

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden to Washington Headquarters Service, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188) Washington, DC 20503.

PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.

1. REPORT DATE (DD-MM-YYYY) 31/12/2001		2. REPORT DATE <i>type</i> FINAL		3. DATES COVERED (From - To) 15/02/1999 to 30/09/2001	
4. TITLE AND SUBTITLE Laboratory Studies of Density Increase on Shelves				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER N00014-99-1-0366	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S) John A. Whitehead				5d. PROJECT NUMBER 0 1 PR00483200	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Woods Hole Oceanographic Institution Woods Hole, MA 02543					
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Office of Naval Research Ballston Centre Tower One 800 North Quincy Street Arlington, VA 22217-5660				10. SPONSOR/MONITOR'S ACRONYM(S) ONR	
				11. SPONSORING/MONITORING AGENCY REPORT NUMBER	
12. DISTRIBUTION AVAILABILITY STATEMENT APPROVED FOR PUBLIC RELEASE - DISTRIBUTION IS UNLIMITED					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT Four laboratory experiments and theories were developed. All have application to the Shelf Basin interaction region and elsewhere. Experiments had a plume of salt water flowing down a slope in a rotating basin filled with fresh water. Results collapse to a diagram showing that the ratio of flow speed to wave speed (Froude number) is the main criterion for waves. Mixing substantially increases with rotation rate. Second, a theory describes the effects of density stratification on the sinking of dense water. A thin surface layer of fresher water (arctic halocline) produces multiple equilibrium behavior when cooled from above. Friction (continued on attached page)					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT UL	18. NUMBER OF PAGES 6	19a. NAME OF RESPONSIBLE PERSON John A. Whitehead
a. REPORT	b. ABSTRACT	c. THIS PAGE			19b. TELEPHONE NUMBER (Include area code) 508-289-2793

20020131 106

14. ABSTRACT

from sea ice enhances hysteresis. Exploratory experiments were started. Third, free surface flows over obstacles in a channel were analyzed and observed. Some parameters allow two steady flow states. An intermediate state is discovered. Fourth, vortex generation is produced in a current of dense water descending a slope and encountering obstacles. Experiments produce the geometry of the Chukchi Sea shelf. Eddy formation exists for select parameters. All experiments indicate that ocean dynamics in the Shelf-Basin Interactions region is complex, with eddy formation, uneven mixing, and sudden water mass formation typical.

a. Project Name

Laboratory Studies of Density Increase on Shelves

PI Name and Address

John A. Whitehead
Woods Hole Oceanographic Institution
MS#21, 360 Woods Hole Road
Woods Hole MA 02543-1541

b. Long Term Goals

The long-term goal is to understand the fluid mechanics of buoyancy and wind driven transport on a polar continental shelf, including along-shelf transport and exchange with the deep Arctic Ocean.

c. Objectives

To understand flows in scaled laboratory experiments in a manner suitable for application to processes in physical oceanography.

d. Approach

Laboratory experiments are designed and approximate theories and scaling are laid out. Their results indicate design requirements for refined experiments that yield observations of flow patterns and quantitative measurements of important parameters. These are compared with theory and ocean data.

e. Tasks Completed

Four laboratory experiments and associated theories have been developed. All have application to the Arctic regions, and some apply to the SBI region. In some cases there are also applications in other ocean locations.

- 1). Two sets of laboratory experiments have been focused on the dynamics of a dense plume of salt water flowing down a slope in a rotating basin that is filled with ambient water of lower salinity.
- 2). A theory has been developed (Whitehead 2000) that describes the effects of density stratification on the sinking of dense water. Some laboratory experiments were started under this project. A thin surface layer of fresher water (like the arctic halocline) produces multiple equilibrium behavior if it is cooled and also subjected to large friction as for example will be found under rough sea ice. Certain boundary conditions such as a fast cooling relaxation time or brine supply from ice formation produce enhanced sinking.
- 3). Free surface flows over obstacles in a channel of constant width are analyzed and observed in the laboratory. There is a range of parameters where two steady flow states are possible (Baines 1995). The state that actually exists is determined by the past history. One of these flow states is supercritical so that no waves can propagate upstream (against the flow) over the obstacle. The other

state has a hydraulic jump that travels upstream to infinity. In the latter case, the flow undergoes a subcritical (i.e. waves can propagate in both directions) to supercritical transition at the obstacle crest.

4). Vortex generation is investigated as a current of dense water descends down a gentle slope and then encounters steep shelf break topography. Laboratory experiments on a rotating turntable (to simulate earth rotation) possess the geometry present near the north-eastern part of the Chukchi shelf: a canyon with a gentle slope (Barrow Canyon, Alaska) and a steep continental shelf break in contact with deep water (Arctic Ocean).

f. Results

1). For the plume experiments, over a wide range of parameters, three flow types are found: laminar flow, waves, and eddies. Regime diagrams illustrate the range of variables that produce these three different types. Using a simple Ekman layer theory to determine the properties of the basic flow, the experimental results collapse to a diagram that indicates that Froude number is the main criterion for wave formation. Experiments further show that the waves produce little mixing for nonrotating fluid, but that mixing increases substantially for rotating fluid. Figure 1 shows a photograph of such a plume in rotating fluid. Results are to be reported by Cenedese et al. (in Prep.).

2). For convection with a thin layer of fresh water near the surface, the sinking rate of dense water becomes very nonlinear as a function of the forcing. Thus in some cases cooling of fresh surface water can suddenly transform to cooling of salty deeper water mixed with surface water as cooling rate gradually intensifies during the winter. Once deep convection is active, it will remain so as cooling declines in the spring. At a second lower value of the cooling rate, the deep cooling will switch off. A laboratory experiment is in progress that is intended to demonstrate this process. Further experiments on this process, will be supported by other projects. These theoretical results completely contradict present numerical and theoretical deep ocean convection parameterization schemes in which the convection is monotonically proportional to cooling rate. Results are published in Whitehead (2000).

3). For flows over an obstacle in the range where two stable steady flows are possible, a new third steady solution has been found in conjunction with P. Baines. This solution involves a hydraulic jump that is stationary over the upstream face of a long obstacle. The mathematical solution is contiguous with the other two other solutions, and in a sense, lies between them. However, this new solution is unstable. If the stationary jump is displaced to a location with a slightly different bottom height, it will move further in the same direction. This criterion thereby dictates that jumps are unstable on upslope flow and stable on downslope flow. Such features have been tested with two series of experiments. Naturally, attempts to observe the new solution were unsuccessful apparently because of its instability. Comparisons were made between the observed abrupt transitions between flow states, and the predictions of hydraulic theory. Qualitatively the agreement is quite good, with differences attributable to experimental factors that are not contained in two-dimensional long wave hydraulics. Results are presented in Baines and Whitehead (2001)

4). The simplified model of dense flow down a canyon produced eddy formation when the dense fluid moves from a gentle slope in a shallow environment, such as the Chukchi shelf, to a steep deep environment, such as the shelf break, as illustrated in figure 2. The project requires additional support for further experiments.

g. Impact for Science

The dependence of dense water formation strength on history will introduce strong challenges to numerical modeling. Some quantitative criteria have been found to help oceanographers determine where convection is likely to be found. Parameters that determine the emergence of mixing and the detachment of eddies into the Arctic ocean are becoming more clearly known. In no case did the flows look like the standard streamtube parameterizations used to describe large ocean overflows. Ekman layer processes, Kelvin-Helmholtz waves, and hydraulic jump processes made their own distinct contribution in shaping the form of the current and in some cases breaking it up into eddies.

h. Relationships to Other Programs

These and related processes were presented clearly in a manner accessible to oceanographers and students at SBI planning meetings and at AGU. The results suggest a number of ocean measurements.

i. Figures/Pictures

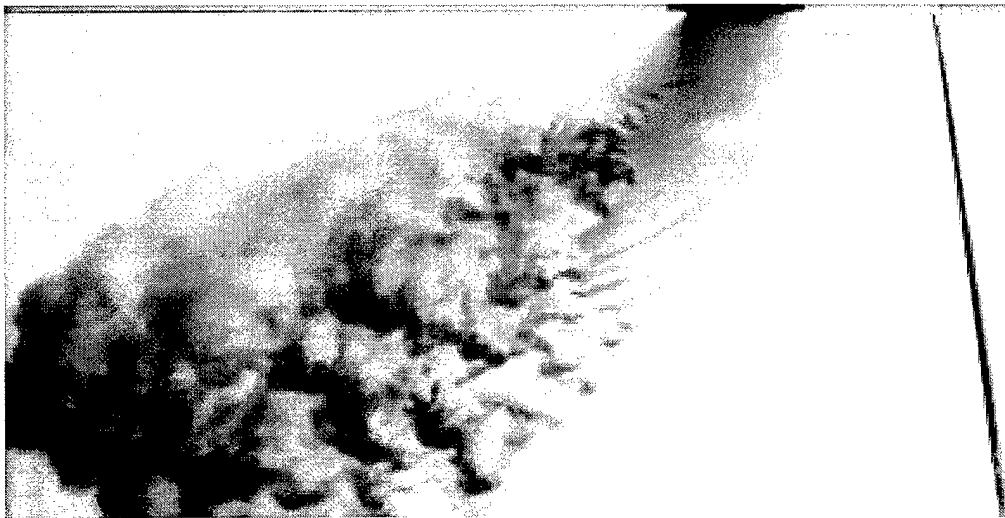


Figure 1. Side view photograph of a plume of dyed salty water sinking downward above a sloping bottom in transparent, fresh rotating water. The intersection of the sloping bottom with a vertical side of the co-rotating rectangular tank is visible on the right. The plume curves toward the right in the direction of flow, but it bends toward the left with depth in this picture as the flow is directed toward the camera. Waves and small-scale turbulence are visible. Also near the source is a patch of mixing that is associated with cyclonic gyre formation in the clear water. The cyclonic gyre typically lifts a lens of blue fluid and moves it to the left with uniform sideways velocity.

Laboratory experimental set up

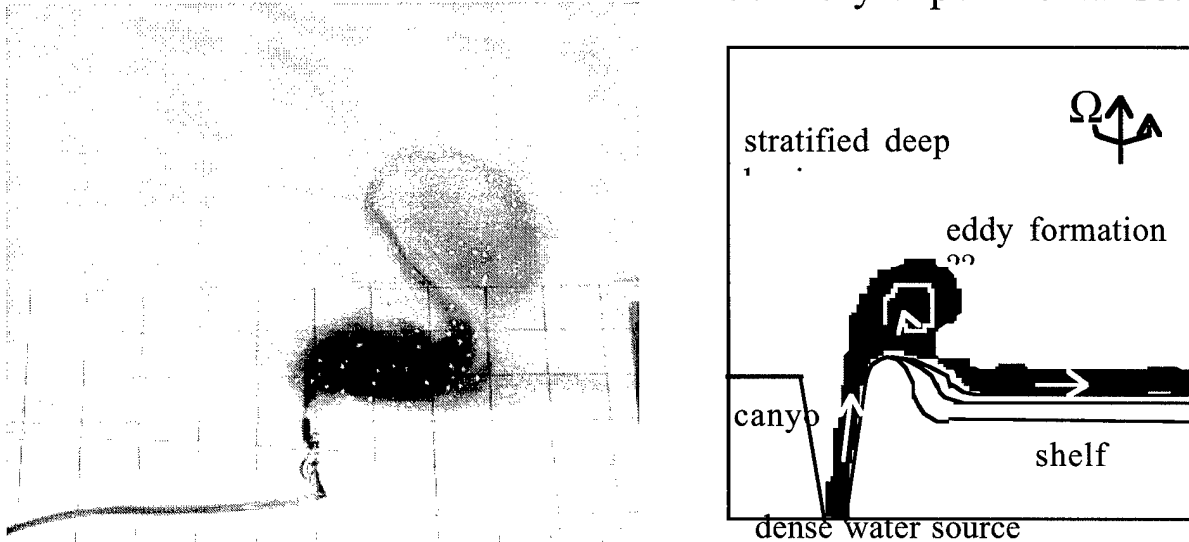


Figure 2. (Left) View from above of a laboratory eddy formed from a jet source of blue dense salty water over sloping topography in linearly stratified rotating water. The eddy is detaching from the bottom and moving into the interior of the basin. (Right) Sketch of recent refined experiments. Flow of dense water down a canyon replaced the point source. For some parameters, the eddy detached and propagated into the interior of the deep basin. [The canyon is shown with the water flowing down it. At the bottom the dense water reaches the level where its density matches the density of the stratified fluid. At this level an eddy detaches and propagates into the model's "deep Arctic" region.]

REFERENCES

- Baines, Peter. G. (1995) *Topographic Effects in Stratified Flows*. Cambridge University Press, New York, 482 pp.
- Baines P. G. and J. A. Whitehead, 2001 On multiple equilibria in single-layer hydraulics, In Preparation.
- Cenedese, C. and J. A. Whitehead (2000) Eddy-shedding from a boundary current around a cape over a sloping bottom *J. Phys. Oc.* 30, 1514-1531.
- Cenedese, Claudia, J. A. Whitehead, Tommoso Ascarelli, and Mitch Ohiwa, A rotating dense current down a slope, In preparation.
- Whitehead, J. A. 2000 Stratified Convection with Multiple States. *Ocean Modelling*, 2, 109-121.