Exploring Ocean Circulation
Background

Ocean Circulation

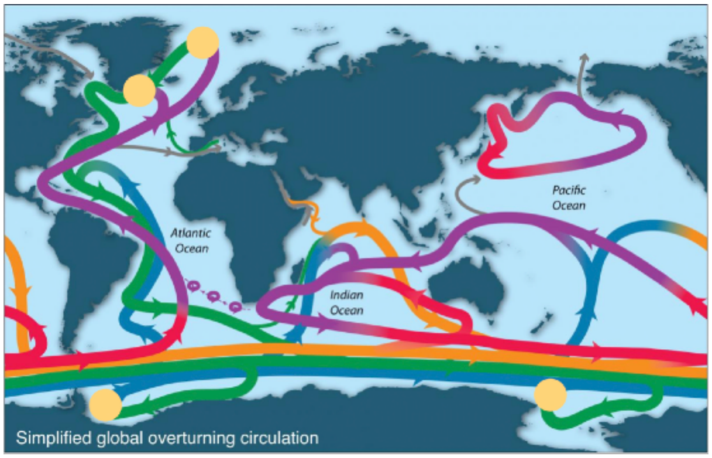

FIGURE 1: WATER DEPTHS: RED: SURFACE, PURPLE: INTERMEDIATE, ORANGE: LOWER INTERMEDIATE, GREEN: DEEP, BLUE: ABYSSAL

Water travels around the globe on a circuitous conveyor belt on a roughly 1000 year timescale. The majority of this trajectory is through the basins, moving from one basin to another by way of the Circumpolar Current that flows around Antarctica. In *Figure 1*, the colored lines show water moving along trajectories of similar relative depth.

In a few localized regions (highlighted by gold circles), water densifies abruptly and sinks, a process called, "water formation." While it is not the primary concern of this discussion, in some cases deeper water mixes enough with less dense water above that it becomes a functionally new watermass (a body of water with similar characteristics that moves as a mass). This and intermediate water formation are noted on the map as gradual transitions between colors rather than as gold circles.

Slicing the Atlantic along 30W exposes the layered structure of the ocean. Water moves in masses with minimal mixing at the boundaries, layered and at equilibrium with the water column: denser water below, less dense water above. North Atlantic Deep Water (NADW) formed in the Nordic and Labrador Seas of the North Atlantic sinks and then traverses the Atlantic basin, filling much of the Atlantic interior. Upon arriving at the Southern Ocean, a fraction of it upwells while the rest feeds the Circumpolar Deep Water (CDW) flowing from west to east around Antarctica. Antarctic Bottom Water (AABW) forms in the Weddell Sea along the Antarctic shelf, sinking and moving north to fill the abyssal Atlantic.

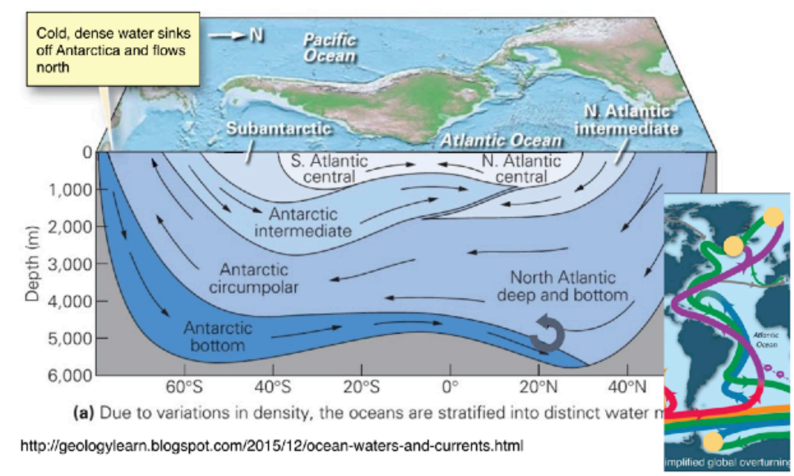

FIGURE 2: SECTION OF VIEW OF ATLANTIC ALONG 30W

Based on measurements of wind velocity, water temperature and salinity, and equations describing the physics of fluids moving on a sphere with given basin geometry, we have a decent understanding of how water moves. In addition, the distribution of the chemical constituents of the ocean throw light on the location, size, and shape of watermasses.

Probing the Data

Tracers

As processes occur in the ocean, the concentration of chemical constituents change. For example, evaporation results in increased salinity, and cell building by organisms takes up dissolved phosphate from the surrounding water, driving down the phosphate concentration. Salinity, and phosphate, in addition to nitrate, oxygen, and temperature (though a physical parameter of the ocean rather than a chemical), among many others, are referred to as "tracers" because when plotted out, they help oceanographers "trace" the paths of water and the processes occurring in the ocean.

World Ocean Atlas 2013

The World Ocean Atlas 2013 is an ocean data product produced by the Ocean Climate Laboratory and the National Oceanographic Data Center. WOA fields include temperature, salinity, phosphate, nitrate, oxygen, silicic acid, among others and are reported at 1 degree resolution at 102 standard depth levels from surface to the abyssal floor (5500m).

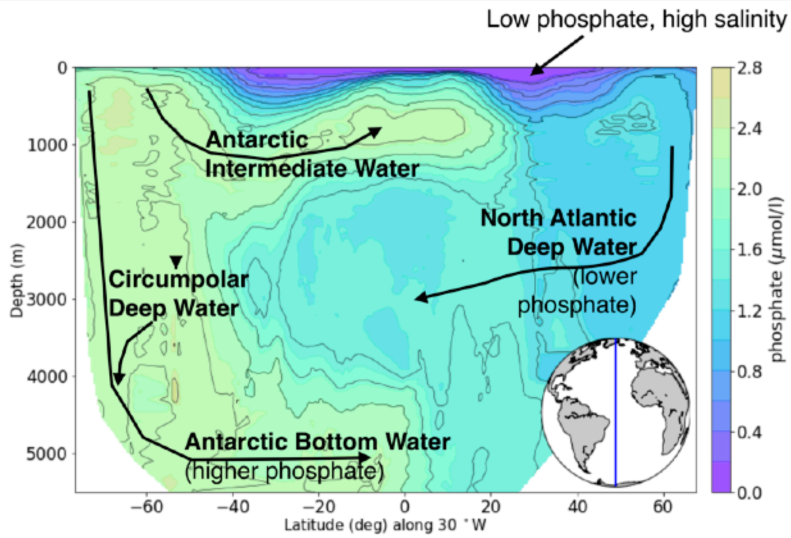

FIGURE 3: SECTION OF PHOSPHATE DATA ALONG 30W FROM 80S TO 70N, WOA13

The "Eyeballing Contours" Approach

Contour plots plus a background in the principles of ocean circulation give oceanographers an overview of the ocean's structured in a particular view. *Figure 3* shows phosphate data from the World Ocean Atlas 2013 along 30W from 80S to 70N. Coloration of the high latitude north and south show vertical homogeneity, consistent with water carrying its surface concentration from the surface to depth in the course of water formation. The tongue of low phosphate (cyan) water coming from the north at ~3000 m appears to be a continuation of NADW into the ocean interior, while the higher phosphate water (yellow-green) creeping down the left and along the bottom suggests the path of AABW northward.

Deep Ocean Tracer Distributions

All three histograms show that the deep high latitude values in the Atlantic bound the values of the deep Atlantic Basin in total and fall within relatively tight ranges. This suggests that deep water in the Atlantic can broken down as a combination of values from the high latitude north and south. When a tracer distribution is strictly determined by ocean circulation and mixing and is unaffected by any additional biogeochemical processes, the tracers is considered "conservative." That said, if the process(es) affecting the distribution of a tracer is slower than the timescale of ocean

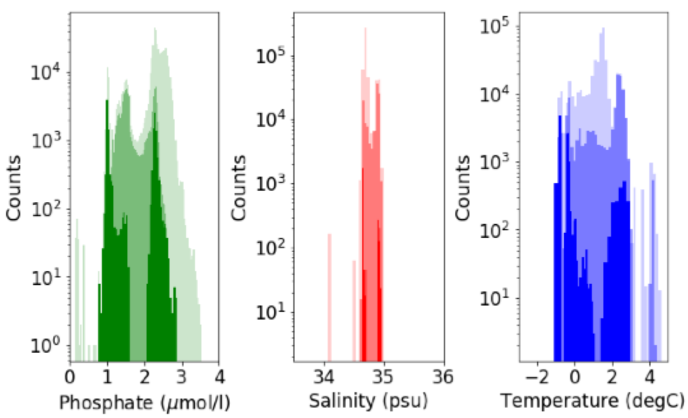

FIGURE 4: (LEFT) PHOSPHATE, (MIDDLE) SALINITY, (RIGHT) TEMPERATURE; LIGHT: GLOBAL OCEAN >3000M, MEDIUM: ATLANTIC BASIN >3000M, DARK: HIGH

circulation, the effect is negligible and the tracers is “effectively conservative.”

On a global scale, salinity is a conservative tracer because there are no processes that alter the distribution of salinity in the deep ocean independently of ocean circulation and mixing. Consistent with this, the values introduced during water formation in the high latitude also bound the global deep ocean salinity distribution. Phosphate, on the other hand, is only a conservative in the Atlantic Basin and not conservative globally because regenerated organic matter can accumulate in slow moving deep water, resulting in the upper values not bounded by the high latitude Atlantic values.

Analytical Investigations

Q1: NADW and AABW, statistically different?

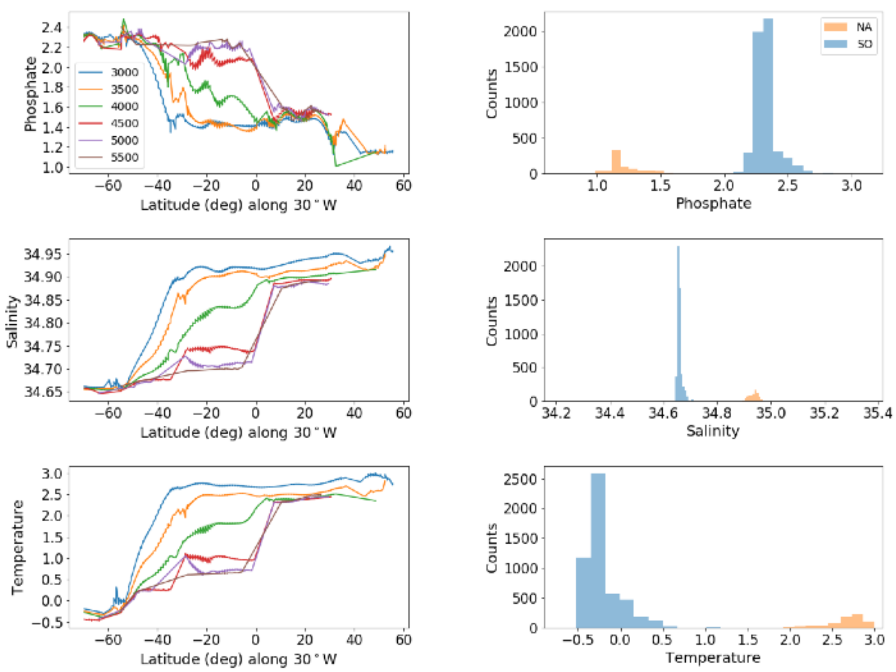

FIGURE 6: COLUMN A: TRACER VALUES ALONG 30W AT 3000, 3500, 4000, 4500, 5000, AND 5500 METERS, COLUMN B: HISTOGRAMS OF HIGH LATITUDE ATLANTIC, BLUE: SOUTHERN OCEAN, ORANGE: NORTH ATLANTIC

Consider *Figure 6* with tracer values at each of several depths along 30W between 68S and 55N for each of the three tracers in column A and histograms of these tracer values in column B. T-test p-values ($p = 0$ in all cases) confirm what one might infer by inspection: these water masses are distinct regardless of which of these three tracers is being considered.

In each of the plots in column A, trajectories show fairly consistent values through the water column at or below 3000m at high latitudes, but show a departure in the mid latitudes where the upper part of the water column (<=3500m) looks like the North Atlantic and the bottom part of the water column (>=4500m) looks like the Southern Ocean. The trajectory for 4000m is roughly diagonal, connecting the high latitude values, suggesting the depth where there is some mixing occurring at the nexus of the two watermasses. The minimum and maximum values of the trajectories fall at the two water formation sites, making them end-members of this process.

Q2: How far does Southern Ocean source water extend?

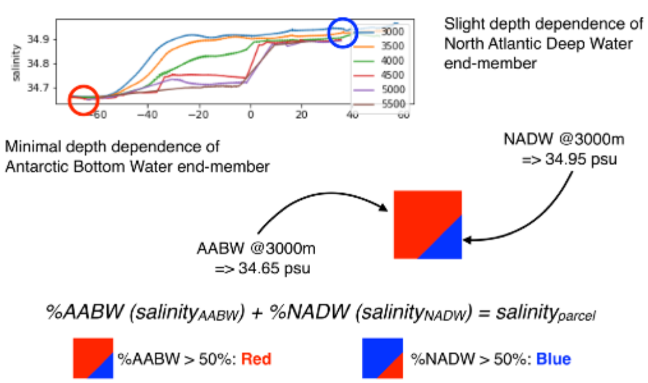

FIGURE 7: SCHEMATIC OF TWO END-MEMBER MIXING

Two end-member mixing models

Consider the deep Atlantic Ocean as a two end-member mixing problem. The basic idea is that any value of a conservative tracer, like salinity, should be a linear combination of Southern Ocean sourced water and North Atlantic sourced water. The color label of the water parcel is determined by which end-member represents a higher percentage of its makeup.

Applying the two end-member mixing model to the Atlantic

This two end-member mixing experiment uses salinity data to probe whether deep water in the Atlantic Ocean most closely resembles the northern or southern end-member value. In keeping with the approach described above, *Figure 8* is the set of labels for each latitude-depth point along 30W, color filled for readability. Labels are missing where there are bathymetry features rising from the seafloor rather than water. It is worth noting that the shoaling that occurs in the North Atlantic is the reason there is no data available below 4000m north of ~35N.

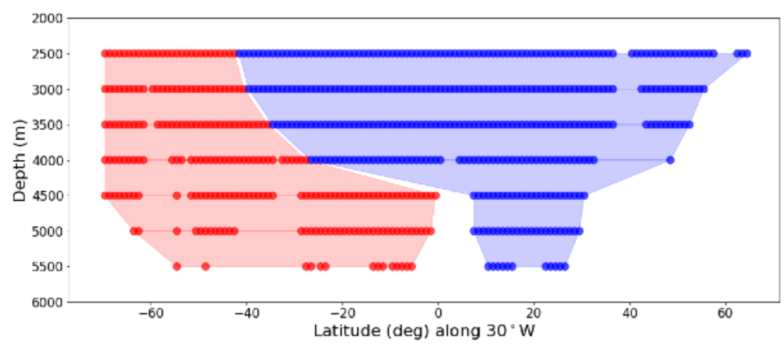

FIGURE 8: TWO END-MEMBER MIXING MODEL LABELLING POINTS ALONG 30W. RED: S SOURCE WATER. BLUE: N SOURCE WATER

While this is a very rough approximation, it is possible to see some of the structure begin to emerge, including the Antarctic Bottom Water coming from the Southern Ocean and North Atlantic Deep Water filling the interior of the Atlantic.

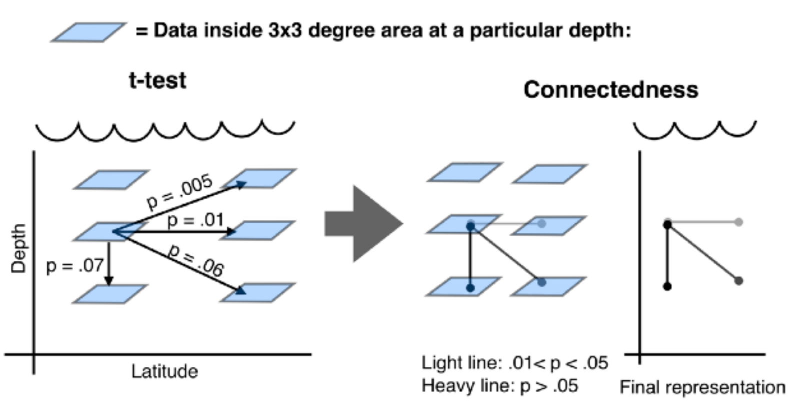

FIGURE 9: SCHEMATIC FOR CONNECTIVITY USING A T-TEST

Q3: Can water formation be traced statistically?

Connectedness using t-test

Consider two columns of water 3 degrees x 3 degrees. Data within these columns at a given depth is compared to the datasets below, to the right, diagonally up, and diagonally down. If the t-test returned a p value >.05, the two datasets were connected with a strong line, if the p value was between .01 and .05, they were connected with a weak line, and if the p value was smaller than .01 they remained disconnected.

Applying connectedness to the Atlantic Ocean

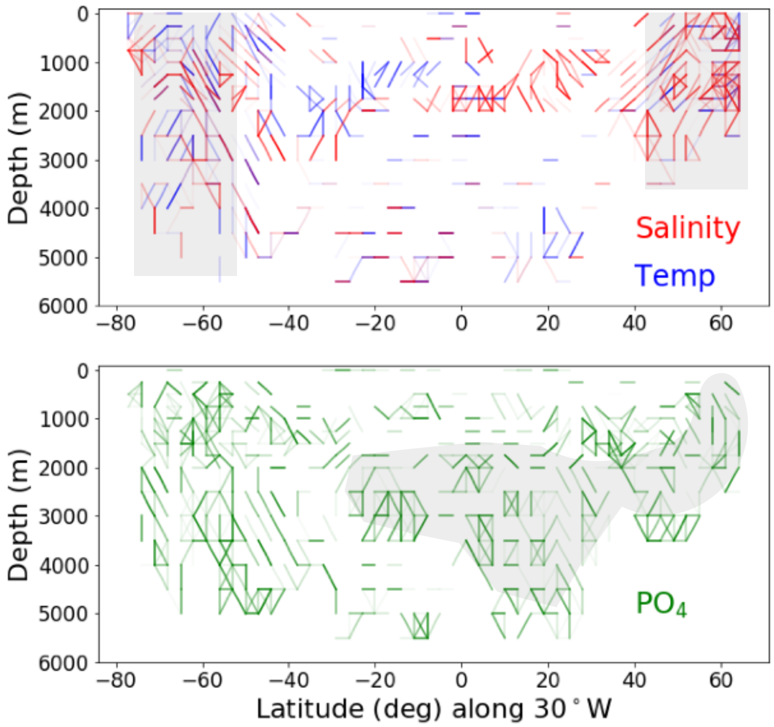

FIGURE 10: APPLICATION OF CONNECTIVITY TO DATA ALONG 30W (TOP) SALINITY AND TEMPERATURE AND (BOTTOM) PHOSPHATE

In areas of water formation, water descends to a density-determined depth and then moves laterally on that density surface with relatively little mixing between layers; the water column is well organized. Though there are features left to be parsed in a future study, there does appear to be more temperature and salinity vertical connectivity at the highest latitudes where one might expect to see more vertical homogeneity due to water formation, and deep water horizontal connectivity in mid and low latitudes where one might expect water to have settled out along consistent depth surfaces.

While structure in temperature and salinity data provides insight about the structure of the water column, once a parcel of water sinks and reaches its density surface, it registers as a horizontal line, without a hint as to its source location. In contrast, a tracer like phosphate that does not vary directly with density (the concentration of phosphate does not contribute materially to water density and is dominated by biological processes), will remain tied to the characteristic value of its source water even after begins its horizontal trajectory. While the ocean interior is a set of parallel horizontal lines in the salinity/temperature space, in phosphate space the interior the Atlantic shows more connectivity, consistent with the distribution of common source water, and there is a discernible buffer between the tongue of NADW and the Southern Ocean (Circumpolar Deep Water around 3500m and AABW below 4500m) where two water masses are abutting each other and the gradient is at a scale smaller than the resolution of the connectivity figure.

Next Steps

Multiple tracers and clustering

How can we use cluster analysis and multiple tracers to better define watermasses and which areas are classified differently depending on the combination of tracers used?

End-member analysis to trace flow trajectory

Rather than use the two end-member model to identify the dominant contributor at each point along a line of longitude, is it possible to trace the path of a water mass through three dimensions based on a characteristic ratio or tracer value?

Role of non-mixing processes on tracer distribution

Can we apply a one dimensional mixing model trained on salinity data to characterize the amount extent to which biology rather than ocean circulation and mixing affect phosphate distribution?

References

Figure References:

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