Exploring Ocean Circulation

Background

Ocean Circulation

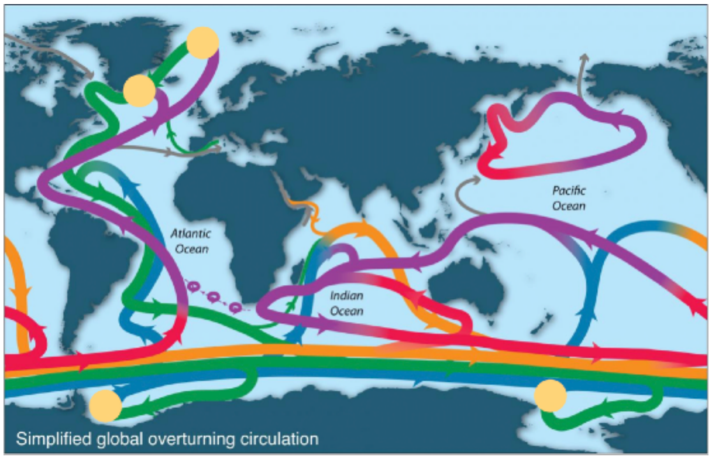

FIGURE 1: WATER DEPTHS: RED: SURFACE, PURPLE: INTERMEDIATE, ORANGE: LOWER INTERMEDIATE, GREEN: DEEP. BLUE: ABYSSAL

Water travels around the globe on a circuitous conveyor belt on a roughly 1000 year time scale. 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 the below figure, the colored lines show water moving along trajectories of similar depth.

In a few localized regions, water densifies abruptly and sinks, a process called, "deep water formation," highlighted by gold circles. While it is not the primary concern of this discussion, intermediate water is formed by either densification of surface water (similar to deep water formation), or by mixing with lighter water facilitated by upwelling and is noted on the map as gradual transitions between colors unmarked by a gold circle.

Slicing the Atlantic along 30W exposes the layered structure of the ocean. During water formation, water descends until it is in 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 descends to depth and traverses the Atlantic basin, filling much of the interior of the Atlantic on its way. Upon arriving at the Southern Ocean, a fraction of it upwells and the rest feeds the Circumpolar Deep Water (CDW) flowing from west to east around Antarctica. Meanwhile Antarctic Bottom Water (AABW) forms along the Antarctic shelf, sinking and moving north to fill the abyssal Atlantic.

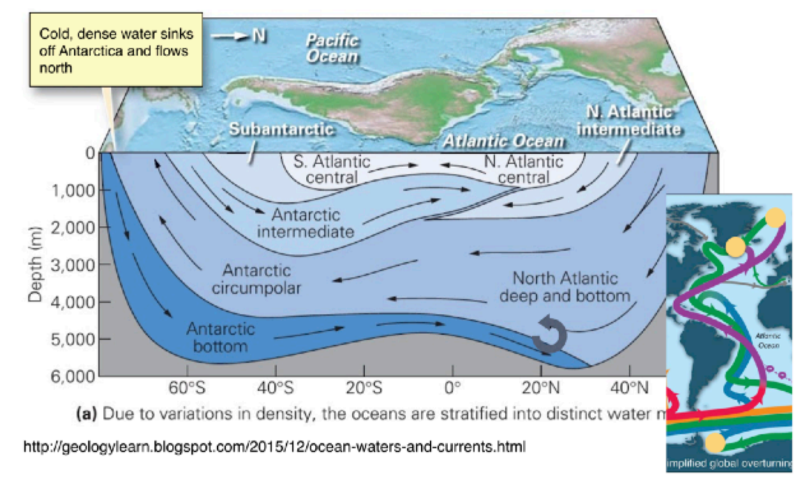

FIGURE 2: SECTION OF VIEW OF ATLANTIC ALONG 30W

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 (a body of water with similar characteristics that moves as a mass).

Probing the Data

Tracers

As processes occur in the ocean, the concentration of chemical constituents change. For example, when water evaporates, salinity goes up, or when organisms grow, they take up phosphate from the water to form cells, so the concentration of those nutrients goes down. Salinity, and phosphate, in addition to nitrate, oxygen and temperature (though a physical parameter of the ocean rather than a chemical) are referred to as "tracers" because when plotted out, they help oceanographers "trace" the paths of water and the processes occurring in the ocean.

The "Eyeballing Contours" Approach

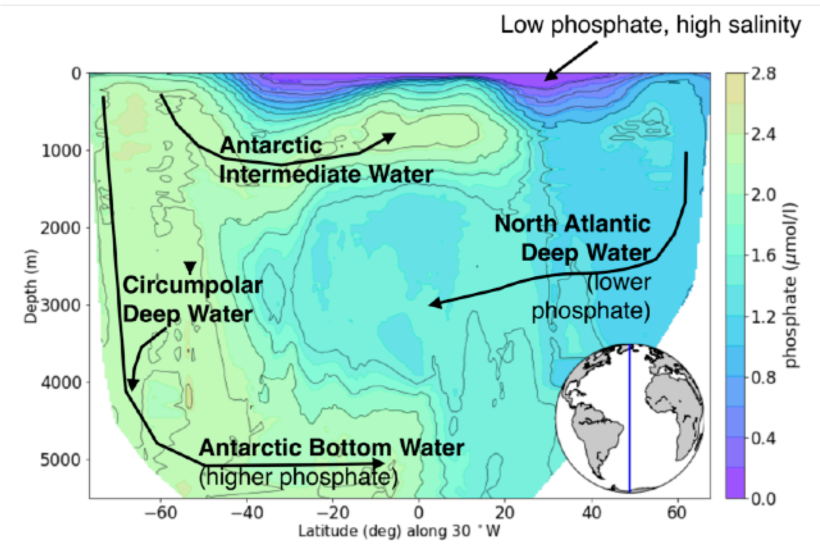

FIGURE 3: SECTION OF PHOSPHATE DATA ALONG 30W FROM 80S TO 70N, WOA13

Making logical deductions about where watermasses are based on coloration and with some background in the principles behind ocean circulation is not a bad way to get a sense of the ocean's structured in a particular place. *Figure 3* shows two areas of vertical homogeneity at the far south and far north, consistent with water going from the surface to depth as part of water formation. The tongue of cyan-colored water coming from the north at ~3000 m reads as an extension NADW into the ocean interior, while the yellow-green water creeping down the left and along the bottom suggests movement 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. Salinity and temperature values also bound the global deep ocean range fairly closely. The distribution of the points outside the Atlantic Basin suggest that the rest of the deep ocean may be fresher with density gradients dominated by temperature rather than salinity. Indeed this is consistent with a quick glance at a contour plot of salinity across the Atlantic and Pacific and supports the notion that salinity is conservative; salt is not added to or removed from the deep ocean by any process besides water formation so its distribution is a function of ocean circulation and related mixing.

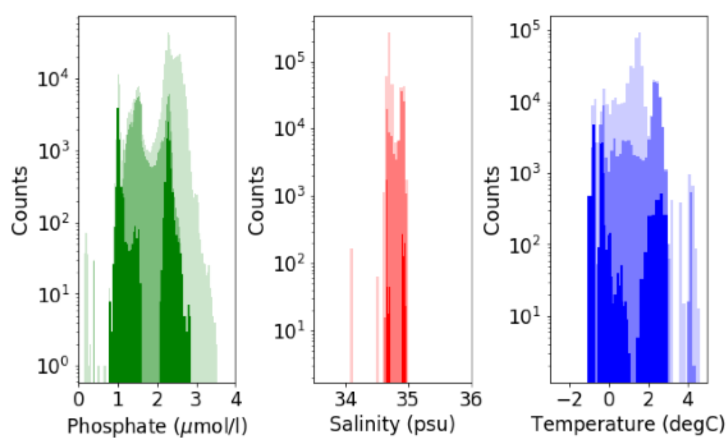

FIGURE 4: (LEFT) PHOSPHATE, (MIDDLE) SALINITY, (RIGHT) TEMPERATURE; LIGHT: GLOBAL OCEAN >3000M, MEDIUM: ATLANTIC BASIN >3000M, DARK: HIGH LATITUDE ATLANTIC

On the other hand, high latitude phosphate values do not bound the global set. Unlike salinity, in the global ocean, phosphate is not conservative. When organic matter dies in the ocean, it sinks, reintroducing some dissolved phosphate at depths below where other photosynthesizing organisms might consume it. Therefore, in places where water moves slowly, like the North Pacific, phosphate accumulates in the water column, leading to the higher values present in the histogram.

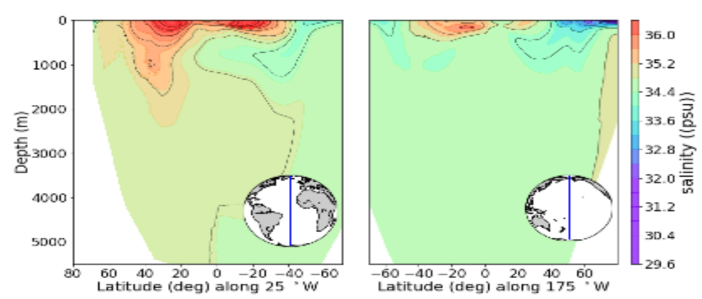

FIGURE 5: SECTION OF SALINITY DATA ALONG (LEFT) 25 W AND (RIGHT) 175W

That said, if the timescale of circulation is shorter than that of accumulation, the accumulation of phosphate due to regeneration of sinking organic matter will not be appreciable and it can be treated as a circulation tracer in the same way as salinity.

Analytical Investigations

Q1: NADW and AABW, statistically different?

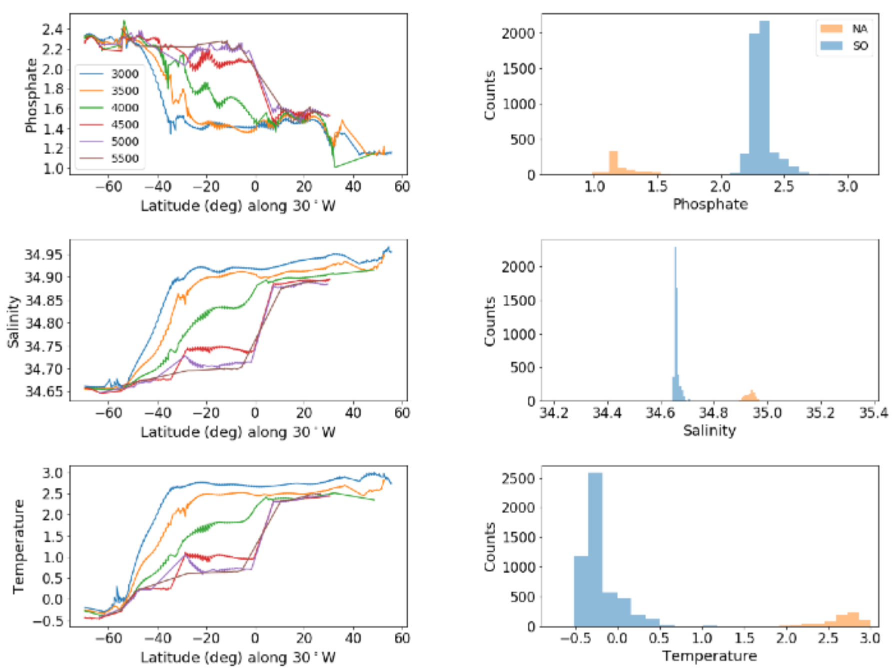

FIGURE 6: COLUMN A: TRACER VALUES ALONG 30W AT 3000, 3500, 4000, 4500, 5000, AND 5500 METERS, COLUMN B: HISTOGRAMS OF HIGH LATITUDE ATLANTIC, BLUE: SOUTHERN OCEAN, ORANGE: NORTH ATLANTIC

Consider the above figure with tracer values at each of several depths along 25W between 68S and 55N for each of the three tracers in column A and histograms of these tracer values in column B. In each case, the figures in column A, show fairly consistent values through the water column below 3000m at high latitudes, but show a departure in the mid latitudes where the upper part of the water column (above 3500m) looks like the North Atlantic and the bottom part of the water column (below 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.

T-test p-values (p = 0 in all cases) confirm what we might draw by inspection: these water masses are distinct regardless of which of these three tracers is being considered. This is highlighted in the plots on the left (in tracer - latitude space) where lines converge to one value in the north and to a different value in the the south.

Q2: How far does Southern Ocean source water extend?

Two end-member mixing models

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

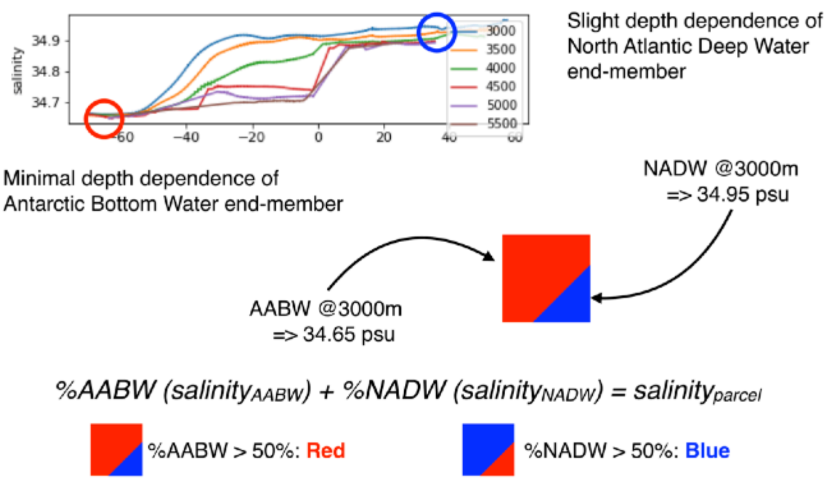

FIGURE 7: SCHEMATIC OF TWO END-MEMBER MIXING MODEL

Applying the two end-member mixing model to the Atlantic

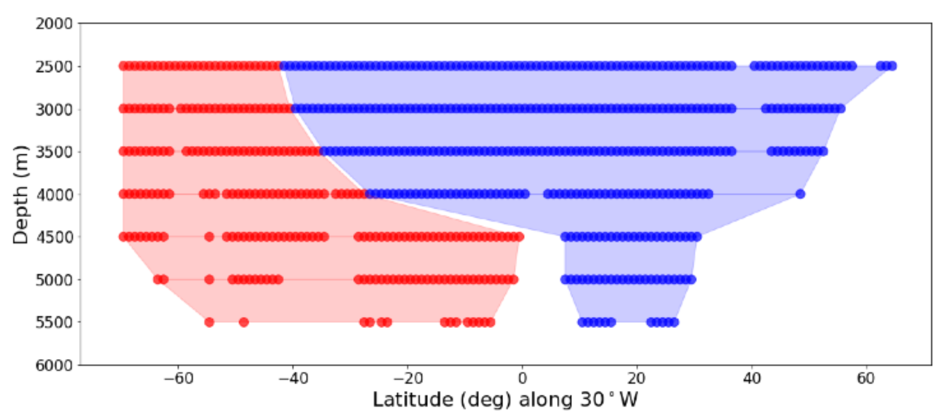

FIGURE 8: TWO END-MEMBER MIXING MODEL LABELLING POINTS ALONG 30W. RED: S SOURCE WATER, BLUE: N SOURCE WATER

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 endmember value. In keeping with the approach described above, this plot 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.

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.

Q3: Can we trace water formation statistically?

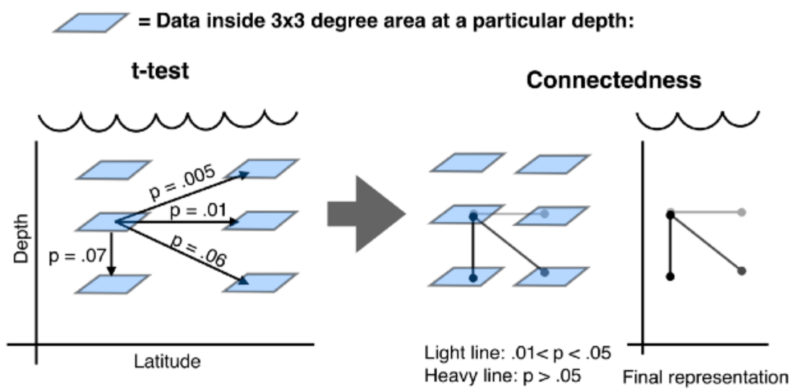

FIGURE 9: SCHEMATIC FOR CONNECTIVITY USING A T-TEST

Connectedness using t-test

Consider two columns of water 3 degrees x 3 degrees. Data within these column by depth, then 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 them 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

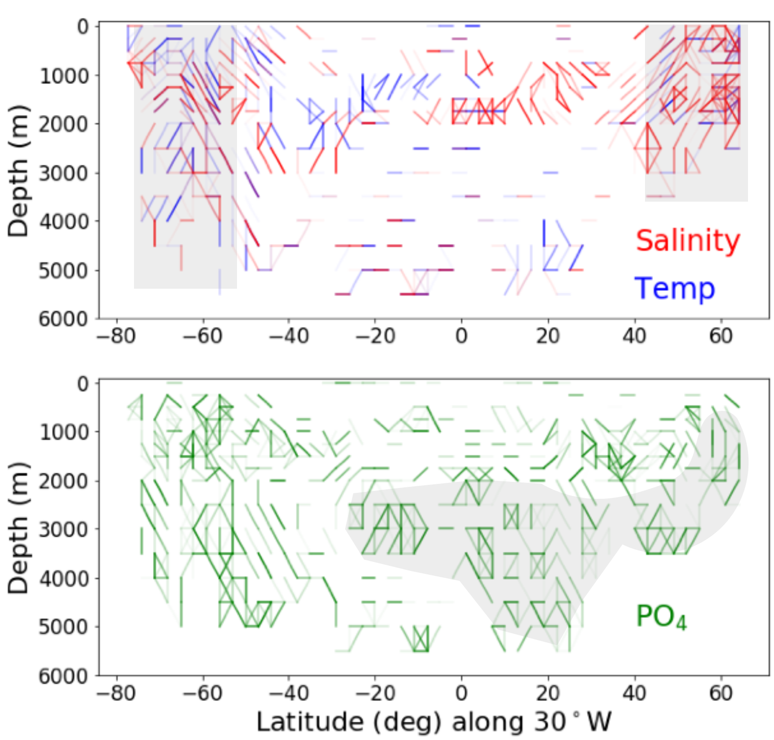

FIGURE 10: APPLICATION OF CONNECTIVITY TO DATA ALONG 30W (TOP) SALINITY AND TEMPERATURE AND (BOTTOM) PHOSPHATE

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 relatively well organized. Though there are features left to be parsed in a future study, we do observe more temperature and salinity vertical connectivity at the highest latitudes where we would expect to see more vertical homogeneity due to water formation, and deep water horizontal connectivity in mid and low latitudes where we would 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 is 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), and 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 plot, 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?
What areas are classified differently depending on the combination of tracers used?
Are those differences interpretable?

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

To understand the contribution by a given process, we need to know how much change is due to mixing; if we use a one dimensional mixing model for salinity and then repeat the process for phosphate, can we use the difference between them to characterize the change in phosphate due to phosphate uptake and regeneration?

References

Figure References:

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