Indian gyre are the ACC, the West Australia Current, the South Equatorial Current, and the Agulhas Current.

Not all of the equatorial water that is moved westward by the trade winds and reaches the continents gets transported to higher latitudes in the gyres, because the Coriolis Effect is weakest along the equator. Instead, some of the water piles up along the western edge of the ocean, and then flows eastward due to gravity, creating narrow Equatorial Countercurrents between the North and South Equatorial Currents (Figure 9.1.2). Some of this water also moves east as equatorial undercurrents that flow at depths between 50-200 m, underneath the Equatorial Currents. These undercurrents are called the Lomonosov Current in the Atlantic, and the Cromwell Current in the Pacific.

9.2 The Gulf Stream

The primary surface current along the east coast of the United States is the Gulf Stream, which was first mapped by Benjamin Franklin in the 18th century (Figure 9.2.1). As a strong, fast current, it reduced the sailing time for ships traveling from the United States back to Europe, so sailors would use thermometers to locate its warm water and stay within the current.

Figure 9.2.1 *Benjamin Franklin's original map of the Gulf Stream (Public domain, via Wikimedia Commons).*

The Gulf Stream is formed from the convergence of the North Atlantic Equatorial Current bringing tropical water from the east, and the Florida Current that brings warm water from the Gulf of Mexico. The Gulf Stream takes this warm water and transports it northwards along the U.S. east coast (Figure 9.2.2). As a western boundary current, the Gulf Stream experiences western intensification (section 9.4), making the current narrow (50-100 km wide), deep (to depths of 1.5 km) and fast. With an average speed of 6.4 km/hr, and a maximum speed of about 9 km/hr, it is the fastest current in the world ocean. It also transports huge amounts of water, more than 100 times greater than the combined flow of all of the rivers on Earth.

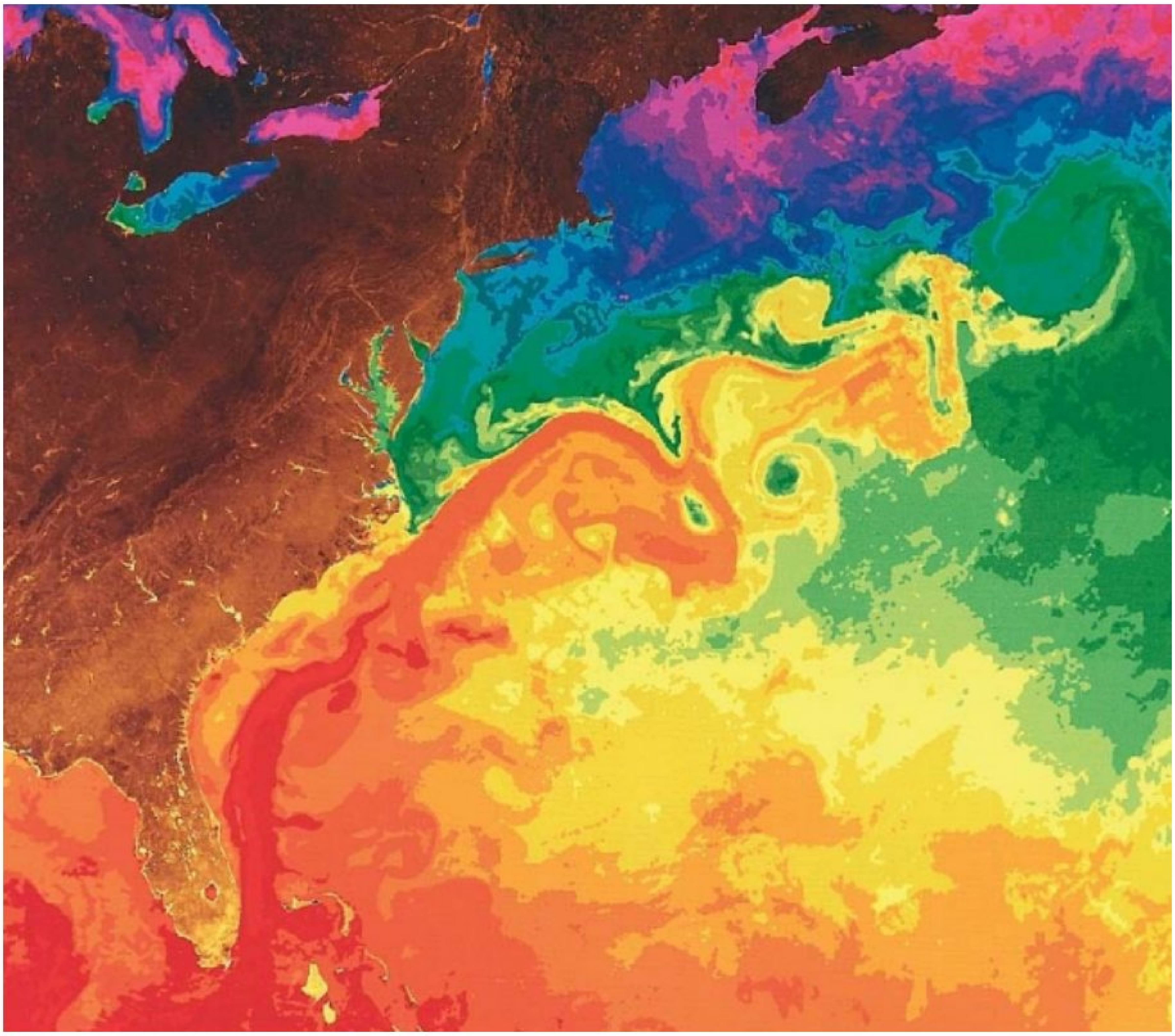


Figure 9.2.2 Sea surface temperature map illustrating the Gulf Stream. Warmer water is shown in red, colder water in blue and violet. Meanders and eddies are visible where the current moves towards the northeast (NASA, Public Domain via Wikimedia Commons).

As the Gulf Stream approaches Canada, the current becomes wider and slower as the flow dissipates and it encounters the cold Labrador Current moving in from the north. At this point, the current begins to meander, or change from a fast, straight flow to a slower, looping current (Figure 9.2.2). Often these meanders loop so much that they pinch off and form large rotating water masses called **rings** or **eddies**, that separate from the Gulf Stream. If an eddy pinches off from the north side of the Gulf Stream, it entraps a mass of warm water and moves it north into the surrounding cold water of the North Atlantic. These **warm core rings** are shallow, bowl-shaped water masses about 1 km deep, and about 100 km across, that rotate clockwise as they carry warm water in to the North Atlantic (Figure 9.2.3). If the meanders pinch off at the southern boundary of the Gulf Stream, they form **cold core rings** that rotate counterclockwise and move to the south. Cold core rings are cone-shaped water masses extending down to over 3.5 km deep, and may be over 500 km wide at the surface.

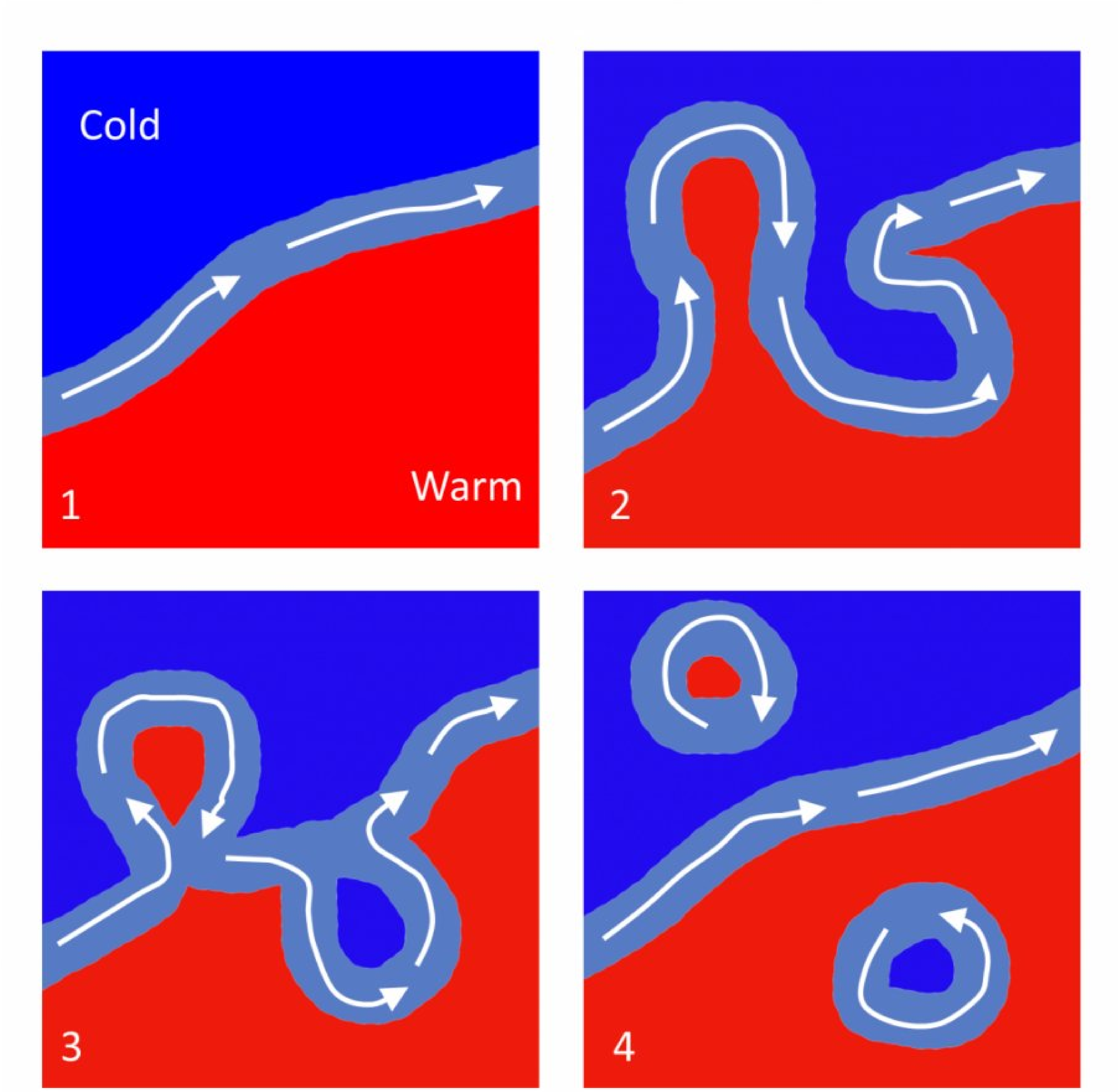


Figure 9.2.3 *Formation of warm and cold core rings from meanders in the Gulf Stream. As the Gulf Stream flows to the northeast (1), it starts to meander as it slows, forming warm or cold water extensions on either side of the current (2). If the meanders pinch off the extensions, they trap pockets of warm or cold water (3), that can separate from the Gulf Stream and travel north or south. Warm core rings rotate clockwise, while cold core rings rotate counterclockwise (4) (PW).*

After the Gulf Stream meets the cold Labrador Current, it joins the North Atlantic Current, which transports the warm water towards Europe, where it moderates the European climate. It is estimated that Northern Europe is up to 9^{o} C warmer than expected because of the Gulf Stream, and the warm water helps to keep many northern European ports ice-free in the winter.

In the east, the Gulf Stream merges into the Sargasso Sea, which is the area of the ocean within the rotation center of the North Atlantic gyre. The Sargasso Sea gets its name from the large floating mats of the marine algae *Sargassum* that are abundant on the surface (Figure 9.2.4). These *Sargassum* mats may play an important role in the early life stages of sea turtles, who may live and feed within the algae for many years before reaching adulthood.

Figure 9.2.4 *Map of the Sargasso Sea (left), and closeup photo of Sargassum algae (right) (Map by USFWS; photo by Bogdan Giușcă; Public Domain via Wikimedia Commons).*

9.3 The Ekman Spiral and Geostrophic Flow

Ekman spiral

Winds blowing over the ocean are ultimately what create the surface currents. However, not all of the water moved by the surface currents is transported in the same direction. The Coriolis Effect causes the surface water to move in a direction about 45 degrees offset from the wind direction, with the deflection to the right of the wind in the Northern Hemisphere and to the left in the Southern Hemisphere. The frictional movement of the topmost layer of water sets in motion the layer directly underneath it, which then sets in motion the next layer under that, and so on as the water gets deeper. Some energy is lost in each transition, so each successive layer of water will not move as far as the layer above it; in other words, there is decreasing energy with increasing depth. But at the same time, the Coriolis Effect deflects each layer relative to the layer above it (again, to the right in the Northern Hemisphere and to the left in the Southern Hemisphere). The movement of the successive layers therefore creates a spiraling pattern of water motion called the **Ekman spira**l, which usually penetrates to about 100 m deep before the motion ceases. If the magnitudes and directions of the movements of each layer are added together, the result is that the net movement of the upper 100 m of the water column is 90° relative to the original wind direction (90° to the right of the wind in the Northern Hemisphere, and 90° to the left in the Southern Hemisphere). This net water movement is called **Ekman transport** (Figure 9.3.1).

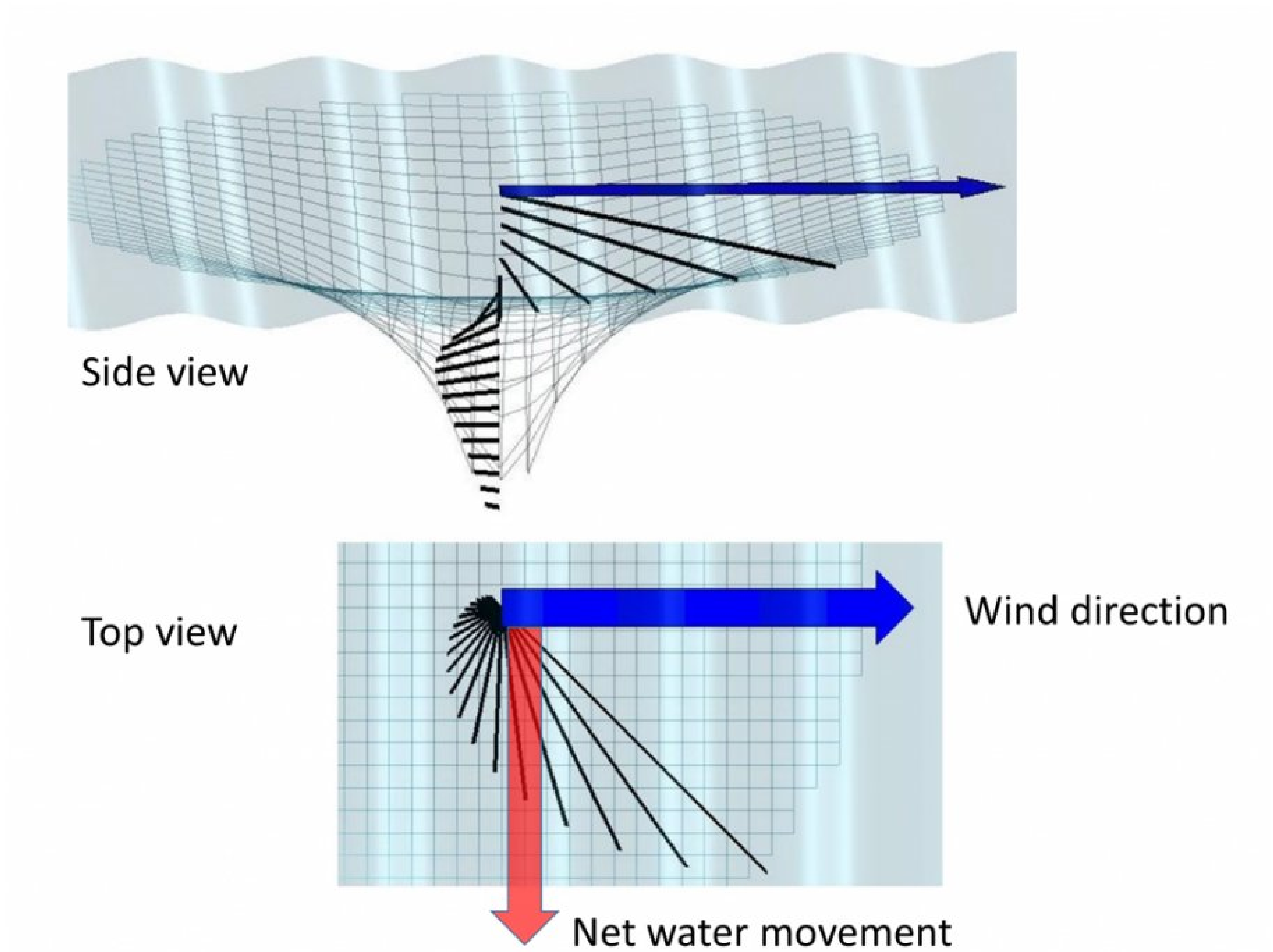


Figure 9.3.1 *The Ekman spiral, shown for the Northern Hemisphere. Wind blowing over the water (blue arrow) creates a surface current 45^{o} offset from the wind. Each successive layer of water is moved and deflected by the layer above, creating a spiraling pattern of water movement that diminishes with depth. The net movement of the water within the spiral is 90^{o} relative to the wind direction (red arrow) (Modified by PW from Ekman spiral By Schlusenbach (unbekannt) [Public domain], via Wikimedia Commons).*

Geostrophic flow

Gyre rotation is dependent on the wind and the Coriolis Effect impacting the surface currents (see section 9.1). But the rotation is also affected by movement below the surface due to Ekman transport. In the Northern Hemisphere, as the gyre rotates clockwise the net movement of the Ekman transport is 90^{o} to the right of the wind; in other words, towards the center of the gyre. The Ekman transport piles up water in the center of the gyre, making the water level higher in the gyre center than on the edges of the gyres. This pile of water then has a tendency to flow back "downhill" due to gravity. As the water flows "downhill" away from the gyre center, it is deflected to the right by the Coriolis force. This results in a clockwise current around the central "hill" called **geostrophic flow**, which moves in the same direction as the rotating gyre. Water is thus pushed into the "hill" by Ekman transport, and away from the "hill" by gravity, with both flows modified by the Coriolis Effect to create the rotation. As with the gyres, geostrophic flow is clockwise in the Northern Hemisphere, and counterclockwise in the Southern Hemisphere.

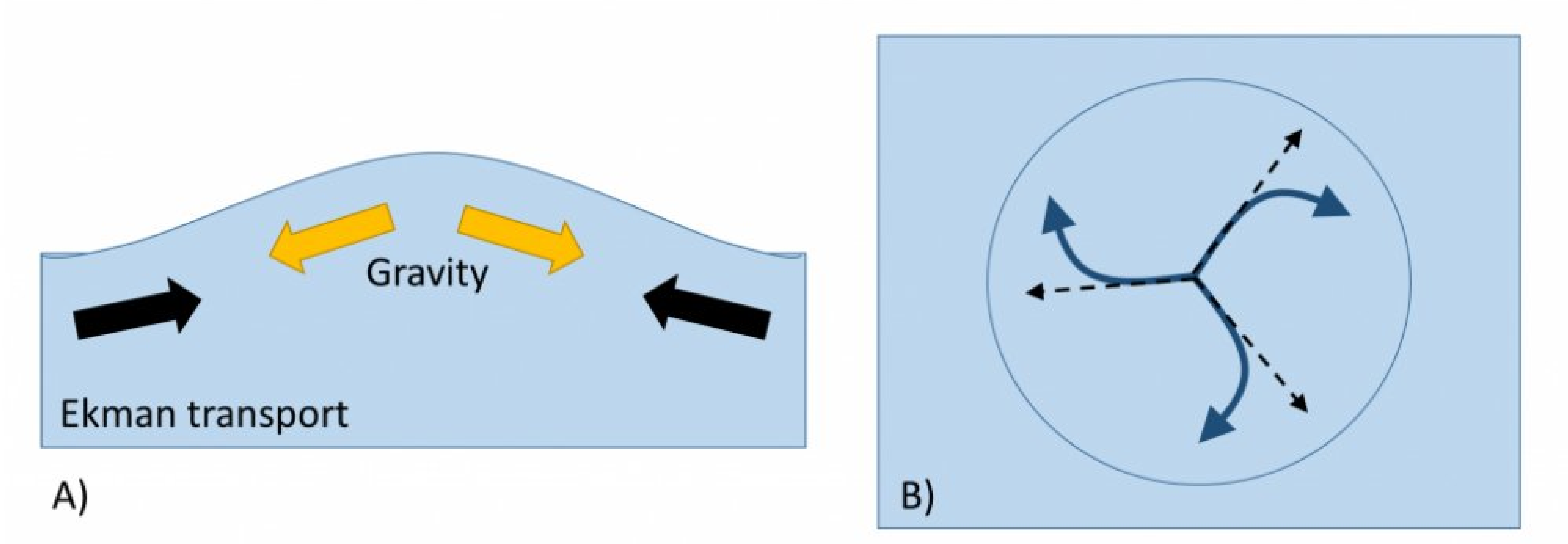


Figure 9.3.2 *Geostrophic flow in the Northern Hemisphere. A) Ekman transport moves water into the middle of the gyre, where it "piles up." Gravity causes the water to flow back "downhill." B) Viewed from above, as the water in the center flows "downhill" (dotted arrows) the Coriolis force deflects the movement to the right (solid arrows), causing the system to rotate clockwise (PW).*

Most major surface currents are a combination of wind-driven and geostrophic currents. Since winds can be variable, geostrophic flow ensure that the gyre currents keep moving at a fairly constant rate even when the wind dies down. The larger the area, and the higher the slope, the longer the geostrophic flow will continue to move and power the gyre after the wind subsides.

9.4 Western Intensification

In both hemispheres, the currents making up the western side of the gyre are much more intense than the currents on the eastern side. In other words, the currents off of the east coast of the continents are more intense than currents off of the west coast of the continents. This phenomenon is known as western intensification, and once again it is due to the Coriolis Effect.

As discussed in section 8.2, the Coriolis Effect is a result of the fact that different latitudes of the Earth are rotating at different speeds, and the apparent path taken by an object is deflected as it moves between areas of different rotation speeds. The greater the change in rotation speed, the stronger the Coriolis force. At the poles, the speed of rotation is 0 km/hr. The speed increases to about 800 km/hr at 60^{o} latitude, 1400 km/hr at 30^{o} latitude, and 1600 km/hr at the equator. Therefore there is an 800 km/hr difference between 60^{o} and 90^{o} latitude, while there is only a 200 km/hr difference between the equator and 30^{o}. Thus the speed of Earth's rotation changes more quickly with latitude near the poles than at the equator, making the Coriolis force strongest near the poles and weakest at the equator.

The high latitude surface currents of the major gyres experience a strong Coriolis force due to their proximity to the poles. As the currents move eastward, the strong Coriolis force begins to deflect the currents towards the equator relatively early. The currents on the eastern side of the gyre are therefore spread out over a wide area as they move towards the equator (Figure 9.4.1). Near the equator, the westward flowing currents experience a much weaker Coriolis force, so their deflection does not happen until the current is all the way over to the western side of the ocean basin. These western currents must therefore move through a much narrower area (Figure 9.4.1). This imbalance means that the center of rotation of the gyre is not in the center of the ocean basins, but it closer to the western side of the gyre.

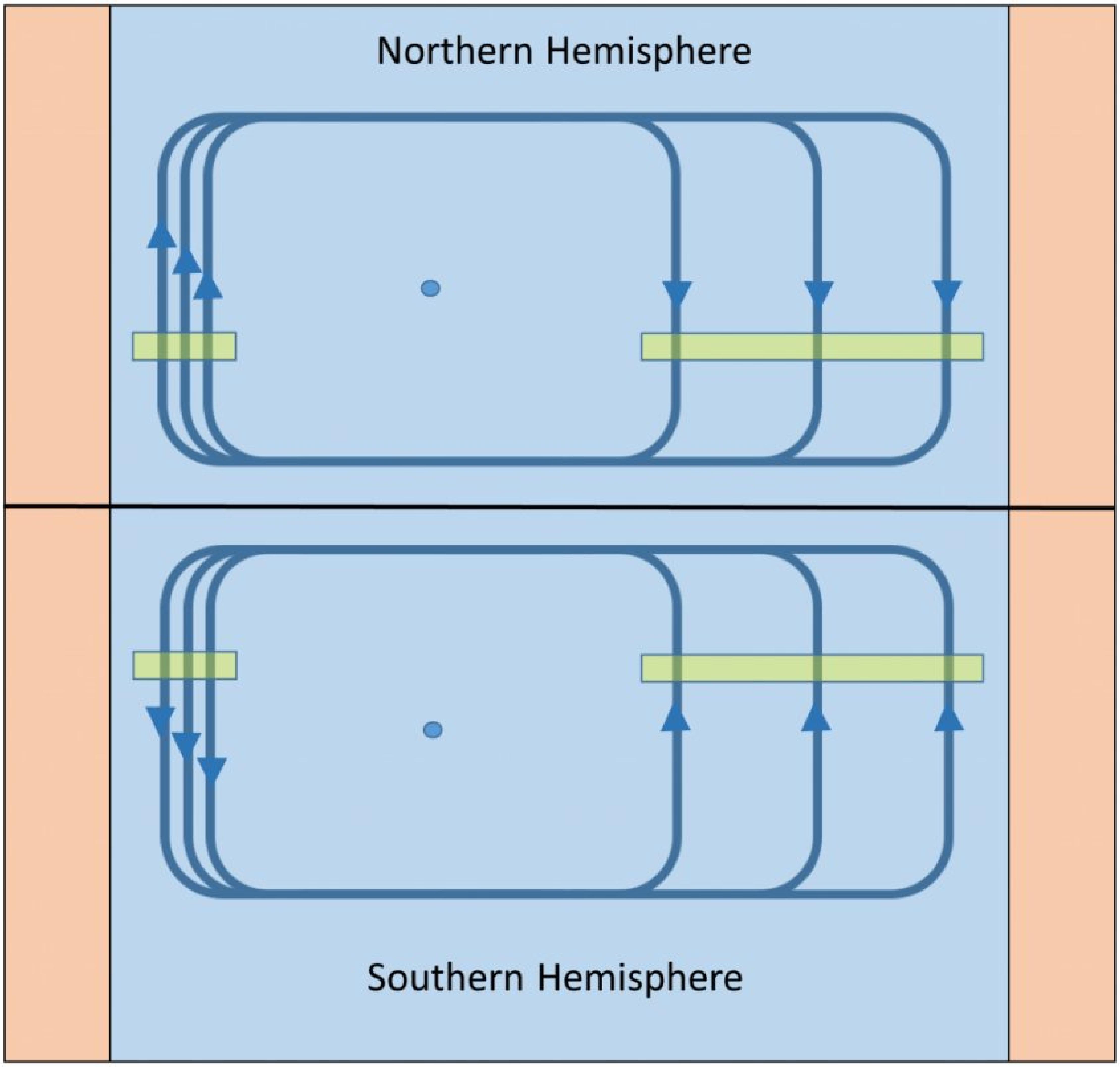


__Figure 9.4.1__ Western intensification. In both hemispheres, currents on the western side of the gyres travel through a much narrower area than the currents on the eastern side (yellow rectangles). To move the same volume of water through each side, western boundary currents are faster, deeper, and narrower than eastern boundary currents. The center of rotation of the gyre is also closer to the western side of the gyre (blue dots) (PW).

The same volume of water must pass through both the east and west sides of the gyre. In the western gyre currents, that volume is passing through a narrower area, so the current must travel faster in order to transport the same amount of water in the same amount of time. On the eastern side of the gyre the current is much wider, so the flow is slower. A simple analogy is the water flowing from a garden hose. You can make the water flow from the hose much faster and more strongly by covering part of the opening with your thumb. The same amount of water is exiting the hose whether the opening is covered or uncovered, but to get that water through the covered opening the flow has to be much faster and stronger. In the same way, western boundary currents are not only faster, but also deeper than eastern boundary currents, as they move the same volume through a narrower space. For example, the Kuroshio Current in the western Pacific is around 15 times faster, 20 times narrower, and 5 times deeper than the California Current in the eastern Pacific.

9.5 Currents, Upwelling and Downwelling

The movement of surface currents also plays a role in the vertical movements of deeper water, mixing the upper water column. **Upwelling** is the process that brings deeper water to the surface, and its major significance is that it brings nutrient-rich deep water to the nutrient-deprived surface, stimulating primary production (see section 7.3). **Downwelling** is where surface water is forced downwards, where it may deliver oxygen to deeper water. Downwelling leads to reduced productivity, as it extends the depth of the nutrient-limited layer.

Upwelling occurs where surface currents are diverging, or moving away from each other. As the surface waters diverge, deeper water must be brought to the surface to replace it, creating upwelling zones. The upwelled water is cold and rich in nutrients, leading to high productivity. Many of the most productive regions on Earth are found in upwelling zones. In the equatorial Pacific, the trade winds blow the North and South Equatorial Currents towards the west, while Ekman transport causes the upper layers to move to the north and south in their respective hemispheres. This creates a divergence zone, and a region of upwelling and high productivity (Figure 9.5.1).

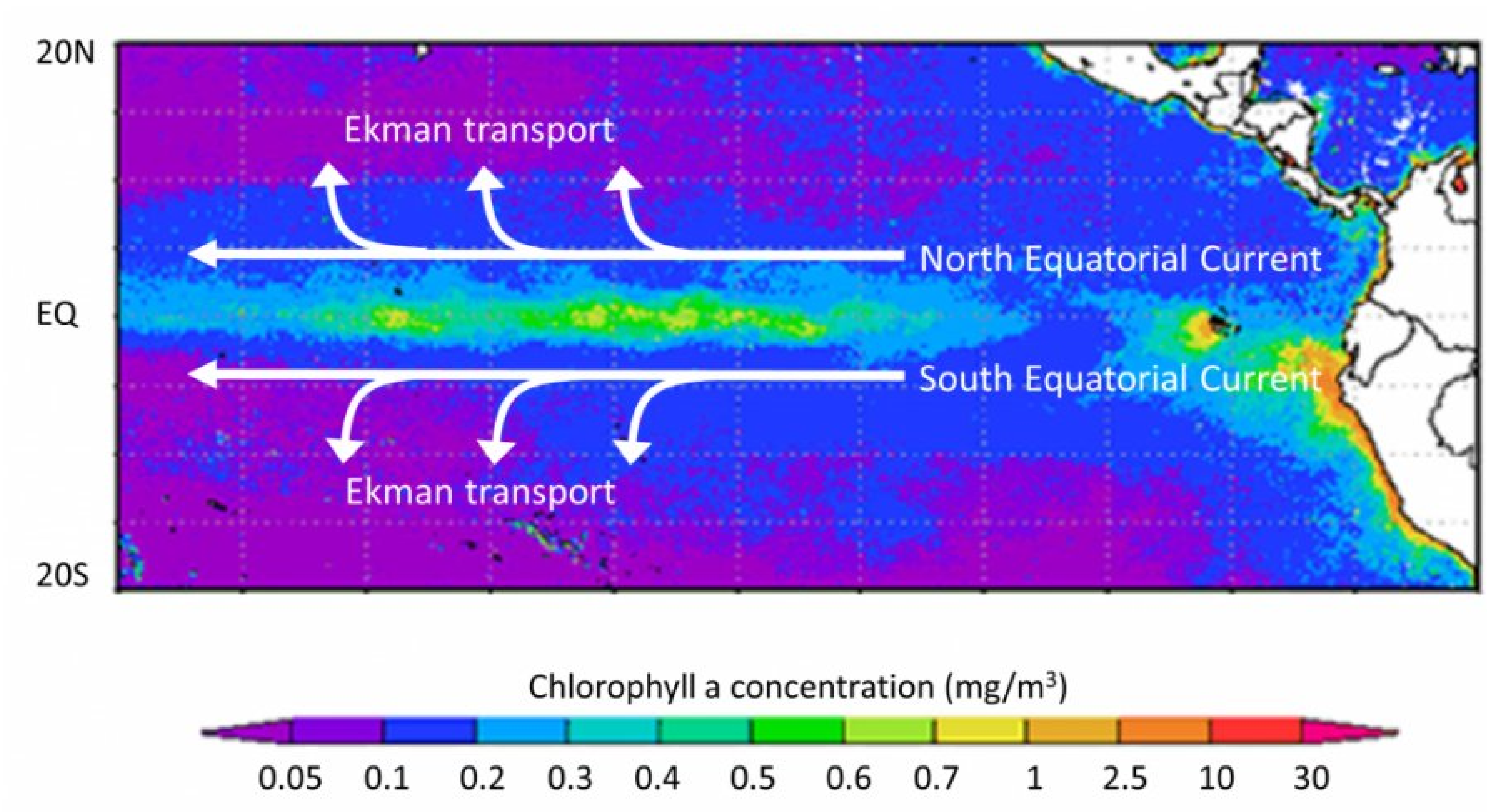


Figure 9.5.1 *Equatorial upwelling and increased productivity as a result of divergence between the north and south equatorial currents (Modified by PW from image by NASA [Public domain], via Wikimedia Commons).*

A similar process occurs near the Antarctic continent, creating one of the most productive regions on Earth, the Antarctic divergence. In this case, the West Wind Drift (Antarctic Circumpolar Current) is flowing parallel to, but in the opposite direction of the East Wind Drift. With both currents occurring in the Southern Hemisphere, Ekman transport will be to the left, so the eastward-flowing West Wind Drift water will be transported to the north, and the westward-flowing East Wind Drift water will be transported to the south, creating a highly productive divergence zone (Figure 9.5.2).

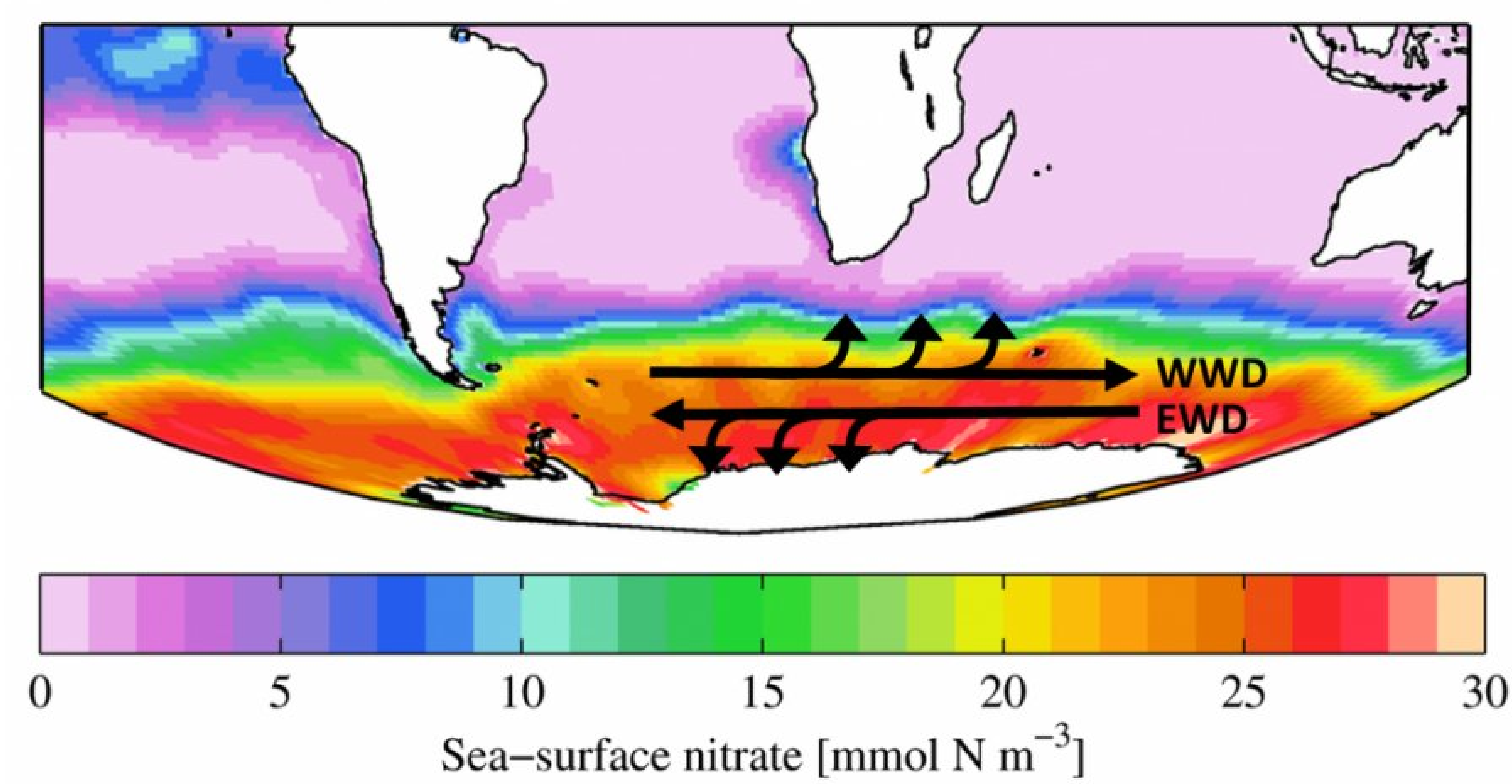


Figure 9.5.2 *High nutrient levels in the Antarctic divergence zone, as a result of the diverging West Wind Drift and East Wind Drift currents creating strong upwelling (Modified by PW from Plumbago (Own work) [CC BY-SA 3.0], via Wikimedia Commons).*

Downwelling occurs where surface currents converge. The converging water has nowhere to go but down, so the surface water sinks. Since surface water is usually low in nutrients, downwelling leads to low productivity zones. An example of a downwelling region is off of the Labrador coast in Canada, where the Gulf Stream, Labrador, and East Greenland Currents converge.

Coastal Upwelling

Upwelling and downwelling also occur along coasts, when winds move water towards or away from the coastline. Surface water moving away from land leads to upwelling, while downwelling occurs when surface water moves towards the land. Historically, some of the most productive commercial fishing grounds have been associated with coastal upwelling. Along the coast of California, the local prevailing winds blow towards the south. Ekman transport moves the surface layer 90° to the right of the wind, meaning the net Ekman transport is in an offshore direction. The water displaced near the coast is replaced by cold, nutrient-rich deeper water that is brought to the surface through upwelling, leading to high productivity (Figure 9.5.3).

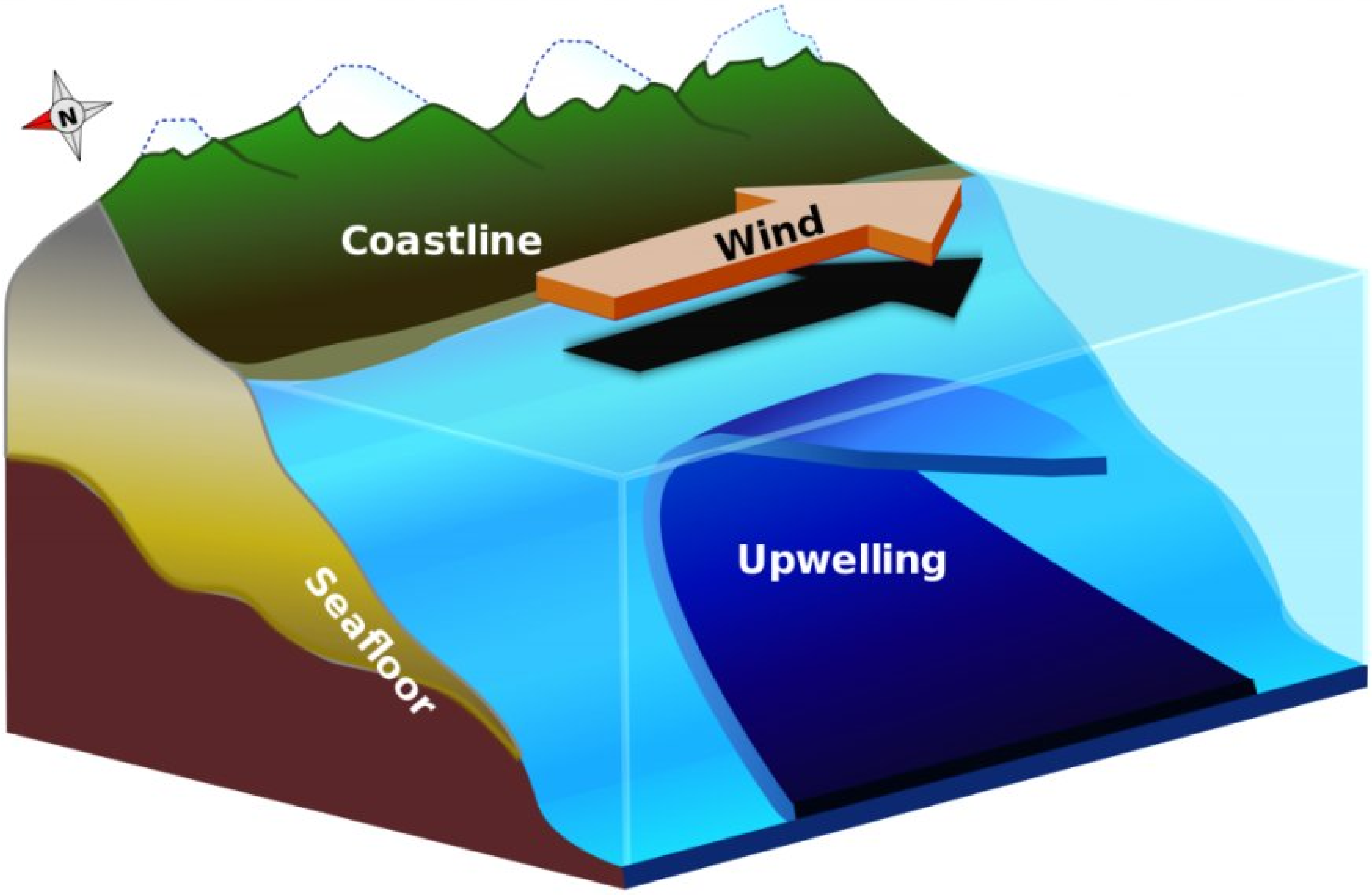


Figure 9.5.3 *Coastal upwelling. As wind blows along a coastline, Ekman transport moves the surface layer in a direction 90^o to the wind. In this figure, it is to the right of the wind, indicating a Northern Hemisphere location. As surface water moves offshore it it replaced by upwelled deeper water (By Lichtspiel [Public domain], via Wikimedia Commons).*

The same process happens off of the coast of Peru, which for a long time had the world's largest commercial fishery. Winds along the Peruvian coast blow towards the north, and since Peru is in the Southern Hemisphere, the Ekman transport is 90^o to the left of the wind, which causes the surface water to move offshore and leads to upwelling and productivity. In any coastal upwelling location, if the winds reverse, surface water moves towards the shore and downwelling is the result.

Upwelling can also occur due to geological features of the ocean floor. For example, as deep water currents encounter seamounts or other raised features, the water is forced upwards, bringing nutrient-rich water to the surface. This helps explain why productivity is often high in the water over seamounts.

9.6 El Niño and La Niña

As we saw in the previous section, coastal upwelling off of Peru makes that region one of the world's most productive fishing grounds. But every so often, the conditions in the region are very different. Every few years, the cold, nutrient-rich water is replaced by unusually warm water that is low in nutrients, leading to a decline in fish populations. In addition, the normally dry areas receive lots of rain. Because this phenomenon occurs in the northern winter close to Christmas, it is called **El Niño** (the child). More formally, the event is referred to as **El Niño-Southern Oscillation (ENSO)**. The Southern Oscillation portion refers to the fluctuating atmospheric conditions that lead to the localized ocean warming of El Niño. While the exact reasons for the oscillation events are unclear, it is easier to understand how they lead to an El Niño.

Under normal conditions in the equatorial Pacific, the trade winds blow towards the west, moving large amounts of warm surface water towards the western Pacific around Southeast Asia. As the surface water moves west, it is replaced by cold, nutrient-rich deep water through upwelling (Figure 9.6.1). The coastal upwelling leads to a shallow thermocline in the eastern Pacific. In terms of atmospheric conditions, the trade winds are part of a convection cell called the Walker Cell. There is low pressure over the western Pacific, leading to rising moist air and significant precipitation in the region. In the eastern Pacific near South America, there is high pressure, leading to drier conditions (Figure 9.6.1).

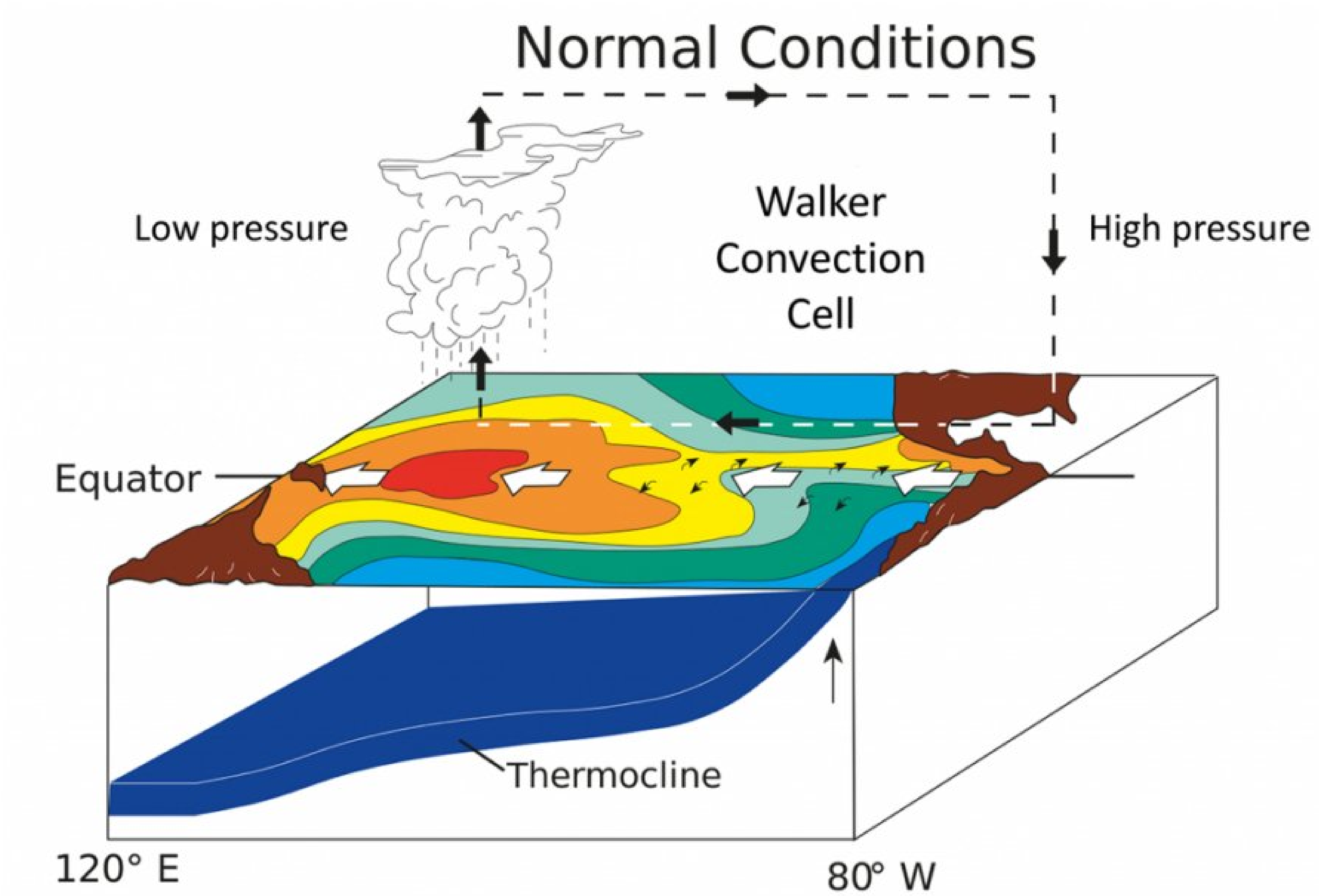


Figure 9.6.1 *Normal conditions in the equatorial Pacific. Low pressure in the western Pacific and high pressure in the eastern Pacific cause the trade winds to move surface water to the west, leading to upwelling and a shallow thermocline near South America (Modified by PW from Fred the Oyster (Own work) [Public domain], via Wikimedia Commons).*

During an El Niño-Southern Oscillation, the high pressure system over the eastern Pacific diminishes, so the trade winds are weakened, or in extreme cases will even reverse. When this happens, warm surface water begins to flow east across the Pacific towards South America (Figure 9.6.2), warming the coastal South American water by up to 8^{o} C in strong ENSO years. This influx of low density warm water deepens the thermocline and prevents upwelling, which dramatically reduces productivity and can devastate populations of fish and other marine life.

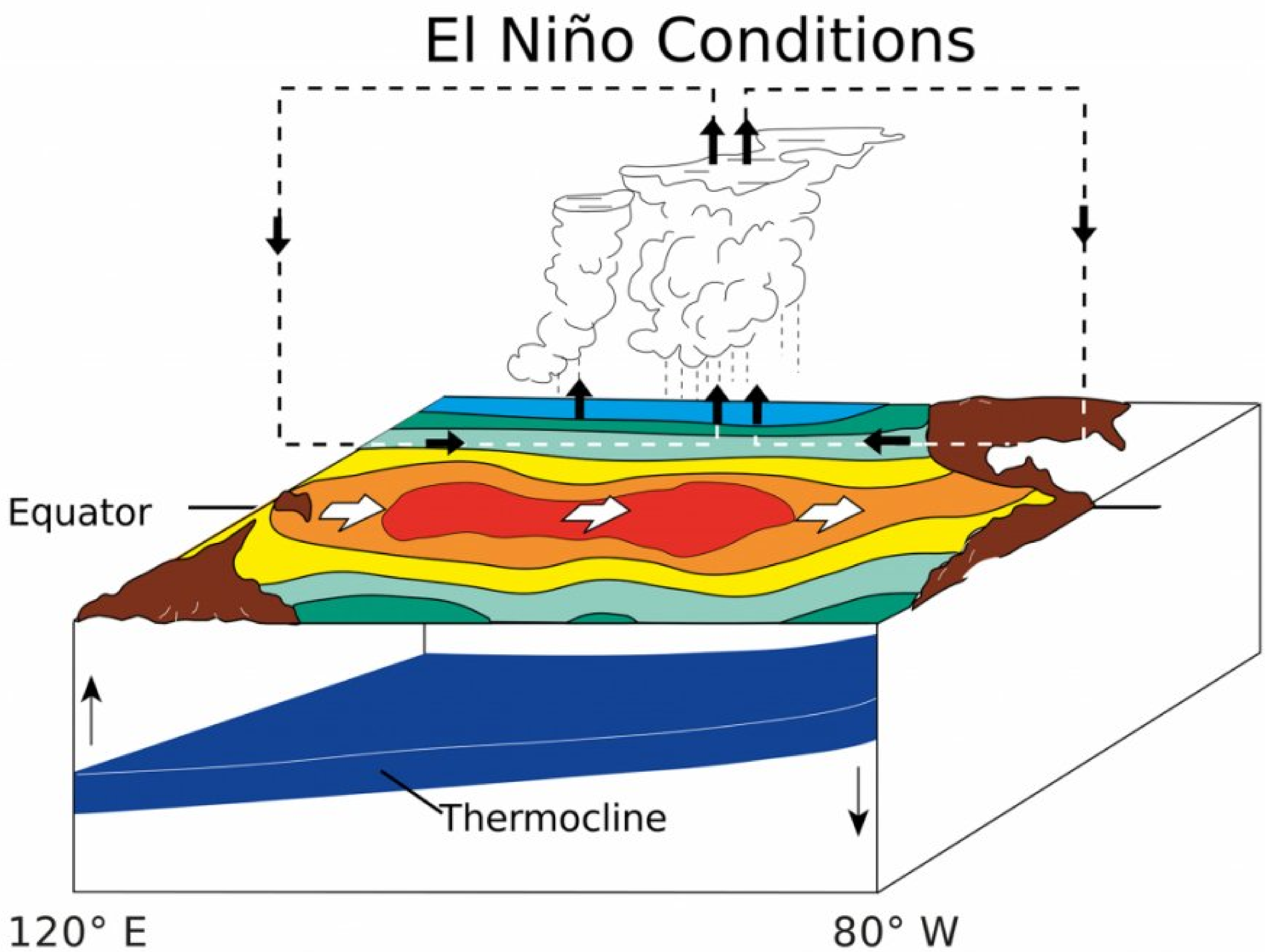


Figure 9.6.2 *El Niño conditions in the equatorial Pacific. Weakening or reversal of the trade winds transport warm surface water eastward towards South America, disrupting coastal upwelling (Public domain, via Wikimedia Commons).*

In the atmosphere, the low pressure system in the western Pacific is replaced by high pressure, bringing dry or even drought conditions to Southeast Asia and Australia. The low pressure system moves east across the Pacific, potentially reaching as far as South America in strong El Niño years. The low pressure over the eastern Pacific brings lots of rain and flooding to South America (Figure 9.6.2). But the effects of El Niño are not just limited to the Pacific; it can influence weather patterns throughout the globe (see box below).

Because the Southern Oscillation is a cyclic pattern, the eastern Pacific is not subject just to unusually warm conditions. There are also periods of abnormally cold water in the region known as **La Niña** events. During a La Niña the trade winds are unusually strong, leading to increased upwelling and transport of deep, cold water to the surface (Figure 9.6.3). The effects of a La Niña are essentially the opposite of an El Niño, bringing cooler and wetter conditions to the northwestern United States and Canada, while the southeastern US receives below-average precipitation. Monsoon seasons in Asia are drier during El Niños but wetter during La Niña events.

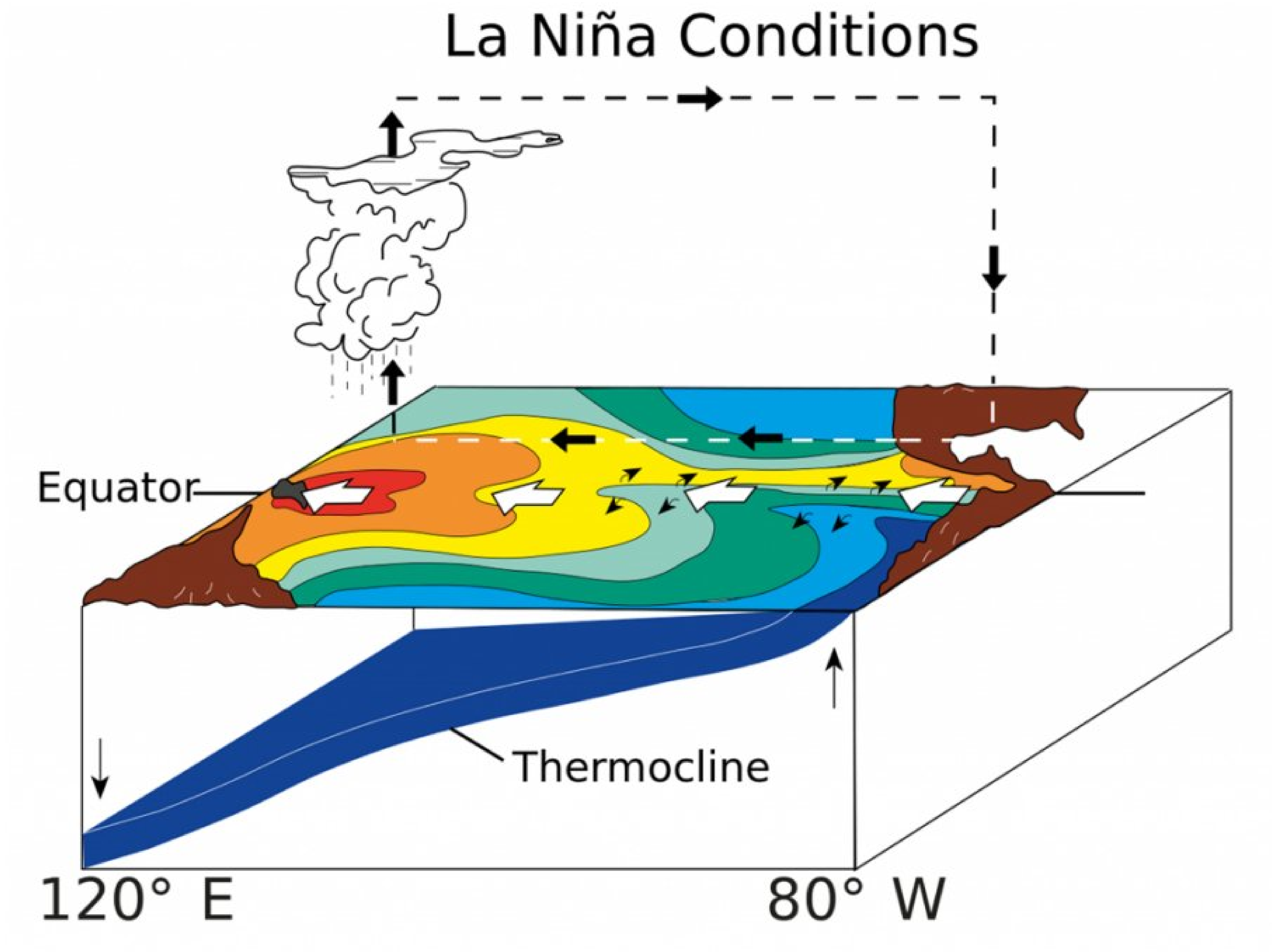


Figure 9.6.3 *La Niña conditions. Stronger trade winds promote more intense upwelling in the eastern Pacific, leading to cooler than usual water temperatures (Public domain, via Wikimedia Commons).*

El Niño and La Niña events alternate, although the presence of one does not always mean the other will automatically follow. El Niños occur roughly every 2-7 years, and each event may last from a few months to a year or more. Although we do not understand exactly why or when the ENSO events will occur, we can anticipate their arrival by monitoring a number of ocean and atmospheric phenomena that make up the Multivariate ENSO Index (MEI). Examination of the MEI over time demonstrates the cyclic nature of ENSO events (Figure 9.6.4).

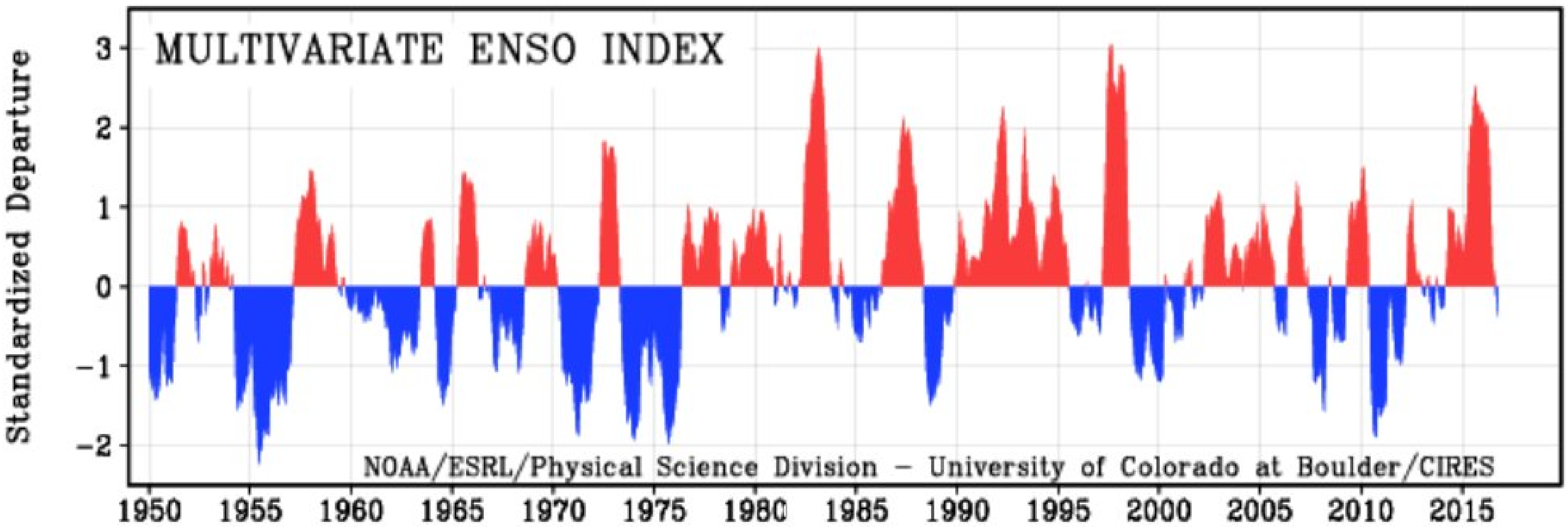
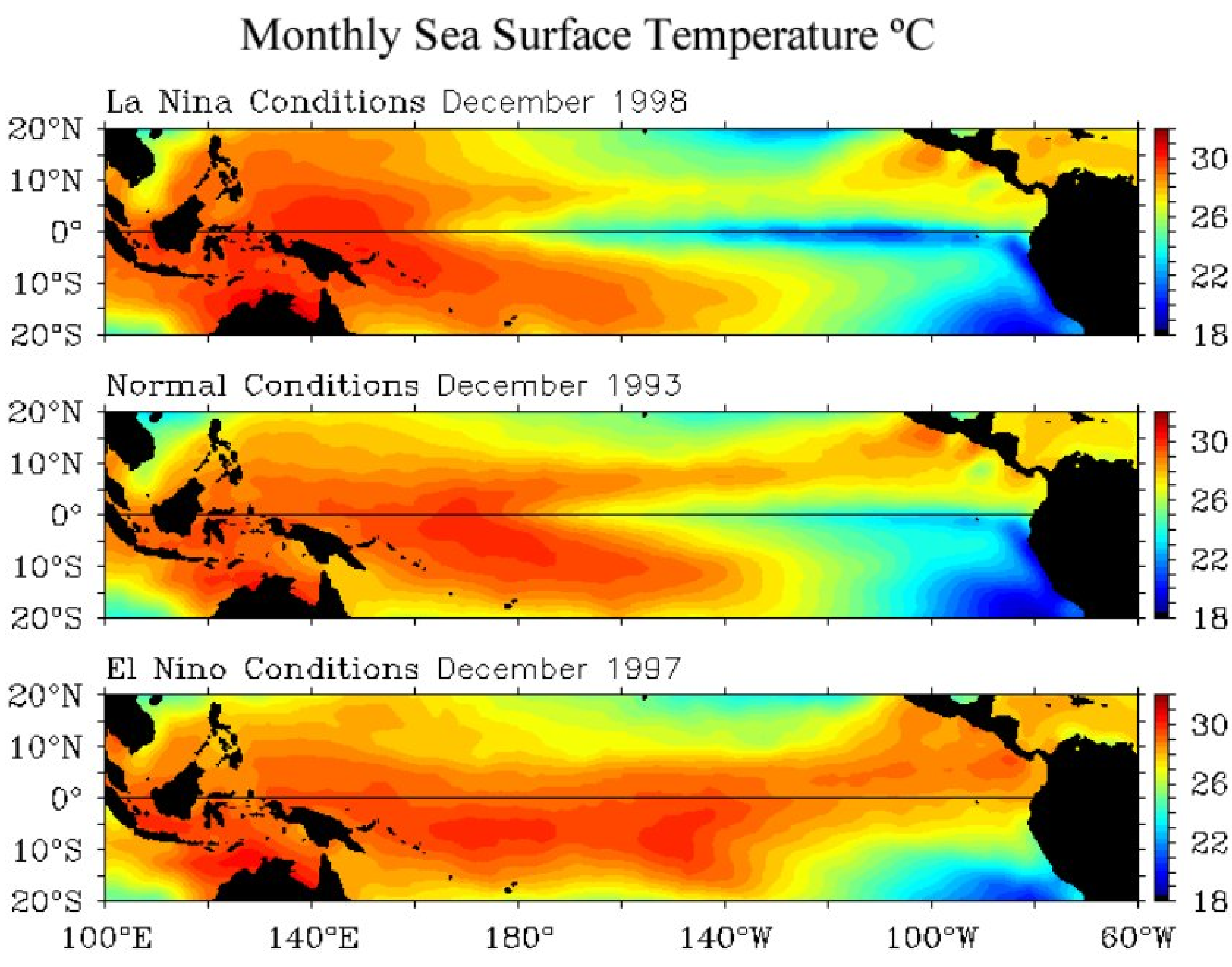


Figure 9.6.4 *Multivariate ENSO Index over time. Positive (red) values indicate warmer than normal conditions, while negative (blue) values represent conditions that are cooler than average. The greater the deviation from zero, the stronger the event. Note the intense El Niños in 1983, 1997-1998, and 2015 (NOAA, https://www.esrl.noaa.gov/psd/enso/mei/).*

Figure 9.6.5 shows a comparison of sea surface temperatures in the equatorial Pacific during normal, El Niño, and La Niña periods.



TAO Project Office/PMEL/NOAA

Figure 9.6.5 *Comparison of mean December sea surface temperatures in the equatorial Pacific during La Niña (top), normal (middle), and El Niño (bottom) conditions (NOAA, http://www.pmel.noaa.gov/elnino/sites/default/files/thumbnails/image/monthly-sst-lanina-normal-elnino.gif).*

Impacts of El Niño

The 2014-2016 El Niño was one of the strongest ENSO events on record (Figure 9.6.4). Some of the recorded global impacts of this El Niño included:

- Widespread droughts in the Philippines and many South Pacific island nations.
- Severe coral bleaching on the Great Barrier Reef in Australia.
- One of the most destructive bushfire seasons in Australia, in part due to low rainfall.
- High rainfall in the southeastern United States and parts of California, leading to flooding.
- Mild, low-precipitation winter in the New England region of the United States.
- Severe flooding in Peru and Argentina.
- Droughts in many portions of southern Africa.
- Nearly 100 million people worldwide suffered a lack of food or water from flooding and droughts.
- Peru suspended its second anchovy fishing season due to low biomass, and an anticipated 20% reduction in the yearly catch.

Additional links for more information

- What are the current ENSO conditions?: https://www.cpc.ncep.noaa.gov/products/precip/CWlink/MJO/enso.shtml

9.7 Langmuir Circulation

One final type of wind-driven surface current occurs on a smaller scale when the winds blow in a consistent direction at relatively high speeds. Underneath these strong winds, water flows in a series of parallel corkscrew patterns called Langmuir cells (Figure 9.7.1 top). Each of the cells may be several meters wide and several meters deep, and adjacent cells rotate in opposite directions. While the overall direction of the corkscrew motion is in the direction of the wind, the rotation of the cells is roughly perpendicular to the wind direction. A divergence zone is created where the surface of the neighboring cells are rotating away from each other, and there is a degree of upwelling between the cells. Where the surface water of neighboring cells is rotating towards each other, a convergent zone is formed, with a region of downwelling between the cells. These alternating regions of divergence and convergence often take debris, foam, or algae floating at the surface and concentrate them along the convergence zones, creating long slicks running parallel to the wind direction (Figure 9.7.1 bottom).

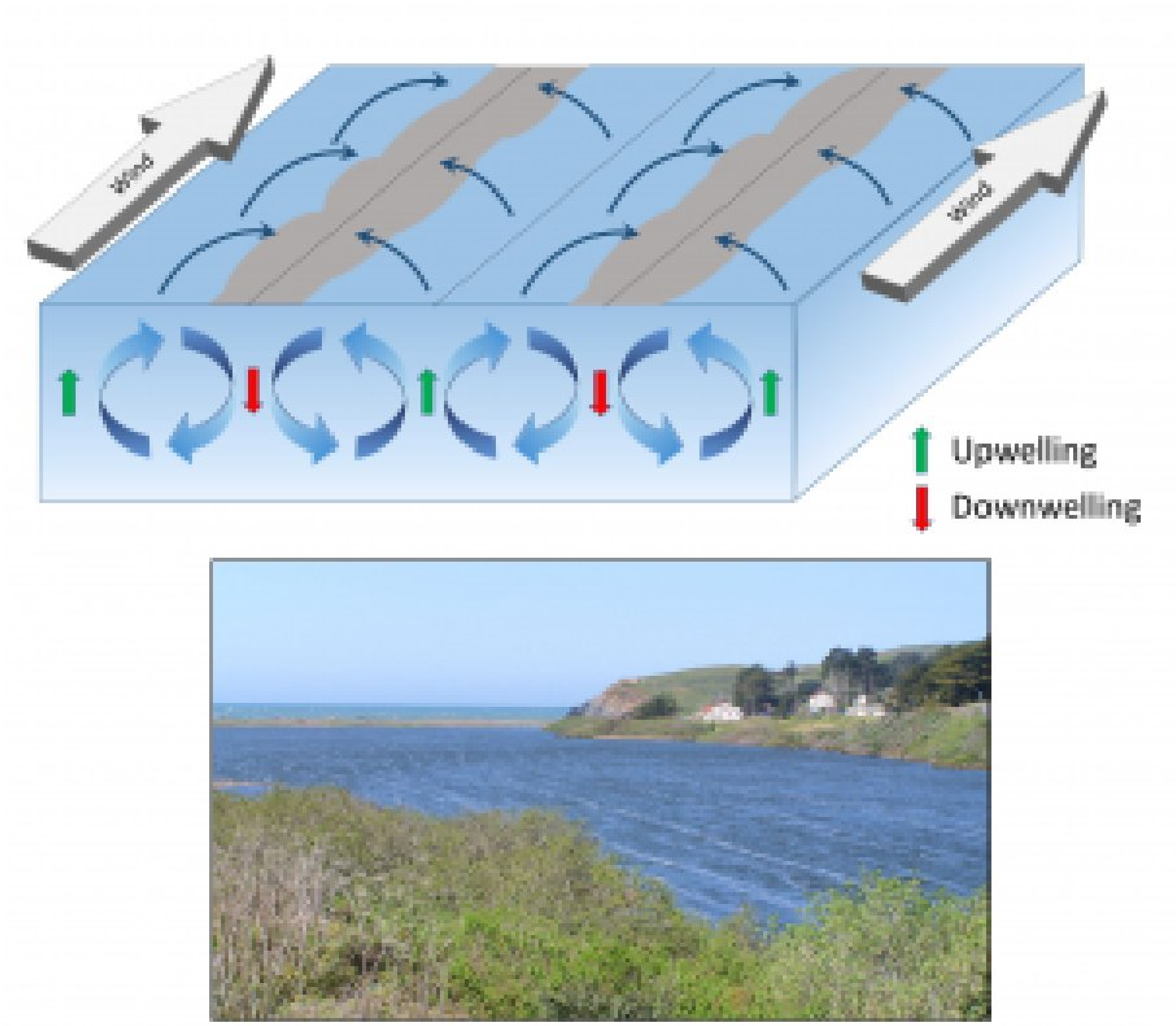


Figure 9.7.1 *(Top) Langmuir cells created by strong, sustained winds (gray arrows). Dark blue arrows show the movement of surface water as a result of the cells, producing downwelling convergence zones where floating material can accumulate (gray shading), and upwelling divergence zones. (Bottom) Parallel patterns of accumulated foam and debris indicating Langmuir circulation (Top: PW; Bottom: Photo By Mmelugin (Own work) [CC BY-SA 3.0 or GFDL (http://www.gnu.org/copyleft/fdl.html)], via Wikimedia Commons).*

9.8 Thermohaline Circulation

The surface currents we have discussed so far are ultimately driven by the wind, and since they only involve surface water they only affect about 10% of the ocean's volume. However, there are other significant ocean currents that are independent of the wind, and involve water movements in the other 90% of the ocean. These currents are driven by differences in water density.

Recall that less dense water remains at the surface, while denser water sinks. Waters of different densities tend to stratify themselves into layers, with the densest, coldest water on the bottom and warmer, less dense water on top. It is the movement of these density layers that create the deep water circulation. Since seawater density depends mainly on temperature and salinity (section 6.3), this circulation is referred to as **thermohaline circulation**.

The main processes that increase seawater density are cooling, evaporation, and ice formation. Evaporation and ice formation cause an increase in density by removing fresh water, leaving the remaining seawater with greater salinity (see section 5.3). The main processes that decrease seawater density are heating, and dilution by fresh water through precipitation, ice melting, or fresh water runoff. Note that all of these processes exert their effects at the surface, but don't necessarily affect deeper water. However, changing the density of the surface water causes it to sink or rise, and these vertical, density-driven movements create the deep ocean currents. These thermohaline currents are slow, on the order of 10-20 km per year compared with surface currents that move at several kilometers per hour.

Water masses

A water mass is a volume of seawater with a distinctive density as a result of its unique profile of temperature and salinity. As stated above, the processes that affect seawater density really only happen at the surface. Once a water mass has reached its particular temperature and salinity profile due to these surface processes, it may sink below the surface, at which point its density properties won't really change. We can therefore distinguish particular water masses by taking salinity and temperature measurements at different depths, and looking for the unique combination of these variables that give it its characteristic density. This is often carried out using temperature-salinity diagrams (T-S diagrams, see box below).

There are several well-known water masses in the ocean, particularly in the Atlantic, that are distinguished by their temperature and salinity characteristics. The densest ocean water is formed in two primary locations near the poles, where the water is very cold and highly saline as a result of ice formation. The densest deep water mass is formed in the Weddell Sea of Antarctica, and becomes the **Antarctic Bottom Water (AABW)**. Similar processes in the North Atlantic produce the **North Atlantic Deep Water (NADW)** in the Greenland Sea (Figure 9.8.1).

Figure 9.8.1 *The primary sites of deep water formation; Antarctic Bottom Water is formed int he Weddell Sea, and North Atlantic Deep water is formed in the Greenland Sea (PW).*

This cold, dense water sinks, and once it is removed from the surface, its temperature and salinity remain unchanged, so it keeps the same characteristics as it moves throughout the ocean as part of the thermohaline circulation. AABW sinks to the bottom in the Weddell Sea and then moves north along the bottom into the Atlantic, and east through the Southern Ocean. At the same time NADW is sinking in the Greenland Sea. This water mass is less dense than AABW and tends to form a layer above the AABW as it flows across the equator to the south (Figure 9.8.2). As the NADW moves towards the Antarctic continent, it is brought to the surface. Recall that near Antarctica there is the Antarctic divergence, where surface waters move horizontally away from each other, and are replaced by deep water upwelling (bringing nutrients to the surface and leading to high productivity; see section 7.3). Since polar water has a weak thermocline, there isn't much of a density difference preventing the deep water from reaching the surface, so some NADW rises as part of the upwelling process (Figure 9.8.2).

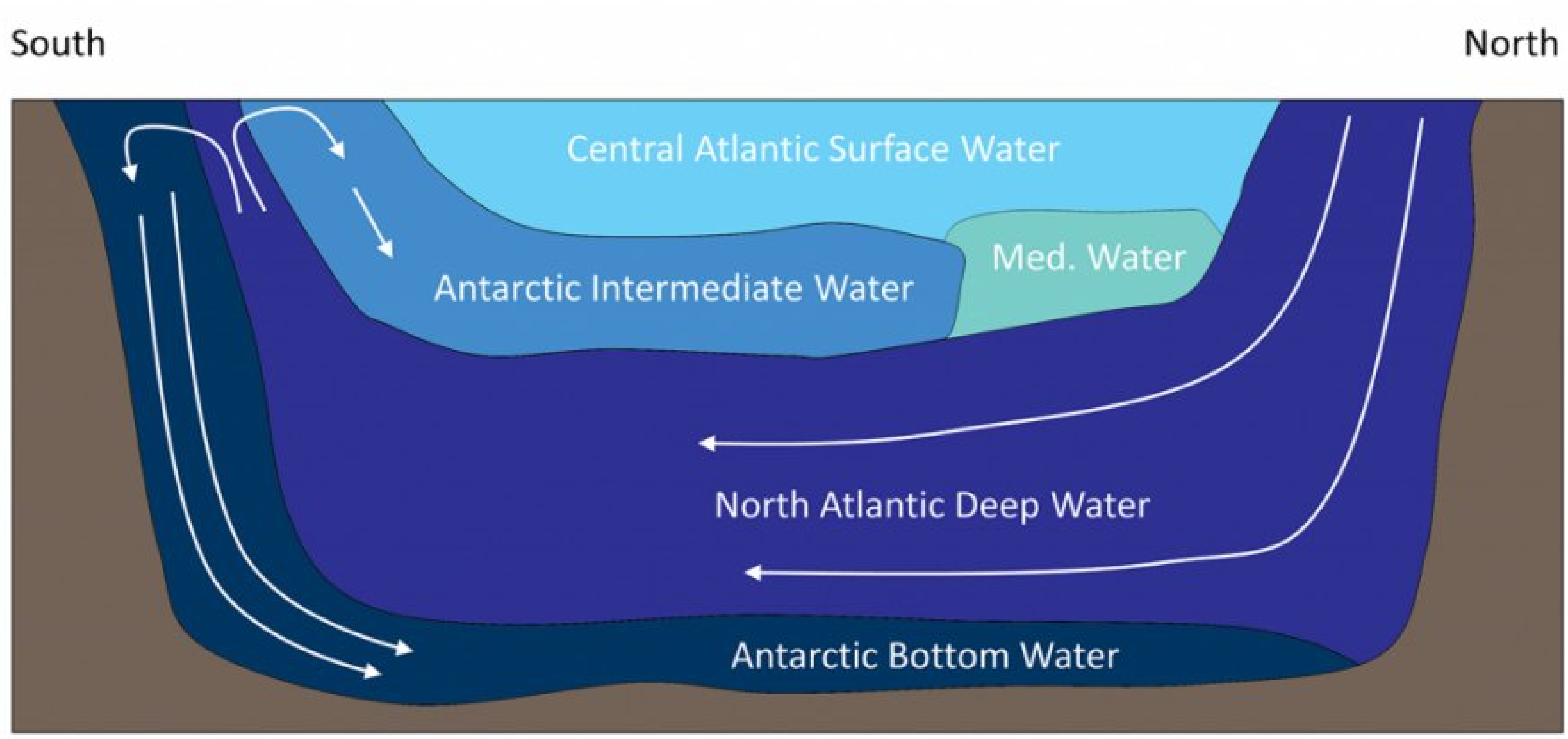


Figure 9.8.2 *The major water masses of the Atlantic Ocean (PW).*

As the rising NADW reaches the surface, some travels south where it will eventually contribute to the production of new AABW. The NADW that moves north encounters the Antarctic convergence, which produces downwelling. This sinking NADW becomes a new water mass; **Antarctic Intermediate Water (AAIW)**, which sinks and creates a layer between the surface water and the NADW (Figure 9.8.2). The surface water in the equatorial Atlantic, also called the **Central Atlantic Surface Water**, is very warm and low density, therefore it remains at the surface and does not contribute much to thermohaline circulation.

In the Atlantic, **Mediterranean Intermediate Water (MIW)** flows through the Straits of Gibraltar into the open ocean. This water is warm and salty from the warm temperatures and high evaporation characteristic of the Mediterranean Sea, so it is denser than the normal surface water and forms a layer about 1-1.5 km deep. Eventually this water will move north to the Greenland Sea, where it will be cooled and will sink, becoming the dense NADW.

T-S Diagrams

A temperature-salinity (T-S) diagram is used to examine how temperature, salinity, and density change with depth, and to identify the vertical structure of the water column, including the water masses it contains. Water temperature is on the y-axis, and salinity appears on the x-axis. Often, instead of the actual temperature of the water, oceanographers plot **potential temperature,** which is the temperature the water would achieve if it was brought to the surface and did not get any additional heat through compression at depth. A T-S diagram shows lines of equal density, or **isopycnals**, for various combinations of temperature and salinity (Figure 9.8.3). You can then plot the values of temperature and salinity on the diagram, and use their point of intersection to calculate the density of the water. In the example in Figure 9.8.3 a temperature of about 11° C and a salinity of 34.6 PSU results in a density of 1.0265 g/cm^3.

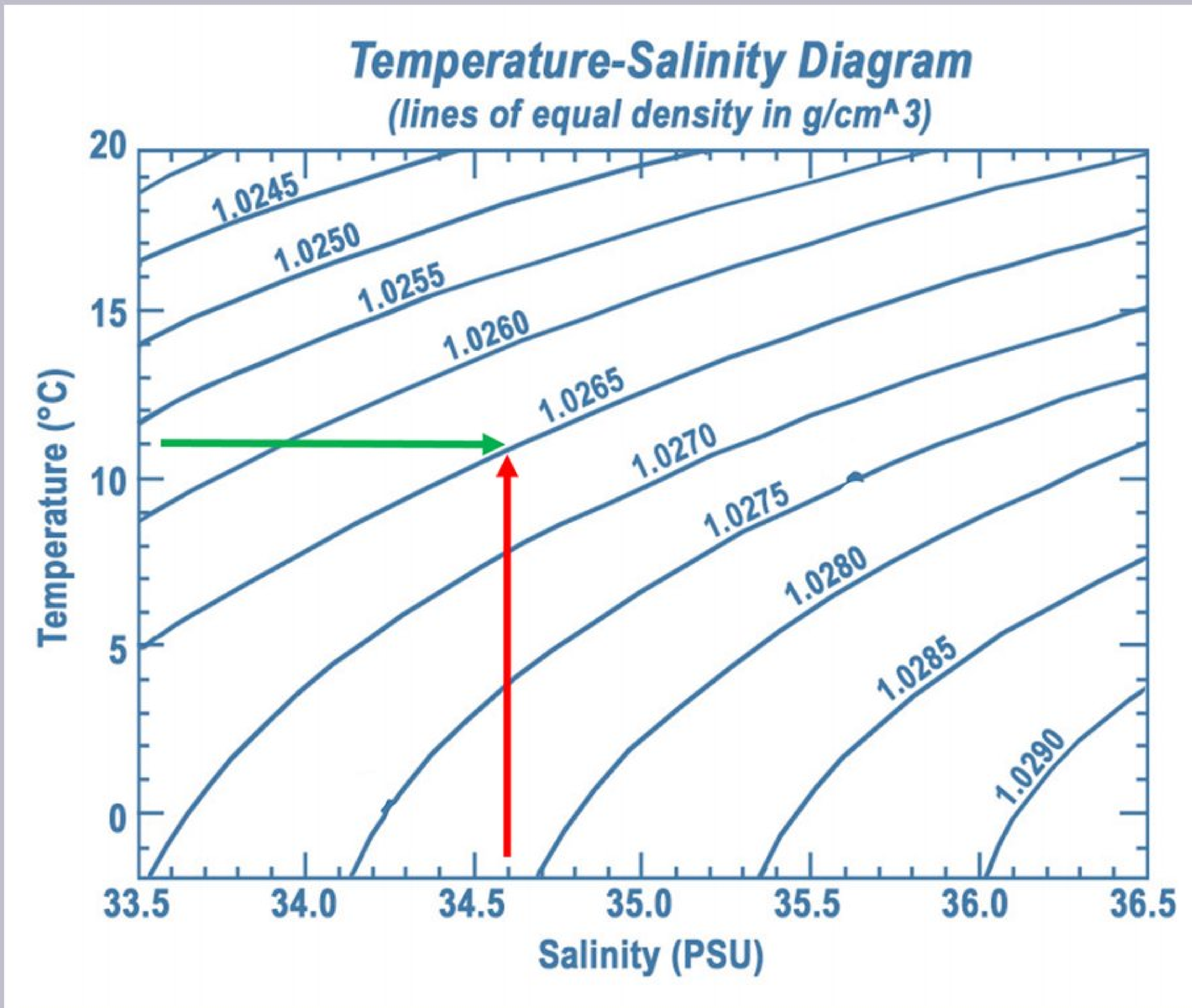


Figure 9.8.3 *Using a T-S diagram to determine density. A temperature of about 11° C (green arrow) and a salinity of 34.6 PSU (red arrow) results in a density of 1.0265 g/cm³.*

Since the range of densities in the ocean is rather small, often the density value is shortened and is expressed as sigma-t or σ_t. Sigma-t is calculated as: (density – 1) x 1000. So it essentially just looks at the last three decimal places of the density value. Thus a density of 1.0275 g/cm^3 would have a σ_t of 27.5.

T-S diagrams can be used to identify water masses. Since each major water mass has its own characteristic range of temperatures and salinities, a deep water sample that falls into that range can presumably have come from that water mass. Figure 9.8.4 shows the typical range of temperature and salinity for the major Atlantic water masses.

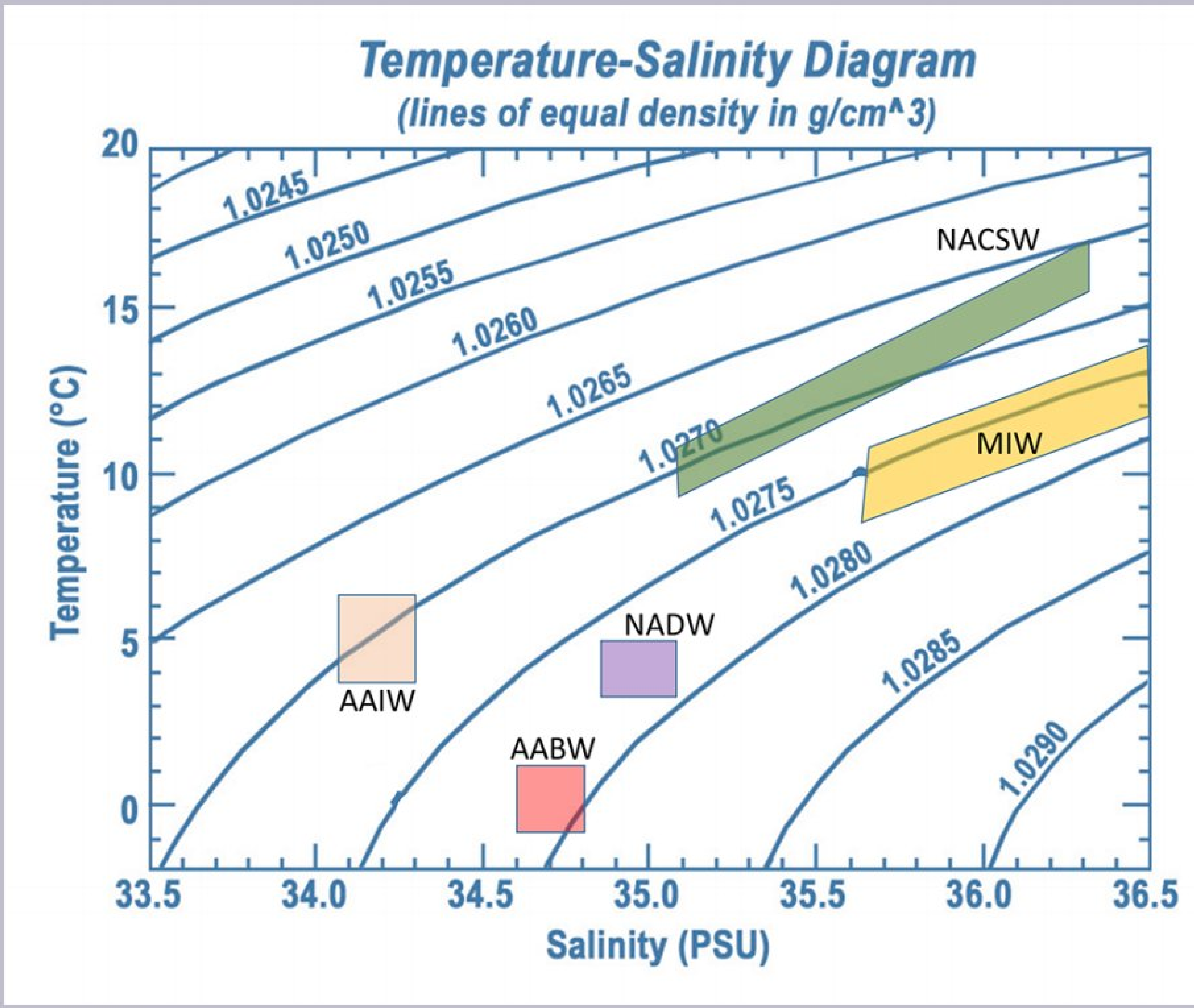


Figure 9.8.4 *Characteristic ranges of temperature and salinity for the major Atlantic water masses; North Atlantic Central Surface Water (NACSW), Mediterranean Intermediate Water (MIW), Antarctic Intermediate Water (AAIW), North Atlantic Deep Water (NADW), and Antarctic Bottom Water (AABW).*

To investigate water masses, oceanographers can take a series of temperature and salinity measurements over a range of depths at a particular location. If the water column was highly stratified and there was no mixing between or within the layers, as the probe was lowered your would get a series of constant temperature and salinity readings as you moved through the first water mass, followed by a sudden jump to another set of different but constant readings as you moved through the next water mass. Plotting temperature vs. salinity on a T-S diagram would result in a distinct and independent point for each water mass. However, in reality, the water masses will show some mixing within and between layers. So as the probes are lowered, they will encounter water that shows traits intermediate between the two points. Therefore, with increasing depth, the points on the T-S diagram will gradually move from one point to the other, creating a line connecting the two points, illustrating mixing between those two water masses.

In the example in Figure 9.8.5, NACSW is present at the surface (0 m depth), and between 0 and about 800 m there is a transition from NACSE into AAIW. Between about 800-2100 m there is a transition from AAIW into the NADW layer just beyond 2000 m. AABW is the deepest water mass, at depths of about 4000 m. The transition between NADW and AABW occurs between about 2100-4000 m.

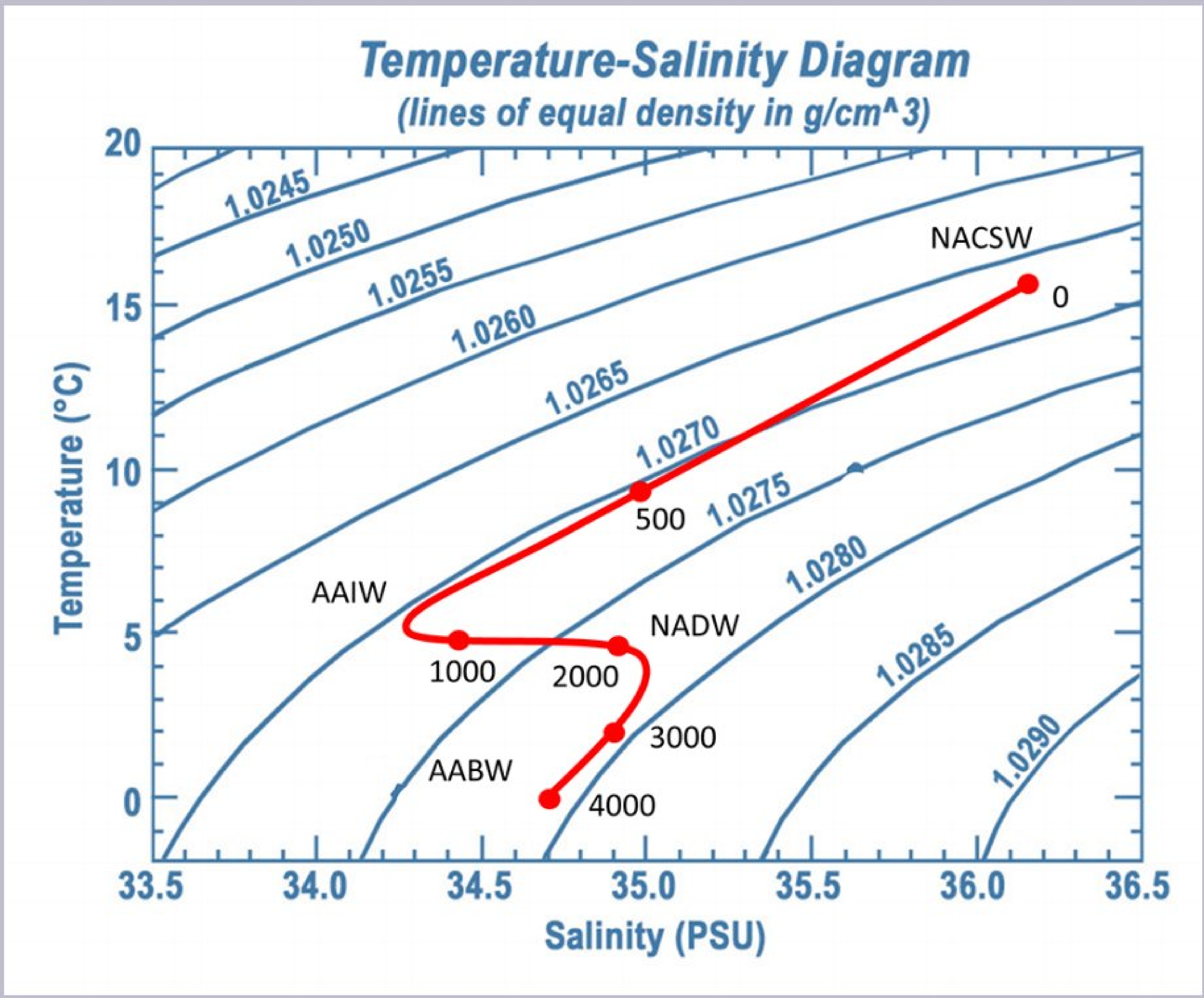


Figure 9.8.5 *Hypothetical T-S diagram for the North Atlantic. Points represent readings taken at the corresponding depths (m). Moving from the surface to the bottom results in water of increasing density, passing through distinct water masses.*

Notice that as the recordings get deeper in Figure 9.8.5, the density is always increasing (i.e. moving towards the bottom right corner). This is because the densest water should be located at the bottom, with the other layers stratified according to their density, otherwise the water column would be unstable.

The "Ocean Conveyor Belt"

The bottom water from the Weddell Sea and Greenland Sea does not just circulate through the Atlantic. NADW moves south through the western Atlantic before meeting the AABW north of the Weddell Sea. Together these water masses move eastwards into the Indian and Pacific Oceans. By this time the NADW and AABW have started mixing, to create what is called **Common Water**. The deep Common Water moves northwards into the Pacific and Indian Oceans and gradually mixes with the warmer water, causing it to eventually rise to the surface. As surface water, it makes its way back to the North Atlantic through the surface currents of the Pacific and Indian Oceans. Once back in the North Atlantic, it cools and once again forms NADW, starting the process anew. This cycle of rising and sinking water transporting water between the surface and deep circulation has been referred to as the global oceanic "conveyor belt", and may take about 1000-2000 years to complete (Figure 9.8.6).

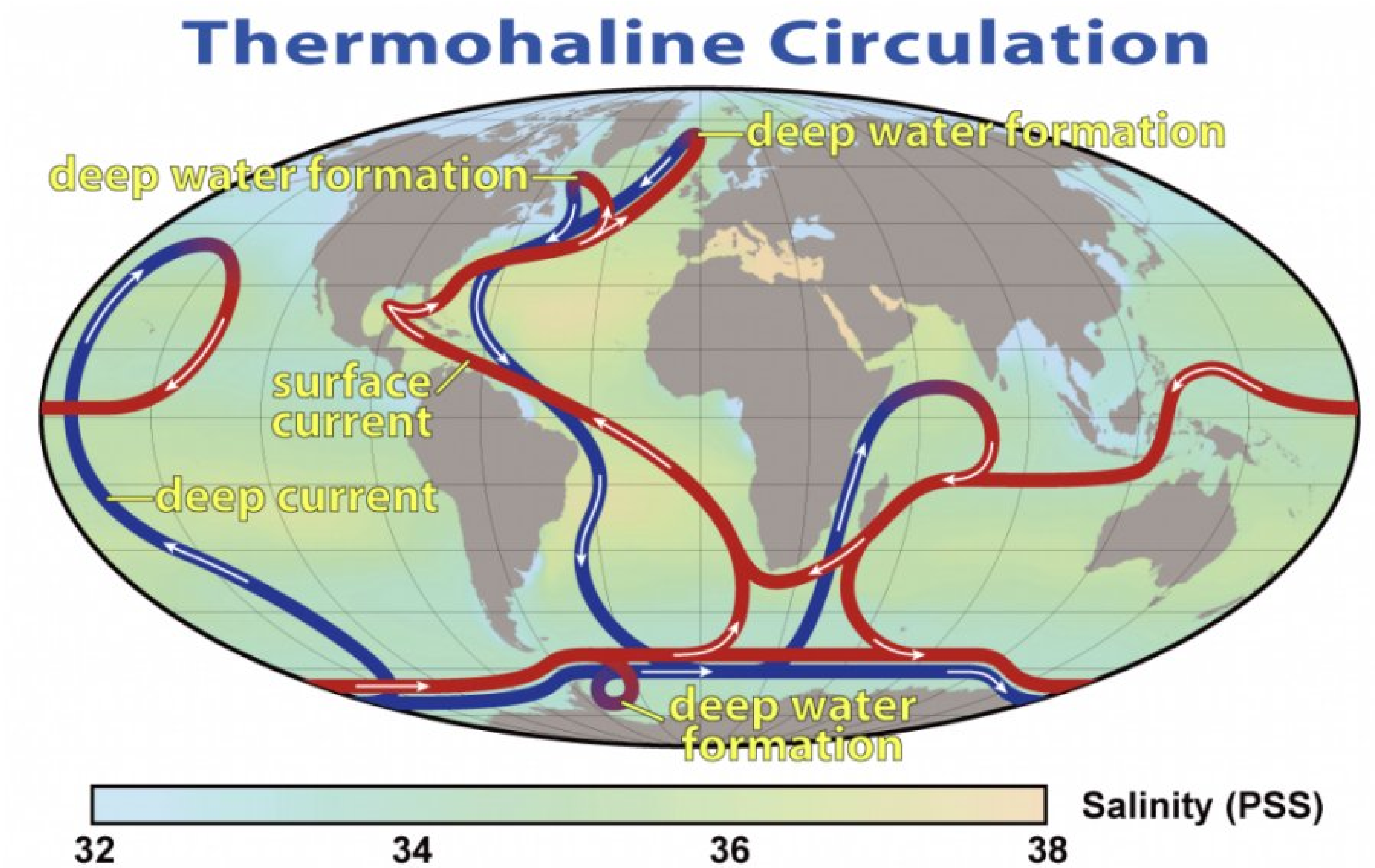


Figure 9.8.6 *The global ocean "conveyor belt." Cold, dense water sinks in the Greenland and Weddell Seas and circulates over the seafloor into the Indian and Pacific Oceans (blue paths). Eventually the water rises to the surface, and returns to the site of bottom water formation via surface currents (red paths), to start the cycle again (By Robert Simmon, NASA. Minor modifications by Robert A. Rohde also released to the public domain (NASA Earth Observatory) [Public domain], via Wikimedia Commons).*

This global circulation pattern has a number of important implications for Earth's environment. For one, it is vital to the transport of heat around the globe, bringing warm water towards the poles, and cold water to the tropics, stabilizing temperature in both environments.

The conveyor belt also helps deliver oxygen to deep water habitats. The deep water began as cold surface water that was saturated with oxygen, and when it sank it brought that oxygen to depth. Thermohaline circulation carries this oxygen-rich deep water throughout the oceans, where the oxygen will be used by deep water organisms. Bottom water in the Atlantic is relatively high in oxygen, as it still retains much of its original oxygen content, but as it travels over the seafloor the oxygen is used up, so that deep water in the Pacific Ocean has much less oxygen than deep Atlantic water, with Indian Ocean water somewhere in between. At the same time, deep water will accumulate nutrients as organic matter sinks and decomposes. Atlantic bottom water is low in nutrients because it has not had much time to accumulate them, and the original surface water was nutrient-poor. By the time this bottom water reaches the Indian Ocean, and after that the Pacific, it has been accumulating the sinking nutrients for centuries, so deep nutrient concentrations are greater in the Pacific than the Atlantic. We can therefore use the ratios of oxygen to nutrients in the deep water to tell the relative age of a water mass, i.e. how long it has been since it sank from the surface. Younger bottom water should be high in oxygen and low in nutrients, while the opposite would be expected for older bottom water.

The ocean conveyor belt may be significantly impacted by climate change disrupting thermohaline circulation. Increased warming, particularly in the Arctic, could lead to continuing melting of the polar ice caps, adding a large amount of fresh water to the polar surface water. This input of fresh water could create a low density, low salinity surface layer of water that no longer sinks, thus disrupting the deep circulation conveyor belt and preventing oxygen and nutrient transport to bottom communities. The sinking of seawater in the Greenland Sea also helps drive the Gulf Stream; as water sinks, more surface water is pulled northwards in the Gulf Stream. If this polar water stops sinking the Gulf Stream could weaken, reducing heat transport to the poles and cooling the northern climate. It seems counter intuitive, but global warming could lead to colder conditions in Europe and the freezing of ports and cities that are usually ice-free due to the warming effects of the Gulf Stream. Recent evidence has already shown that the strength of the Gulf Stream is waning, likely due to the increased melting of Arctic ice.

CHAPTER 10: WAVES

Chapter 10: Waves

Learning Objectives

After reading this chapter you should:

- know the parts of a basic wave
- know the terminology used to describe the motion of a wave (i.e. period, frequency, speed etc.)
- understand the circular motion of water particles involved in wave motion
- understand the difference between deep water waves and shallow water waves
- know what factors influence wave speed in deep and shallow waves
- know the three factors that determine the energy of wind-generated waves
- understand the concept of restoring force
- understand the difference between seas and swell
- understand the concepts of destructive, constructive and mixed interference
- understand why waves break as they approach shore
- know the differences in the different types of breakers, and how the bottom topography impacts breaker type
- understand why waves always approach parallel to shore, and why waves are larger off of points and smaller in bays
- understand what causes tsunamis, and how they behave in the ocean

Waves come in many shapes and sizes; a 100 foot wave might be a surfer's dream, but a ship captain's nightmare. What was the largest wave ever recorded? 50 feet? 100 feet? Not even close. That record belongs to a wave created in Lituya Bay, Alaska, on July 9, 1958 (Figure 10.1). On that day, a magnitude 7.8 earthquake caused a massive rockslide that slid down a mountainside and into the headwaters of the bay. The rockslide created a splash wave that was high enough to flatten vegetation up to 1722 ft (525 m) above sea level! The wave then moved through the narrow bay towards the sea, destroying a number of fishing boats along the way. Miraculously, a father and son on one fishing boat were carried above the trees by the wave, and survived to tell the story. This is by far the largest wave, a megatsunami, ever reliably recorded. The waves we will discuss in this chapter may not be quite that dramatic, but it is still important to know how they form, how they are propagated, and what happens to them as they interact with the shore.

Figure 10.1 *A view of Lituya Bay taken a few weeks after the 1958 megatsunami. The rockslide occurred in the mountains at the head of the bay, producing the wave that them moved through the bay towards the sea (D.J. Miller, United States Geological Survey, [Public domain], via Wikimedia Commons).*

10.1 Wave Basics

Waves generally begin as a disturbance of some kind, and the energy of that disturbance gets propagated in the form of waves. We are most familiar with the kind of waves that break on shore, or rock a boat at sea, but there are many other types of waves that are important to oceanography:

- **Internal waves** form at the boundaries of water masses of different densities (i.e. at a pycnocline), and propagate at depth. These generally move more slowly than surface waves, and can be much larger, with heights exceeding 100 m. However, the height of the deep wave would be unnoticeable at the surface.
- **Tidal waves** are due to the movement of the tides. What we think of as tides are basically enormously long waves with a wavelength that may span half the globe (see section 11.1). Tidal waves are not related to tsunamis, so don't confuse the two.
- **Tsunamis** are large waves created as a result of earthquakes or other seismic disturbances. They are also called seismic sea waves (section 10.4).
- **Splash waves** are formed when something falls into the ocean and creates a splash. The giant wave in Lituya Bay that was described in the introduction to this chapter was a splash wave.
- **Atmospheric waves** form in the sky at the boundary between air masses of different densities. These often create ripple effects in the clouds (Figure 10.1.1).

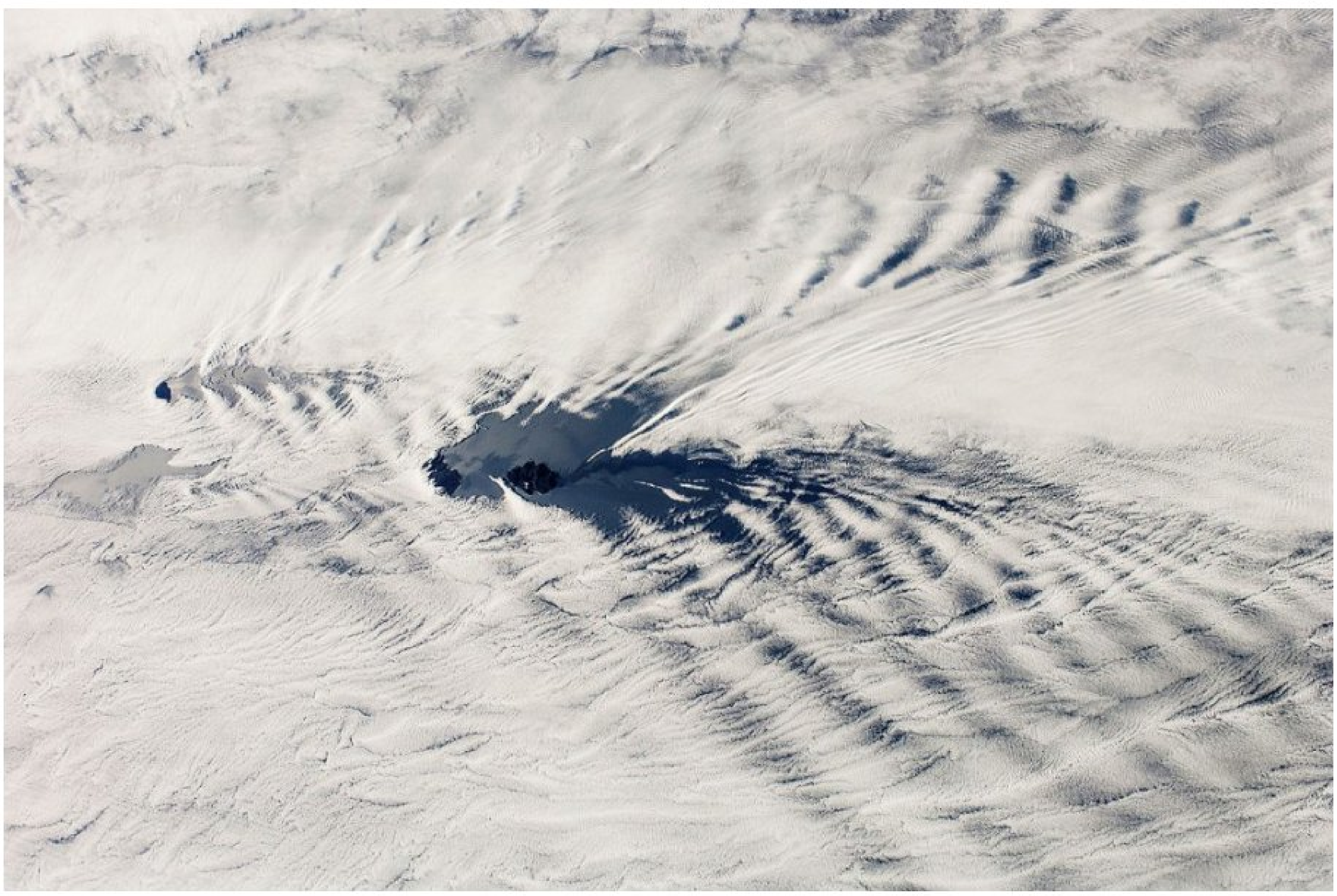


Figure 10.1.1 *Wake patterns in cloud cover over Possession Island, East Island, Ile aux Cochons, Ile de Pingouins. The ripple pattern is a result of internal waves in the atmosphere (NASA [Public domain], via Wikimedia Commons).*

There are several components to a basic wave (Figure 10.1.2):

- **Still water level:** where the water surface would be if there were no waves present and the sea was completely calm.
- **Crest:** the highest point of the wave.
- **Trough:** the lowest point of the wave.
- **Wave height:** the distance between the crest and the trough.
- **Wavelength:** the distance between two identical points on successive waves, for example crest to crest, or trough to trough.
- **Wave steepness:** the ratio of wave height to length (H/L). If this ratio exceeds 1/7 (i.e. height exceeds 1/7 of the wavelength) the wave gets too steep, and will break.

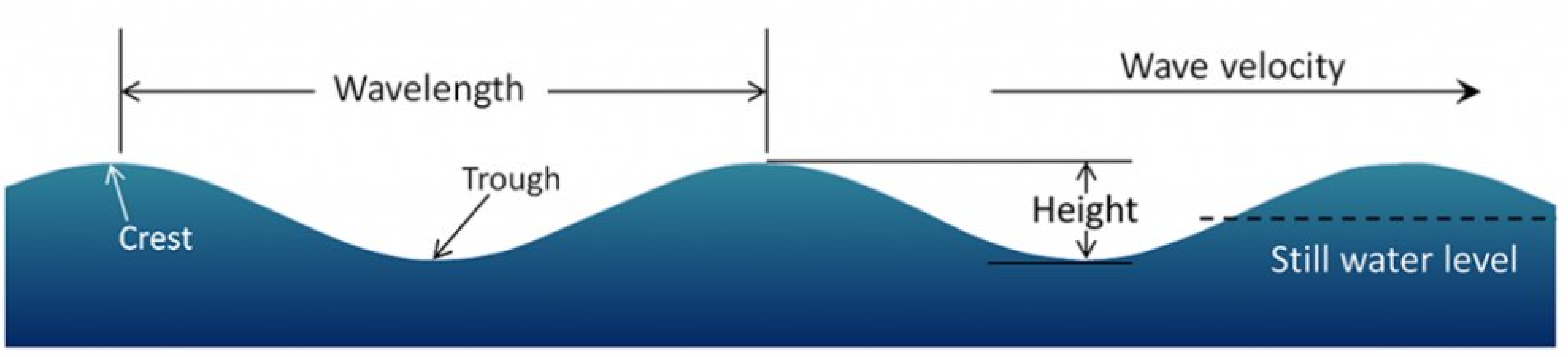


Figure 10.1.2 *Components of a basic wave (Modified by PW from Steven Earle "Physical Geology").*

There are also a number of terms used to describe wave motion:

- **Period:** the time it takes for two successive crests to pass a given point.
- **Frequency:** the number of waves passing a point in a given amount of time, usually expressed as waves per second. This is the inverse of the period.
- **Speed**: how fast the wave travels, or the distance traveled per unit of time. This is also called celerity (c), where

$$c = \text{wavelength} \times \text{frequency}$$

Therefore, the longer the wavelength, the faster the wave.

Although waves can travel over great distances, the water itself shows little horizontal movement; it is the *energy* of the wave that is being transmitted, not the water. Instead, the water particles move in circular orbits, with the size of the orbit equal to the wave height (Figure 10.1.3). This orbital motion occurs because water waves contain components of both longitudinal (side to side) and transverse (up and down) waves, leading to circular motion. As a wave passes, water moves forwards and up over the wave crests, then down and backwards into the troughs, so there is little horizontal movement. This is evident if you have ever watched an object such as a seabird floating at the surface. The bird bobs up and down as the wave pass underneath it; it does not get carried horizontally by a single wave crest.

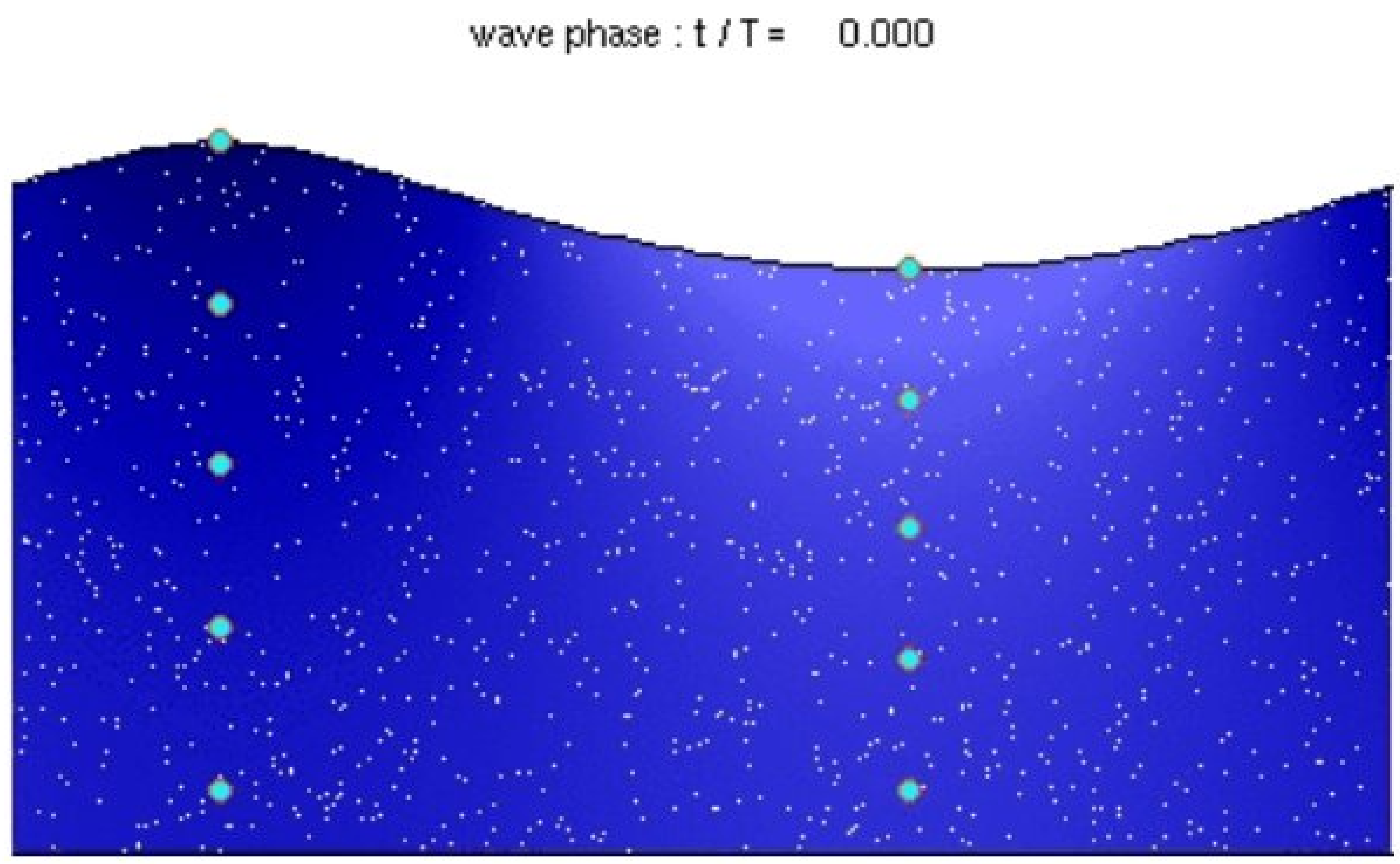


Figure 10.1.3 *Animation showing the orbital motion of particles in a surface wave (By Kraaiennest (Own work) [GFDL (http://www.gnu.org/copyleft/fdl.html) or CC BY-SA 4.0], via Wikimedia Commons).*

The circular orbital motion declines with depth as the wave has less impact on deeper water and the diameter of the circles is reduced. Eventually at some depth there is no more circular movement and the water is unaffected by surface wave action. This depth is the **wave base** and is equivalent to half of the wavelength (Figure 10.1.4). Since most ocean waves have wavelengths of less than a few hundred meters, most of the deeper ocean is unaffected by surface waves, so even in the strongest storms marine life or submarines can avoid heavy waves by submerging below the wave base.

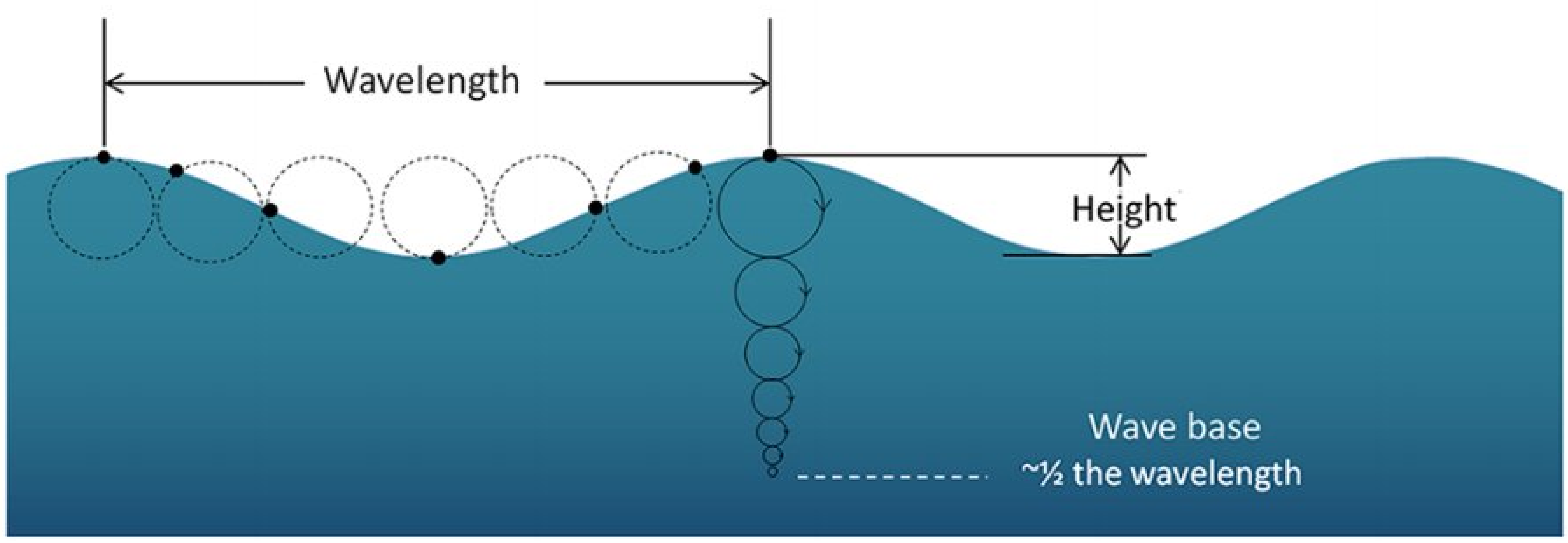


Figure 10.1.4 *Orbital motion of water within a wave, extending down to the wave base at a depth of half of the wavelength (Modified by PW from Steven Earle, "Physical Geology").*

When the water below a wave is deeper than the wave base (deeper than half of the wavelength), those waves are called **deep water waves.** Most open ocean waves are deep water waves. Since the water is deeper than the wave base, deep water waves experience no interference from the bottom, so their speed only depends on the wavelength:

$$\text{speed (m/s)} = \sqrt{\frac{gL}{2\pi}}$$

where *g* is gravity and *L* is wavelength in meters. Since *g* and *π* are constants, this can be simplified to:

$$\text{speed (m/s)} = 1.25\sqrt{L}$$

Shallow water waves occur when the depth is less than 1/20 of the wavelength. In these cases, the wave is said to "touch bottom" because the depth is shallower than the wave base so the orbital motion is affected by the seafloor. Due to the shallow depth, the orbits are flattened, and eventually the water movement becomes horizontal rather than circular just above the bottom. The speed of shallow water waves depends only on the depth:

$$\text{speed (m/s)} = \sqrt{gd}$$

where *g* is gravity and *d* is depth in meters. This can be simplified to:

$$\text{speed (m/s)} = 3.13\sqrt{d}$$

Intermediate or **transitional waves** are found in depths between ½ and 1/20 of the wavelength. Their behavior is a bit more complex, as their speed is influenced by both wavelength and depth. The speed of an intermediate wave is calculated as:

$$\text{speed (m/s)} = \sqrt{\frac{gL}{2\pi}\tanh(2\pi\frac{d}{L})}$$

which contains both depth and wavelength variables.

10.2 Waves at Sea

Most ocean waves are generated by wind. Wind blowing across the water's surface creates little disturbances called **capillary waves**, or ripples that start from gentle breezes (Figure 10.2.1). Capillary waves have a rounded crest with a V-shaped trough, and wavelengths less than 1.7 cm. These small ripples give the wind something to "grip" onto to generate larger waves when the wind energy increases, and once the wavelength exceeds 1.7 cm the wave transitions from a capillary wave to a wind wave. As waves are produced, they are opposed by a **restoring force** that attempts to return the water to its calm, equilibrium condition. The restoring force of the small capillary waves is surface tension, but for larger wind-generated waves gravity becomes the restoring force.

Figure 10.2.1 *Small capillary waves or ripples caused by winds blowing over the surface of calm water (By Blue Elf (Own work) [GFDL (http://www.gnu.org/copyleft/fdl.html) or CC BY-SA 3.0], via Wikimedia Commons).*

As the energy of the wind increases, so does the size, length and speed of the resulting waves. There are three important factors determining how much energy is transferred from wind to waves, and thus how large the waves will get:

- Wind **speed.**
- The **duration** of the wind, or how long the wind blows continuously over the water.
- The distance over which the wind blows across the water in the same direction, also known as the **fetch**.

Increasing any of these factors increases the energy of wind waves, and therefore their size and speed. But there is an upper limit to how large wind-generated waves can get. As wind energy increases, the waves receive more energy and they get both larger and steeper (recall from section 10.1 that wave steepness = height/wavelength). When the wave height exceeds 1/7 of the wavelength, the wave becomes unstable and collapses, forming whitecaps.

The ocean surface represents an irregular mixture of hundreds of waves of different speeds and sizes, all coming from different directions and interacting with each other. A histogram of wave heights within this mixture reveals a bell-shaped curve (Figure 10.2.2). In addition to basic statistics such as mode (most probable), median and mean wave height, wave heights are also reported in other ways. Marine weather forecasts and ship and buoy data often report **significant wave height (H_S)**, which is the mean height of the largest one-third of the waves. Mean wave height is approximately equal to two-thirds of the significant wave height. Finally, there is the minimum height of the highest 10% of waves (the 90th percentile of wave heights), often expressed as $H_{1/10}$.

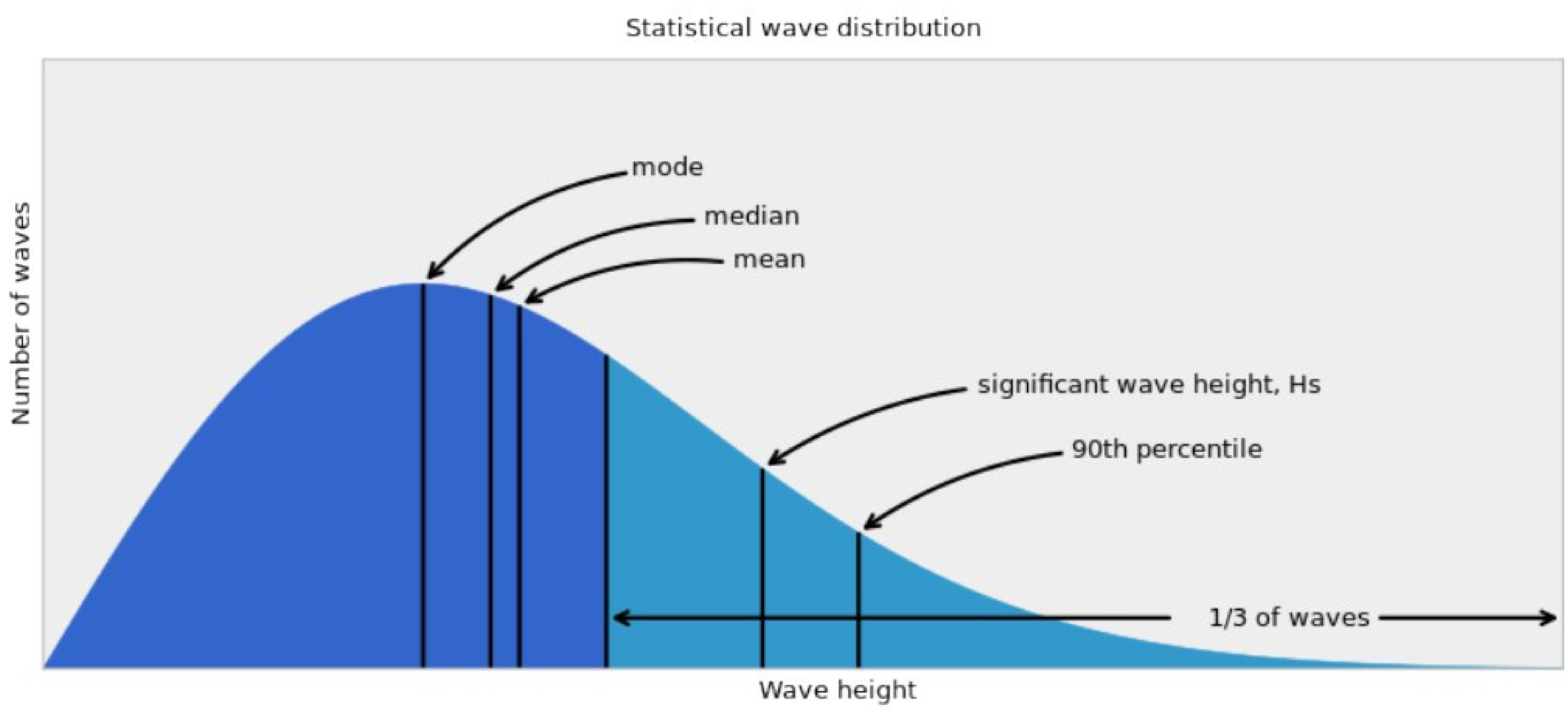


***Figure 10.2.2** Histogram of typical wave height distribution at sea, showing common statistical measurements (NOAA, Public Domain via Wikimedia Commons).*

Under strong wind conditions, the ocean surface becomes a chaotic mixture of choppy, whitecapped wind-generated waves. The term **sea state** describes the size and extent of the wind-generated waves in a particular area. When the waves are at their maximum size for the existing wind speed, duration, and fetch, it is referred to as a fully developed sea. The sea state is often reported on the **Beaufort scale**, ranging from 0-12, where 0 means calm, windless and waveless conditions, while Beaufort 12 is a hurricane (see box below).

The Beaufort Scale

The Beaufort scale is used to describe the wind and sea state conditions on the ocean. It is an observational scale based on the judgement of the observer, rather than one dictated by accurate measurements of wave height. Beaufort 0 represents calm, flat conditions, while Beaufort 12 represents a hurricane.


BEAUFORT FORCE 0
WIND SPEED: LESS THAN 1 KNOT
SEA: SEA LIKE A MIRROR
BEAUFORT FORCE 1
WIND SPEED: 1-3 KNOTS
SEA: WAVE HEIGHT .1M (.25FT), RIPPLES WITH THE APPEARANCE OF SCALES, BUT WITHOUT FOAM CRESTS
BEAUFORT FORCE 2
WIND SPEED: 4-6 KNOTS
SEA: WAVE HEIGHT .2-.3M (.5-1FT), SMALL WAVELETS, CRESTS HAVE A GLASSY APPEARANCE AND DO NOT BREAK
BEAUFORT FORCE 3
WIND SPEED: 7-10 KNOTS
SEA: WAVE HEIGHT .6-1M (2-3FT), LARGE WAVELETS, CRESTS BEGIN TO BREAK, ANY FOAM HAS GLASSY APPEARANCE, SCATTERED WHITECAPS
BEAUFORT FORCE 4
WIND SPEED: 11-16 KNOTS
SEA: WAVE HEIGHT 1-1.5M (3.5-5FT), SMALL WAVES BECOMING LONGER, FAIRLY FREQUENT WHITE HORSES
BEAUFORT FORCE 5
WIND SPEED: 17-21 KNOTS
SEA: WAVE HEIGHT 2-2.5M (6-8FT), MODERATE WAVES TAKING MORE PRONOUNCED LONG FORM, MANY WHITE HORSES, CHANCE OF SOME SPRAY
BEAUFORT FORCE 6
WIND SPEED: 22-27 KNOTS
SEA: WAVE HEIGHT 3-4M (9.5-13 FT), LARGER WAVES BEGIN TO FORM, SPRAY IS PRESENT, WHITE FOAM CRESTS ARE EVERYWHERE
BEAUFORT FORCE 7
WIND SPEED: 28-33 KNOTS
SEA: WAVE HEIGHT 4-5.5M (13.5-19 FT), SEA HEAPS UP, WHITE FOAM FROM BREAKING WAVES BEGINS TO BE BLOWN IN STREAKS ALONG THE WIND DIRECTION
BEAUFORT FORCE 8
WIND SPEED: 34-40 KNOTS
SEA: WAVE HEIGHT 5.5-7.5M (18-25FT), MODERATELY HIGH WAVES OF GREATER LENGTH, EDGES OF CREST BEGIN TO BREAK INTO THE SPINDRIFT, FOAM BLOWN IN WELL MARKED STREAKS ALONG WIND DIRECTION.

(Images by United States National Weather Service (http://www.crh.noaa.gov/mkx/marinefcst.php) [Public domain], via Wikimedia Commons).

A fully developed sea often occurs under stormy conditions, where high winds create a chaotic, random pattern of waves and whitecaps of varying sizes. The waves will propagate outwards from the center of the storm, powered by the strong winds. However, as the storm subsides and the winds weaken, these irregular seas will sort themselves out into more ordered patterns. Recall that open ocean waves will usually be deep water waves, and their speed will depend on their wavelength (section 10.1). As the waves move away from the storm center, they sort themselves out based on speed, with longer wavelength waves traveling faster than shorter wavelength waves. This means that eventually all of the waves in a particular area will be traveling with the same wavelength, creating regular, long period waves called **swell** (Figure 10.2.3). We experience swell as the slow up and down or rocking motion we feel on a boat, or with the regular arrival of waves on shore. Swell can travel very long distances without losing much energy, so we can observe large swells arriving at the shore even where there is no local wind; the waves were produced by a storm far offshore, and were sorted into swell as they traveled towards the coast.

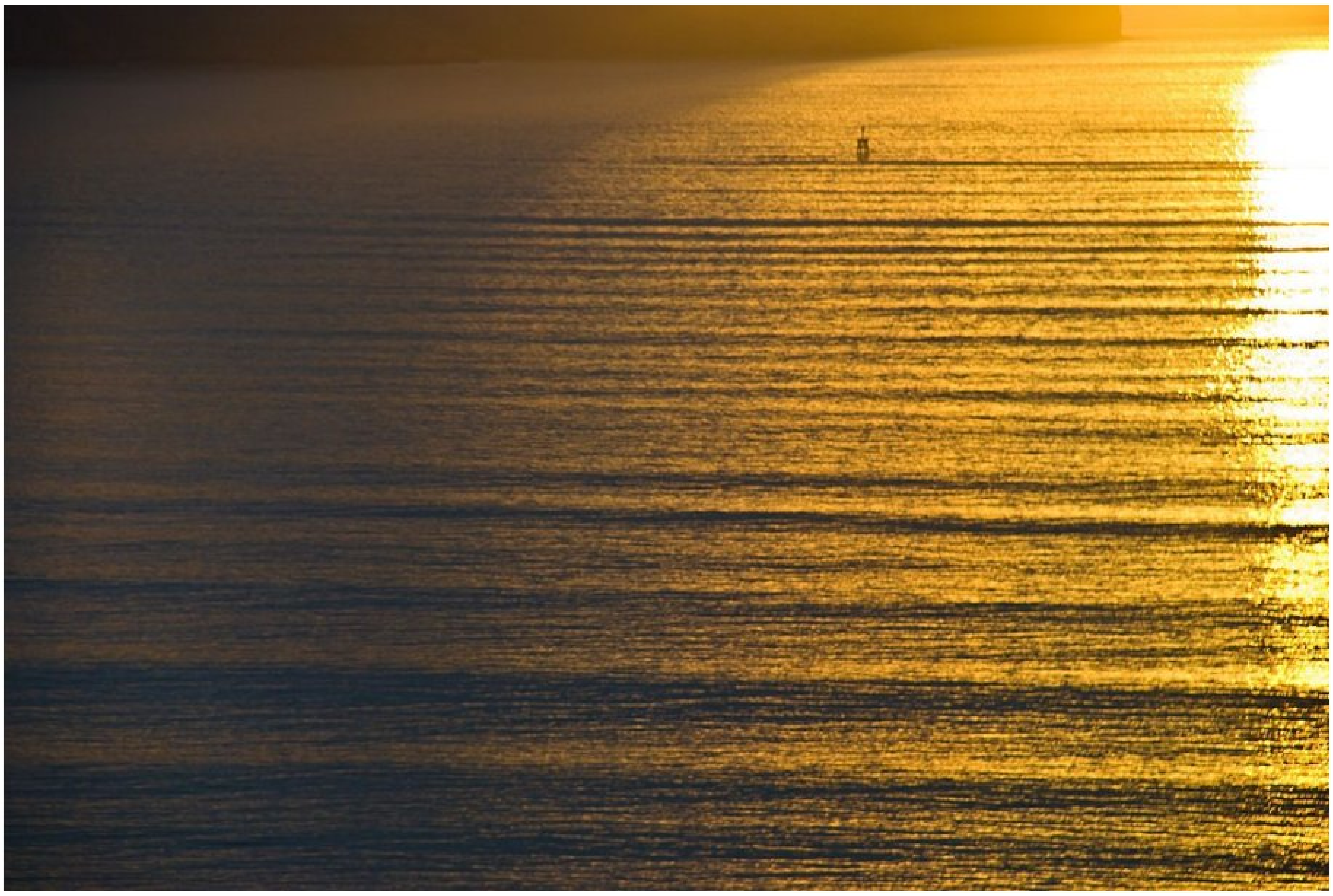


Figure 10.2.3 *Ocean swell, the regular pattern of waves of equal wavelength (Phillip Capper [CC BY 2.0], via Wikimedia Commons).*

Because swell travels such long distances, eventually swells coming from different directions will run into each other, and when they do they create interference patterns. The interference pattern is created by adding the features of the waves together, and the type of interference that is created depends on how the waves interact with each other (Figure 10.2.4). **Constructive interference** occurs when the two waves are completely in phase; the crest of one wave lines up exactly with the crest of the other wave, as do the troughs of the two waves. Adding the two crest together creates a crest that is higher than in either of the source waves, and adding the troughs creates a deeper trough than in the original waves. The result of constructive interference is therefore to create waves that are larger than the original source waves. In **destructive interference**, the waves interact completely out of phase, where the crest of one wave aligns with the trough of the other wave. In this case, the crest and the trough work to cancel each other out, creating a wave that is smaller than either of the source waves. In reality, it is rare to find perfect constructive or destructive interference as displayed in Figure 10.2.4. Most interference by swells at sea is **mixed interference**, which contains a mix of both constructive and destructive interference. The interacting swells do not have the same wavelength, so some points show constructive interference, and some points show destructive interference, to varying degrees. This results in an irregular pattern of both small and large waves, called **surf beat**.

It is important to point out that these interference patterns are only temporary disturbances, and do not affect the properties of the source waves. Moving swells interact and create interference where they meet, but each wave continues on unaffected after the swells pass each other.

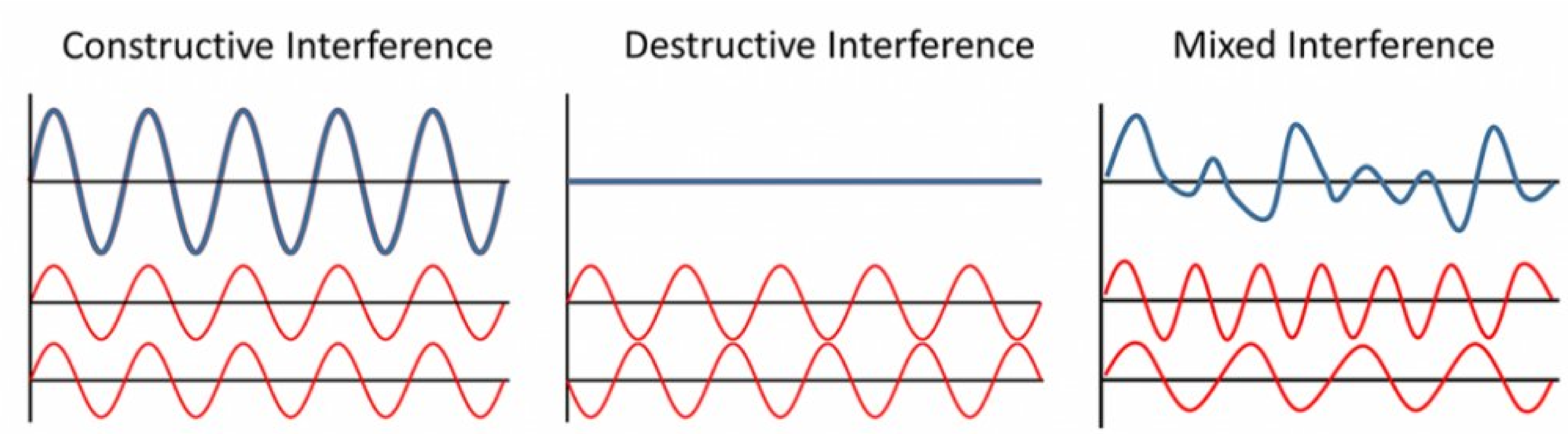


Figure 10.2.4 *Wave interference patterns. In constructive interference the source waves (red) are completely in phase, and when added together produce waves that are larger than the original waves (blue). In destructive interference the source waves are out of phase, so they cancel each other out and produce waves that are smaller than the originals. In mixed interference, constructive and destructive interference occur at various point, creating an irregular wave pattern. (Modified by PW from original version: Haade; vectorization: Wjh31, Quibik (Vecorized from File:Interference of two waves.png) [CC BY-SA 3.0 or GFDL (http://www.gnu.org/copyleft/fdl.html)], via Wikimedia Commons).*

About half of the waves in the open sea are less than 2 m high, and only 10-15% exceed 6 m. But the ocean can produce some extremely large waves. The largest wind wave reliably measured at sea occurred in the Pacific Ocean in 1935, and was measured by the navy tanker the USS Ramapo. Its crew measured a wave of 34 m or about 112 ft high! Occasionally constructive interference will produce waves that are exceptionally large, even when all of the surrounding waves are of normal height. These random, large waves are called **rogue waves** (Figure 10.2.5). A rogue wave is usually defined as a wave that is at least twice the size of the significant wave height, which is the average height of the highest one-third of waves in the region. It is not uncommon for rogue waves to reach heights of 20 m or more.

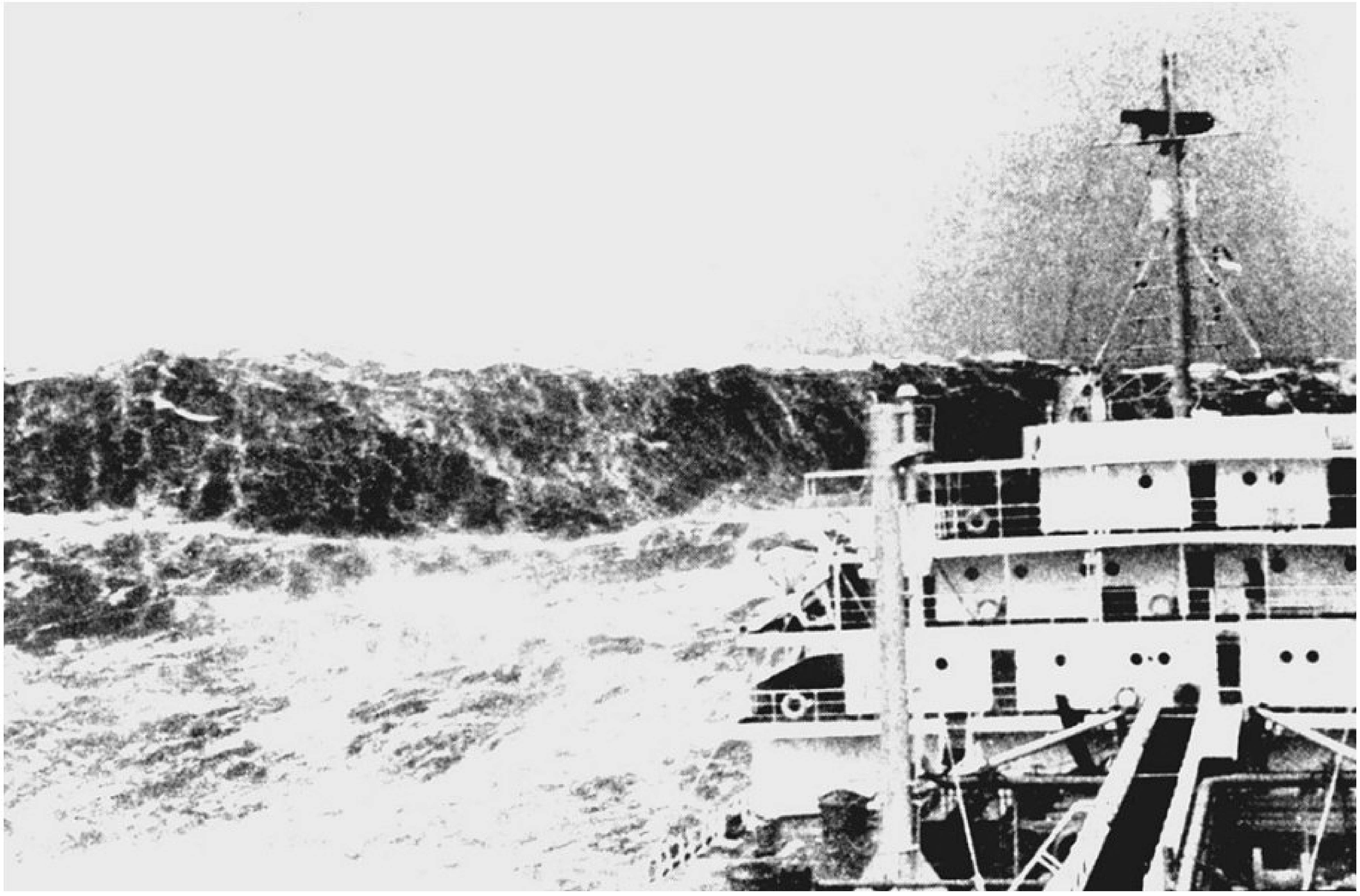


Figure 10.2.5 *A rogue wave in the Bay of Biscay, off of the French coast, ca. 1940 (NOAA, [Public domain], via Wikimedia Commons).*

Rogue waves are particularly common off of the southeast coast of South Africa, a region referred to as the "wild coast." Here, Antarctic storm waves move north into the oncoming Agulhas Current, and the wave energy gets focused over a narrow area, leading to constructive interference. This area may be responsible for sinking more ships than anywhere else on Earth. On average about 100 ships are lost every year across the globe, and many of these losses are probably due to rogue waves.

Waves in the Southern Ocean are generally fairly large (the red areas in Figure 10.2.6) because of the strong winds and the lack of landmasses, which provide the winds with a very long fetch, allowing them to blow unimpeded over the ocean for very long distances. These latitudes have been termed the "Roaring Forties", "Furious Fifties", and "Screaming Sixties" due to the high winds.

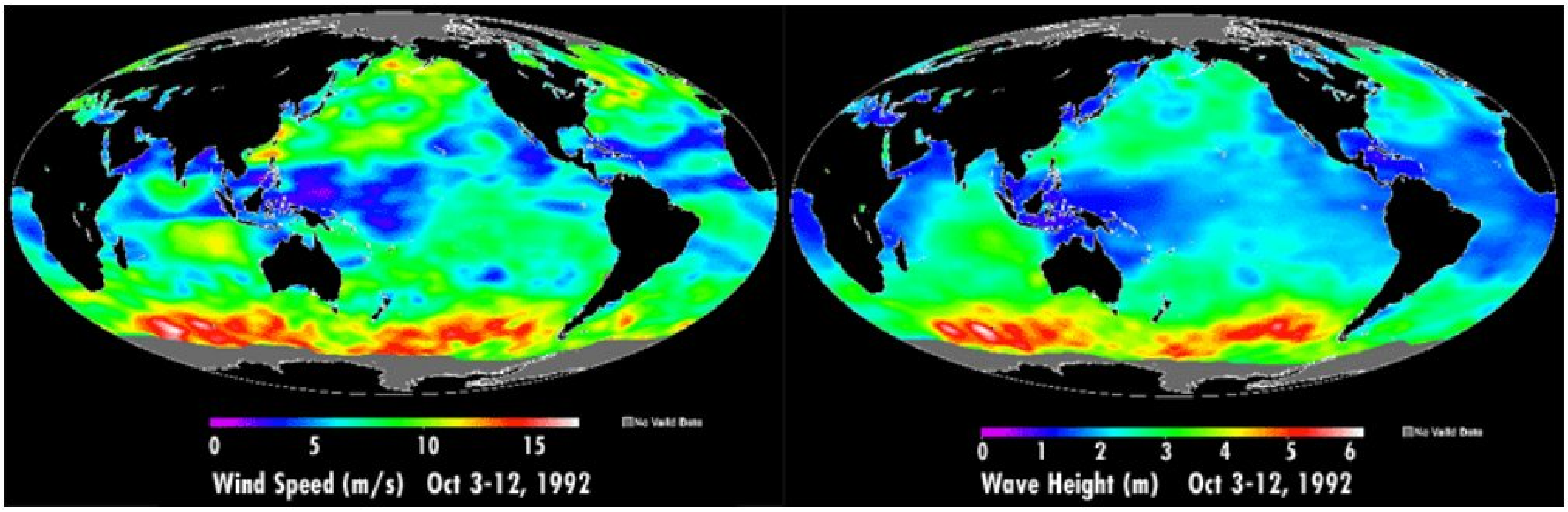


Figure 10.2.6 *Wind speed and wave height data for a 9-day period in 1992. The Southern Ocean is notorious for its high winds and large waves (NASA, Public Domain via Wikimedia Commons).*

10.3 Waves on the Shore

Most of the waves discussed in the previous section referred to deep water waves in the open ocean. But what happens when these waves move towards shore and encounter shallow water? Remember that in deep water, a wave's speed depends on its wavelength, but in shallow water wave speed depends on the depth (section 10.1). When waves approach the shore they will "touch bottom" at a depth equal to half of their wavelength; in other words, when the water depth equals the depth of the wave base (Figure 10.3.1). At this point their behavior will begin to be influenced by the bottom.

When the wave touches the bottom, friction causes the wave to slow down. As one wave slows down, the one behind it catches up to it, thus decreasing the wavelength. However, the wave still contains the same amount of energy, so while the wavelength decreases, the wave height increases. Eventually the wave height exceeds 1/7 of the wavelength, and the wave becomes unstable and forms a **breaker**. Often breakers will start to curl forwards as they break. This is because the bottom of the wave begins to slow down before the top of the wave, as it is the first part to encounter the seafloor. So the crest of the wave gets "ahead" of the rest of the wave, but has no water underneath it to support it (Figure 10.3.1).

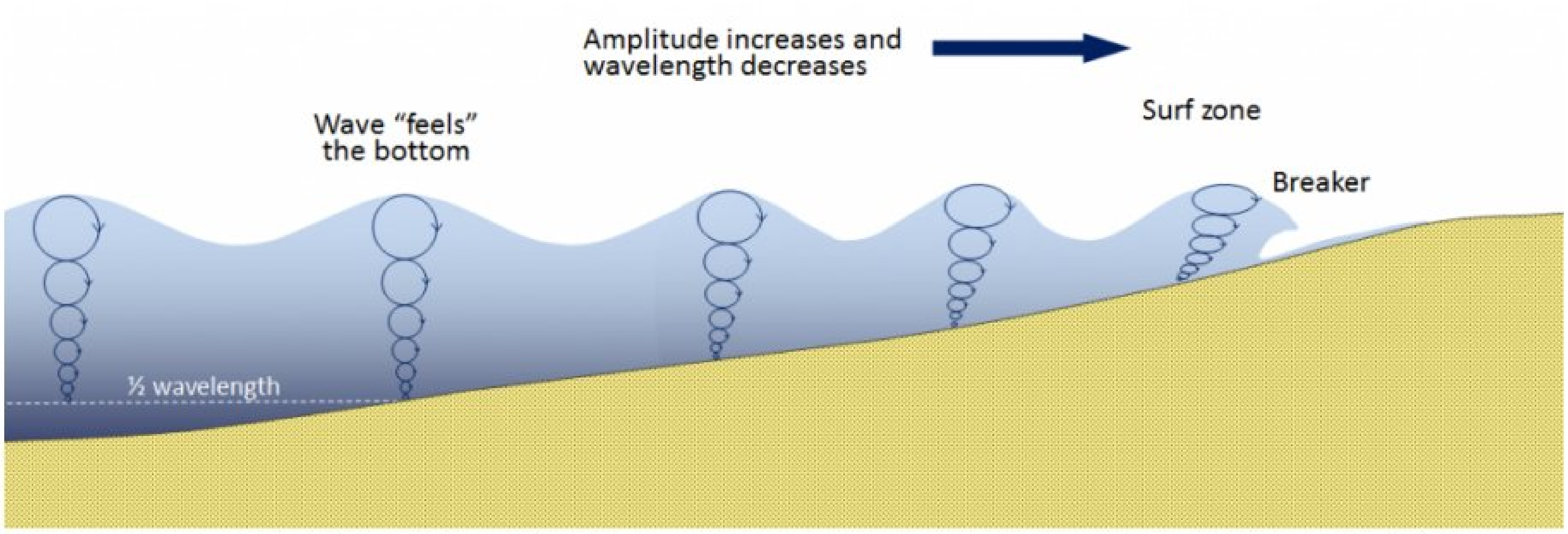


***Figure 10.3.1** As waves approach shore they "touch bottom" when the depth equals half of the wavelength, and the wave begins to slow down. As is slows, the wavelength decreases and the wave height increases, until the wave breaks (Steven Earle "Physical Geology").*

There are three main types of breakers: spilling, plunging, and surging. These are related to the steepness of the bottom, and how quickly the wave will slow down and its energy will get dissipated.

- **Spilling** breakers form on gently sloping or flatter beaches, where the energy of the wave is dissipated gradually. The wave slowly increases in height, then slowly collapses on itself (Figure 10.3.2). For surfers, these waves provide a longer ride, but they are less exciting.

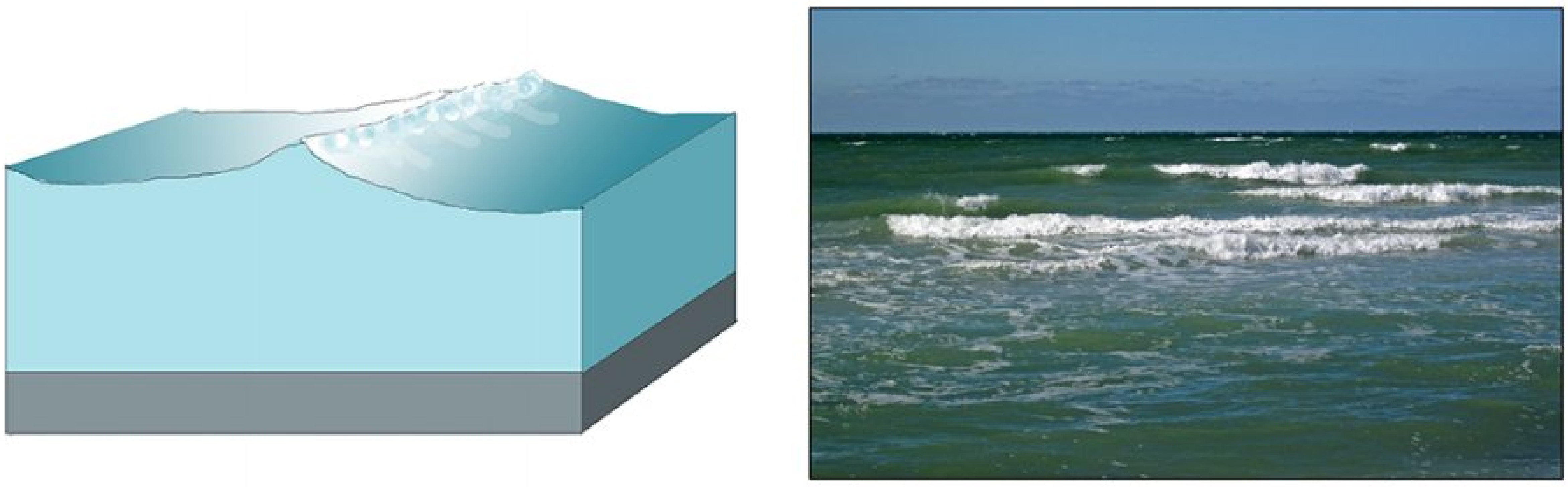


__Figure 10.3.2__ A spilling breaker. The gentle slope of the bottom causes the wave height to slowly increase until the wave collapses on itself (left: JR, right: James St. John, [CC-BY-2.0], https://www.flickr.com/photos/jsjgeology/23769708334).

- **Plunging** breakers form on more steeply-sloped shores, where there is a sudden slowing of the wave and the wave gets higher very quickly. The crest outruns the rest of the wave, curls forwards and breaks with a sudden loss of energy (Figure 10.3.3). These are the "pipeline" waves that surfers seek out.

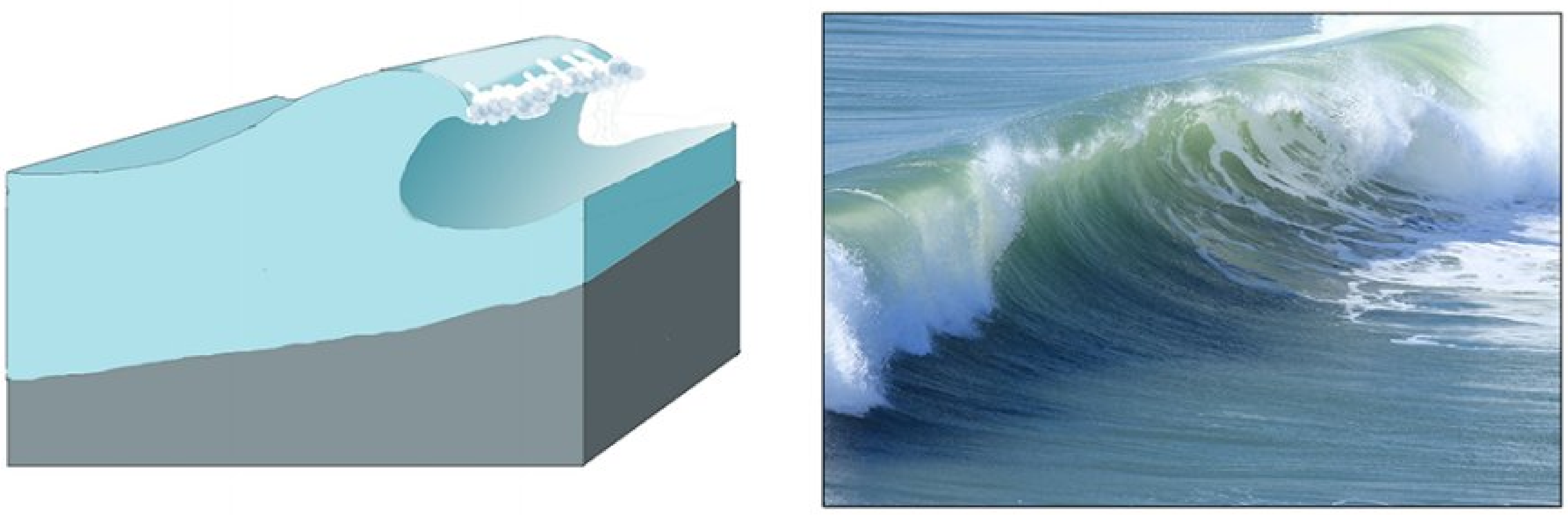


__Figure 10.3.3__ A plunging breaker. The steeper slope causes the wave height to increase more rapidly, with the crest of the wave outrunning the base of the wave, causing it to curl as it breaks (left: JR, right: Andrew Schmidt, Public Domain [CC-0], publicdomainpictures.net).

- **Surging** breakers form on the steepest shorelines. The wave energy is compressed very suddenly right at the shoreline, and the wave breaks right onto the beach (Figure 10.3.4). These waves give too short (and potentially painful) a ride for surfers to enjoy.

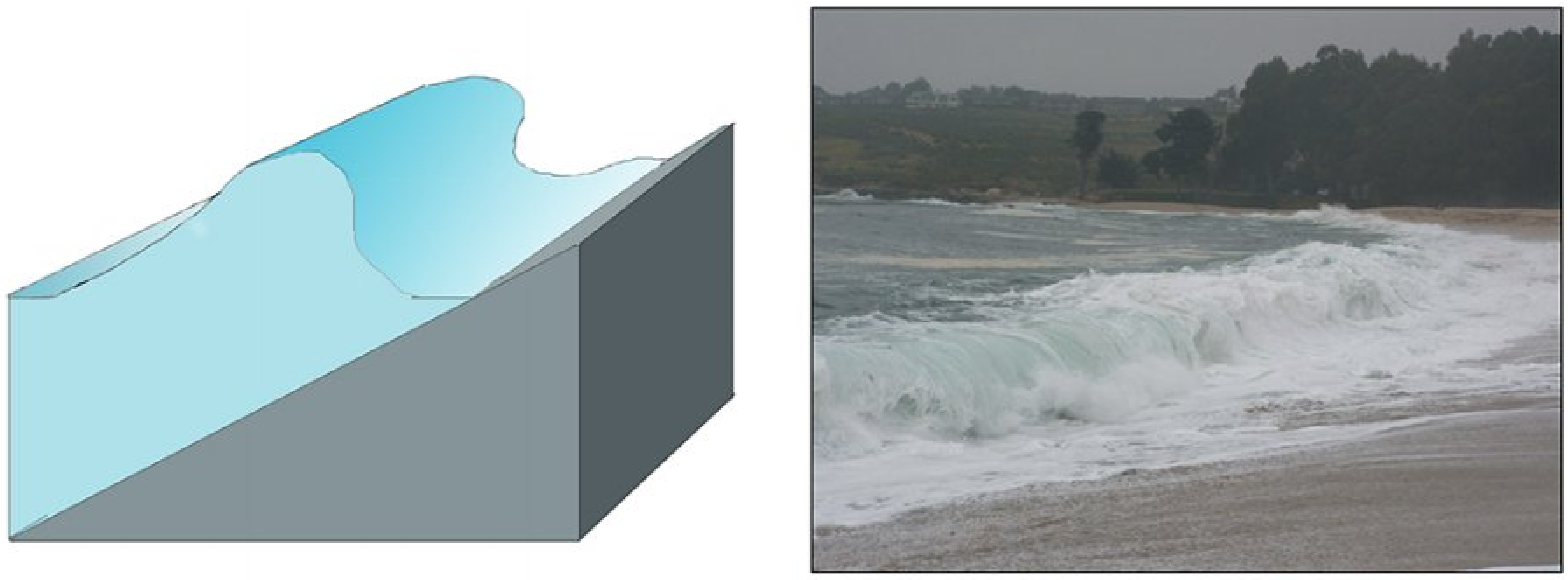


Figure 10.3.4 A surging breaker. The very steep slope causes the wave height to increase suddenly and break right on the beach (left: JR, right: Tewy, [CC-BY-SA-3.0], via Wikimedia Commons).

Wave Refraction

Swell can be generated anywhere in the ocean and therefore can arrive at a beach from almost any direction. But if you have ever stood at the shore you have probably noticed that the waves usually approach the shore somewhat parallel to the coast. This is due to wave refraction. If a wave front approaches shore at an angle, the end of the wave front closest to shore will touch bottom before the rest of the wave. This will cause that shallower part of the wave to slow down first, while the rest of the wave that is still in deeper water will continue on at its regular speed. As more and more of the wave front encounters shallower water and slows down, the wave font refracts and the waves tend to align themselves nearly parallel to the shoreline (they are refracted towards the region of slower speed). As we will see in section 13.2, the fact that the waves do not arrive perfectly parallel to the beach causes longshore currents and longshore transport that run parallel to the shore.

Refraction can also explain why waves tend to be larger off of points and headlands, and smaller in bays. A wave front approaching shore will touch the bottom off of the point before it touches bottom in a bay. Once again, the shallower part of the wave front will slow down, and cause the rest of the wave front to refract towards the slower region (the point). Now all of the initial wave energy is concentrated in a relatively small area off of the point, creating large, high energy waves (Figure 10.3.6). In the bay, the refraction has caused the wave fronts to refract away from each other, dispersing the wave energy, and leading to calmer water and smaller waves. This makes the large waves of a "point break" ideal for surfing, while water is calmer in a bay, which is where people would launch a boat. This difference in wave energy also explains why there is net erosion on points, while sand and sediments get deposited in bays (see section 13.3).

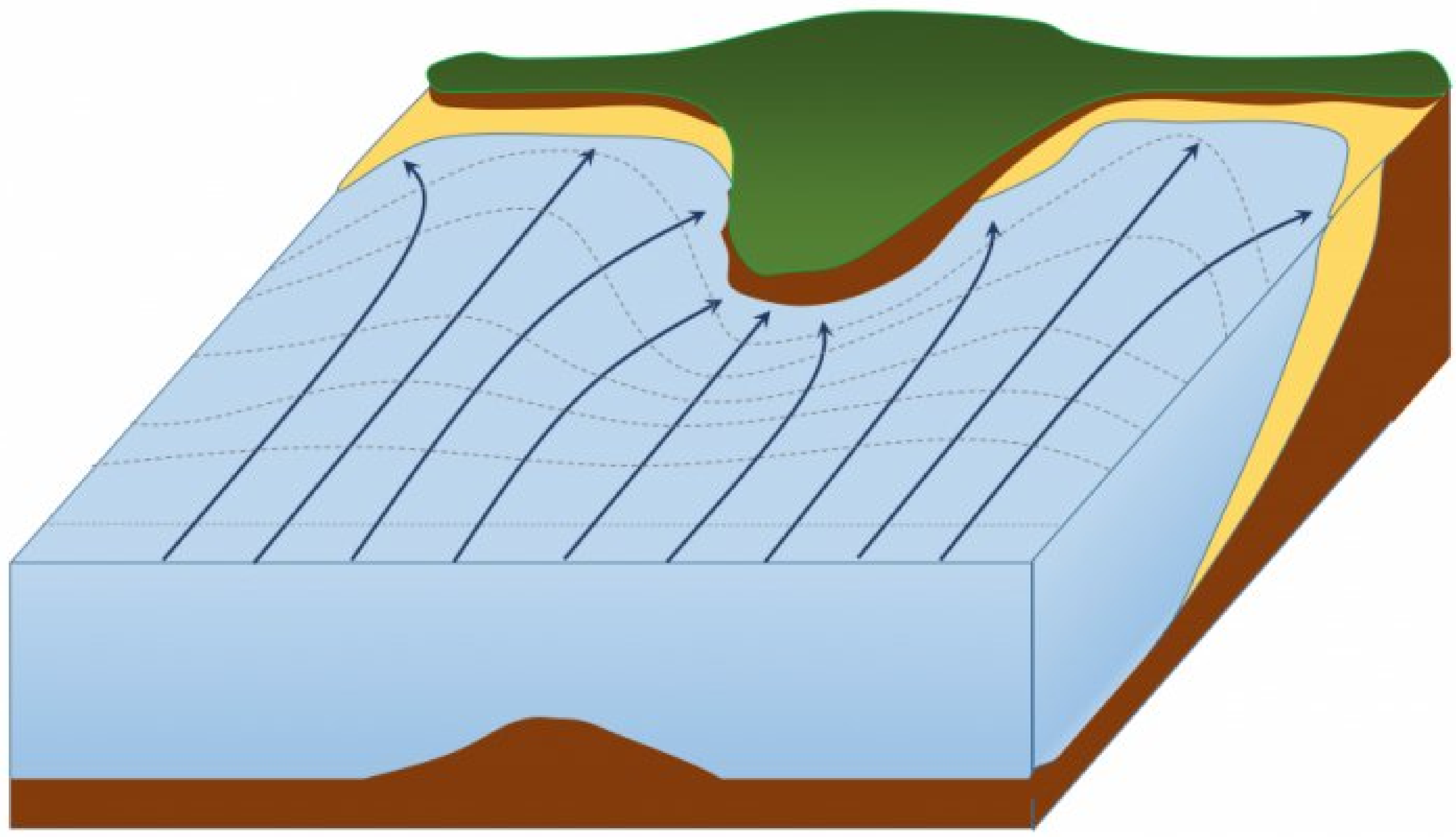


Figure 10.3.6 *Waves approaching shore (blue lines) touch bottom sooner off of points and are refracted towards the points, concentrating their wave energy. Wave energy is spread out in bays, causing smaller waves. Dotted lines represent the bottom contours (PW).*

10.4 Tsunamis

Tsunamis loom large in popular culture, but there are a number of misconceptions about these large waves. First, tsunamis have nothing to do with the tides, so it is a misnomer to refer to them as "tidal waves." There are actual tidal waves (see section 11.1), but they are not related to tsunamis. Second, the giant, curling wave that is taller than skyscrapers and destroys cities in science fiction movies is also a fabrication, as tsunamis do not behave that way, as described below.

Tsunamis are large waves that are usually the result of seismic activity, such as the rising or falling of the seafloor due to earthquakes, although volcanic activity and landslides can also cause tsunamis in the form of splash waves (see section 10.1). As the seafloor rises or falls, so does the water column above it, creating waves. Only vertical seismic disturbances cause tsunamis, not horizontal movements. These vertical seafloor movements are usually less than 10 m high, so the resulting wave will be of an equal or lesser height at sea. While the tsunamis have a relatively small height at the point of origin, they have very long wavelengths (100-200 km). Because of the long wavelength, they behave as shallow water waves throughout the entire ocean; the depth of the ocean is always shallower than half of their wavelength. As shallow water waves, their speed depends on water depth, but they can still travel at speeds over 750 km/hr (Figure 10.4.1)!

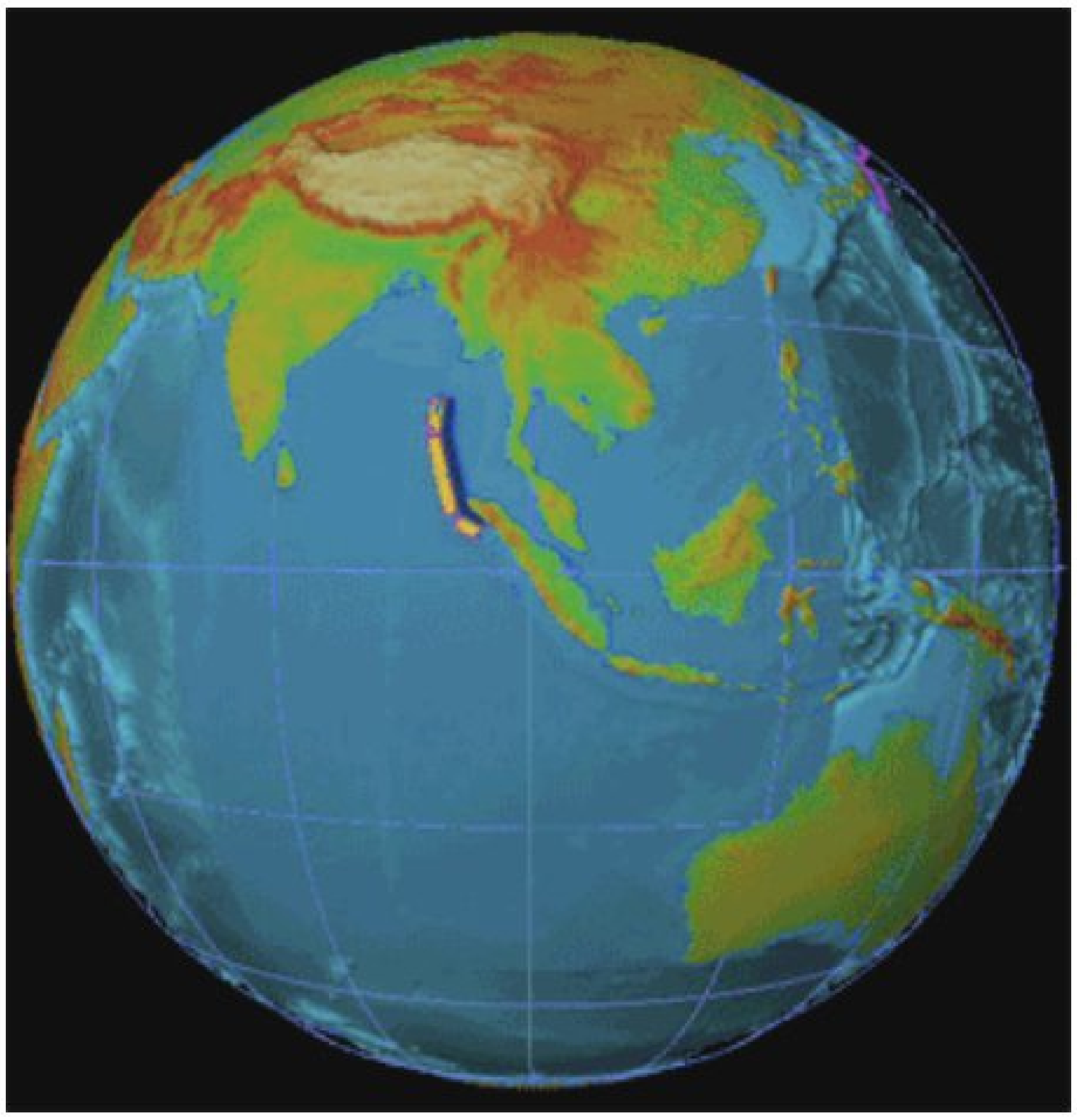


Figure 10.4.1 *Animation of the spread of tsunamis created during the 2004 Indonesia earthquake (NOAA Center for Tsunami Research (NCTR) [Public domain]).*

When tsunamis approach land, they behave just like any other wave; as the depth becomes shallower, the waves slow down and the wave height begins to increase. However, contrary to popular belief, tsunamis do not arrive on shore as giant, cresting waves. Since their wavelength is so long, it is impossible for their height to ever exceed 1/7 of their wavelength, so the waves don't actually curl or break. Instead, they usually hit the shore as sudden surges of water causing a very rapid increase in sea level, like that of an enormous rise in tide. It may take several minutes for the wave to pass, during which time sea level can rise to 40 m higher than usual.

Large tsunamis occur every 2-3 years, with very large, damaging events happening every 15-20 years. The most devastating tsunami in terms of loss of life resulted from a magnitude 9 earthquake in Indonesia in 2004 (Figure 10.4.2), which created waves up to 33 m tall and left about 230,000 people dead in Indonesia, Thailand, and Sri Lanka. In 2011 a 9.0 magnitude earthquake in Japan triggered a tsunami up to 40.5 m high, which resulted in over 18,000 deaths. This earthquake also caused the Fukishima nuclear accident, and moved Japan about 8 inches closer to the U.S.

Figure 10.4.2 *A village in Sumatra following the Indonesia Tsunami in December 2004 (U.S. Navy photo by Photographer's Mate 2nd Class Philip A. McDaniel [Public domain via Wikimedia Commons]).*

CHAPTER 11: TIDES

Chapter 11: Tides

Learning Objectives

After reading this chapter you should:

- understand that tides are just very long waves, with crests and troughs
- understand Newton's Law of Universal Gravitation and how it applies to tides
- understand why most places on Earth experience two tides per day, not just the one predicted from gravitational attraction between the Earth and moon (i.e. inertial force)
- understand how the Earth, sun and moon interact to create spring and neap tides
- understand why the gravitational pull of the sun on tides is less than the pull of the moon
- understand why tides do not occur at the same time every day
- understand why amphidromic circulation occurs as a result of tides
- know the difference between diurnal, semi-diurnal, and mixed tides
- know the phases of a tidal current
- know what causes a tidal bore

The previous chapter discussed various types of waves at sea and along the shore. However, at least in terms of wavelength, the largest waves in the ocean are the tides, where one wavelength stretches halfway around the Earth. The crests of these long waves represent the high tides, while the troughs create low tides.

You probably learned when you were younger that the basic cause of the tides is the gravitational attraction between the Earth and moon. This is a very old idea, as the Greek scientist Pytheas first made the connection between the tides and the moon back in 330 B.C.E. Isaac Newton's gravitational work the 1600s led to our modern understanding of tidal cycles, however, we now know that the tides involve a lot more than just the Earth and the moon. There are many variables that influence the tides, yet despite this complexity, we are able to create accurate tide charts predicting the heights and timing of tides months or even years in advance.

11.1 Tidal Forces

Our modern understanding of tide formation stems from Isaac Newton's Law of Universal Gravitation, which states that any two objects have a gravitational attraction to each other. The magnitude of the force is proportional to the masses of the objects, and inversely proportional to the square of the distance between the objects, according to the equation in Figure 11.1.1.

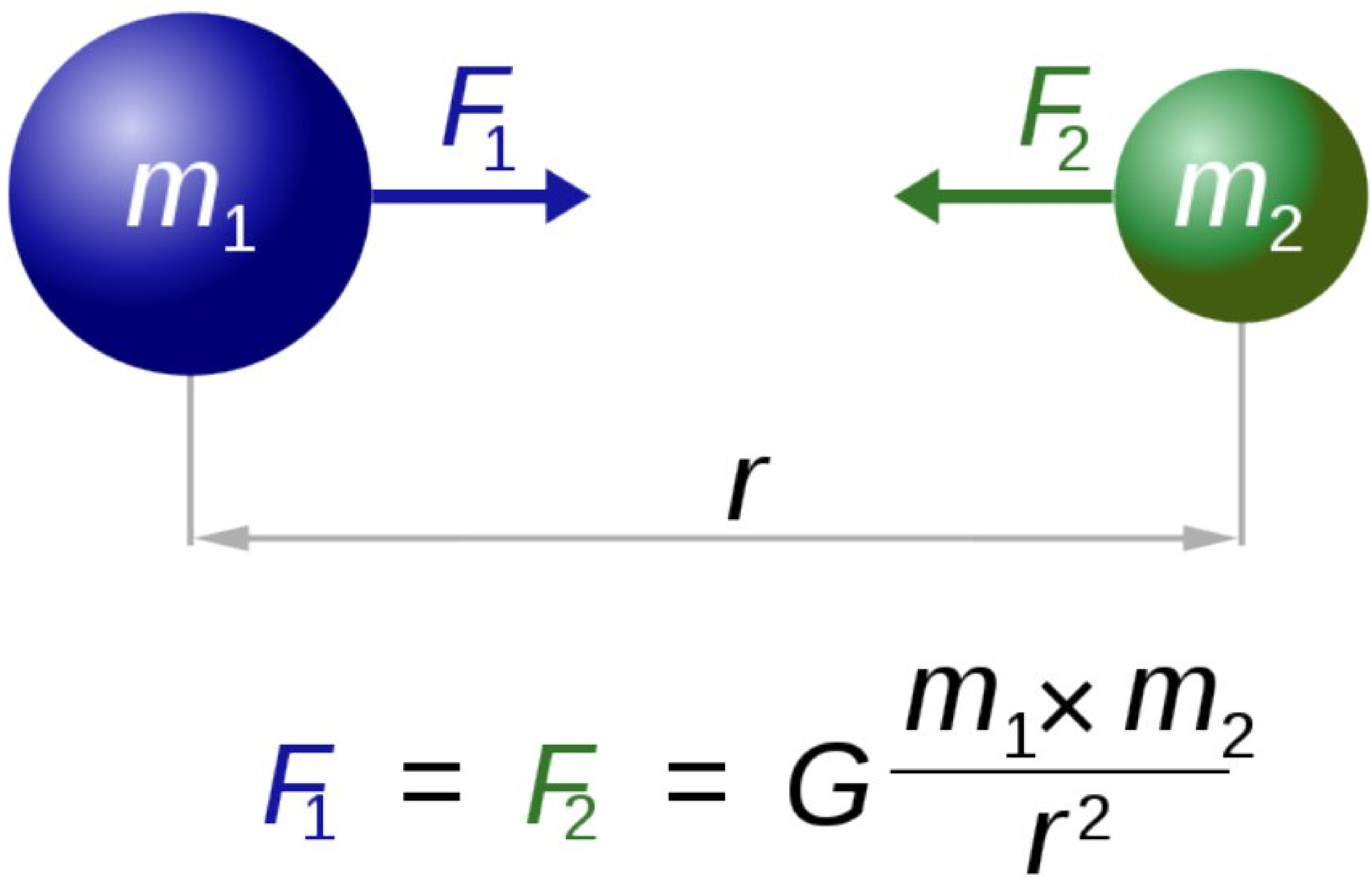


Figure 11.1.1 *Newton's Law of Universal Gravitation. The gravitational force between two objects (F) is calculated as the product of the two masses (m_1 and m_2) divided by the distance between them (r) squared. G is the universal gravitational constant; 6.67408 × 10^{-11} m^3 kg^{-1} s^{-2} (By I, Dennis Nilsson [CC BY 3.0], via Wikimedia Commons).*

In the case of tides, there are a few other factors that modify this equation so that the distance (r) is cubed rather than squared, giving distance an even greater impact on tidal forces. But for our purposes, the important lesson is that the greater the masses of the objects, the greater the gravitational force, and the farther the objects are from each other, the weaker the force.

Such a gravitational force exists between the Earth and moon, attempting to pull them towards each other. Since the water covering Earth is fluid (unlike the solid land that is more resistant to tidal forces), this gravitational force pulls water towards the moon, creating a "bulge" of water on the side of the Earth facing the moon (Figure 11.1.2). This bulge always faces the moon, while the Earth rotates through it; the regions of Earth moving through the bulge experience a high tide, while those parts of the Earth away from the bulge experience a low tide.

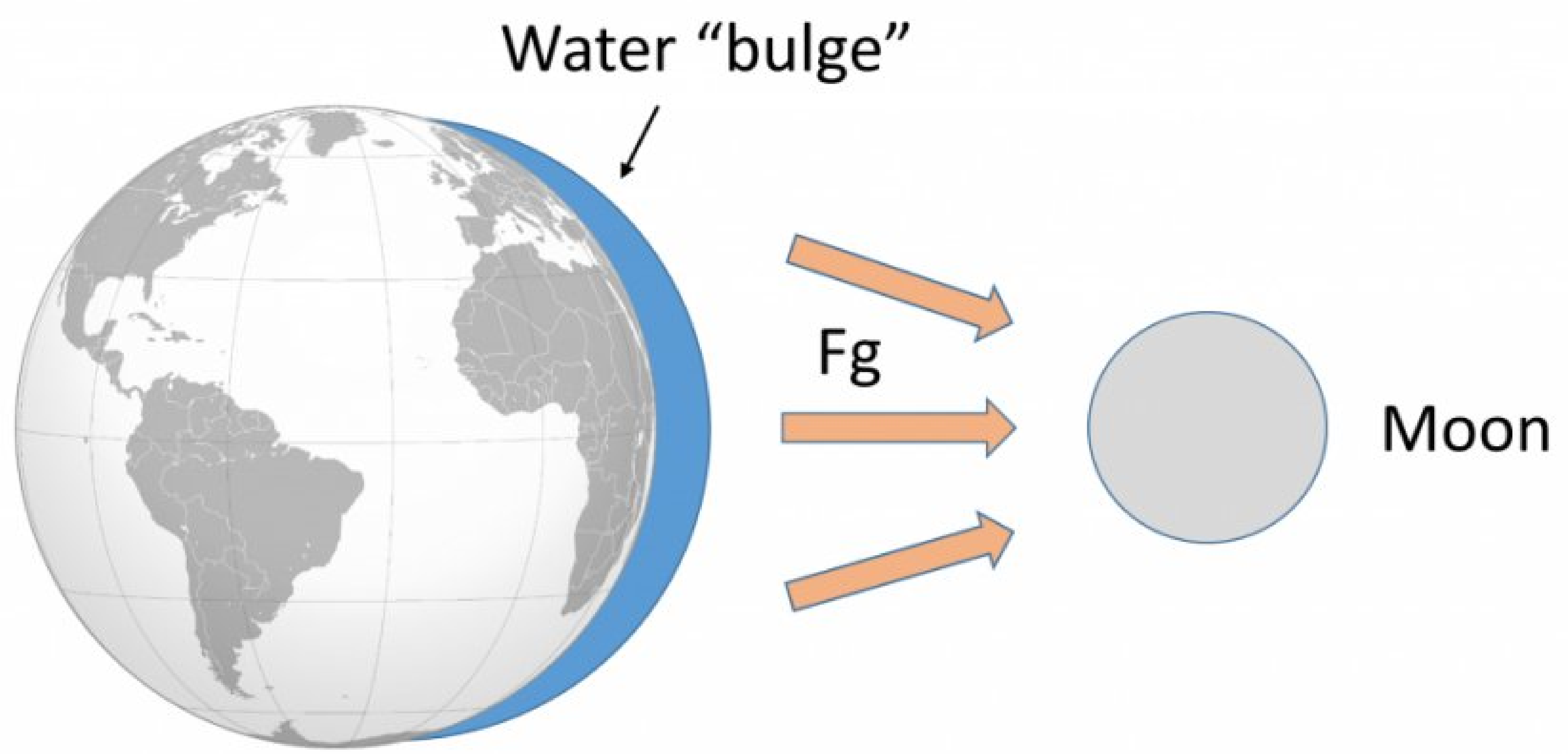


Figure 11.1.2 *Gravitational forces between the Earth and moon cause a bulge of water to appear on the side of the Earth facing the moon (PW).*

If the tides were this simple, everywhere on Earth would see one high tide per day, as there would only be a bulge of water on the side closest to the moon. However, if you have ever looked at tide charts, or lived near the ocean, you probably know that in most places there are two high tides and two low tides per day. Where is this second high tide "bulge" coming from?

The gravitational force between the Earth and moon might be expected to draw the two objects closer together, however, this is not happening. This is because the inward gravitational force is opposed by outward forces that keep the Earth and moon apart. The outward force is an **intertial force** created by the rotation of the Earth and moon. Contrary to popular belief, the moon is not simply rotating around the Earth; in fact, the Earth and moon are both rotating around each other. Imagine the Earth and moon as equal-sized objects revolving around a point at their center of mass. If both objects had the same mass, the center of rotation would be a point equidistant between the two objects. But since the mass of the Earth is 82 times greater than the mass of the moon, the center of revolution must be closer to the Earth. As an analogy, think about two people on a see-saw. If the people are of roughly equal size, they can sit on either end of the see-saw at it will rotate around a point at equal distance between them. But if the two people have very different masses, such as a large adult and a small child, the larger person must move closer to the pivot point for the see-saw to rotate effectively. In the same way, the center of rotation between the Earth and the moon (the **barycenter**) must be located closer to the Earth. In fact, the center of rotation lies *within* the Earth, about 1600 km below the surface. As the Earth and moon rotate around the barycenter, the moon travels much farther than the Earth, giving the impression that the moon is rotating around Earth (Figure 11.1.3).

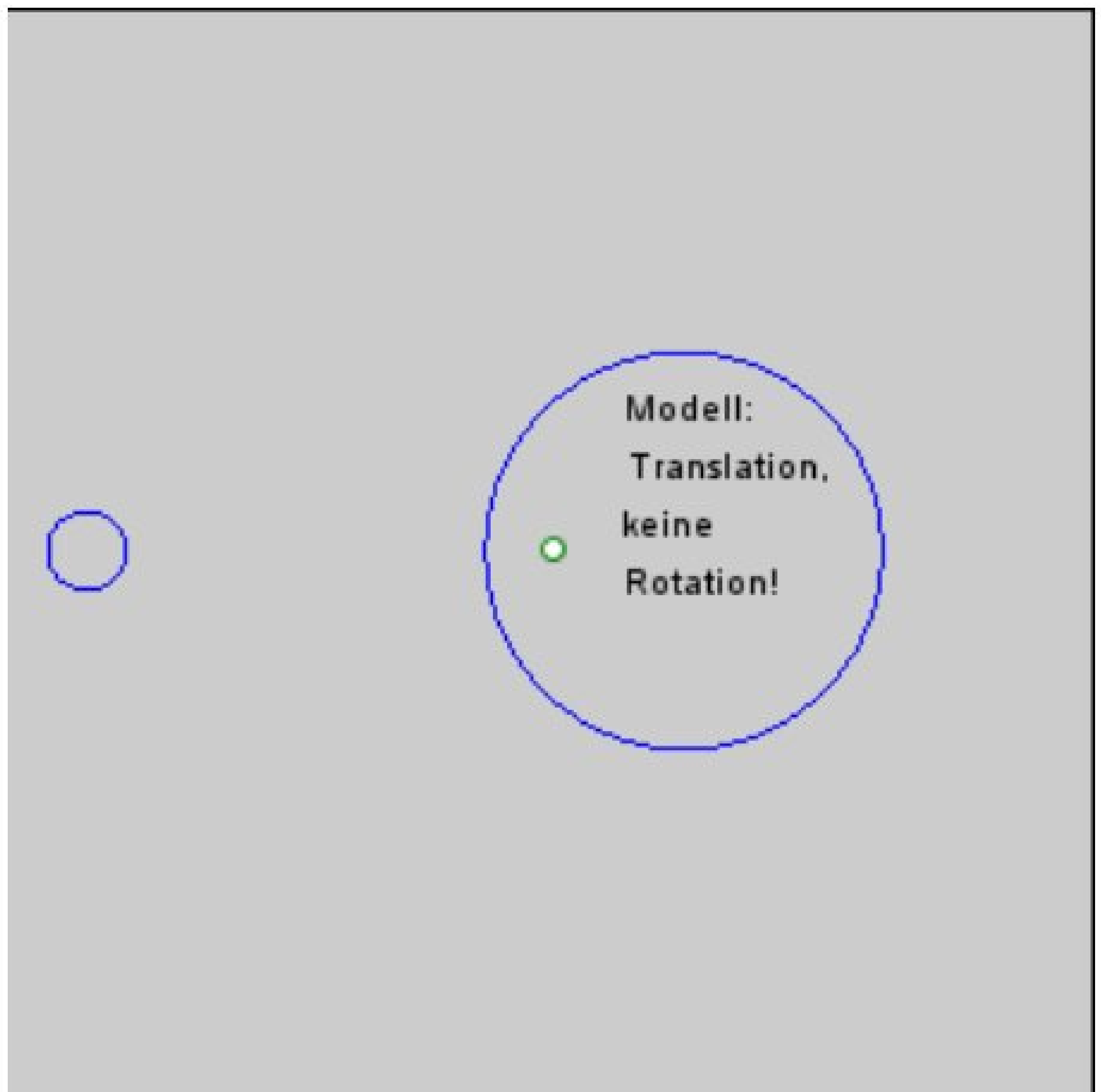


Figure 11.1.3 *Rotation of the Earth and moon around the barycenter (white dot). Because of its larger mass, the center of rotation lies closer to the Earth than to the moon (By Modalanalytiker (Own work) [CC BY-SA 3.0 or GFDL (http://www.gnu.org/copyleft/fdl.html)], via Wikimedia Commons).*

The rotation of the Earth-moon system creates an outward inertial force, which balances the gravitational force to keep the two bodies in their orbits. The inertial force has the same magnitude everywhere on Earth, and is always directed away from the moon. Gravitational force, on the other hand, is always directed towards the moon, and is stronger on the side of the Earth closest to the moon. Figure 11.1.4 describes how these forces combine to create the tidal forces. At point O in the center of the Earth, the gravitational force (F_g) and the inertial force (F_r) are equal, and cancel each other out. On the side of Earth closest to the moon, the inward gravitational force (F_g) is greater than the outward inertial force (F_r); the net resulting force (A) is directed towards the moon, and creates a bulge of water on the side facing the moon. On the side of Earth opposite the moon, the outward inertial force is greater than the inward gravitational force; the net resulting force (C) is directed away from the moon, creating a water bulge directed away from the moon.

Now, as the Earth rotates through a 24 hour day, each region passes through two bulges, and experiences two high tides and two low tides per day. This represents Newton's **Equilibrium Theory of Tides,** where there are two high tides and two low tides per day, of similar heights, each six hours apart. But as with everything else in oceanography, reality is much more complex than this idealized situation.

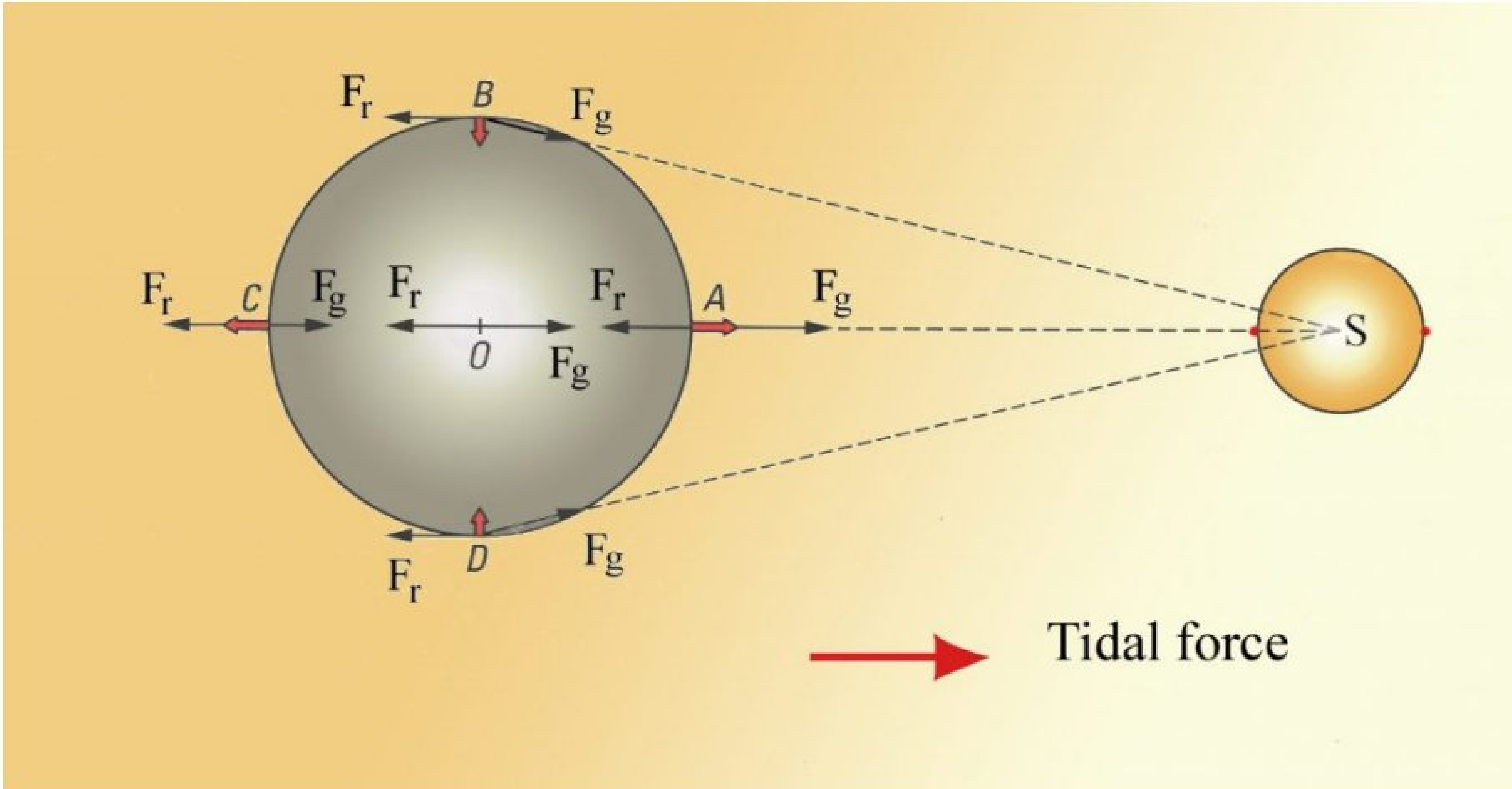


Figure 11.1.4 *Gravitational force (F_g) are strongest closer to the moon and weaker opposite the moon. Inertial forces (F_r) are equal throughout the Earth and directed away from the moon. The tidal forces A and C are the result of the interaction between F_g and F_r and create water bulges on both sides of the Earth, leading to two high tides per day (Vitold Muratov (Own work) [CC BY-SA 3.0], via Wikimedia Commons).*

Some of the additional complexity is because in addition to the moon, the sun also exerts tide-affecting forces on Earth. The solar gravitational and inertial forces arise for the same reasons described above for the moon, but the magnitudes of the forces are different. The sun is 27 million times more massive than the moon, but it is 387 times farther away from the Earth. Despite its larger mass, because the sun is so much farther away than the moon, the sun's gravitational forces are only about half as strong as the moon's (remember that distance is cubed in the gravity equation). The sun thus creates its own, smaller water bulges, independent of the moon's, that contribute to the creation of tides.

When the sun, Earth and moon are aligned, as occurs during new and full moons, the solar and lunar bulges are also aligned, and add to each other (constructive interference; see section 10.2) creating an especially high tidal range; high high tides and low low tides (Figure 11.1.5). This period of maximum tidal range is called a **spring tide**, and they occur every two weeks.

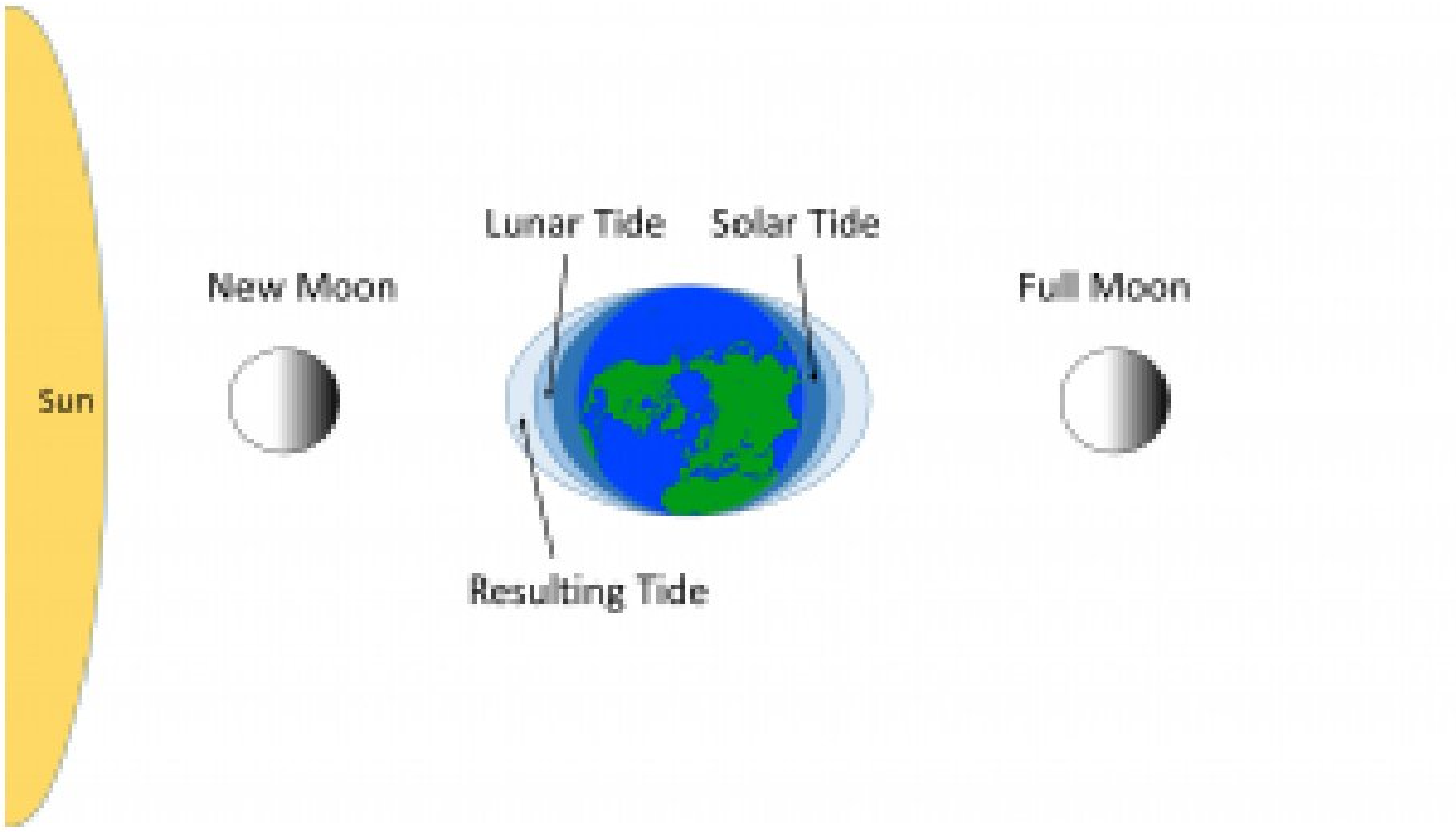


Figure 11.1.5 *Spring tides with high tidal ranges occur when the solar and lunar tides are added together during full and new moons when the Earth, sun and moon are aligned (PW).*

When the sun, Earth and moon are at 90° to each other, the solar and lunar bulges are out of phase, and cancel each other out (destructive interference). Now the tidal range is small, with low high tides and high low tides (Figure 11.1.6). These are **neap tides**, and occur every two weeks, when the moon is in its 1/4 and 3/4 phases (Figure 11.1.7).

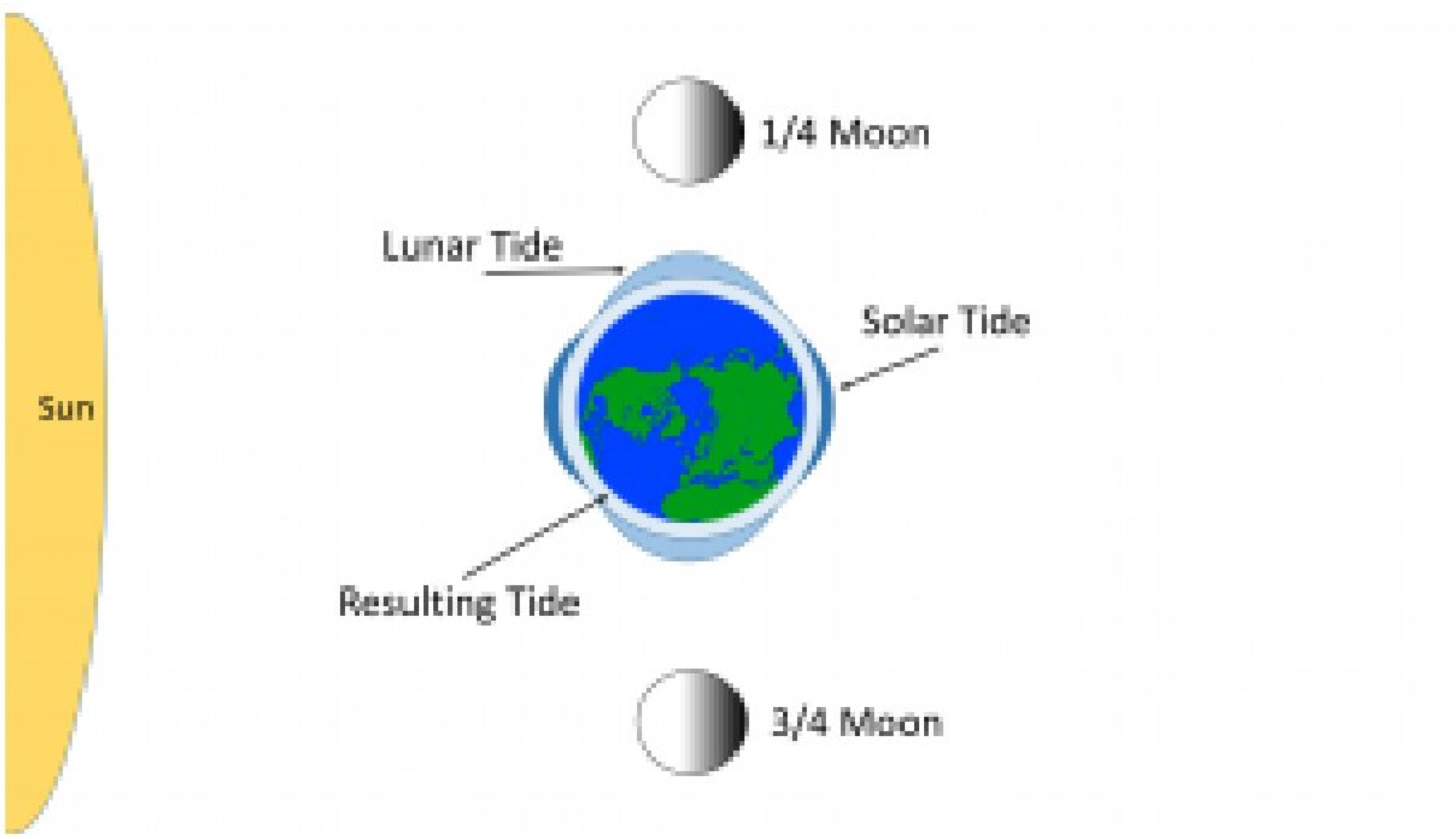


Figure 11.1.6 *Neap tides are created during 1/4 and 3/4 moons when the Earth, sun and moon are perpendicular to each other. The solar and lunar tides cancel each other out, resulting in a small tidal range (PW).*

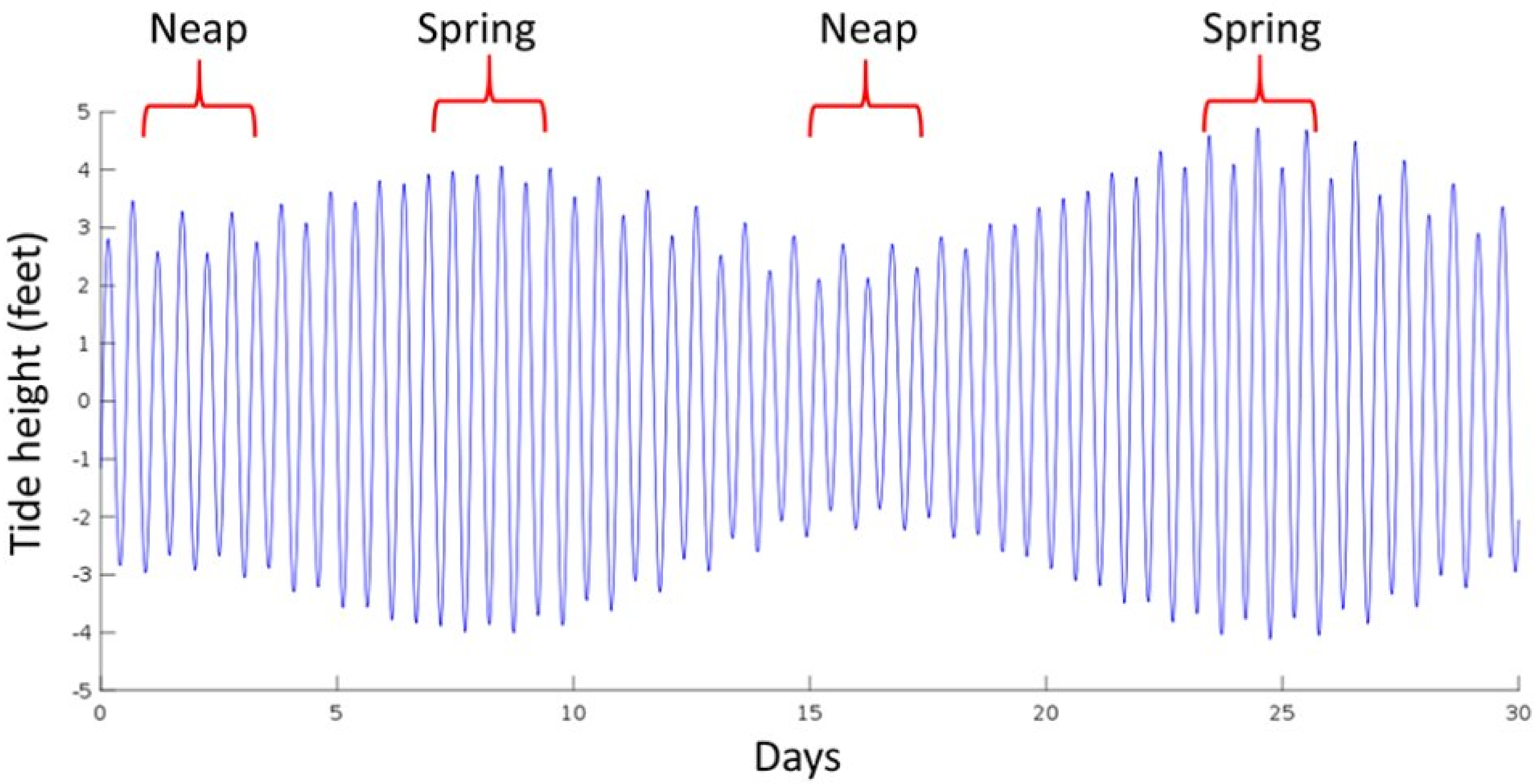


Figure 11.1.7 *30 days of tidal data from Bridgeport, CT, USA, showing spring and neap tidal ranges (Modified by PW from Cody Logan (clpo13), Public Domain via Wikimedia Commons).*

11.2 Dynamic Theory of Tides

The Equilibrium Theory of tides predicts that each day there will be two high and two low tides, each one occurring at the same time day after day, with each pair producing tides of similar heights. While this view provides a basic explanation for the primary forces that generate the tides, it does not take into account such variables as the effects of the continents, the depth of the water, and many other factors. In all, there are almost 400 variables that must be incorporated into predicting the tides! The **Dynamic Theory** of tides takes these other factors into account, and shows that the tides are much more complicated and variable from place to place than the Equilibrium Theory would suggest. For example, some areas receive only one high and one low tide per day (see section 11.3). Furthermore, the tidal range varies greatly across the globe; in the Mediterranean Sea, there can be a difference of only 10 cm between high and low tides, while the Bay of Fundy in Canada experiences a tidal range of up to 17m (56 ft) every day (Figure 11.2.1).

Figure 11.2.1 *Tidal range in the Bay of Fundy, Canada. Both photographs were taken on the same day in July 2003 (By Dylan Kereluk from White Rock, Canada (Flickr) [CC BY 2.0], via Wikimedia Commons).*

Examination of any tide chart will show that the tides don't occur at same time each day; in fact, each tidal peak occurs about 50 minutes later than it did in the previous day. This is due to the orbit of the moon around the Earth. Imagine a high tide that occurs at a particular location (X) at 1:00 pm (Figure 11.2.2). The high tide occurs as location X moves through the bulge of water facing the moon. It will take the Earth 24 hours to complete one revolution, to bring location X back to site of the water bulge that caused that high tide. However, during those 24 hours, the moon has also moved as it orbits the Earth, so the high tide bulge has moved beyond its original location. The Earth thus has to rotate an additional distance for location X to reach the bulge and experience that same high tide. Because it takes the moon about 28 days to orbit the Earth, the moon gets "ahead" of the Earth's rotation by about 50 minutes per day. Therefore, it takes location X 24 hours and 50 minutes to rotate through the same tidal bulge, and as a result, the tidal peaks occur about 50 minutes later each day. In our example, an afternoon high tide at 1:00 pm on one day would be followed by a high tide at about 1:50 pm the following day. This 24 hour and 50 minute cycle is referred to as a **tidal day**.

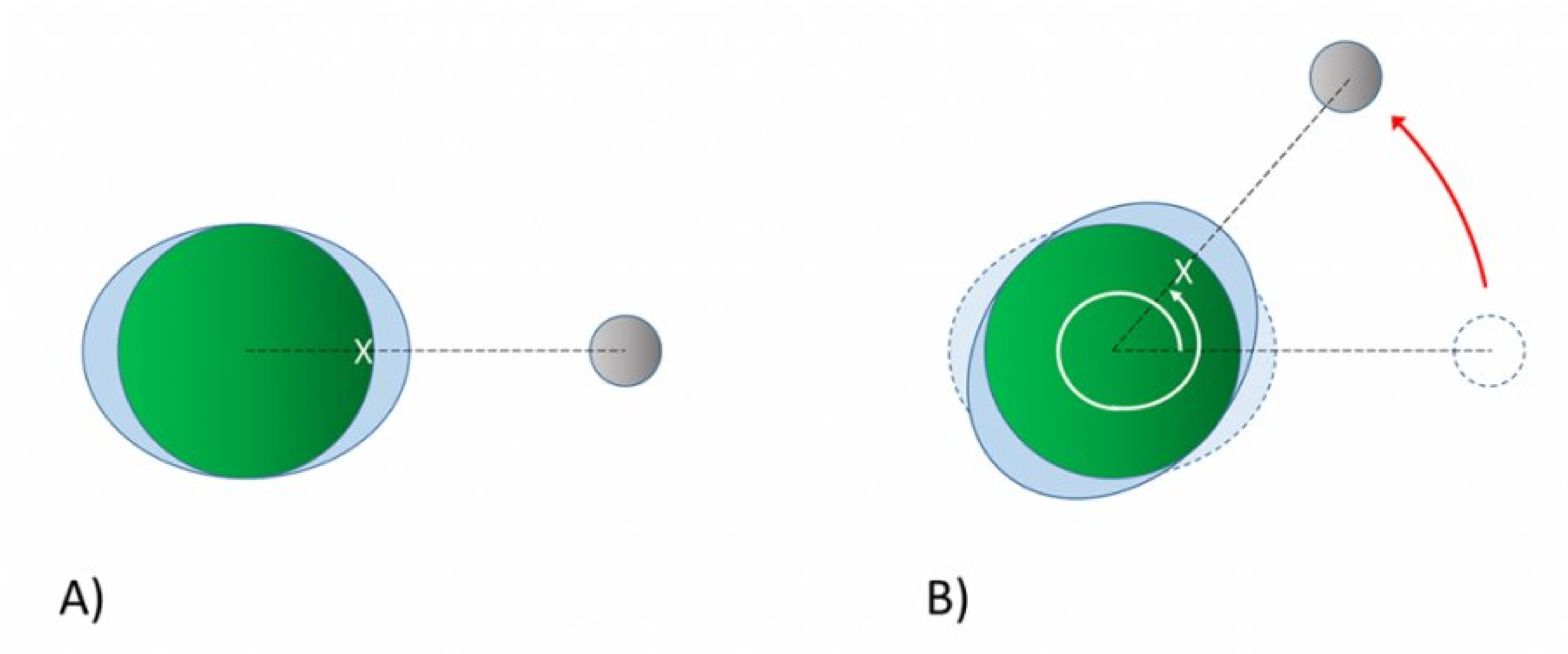


Figure 11.2.2 *In A) a high tide is occurring at point X on Earth's surface. 24 hours later, X has made a complete rotation and is back in its original position. However, the moon has moved during that time (B), so X must travel an additional distance (white arrow) to once again become aligned with the moon and experience a high tide. For this reason, corresponding tides occur approximately 60 minutes later each day (PW).*

The motion of the moon impacts the tidal cycles in other ways. As the moon orbits the Earth, its orbital plane is at an angle relative to the rotational plane of Earth. This angle, or **declination**, means than the moon fluctuates between an angle of 28.5^{o} north of the equator, to 28.5^{o} south of the equator roughly every two weeks (the cycle from maximum to minimum and back takes about 27 days). Figure 11.2.3 illustrates a case where the moon is at its maximum declination 28.5^{o} north of the equator, creating its corresponding tidal maxima. A point on the Earth at the latitude indicated by the red line would experience two high tides as it rotated through 24 hours, at points A and B. But the two high tides would not be of equal heights; the high tide at A would be higher than the high tide at B. This helps create a mixed semi-diurnal tide; two high tides of different heights per day (see section 11.3).

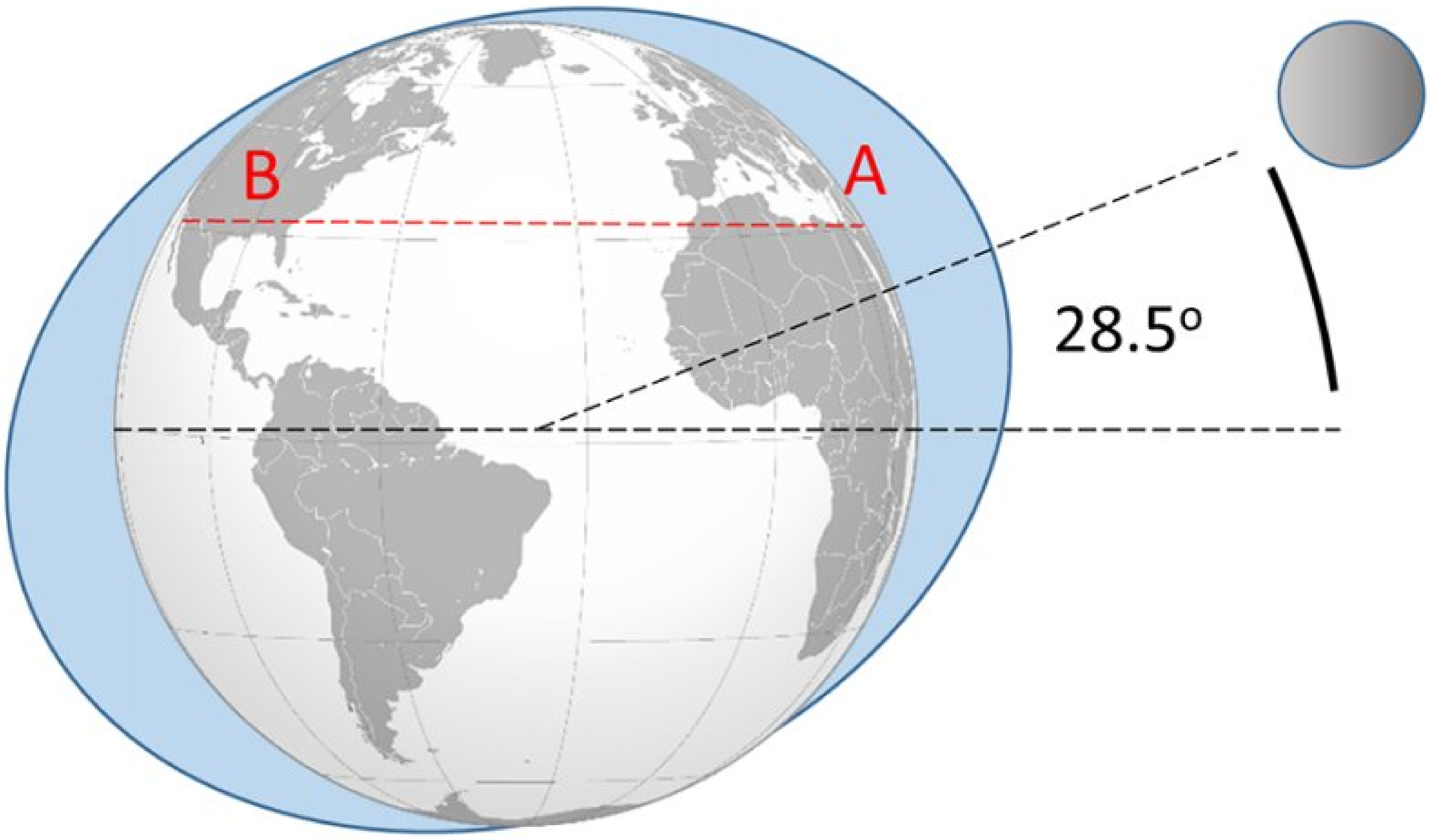


Figure 11.2.3 *The effect of the moon declination on tide heights. The moon oscillates between 28.5° north and 28.5° south of the equator every two weeks, leading to uneven tidal heights each day at a particular latitude (PW).*

Finally, the continents and the bottom topography of the oceans have an impact on the tides that are experienced in an area. Because the tides are essentially waves with extremely long wavelengths extending halfway across the Earth, they behave as shallow water waves, and they are influenced and refracted by the bottom contours, leading to regional tidal variations. When the tidal crests encounter land, they are are reflected, and the wave moves back out to sea, theoretically until it encounters another continent on the opposite side of the ocean basin. The crest is once again reflected, and the water oscillates back and forth as a standing wave across the ocean basin. However, because of the scale over which these tidal waves move, we must take into account the influence of the Coriolis Effect. As the tidal crest is reflected back across the ocean basin, its path is deflected by the Coriolis force; to the right in the Northern Hemisphere, and to the left in the Southern Hemisphere (see section 9.1). Using the Northern Hemisphere as an example, imagine a tidal crest that has reached land on the western side of an ocean basin. It would have a tendency to be reflected and move across the basin towards the east. But the Coriolis force deflects the movement to the right, causing the crest to instead head south. When the crest hits land in the south, it would now tend to reflect towards the north, but once again the Coriolis deflection to the right kicks in, and the wave instead moves to the east. From the east the reflected wave is deflected to the north, and so on. The result of all of this is that instead of a simple standing wave moving back and forth across the ocean, the tidal crest follows a circular pattern around the ocean basin, counterclockwise in the Northern Hemisphere and clockwise in the Southern Hemisphere. This is analogous to shaking a pan full of water in a circular manner, and watching the water follow a similar circular path as it sloshes around inside. This large scale circular rotation pattern of tides is called **amphidromic circulation** (Figure 11.2.4). The rotation occurs around a central **amphidromic point** or **node**, that shows little tidal variation, while the largest tidal ranges occur on the edges of the circulation pattern. In Figure 11.2.4 the amphidromic points are indicated by the dark blue areas where the white lines converge, like spokes from a bicycle wheel, and the dark red and brown areas show the regions of maximum tidal heights. The tidal maxima will rotate around the amphidromic points, taking about 12 hours for a complete rotation, leading to two high and two low tides per day in many places. If a tidal maximum is occurring along one of the white lines in Figure 11.2.4 at a certain time in the Northern Hemisphere, one hour later that high tide will have moved to the white line to the left (counterclockwise), and so on until it completes a rotation. In the Southern Hemisphere, the tide will move to the line to the right for clockwise rotation.

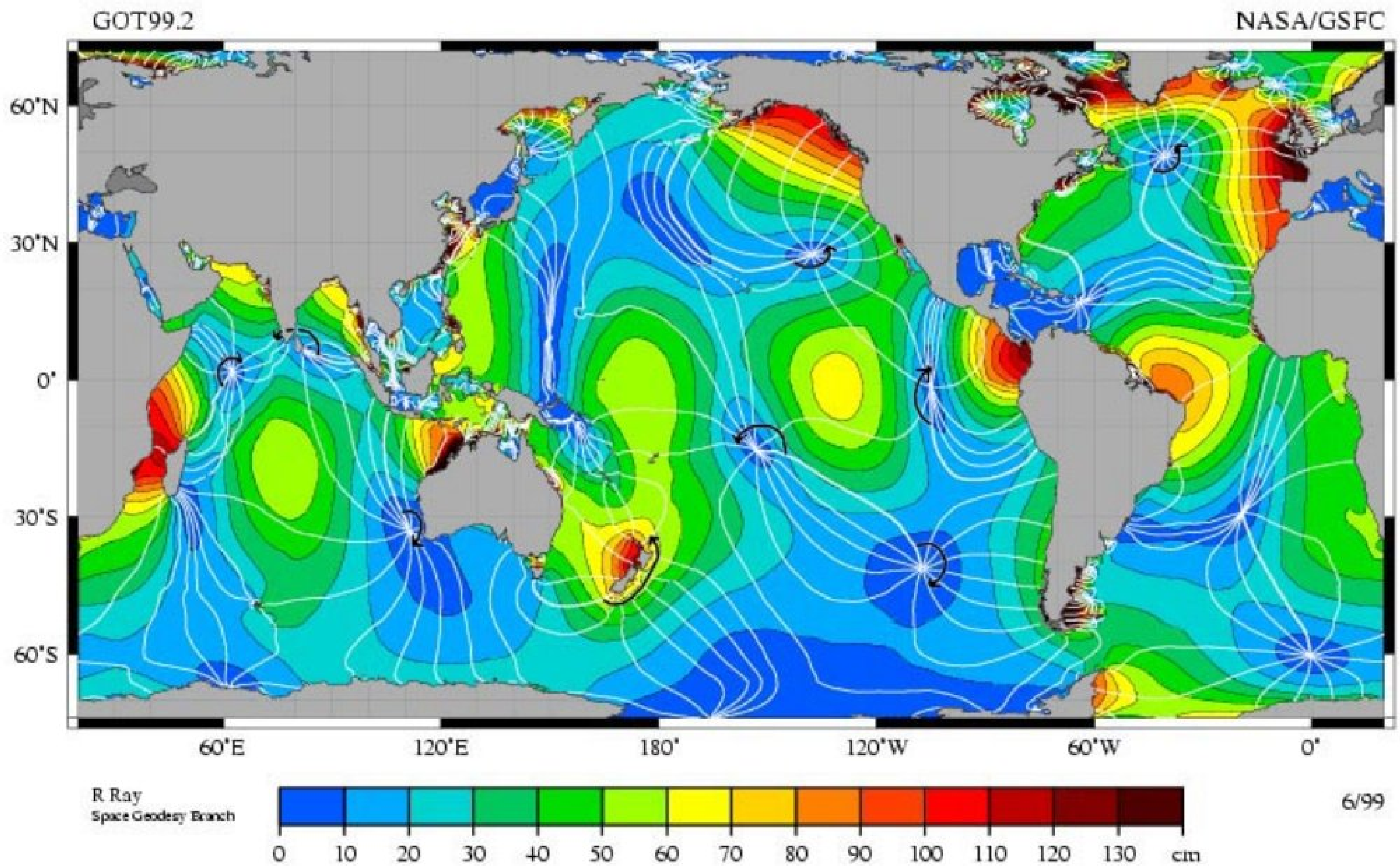


Figure 11.2.4 *Amphidromic circulation. Amphidromic points are represented where the white lines converge in areas of minimal tidal range. Tidal crests rotate around the amphidromic points, clockwise in the Northern Hemisphere and counterclockwise in the Southern Hemisphere. See text for details (NASA, Public Domain via Wikimedia Commons).*

The result of all of these variables is that the tides will not always occur twice each day, at the same time and with equal heights as the Equilibrium Theory of tides may suggest. Instead, each region of the oceans has a unique set of factors that contribute to the types of tides it will experience. The major types of tides are discussed in the next section.

11.3 Tide Classification

With so many variables playing a role in the production of tides, it is understandable that not every place on Earth will experience exactly the same tidal conditions. There are three primary classifications for tides, depending on the number and relative heights of tidal cycles per day.

A **diurnal tide** consists of only one high tide and one low tide per day (Figure 11.3.1). "Diurnal" refers to a daily occurrence, so a situation where there is only one complete tidal cycle per day is considered a diurnal tide. Diurnal tides are common in the Gulf of Mexico, along the west coast of Alaska, and in parts of Southeast Asia.

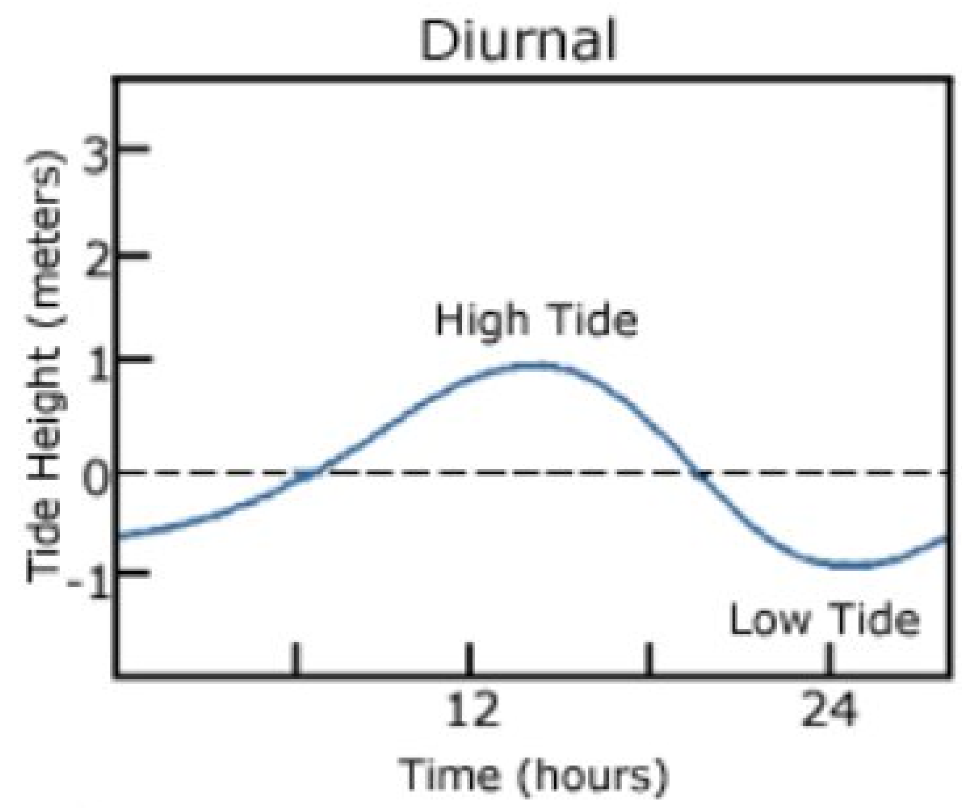


Figure 11.3.1 *A diurnal tide, with one high and one low tide per day (By NOAA [Public domain], via Wikimedia Commons).*

A **semidiurnal tide** exhibits two high and two low tides each day, with both highs and both lows of toughly equal height (Figure 11.3.2). "Semidiurnal" means "half of a day"; one tidal cycle takes half of a day, therefore there are two complete cycles per day. Semidiurnal tides are common along the east coasts of North America and Australia, the west coast of Africa, and most of Europe.

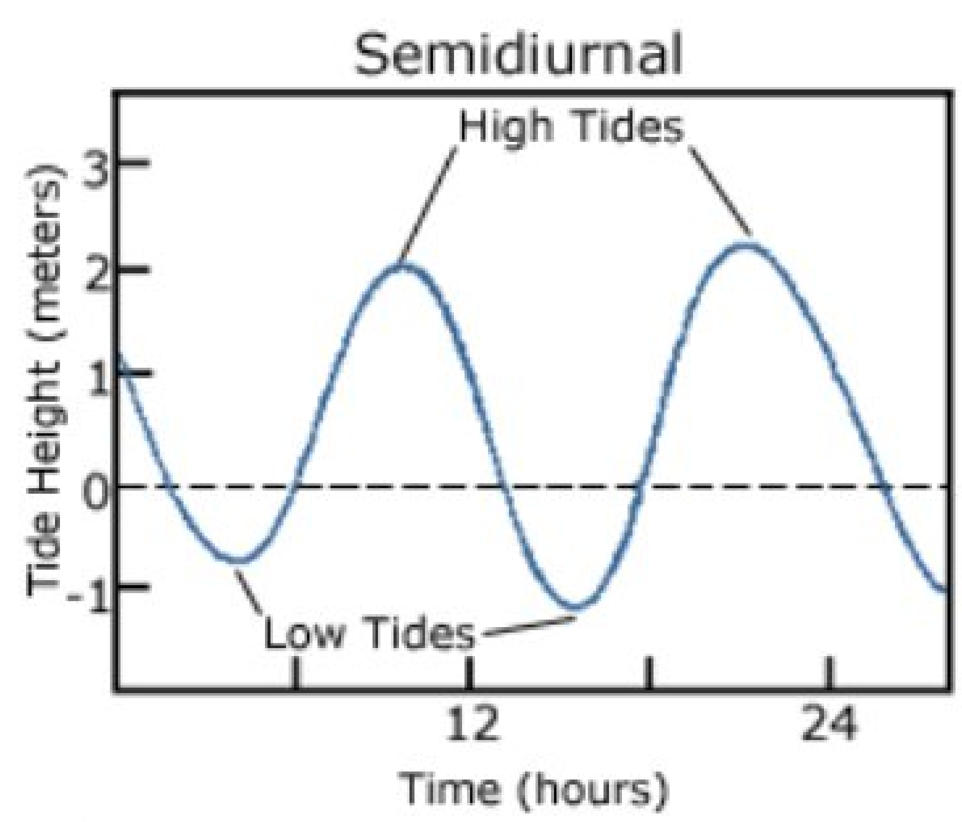


Figure 11.3.2 *A semi-diurnal tide, with two high and two low tides per day, each of roughly equal heights (By NOAA [Public domain], via Wikimedia Commons).*

Mixed semidiurnal tides (or **mixed tides**), have two high tides and two low tides per day, but the heights of each tide differs; the two high tides are of different heights, as are the two low tides (Figure 11.3.3). The differences in height may be the result of amphidromic circulation, the angle of the moon, or any of the other variables discussed in section 11.2. Mixed semidiurnal tides are found along the Pacific coast of North America.

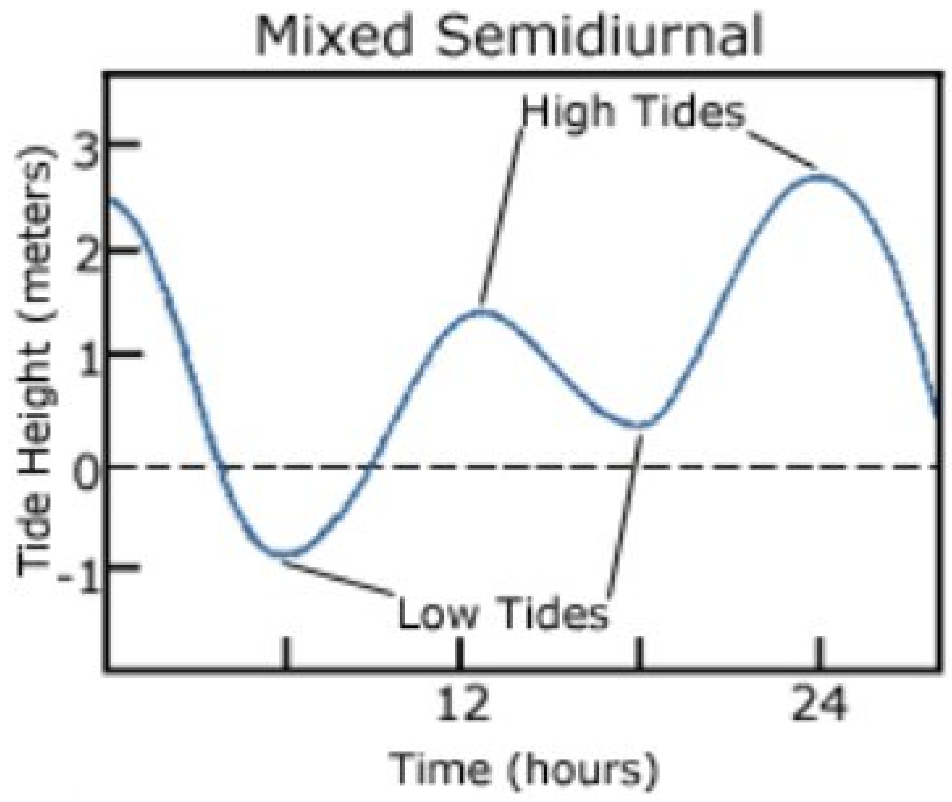


Figure 11.3.3 *A mixed semi-diurnal tide, with two high and two low tides per day, each with a different height (By NOAA [Public domain], via Wikimedia Commons).*

Figure 11.3.4 shows the distribution of the various tide types throughout the world.

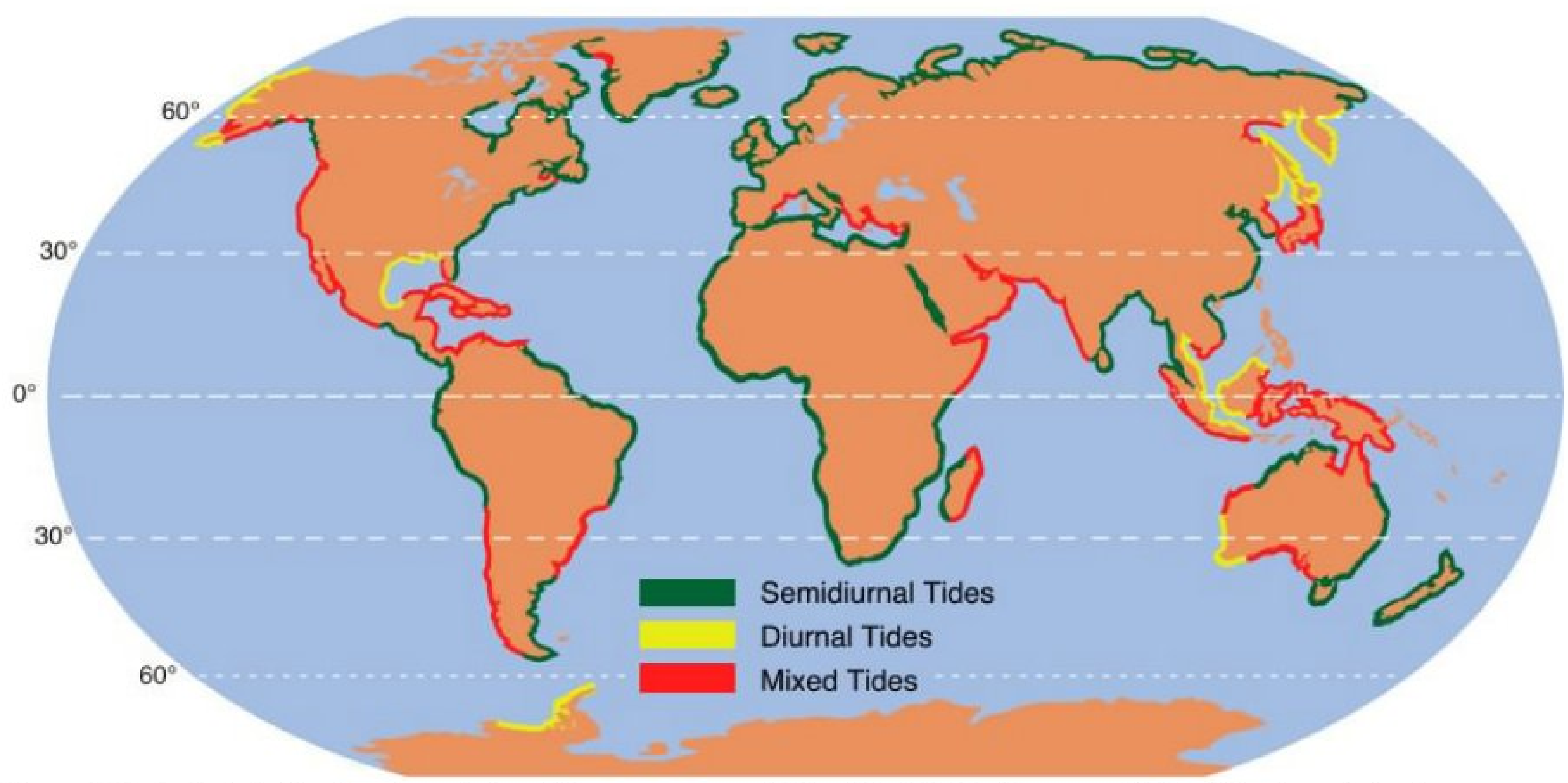


Figure 11.3.4 *Global distribution of the different types of tides (By KVDP (Own work) [Public domain], via Wikimedia Commons).*

Tidal Currents

The movement of water with the rising and falling tide creates tidal currents. As the tide rises, water flows into an area, creating a **flood current**. As the tide falls and water flows out an **ebb current** is created. **Slack water**, or **slack tides** occur during the transition between incoming high and outgoing low tides, when there is no net water movement.

The strength of a tidal current depends on the volume of water that enters and exits with each tidal cycle (the **tidal volume** or **tidal prism**), and the area through which the water flows. A large tidal volume moving through a large area may create only a weak tidal current, as the volume is spread over a wide area. On the other hand, a narrow area may produce a strong tidal current even if the tidal volume is small, as all of the water is forced through a small area. It follows that the strongest tidal currents will result from a large tidal range moving through a narrow area.

Tidal bores occur where rivers meet the ocean. If the incoming tidal current is stronger than the river outflow, the tidal bore appears as a wave, or moving wall of water that moves up the river as the tide comes in (Figure 11.3.5).

Figure 11.3.5 *A tidal bore near Silverdale in the United Kingdom (Arnold Price [CC BY-SA 2.0], via Wikimedia Commons).*

In many cases these tidal bores may move through a river or inlet for many kilometers, and if they are large enough they can form continually breaking waves that surfers can ride much farther and longer than a traditional ocean wave, such as the Severn Bore in England, shown in the video below.

A YouTube element has been excluded from this version of the text. You can view it online here: [*https://rwu.pressbooks.pub/webboceanography/?p=347*](https://rwu.pressbooks.pub/webboceanography/?p=347)

Additional links for more information

- For an even more dramatic tidal bore, watch this video of the [“Silver Dragon” on China’s Qiantang River](#)