Final Report:
Curricular Development Challenge Fund

Physical Laboratory Experiments for Atmosphere-Ocean Studies

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October 29, 2001
# Table of Contents

Cover Page -

Table of Contents 2

Overview 2

Laboratory Equipment 4

Laboratory Experiments 7
  Experiment 1: Ekman Layers 9
  Experiment 2: Jet Stream 11

Summary 14

Bibliography 16

Appendices
  A Dantec Seminar at CAOS 17
  B Physical Laboratory Web Page 18
  C Course Outline Spring 2002 19
Overview

The Courant Institute of Mathematical Sciences and the Faculty of Arts and Sciences, New York University (NYU), have recently established the Center for Atmosphere-Ocean Science (CAOS). A main goal of the Center is to foster vigorous research and educational activities in environmental science. The development of a physical laboratory for the study of environmental flows is an important component of this initiative. Such a laboratory serves as an important pedagogical tool enabling students to carry out experiments that demonstrate the fundamental principles underlying numerous environmental phenomena. Basic experiments are now being implemented into the core curriculum in the form of classroom demonstrations and student term projects under the mentorship of the PI.

This report describes activities carried out from May 2001 to September 2001 under the NYU Curriculum Development Challenge Fund (CDCF). First, a brief introduction to the fluids laboratory is given as well as descriptions and illustrations of equipment purchased under the award. Second, the experiments that have been thus far developed and integrated into the PIs curricular repertoire are described.
**Laboratory Equipment**

The physical laboratory is located in Room 103 of Warren Weaver Hall (Fig. 1) and is part of the Applied Mathematics Laboratory of the Courant Institute of Mathematical Sciences. A centerpiece of the physical laboratory is a turntable (i.e., a circular rotating platform). The laboratory currently has a small (0.25 m diameter) turntable that is supported on an air cushion generated by an air compressor (Fig. 2). A larger (1.0 m diameter) research-quality table is currently on order ($110 K).

An important capability of a physical laboratory is the visualization of the fluid flows under study. This is achieved through use of a high-resolution video camera and display device (see Fig. 3). This past summer a professional-quality video camcorder and a large plasma display unit were purchased ($25 K) and are now operational in the laboratory. The equipment were purchased under a National Sciences Foundation grant but their installation and operation were a key part of the laboratory development activities carried out this past summer under the CDCF.
Another important component of the physical laboratory equipment are model basins capable of holding a stratified fluid (i.e., varying in density from top to bottom). Basins of varying geometry are needed, depending upon the particular experiment being performed. A local neighborhood plastics store (Industrial Plastics, Canal Street) is capable of producing most any form of geometry, hence topography, in Plexiglas and at a reasonable cost. The following basins as well as other laboratory apparatus were designed and purchased ($1 K) under the CDCF grant (Figs. 5 - 8):

Fig. 5: **Estuary Tank.** Used for study of estuarine circulation, wave propagation, wave motion, and hydraulic jumps. Has a detachable sloping cover.

Fig. 6: **Various Sized Cylindrical Tanks.** Used for the study of fluid motion such as Jet Stream and Taylor Curtain. Has an attachable cover for video camera.
Fig. 7: Plastic Inserts and Metal Cylinders. Used to mimic bottom topography such as underwater mountains and sloped bottoms. Allows for cooler water to be partitioned from warmer water.

Fig. 8: Mechanical Pumps, Hoses, Thermometers, etc. Used for filling and draining water from tanks and for water temperature measurement.

While the above equipment represents an excellent starting point for the equipment inventory, the PI will be continually upgrading the breadth and the quality of the equipment. One piece still to be acquired is a laser-based particle image velocimetry (PIV) system, needed for research-quality fluid flow measurement. During the course of the CDCF (i.e., summer 2001), such laser technology was demonstrated in a special seminar given at NYU by industrial experts in this field (See Appendix A). Further funding ($220 K) is now being sought from the Office of Naval Research to purchase this equipment so as to further enhance the quality of the educational and research activities that can be performed.
Laboratory Experiments

The atmosphere and ocean share many common traits. First and foremost is that they may both be considered as relatively shallow layers of fluid, albeit of different density and composition, covering the surface of a large rotating body, the Earth, and are driven by the energy of the Sun. These fluids obey the same conservation equations regarding mass, momentum, and energy. It is the existence of these underlying dynamical similarities that allows the construction of physical laboratory experiments that can be used to explore and develop an understanding of either the atmosphere, ocean, or both.

Significant insight can be gained by performing experiments with real fluids such as water in a laboratory tank situated upon a rotating table that represents a scaled-down version of the global ocean (or atmosphere). While such experiments have limitations in serving as surrogates of the real global ocean (or atmosphere), they nonetheless have the advantage of allowing one to work with real fluids instead of computationally approximated ones.

The primary use of the CDCF monies ($7 K) was the hiring of a summer student to aid the PI with laboratory development in both a technical and experimental direction. As mentioned previously, plastic basins were purchased. These basins were designed by the student based on discussions with the PI about the types of experiments that would be carried out in the lab. In addition to preparing the laboratory space itself, the student
began development of a laboratory web page, which will be used by students in upcoming courses by the PI (See Appendix B).

At the heart of this past summer’s laboratory development was the step-by-step preparation of the experiments. Seven particular experiments were identified as being the most relevant to the teaching of atmosphere-ocean science. The experiments were: (1) Ekman Layers, (2) Jet Stream, (3) Gulf Stream, (4) Taylor Column, (5) Taylor Curtain, (6) Estuary, and (7) Double Diffusion. They represent the most important experiments performed in atmosphere-ocean science over the last decades. Given the time limitations of one summer, the goal was set to implement the first two experiments (Ekman Layers and Jet Stream). The remaining experiments being marked for implementation at a later date.

The two experiments developed are to be used in both the undergraduate and graduate courses. In the undergraduate course, the experiments will serve primarily to show the student that real world phenomenon can be simulated in an experimental laboratory and quantitative insight into the workings of nature can be obtained. In the graduate course, the experiments will be presented in a more quantitative fashion. Students will explore phenomena both in the physical laboratory setting but also from a mathematical perspective. This dual approach will reinforce and deepen the student’s understanding of the most fundamental concepts of geophysical fluid dynamics, the subject that lies at the heart of understanding the workings of the atmosphere and oceans. The two experiments are now described.
Experiment 1:  Ekman Layers

The purpose of this experiment is to simulate the stress that is exerted on the Earth’s oceans by the winds and the resulting fluid flow patterns. The rotation of the tank simulates the rotation of the Earth and imparts a Coriolis force on the fluid that affects the velocity and distribution of the fluid.

Equipment Needed:

- Cylindrical tank
- Liquid glycerin
- Dye
- Safety goggles, lab coat, rubber gloves, pencil, notepad

Perform Experiment:

Step 1:  Choose 30 cm cylindrical tank. Rinse and clean tank. Fill to depth of 12 cm with glycerin solution.

Step 2:  Gently introduce dye to center and edge of fluid surface. Place 29 cm cylindrical tank on top of fluid surface.

Step 3:  Power on rotating table. First turn air pump switch from off to auto. Turn the motor control main switch to on position. Set rotation speed to 100.

Allow rotation to occur for approximately 5 minutes. Note the pattern of the dye. Increase the rotation speed to 500. After 5 minutes describe again the pattern made by the dye.

Step 4:  When experiment is complete, decrease rotation speed to 0. Turn off motor control main switch. Turn air pump switch from auto to off.
Fig. 9: Configuration of apparatus for Ekman Layers experiment. Dyes are introduced into the main reservoir. The downward motion of the fluid along the axis of rotation is clearly revealed by the flow pattern of the dyes.
Experiment 2: The Jet Stream

The purpose of this experiment is to demonstrate the formation of a jet stream in a rotating annulus filled with water. The inner wall (the “north polar region”) of the annulus is in contact with ice while the outer wall (the “tropical region”) is above room temperature. The resulting temperature gradient produces a pressure gradient that causes a radial flow (i.e., north-to-south). However, because the annulus is rotating, the radial flow transforms itself into a concentrated, azimuthal jet (i.e., west-to-east). Furthermore, that jet develops a wave-like instability that results in the production of large, eddy features (i.e., storm systems). The laboratory features so generated can be easily compared with those observed in the real atmosphere and oceans.

Equipment Needed:

- Cylindrical tank with insert bottom
- Metal canister filled with ice, kettle for hot water
- Dye
- Rotating table
- Safety goggles, lab coat, rubber gloves, pencil, notepad

Perform Experiment:

Step 1: Choose 30 cm cylindrical tank. Rinse and clean tank.
Step 2: Place white plastic circular insert inside bottom of tank.
Step 3: Place steel cylindrical insert inside tank.
Step 4: Place frozen ice block inside steel cylinder. Fill any space with water to 2 cm from top of canister.
Step 5: Place tank on small rotating table. Fill middle section of tank with room temperature water slowly until water level measures 2 cm from top of steel cylinder. Fill the outer ring with hot water.
Step 6: Carefully drop dye on top of water.

Step 7: If using the remote camera, now position it on its plastic housing.

Step 8: Power on rotating table. First turn air pump switch from off to auto. Turn the motor control main switch to on position. Set rotation speed to 100.

Allow rotation to occur for approximately 5 minutes. Note the pattern of the dye. Increase the rotation speed to 500. After 5 minutes describe again the pattern made by the dye.

Step 9: When experiment is complete, decrease rotation speed to 0. Turn off motor control main switch. Turn air pump switch from auto to off.

Fig. 10: Dye patterns tracing out flow patterns for baroclinically unstable fluid flow. The dyes show the fluid sinking and rising predominantly along the perimeter of the basin.
These two experiments are now integrated into the PI's graduate course for Spring 2002 (See Appendix C). During week 4 of that course, the concept of rotation of a fluid is introduced. Here, the Ekman Layers experiment will be demonstrated. During week 8, instability of fluid flow is covered and the Jet Stream experiment will provide a demonstration of this concept. Based on the experience gained by the PI in integrating these two experiments into the classroom, five additional experiments are planned for integration the following year.
Summary

The present state of the Earth's climate system is the result of an intricate and delicate balance among several components of the systems, such as the atmosphere, oceans, and biosphere to mention a few. Program developments over the last few years at the Courant Institute of Mathematical Sciences and the Faculty of Arts and Sciences have lead to the creation of a new science program, the Center for Atmosphere-Ocean Science (CAOS). The motivation behind this activity is the widely recognized need to address challenging problems relating to the understanding of complex facets of the Earth’s climate system and its susceptibility to change. In particular, it is the atmospheric and oceanic components that have been chosen as the research focus of the CAOS program and accordingly new undergraduate and graduate level courses are currently being developed in those areas seeking to highlight the underlying mechanisms controlling the Earth’s climate system as well as to illustrate the present-day skill levels in predicting possible changes in the system. The ability to accurately predict major changes in the climate system has obvious social and economic ramifications on a global scale.

One of the main physical concepts to be understood by students in the CAOS program involves the understanding of the behavior of fluid flow in a rapidly rotating environment (i.e., the atmosphere and oceans on the spinning Earth). The behavior of such fluids is highly non-intuitive, principally because of the presence of the Coriolis force. A physical laboratory model helps students better understand the role of the Coriolis force. This
understanding is achieved in a practical context by setting up a container of fluid on a turntable and forcing it to flow in various ways. Using video cameras attached to the rotating basins, the flow of fluid in the rotating environment is transmitted to a non-rotating laboratory frame. In this manner, the students can see with their own eyes the development of natural phenomenon that is unique to rotating fluids (see Fig. 12).

The summary of the activities carried out during the summer of 2001 with the support from the CDCF is that the PI purchased laboratory equipment as well as hired and trained an NYU undergraduate student. Two fluid dynamical laboratory experiments were developed and have now been implemented into the PI’s curriculum within CAOS. An additional five experiments are planned for development in the near future.
Bibliography

Appendix A: Dantec Seminar at CAOS

Web page of CAOS Student Seminar in Geophysical Fluid Dynamics (http://fish.cims.nyu.edu/student_GFD/) announcing the Dantec PIV seminar and demonstration.

Student Seminar in
Geophysical Fluid Dynamics

Next Seminar Particulars Contacts Other Seminars

Semester
- Spring '02
- Fall '01
- Summer '01
- Spring '01
- Fall '00
- Summer '00
- Spring '00

Next Discussion Leader

Khaled HAMMAD
Dantec Dynamics Inc.
Particle Image Velocimetry
July 20, 2001
3:30 pm
Room 1314
WWH

Abstract

Particle Image Velocimetry is a whole field measurement technique, providing flow visualization and quantitative measurement of two and three-dimensional velocity vector fields. The seminar will present theory, implementation, and some recent applications of Particle Image Velocimetry (PIV). The detailed coverage of basic principles will include description of PIV measurement process and parameters, spatial and temporal resolution, correlation analysis, dynamic range, optimizing measurements, error factors; stereoscopic viewing and Scheimpflug condition for planar 3-D measurements. Time will be available for questions and to discuss possible PIV applications at NYU.
Appendix B: Physical Laboratory Webpage

Web page of the Physical Laboratory of Center for Atmosphere-Ocean Science at the Courant Institute of Mathematical Sciences (http://fish.cims.nyu.edu/educational_pages/lab_physical/overview.html).

Physical Laboratory

- **Purpose**
  - **Experiment**
  - **Validate**
  - **Educate**
- **Space**
- **Equipment**
- **Supplies**
- **Safety**
- **Other Labs**
- **Acknowledgments**

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**Purpose**

The physical laboratory offers researchers and students an opportunity to carry out Geophysical Fluid Dynamics (GFD) experiments, i.e., those requiring a rotating reference frame. The specific purpose of the laboratory is threefold: **Experiment**, **Validate**, and **Educate**.

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**Acknowledgments**

Laboratory support comes from the **Office of Polar Programs (OPP)** of the **National Science Foundation (NSF)** under a CAREER Award. Additional support is from the Office of the Provost, **New York University**, under the Curricular Development Challenge Fund.
Appendix C: Course Outline Spring 2002

A portion of the web page of PI’s Introduction to Physical Oceanography Course (see http://fish.cims.nyu.edu/educational_pages/syllabus_intro_phys_ocn_2002.html).

COURSE OUTLINE

Introduction to Physical Oceanography

Spring 2002

G63.2840.002

Course Schedule

<table>
<thead>
<tr>
<th>Lecture</th>
<th>Date</th>
<th>Topic</th>
<th>Laboratory</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>January 22</td>
<td>Basic Equations</td>
<td></td>
<td>Assign 1, Prob. 1-6</td>
</tr>
<tr>
<td>2</td>
<td>January 29</td>
<td>Basic Equations (cont')</td>
<td></td>
<td>Assign 2, Prob. 2-3</td>
</tr>
<tr>
<td>3</td>
<td>February 5</td>
<td>Boundary Conditions</td>
<td></td>
<td>Assign 3, Prob. 3-2</td>
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<tr>
<td>4</td>
<td>February 12</td>
<td>Geostrophic Flow</td>
<td>Ekman Layers</td>
<td></td>
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<tr>
<td>5</td>
<td>February 19</td>
<td>Planetary Boundary Layers</td>
<td></td>
<td>Assign 4, Prob. 4-8</td>
</tr>
<tr>
<td>6</td>
<td>February 26</td>
<td>Barotropic Circulation</td>
<td></td>
<td>Assign 5, Prob. 5-6</td>
</tr>
<tr>
<td>7</td>
<td>March 5</td>
<td>Barotropic Circulation (cont') and Mid-Term Exam</td>
<td>Ekman Layers</td>
<td>Assign 6a, Prob. 6-1</td>
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<tr>
<td></td>
<td>March 12</td>
<td>Spring Break (No Lecture)</td>
<td></td>
<td>Assign 6b, Prob. Handout</td>
</tr>
<tr>
<td>8</td>
<td>March 19</td>
<td>Baroclinic Circulation</td>
<td>Jet Stream</td>
<td>Assign 7, Prob. 7-4, 7-6</td>
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<tr>
<td>9</td>
<td>March 26</td>
<td>Bottom Topography</td>
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<td>Assign 8, Prob. 8-4</td>
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<td>April 2</td>
<td>Surface Gravity Waves</td>
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<td>Assign 9, Prob. 9-12</td>
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<td>April 9</td>
<td>Inertial Motions</td>
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<td>Assign 10, Prob. 10-8</td>
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<td>April 18</td>
<td>Astronomical Tides</td>
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<td>April 30</td>
<td>Review</td>
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<td></td>
<td>May 14</td>
<td>Final Exam</td>
<td></td>
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</table>

The integration of the physical laboratory into the course curriculum is seen under the column labeled “Laboratory”. The two experiments developed this past summer appear in that column as “Ekman Layers” and “Jet Stream”.  

David Holland - Educational Activities