AMERICAN METEOROLOGICAL SOCIETY



# Project Ocean

## Density-Driven Ocean Circulation

### TEACHER'S GUIDE

## Project Ocean

This guide is one of a series produced by Project Ocean, a U.S. Office of Naval Research-sponsored initiative of the American Meteorological Society (AMS), in recent partnerships with St. Mary's College of Maryland, Washington College, and the United States Naval Academy. Project Ocean is a continuation of past projects focused on creating and training a network of master teachers to provide peer training sessions in pre-college (K-12) physical oceanographic education. To support these teachers in their teacher training, Project Ocean develops and produces course modules and other educational materials.

For further information, and the names of the trained master teachers in your state or region, please contact:

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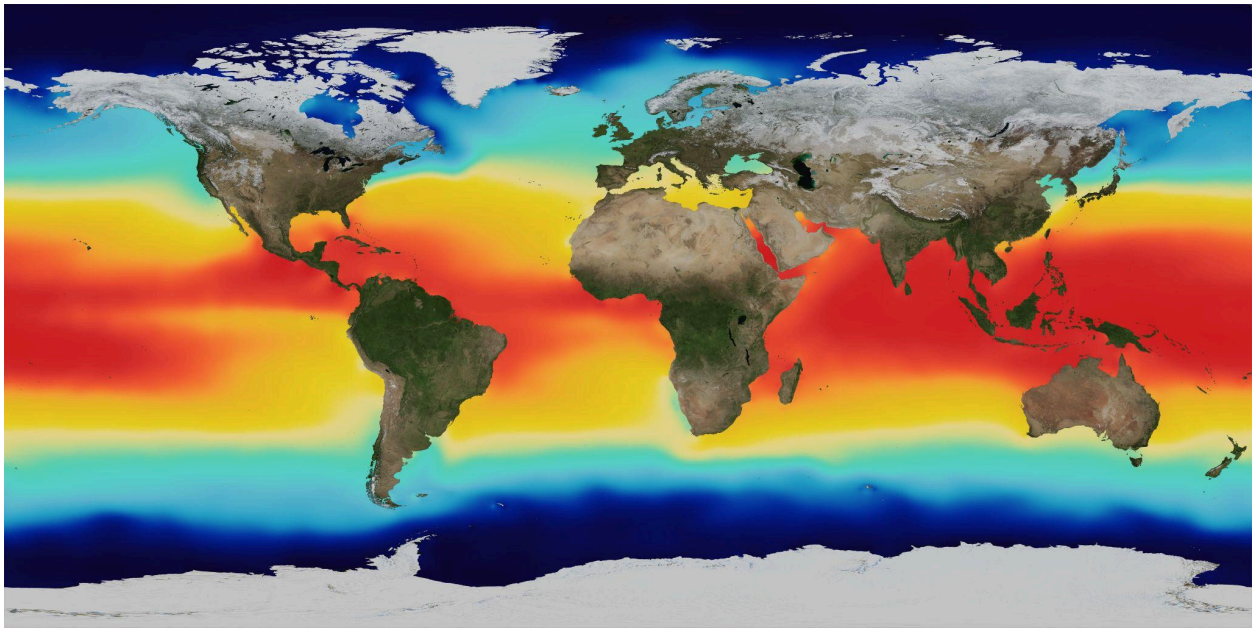


**Figure i.** Map of average ocean sea-surface temperatures, which are influenced by many factors, including the ocean's density-driven circulation. [NASA]

**"The paleoclimate record shouts to us that, far from being self-stabilizing, the Earth's climate system is an ornery beast which overreacts even to small nudges."**

- Wallace Smith Broecker, 'Grandfather of Climate Change' (1931-2019)

**Module:** Density-Driven Ocean Circulation
**Audience/Grade Level:** K-12 Educators

## Learning Objectives

After completion of this module participants will be able to:

**1. Ocean Basics: Size and Scale**

- Describe the proportion of Earth's surface covered by oceans and their average depth.

**2. Properties of Seawater**

- Define salinity and describe its average value and variability in seawater.
- Compare the physical properties of seawater and freshwater (e.g., density, boiling/freezing points, conductivity).

**3. Open Ocean Water Column Structure**

- Define a water column and explain how it is used in oceanography.
- Describe what characteristics define a water mass.
- Describe the relationship between temperature, salinity, pressure, and seawater density.
- Explain how pressure acts on a parcel of seawater, describe the concept of hydrostatic balance in the ocean, and analyze how pressure influences seawater density and temperature with increasing depth.
- Explain how temperature, pressure, and salinity interact to influence the in situ and potential temperature of seawater parcels, and analyze how changes in temperature affect seawater density through molecular kinetic energy and spacing.
- Explain the Equation of State for Seawater and its significance.
- Define the surface mixed layer, intermediate water, deep water, and bottom water.
- Describe how vertical changes in ocean salinity and temperature, and thereby density, drive the position of the halocline, thermocline, and pycnocline.
- Identify key characteristics of surface, intermediate, deep, and bottom waters.
- Analyze how stratification contributes to ocean stability and inhibits mixing.

**7. Density-Driven, Deep Ocean Circulation**

- Define thermohaline circulation and identify the properties that drive it.
- Describe how surface water becomes dense enough to sink and how this initiates convection.

- Explain the role of temperature decrease, evaporation, and sea ice formation in increasing seawater density.
- Differentiate between open ocean convection and shelf-slope convection processes.
- Identify the primary regions of deep water formation in the polar oceans and the corresponding water masses that are formed.
- Explain how density-driven circulation forms Mediterranean Intermediate Water.
- Describe how density-driven circulation contributes to ocean ventilation and nutrient/gas transport.
- Trace the movement and modification of water masses as they descend and spread in the deep ocean.
- Explain the global ocean conveyor belt (meridional overturning circulation) and its climate relevance.
- Interpret how changes in the Atlantic Meridional Overturning Circulation (AMOC) may affect regional climate.

## **STANDARDS**:

**Project Ocean Understandings:**

***Ocean Basics: Size and Scale (1.1, 1.4)***
***Properties of Seawater (2.1, 2.3)***
***Open Ocean Water Column Structure (3.1-3.14)***
***Density-Driven, Deep Ocean Circulation (7.1-7.18)***

**Applicable Ocean Literacy Principles:** 1.C, 3.A, 3.B, 3.F, 7.D., 7.F

**Next Generation Science Standards:**

Performance Expectations

5-ESS2-1. Develop a model using an example to describe ways the geosphere, biosphere, hydrosphere, and/or atmosphere interact.

MS-ESS2-4. Develop a model to describe the cycling of water through Earth's systems driven by energy from the sun and the force of gravity.

MS-ESS2-6. Develop and use a model to describe how unequal heating and rotation of the Earth cause patterns of atmospheric and oceanic circulation that determine regional climates.

HS-ESS2-2. Analyze geoscience data to make the claim that one change to Earth's surface can create feedbacks that cause changes to other Earth systems.

Disciplinary Core Ideas

ESS2.A: Earth Materials and Systems
ESS2.C: The Roles of Water in Earth's Surface Processes
ESS2.D: Weather and Climate

Crosscutting Concepts

4. Systems and system models.
5. Energy and matter: Flows, cycles, and conservation.
7. Stability and change.

Science and Engineering Practices

2. Developing and Using Models
4. Analyzing and Interpreting Data
5. Using Mathematics and Computational Thinking

## *Engage* | The Global Ocean Conveyor Belt

The ocean is vital to our planet. There are many reasons why this is true, but one important reason is that the ocean plays a major role in regulating weather and climate on Earth. The Global Ocean covers ~71% of the surface area of the Earth within average depth of ~3700 m. Given the high **specific heat capacity** of water, the ocean can absorb and store a lot of heat.

**Figure 1** illustrates the '**Great Ocean Conveyor Belt**' as described by Broeker (1987). This circulation, driven by differences in temperature and salinity, is also known as the **thermohaline circulation**. The thermohaline circulation is made up of massive, slow-moving, density-driven currents that connect warmer surface waters to colder, deeper waters below.

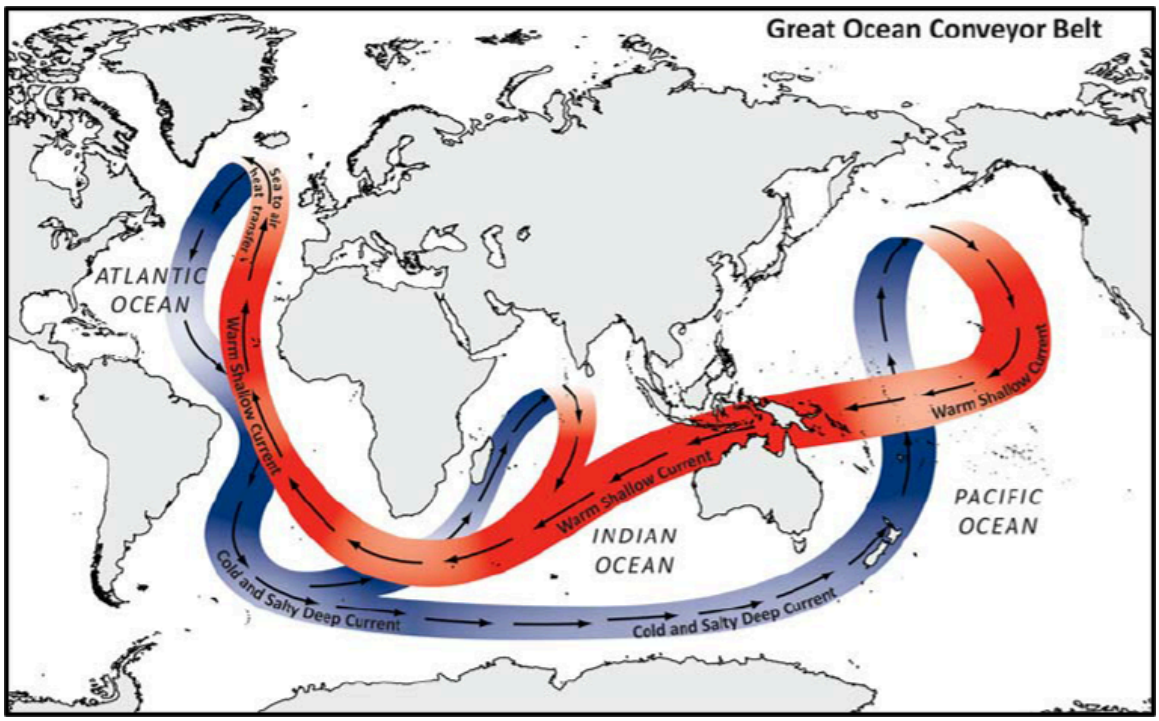



**Figure 1.** The Great Ocean Conveyor belt shown by *Broecker (1987)* as illustrated by Joe Le Monnier, Natural History Magazine.

The thermohaline circulation and the system of wind-driven surface currents (including ocean gyres) constitute the **Meridional Overturning Circulation (MOC)**. Note that the wind-driven component of the MOC is detailed in two other Project Ocean modules. The MOC circulates water on a global scale at time scales of $10^2$ to $10^3$ years. The thermohaline circulation connects both poles and all the world's major ocean basins. It plays a very important role in exchanging constituents like gases and nutrients between

surface and deep waters. It can even transport biological organisms. The MOC plays an important role in regulating regional and global climate. Northwestern Europe owes its relatively moderate climate to the Atlantic branch of the MOC (known as the Atlantic Meridional Overturning Circulation or AMOC) (**Figure 2**). The Earth's climate history shows periods when the MOC has slowed or changed modes, affecting regional and global climate. So, future changes have the potential to abruptly change climate.

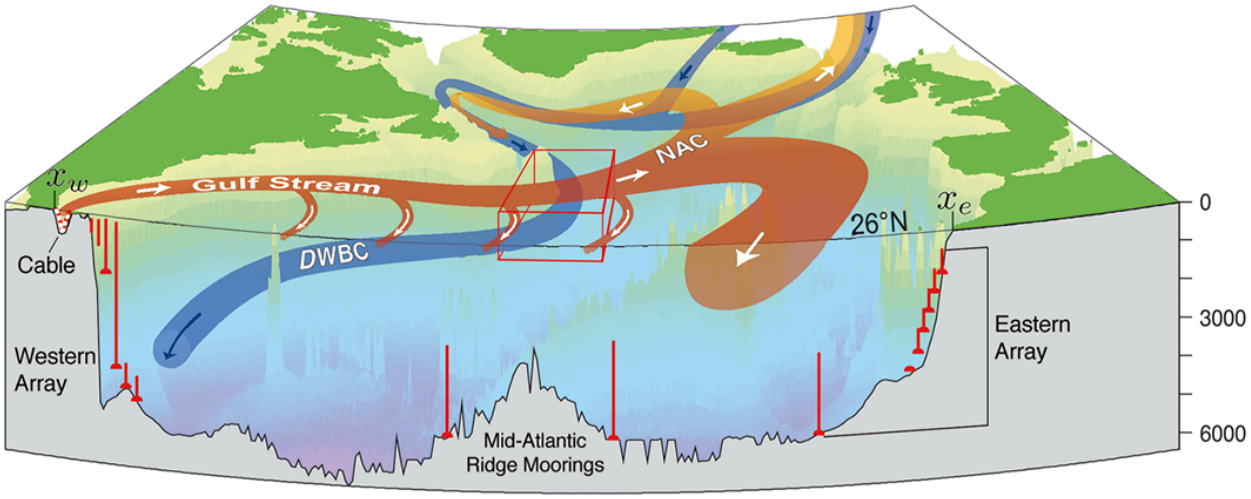



**Figure 2.** Diagram of the northern portion of the AMOC. [NOAA]

Thermohaline circulation is density-driven, so before delving deeper into it, we must first review the factors that can affect seawater density. This circulation is influenced by changes in the temperature and salinity of surface waters, leading to the formation of distinct water masses.

**Group Review and Discussion:**

1.) *What drives the thermohaline circulation?*
2.) *Speculate on how changes in seawater pressure, temperature, and salinity affect water density.*
3.) *What are the components of the Meridional Overturning Circulation?*

## ***Explore*** **| Ocean Layering, Water Masses, and Density-Driven Circulation**

Ocean **density** increases with depth due to **pressure** alone, but the largest differences in the ocean density gradient occur in the upper 1000 m of the ocean due to the combined effects of **temperature** and **salinity**. The combined effects of temperature, salinity, and pressure result in an ocean water column that is horizontally **stratified**.

**Stratification** is the layering of fluids according to density. Ocean **stability** generally increases with depth as density increases. The movement of water masses in the deep ocean is driven by differences in density. Changes in surface water temperature and salinity can lead to surface waters becoming denser than the waters below them. These waters are then prone to sinking until they reach a depth just above waters of a higher density, where they will spread out laterally.

To visualize the impact of temperature and salinity on water density, view the 3-minute video Ocean Stratification: Salinity, Temperature, and Density.

**Group Review and Discussion:**

1.) *What happens to seawater density if temperature changes but salinity and pressure stay constant? Explain your answer.*
2.) *What happens to seawater density if salinity changes but temperature and pressure stay constant? Explain your answer.*
3.) *Which is more stable, a stratified water column or a mixed water column? Explain your answer.*

## *Explain* | Density-Driven Ocean Circulation

### Ocean Structure

The oceans are stratified, layered systems. This layering occurs due to density (mass per unit volume) differences of seawater as a function of pressure, temperature, and salinity. Salinity, or the amount of dissolved salt, in the world's oceans averages about 35 and varies typically between 33 and 37, mainly near the ocean surface due to evaporation, precipitation, and freshwater inputs. For two water samples of the same temperature and volume, the saltier sample will be denser due to its greater mass. For two water samples of the same salinity and mass, the colder sample will be smaller in volume, and thus denser. In the surface waters of the open ocean, temperature generally varies more than salinity, and so has a greater effect on density. Since the majority of heat in the ocean comes from the transfer of energy from the Sun across the air-sea interface, surface waters are typically warmer than deeper ocean waters and are, therefore, less dense. And lastly, pressure increases with depth in an ocean water column. In the deep ocean, where temperature and salinity are relatively constant, seawater density increases as pressure increases. This results in a stratified ocean water column. The stability of the upper ocean is controlled largely by temperature, with warmer, less dense surface waters on top of colder, more dense intermediate, deep, and bottom waters. These deeper waters make up ~80% of the total ocean volume.

## Temperature and Salinity and the Density of Seawater

Winds blowing across the ocean surface can create waves and drive currents that can ‘stir’ the ocean surface to depths of a few hundred meters and form a **surface mixed layer** that has a relatively uniform temperature and salinity. Surface currents from wind action are limited to the upper few hundred meters of the ocean and cannot move deeper ocean waters. The movement of surface waters along the equator, at the boundaries of the oceans near coasts, or in areas of intense rotation can cause intermediate waters below the surface mixed layer to upwell towards the surface, but these upwelling regions are limited in extent.

Generally, below the surface mixed layer, the circulation of deep ocean water is driven by density differences. Subtle differences in temperature and salinity result in distinct **water masses** with different densities. The density differences in these water masses set up density-driven circulation, which sets in motion deep ocean currents that slowly flow through and connect all the Earth’s oceans, moving water as a ‘global ocean conveyor belt’ that slowly moves deeper waters along meridians transporting energy (heat), matter, and even organisms.

**Convection** is fluid motion driven by density differences. Small differences in seawater density drive the convective flow and circulation of the deep ocean. The density variations driving the circulation of the deep ocean are due to differences in temperature (thermo-) and salinity (haline-) so it is also referred to as thermohaline circulation.

## Ocean Water Column Stability

Thinking back to water column stratification and stability, surface water that is more dense than the surrounding surface water results in an **unstable** water column. These waters are prone to sinking. When they do sink, they will continue to sink and slowly mix with the waters around them until they reach a depth where they are more dense than the waters above them but less dense than the waters below. As stability is established, these waters spread horizontally as more water of the same density arrives from the surface above. More dense seawater displaces less dense seawater as it sinks. The displaced less dense water is pushed towards the surface, where it can be conditioned by the same physical process that lowers the density of the initial surface waters.

## Air-Sea Heat Exchange, Evaporation, and Brine Rejection

The temperature of surface waters can decrease due to a lowered **heat content** due to latent and sensible heat exchange with the atmosphere. As surface waters cool, density increases. The salinity of surface waters can increase due to the **evaporation** of water into the atmosphere or through the formation of **sea ice**. As seawater freezes, it is the water that freezes, so salts are rejected as **brine** and eventually released to the surrounding surface water. This **brine rejection** increases the salinity of the surrounding surface water. As salinity increases, seawater density increases. **Advection** of and mixing with different water masses can also change surface water density.

## Mediterranean Intermediate Water

Surface waters with a density that is significantly altered by air-sea interactions are said to be conditioned. For conditioned surface waters to sink past the base of the main pycnocline, they must become much denser than the waters around them. This typically requires the combined effects of both decreasing temperature and increasing salinity. Sinking is promoted by an initial “kick,” which further lowers water column stability. Wind mixing or gravity are the major forcing agents that facilitate and sustain surface water sinking. Density-driven circulation drives convective flows that are much slower than wind-driven advective flows associated with surface ocean circulation. In the absence of mechanical forcing, sinking water masses are slow to mix with surrounding water, maintaining their narrow temperature and salinity ranges. This permits water mass identification and tracing.

There are limited regions of the world ocean where conditions are right to promote **deep ocean convection** and the formation and circulation of **intermediate**, **deep**, and **bottom waters**. These regions are found primarily in the **polar regions**: marginal seas bordering the **North Atlantic** in the Arctic and near major **ice shelves** off of Antarctica in the **Southern Ocean**. Density-driven circulation can form bottom waters but can also form intermediate waters and deep waters in the **Mediterranean Sea** and other areas. As conditioned, dense waters sink, they are slowly mixed with less dense waters around them. They will continue to sink toward the seafloor as long as they remain denser than the waters around them. If they do not remain denser than the waters around and below them, they will establish a new equilibrium at an intermediate depth or depth off the bottom and then spread. **Mediterranean Intermediate Water (MIW)** is a water mass that forms in the warm but highly salty Mediterranean. It flows into the Atlantic Ocean and spreads outward for over two thousand kilometers just below the base of the main **thermocline** at a depth of approximately 1,000 meters. **Figure 3** shows the location of

various intermediate, deep, and bottom water masses in the Atlantic, Pacific, and Indian Ocean basins.

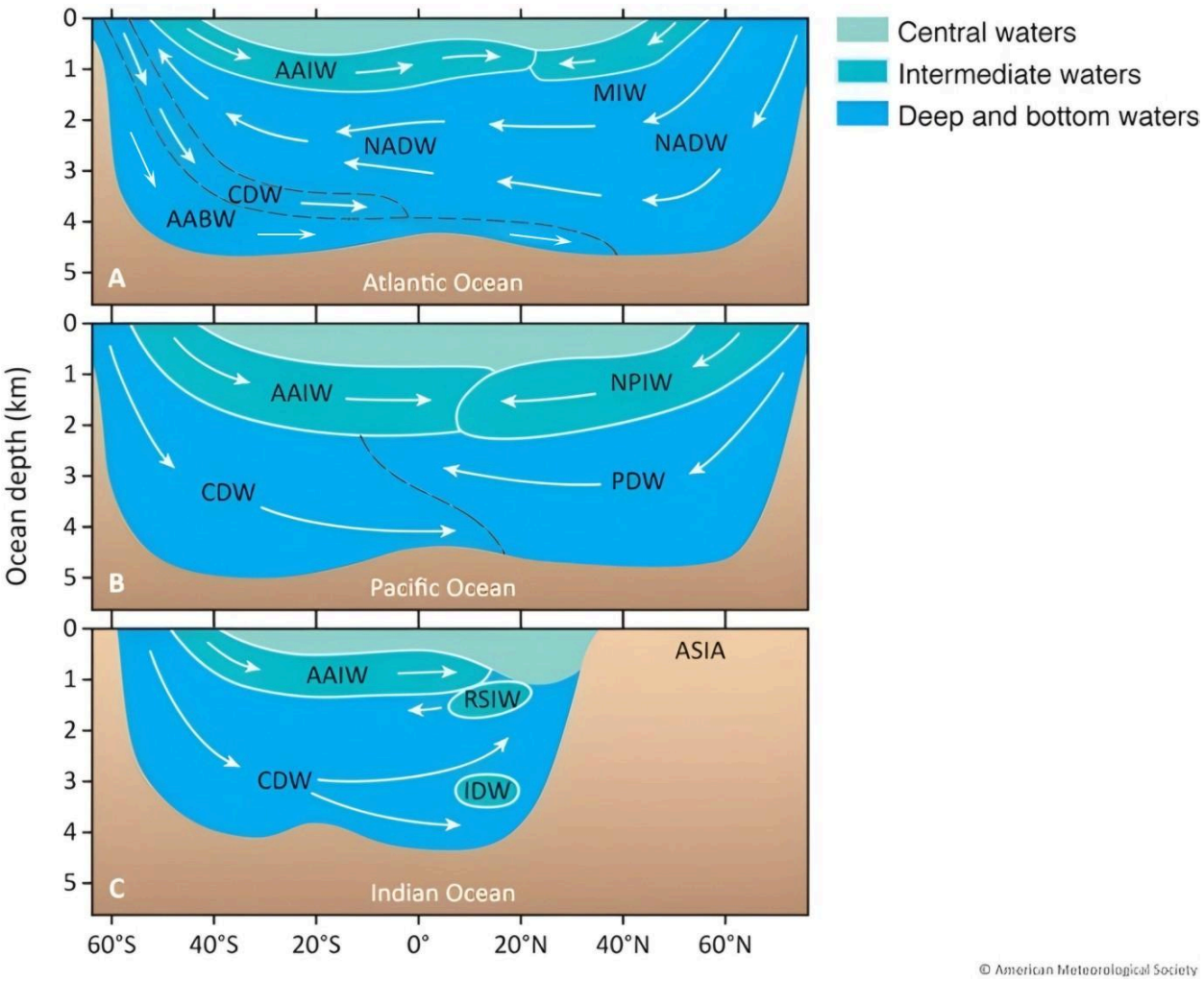



**Figure 3.** Vertical distribution of water masses in the (A) Atlantic, (B) Pacific, and (C) Indian Oceans. [Moran, 2011]

### Open Ocean Convection and Shelf-slope Convection

There are two main mechanisms for **deep ocean convection**: **open ocean convection** and **shelf-slope convection**. Open ocean convection occurs in limited regions of marginal seas where warmer warmers cool as they exchange heat with the atmosphere, thereby becoming more dense. Smaller subpolar **gyres** cause cooler surface waters to **diverge** leading to the **upwelling** of colder **intermediate** waters, which cool further becoming even more dense. Additionally, sea ice formation leads to brine rejection which increases the salinity of surface waters in the subpolar gyre therefore increasing the density to the point of instability. Wind-driven mixing causes dense surface waters to

sink. These waters may be mixed somewhat with less dense waters around them as they sink, but they will continue to sink toward the seafloor as long as they remain denser than the waters around them. When these waters reach the seafloor or a depth where they are less dense than the waters below them, they spread.

Shelf-slope convection occurs in shallow basins of the continental shelf that are separated from deeper waters by a sill or by a shelf break. Intense cooling and/or evaporation over the semi-enclosed area produces dense water that sinks and spreads to fill the basin separated from the open ocean by the shelf or sill. In some shelf-slope systems, intense evaporation can cause salinity and, therefore, density to increase even further (see the case of MIW). In polar shelf-slope systems, sea ice formation can also increase salinity and surface water density. Once conditioned surface water fills the shallow basin, gravitational forcing towards deeper waters beyond the shelf-break provides the mechanism for surface waters to sink toward the bottom. And as with all sinking waters, these waters may be mixed somewhat with less dense waters around them as they sink but they will continue to sink towards the seafloor as long as they remain more dense than the waters around them. When these waters reach the seafloor or a depth at which they are less dense than the waters below them, they spread horizontally.

**The Arctic Halocline**

Open ocean convection tends to dominate deep water convection in the Arctic. Prominent areas of open ocean convection occur in the **North Atlantic** in the **Greenland Gyre**, the **Labrador Sea**, and the **Irminger Sea**. These regions contribute to the formation of **North Atlantic Deep Water (NADW)**. The presence of a deep, dense layer of warmer, saltier North Atlantic water below fresher surface waters forms the Arctic **halocline** that tends to inhibit open ocean convection in the Arctic Ocean. Open ocean convection can occur in very limited areas in the Southern Ocean near Antarctica.

**Katabatic Winds, Polynyas, and Antarctic Bottom Waters**

Shelf-slope convection tends to dominate deep water convection in the **Southern Ocean** near Antarctica. Antarctica is covered by a massive **ice sheet** that, in some regions, extends off the continent onto the **continental shelf** in the form of ice shelves. The surface waters in the shallow basins off the front of Antarctica's major ice shelves are subject to intense cooling and sea ice formation, which rejects brine, increasing salinity and surface water density. Additionally, **sea ice** is pushed away from the continent by **katabatic winds,** which creates areas of persistent open water called

**polynyas** where already dense surface waters are re-exposed to the cold atmosphere allowing further cooling and additional sea ice formation. This leads to the formation of very dense waters that sink past the shelf break. The regions off the Ross and Ronne ice shelves are very important areas for the formation of **Antarctic Intermediate Water (AAIW)** and **Antarctic Bottom Water (AABW)**, the densest water mass in the ocean. There is some limited shelf-slope convection near ice shelves off the **Greenland ice sheet** driven by katabatic wind forcing.

**Global, Meridional Overturning Circulation**

Deep water convection is the only means by which bottom and deep waters are formed in the oceans. It allows for the exchange of properties between deep and surface ocean waters (heat, salinity, gases, and other constituents). Deep waters are replenished with modified surface waters that, before sinking, were actively exchanging gases with the atmosphere. This phenomenon is referred to as ocean ventilation. Deep ocean convection drives thermohaline circulation, which connects surface waters to deeper waters. This Meridional Overturning Circulation, encompassing the thermohaline circulation and wind-driven surface currents, connects all the world's ocean basins.

The MOC is composed of massive, slow-moving currents that connect warmer surface waters to colder, deeper waters below. It circulates water on a global scale at time scales of $10^2$ to $10^3$ years. In other words, water leaving the surface via thermohaline circulation may not return to the surface for hundreds or thousands of years. The MOC connects both poles and all the world's major ocean basins. It plays a vital role in exchanging constituents, such as gases and nutrients, between surface and deep waters; it can even transport biological organisms. But one of the most important aspects of the MOC is the role it plays in regulating regional and global climate. Areas of deep water formation are important areas where the oceans release heat to the atmosphere.

**Climate Change and AMOC**

The Earth's Climate history shows periods when the Meridional Overturning Circulation has slowed or changed modes, affecting regional and global climate. It follows that future changes have the potential to abruptly change climate. One of the most important branches of the MOC is the Atlantic Meridional Overturning Circulation. Warm surface waters are carried poleward from the Tropics along the western boundary of the Atlantic basin to the North Atlantic by the **Gulf Stream**. These waters are entrained in the **North Atlantic Current,** which feeds open ocean convection regions in the Greenland, Labrador, and Irminger Seas. Here, North Atlantic Deep Water forms, sinks, and moves

south along the bottom to the Southern Ocean until it encounters the densest water mass on Earth, **Antarctic Bottom Water** and rises again towards the surface. Northwestern Europe owes its relatively moderate climate to this AMOC. Changes in the AMOC can have profound effects on Northern Hemisphere and global climate.

**Group Review and Discussion:**

1.) *Density-driven circulation in the ocean depths is primarily a consequence of the interaction between the atmosphere and the ocean. Explain why this is the case.*
2.) *The Sun is viewed as the ultimate source of energy for the density-driven circulation in the ocean depths. Explain why this is the case.*
3.) *Explain why density-driven circulation plays an important role in regulating global climate and global biogeochemical cycles.*

## *Elaborate* | Deep Ocean Water Masses

The density (mass per unit volume) of seawater is a function of pressure, temperature, and salinity. Subtle changes in seawater density can result in changes in water column stability and promote the vertical movement of water masses. The most important factors determining the structure and stability of the upper ocean water column (< 1000 m) are temperature and salinity. Together they help to govern the density of surface waters, which is the major factor driving vertical movement and circulation of intermediate and deep waters. The accumulation of temperature and salinity measurements from water samples taken at a variety of locations and depths throughout the Global Ocean has revealed that there is a three-dimensional structure to the ocean consisting of different water masses. This multiple-layered ocean structure is maintained by vertical density-driven circulation. The following activity investigates density-driven circulation by using a set of temperature and salinity measurements from simulated shipboard water samples taken at different depths at a single location in the Atlantic Ocean. The objective of this activity is to build a global perspective of deep ocean structure and density-driven circulation in the Atlantic Ocean Basin.

***Materials (found near end of the module):***

- ***Water Sample Table***
- ***Water Sample Temperature-Salinity (T-S) Diagram***
- ***Density T-S Diagram*** (if possible, printed or copied onto a clear plastic overlay)
- ***Water Mass T-S Diagram*** (ideally a clear, plastic overlay)
- ***Atlantic Ocean Source Area Chart*** and ***Vertical Cross Section Diagram***

After completing this investigation, you should be able to utilize T-S Diagrams to identify different water masses, describe the layered, stratified structure of the Atlantic Ocean, and describe how density-driven circulation drives deep ocean currents.

***Activity - Density Detective:***
Examine the ***Water Sample Table***. The depth at which the simulated water samples were taken is in meters (m). The temperature of the samples is in degrees Celsius (℃). The salinity of each sample is measured in **Practical Salinity Units (PSU)**. Note that the temperature and salinity values are different for each sample.

Examine the ***Water Sample Temperature-Salinity (T-S) Diagram***. The T-S diagram is a simple but powerful tool used in studies of the density and movement of water masses. On the blank diagram, plot each water sample reported in the ***Water Sample Table*** by placing a dot (·) at the place determined by its temperature and salinity. Label each point by writing its depth next to it.

Examine the ***Density T-S Diagram***. Note that the density of each seawater sample needs to be determined to several decimal places before significant differences can be seen. Density may be determined by either a lengthy calculation using the **Equation of State for seawater**, a linear approximation to the Equation of State, or by the use of a T-S diagram such as this one. To find the density of each water sample, place the overlay of the ***Density T-S Diagram*** on the ***Water Sample T-S Diagram***. Interpolating to obtain the second decimal place, determine the density for each sample and record it in the ***Water Sample Table***.

Examine the ***Water Mass T-S Diagram***. Waters of different densities tend not to mix. Instead, they tend to flow over and under each other in layers, with the denser layers below. This lack of mixing means that each layer, called a water mass, retains its original characteristics, including temperature and salinity. These characteristics, in turn, are used to identify and track the water mass.

Place the overlay of the ***Water Mass T-S Diagram*** on the ***Water Sample T-S Diagram*** and determine the name of the water mass “box” in which each sample is located. Note that the name for each water mass contains both the source area from which it originated (Antarctic, Mediterranean, or North Atlantic) and the relative depth (central (surface), intermediate, deep, or bottom) at which it is found. Record the initials for each water mass in the table.

Examine the ***Atlantic Ocean Source Area Chart***. This chart shows where the sampling took place as well as the general locations of the water mass source regions. Note that

almost all the water samples originated from relatively small regions of the ocean surface where a density increase, due to low temperature, high salinity, and/or mixing, results in water mass formation and sinking.

Examine the ***Vertical Cross Section***. It shows the general form of the layered structure of the Atlantic Ocean. Arrows describe the density-driven circulations of water masses. Note that for most water in the ocean, the circulation is driven by the sinking of cold, dense water at high latitudes. Similar water masses and deep currents also circulate through the other major ocean basins.

Use the density and water mass information recorded in the ***Water Sample Table*** to identify the water masses shown in the ***Vertical Cross Section***. On the vertical line at the sample site, plot the depths at which the samples analyzed in this activity were taken, converting meters to kilometers. Label each water mass with its initials from the table. To help, you can fold the page along the boundary between the Atlantic Ocean Source Area Chart and the Vertical Cross Section to get a 3-dimensional view of the Atlantic Ocean structure and density-driven circulation.

## *Evaluate* | Deep Ocean Water Masses

Utilize what you've learned from this activity in the Elaborate section, referencing explanations from other sections of this module as needed, to respond to the following questions about density-driven circulation.

1. When compared to the approximately 1.0 kilometer per hour speed of most wind-driven surface currents, the velocity of a density-driven deep ocean current is much slower, covering about 1.0 meter per hour. At this speed, how long would it take for a density-driven current such as North Atlantic Deep Water to travel the approximately 9,000 km path from its source region in the North Atlantic to Antarctica?
   a. 10 years
   b. 100 years
   c. 1000 years
   d. 10,000 years

2. The ***Water Sample Table*** shows that with depth, the temperature and salinity of ocean water _____.
   a. is constant
   b. varies

3. Looking at the densities you determined for the water samples, the ocean water densities at this site in the Atlantic Ocean _____ with depth.
   a. decrease
   b. increase

4. From the ***Density T-S Diagram***, it can be seen that with increasing temperature, you would expect the density of seawater to _____.
   a. decrease
   b. increase

5. With decreasing temperature, you would expect the density of seawater to _____.
   a. decrease
   b. increase

6. From the ***Density T-S Diagram***, it can be seen that with increasing salinity, you would expect the density of seawater to _____.
   a. decrease
   b. increase

7. With decreasing salinity, you would expect the density of seawater to _____.
   a. decrease
   b. increase

8. The circulation of the deep ocean is driven by the increase in the density of surface water due to changes in temperature and salinity. A major way the density of surface water in the high latitude regions of the ocean is increased by _____.
   a. cooling
   b. heating

9. The density of surface water in the low latitude regions of the ocean is increased by net _____.
   a. evaporation
   b. precipitation

## *Extend* | Further Exploration of Temperature, Salinity, and Density

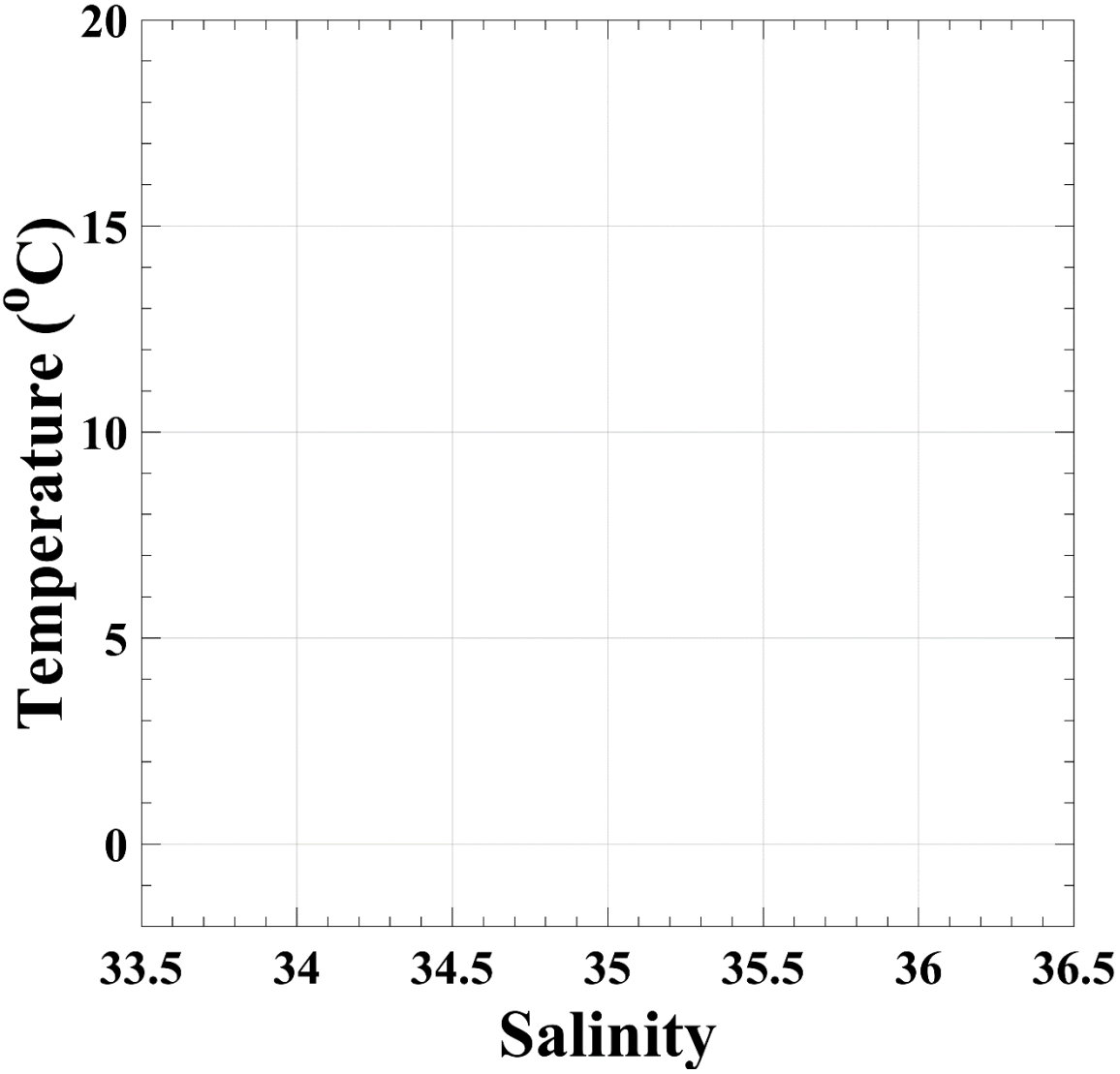
### Group Demonstration: Salinity and Temperature - How Dense Can You Get?

### *Water Sample Table*

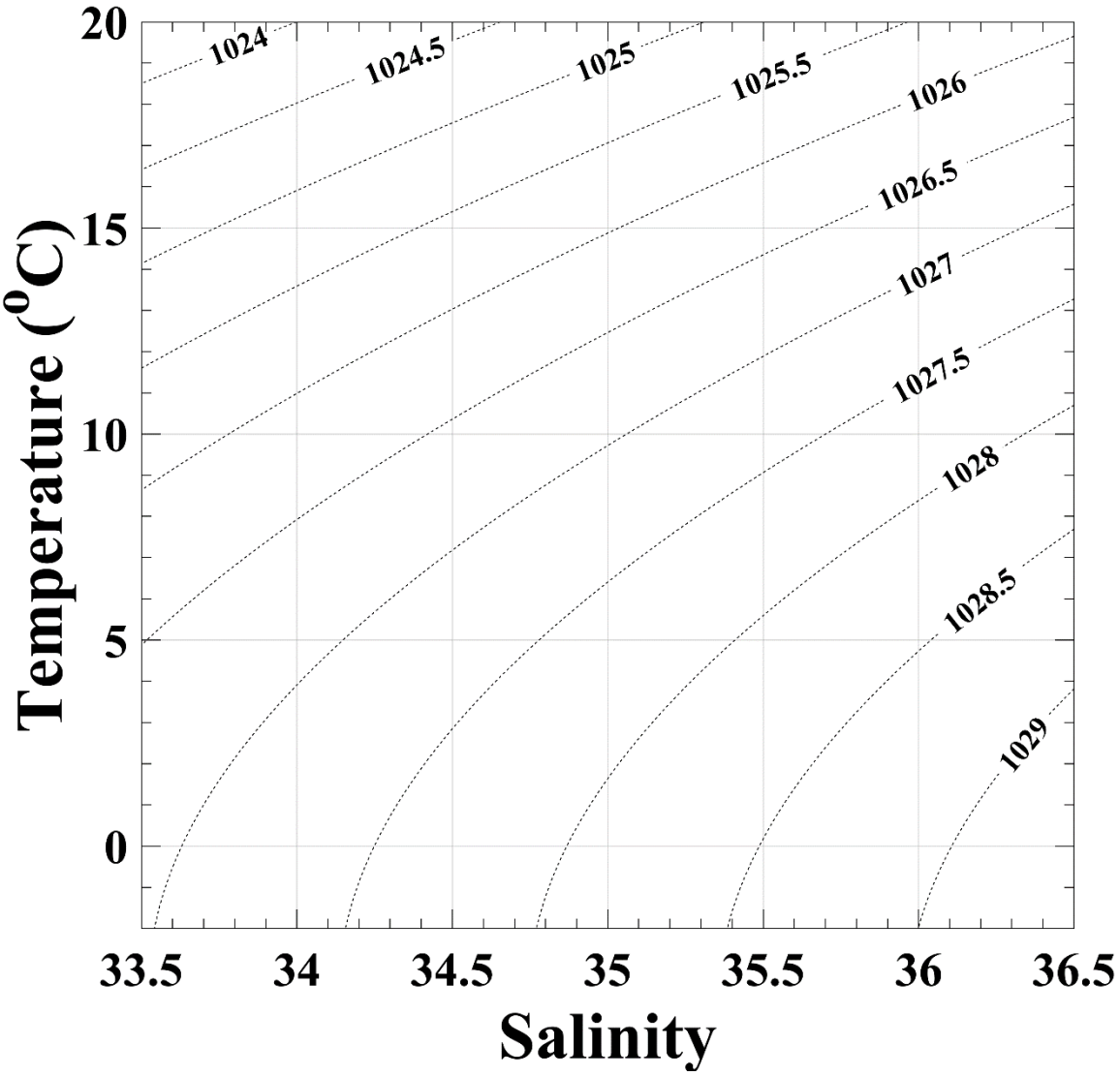
| Depth (m) | Temperature (°C) | Salinity (PSU) | Density (kg/m$^3$) | Water Mass |
|---|---|---|---|---|
| 100 | 15.0 | 36.0 | | |
| 500 | 4.0 | 34.2 | | |
| 1000 | 10.0 | 35.8 | | |
| 2000 | 4.0 | 34.9 | | |
| 4000 | 0.0 | 34.7 | | |

*Note: These are simulated data.*

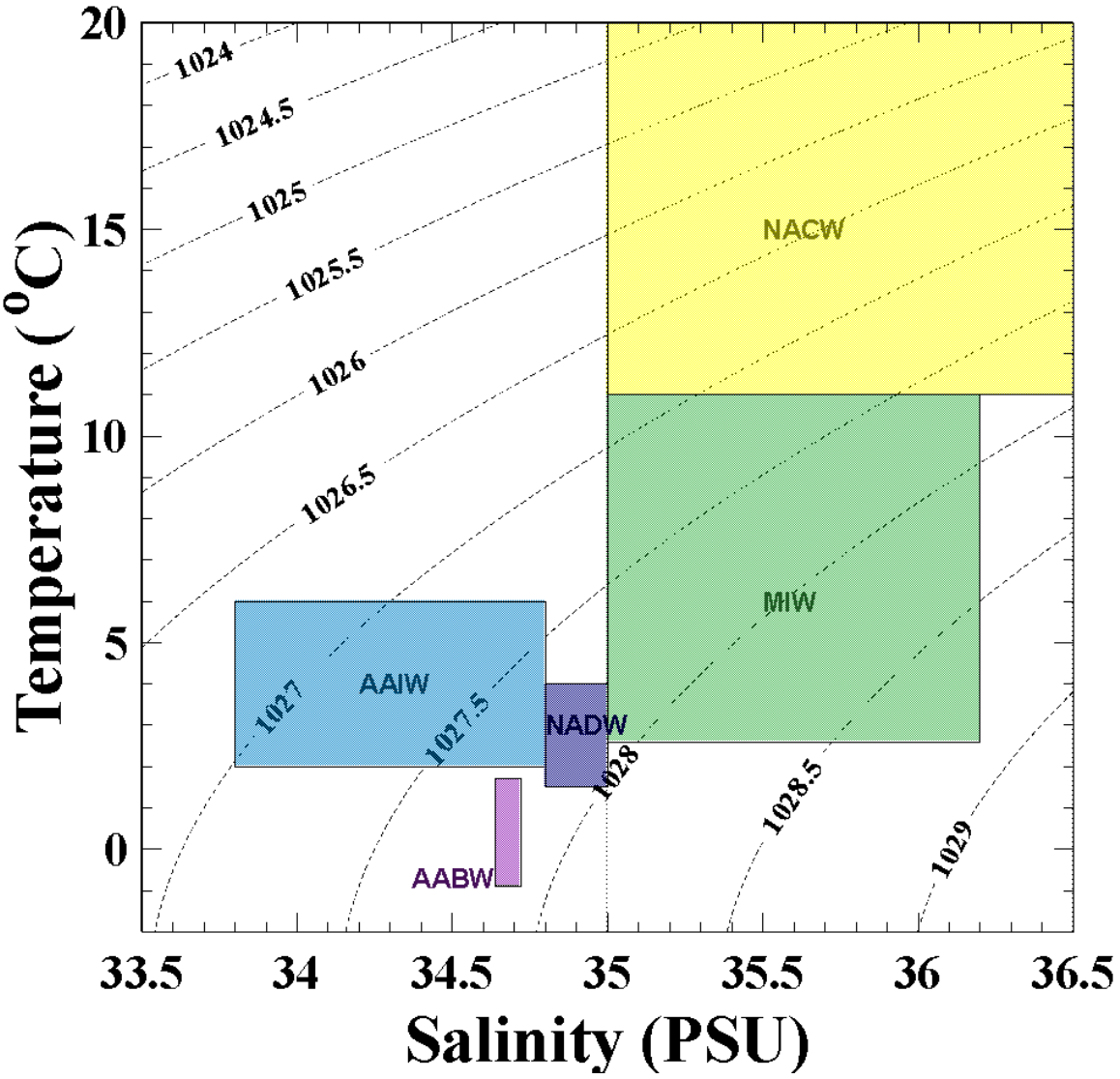
***Water Sample Temperature-Salinity (T-S) Diagram***



***Density T-S Diagram***



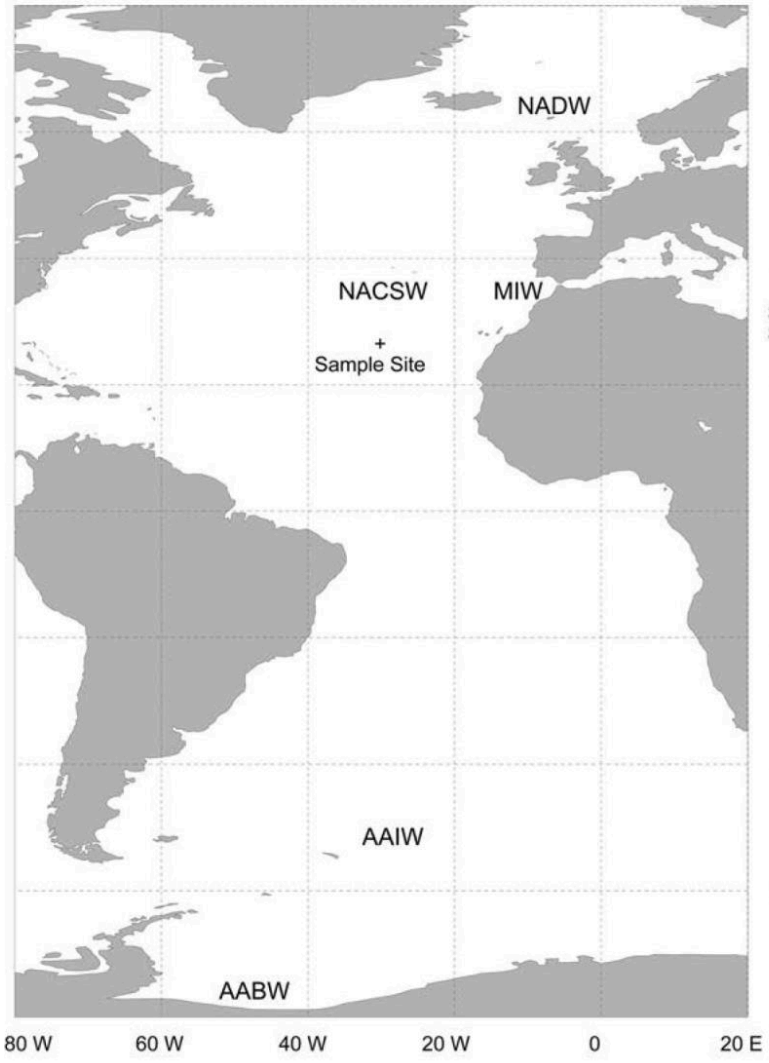
***Water Mass T-S Diagram***



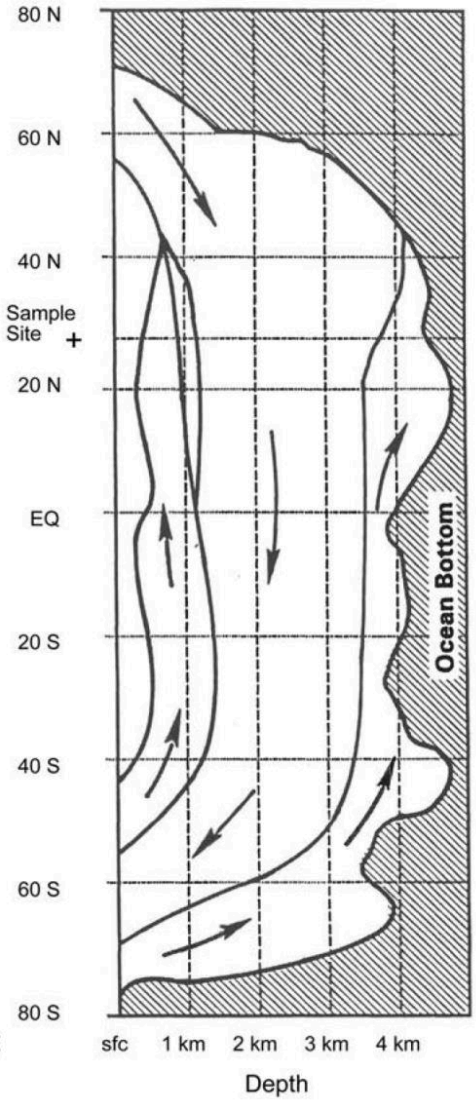

**North Atlantic Central (Surface) Water = NAC(S)W**
**Mediterranean Intermediate Water = MIW**
**North Atlantic Deep Water = NADW**
**Antarctic Intermediate Water = AAIW**
**Antarctic Bottom Water = AABW**

Modified from: Emery, W.J., 2001: Water Types and Water Masses, Encyclopedia of Ocean Sciences (2nd Edn), edited by John H. Steele, Academic Press, pp. 291–299.

## Atlantic Ocean Source Area Chart




## Vertical Cross Section




Water Mass Source Areas:

-- Antarctic Bottom Water (AABW)

-- Antarctic Intermediate Water (AAIW)

-- North Atlantic Central Surface Water (NACSW)

-- North Atlantic Deep Water (NADW)

-- Mediterranean Intermediate Water (MIW)

***Additional Resources***

General Information:

National Geographic:
https://www.nationalgeographic.org/education/resource-library/?q=ocean%20conveyor%20belt&page=1&per_page=25

National Aeronautics and Space Administration (NASA):
https://www.nasa.gov/education/materials/
https://gpm.nasa.gov/education/sites/default/files/videos/thermohaline_conveyor_30fps.mp4

National Oceanic and Atmospheric Administration (NOAA):
https://oceanexplorer.noaa.gov/facts/currents.html

Density Demos:

Teacher Tube:
https://www.teachertube.com/videos/salinity-density-demonstration-16140

Scientific American:
https://www.scientificamerican.com/article/seawater-science-model-ocean-currents-in-your-kitchen/

Science Buddies - Lesson Plan Resources:
https://www.sciencebuddies.org/teacher-resources/lesson-plans/oceanic-circulation

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