

The Role of Eddies in Buoyancy Flux

by

Michael J. Ring

Submitted to the Department of Physics
and the Department of Earth, Atmospheric, and Planetary Sciences
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and

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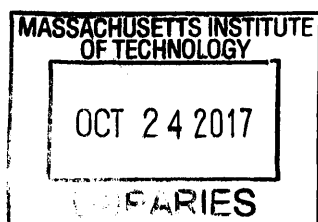
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**Michael J. Ring
June 2001**

Advisor: John C. Marshall

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Abstract

This thesis explores the role of eddies in determining the stratification of the ocean through a laboratory experiment. The experiment uses a dual-tank apparatus, with a smaller tank sitting inside the larger tank. Both tanks sit on a rotating turntable, which simulates the rotation of Earth. During the experiment, salty water is pumped from the outer tank through small holes in the base of the inner tank, which is initially filled with fresh water. The evolution of the dense fluid in the inner tank is observed, with particular regard to the number of eddies that form. These observations are checked against theoretical predictions, derived from analysis of buoyancy flux, for the number of eddies expected to form.

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Chapter 1

Introduction

Eddies play a crucial role in the dynamics of Earth's atmosphere and ocean through the transport of physical quantities such as heat, salinity, and buoyancy. Eddies form in response to unstable regimes in the atmosphere and ocean and seek to bring the fluids to a state of lower energy.

Eddies of myriad scales may be found in Earth's atmosphere and ocean. Atmospheric eddies range in size from the large storms spanning the mid-latitude and polar regions to tiny swirls of wind escaping from an open door or window. Similarly, oceanic eddies may mix parcels of water on the scale of hundreds of kilometers or hundreds of meters. The large-scale eddies in the atmosphere and ocean are dynamically analogous — eddies in both fluid bodies form in response to gradients of temperature, density, or another physical quantity, and in each case the eddies work to lessen the gradient of that quantity.

The potential role of eddies in setting the stratification of the atmosphere and the ocean is a subject of recent research. In the atmosphere, eddies may serve to set the height of the *tropopause*, the boundary between the troposphere and the stratosphere. Likewise, eddies in the ocean may play an important role in determining the depth of the *thermocline*, the region of the ocean where water temperature decreases sharply as a function of depth. Marshall et al. (2000) propose a role for eddies in setting the density stratification of the ocean, including determining the depth of the thermocline. Included in their experiment are laboratory trials with a rotating tank of fluid, on

the surface of which a heating pad is placed.

My motivation for this project is to explore further the role of eddies in setting the thermocline (or tropopause) by conducting laboratory simulations of Ekman pumping. The apparatus, which I helped design and manufacture, is a considerable advance, we believe, over that used in Marshall et al.

In Chapter 2, I discuss the physics involved in buoyancy flux and present a theory developed by Marshall et al. to explain the role of eddies as carriers of buoyancy flux. Chapter 3 details the design and construction of the apparatus, as well as the experimental procedure. Results are presented and discussed in Chapter 4, and suggestions for further research are given. I present conclusions and summarize the findings of the experiment in Chapter 5.

Chapter 2

Theory

One of the roles recently suggested for oceanic eddies is the setting of the thermocline. Similarly, atmospheric eddies may be involved in the setting of the tropopause. This chapter will discuss the thermocline and examine a theory suggested for the role of eddies in determining the thermocline's depth and stratification.

2.1 Ekman Pumping and the Thermocline

Figure 2-1 is a schematic diagram of the ocean's thermocline. The *thermocline* is the region where temperature varies strongly as a function of depth.

Stretching from the surface of the ocean to a depth of about 100 meters is a layer of roughly uniform temperature, known as the *mixed layer*. The thermocline is below the mixed layer, penetrating to about 1 kilometer. Below 1 kilometer, the ocean water reaches its fairly uniform abyssal temperature.

Water, warmed at the surface, is pumped down into the ocean by the action of the winds. The *Coriolis acceleration* deflects water into the center of gyres rotating clockwise in the subtropical oceans of the Northern Hemisphere. As the water accumulates in the center of the gyres, it is pumped downward through a mechanical process known as *Ekman pumping*. Ekman pumping and air-sea interactions result in the formation of a warm water lens extending downward from the surface of the ocean to create subtropical gyres.

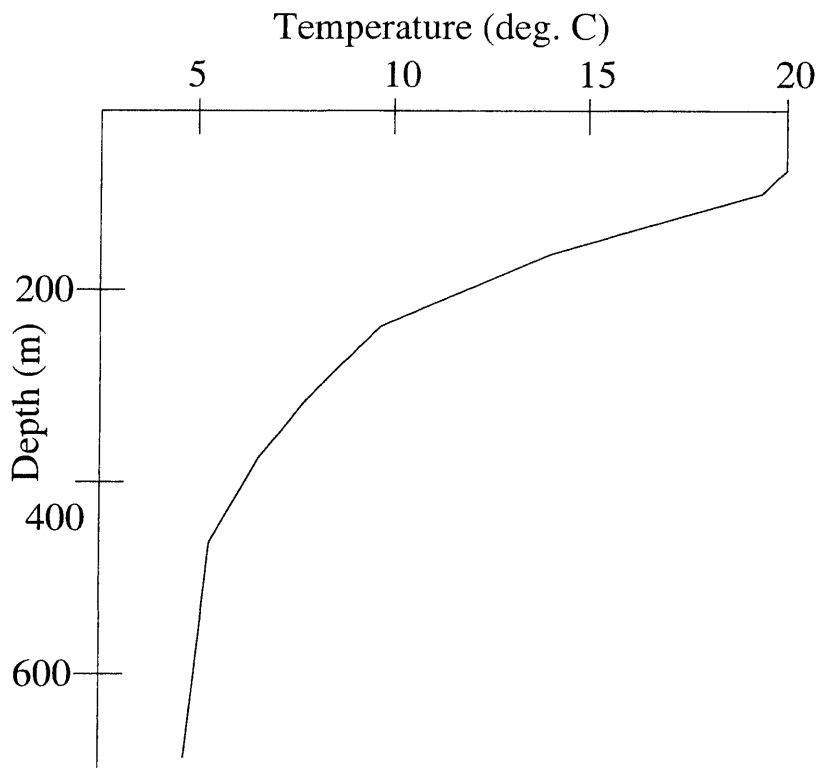


Figure 2-1: Schematic plot of ocean temperature versus depth.

However, it has already been observed that the temperature of the ocean is roughly constant beneath a depth of 1 kilometer. Why does the thermocline halt there, rather than extending, for example, to the bottom of the ocean? One idea is that the lateral transport of buoyancy by eddies stops the deepening of the thermocline. The lateral buoyancy flux carried by eddies balances the downward buoyancy flux from the surface, and the deepening of the thermocline is arrested. This is the idea that is investigated in the laboratory model.

2.2 Results of a Previous Pumping Experiment

Very little laboratory research has been conducted concerning the potential role of eddies in setting the height of the thermocline or tropopause. Most prior laboratory research focuses on fluid convection, which is not a process relevant to the experiment here.

However, Marshall et al. have proposed that eddies are responsible for transporting buoyancy flux laterally away from regions of Ekman pumping in the ocean, hence setting the height of the thermocline.

The authors examined the behavior of fluid heated from above. Their experimental design consisted of a rotating tank of diameter 1.15 meters, filled with fluid initially of uniform temperature. At the surface of the fluid was a disc, of diameter 1.10 meters, which rotated with a different angular velocity than that of the tank. A heating pad of diameter 30 centimeters was attached the bottom of, and insulated from, the rotating disc.

The rotating disc applied a torque to the underlying fluid, which in turn caused a vertical velocity in the fluid. Additionally, the heating pad warmed the water below it, producing a lens of warm-water fluid extending down from the surface of the tank. Through these processes, Marshall et al. simulated Ekman pumping in their laboratory apparatus. The authors recorded the temperature profile of the water with a vertical chain of thermistors extending into the water from the center of the heating pad. During their trials they varied the heating rate, rate of rotation of the tank,

Figure 2-2: A photograph from the laboratory trials of Marshall et al.

and rate of rotation of the disc. Figure 2-2 is a photograph of one of their laboratory trials (reproduced with the permission of the author) showing the presence of eddies in the fluid.

In all their trials, the authors observed that a lens of warm water would form under the heating disc. At first the lens would appear to grow stably, but after some time the lens would become unstable and eddies would be observed. In all the trials, Marshall et al. noted that the deepening of the warm fluid lens was stopped by the production of eddies.

The group also used numerical models to analyze the motion in the tank. Their numerical results also showed an arresting of the deepening of the lens, accompanied by the spawning of eddies transporting heat away from the center of the tank. Quantitatively, Marshall et al. found their results agreed with the equations presented below.

However, the design employed by the group did have some problematic aspects. In order to achieve the desired Ekman pumping, Marshall et al. needed both a me-

chanical and a thermal component. They found that use of the disc was needed to suppress edge effects which might have interfered with the development of the thermal lens. Use of the disc, however, introduced a moving component into the experiment, resulting in a more complicated apparatus.

The experimental design used in this paper seeks to improve on that described above, while demonstrating the same physics. Essentially, the design here flips that of Marshall et al. (and the pumping orientation in the ocean) upside-down. While Marshall et al. examined the formation of eddies caused by pumping warm water down from the surface of the fluid, this study analyzes the formation of eddies caused by pumping dense water up from the bottom of the fluid.

2.3 Buoyancy Fluxes and Balances

By investigating buoyancy balances and fluxes associated with a lens of fluid, we may derive expressions for the expected depth of the warm water lens and the number of eddies expected to form around a pumping region. These calculations are used by Marshall et al. to demonstrate their theory for the role of eddies in ocean stratification. Further discussion of the principles of buoyancy flux may be found in Visbeck et al. (1996).

In the center of ocean gyres, water converges and is pumped downward from the surface. Let us consider the buoyancy anomaly of this water. The lighter, accumulating water has density ρ_a , while the water in the surrounding environment has a density ρ_b . The water accumulating in the gyre has a buoyancy density anomaly Δb , where

$$\Delta b = g \frac{\rho_b - \rho_a}{\rho_a}. \quad (2.1)$$

Here $\Delta b > 0$, because the gyre is a warm water lens “floating” above denser abyssal water.

The Ekman pumping is responsible for the downward transport of this buoyancy anomaly. If the velocity of Ekman pumping is w_{ek} , then the rate of downward buoy-

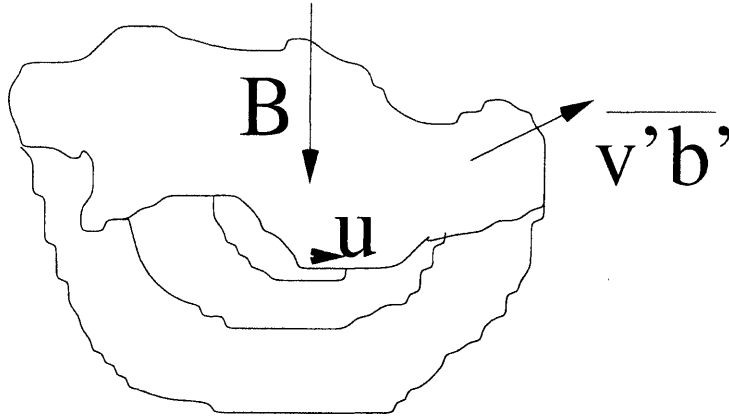


Figure 2-3: Buoyancy flux balance in the region of Ekman pumping.

buoyancy transport is simply the product of the pumping rate and buoyancy anomaly,

$$B = w_{ek} \Delta b, \quad (2.2)$$

Now consider a number of eddies which form around the side of the lens and transport buoyancy away from the region, as shown in Figure 2-3. If the eddies move with a lateral velocity v' and transport water of buoyancy anomaly b' , then the rate of buoyancy transport by the eddies B_{eddies} is simply the product of these two quantities,

$$B_{eddies} = \overline{v'b'}. \quad (2.3)$$

Now, we have an expression for the buoyancy transport down from the surface of the ocean, and for the transport laterally away from the region of Ekman pumping. If the pumping region is in equilibrium — that is, it is no longer deepening — then the buoyancy flux across the sides of the region must exactly balance the buoyancy flux from the surface of the water. Considering the downward transport over the cross-sectional area of the lens, and the lateral transport through the side of the region, yields

$$\iint B dA = \int_h^0 \oint \overline{v'b'} dl dz. \quad (2.4)$$

Integrating, we find

$$\pi r^2 B = 2\pi r h \overline{v'b'}, \quad (2.5)$$

where h is the depth of the lens.

This leaves for $\overline{v'b'}$,

$$\frac{rB}{2h} = \overline{v'b'}. \quad (2.6)$$

As we are assuming that eddies are responsible for the transfer of buoyancy away from the Ekman pumping column, we may also express the quantity $\overline{v'b'}$ in terms of an eddy transfer expression,

$$\overline{v'b'} = -K \frac{\Delta b}{r}, \quad (2.7)$$

where K is an eddy transfer coefficient equal to the product of the velocity of the eddies and their length scale, or $\overline{v'l'}$.

It seems reasonable to suppose that the eddy velocity v' is typically on the order of the mean flow u around the center of circulation. Additionally, we may assume the eddy transfer scale is set by the radius of the pumping region r . Then we may re-express our formula for K as

$$K = cur, \quad (2.8)$$

where c is a constant.

Combining the above,

$$\overline{v'b'} = cu\Delta b. \quad (2.9)$$

Next, consider the effects of the *thermal wind* relation on velocity. The thermal wind describes a vertical shear on fluids in the presence of a horizontal temperature gradient. The thermal wind relation may be written as:

$$\frac{\partial u}{\partial z} = \frac{1}{f} \frac{\partial \Delta b}{\partial r}. \quad (2.10)$$

where f , the *Coriolis parameter*, is equal to the product of twice the rate of rotation and the sine of the latitude.

Given this expression for thermal wind, we may obtain a scaling relation,

$$\frac{fu}{h} = \frac{\Delta b}{r} \quad (2.11)$$

relating the velocity u to other parameters in the problem.

2.4 The Depth of the Lens and the Number of Eddies

Now the pieces of our theory are complete, and we may determine the depth of the fluid lens — and hence the expected depth of the thermocline. Using Equation 2.9 and substituting for u from Equation 2.11, we find that

$$\overline{v'b'} = \frac{c(\Delta b)^2 h}{rf} \quad (2.12)$$

Next, from our buoyancy balance in Equation 2.5, we may write

$$B = \frac{2c(\Delta b)^2 h^2}{r^2 f} \quad (2.13)$$

Hence, the depth of the Ekman pumping region may be rewritten as

$$h^2 = \frac{BR^2 f}{2c(\Delta b)^2} \quad (2.14)$$

But from Equation 2.2, $\Delta b = B/w_{ek}$, so

$$h^2 = \frac{R^2 f}{2cB} w_{ek}^2. \quad (2.15)$$

Taking the square root, we arrive at our expression for the depth of the lens,

$$h = \left(\frac{f}{2cB}\right)^{\frac{1}{2}} w_{ek} R. \quad (2.16)$$

Using the expression for height just derived in Equation 2.16, we may also find an expression for the number of eddies expected to form in our tank. Let us assume that the *deformation radius* L_ρ of an eddy, or the length scale over which the eddy varies, is equal to $(\frac{h\Delta b}{f^2})^{1/2}$. The length scale between eddies is $2\pi L_\rho$. The total circumference of the pumping region is $2\pi R$. The number of eddies expected to form will simply be the circumference of the tank divided by the length scale of each eddy, or $\frac{R}{L_\rho}$.

The ratio $\frac{L_\rho^2}{R^2}$, which should be minimized to produce the maximum possible number of eddies, may be expressed as

$$\frac{L_\rho^2}{R^2} = \frac{h\Delta b}{Rf^2}. \quad (2.17)$$

Using Equation 2.14, we may express this ratio, up to a constant, as

$$\frac{L_\rho^2}{R^2} = \frac{1}{R} \left(\frac{B}{f^3}\right)^{\frac{1}{2}}. \quad (2.18)$$

But substituting for B , we find that

$$\frac{L_\rho^2}{R^2} = \frac{1}{R} \left(\frac{w_{ek}\Delta b}{f^3}\right)^{\frac{1}{2}}. \quad (2.19)$$

Equation 2.19 provides motivation for the design of the apparatus. w_{ek} , Δb , and f are all parameters which we may vary and directly measure in the experiment. In order to observe the maximum possible number of eddies, we seek to maximize the rate of rotation, minimize the buoyancy anomaly, and minimize the pumping rate.

Chapter 3

Experimental Design

3.1 Apparatus

The goal in designing the equipment was to produce an apparatus which would allow for the study of buoyancy flux but improve on the design used by Marshall et al. Much of the effort of this project was involved in the design and construction of the tanks.

In order to observe a large number of eddies in the tank, the design was motivated by the desire to produce as small a deformation radius as possible. In order to do so, following from Equation 2.17, one needs to maximize the radius of the pumping region and rate of rotation while minimizing the buoyancy.

The setup uses two tanks, connected by a pumping mechanism. A smaller, inner tank sits inside the larger, outer tank. The tanks sit together on a rotating turntable, which simulates the motion of Earth. When the pumping is started, dense water from the outer tank flows through tubes to the base of the inner tank, where it seeps into the inner tank through about two hundred small holes drilled in the base of the inner tank. Figures 3-1 and 3-2 are top and side views, respectively, of the dual-tank apparatus.

The outer tank measures 100 centimeters square, while the circular inner tank is of diameter 75 centimeters and sits on stilts. The outer tank is initially filled with denser water, while the inner tank is initially filled with fresh water. In these trials

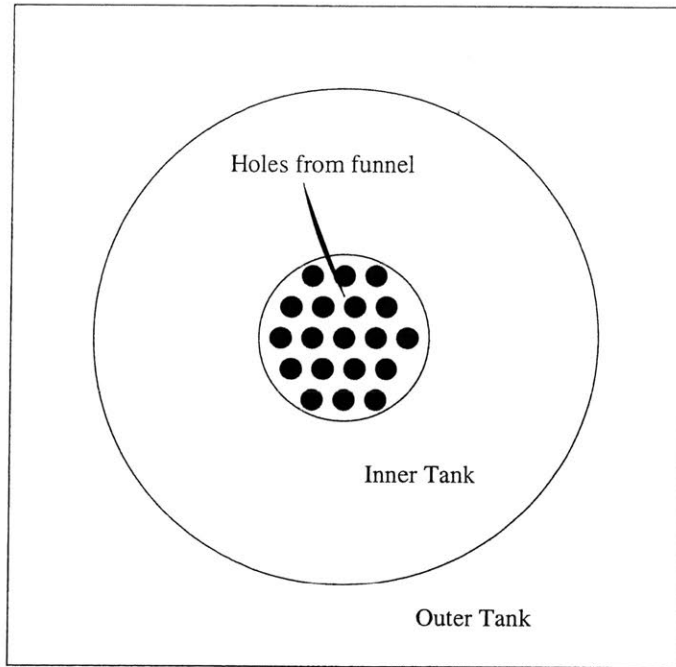


Figure 3-1: Top view of the apparatus.

the density difference between the fluids contained in the two tanks ranged from $\Delta\rho = 0.48 \frac{kg}{m^3}$ to $\Delta\rho = 1.94 \frac{kg}{m^3}$.

An adjustable-flow pump is used to allow for the study of the motions of the fluid at several different rates of pumping. Here the rates of pumping varied from $Q = 0.13 \frac{L}{s}$ to $Q=0.50 \frac{L}{s}$. The rate of pumping is measured with a flow meter, and dye is injected to mark the dense, pumped fluid. The fluid is then pumped to a funnel at the base of the inner tank. The funnel contains a mixture of pebbles and foam, which is designed to spread the fluid evenly over the entire width of the funnel and damp out any anomalous vertical motions.

About two hundred holes, each measuring $\frac{1}{4}$ inch in diameter, are drilled into the base of the inner tank. The diameter of this region is 25 centimeters. The apparatus uses many small holes rather than one large hole to simulate more accurately the fluid motion in the ocean. The interspersing of many small holes dampens vertical motions and prevents large fluxes of momentum from erupting through the surface of the tank. In order to observe eddies, a slow, steady vertical upwelling is desired, and

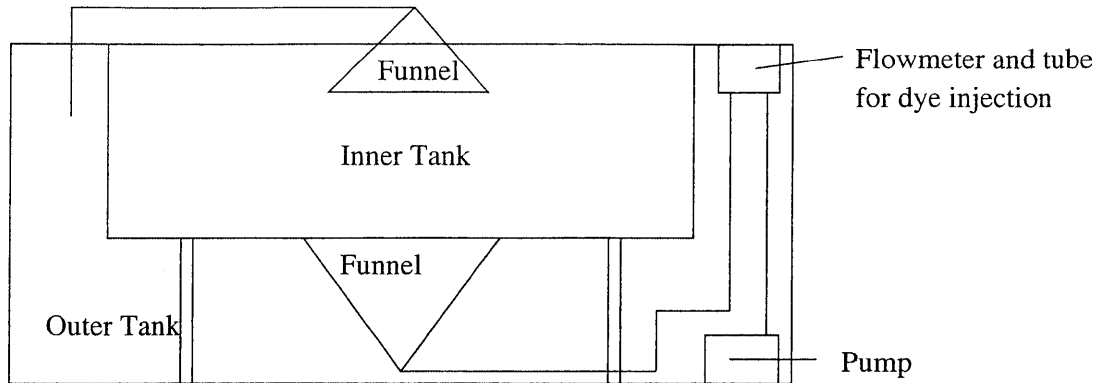


Figure 3-2: Side view of the apparatus.

permitting sudden jets of denser fluid to break into the inner tank may disrupt the formation of the lens.

A second funnel is placed just below the surface of the water of the inner tank. This funnel is attached to a tube terminating just below the water surface in the outer tank. The purpose of this second funnel is to maintain the level of water in the inner tank. After the tanks are filled, a suction is created in the funnel and tube to start flow through the tube. This suction is maintained throughout the trials, balancing water levels in the two tanks.

The tanks sit together on a rotating turntable, which could achieve rates of rotation between $f = 0 \text{ Hz}$ and $f = 4.000 \text{ Hz}$. Use of the turntable ensures that rotationally induced effects, which are important to fluid motions in the atmosphere and ocean, would be simulated in this laboratory experiment.

3.2 Procedure

To set up a trial, salt is added to buckets of water to achieve the desired buoyancy anomaly Δb . This salty water is then pumped into the exterior tank, while fresh water is pumped into the inner tank.

Once the tanks are filled, the rotating turntable is switched on and set turning anti-clockwise. The tanks are left rotating for several hours to allow the water to

reach co-rotation with the tank. Once co-rotation has been achieved, the pumping of salty water commences and the evolution of fluid in the inner tank is observed.

After several minutes of pumping, the salty water will reach the base of the inner tank and begin to seep through. Initially, the salty water should collect in a dome-shaped region above the holes drilled in the inner tank. As time progresses, however, eddies are expected to spawn from the dome and carry salty water away from the center of the inner tank and toward the edges.

Chapter 4

Results and Discussion

The evolution of the fluid in the tank qualitatively conforms to the theoretical behavior outlined in Chapter 2. Additionally, a quantitative analysis of the number of eddies in the tank reveals agreement between theory and experiment to better than an order of magnitude.

4.1 Evolution of the Fluid

The motion of the dense fluid was recorded through a series of photographs. The photographs presented here are from Trial 5 (see Table 4-1 below for initial parameters) and demonstrate the typical evolution of the dense water lens and eddies observed during the experiment.

Dense fluid entering the inner tank through the small holes drilled in the tank's base slowly accumulates at the base of the inner tank during the first few minutes of the experimental run, as seen in Figure 4-1. The mound of dense fluid continues to build in the region of Ekman pumping, as seen in Figure 4-2.

However, eddies are observed to form in the inner tank after about 10-15 minutes. At this time the mound of dense fluid reaches its maximum height, and is not observed to grow any further. Figure 4-3 shows a trial in which five eddies formed. The eddies carry fluid toward the exterior of the tank, as seen clearly in Figure 4-4. After about 25-35 minutes, dense fluid has completely spread across the base of the inner tank.

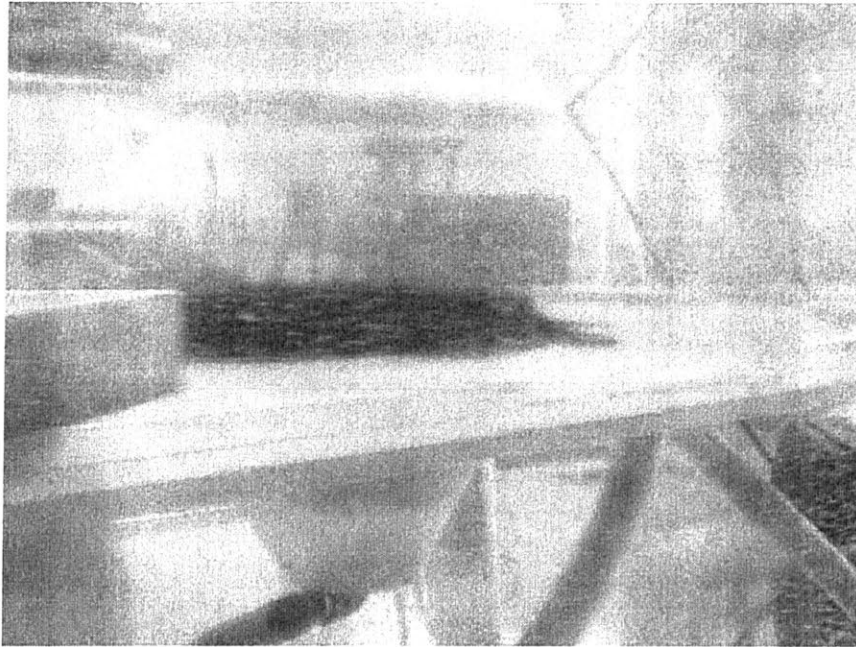


Figure 4-1: Dense water seeps through the holes in the base of the inner tank.



Figure 4-2: A mound of dense fluid builds over the region of Ekman pumping.

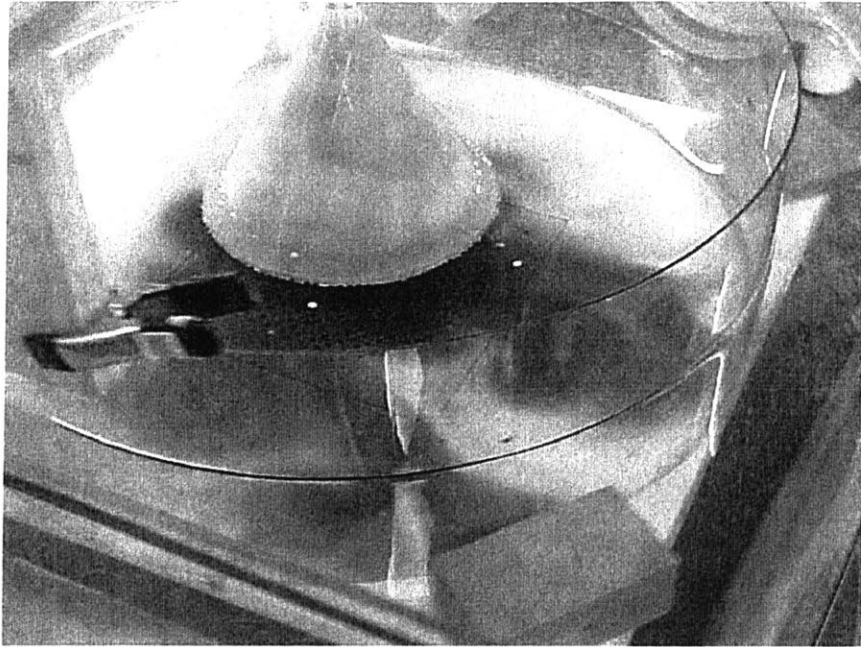


Figure 4-3: A trial in which five eddies are observed to form.

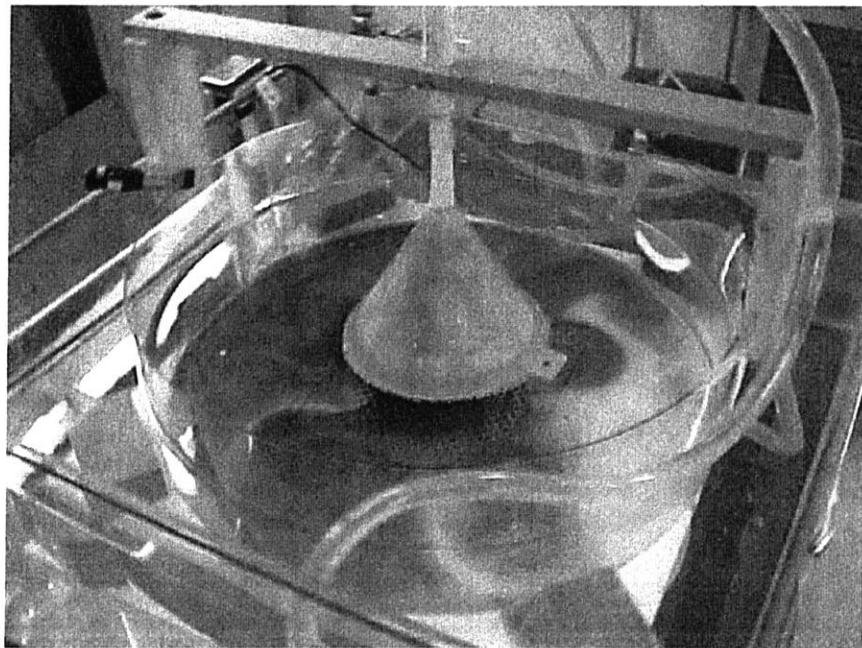


Figure 4-4: Eddies spreading the dense fluid across the base of the inner tank.

4.2 Prediction of the Number of Eddies

The theory presented in Chapter 2 may be used to predict the number of eddies expected during each laboratory trial. This prediction is then compared to the actual number of eddies observed. The results from this experiment show that the observed number of eddies is better than within an order of magnitude of the predicted values.

Equation 2.16 states that, to within a constant, the height of the lens is

$$h = \left(\frac{f}{B}\right)^{\frac{1}{2}} w_{ek} R. \quad (4.1)$$

For now let us consider the constant to be 1, in order to assess the scaling.

Using Equation 2.2, Equation 2.16 may be rewritten as

$$h = \left(\frac{f w_{ek}}{\Delta b}\right)^{\frac{1}{2}} R. \quad (4.2)$$

If we substitute this expression into Equation 2.17, we find in Equation 2.19 that

$$\frac{L_{\rho}^2}{R^2} = \frac{1}{R} \left(\frac{w_{ek} \Delta b}{f^3}\right)^{\frac{1}{2}}. \quad (4.3)$$

The parameters selected for the eight trials conducted in this experiment are now used to predict the number of eddies that should be observed for each. Below is a table of the values selected for density difference, rotation rate, and pumping rate in each trial. I have excluded values from trials 1, 2, and 3 since those trials were hampered by mechanical difficulties.

Trial Number	f(Hz)	Density Difference($\frac{kg}{m^3}$)	Pumping Rate($\frac{L}{s}$)
4	2.000	1.94	0.20
5	2.000	1.94	0.13
6	2.000	0.97	0.50
7	2.000	0.97	0.36
8	2.000	0.48	0.22

Table 4-1. Values of rotation, density difference, and pumping rate for each trial.

Knowing that the Ekman pumping region is of radius .125 meters and that the

Ekman flow rate w_{ek} is Q/A , w_{ek} may be calculated. Additionally, from Equation 2.1, the density differences may be used to calculate Δb . With these figures, the calculation of the ratio between the radius of the lens and the deformation radius follows from Equation 4.3, and hence the number of eddies expected in each trial is determined. The predictions of Equation 4.3 for the number of eddies in each trial based on the initial parameters in Table 4-1 are listed below in Table 4-2. Additionally, I display the number of eddies actually observed in each trial.

Trial Number	Observed Number of Eddies	Predicted Number of Eddies
4	4	6
5	5	7
6	5	6
7	6	7
8	7	9

Table 4-2. Observed and predicted number of eddies for each trial.

These results for the number of eddies from each trial are better than within an order of magnitude of the expected results from each trial. In fact, for each trial the number of observed eddies is slightly fewer than the number of predicted eddies. From inspection of the results above, the value of the constant $(1/2c)^{1/2}$ neglected in Equation 2.16 in order to examine the order of magnitude may be on the order of 1.2 – 1.5. Additional experimental trials would be most helpful in determining an exact value for the constant.

Another quick check of the theory presented by Marshall et al. is to estimate the height of the lens that should be observed from Equation 4.2. For the parameters used in this trial, Equation 4.2 predicts lens heights of between 5 and 20 centimeters, depending on the initial parameters. This is the correct scale observed in the experiment — lens heights in the tank were typically on the order of 10-15 centimeters.

4.3 Suggestions for Further Research

While I was able to demonstrate qualitatively the formation of eddies in response to Ekman pumping and obtained some quantitative evidence supporting the buoyancy theories outlined in Chapter 2, my experience here leaves several intriguing questions for future research with this apparatus.

Further quantitative analysis is limited by the inability to obtain temperature and salinity data from the experiment. I have obtained a temperature and salinity probe but have been repeatedly unable to get the probe to communicate with its software. Ideally, the probe would have been available to sample the temperature and salinity of water at several points in the tank. This information would have given a more complete, quantitative picture of the fluid evolution inside the tank. With knowledge of the change in temperature and salinity at selected positions around the tank, it would have been possible to profile quantitatively the flow of denser fluid to the exterior of the tank through the actions of eddies. Information of these probes would allow an accurate estimation of lateral velocity and buoyancy flux.

Another potentially fruitful area for further research is the examination of fluid evolution at extremely low pumping rates. During this experiment the pumping rate was found to be an important factor in whether eddies would be observed in the tank. At pumping rates greater than $0.5 \frac{L}{min}$, the fluid was found not to seep slowly through the holes in the tank but rather to burst through. These undesirable eruptions may create disturbances in the fluid surrounding and disrupt the slow, stable evolution which is of interest to us. Examining the evolution of the fluid for pumping rates Q of hundredth of cubic meters per second (compared to the rates on the order of tenths of cubic meters per second used here) is another suggestion for future research.

Finally, a third suggestion for future inquiry is to start with a stratified fluid in the inner tank. For simplicity here we used initially unstratified fluid in the inner tank. While the density of fluid in the ocean does not vary greatly with depth, consideration of density variations at different heights is absolutely critical to understanding the dynamics of Earth's atmosphere.

Chapter 5

Conclusions

A rotating tank apparatus is used to investigate the potential role of eddies in setting the depth of the thermocline in the ocean (or, similarly, the height of the tropopause in the atmosphere).

Ekman pumping in the ocean is simulated by pumping dense water through the base of the inner tank. At first, the dense water accumulates in a lens-shaped formation above the holes in the inner tank. However, the growth of the lens does not continue throughout the trials. Instead, the growth is arrested and eddies are observed to spawn from the dome of salty water. The number of eddies which form vary with parameters such as rotation rate and buoyancy.

The number of eddies observed to form during the trials is of the correct order of magnitude suggested by theory. Further, the difference between the number of eddies predicted and observed suggests a value for a constant relating the height of the lens to the buoyancy flux, rotation rate, and Ekman pumping rate from Equation 2.16.

Further quantitative analysis is hindered by the inability to set up a functioning temperature and salinity probe. Data gathered from this probe would aid greatly in exploring fluid motion within the eddies. Still, the presence of the eddies and the number in which they form appear to be consistent with the theory in Chapter 2, suggesting that eddies may play an important role in setting the stratification of the ocean (and the atmosphere).

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