Ocean Circulation

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1 Introduction

Ocean circulation is a key component of physical oceanography that is really a mix of oceanography and meteorology — ocean circulation is all about air-sea interactions, thus it is highly critical that you are familiar with basic meteorology concepts, which you can learn (in case you haven't already) from our meteorology handouts.

2 Main Components of Ocean Surface Circulation

2.1 Gyres and Currents

Ocean circulation is dominated by gyres, which are rotating "loops" of water in the world's main oceans. There exists many gyres in the world ocean as shown below.

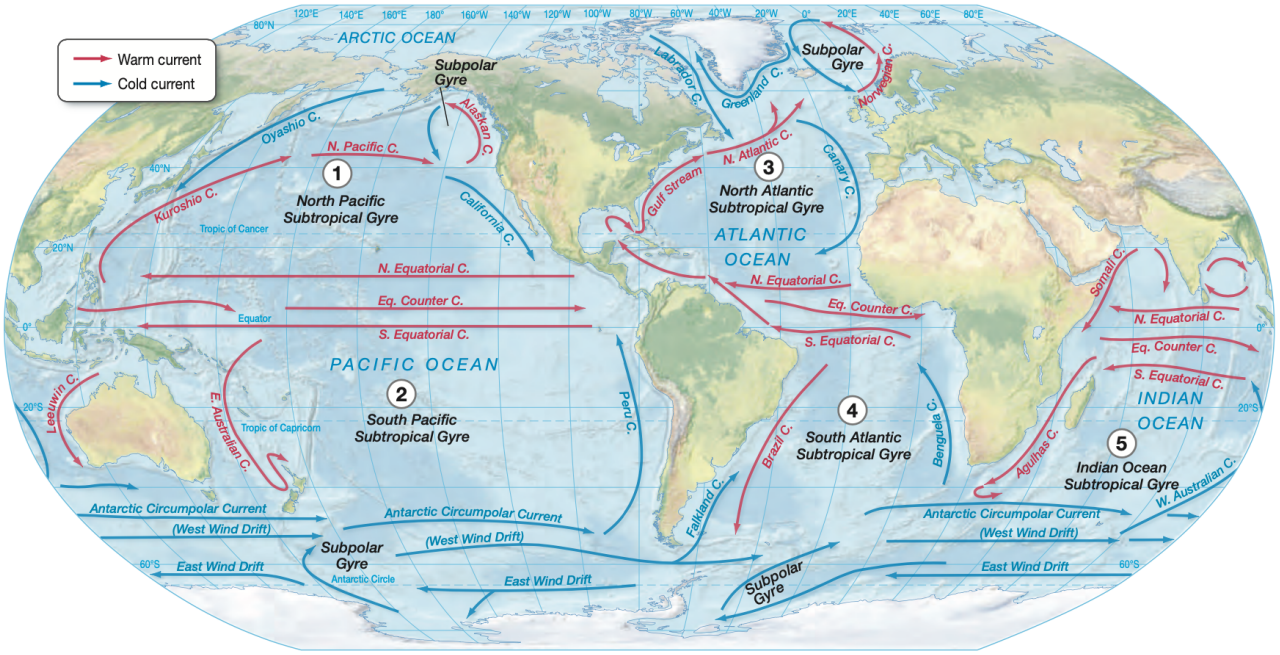


Figure 1: Main gyres of the world ocean. (Source: Trujillo)

Gyres owe their formation to an important concept: the **Coriolis effect**.

The Coriolis force exists due to the difference in velocity of Earth's rotation at various parts of the globe; for instance, a stationary object at the equator revolves with Earth's rotation faster than the same object at the poles. Thus, when the object attempts to travel a straight line across a long distance, the Coriolis force bends it rightward in the northern hemisphere and leftward in the southern hemisphere. (Figure 2).

The Coriolis effect is derived from this force, describing a moving mass's degree of deflection as proportional to the speed of movement. This effect is primarily used to describe large-scale systems such as weather air masses and ocean circulation.

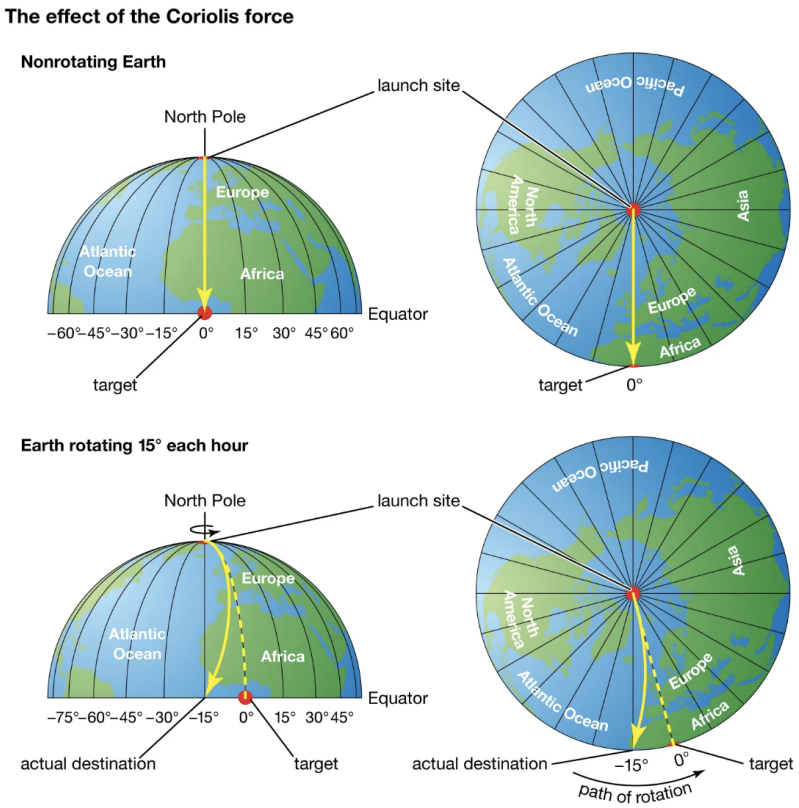


Figure 2: Coriolis force bends traveling objects rightward in the northern hemisphere. (Source: Britannica)

It is precisely due to the Coriolis effect that ocean waters of the northern hemisphere rotate clockwise (rightward), forming gyres. Thus, southern hemispheric gyres would rotate counterclockwise (leftward).

Notice how the warm (red) currents in Figure 1 always move away from the equator (excluding the equatorial currents), and the cold (blue) currents always move away from the poles/toward the equator. Because of this, warm currents bring the heat from the equator to the middle latitude/polar regions, which frequently warms the local weather and climate. For example, the tropical Gulf Stream's movement toward England warms it to a higher mean annual temperature than Canada, although they are located at the same latitude.

3 Factors Affecting Ocean Surface Circulation

3.1 Ekman Transport

When wind blows over a body of water in the northern hemisphere, the water will tend to move rightward due to the Coriolis effect. The **Ekman transport** phenomenon describes the motion of a body of water as angled when blown by a straight line of wind. Surface water is affected by an angle of 45°, but each successive layer of water is increasingly affected by the Coriolis effect and friction that reduces influence of the original wind direction. Thus, a spiral is created and

average water transport is around 90°. This spiral is deflected clockwise (right) in the Northern Hemisphere and counterclockwise (left) in the Southern Hemisphere.

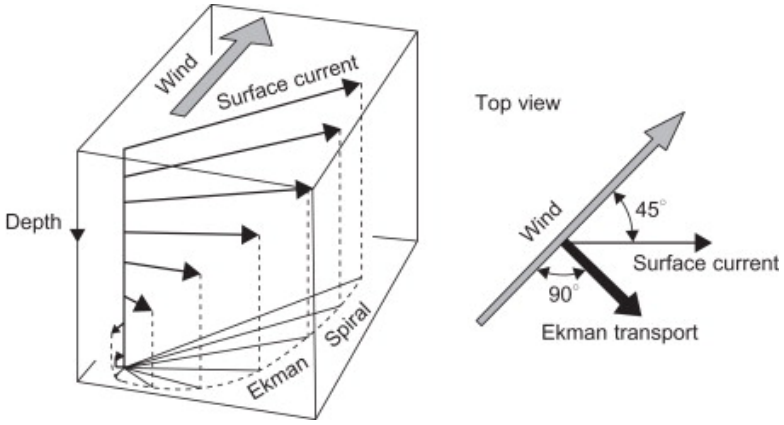


Figure 3: Ekman transport depicting surface water moving at 45°, while net water transport is at a right angle. (Source: ScienceDirect)

3.2 Geostrophic Currents

In an ocean gyre in the northern hemisphere, water is always directed rightward due to the Coriolis effect. Thus, this accumulates a bulge, often called a "hill", of water in the middle of a gyre. Due to gravity, this hill will want to descend back down vertically. However, due to the Coriolis effect, the descending water will turn rightward in the northern hemisphere. If the Coriolis effect balances out with gravity, the water will essentially travel indefinitely in a circle. This is known as a **geostrophic current**. In actuality, though, friction exists, so the actual current will slowly descend down the bulge. This also causes the gyre hill to be offset west in the northern hemisphere and east in the southern hemisphere.

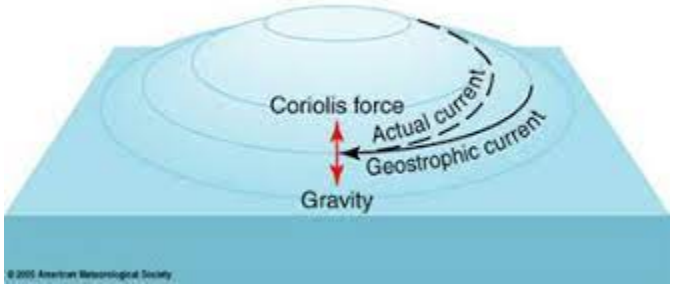


Figure 4: Geostrophic current diagram. (Source: NASA)

3.3 Western Intensification

Due to Earth's west-to-east rotation and increased intensity of the Coriolis effect in the westerlies, currents at the western side of an ocean basin (e.g. Pacific ocean) move *faster*, are *narrower and deeper*, and transport more water than its eastern counterpart. This is the phenomenon known as **western intensification**.

4 Upwelling and Downwelling

In this section we'll discuss what upwelling and downwelling are and what they are caused by. However, it is important to note that intense thermohaline stratification often prevents the formation of internal mixing waves.

- **Upwelling** occurs when ocean water from the deep is brought to the surface, which often brings up abundant nutrients and leads to high marine productivity at the ocean surface, translating to increased productivity in coastal fishing industries.

Upwelling occurs in a number of ways; most of the time, when a wind blows over the ocean surface, surface water is displaced away from the wind as we discussed earlier. With surface water now displaced, water from the depth now rises up to make up for the displacement. This happens most commonly at the equator:

- **Equatorial upwelling** occurs when the southeast-to-northwest moving trade wind (aka southeast trade wind) blows over waters at the equator. As the equator is directly in the middle of the globe, the water above it is displaced rightward due to being in the northern hemisphere, and the water below it is displaced leftward due to being in the southern hemisphere.

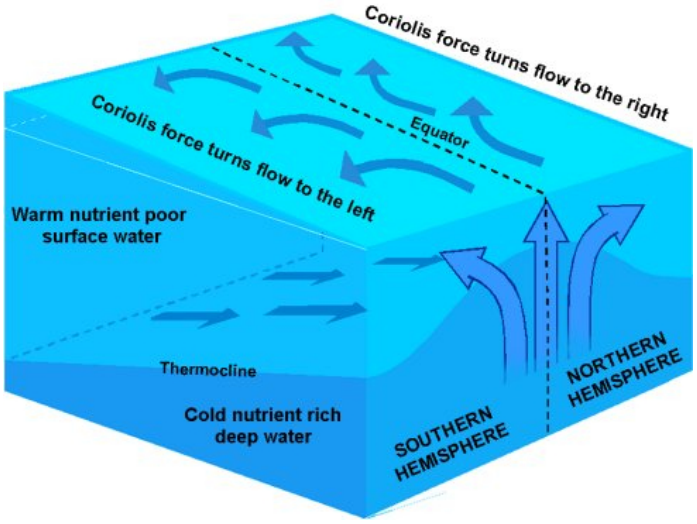


Figure 5: Equatorial upwelling as caused by the southeast trade wind. (Source: SEOS)

- **Downwelling** occurs when ocean water from the surface sinks into the deep.

Downwelling occurs when waters converge, similar to the convergence plate boundary where one plate is forced to move downward.

Now let us examine coastal upwelling and downwelling:

- In the northern hemisphere, coastal upwelling occurs when wind blows parallel to shore AND the shore is at the *left* to the perspective of the wind blowing in its direction. This way, coastal water will move rightward from the wind, which is away from the shore.

- When the shore is at the *right* to the perspective of the wind, downwelling occurs, because water will displace rightward, which is towards the shore. As the shore is a physical barrier to horizontal water movement, water will sink underneath.

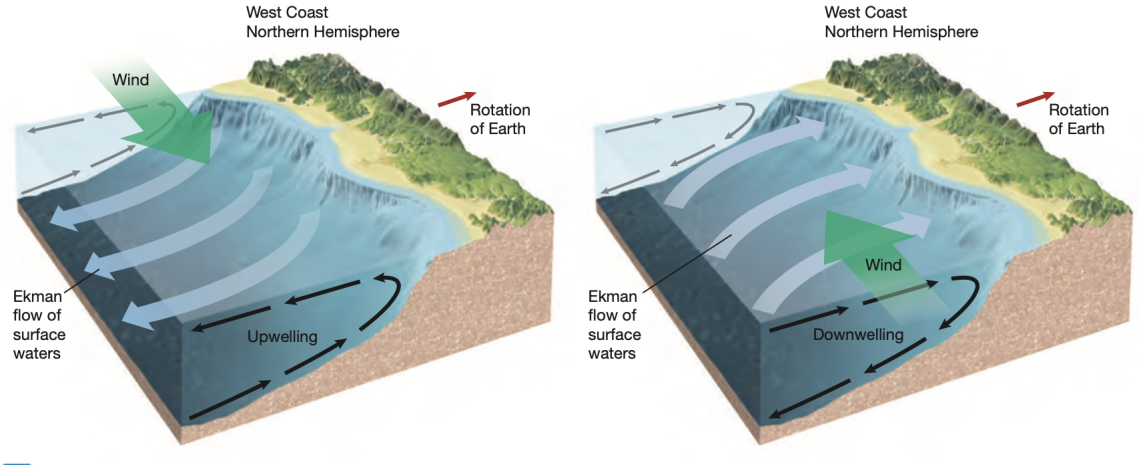


Figure 6: Coastal upwelling and downwelling can be produced by winds that blow parallel to the coast. (Source: Trujillo)

5 Circulations of Numerous Ocean Basins

Here we'll cover the most important ocean basins to know and details about their circulations.

5.1 Antarctic Circulation

- **Antarctic Circumpolar Current** (West Wind Drift) travels west-to-east around Antarctica at around 50° south. It is a very powerful current that runs around the entire Antarctica, powered by the prevailing westerly wind belt.
- **East Wind Drift** is a current that moves east-to-west along the margin of the Antarctic continent, powered by the polar easterlies.
  - Because the two aforementioned currents move in conflicting directions, **Antarctic Divergence** occurs at the boundary shared between the two currents. This divergence is a zone of upwelling.
  - **Antarctic Convergence** occurs at the northern-most boundary of the Antarctic Ocean, where cold and dense Antarctic waters meet warmer waters from the middle latitudes and sink underneath (downwelling).

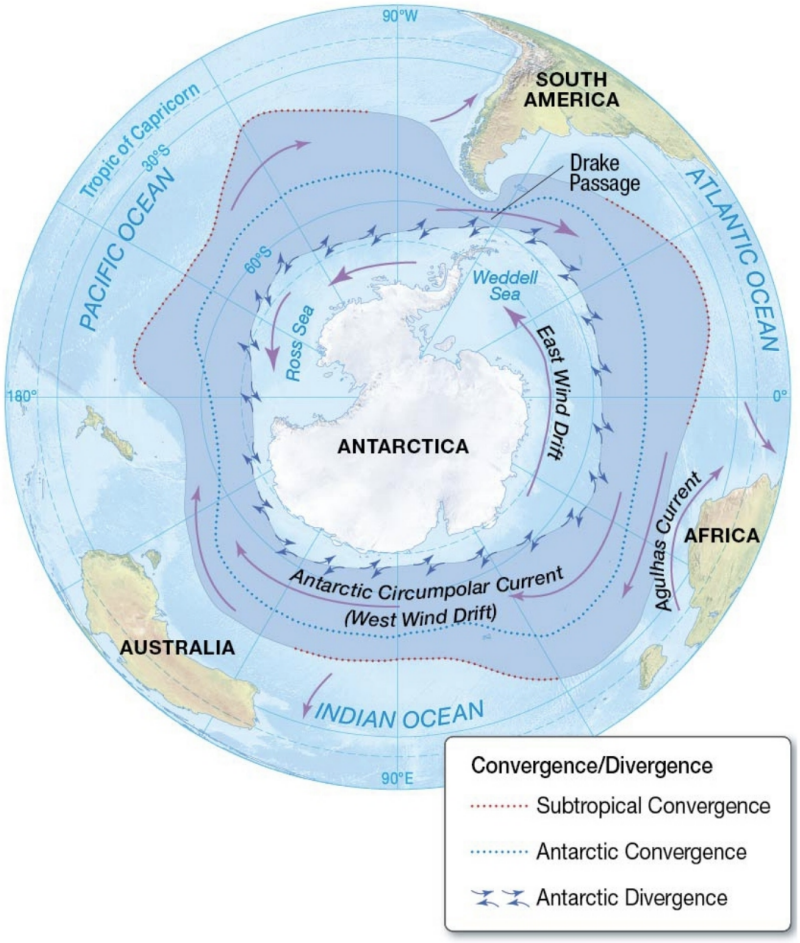


Figure 7: Antarctic circulation diagram. (Source: Trujillo)

5.2 Atlantic Circulation

We'll be focusing on the most prominent and well-studied current: the Gulf Stream.

- **Gulf Stream** carries warm water from the equator towards the higher latitudes. Like a stream in a river, the Gulf Stream eventually meanders into a snake-like shape at the northeast tip of the United States.
- Similar to how an oxbow lake forms, when the Gulf Stream meanders to the point where two of its "channels" make contact with each other, an eddy (looping hole of water) forms.
  - **Warm-core eddies** form when warm water from the south of the Gulf Stream moves into the cold water region located at the north of the stream due to the meanders. When the meander breaks off, the warm water is surrounded by cold waters in the north, forming a warm-core eddy.
  - **Cold-core eddies** form with a similar process, except this time, cold water from the north of the stream moves into the warm region located south of the stream, surrounded by warm waters. As cold water contains more nutrients, a cold-core eddy is an abode of marine life for a short period of time, until it dies off.

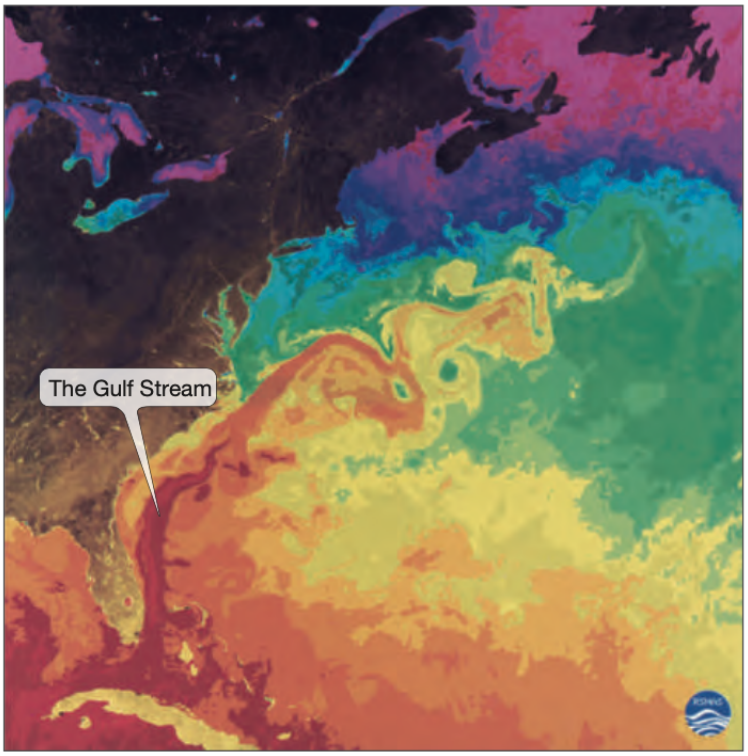


Figure 8: False-color image showing the temperature of the Gulf Stream. Warm waters = red and orange; cool waters = green, blue, purple, pink. (Source: NOAA)

- The Gulf Stream plays a key role in moderating temperatures in the North Atlantic. The stream transfers equatorial heat into Europe, raising both the average sea temperature and land temperature there.

5.3 Indian Circulation

Circulation in the Indian Ocean is closely tied with Monsoons.

- In the winter, land is colder than the ocean due to water's high specific heat preventing it from easily changing temperatures. The cool land creates a zone of high pressure. Since air tends to flow from areas of high pressure to low pressure, air from the Indian continent flows towards the Indian Ocean, generating monsoon wind.
- In the summer, the process is reversed (as land now heats up more than the ocean), so the monsoon wind is now directed from ocean to land.

Monsoon winds have significant effects on the entire Indian Ocean.

- In the summer, the strong monsoon wind from ocean to land generates a strong Southwest Monsoon Current, causing the **Somali Current** to switch directions, now flowing towards the northeast.
- As this now-reversed current flows along the coast of Saudi Arabia, upwelling occurs, generating high productivity in the summer.

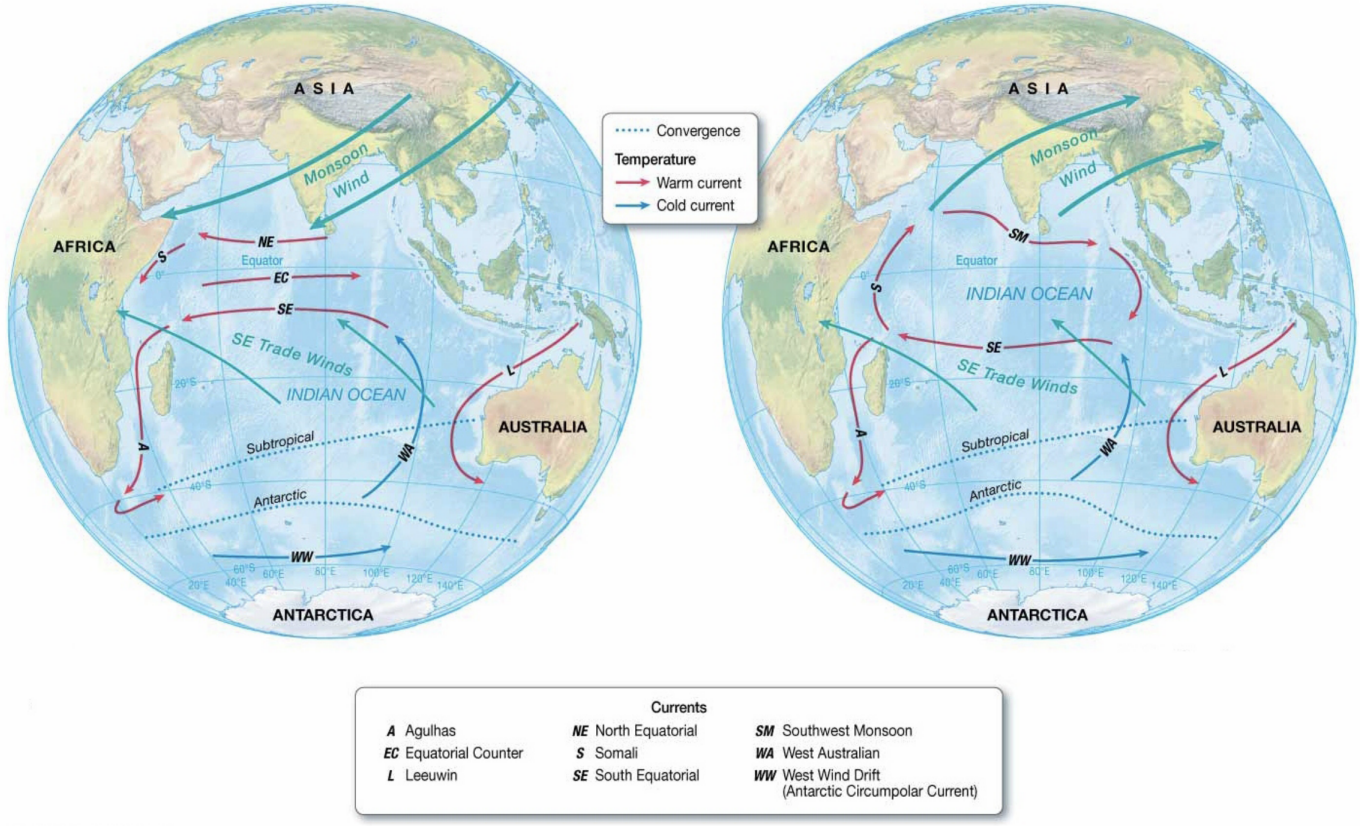
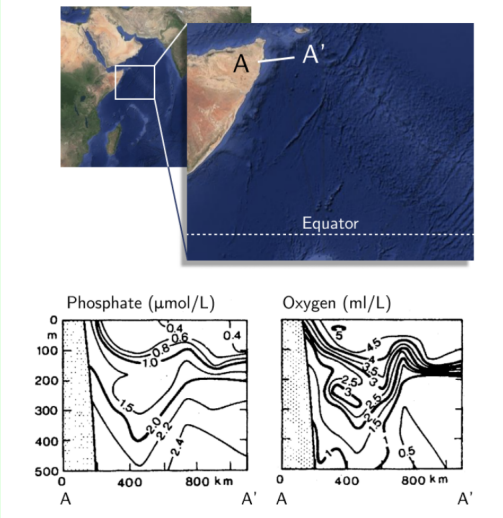


Figure 9: Indian Ocean Circulation showing monsoons. (Source: Trujillo)

Example 5.1 (USESO Training Camp Hydrology Exam 2021) The figure below shows phosphate and dissolved oxygen profiles off of the coast of Somalia. The transect is denoted on the map with endpoints at A and A'.



(a) During which month were these profiles taken?

(A) December
(B) April
(C) August

(b) During this month, towards which direction does the depth-averaged transport passing through the transect flow?

(A) North
(B) South
(C) East
(D) West

Solution: Consulting the phosphate and oxygen curves, we find that there is strong upwelling on the Somali coast. This indicates that the wind stress must be southwesterly, which corresponds to the Southwest Monsoon. This occurs during summer months → August. Considering the wind during August, the Somali current must flow north through the transect.

6 Deep-Ocean Currents

Deep-ocean currents form due to density differences. In the cold polar regions, sea ice forms. Salt cannot be incorporated into the crystal structures of ice and thus is "rejected". This leads a high concentration of salt in polar waters. As salt water has higher density than freshwater, these salty waters now sink into the depth of the ocean, initiating deep currents. The circulations of deep currents is known as **thermohaline circulation.**

6.1 Thermohaline Circulation

The thermohaline circulation has a conveyor-belt like motion — as warm water reaches the polar regions, it sinks, becoming deep water that now moves at great depths towards other ocean basins. Upwelling brings up deep water, which could potentially heat up and become warm water again.

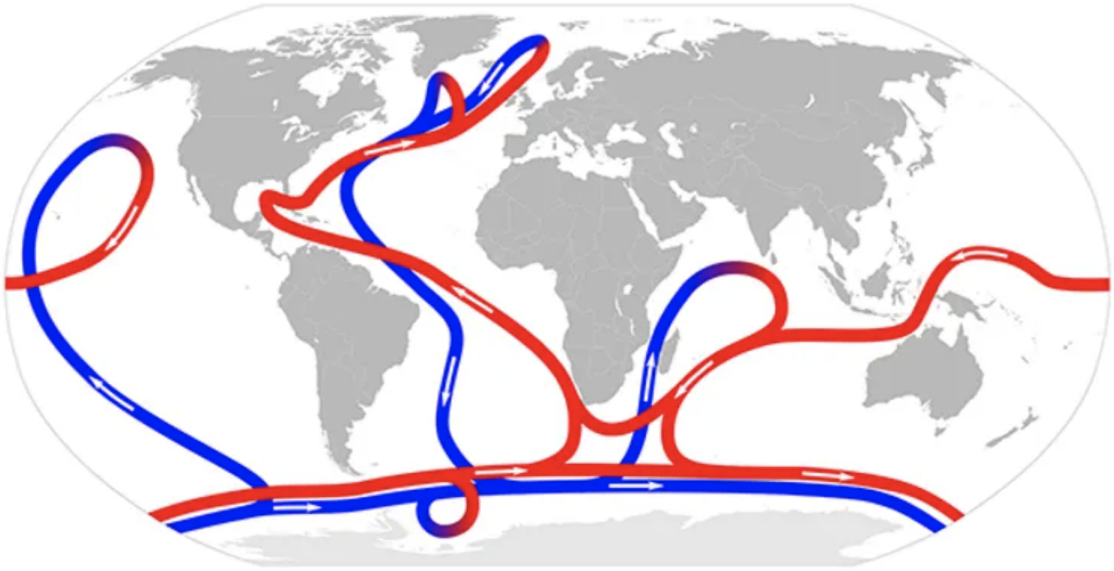


Figure 10: Conveyor-belt motion of thermohaline circulation. Red = warm water, blue = cold/deep water. (Source: NASA)

6.2 Bottom Waters

Bottom waters are characterized by unique temperatures, salinity, and dissolved oxygen levels. Its high density originates from water created at the poles and plays a significant role in global thermohaline circulation, as well as biologically through the storage of CO2 and nutrients.

- **Antarctic Bottom Water** is the densest water in the world. Thus, it flows at the deepest depths — slowly spreading towards the other ocean basins across the world.
- **North Atlantic Deep Water** is another very dense but not as dense deep water that originates from the North Atlantic.
- At the Antarctic Convergence (refer back to section 5.1), Antarctic water, being colder and less dense, obviously sinks below warmer middle latitude water. This sinking water is called **Antarctic Intermediate Water**, and is less dense than the North Atlantic Deep Water so it stays a layer on top.

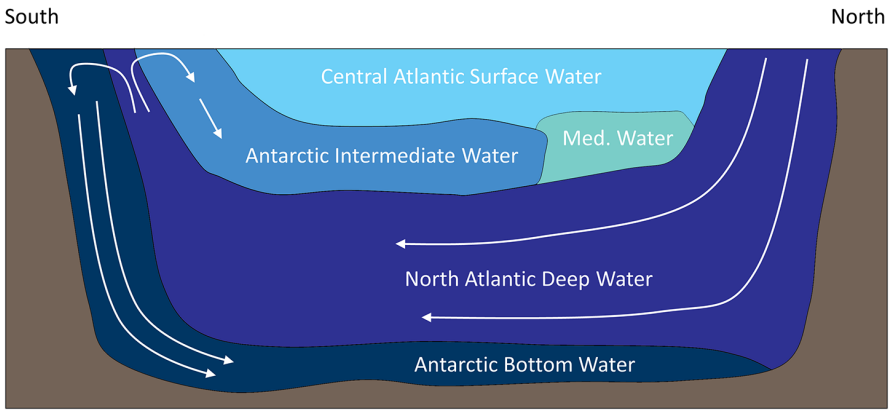
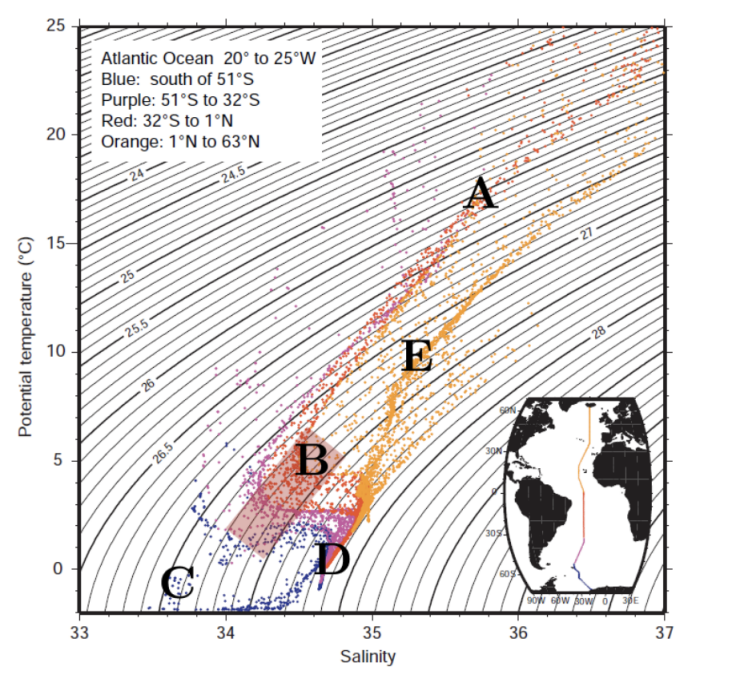


Figure 11: Diagram depicting layers of deep water. (Source: RWU)

Example 6.1 (USESO Open Exam 2022) Figure 3d: T-S diagram of water samples (at various depths) along the transect shown in the bottom right.



Antarctic Bottom Water (AABW), is a water mass formed in the Southern Ocean. Its formation can be represented as a transformation from an initial water mass. Which two letter sequence best represents AABW formation? (e.g., A → B)

Solution: Recall that AABW forms when warmer/less dense currents reach the Antarctica region, they sink as they become more dense due to sea ice formation. Thus, we should expect to see an increase in salinity near the Antarctic region. So we pick C → D.