Understanding the Interior Flow of the Ocean at Different Densities

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Introduction

Ocean currents are important to life on Earth. Ocean currents regulate temperatures throughout the planet, influence human migration and trade, and sustain marine life. On the surface, currents are driven by surface winds (Figure 1). At the bottom of the ocean, currents are driven by thermohaline circulation: the change in temperature and salinity in the lower ocean (Figure 2). In each of these cases, we understand the influence of external forces: atmospheric wind and drag from the ocean floor. However, the interior of the ocean has no external forces. Thus, because the flow is not driven by external forces, we would like to explore the movement of the ocean in the interior.

Although understanding the circulation of water at the surface and at the bottom of the ocean is important, it raises an important question: "What do currents look like in the interior of the ocean?" In this report we will explore how the velocity of water changes in different densities. First, we will perform a tank experiment, modeling the density difference in the ocean using a two layer model. Then, we will use EsGlobe to understand the change of velocity in the interior of the ocean.

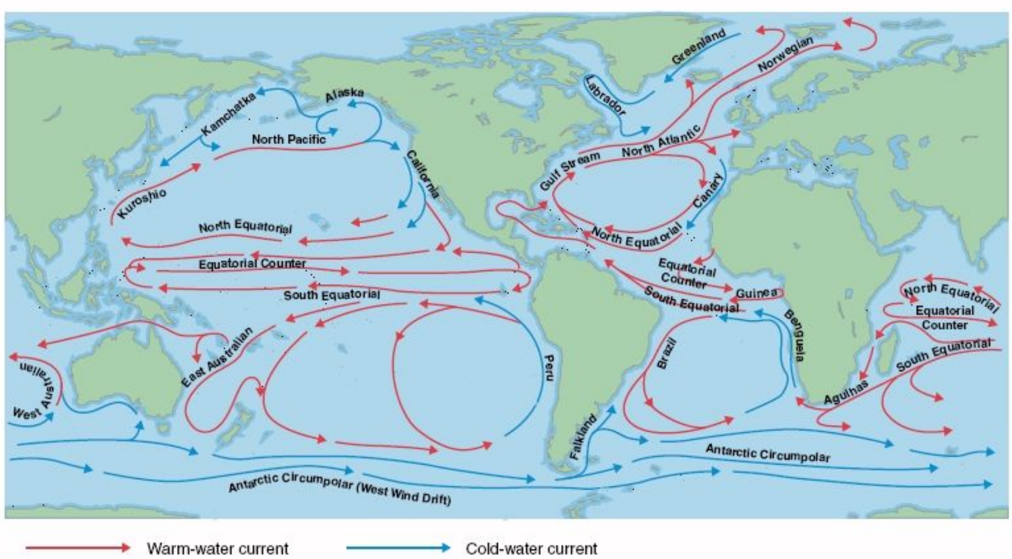

Figure 1: Map of Surface Ocean Currents. Courtesy of Satellite Applications for Geoscience Education.

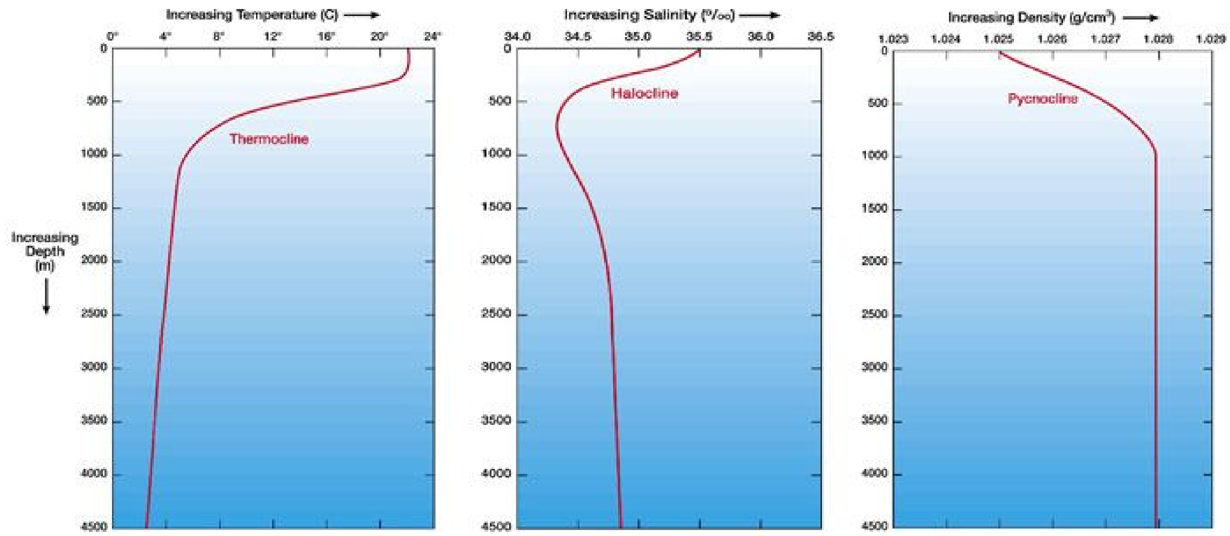

Figure 2: Diagram of Thermocline, Halocline, and Pycnocline with Increasing Depth. Courtesy of Windows to the Universe.

Tank Experiment Set Up

We set up a tank on a rotating table with two fans on opposite sides of the tank (Figure 3). We set up the fans to blow clockwise. We filled half the tank with freshwater. Then, we created a salt water mixture which had about 10% salinity and dyed the salt water orange. We used a funnel connected to a diffuser to slowly filter salt water underneath the freshwater (Figure 4). As we filled the funnel with our salt water mixture, the second layer of our system began to form. The tank was then fresh water on top and salt water on the bottom (Figure 5).

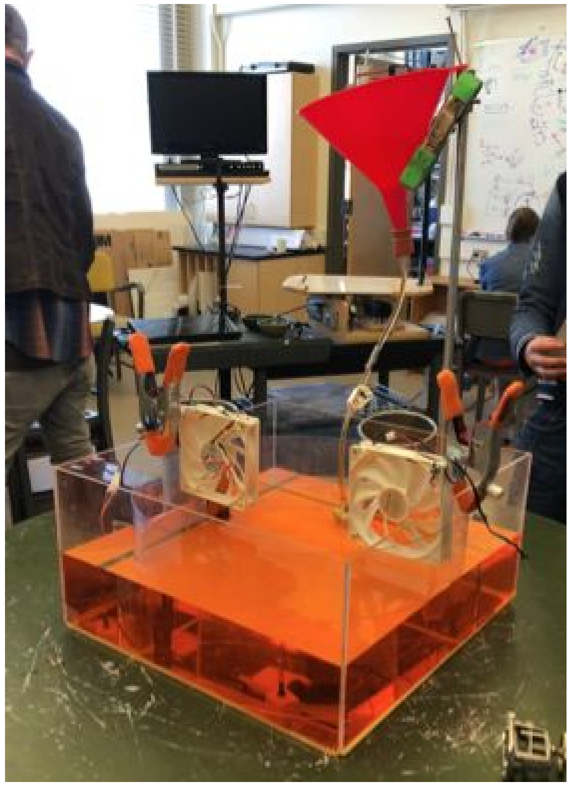

Figure 3: Set Up of the Tank Experiment. Two fans are set-up to blow anti-clockwise. In the background of the photo is the funnel connected to a diffuser.

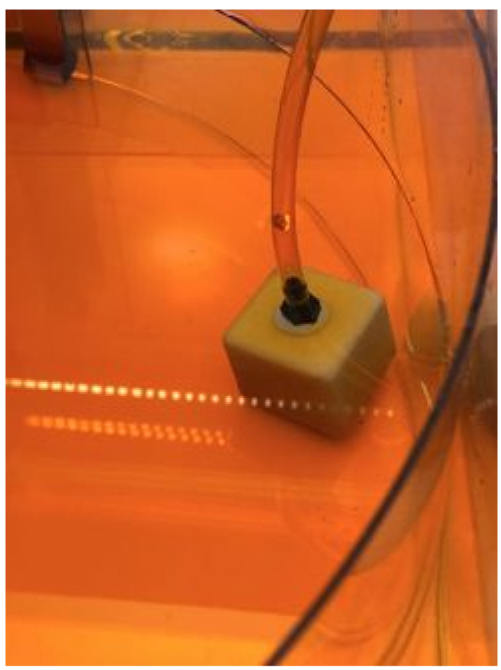

Figure 4: The Diffuser.

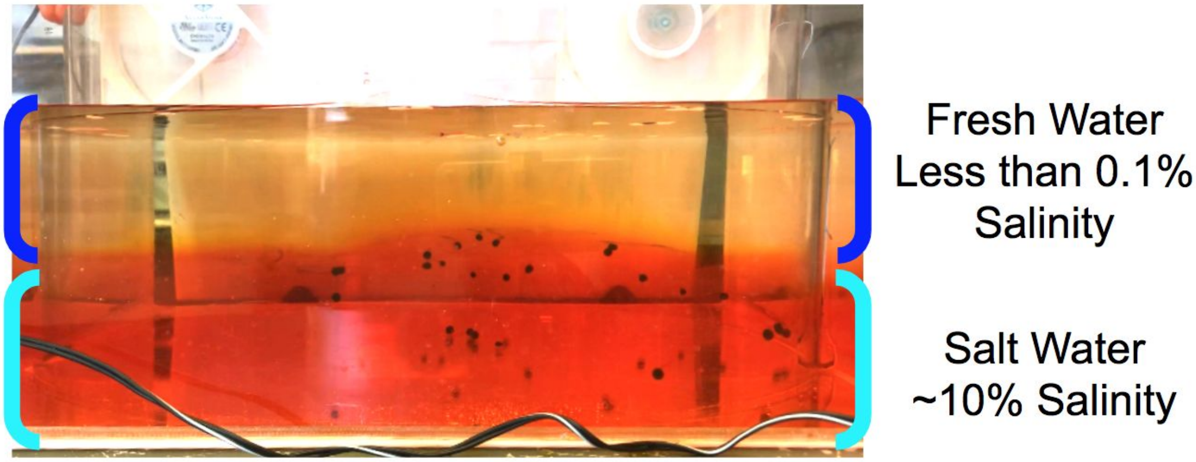

Figure 5: Side View of Tank. After the tank was half filled with salt water and half filled with fresh water, there was a clear division between the two layers due to the density difference.

Next, we slowly spun the table to solid body rotation, increasing the speed about 500 mF each time up to 1750 mF (8.5 rotations per minute). Once the system was in solid body rotation, we began the observations of the experiment. We suspended gelatin balls in the center of the tank and used a particle tracker to collect data.

Theory

To understand the geostrophic flow in the center, we begin with the equations for the azimuthal and radial momentum at the top and the bottom of the tank. From past experiments, we can express the flow at the surface using the following equations:

$$-2\Omega v_{\theta T} + g\frac{\partial h}{\partial r} = 0 \tag{1a}$$
$$2\Omega v_{rT} = F_{\theta} \tag{1b}$$

where Ω is the rotation rate, $v_{\theta T}$ is the azimuthal velocity at the top of the tank, g is the gravitational constant, $\frac{\partial h}{\partial r}$ is the slope of the free surface, v_{rT} is the radial velocity, and F_{θ} is the force of the fans blowing at the surface of the tank.

And at the bottom of the tank:

$$-2\Omega v_{\theta B} + g\frac{\partial h}{\partial r} = -\varepsilon v_{rB} \tag{2a}$$
$$2\Omega v_{rB} = -\varepsilon v_{\theta B} \tag{2b}$$

Where $v_{\theta B}$ is the azimuthal velocity at the bottom of the tank, ε is the drag coefficient, and v_{rB} is the radial velocity at the bottom of the tank.

We must adjust these equations to be able to understand the geostrophic flow in the interior. Because there is no forcing or drag, the right hand side of Equations 2a and 2b are both zero.

$$-2\Omega v_{\theta I} + g\frac{\partial h}{\partial r} = 0 \qquad (3a)$$

$$2\Omega v_{rI} = 0 \qquad (3b)$$

Equations 3a and 3b are useful for a homogeneous fluid. However, our experiment involves two layers (Figure 6). Thus, we must consider the influence of density on the velocity of the fluid.

We are able to measure the interior azimuthal velocity of the salt layer by tracking particles. In addition, we would like to measure the interior azimuthal velocity of the freshwater. We can derive a relationship between the flow at different levels.

$$2\Omega(u_t - u_b) = g'tan\gamma \qquad (4)$$

Where u_t is the velocity in the top layer, u_b is the velocity in the lower layer, and γ is the angle of the paraboloid at different radii. In addition, $g' = \frac{\Delta\rho}{\rho}$.

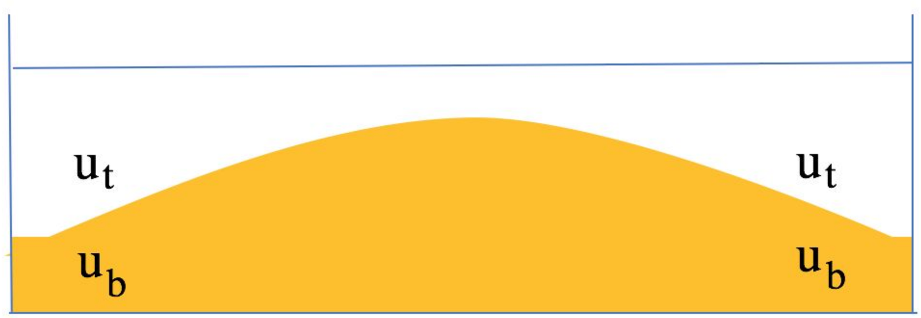

Figure 6: Diagram of Cyclonic Tank with Different Interior Velocities Labeled. Orange represents the salt water layer and white represents the freshwater layer.

Tank Results

In the tank, as the angle of the interface between the salt and freshwater decreased, the difference between the azimuthal flow in the top and bottom decreased.

To calculate the azimuthal velocity of the interior of the salty layer, $v_{\theta I}$, we tracked particles to observe the distance covered over a set period of time. Our table was rotating at 8.5 rotations per minute, which means that $\Omega = 0.89$. Then, we solved for u_t using Equation 4:

$$u_t = g' tan\gamma \frac{1}{2\Omega} + u_b \tag{5}$$

Finally, with Equation 5, we compared the experimental azimuthal flow at the top of the tank to the calculated azimuthal flow (Figure 7).

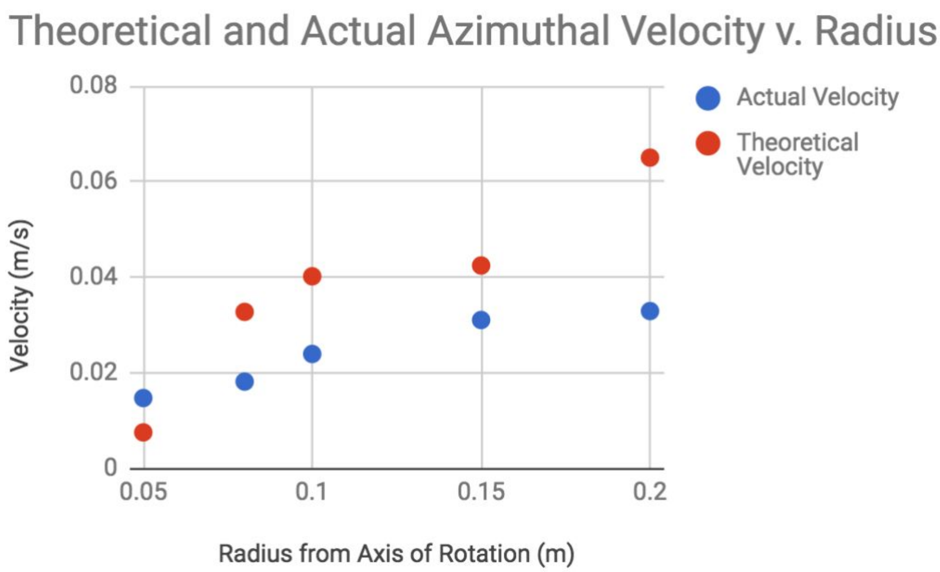

Figure 7: Chart Comparing Theoretical and Actual Azimuthal Velocity.

Overall, the speed of the upper flow is larger than the bottom flow. The velocity of both flows decreases as the distance from the axis of rotation decreases. The larger velocities in the upper flow correlate with a steeper slope of the parabola in the center of the tank. On the edges of the tank, the boundary between saltwater and freshwater is steeper. Thus, a greater density gradient allows for a faster current to flow on the top layer. The same is true for the bottom layer just below the fresh and saltwater boundary.

The theoretical velocity tended to be higher than the calculated velocity. There may be a few factors that cause the discrepancy between the theoretical and actual values. First, because there is a layer of mixing between the salt water layer and the fresh water layer, the measurement of the angle of the interface may be different than what was measured. Another factor contributing to the difference is determining the experimental azimuthal speed from the paper dots at the surface and not balls floating in the interior.

Real World Application

Although our experiment was cyclonic direction, ocean gyres are anticyclones. Because of this type of circulation, we expect downwelling of freshwater in the center of the gyres. To correlate this with our tank experiment, we would flip our fans to blow wind clockwise and produce a downwelling effect (Figure 8).

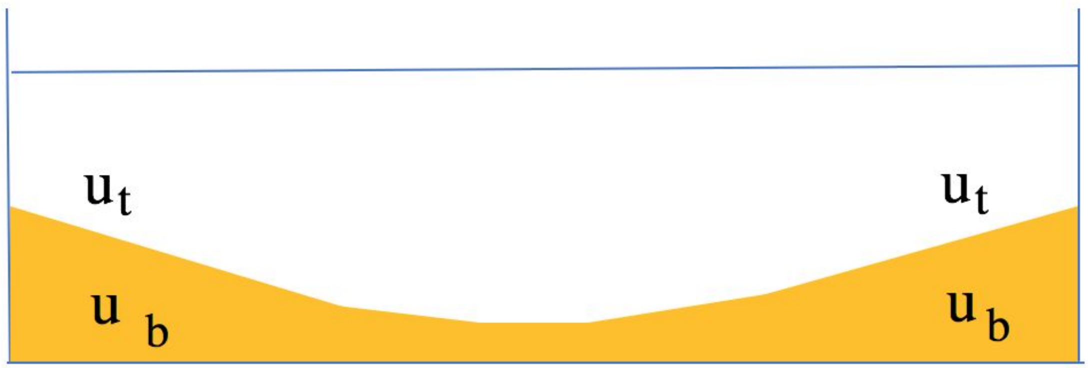

Figure 8: Diagram of Anti Cyclonic Tank with Different Interior Velocities Labeled. Orange represents the salt water layer and white represents the freshwater layer.

Particles released at 5 meters and 105 meters follow different paths in the ocean. When released at 5 meters, particles gather in the five main 'garbage patches' at the surface of the water (Figure 9a). When released at 105 meters, particles move away from where the surface gyres are (Figure 9b).

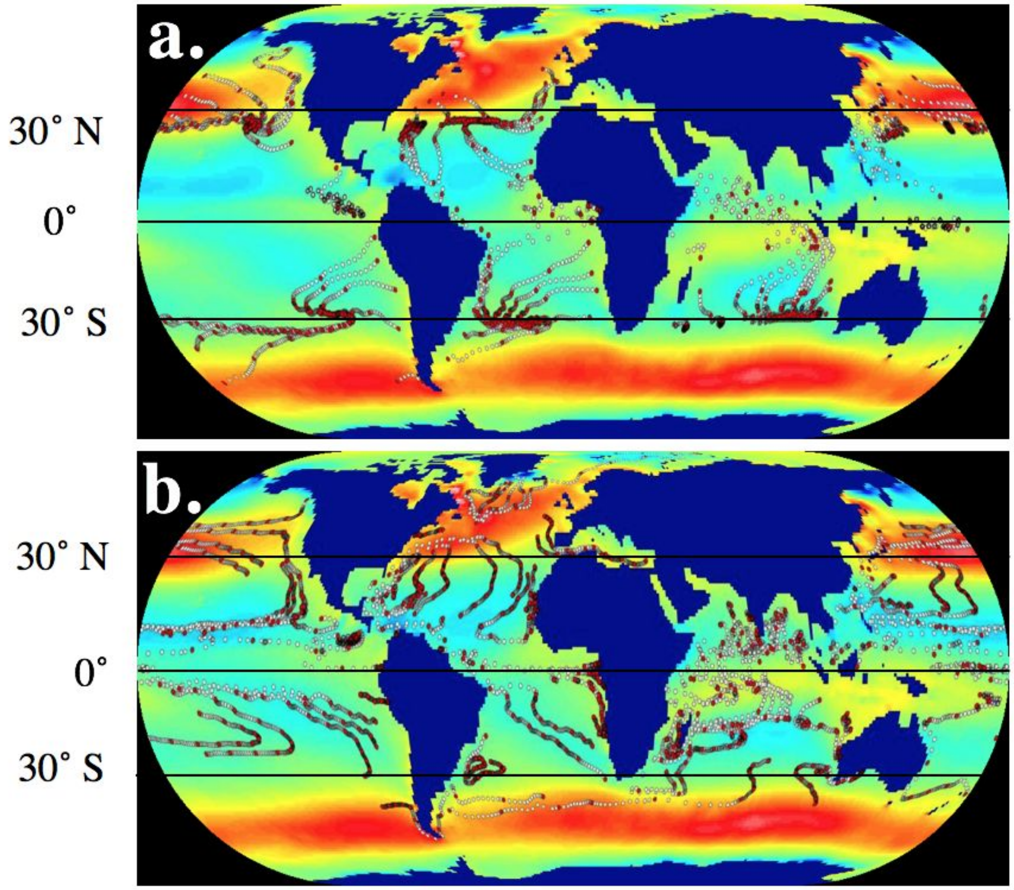

Figure 9 (a-b): Map of Particles Released Around the World. The colors on the ocean are the Eastward wind stress. Red represents Easterly wind and blue represents Westerly wind. Figure 9a are particles released at 5 meters and Figure 9b are particles released at 105 meters. The white dots are particles released at a depth of 5 meters. White dots are the movement of particles each month and red dots are the movement of the particles each year. This model was run over a time scale of 10 years.

There are large dips in lower density water at about 30˚ N and 30˚ S (Figure 10). These low density areas correlate with the approximate location of the main ocean gyres at 5 meter depth (Figure 9a). From our experiments, we know there is downwelling at the center of each of the ocean gyres. Thus, the dips in low density water can be associated with the downwelling.

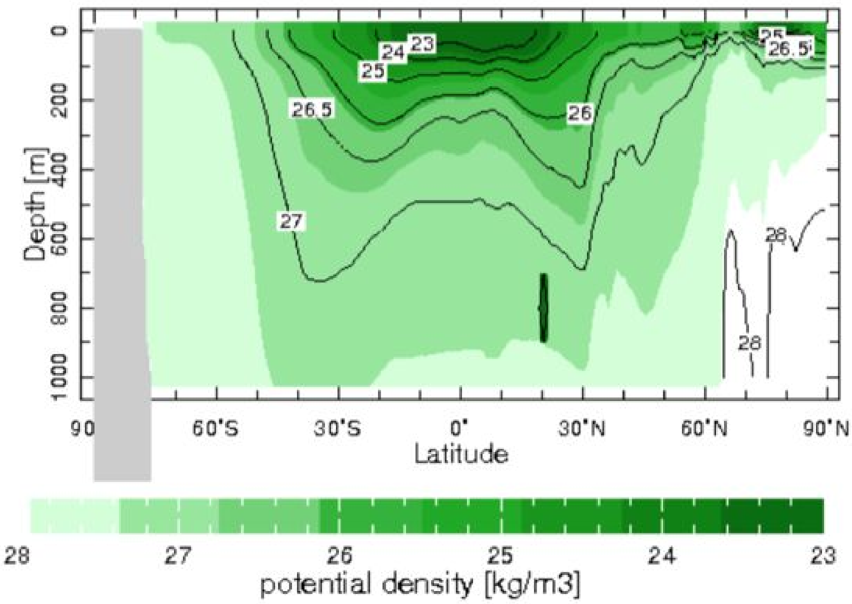

Figure 10: Cross Section of Zonal Average Potential Density Over top Kilometer. Courtesy of Marshall and Plumb.

Conclusion

Difference in density plays an important role in the flow of the interior of the ocean. As seen in our tank experiment and real world analysis, upwelling and downwelling influence the flow of the interior of the ocean between different density layers. By studying the interior flow of the ocean, we will be able to better understand ocean currents in the interior.

References

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