Mixing a Stratified Fluid: Flux Laws and the Resulting Circulation

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This constitutes my final report for the Comer/OCCI project entitled “Mixing a Stratified Fluid: Flux Laws and the Resulting Circulation”

Deep ocean circulation has received relatively little attention compared to the upper circulation, which has been studied in hundred of research reports and numerous books. The knowledge of the deep component is required if we are to quantify the contribution of deep ocean circulation to Earth’s climate. For example, quantifying the heat flow rate of the overturning circulation is required for any prediction of future climate change. In addition, deep ocean circulation has important consequences to biological and chemical changes within the ocean, including sequestering of the atmospheric CO_2 by the deep ocean.

Deep circulation (below about 2 kilometers) has many features that are different from the circulation in the ocean above that level. First the deep circulation is very slow, with deep-water renewal in some locations estimated to take up to 1500 years. For comparison, circulation in the upper ocean is typically completed in between 1 to 10 years. Second, turbulent mixing within the deep regions helps to drive the deep flow. The mixing is driven predominantly by tides, whereas the circulation near the surface is predominantly wind-driven. We need to understand the dynamics of each of these circulations and ultimately to combine them into one unified view. This project is intended to give a clearer understanding of the dynamics of the deep overturning circulation alone.

In this project, a model of deep ocean circulation is produced in a rectangular laboratory tank. In the upper ocean, an equatorial region contains hot, lighter water, and a polar region contains cold, denser water at the surface. We designed our experiment to have this condition in the upper surface. A density change from salinity difference in the laboratory experiment substitutes for the density change from thermal difference in the ocean. In addition, the experiment has only one basin, with a tropical region at one end and a polar region at the other. In the apparatus, fresh water gently flows in at the top of one end of the rectangular tank, dense salt water enters at the other end, and an overflow in between removes the same amount of water. With no mechanical mixing, the salt water fills the entire tank except for a thin layer of fresh water at the top. Deep circulation in the tank is virtually zero. The unique aspect of this experiment compared to any other laboratory study to date is that we drive the circulation by adding a quantifiable mixer. A rod, extending from top to bottom of the tank, mixes by traveling back and forth at constant speed near the fresh water source. The turbulence from the wake of the rod mixes the deep salt water with the surface fresh water. The mixed layer deepens and spreads across the entire tank. At the end with salt water entering, we observe that a turbulent plume penetrates this deepened layer and it descends from the top to the bottom of the tank (visible in Figure 1). This corresponds to a deep overflow in the ocean, with the plume being the descending portion of the overturning circulation. The rising portion is spread over the entire tank. Therefore, this experiment shows that the turbulence directly produces the overturning circulation. It also clearly shows that part of that circulation is a descending plume, which possesses additional turbulence.

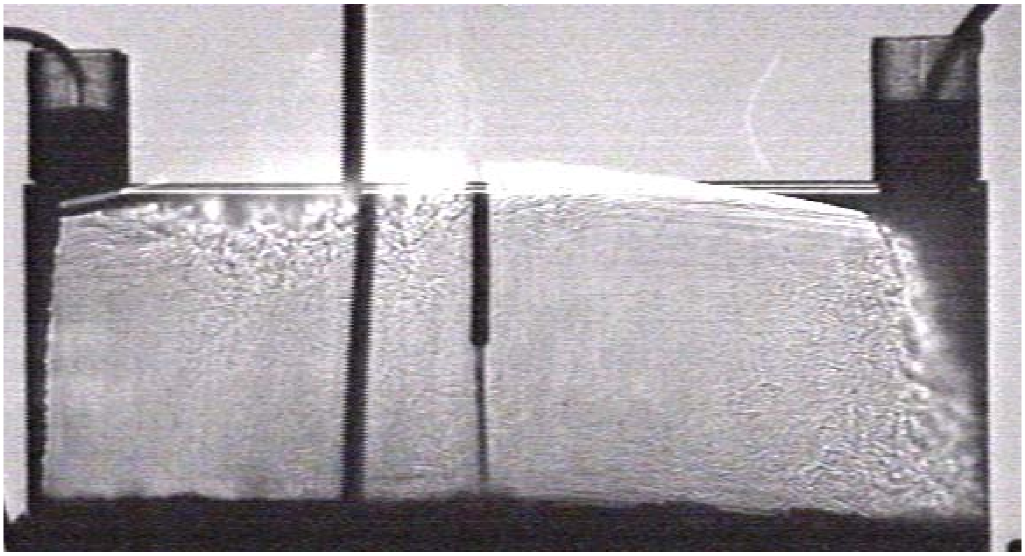

Figure 1. Shadowgraph of the experiment. Fresh water source is on the left and saltwater source is on the right. The drainage tube for the spillway is in the middle. The regions with turbulence exhibit scattered light. There are two such regions, one behind the rod toward the left and the other in the plume under the saltwater source on the right. The turbulent plume on the right corresponds to the sinking component of the deep ocean circulation.

The experiments are conducted over a wide range of parameters that determine the strength of the circulation. Only four governing parameters determine the speed of circulation and the time-averaged density field. These are rod velocity, rod diameter, the pumping rates, and the density difference between salt and fresh water. These parameters can be combined into two groups (technically called "dimensionless numbers") that completely determine the velocity of circulation and the variation of density with depth. The simplicity allows a development of a simple theory that has reasonable agreement with the data. This is gratifying since the turbulence that drives the flow is not simple to fully describe. It is possible to show that the rate of potential energy decrease by the sinking plume on the right of figure 1 is exactly equal to the rate of potential energy increase by the mixing that is shown on the left, which is in turn proportional to the rate of turbulent dissipation. Note that in the picture the light scattering seems to be about the same intensity in the left and right. The proportionality of potential energy decrease to dissipation rate for the deep ocean was unknown to my knowledge before this work and it is now reasonably well understood.

This simple equipartition principle does not necessarily apply to the <u>entire</u> ocean, but it seems to apply to the deeper ocean and to isolated basins where other energy sources (such as the work from surface wind stress) are negligible to the energy balance.

Results are published in

Whitehead, J. A. and W. Wang, 2008. A laboratory model of vertical ocean circulation driven by mixing, J. Physical Oceanogr. 38. 1091-1106.

Another experiment using the same apparatus and measurement instrument shows that turbulent mixing has a surprisingly simple consequence.

Results are published in
Whitehead, J. A. 2008, The similarity solution for turbulent mixing of two-layer stratified fluid, Environ. Fluid Mech. 8, 551-560. (open access)