Experimental investigation of theory for stratified ocean convection

Chris Sonekan

1 Introduction

The ocean forms over seventy percent of the surface area of the earth. It is endowed with rich marine life of immense biological diversity and other interesting phenomena. Just as the atmosphere is inextricably linked to the oceans, so also man and his activities are connected with the oceans in a sort of symbiotic relationship. The teeming biological diversity and water have supplied some of the resources needed for the survival of man. On the other hand, the activities of man produce nutrients and minerals required by marine organisms lower on the food chain. Oceans also have a kind of thermostatic control on climate as they absorb and release water and carbon dioxide, as well as other gases.

However, not all characteristic features of the ocean are well understood. Between the warm well-mixed surface layer and the cold waters of the main body of the ocean is the thermocline, the zone within which temperature decreases markedly with depth [1]. The density of the oceans is dependent mainly on pressure, temperature, and salinity. The ocean has a unique density structure. The density field varies significantly in all three spatial directions, with the largest variations occurring in the upper two kilometers. This suggests stratification of density and other properties. A complete dynamical theory should explain and predict the three-dimensional variation of the density and velocity field. “This is the problem of the thermocline. It is non-linear and difficult" [2]. In addition to this, “the three-dimensional structure of the oceans is complex and very poorly understood" [1]. Moreover, Michael McIntyre [3] makes a similar comment, “ocean circulation - ill understood: a profoundly different and more difficult problem."

The vertical, density-driven circulation that results from cooling and/or increase in salinity, that is, changes in the heat and/or salt, is known as thermohaline circulation. In certain polar regions water, that has been subjected to extreme cooling, sinks and flows equatorward in the thermohaline circulation [1]. In a few localized regions, the circulation is confined to a small area and is pronounced in the vertical direction leading to the formation of convection cells.

Comprehensive studies have been done on ocean convection and even expeditions have been undertaken to carry out field experiments on the phenomenon. Killworth [4] gives a qualitative description of convection as it occurs in the World Ocean. Two types of convection are illustrated - continental boundary and open-ocean convection. The former occurs on continental shelf slope systems, as typified by various locations around the Antarctic coast. “The freezing of sea-ice, and resulting brine ejection, creates dense salty water on the shelf which descends the slope under a balance of Coriolis, gravity, and frictional forces, entraining the surrounding warm deep water as it goes." The second process occurs in locations such as the Mediterranean, the Labrador Sea, and two locations in the Weddell gyre, and is hypothesized to occur in the Greenland Sea. Open-ocean convection has many similarities in all these areas: it occurs in narrow (20-50 km) areas; it

forms about $10^3 m^3/s$ of deep water; it occurs in regions of cyclonic mean circulation; more than one water mass in the mean circulation is involved; a preconditioning seems to be required; some surface forcing (cooling or sea-ice formation) is necessary; a violent breaking up of water mass frequently occurs on time scales of two weeks. Preconditioning refers to the weakening of vertical static stability in the surface layer. This results from a 'doming' of the isopycnal surfaces in the cyclonic gyre [4].

Field experiments undertaken to study oceanic convection include The Labrador Sea Deep Convection Experiment [5] and The Medoc Project [6]. Rudels [7] reports of convection observed in the Greenland Sea in the winter of 1987-1988. A study or summary of theoretical models of the thermohaline circulation has been done by Veronis [8]. And Whitehead [9] presents a summary of the models of the thermohaline ocean processes.

A new laboratory experiment has been undertaken that follows from the analytical model developed by Whitehead (manuscript in preparation). He showed that two states of flow for the same localized surface cooling conditions might exist for a salt-stratified isothermal body of water. In one case, freshwater is cooled and convective circulation is shallow. In the second state, salty water is entrained and deep convection of mixed water occurs. The two flows can be found for the same driving parameters in a certain range. Some special conditions are required for the multiple equilibrium flow to exist in this configuration. For example, it is necessary for the resistance of flow for the surface water to be greater that the resistance of deep flow. A numerical analysis of the model was done. The purpose of this project was to design, construct, and test a laboratory apparatus that might demonstrate the two flow-states.

2 Method

A simple physical model for investigating the theory for convection was built in the laboratory. The apparatus consists of two chambers — a small chamber (a vertical cylinder 5 cm in diameter and 23.9 cm deep), and a bigger one (a rectangular box measuring 21.8 cm in length, 22 cm in width, and 21.5 deep). Both were connected laterally with three tubes of different diameters close to the top, the middle, and close to the bottom. Tube spacing was 9.5 cm. Tube diameters were 0.9, 0.6, and 0.3 cm, respectively. The small chamber had a copper base. The copper bottom is encased in a metal cup connected to two plastic tubes on both sides. The other ends of the tubes are connected to a hot water bath. The bigger vessel also contains three other hoses — one brings in saltwater to the bottom, the other brings in freshwater to the top, and the third hose removes a mixture of both waters at the interface of the two fluids. The two in flows were pumped at a steady rate. Both containers were filled with a layer of salt water about 3.5 cm thick, on top of which is a layer of freshwater about five times as deep. The bigger chamber is kept at about 20ºC. A marker — blue dye — identified the layer of saltwater, while the freshwater is unmarked and stays colorless. The hot-water-bath temperature range for the experimental runs was between 24.3 and 30ºC. The water bath's systems automatically recorded the temperature of the bath in digital mode, while the temperature of the top, mid-depth, and bottom of both chambers were measured with a standard thermometer. By depositing a red color dye at the mouth of the connecting tubes, the flow direction and time were measured. Samples of fluid were extracted from the top, middle, and bottom portions of the fluid, and the density was measured with densiometer. A Matlab program was used to find the equivalent salinity of the density. Earlier runs were made at half-hourly and hourly intervals, and later runs were made at half-hourly intervals.

In his analytical and numerical model in progress, Whitehead (2000) assumed flow through the tubes are governed by laminar viscous flow laws, so that flux through each tube is proportional to the pressure difference across the tube. Effects of rotation were neglected.

3 Data

The measured quantities are accumulated in seven tables, which are too long and detailed for this report. The temperature of the fluid at the top, the middle, and bottom portions of the fluid are tabulated for different bath temperatures. Also, the time of flow, density, and salinity are presented. In addition to these, the dimensions of the chambers are given.

4 Results

Experimental results for the flow rates through the top, middle, and bottom connecting tubes are summarized in Table 10 (not shown). Theoretical calculations for the flow rates are also presented in two tables. According to theory, for limited cooling, only the top and middle tubes are involved in vigorous circulating fluid as happens in a convection cell. A comparison of results for theory and experiment show disparity of considerable proportions. Theory predicts that for strong cooling, all three connecting tubes circulate fluid. Again, comparison of theoretical calculations of flow rates and values obtained from experiment indicate poor agreement between theory and experiment.

5 Discussion

The dynamics as determined by theory suggests that several stages of flow exist for small, moderate, strong, and very strong cooling. Agreement between experiment and theory was very poor, and the reason for this is unknown at this time. Possibly, the resistance coefficient of the bottom tube was too great. New experiments with a smaller resistance coefficient for the bottom tube are continuing with much better agreement between experiment and theory (Whitehead, Private Communication). In this experiment a major change from theory was made regarding the effect of heat on the fluid system. The theory focuses on heat removal from the variant chamber and ignores the effect of conduction of heat in the body of the fluid. Also, while cooling makes the fluid column dynamically unstable from the top, heating triggers rising motion from the bottom. Moreover, the gradient of temperature or pressure on both sides of the connecting tube may be different for the case of cooling.

Experimental errors may have been incurred as measurements were made manually and recorded. The heating bath temperature was unsteady most of the time, and the device would not adjust to a temperature of about 24ºC.

Certain approximations were made in the computations. Since the saltwater was one part ocean water and nine parts freshwater, the salinity was different from pure ocean water. Using the appropriate equation-of- state parameters, such as specific values of thermal expansion coefficient and salt contraction coefficient, could have improved the theoretical values and made them more realistic. The approximations used may underestimate the effect of low salinity levels on the density, and, hence, the effects on the values of the flow rate. Eventually the integrity of the dynamics of the system may be undermined by such estimates, causing major differences between the results of theory and experiment.

6 Conclusion

An attempt has been made to check the authenticity of a theory for oceanic convection. To do this, a laboratory experiment was done. The laboratory method differed from the theory. Heating from underneath the fluid chamber instead of cooling from above, may have altered the dynamics and caused theory and experiment results to agree less. In spite of this drawback, the experiment

went well. Ample evidence of convection was demonstrated. The theory, being under development, may probably work for a system that is cooled from the top. Possibly the experimental data may provide grounds for further development of the theory.

7 Acknowledgements

A special thanks is credited to Dr. Jack Whitehead who was a source of encouragement and inspiration to me.

References

[1] Brown et al., "Ocean circulation," Open University Oceanography Course Team. Pergamon Press, New York (1996).

[2] J. Pedlosky, "Ocean circulation theory," Springer-Verlag, Germany (1996).

[3] M. McIntyre, "On global scale atmospheric circulations and remarks on oceans and solar spinoff," Geophysical Fluid Dynamics, Summer 2000, Talk/Seminar (2000).

[4] P. D. Killworth, "Deep convection in the world oceans," Reviews of Geophysics and Space Physics **21**, 1-26 (1983).

[5] Lab Sea Group, "The Labrador sea deep convection experiment," Bulletin of the American Meteorological Society **10**, 2033-2058 (1998).

[6] Medoc Group, "Observations of formation of deep water in the Mediterranean Sea.," Nature, **227**, 1037-1040 (1969).

[7] B. Rudels, "Greenland Sea convection in winter of 1987—1988," Journal of Geophysical Research **94** (C3), 3223-3227 (1989).

[8] G. Veronis, "On Theoretical models of the thermocline circulation," Deep Sea Research **16**, 301-323 (1969).

[9] J. A. Whitehead. "Thermohaline Ocean Processes and Models," Annual Review of Fluid Mechanics **27**, 89-114 (1995).

[10] J. A. Whitehead, "Stratified Convection with Multiple States," Ocean Modelling, In Press *(2001)*.