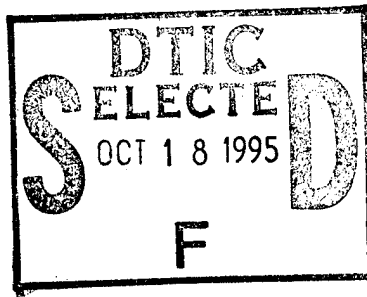


UNIVERSITY OF WASHINGTON  
SEATTLE, WASHINGTON 98195

*School of Oceanography, WB-10*

10 March 1995

Dr. Steven Ramberg  
Code 3210  
Office of Naval Research  
800 North Quincy Street  
Arlington, VA 22217-5660



RE: N00014-90-J-1477

Dear Dr. Ramberg:

Attached is the final technical report for the project, "Laboratory Studies in Ocean Circulation, Spin-up & Mixing" (Ocean Science Educators' Award), Peter B. Rhines, Principal Investigator.

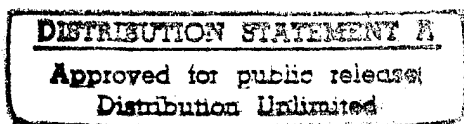
Sincerely,

A handwritten signature in cursive script that reads "Laurie K. Bryan".

Laurie K. Bryan  
Manager

Encl.

cc: Administrative Grants Officer, ONR  
Director, Naval Research Laboratory  
✓ Defense Technical Information Center  
Grant & Contract Services, UW



19951013 053



OFFICE OF THE UNDER SECRETARY OF DEFENSE (ACQUISITION)  
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TO: OFFICE OF NAVAL RESEARCH  
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1. Reference: DoD Directive 5230.24, Distribution Statements on Technical Documents, 18 Mar 87.

2. The Defense Technical Information Center received the enclosed report (referenced below) which is not marked in accordance with the above reference.

FINAL TECH REPORT  
N00014-90-J-1477  
TITLE: LABORATORY STUDIES IN  
OCEAN CIRCULATION SPIN-UP  
MIXING(OCEAN SCIENCE EDUCATORS  
AWARD)

3. We request the appropriate distribution statement be assigned and the report returned to DTIC within 5 working days.

4. Approved distribution statements are listed on the reverse of this letter. If you have any questions regarding these statements, call DTIC's Cataloging Branch, (703) 274-6837.

FOR THE ADMINISTRATOR:

1 Encl

GOPALAKRISHNAN NAIR  
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The cited documents has been reviewed by competent authority and the following distribution statement is hereby authorized.

A

(Statement)

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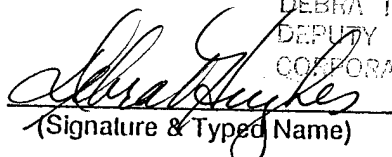
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19 SEP 1995

  
(Signature & Typed Name)

(Assigning Office)

(Date Statement Assigned)

## FINAL REPORT

ONR GRANT N00014-90-J-1477  
Ocean Sciences Educators' Award

Peter B. Rhines  
University of Washington  
School of Oceanography  
Box 357940  
Seattle, WA 98195-7940

This research grant provided three years of support for a postdoctoral investigator, Dr. Dan Ohlsen, between 1 Oct 90 – 30 Sep 93 (the budget period of the grant was 1 Jan 90 – 31 Dec 93). Dr. Ohlsen came from a physics background and used this opportunity to develop his knowledge of physical oceanography while working in the Geophysical Fluid Dynamics Laboratory of the School of Oceanography.

The principal research results from this grant are:

- (1) the development of a laboratory model of Rossby waves on experiments on a rotating, spherical Earth, using ferromagnetic fluids;
- (2) the use of ferromagnetic fluids in generating internal waves and observing wave/mean-flow interaction in a nonrotating laboratory experiment;
- (3) the laboratory simulation of deep-ocean flow through a channel between two oceanic basins.

Publications are indicated in the text below.

### Detailed Results

*(1) Ferromagnetic analogs of the Earth's radial gravity field allow equatorial waves to be observed in the laboratory.*

It is well known that the beta effect, which dominates large-scale ocean dynamics, cannot be generally simulated in the laboratory. This is because 'beta' depends upon both the spherical form and the rotation of the Earth. One wants a gravity vector varying in space (as with the central field of the Earth), with rotation about a Pole. Analogs of the beta effect, using sloping boundaries, can simulate mid-latitude, small amplitude dynamics in a fluid with one or two constant-density layers.

In order to see, for the first time in the laboratory, the dynamics of the equatorial zone and of a fully stratified rotating Earth, we employed a new technology of engineered fluids with ferromagnetic properties. They consist of a dilute suspension of small (100 Angstrom) magnetic dipoles, each coated with a surface-active substance that prevents them from agglomerating. Under an imposed magnetic field they become strongly magnetized; we have demonstrated that this gives us a way of producing a potential force field that acts like the gravitational potential.

By enclosing rare-Earth solid magnets in a ceramic sphere, we could coat the sphere with a layer of magnetic fluid, suspending the whole "planet" in a carrier fluid of the same physical density (silicon oil plus freon). The result was a successful analog of a one-layer ocean on a sphere. We then placed this on a rotating table and excited wave modes by moving magnets, which are essentially "tidal" forcing.

We successfully recorded, quantitatively, the propagation of equatorial Kelvin and Rossby waves in this experiment.

The ferromagnetic "Earth" has attracted some media interest, appearing in local newspapers and on a nationally broadcast science-news radio program.

Ref.: Ohlsen, D. and P.B. Rhines, 1994, Laboratory experiments on equatorially trapped waves using ferrofluid, J. Fluid Mech, accepted.

*(2) Internal wave/mean-flow interaction with a ferromagnetic wavemaker.*

This project, not yet completed, involved the use of a layer of ferromagnetic fluid (described above) as a "wavemaker". A uniform salinity stratification was produced in a cylindrical container, with a layer about 2 cm thick of ferrofluid at its base. A turntable beneath the cylinder moved an array of permanent magnets in such a way as to produce a travelling wave in the ferrofluid. This in turn generated a nearly monochromatic internal gravity wave propagating upward in the cylinder. It is a "textbook" example in which strong horizontal mean flow (in the same direction as the phase propagation of the wave) was generated by the internal wave. This wave/mean-flow interaction had the unusual property that jets of mean flow occurred at the free surface where partial reflection occurred. We find quite generally that jets occur at sites like the base of the upper mixed layer, where total internal reflection is modified by viscosity. A parallel numerical model has showed strong, though presently only qualitative, agreement.

*(3) Laboratory simulation of the flow through a deep passage between two ocean basins: a rare opportunity to witness boundary-layer driven overturning*

Many geophysical circulations are essentially controlled by subtle, slow secondary flows in boundary layers. Though Ekman suction is a cornerstone of our understanding of the ocean circulation, its detailed workings can rarely be seen directly. In this laboratory experiment, Ohlsen worked with Dr. Gregg Johnson, motivated by velocity and hydrography measurements in the Faeroe Bank Channel, which runs into the Iceland Basin, carrying overflow waters from the Norwegian Sea.

Two large basins containing water of different densities were connected by a straight channel. When a barrier was removed, the "lock exchange" flow, a pair of light and heavy gravity currents, began exchanging the fluid between basins. On a rapidly rotating table, the flows veered to the "right", the interface separating them tilted, and Ekman-layer driven secondary flows climbed the walls and spiralled into the interior of the channel. The flow was visualized using an innovative technique (due to R. Breidenthal of Aerospace Dept., Univ. of Washington): the two basins of source water were made respectively basic and acidic, and a fluorescein was mixed into the acidic fluid. The acid neutralizes the brilliant dye color until it becomes mixed at the density interface, altering its pH. Thus only fluid that has been mixed above  $\text{pH}=4$  appears as bright yellow-green. This and other dye injections allowed the mapping of the secondary flow, overturning, and mixing.

Ref.: Johnson, G. and D. Ohlsen, 1994, Frictionally modified rotating hydraulic channel exchange in oceanic outflows, J. Phys. Oceanogr. 24, 66-78.

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