

1 Introduction

1.1 The role of fluid laboratories in teaching and research

Laboratory experiments have made a central contribution to our understanding of the fluid mechanics of ‘natural fluids’, the field of Geophysical Fluid Dynamics (GFD). For example, laboratory experiments were the first to demonstrate that rotating fluids do not behave like fluids at all - they become rigid parallel to the axis of rotation, a result that has wide implications to phenomena ranging from Jupiter’s Red Spot, to the circulation of the atmospheres and oceans - see the discussion in [1]. Regime transitions in rotating annulus experiments led Lorenz to ask fundamental questions that set the stage for his discovery of chaos [2] and a new branch of science. A review of the immense influence of laboratory experiments on the development of GFD can be found in [3].

Laboratory experiments should be, but are often not, at the centre of teaching GFD at graduate and undergraduate levels. Typically, students coming to the field have no background in fluid mechanics and no exposure to the non-intuitive nature of rotating fluid dynamics. Moreover, many undergraduates are not prepared for a full theoretical development of the subject. Our experience is that simple, but artfully chosen laboratory experiments are the most effective way of educating all students - irrespective of their mathematical sophistication or physical intuition - in basic fluid principles and teaching them how to move between phenomena in the real world, laboratory abstractions, theory and models.

In 1993, we decided that some of the ‘classic’ rotating tank fluid experiments would be a valuable addition to our classes and built a portable rotating table which is taken on a cart into the classroom for demonstration purposes. These are now a central element of an introductory fluids course developed by Marshall and Plumb, ‘Physics of the fluid earth’ (12.003 in MIT-speak, [4]), offered to undergraduates at MIT. Notes from the course are to be turned in to a text book. The opportunity for quantitative, hands-on laboratory work with rotating fluids is now being offered to our undergraduates in

a new ‘Institute Laboratory Course’¹, (12.307, see [5]). Such courses are central to the educational activities of our Department and MIT, as evidenced by start-up support that we have received from the Institute - see section 6.

In this proposal we seek support to develop the laboratory course further - both in terms of content and enabling laboratory tools - that will culminate in a Laboratory Guide (to accompany our undergraduate text) which makes use of both meteorological observations and laboratory experimentation. This will provide a reference for students and faculty in their own laboratory-based teaching and learning at other schools.

2 Prior NSF support

Marshall, Flierl and Plumb are very active in teaching and research. Between them they have authored hundreds of research papers in GFD, dynamical meteorology and oceanography. They are currently engaged in several NSF-supported research projects. However, they have never received NSF grants pertaining to undergraduate education.

3 Use of fluid experiments in undergraduate teaching

3.1 The experience at MIT

The educational programs in the Department of Earth, Atmospheric and Planetary Sciences (EAPS) at MIT attract men and women in equal numbers. Students are exposed to real fluids in laboratory experiments. The fluid laboratory of EAPS:

I is used for demonstration purposes in courses offered to students majoring in EAPS - specifically 12.003, Physics of the Atmosphere and Ocean

II forms the basis of a new ‘Institute Laboratory’: 12.307, Weather and Climate Laboratory, making use of real-time meteorological observations and fluid experiments

¹An Institute Laboratory is a Laboratory course that has been approved by MIT as satisfying the mandatory undergraduate laboratory requirement. Students plan the project, define the measurement, select the instruments, carry out the construction, make the measurement and interpret the results.

The proposers have developed and teach these undergraduate courses. Our graduate students and postdocs are keen to help as TA's - the experiments are fun to teach with because they expose fundamental ideas in a clear and immediate way. Thus our undergraduate teaching benefits from our graduate programs - and involvement of graduate students and postdocs in undergraduate education is helping to train the next generation of teachers in fluid dynamics.

3.1.1 12.003: Physics of the fluid earth

12.003 is an introductory MIT undergraduate course in meteorology and oceanography developed over the past 7 years by Marshall and Plumb - see course outline in Appendix I. Students taking the course are typically sophomores, juniors and seniors majoring in earth science or environmental engineering, with a few undergraduate and graduate students from other science or engineering disciplines. It sets the foundation on which many other courses build. No previous experience in meteorology, oceanography or any other branch of fluid dynamics is assumed. Prerequisites are relatively modest: mathematics only as far as elementary vector calculus; classical mechanics; and some thermodynamics.

A distinguishing feature of the course is that both atmospheric and ocean circulation are discussed together and the theoretical treatment is complemented by \sim ten 'classic' laboratory demonstrations of (usually rotating) fluid experiments. We have found this to be a very successful component of the course and a very effective way of communicating the subject matter to students.

Accompanying Text book We have prepared a comprehensive set of class notes for course 12.003. It is now intended that these notes be expanded and published as a text book [working title - Circulation of the Atmosphere and Oceans: an introductory text, by Marshall & Plumb]. After preliminary discussions with Academic Press, we have been encouraged to submit a formal proposal. Other texts - see, e.g. [6] - allude to laboratory experiments but none weave them in to the fabric of the text, as we have attempted to do. The book would be useful as the required text or supplementary material for an undergraduate or beginning graduate class for meteorology and oceanography majors, or for more

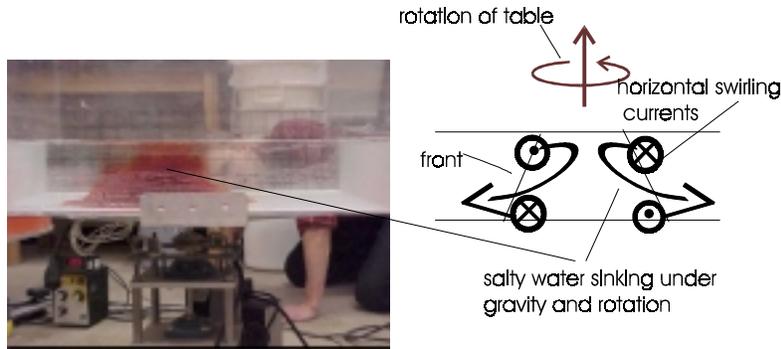


Figure 1: *On the left we see a cylinder of dyed salty (and hence dense) water collapsing under gravity in to a rotating tank of fresh water. Its final state is not the intuitive one, with resting light fluid over dense separated by a horizontal interface. The schematic on the right indicates how the slumping column ‘concentrates’ and ‘dilutes’ the angular momentum of the rotating tank to generate horizontal swirling motions that prevent the column from collapsing.*

advanced classes for those outside these specializations who wish to get a “big picture” perspective on the physics of the climate system. It could also serve as supplementary material for those who wish to understand the fluid dynamics of the atmosphere-ocean system, and of climate, but who are not specialists in dynamics.

3.1.2 12.307 Weather and Climate Laboratory

This Institute Laboratory is designed to illustrate, by means of “hands on” projects, the basic dynamical and physical principles which govern the general circulation of the atmosphere and the day to day sequence of weather events. It expands, in a laboratory/observational/experimental setting, central elements of 12.003, to which it is closely related. Fluid experiments are used to help students explore in a controlled setting the fluid dynamical principles that underlie the natural phenomena they observe in the atmosphere. Students are encouraged to plan the experiment, explain ideas to be tested, observe and record the data. They access and study real-time meteorological observations that complement the laboratory experiments.

During the course of a semester, students working in small groups are engaged in four distinct projects - summarized in Appendix I. Each project lasts for three weeks. Students are required to report on their projects orally to the whole class and discuss the results with their peers. Finally students are asked to critically summarize the results of each project in a written Assignment Report, on which grades are based.

Our aim is to give the students insight into the value of different methods to study and test dynamical ideas and also to illustrate some of the methods used in modern research in dynamical meteorology and oceanography

Perhaps the nature of the Laboratory is best illustrated by outlining an example from Project 2 - FRONTS (see appendix I). Fig.1 shows a laboratory experiment carried out using a rotating table. A front - a region of sharp density contrast - is created by allowing a cylinder of dyed salty (and hence dense) water collapse under gravity in to a rotating tank of fresh water. Because of the spin imparted to the fluid by the rotation of the table, the collapsing column must satisfy an angular momentum constraint. Its final state is not the intuitive one, with resting light fluid over dense separated by a horizontal interface. Instead the collapsed column remains tilted and the fluid contained within it is in horizontal swirling motion having ‘concentrated’ (at the top) and ‘diluted’ (at the bottom) the angular momentum of the rotating table - see schematic in fig.1. The action of gravity trying to make the interface horizontal is balanced by the (difference in) centrifugal forces on the swirling currents induced by angular momentum. The equation expressing this balance of forces - known as the ‘thermal wind equation’ - is central to dynamical meteorology and oceanography. Rather than formally deriving the equation², students end up deducing a discrete version of it - Margule’s formula - by thinking about the balance of torques on the tilted laboratory fronts. They then test it out quantitatively in the laboratory.

As part of the laboratory course students also inspect fronts crossing the country associated with day-to-day variations in the weather using real-time atmospheric observations

²invariably presented in texts as an arid algebraic slight of hand in which the pressure gradient force is eliminated in favor of a density variable, by cross differentiation between the horizontal momentum and hydrostatic equations in the limit of small Rossby number.

using the facilities of our synoptic laboratory. They can check that the observed changes in winds and temperature across the front is consistent with Margule's formula and see that the dynamical balance at work in the atmosphere is the same as in the rotating tank - the laboratory is an abstraction which exposes the underlying processes in a transparent way.

As detailed in appendix I, three other projects are pursued during the course of the semester, each involving a mix of laboratory experimentation and work with meteorological data. We look at how water goes down a drain hole in a rotating system in a 'radial inflow experiment' and its connection to hurricanes; we study convection in a stratified fluid warmed from below as an abstraction of atmospheric convection; we study the rotating annulus as an analogy of the general circulation of the atmosphere.

The course has been offered once, this last semester - as discussed in section 4.1.1 below. We were delighted with how it went, but one major problem recurred and made it difficult to achieve all our objectives. To make our laboratory experiments useful in quantitative study we need to significantly improve the tools we have available to measure velocity and density (salinity and temperature measurements). We are seeking support for the development of quantitative tools.

3.2 Laboratory teaching in GFD at other universities

We are aware of several groups around the country that use rotating fluids laboratories for research in Geophysical Fluid Dynamics: see list in [7]. There are almost certainly many more, particularly if engineering, as well as geophysical applications are included. It is not clear to what extent research activities have yet had a real influence on undergraduate education at many of these institutions. Indeed one of the goals of the present proposal is to find out what is going on - see section 4.1.3. Peter Rhines and William Wilcock at UW are using fluid laboratories to teach undergraduates - see [8]. We have discussed our undergraduate teaching experiences with them and have common goals and approaches. We collaborate closely with WHOI in our research program and in the teaching of graduate students in laboratory experimentation. Jack Whitehead has advised on the design and

physical realization of our undergraduate laboratory.

4 Detailed project plan

4.1 ‘Proof of concept’ laboratory course

4.1.1 Prototype

This last semester we offered our lab course to undergraduates for the first time. Six students enrolled and completed the course. During the 13 week semester, students were involved in 4 core projects, as described in section 3.1.2. Having run through it once we are convinced that the format is a very exciting and effective way of teaching science to undergraduates. We think it makes an excellent prototype.

All enjoyed the experience - the students frequently commented on how much they appreciated the mix of experiment, theory and observation. They enjoyed that the course was not prescriptive but instead encouraged them to help in the design of their experiments - improving them, making them quantitative, suggesting new experiments or introducing twists. The parallel phenomenological studies using real-time meteorological observations succeeded in making the students aware that the laboratory was really just a controlled setting for study of processes going on in nature all the time.

The informality fostered by the laboratory setting enabled instructors to get to know each student very well, both academically and as a person. As instructors it was the closest we have come to creating a research setting with undergraduates - it just does not happen in conventional classes.

Although a success, it is clear that the course would benefit greatly if more quantitative tools could be developed to measure flow vectors and temperature and salinity profiles. Until fairly recently it has been very difficult to get quantitative measurements from laboratory fluid experiments - at the moment we make use of paper dots as fluid markers and tracers (food coloring) to monitor fluid flow. But new technologies - see section 4.2.2 - are now available that will allow us to remotely probe the fluid.

4.1.2 Pilot test

The lab course will be offered in the spring semester in the next three years. We propose to develop the course in the years ahead, testing out ideas and approaches and improving the quantitative elements of the laboratory. We expect enrolment to grow to ~ 12 students working in groups of two or three, rotating between atmospheric data and laboratory experiment. Undergraduate students will be involved in the development and evaluation of the course.

4.1.3 Reports and dissemination of results

Book During the course of the grant we expect to complete and publish the book [Circulation of the Atmosphere and Oceans: an introductory text], by Marshall & Plumb.

Films and web tutorials In the 60's, the National Committee on Fluid Mechanics Films produced 22 films examining basic fluid mechanics. However, only a couple of these deal with rotating flows and they do not cover the topics described above in any detail. Recorded versions of our demonstrations in video recorder and/or web format will provide others the opportunity to show examples of the phenomena without constructing the lab equipment.

Development of laboratory guide We plan to develop a laboratory guide that is strongly linked to the above book. The self-contained guide will present our project-based learning laboratory course, 12.307. It will describe how to manufacture and/or assemble the equipment required to carry out the laboratory demonstrations and take quantitative measurements - see section 4.2 below. We will describe a staged approach in which, for an initial investment of $\sim \$10,000$, a rotating laboratory can be set up and experiments begun.

Market research We believe that the approach to undergraduate teaching that is the focus of this proposal could benefit a wide variety of courses in earth science, meteorology, oceanography, environmental engineering and physics. Sophomores, juniors and seniors

can all benefit because the experiments can be viewed on several levels. We have found that laboratory demonstrations are also very effective in Freshman Seminars drawing them in to undergraduate activities, giving them a feel for a research setting and providing an informal setting in which Professors and undergraduates can get to know one another.

We are aware that much may be going on in the teaching of undergraduates using fluid experiments, of which we are not yet aware - we propose to do an exhaustive survey of the literature (e.g American Journal of Physics; The Physics Teacher) and of our universities - see [7] and [8] - to see what is going on. Faculty at other universities will be asked to help evaluate our ideas - see 4.3.

4.2 Development of supporting experimental apparatus

The philosophy of our lab is to provide students with the tools required to make quantitative measurements of fluid flow and density variations within it. Two portable rotating tables are presently used in our fluids laboratory. Designed for classroom demonstration, they are not ideally suited for the controlled, quantitative experiments that make up 12.307. We require a larger fixed table around which we can deploy instruments - cameras, lasers, computers and probes - to make quantitative measurements.

4.2.1 Construction of 'fixed' rotating table

The proposed rotating table - sketched in fig.2 - is based around a well-braced cube of side 36 inches consisting of four legs, with a $\frac{1}{2}$ inch metal plate on the top and bottom. The bottom plate is pierced by three adjustable feet, used to level the turntable. The drive assembly consists of $\frac{3}{4}$ horsepower AC motor and controller, a worm gear reduction drive coupled to the turntable drive shaft with a cog belt. The motor assembly is mounted on a shelf attached to all four legs. Two sides are open for access and the other two sides have metal panels used for bracing and for mounting the motor controller and accessories used during the experiments. Rotation rates between 0 and 10 revolutions per minute (rpm) are possible with a tolerance of ± 0.02 rpm.

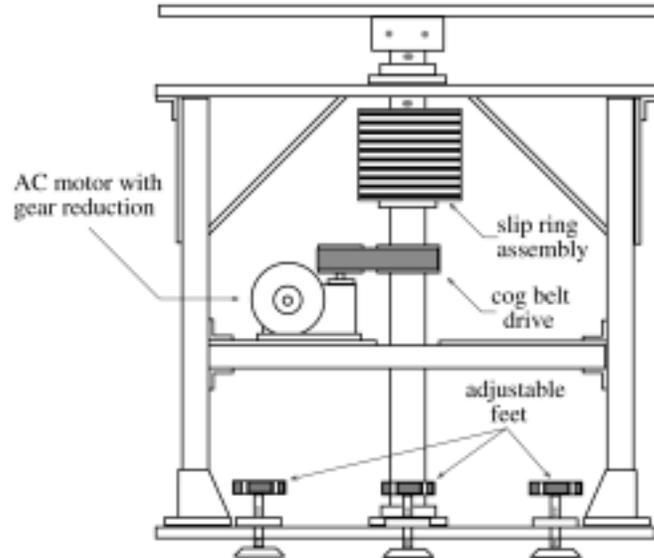


Figure 2: *The Rotating table to be manufactured. Based on a well-braced cube of side 36 inches, the platform can rotate at speeds up to 10 revs per minute.*

4.2.2 Flow visualization

Quantitative measurements are fundamental to the success of our undergraduate lab; consider, for example, “geostrophic balance” in which the Coriolis acceleration should be nearly equal to the pressure gradient force per unit mass associated with the slope of the free surface. To be convincing, the students must be able to measure surface height and fluid velocity accurately. Likewise, in the cylinder collapse problem described in section 3, measurements of density, together with the hydrostatic equation, give pressure information which can be related to the differences between the velocities at various depths. Properties which must be measured are:

1. Velocity (at least two components) at various horizontal positions and depths. Characteristic values are mm/s to cm/s .
2. Surface height variations on the order of millimeters.
3. Density variations produced by temperature (T) or salinity (S) differences. The ΔT values are at most a few degrees and may be a few hundredths of a degree, while

Figure 3: *A co-rotating camera is used to track particles illuminated by a sheet of laser light to obtain velocity measurements. A profiling temperature and salinity probe (conductivity, temperature and density - ctd) moving along a fixed track is used to make in-situ T and S measurements.*

ΔS can be several parts per thousand.

In addition to instrumentation which can provide such information with minimal disturbance to the flow, we must also devise procedures for sampling the fluid at different points — a non-trivial problem, since the whole apparatus is rotating so that we cannot directly reposition probes by hand. We are considering a sampling platform which can be controlled remotely by signals sent through the slip rings - see fig.2.

We plan to put together, with the help and involvement of students, the following set of tools which should provide the capability of measuring the properties of the flow; however, we also anticipate that we may need to try several approaches.

1) Velocity: we will mount a camera so that it rotates in synchrony with the table and seed the fluid with pyrolite particles. The output from the camera will be digitized by a frame grabber and saved to disk. This will provide both visualization of the flow and, by tracking the particles using PIV software (Particle Image Velocimetry - see [9]), velocity

data. We can obtain horizontal velocities at particular depths by illuminating the tank with a sheet of laser light as sketched in fig.3. By varying the position of the light, we can determine the horizontal velocity as a function of the three spatial coordinates. For other experiments, the camera can be mounted on the side of the table and measure one horizontal and the vertical component of the flow. We will also test various flowmeter designs.

2) Surface height: we have thought of a number of possibilities here, but need to examine each carefully. Conductivity can be used to determine when a probe enters the water or the amount of wire which is submerged. We may be able to determine the angle of the surface from horizontal (which is directly related to the pressure gradient) by measuring the reflection of a light beam.

3) Temperature: we plan to use high-accuracy thermistors - see [10] - mounted either on a probe arm or on a track attached to the tank. Salinity: the salt content of water is usually determined by measuring the conductivity and the temperature. We will try various possibilities to find an adequately accurate and inexpensive solution.

4.2.3 Synoptic laboratory

We have long experience in our Synoptic Laboratory in the use of GEMPAK (the Unidata Meteorological Package) to display and manipulate meteorological data - see Appendix II. We are seeking support to purchase PC's running Linux - the Linux version of GEMPAK is now supported by Unidata. Addition of PC's to the lab will be a cost-effective way of making the facilities of our Synoptic laboratory available to undergraduates. One of the PC's will also be used for controlling the data acquisition apparatus shown in fig.3.

4.3 Evaluation

The following approaches will be used:

1. a natural experiment on the students. We are aware of the tension between, on the one hand, the desire to obtain quantitative information from the experiments to build intuition in a facile way and, on the other, that instrumentation can 'get

in the way'. We will compare groups who use the 'unadorned' apparatus without the benefit of precise measurement techniques with groups who make use of the paraphernalia sketched in fig.3. We will ask the students about their experience, compare reports and develop measures of what was learned. Did the technology improve the educational experience?

2. interest and experience of colleagues: we will ask colleagues, both at MIT and other universities - see [7] - (i) what types of experiments would be the most useful in support of their own teaching (ii) which experiments, if any, are commonly used? (iii) is there a need for them? etc.
3. TA's will be asked to fill out forms listing the successes, problems and difficulties encountered on the course. How hard are the experiments, which ones work, which ones do not, which were their favorite experiments?
4. Students will be asked what they think of the course, both in the context of organized feedback through the course evaluation procedure run at MIT, and through questionnaires about their experiences on the course.

5 Experience of the Principal Investigators

Glenn Flierl, John Marshall and Alan Plumb are Professors in the Department of Earth, Atmospheric and Planetary Sciences at MIT - they have collaborated in teaching and research for many years. They have designed many of the core courses used to teach fluid dynamics and dynamical meteorology and oceanography to graduates and undergraduates in EAPS. They are very involved in undergraduate teaching, acting as Freshman Advisors and teaching key courses. They have worked together very closely in designing the undergraduate laboratory that is the focus of the present proposal. They were instrumental in getting the course recognized by MIT as an Institute Laboratory.

Flierl has taught at MIT for 25 years, Marshall was in the Physics Department at Imperial College, London for 10 years before moving to MIT in 1991. Plumb has taught

at MIT since 1987.

Flierl, Marshall and Plumb are also very active in research - see their respective CV's.

6 Resources sought

We request resources to help in the manufacture of the rotating table (section 4.2.1), flow visualization equipment (section 4.2.2) and associated software development. Details can be found in the budget justification. In broad terms the equipment costs are \$40K in year 1, \$10K in year 2 and \$7K in year 3.

To manufacture the apparatus, test it out and develop the associated software, we are requesting support of (i) a technician (Bud Brown) for 2 months in years 1 and 2, and 1 month in year 3 and (ii) a lecturer (Lodovica Illari) for 6 weeks in year 1 and 1 month in years 2 and 3. She will carry out the setting up of GEMPAK (a meteorological data analysis package) on PC's running LINUX and support the data logging and remote control software for the flow visualization hardware.

Bud Brown is an experienced technician who has developed our portable rotating tables and oversees our fluids laboratory. Lodovica Illari is a lecturer in EAPS with a Ph.D in Meteorology and 15 years of experience in research and teaching in meteorology. She maintains the Synoptic Laboratory of EAPS.

6.1 Cost-sharing

The laboratory course is important to the educational activities of our Department and MIT. The Institute makes available part support for Brown and Illari. In addition we received start-up funds for 12.307 ~ \$10K - from MIT. These were used in the renovation of the laboratory space and the purchase of new tanks in which to carry out our experiments. We now have a pleasant and more spacious space in which to teach our laboratory courses.

MIT is happy to cost-share the cost of the proposed work - see enclosed letter contributing \$71,320.

7 Future intent

If the prototype is successful we plan to seek further support, under CCLI-EMD/ND, for fuller development of the educational materials and ideas that have been produced. We plan to publish the laboratory guide as a book which would companion our undergraduate book: Circulation of the Atmosphere and Oceans: an introductory text. The guide would set out the science and curriculum context, describe experiments in detail (including how to manufacture and assemble the apparatus) and the parallel studies possible with meteorological data.

We would also seek support to organize interested parties to meet for summer tutorials to discuss our experiences, exchange information and know-how. One important element for discussion is the way in which the laboratory content can be broadened to embrace other disciplines, so that it transcends rotating fluid dynamics and makes connections with, for example, geophysics, planetary science, biology etc. Most likely this would be carried out in collaboration with Jack Whitehead of Woods Hole and Peter Rhines of University of Washington.

Depending on the scale of interest, we would consider approaching a company for commercial manufacture of key laboratory components.

8 References

- [1] Modern Classical Physics through the work of G.I. Taylor by M. Brenner and H. Stone; May 2000 Physics Today
- [2] Chaos Rules by S. Gedzelman, August/September 1994; Weatherwise
- [3] Development of geophysical fluid dynamics: The influence of laboratory experiments by J. S. Turner; Appl Mech. Rev vol 53, no3, March 2000
- [4] 12.003: Physics of the fluid earth
- [5] 12.307: Weather and Climate Institute Laboratory
- [6] The following are excellent text books. However, none make use of laboratory experiments and only one - Hartmann - treats both the atmosphere and the ocean

Hartmann: Global Physical Climatology

Holton: An Introduction to Dynamic Meteorology

Wallace and Hobbs: Introduction to Atmospheric Sciences

Houghton: The Physics of Atmospheres

[7] We are aware of several groups that use rotating fluids laboratories for research in GFD - this is an incomplete list.

Arizona State University: <http://www1.eas.asu.edu/~pefdhome/PEFDLab.html>

Florida State University: <http://www.gfdi.fsu.edu/>

University of Colorado: Dr. John Hart

University of Rhode Island - <http://www.gso.uri.edu/facilities.html>

University of Southern California: http://ae-www.usc.edu/rsg/gfd/gfd_index.html#rsp

University of Washington: <http://www.ocean.washington.edu/fluids/>

Virginia Tech: <http://www.aoe.vt.edu/aoe/physical/fms.html>

Woods Hole Oceanographic Institution: <http://www.whoi.edu/science/PO/dept/>

[8] William Wilcock's undergraduate fluid lab at UW: <http://fluids4.ocean.washington.edu/>

[9] Time-series PIV measurements in a large rotating tank by L. Tarbouriech, H Didelle and D. Renouard: Experiments in fluids 23 (1997) 438-440

[10] Information on ctd probes: http://fluids4.ocean.washington.edu/using_equipment/index.html