Introduction

The world ocean accounts for over 70% of the Earth's surface. Thus, the interactions between the ocean and atmosphere are very important in our endeavor to understand the climate system. The ocean contributes to meridional heat transport, allowing for mild temperatures throughout much of the world, making Earth a habitable planet. The obstacle that presents itself with the study of the ocean however is that its vastness and long timescales of motion make it difficult obtain observations of its processes. Luckily, through a combination of the observational data we do have, models, and equations, we can come up with strongly supported hypothesized circulation patterns, however further research and analysis is still required for a complete understanding of the ocean.

For this report I will start off by introducing and summarizing the Ekman transport process, which relates wind stress and vertical velocities in the ocean surface layer as discussed in the previous laboratory exercise. Moving down into the thermocline, I will then discuss how the Ekman process influences the wind-driven circulation patterns and the flow of the interior ocean layer. Finally, analysis of the abyssal circulation will be introduced in order to collectively report a holistic view of how the ocean layers interact.

Theory

Wind stress exerted on the ocean surface is transferred to greater depths through friction and turbulence. The transfer of momentum is responsible for what is known as Ekman suction and pumping. The relationship between wind stress and mass transport, $\vec{M}_{Ek}$, is shown in Equation 1[1]. This expression indicates mass transport of the Ekman layer is 90° to the right (left) of the surface wind in the northern (southern) hemisphere.

$$\vec{M}_{Ek} = \frac{\vec{\tau}_{wind} \times \hat{z}}{f} \qquad \text{Equation 1}$$

Vertical motion is a result of transport and conservation of mass within the Ekman layer. These downward and upward vertical velocities are referred to as Ekman pumping/suction, corresponding to negative and positive values of w_{Ek}. As shown in Equation 2, Ekman pumping/suction is a function of mass transport and consequently wind stress. Thus, the pattern of w_{Ek} is largely determined by variations in τ.

$$w_{Ek} = \frac{1}{\rho_{ref}} \nabla_h \cdot \vec{M}_{Ek} \qquad \text{Equation 2}$$

Moving down into the thermocline, the basin's meridional flow responds to this w_{Ek} value through the Sverdrup balance. Beginning with the assertion that beneath the Ekman layer the flow is geostrophic and negating our previous assumption that the fluid is non-divergent, we can derive this balance relationship from the basic continuity and momentum equations. After some mathematical manipulations Equation 3 results:

$$\frac{-1}{f} \frac{\partial f}{\partial y} v_g + \frac{\partial w}{\partial z} = 0 \qquad \text{Equation 3}$$

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[1] For a more detailed derivation of mass transport within the Ekman layer see Marhsall and Plumb, 2008.

The change in f with y is known as beta (β) and is equivalent to $\frac{2\Omega}{a}\cos\phi$ with a being the radius of the Earth, and Φ the latitude. This accounts for the change in rotation rate between the equator and the poles.

The Sverdrup balance relates horizontal and vertical currents in the ocean. Equation 4 makes the relationship clear; a negative w_{Ek} value requires a negative v_g value to balance the flow.

$$\beta v_g = f\frac{\partial w}{\partial z} \qquad \text{Equation 4}$$

Therefore, focusing on the subtropical gyre in the northern hemisphere as an example, in this region of Ekman pumping there will be a corresponding south-ward meridional flow acting to balance the vertical forcing ($w_{Ek} < 0$). This results in an equator-ward current throughout the mid-latitude oceans at a rate of 0.01 m/s (obtained using global estimates of β, f, w_{Ek}, and assuming a thermocline depth of 1km). However, due to the conservation of mass requirement of the system, this equator-ward flow must be balanced by a return flow somewhere in the ocean basin. This requires the Sverdrup balance to break down at some point, and allow w_{Ek} and v_g to be of opposite signs. This occurs in what is known as the Western Boundary Current.

The western boundary current is simply the concentrated return flow of the basin-wide interior flow. It occurs along the western boundary of the ocean basins due to predominate wind patterns experienced over the latitudinal bands (easterlies in the tropics and westerlies in the mid-latitudes). Observed examples of this phenomenon include the Gulf Stream in the North Atlantic and the Kuroshio in the Pacific Ocean, off the coast of Japan.

Transitioning down into the abyssal ocean circulation where currents are much slower and changes occur on very long timescales, the Sverdrup balance remains in effect. The dominant deep ocean source in the northern hemisphere is the high latitudes of the North Atlantic Ocean. Cold temperatures, due to a strong release of heat by the ocean in high latitudes, cause the water to sink into the depths of the ocean, below the thermocline.

Again, remembering that the conservation on mass requires that this sinking mass of water be balanced by an equal upwelling of water, we can assume upwelling in another area of the ocean and assign a positive w_{Ek} value. Through the study of temperature and salinity profiles over the world's oceans, scientists have determined that the resulting upwelling that counteracts the deep-water formation in the North Atlantic actually is a widespread phenomenon, occurring over the entire ocean, and not just a local event.

Using the Sverdrup balance (refer to Equation 4) to determine the meridional motions of water in the deep ocean, it is evident that v_g must be a positive value, just as w_{Ek} is positive (upwelling) in the abyss. This results in a pole-ward movement of abyssal water- a direction towards the source. This may seem counterintuitive but the requirement of Taylor columns retaining their length confirms this pole-ward movement.

Once again, with this mass of abyssal water transported north, there must be a return current in order to maintain mass conservation. A western boundary current moving abyssal water southward along the western side of each ocean basin is the balancing force. While this current is difficult to measure directly, there is strong support of this theory from greenhouse gas distribution patterns.

Methodology

The rotating tank set up for the wind-driven circulation lab included the 16”x16” square tank along with the mesh grid (situated against the edge of the tank furthest from the camera pole) and an additional 16”x16” white board inserted on top of the mesh grid in order to create a sloping bottom. Two fans were clamped perpendicularly onto opposite sides of the tank to produce the correct wind stress.

A cyclonic circulation (fans circulate air in the direction of rotation) was established. The tank was filled with room-temperature water, to a level about ½ an inch below the bottom of the fans. The fans were organized to blow horizontally across the water surface, to prevent excessive ripples on the surface.

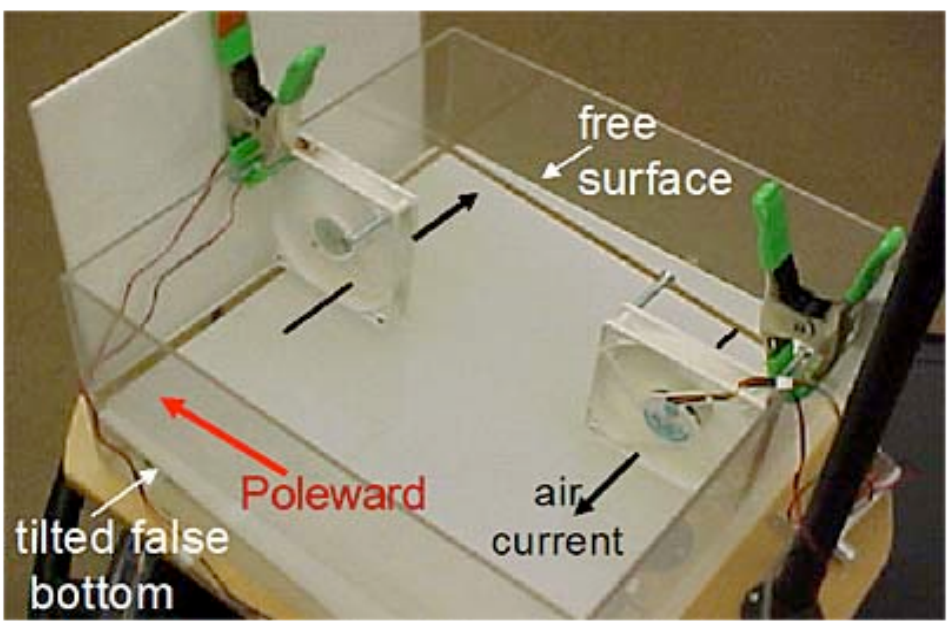

Figure 1: Tank set-up of wind-driven circulation lab

The tank was set to 10 rpm and left in motion until solid body rotation was achieved. Once in solid body rotation, dye was introduced to the tank. Assuming the shallow end of the tank represents the polar regions and the deep end the equatorial regions, the dye was added to the northeast and southwest corners of the tank. The speed of the flow on each edge of the tank was recorded by taking observations every 30 seconds for the first 2 minutes of the experiment. Other important variables to record include the height of the water at both the shallow and deep end of the tank and the speed of the wind (determined by holding a handheld anemometer in front of the fans). Video recordings of the multiple runs are also useful in tracking ongoing motions of the dye.

The tank set up for the thermohaline circulation lab included the 16"x16" square tank along with the tall, cylindrical tank inserted at one side. Inserting a smaller white sheet into the tank allows a sloping bottom to be created by abutting the white plastic sheet against the towering tank at an angle. Next, fill the tower about 80% full with room temperature water, then fill the square tank with water until the slanted bottom is covered by at least 2 inches in all areas.

A siphon arrangement is used to transfer water from the tower "source" tank to the square simulation tank. By attaching a diffuser to each end of a thin tube, and stringing it from one tank to the other (using a clamp at the top to secure it in place) we are able to slowly transfer water from one tank to the other. A control valve is attached to the tube as well to help control the speed of water being introduced. Before this siphon system will be ready to use it must be charged by filling the entire system with water and closing the valve so none can escape. This allows the water pressure above the siphon in the tower tank to force water to travel up the tube, over the tank's wall, and down into the simulation tank. If any air pockets remain before starting the experiment, it may not be effective.

Arrange the siphons so that one is near the bottom of the tower tank and the other sits in the top right corner of the simulation tank (assuming the tower tank is on the top or "north" side). The control valve should be easily accessible and clamped to the top of the tower. Finally, add dye to the water in the tower, stirring to create an even color.

Setting the rotation speed to be close to 10 rotations per minute, allow the tank to spin up for about 20 minutes before opening the valve and allowing the experiment to progress. Important observations include height of the water in the tower prior to beginning experiment as well as height at the completion of experiment, depth of the water at the shallow end of the tank as well as the deep end. The camera mounted on the rotating table will capture visual observations.

Results

The wind-driven lab was completed three times, each with a rotation rate between 10.1 and 10.5rpm. When dye was introduced into the northeast corner of the tank it did not disperse quickly and only after two to three minutes could you detect it moving down the eastern edge of the tank. The experiment was not run long enough for the dye to reach the bottom edge of the tank, however table 1 contains estimates of how long it took to reach the halfway point of the tank.

In contrast to this slow moving dye on the eastern edge of the tank, the dye added to the southwest corner of the tank quickly made its way up the western side and continued to circulate through the tank's interior with a very non-laminar flow. This is a representation of the western boundary current that acts as a return-flow for the southward interior flow of the subtropical gyre. The tank's eastern edge's slow-moving characteristic is a representation of the interior motions of the thermocline layer of the ocean.

Run	Time to reach half-way down the eastern edge	Time to travel the length of the western edge of the tank
1	2:51	0:36
2	2:33	0:20
3	2:58	0:33

Table 1: Observations of travel time from wind-driven tank experiment

When these time calculations are converted to velocity values the interior flow has an average velocity of -6.7 cm/min over the three runs. If instead of direct observations from this lab we were to use the W_{Ek} value estimated from the Ekman lab we did as a class (-1.25×10^{-4} m/sec), using the Sverdrup balance equation we would predict an interior flow moving southward at 8.33×10^{-4}m/sec, or about -5cm/min. This value is comparable to our estimates from visual observations, thus validating the experiment in regards to the Sverdrup balance equation.

The resulting western boundary current observed produces a much faster velocity, averaging 1.3cm/sec over the three runs. This allows for the system to keep up mass conservation despite having a much smaller area of northward flow.

For the thermohaline tank experiment calculations were recorded in reference to the amount of water added to the simulation tank during the duration of the experiment. This volume gained by the tank can be manipulated to give us a vertical velocity measurement for the pole-ward moving interior flow. Using the area of the simulation tank and the volume of water lost from the tower, simple mathematical computations will result in the number of centimeters that the free surface has risen during the duration of the experiment. For this lab, the water rose a total of 3.1 cm over 13 minutes, giving a vertical velocity, w, of 0.24 cm/min. The meridional velocity in the tank was estimated using the calculated w and α, which is the slope of the tank. The polar side of the tank was 6cm shallower than the deep end of the tank, resulting in a slope of 0.18. Dividing the vertical velocity by the slope, we find that the movement of the interior water of the tank is 1.6cm/sec- a positive number, meaning a mass transport towards the shallow end of the tank (northward).

The western boundary current in this experiment is clearly visible, transporting dyed water, first across the northern edge of the tank, and then towards the deep end of the tank at an estimated speed of nearly 17cm/min.

Discussion

The most important result from this lab was the conclusion that there is in fact a western boundary current in both the thermocline and the abyss, and they move much faster than the speed of the interior ocean flow, however, the two currents act in very different ways, actually transporting water in opposite directions.

Below is a chart comparing the calculated interior flow speeds and western boundary current velocities from the wind-driven circulation lab to real-world observed ocean velocities.

		Experimental	Real World
THERMOCLINE	Interior flow	0.1 cm/sec	1 cm/sec
	WBC	1.35 cm/sec	40 cm/sec

As shown above, our experimental values of the ocean's flow were much smaller than those observed in the real world, however the fact that the difference between the interior and WB current flows are an order of magnitude in each case shows that the experiment was consistent.

Less is known about the abyssal ocean due to its long time-scales and the difficulties in taking measurements at depths greater than 2km from the surface. Much of the current knowledge has been based on the comparison of theoretical equations to the few collections of observations that have been made. One fantastic source of information is the tracking of chlorofluorocarbons (CFCs) in the deep ocean. The equator-ward motion of the abyssal western boundary current is confirmed by measurements taken of CFC concentrations in the North Atlantic. Also substantiated from these observations is the theory that upwelling occurs over the entire ocean basin and not just in one localized area.

The higher concentrations in the North Atlantic show the primary area of uptake by the ocean. The extent of CFC traces on the western side of the basin is further than the progress made in the interior or eastern edge, thus tracing the southward flowing abyssal western boundary current.

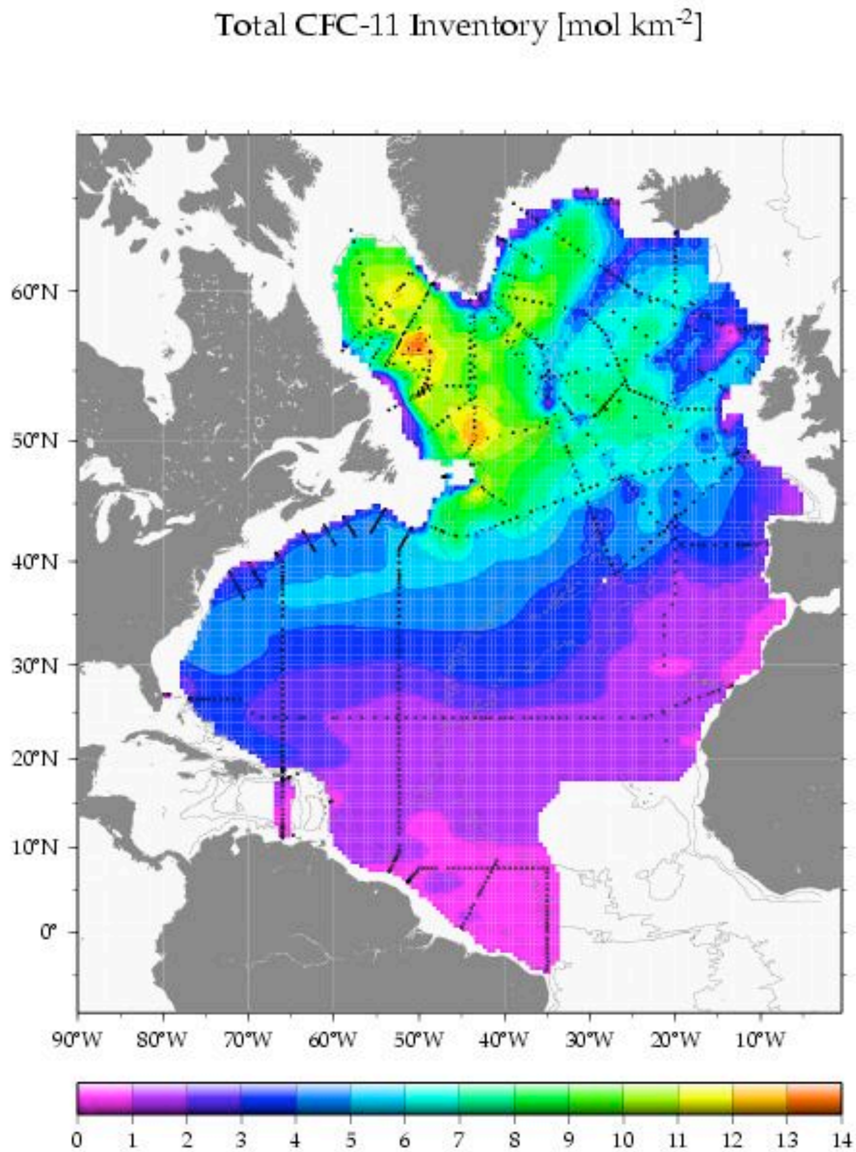

Figure 2: CFC concentration throughout the North Atlantic deep ocean
http://www.ocean.washington.edu/people/faculty/susanh/423/Graphics/CFC.NAtl.jpg

Conclusions

The Ekman layer of the ocean is influenced by atmospheric forcings, which ultimately impact various features of ocean surfaces as well as the layers below. The balance between the vertical and horizontal motions in the ocean layers prescribed by the Sverdrup balance, predict the direction of ocean flows. However, in both the thermocline and abyss a boundary current is necessary to maintain mass conservation requirements.

Data from the wet-lab experiments correspond well to observations available from global ocean research. The results indicate equator-ward interior motions in the midlatitudes of the thermocline and pole-ward motions in the higher latitudes. In the abyss, a global upwelling of deep ocean water corresponds to a pole-ward flow. The western boundary current of the thermocline counteracts the equator-ward motions with a quick return flow pole-ward on the western edge of the ocean basin while the abyss WBC flow in the opposite meridional direction, instituting a equator-ward return flow.

References:

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