

# “WEATHER IN A TANK”

## Exploiting Laboratory Experiments in the Teaching of Meteorology, Oceanography, and Climate

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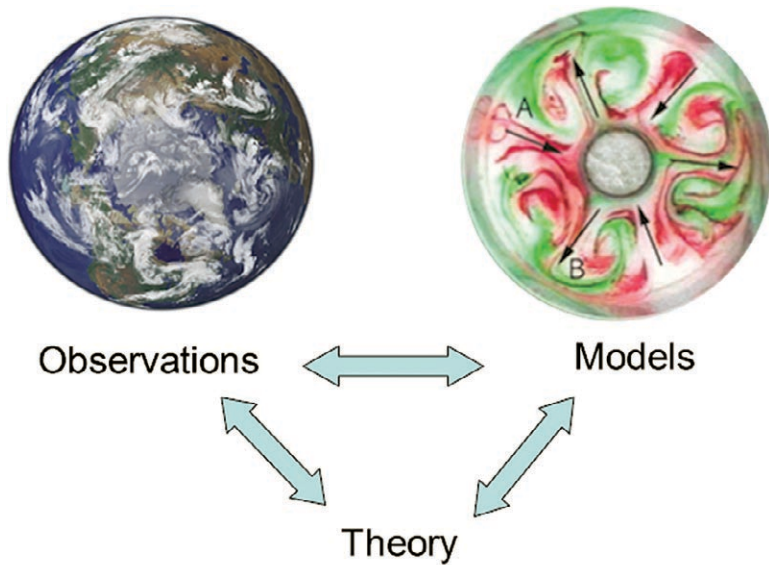
Six universities collaborated to improve the teaching of atmosphere/ocean dynamics using rotating lab experiments and real-time data, in the process helping students move more adeptly between theory, models, and observations.

According to the American Meteorological Society (AMS), roughly 85 universities offer undergraduate degrees in meteorology and/or oceanography in the United States, and the undergraduate meteorology population is rapidly expanding (see Knox 2008). Laboratory fluid experiments, however, play a minor role in the education of these students. This is in the context of a field of research that is increasingly dominated by large coordinated programs to gather observations, present and manipulate those observations using Web resources, and attempt to simulate them on the computer. We argue here that an educational experience that focuses on fundamentals, and involves the study of idealized abstractions in the context of real-world data, would greatly aid our students' understanding and intuition about the dynamics of a fluid on a rotating, differentially heated sphere and how that dynamics helps to shape the climate of the Earth.

To give an immediate example of the approach we advocate, Fig. 1 (following page) shows a satellite image of the Earth revealing midlatitude weather systems (the North Pole is in the middle) “stirring” properties between the Equator and the Pole. On the right is a dishpan laboratory experiment in which a bucket of ice placed in the center of a rotating tank of water induces a horizontal temperature gradient. Paper dots and colored dyes reveal circulation patterns in the laboratory that arise from the same fundamental principles that govern atmospheric synoptic-scale weather systems. The laboratory model is a simplified system that abstracts the essence of ►

Detail of patterns in Jupiter's atmosphere. See Fig. 5 for more information





$$\begin{aligned} \left(\frac{DA}{Dt}\right)_{in} &= \hat{x} \frac{DA_x}{Dt} + \hat{y} \frac{DA_y}{Dt} + \hat{z} \frac{DA_z}{Dt} \\ &+ \left(\frac{D\hat{x}}{Dt}\right)_{in} A_x + \left(\frac{D\hat{y}}{Dt}\right)_{in} A_y \\ &+ \left(\frac{D\hat{z}}{Dt}\right)_{in} A_z \end{aligned}$$

a seemingly complex phenomenon so that its essential cause can be studied in isolation. Through the study of this laboratory system, in the context of, and motivated by, atmospheric observations and appropriate mathematical theory—the third “leg of the stool” in Fig. 1—students learn that weather systems are the result of two essential ingredients: the Earth’s rotation

**FIG. 1.** An educational approach is advocated here that draws together the three elements illustrated in the figure. **(left) Observations:** a view of the Earth over the North Pole with Arctic ice in the center. The white swirls are clouds associated with atmospheric weather patterns. **(right) Laboratory models:** baroclinic eddies, dynamically analogous to weather systems seen in the satellite picture, created by the instability of the thermal wind gradient in a dishpan induced by the presence of the ice bucket at the center of the rotating tank. **(bottom) Theory** of rotating fluids is used, for example, to identify key nondimensional numbers, write down simple solutions, and generally build the link between real-world phenomena and laboratory abstractions.

and the pole–equator temperature gradient.

Such 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 (Turner 2000)—they become rigid parallel to the axis of rotation, a result that has wide implications for phenomena ranging from Jupiter’s Giant Red Spot to the circulation of the atmospheres and oceans (Brenner and Stone 2000). Regime transitions in rotating annulus experiments led professor Edward Lorenz of Massachusetts Institute of Technology (MIT) to ask fundamental questions that set the stage for his discovery of chaos and a new branch of science (Gedzelman 1994).

Laboratory experiments should be, but are often not, at the center of teaching meteorology, oceanography, and climate at undergraduate and graduate levels. At a recent AMS education symposium, for example, Pandya et al. (2004) called for a reform of geoscience education, including the atmospheric and related sciences, stressing “efforts to improve the authenticity of the science experience, by building inquiry and investigation into formal and informal science experience.” Typically, students coming into our field have no background in fluid mechanics or exposure to the nonintuitive nature of rotating fluid dynamics. Moreover, many undergraduates are not prepared for a full theoretical development of the subject. As discussed in a recent article by Roebber (2005), there is a need to bridge the gap

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between theory and real phenomena. Because rotation is considered a rather abstract and challenging concept, it is tempting to postpone the discussion to more advanced courses. Instead, here we advocate for rotating fluid experiments as a wonderful vehicle that can be used to broach the fundamentals and bridge the gap between the phenomena and theory. Our experience is that simple but artfully chosen 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 link phenomena in the real world to laboratory abstractions, theory, and models. Moreover, it is not widely appreciated that sophisticated equipment, and the backup of a research quality GFD laboratory, is not required: much can be achieved with simple, relatively inexpensive equipment (McNoldy et al. 2003).

To test if such an approach to undergraduate teaching can benefit a wide variety of students enrolled in earth science, meteorology, oceanography, environmental engineering, and physics, faculty and students at the following six universities have been working collaboratively in a National Science Foundation (NSF)-funded project entitled *Weather in a Tank* (see Illari and Marshall 2006): University of Massachusetts (UMass) at Dartmouth, The Johns Hopkins University, Millersville University, Pennsylvania State University, University of Wisconsin—Madison, and Massachusetts Institute of Technology (lead institution). Now, as the project nears completion, some 500 students have been exposed to the experiments across this diverse range of institutions. As described here, we are finding that the approach is effective in a rich variety of settings: from outreach activities and demonstrations to large introductory classes for nonscience majors, mainstream meteorology and oceanography courses, and more advanced laboratory courses for undergraduate majors in atmosphere/ocean/climate sciences. Figure 2 shows a collage of photographs of students engaged

with rotating fluid experiments, ranging from middle-school students through to undergraduate freshmen. Students are fascinated by the direct experience with rotating fluids: they love to get their hands “wet” and are intrigued and surprised by the unusual behavior of rotating fluids.

Our account is set out as follows. A description of the development of laboratory experiments and equipment, together with associated curriculum and projects, is described in the “Combining laboratory experiments, observations, and theory” and “Development of supporting materials” sections. Vignettes, giving examples of the experiences of each of the participating universities, are presented in the “Implementation and experience of collaborating universities” section. Evaluation methods developed for the project, and preliminary results of that evaluation, are presented in the “Evaluation of the project” section. We summarize and conclude with the “Summary and future plans” section, where we also emphasize the use of laboratory experiments in outreach activities, briefly place our study in the wider context of related educational initiatives, and discuss our plans for the future.



**FIG. 2. A collage of photographs showing students interacting with *Weather in a Tank* experiments: (clockwise from top left) undergraduate laboratory class at MIT, Cambridge, MA; middle-school girls involved in a *Women in Science* activity at Melida Middle School, Northborough, MA; incoming MIT freshmen; and high-school students at the Monona Grove High School in Madison, WI.**

### COMBINING LABORATORY EXPERIMENTS, OBSERVATIONS, AND THEORY.

Perhaps the philosophy we are advocating is best illustrated by outlining an example from a project on atmospheric fronts (see Fig. 3). A front, a region of sharp density contrast, is created by allowing a cylinder of dyed salty (and hence dense) water to collapse under gravity into a rotating tank of freshwater. 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 upright, 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. 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 (see Fig. 3, top right). The equation expressing this balance of forces—known as the “thermal wind equation”—is central to dynamical meteorology and oceanography.

Rather than just formally deriving the equation (invariably presented in texts as an arid algebraic sleight 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), students end up deducing a discrete version of it—Margules’ formula—by thinking about the balance of torques on the tilted laboratory fronts, as sketched in Fig. 3 (bottom right), showing a two-layer system with light fluid  $\rho_2$  on top of dense fluid  $\rho_1$ , separated by a discrete interface sloping at angle  $\gamma$ :

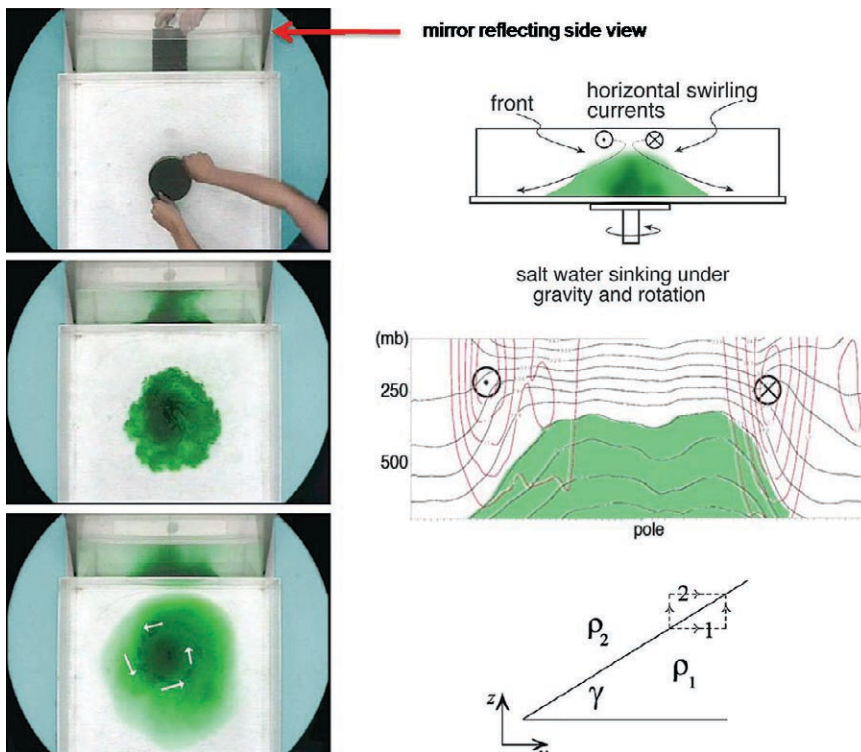
$$v_2 - v_1 = \frac{g' \tan \gamma}{f}, \quad (1)$$

where  $v_{1,2}$  are the component of the current parallel to and on either side of the front,

$$g' = g \frac{(\rho_1 - \rho_2)}{\rho_1}$$

is the “reduced gravity,” and  $f = 2\Omega$  is twice the rotation rate  $\Omega$  of the tank.

Students can use Eq. (1) to predict the slope of the sides of the cone observed in the laboratory



**FIG. 3. Fronts experiment:** (left) series of pictures charting the creation of a dome of salty (and hence dense) dyed fluid collapsing under gravity and rotation. The fluid depth is 10 cm. (bottom left) The white arrows indicate the sense of rotation of the dome and table. At the top of each panel we show a view through the side of the tank facilitated by a sloping mirror. (top right) A schematic diagram of the column of salty water. The column is prevented from slumping all the way to the bottom by the rotation of the tank. Differences in Coriolis forces acting on the spinning column provide a “torque” that balances that of gravity acting on the salty fluid trying to pull it down. (middle) Observations of the dome of cold air are over the North Pole (in green) associated

with strong upper-level winds, marked by  $\otimes$  and  $\odot$  and contoured in red. (bottom) A simple model of a front following Margules (1906). We imagine a two-layer system with light fluid  $\rho_2$  on top of dense fluid  $\rho_1$ , separated by a sloping, discrete interface. The horizontal axis is  $x$ , the vertical axis is  $z$ , and  $\gamma$  is the angle the interface makes with the horizontal. For more details see Section 7.3.3 of Marshall and Plumb (2008).



experiments from the difference in density between the cone and the ambient fluid, and the measured swirl velocities and density gradients. Students also inspect fronts crossing the country associated with day-to-day variations in the weather using real-time atmospheric observations (see Fig. 3, right) and the “Observations” section. They can verify that the observed changes in winds and temperature across the front are consistent with Margules’ formula and discover that the dynamical balance at work in the atmosphere is the same as in the rotating tank—the laboratory is an abstraction that exposes the underlying processes in a transparent way.

**DEVELOPMENT OF SUPPORTING MATERIALS.** The success of the project hinged on the development of the following components:

- simple, transparent experiments targeting fundamentals that are easy to perform, suitable for demonstrations in lecture-based courses and/or in laboratory courses, and able to capture the interest of students;
- curricular materials designed for use with the experiments that make direct links to observed phenomena in the context of theory; and
- portable, cost-effective, and easy-to-use equipment.

*Experiments and associated curriculum.* Great effort has been put into the development of a growing number of projects, of the kind presented in the previous section, ranging from introductory, fundamental aspects of rotating fluid dynamics to those that draw a number of elements together and relate, for example, to the general circulation of the atmosphere and the ocean. A list of all the projects together with a brief description can be found in Table 1 and the project Web site (<http://paoc.mit.edu/labguide> and its associated Wiki site) where students are encouraged to post their results and experiences. Experiments that pertain to both atmospheric and oceanographic phenomena are supported.

Each project is organized as follows: 1) an experiment is described; 2) resources—such as data, movie loops, maps, photographs, among others—that relate to phenomena in the real world are indicated; and 3) relevant theory is highlighted. Our desire is to provide a resource rather than to be prescriptive. We do not expect professors and teachers to adopt all experiments or even all aspects of a particular experiment. We invite them to pick and choose, to modify as appropriate to fit the particular students, context, and type of the course in which they are involved.

*Laboratory equipment.* The experiments listed in Table 1 have been chosen for their transparency and simplicity—indeed, this is a large part of their appeal and effectiveness in pedagogy. The experiments do not require sophisticated or expensive apparatus to carry them out. An expenditure of a few thousands dollars is all that is required. The central piece of equipment required to perform the experiments is a turntable. An example of the turntable we employ is shown in Fig. 4. The turning platform—the dial—is 18 in. × 24 in. The turntable has a simple but effective design; drive is achieved through a friction wheel on the underside of the dial driven by a variable speed motor (Fig. 4c). This endows the machine with a built-in clutch, so should someone inadvertently grab hold of the turntable or bump it, it will immediately come to rest and the motor remains spinning. The experiments are carried out in a square 16 in. × 16 in. tank placed on the rotating dial, as can be seen in Fig. 4. A circular insert can be placed inside the square tank and is perfectly adequate for those experiments that demand a circular geometry.

The experiment is viewed from a video camera corotating with the dial, whose signal is passed through a slip ring for display in the laboratory frame, either on a monitor or a projection device. There is a digital readout of the speed in revolutions per minute (rpm): the table can turn at between 1 and 30 rpm. Power to the table is only 12V, an added safety feature because of the close proximity of water, but sufficient to power (via the slip ring) pumps and fans in the rotating frame. Four 110 AC ground fault circuit interrupter (GFCT) power outlets are supplied on the monitor support to power the 12V system, video monitor, and any other ancillary equipment. The table itself is sturdy and lightweight, being constructed of high-quality, cabinet-grade plywood and finished with a water-resistant precatalyzed lacquer.

The turntable can be installed on the mobile cart (shown in Fig. 4a), which can be used to transport the equipment to where it is to be used and as a platform to carry the experiment. The cart is equipped with a 10-gal water storage tank (blue) and pump, a tray to store and carry assorted materials—such as ice buckets, cans, beakers, dyes, among others—and a post on which to place a liquid crystal display (LCD) television monitor for convenient display of the experiment from the rotating camera.

All collaborators have found the apparatus easy to use and to transport. The entire system (turntable, cart, camera, display, motors, electronics, pumps, tanks, and assorted equipment in support of many

of the experiments) is available from Dana Sigall (e-mail: dsigall@gmail.com), a craftsman working in Gloucester, Massachusetts. More details of the apparatus and the equipment required to carry out the experiments can be found online (<http://paoc.mit.edu/labguide/apparatus.html>).

**Observations.** The utility and availability of the NSF's University Corporation for Atmospheric Research (UCAR) Unidata's Internet Data Distribution (IDD) system cannot be overemphasized in the implementation of our project because it enables students to acquire and use real-time atmospheric and related data. We have made use of the infrastructure already

in place but have significantly customized it for use in the project. In particular, we have created a synoptic laboratory Web site at MIT (see Illari 2001) with a front end to Unidata's services, which readily serves up meteorological data to a student sitting at a browser in a manner that is customized for our projects (sections, vertical profiles, and horizontal maps cutting through the atmosphere). It allows instructors to plot fields interactively during class time, engaging students with "real" examples and, along with the laboratory experiments, helping to bring the data to life. This is consistent with the efforts by our community to bring data (atmospheric and oceanographic) into the classroom (see Kruger et al. 2005).

**TABLE 1. The projects currently supported in the Weather in a Tank project, as of summer 2008. This list is continually expanding. The listed projects are fully developed in the project Web site (<http://paoc.mit.edu/labguide/introduction.html>). A significant number of the projects are also woven into the text of a new undergraduate book by Marshall and Plumb (2008). The experiments are broadly grouped into atmosphere and ocean categories; however, many experiments have relevance to both categories. The three elements—1) experiment, 2) real-world example, and 3) theory—are indicated.**

List of projects	
Atmosphere	
Dye stirring	1. Interleaving patterns of colored dyes stirred into a rotating fluid
	2. Earth's water vapor distribution, imagery of the giant gas planets
	3. Taylor–Proudman theorem, Rossby number
Solid-body rotation	1. Parabolic shape of free surface of water in solid-body rotation
	2. Geoid, shape of rotating planets: Earth, Jupiter
	3. Gravity, equipotential surfaces
Balanced motion	1. Radial inflow: Flow of water down a drain hole in a rotating system
	2. Intense atmospheric vortices, such as polar lows, hurricanes
	3. Rossby number, balanced motion, angular momentum conservation
Fronts	1. Cylinder collapse under rotation, gravity
	2. Atmospheric fronts are studied using synoptic charts, sections
	3. Thermal wind: Rossby adjustment problem
Ekman layers	1. Ageostrophic flow in a bottom Ekman layer
	2. Surface, upper-air winds fields in highs, lows
	3. Ekman layers, ageostrophic motion
Convection	1. Convection in a stratified fluid heated from below
	2. Evolution of dry atmospheric convection during the day
	3. Potential temperature, stability
General Circulation: Hadley regime	1. Axisymmetric flow at low rotation in a dishpan
	2. Hadley circulation, westerly winds, trade winds
	3. Thermal wind, angular momentum transfer
General Circulation: Eddy regime	1. Baroclinic instability at high rotation in a dishpan
	2. Weather systems, global energy balance
	3. Baroclinic instability, eddy heat transfer

**FIG. 4.** (a) Turntable on a portable cart equipped with water supply (10-gal blue tank), pump, power, and tray to store and carry assorted materials, flat screen monitor for display, and digital video disk (DVD) recorder. (b) Turntable with 16 in. × 16 in. × 8 in. perspex tank placed on top of the dial in which experiments are carried out. A circular insert is used to render the tank cylindrical, convenient in some applications. The experiment is viewed from a video camera with the zoom lens corotating with the turntable, whose signal is passed through a slip ring for display in the laboratory frame, either on the flat screen monitor and/or projection device for large audiences. (c) Drive is achieved through a friction wheel on the underside of the dial driven by a variable-speed motor, giving the device a built-in clutch mechanism. For more information on the turntable, contact Dana Sigall (dsigall@gmail.com).

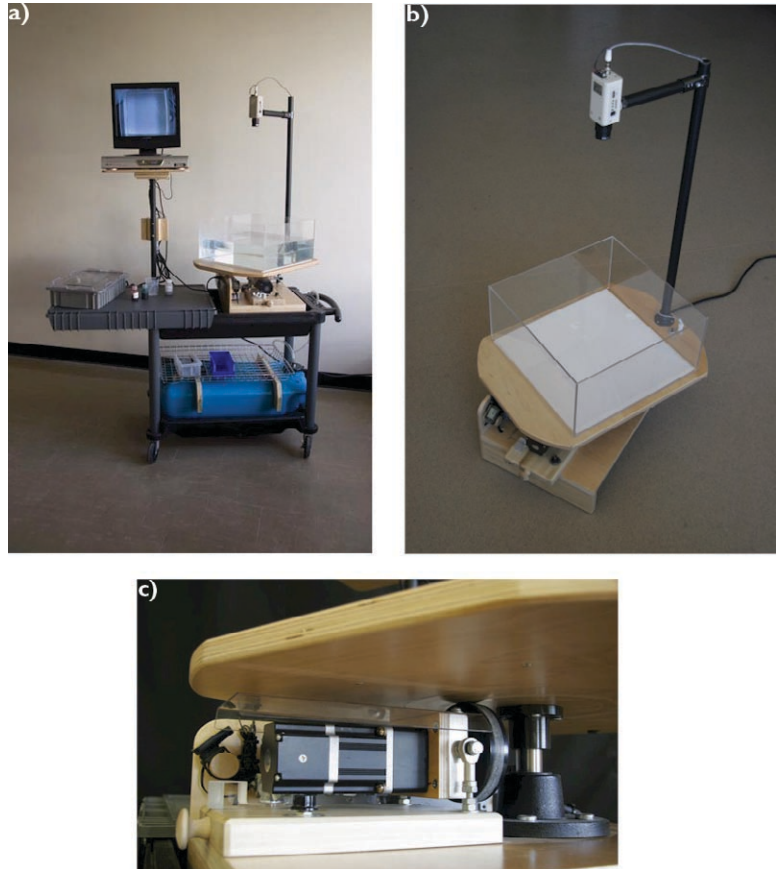


TABLE I. Continued	
<b>Ocean</b>	
Taylor columns	1. Flow over a submerged obstacle
	2. Flow over mid-Atlantic Ridge
	3. Taylor–Proudman theorem
Density currents	1. Marsigli experiment
	2. Density-driven currents
	3. Hydrostatic balance, available potential energy
Ekman pumping	1. Wind-driven circulation (using fans)
	2. Large-scale upwelling, downwelling
	3. Coriolis force, Ekman pumping, suction
Ocean gyres	1. Wind-driven circulation on a $\beta$ plane
	2. Ocean gyres, western boundary currents
	3. Sverdrup theory
Thermohaline circulation	1. Stommel–Arons experiment
	2. Thermohaline circulation of ocean
	3. Taylor–Proudman on the sphere
Source–sink flow	1. Source–sink flow on a $\beta$ plane
	2. Middepth/abyssal circulation of ocean
	3. Flow along $f/h$ contours, zonal jets

For example, in the fronts project shown in Fig. 3, sections across the polar front and across synoptic frontal systems are drawn from current weather data and similarities/differences with the laboratory are drawn out. The theory [Eq. (1)] used to rationalize the laboratory data is also used to interpret observed wind shears and frontal slopes.

*“Rollout” in class.* Many of us have likely experienced the dismay—and frustration—of having worked for days on a new experiment, only for it to work perfectly yet flop pedagogically and singularly unimpress when it is unveiled in class. This is invariably because insufficient attention was spent on the educational context—the “rollout” in class. The Weather in a Tank group have exchanged many tips on how best to use the experiments in both a classroom (demonstration) and laboratory (hands on) setting. Nearly all the experiments listed in Table 1 are robust, work every time, and are easy to carry out once they have been explored (offline) by the instructor.

Here are some general tips:

1. Set up the experiment before class—it typically takes 5–10 minutes or so. Never set up live in front of the class.
2. Even if you have a technician or teaching assistant available, do the experiment yourself. Even better, invite one or two students from the class to help you—for example, administer dye or float paper dots.

3. Attempt to weave the experiment into the narrative of the class and the course.
4. Encourage students to make predictions (see next tip).
5. Avoid attempting to explain everything while it is happening—let the students observe.
6. Always connect the experiment to the real world using theory as appropriate.

Tips on individual experiments can be found on the Web site. By way of example, here we describe ways of deploying the “dye stir” experiment (see Fig. 5). This is a memorable demonstration that can be used to introduce students to the remarkable properties of rotating fluids. It is particularly effective in outreach and introductory classes, but it is useful at all levels. Easy to carry out, it involves squirting in colored dyes shortly after a rotating fluid, initially in solid-body rotation, is gently agitated with one’s hand. Patterns of great aesthetic beauty result, which have a direct link to the real world, as shown in Fig. 5. If one is somewhat parsimonious in the application of dye, it can be repeated several times in sequence without the need to drain and recharge the tank.

We have found it useful to present the experiment (as for many of the experiments listed in the table) as one of a matrix of four shown in Fig. 6; in this case the axes are “rotation” and “agitation.” Students are introduced to each experiment, starting from the simplest (experiment 1, the null experiment in which there is no agitation or rotation) to the most complex (experiment 4, in which both effects are present). Before each

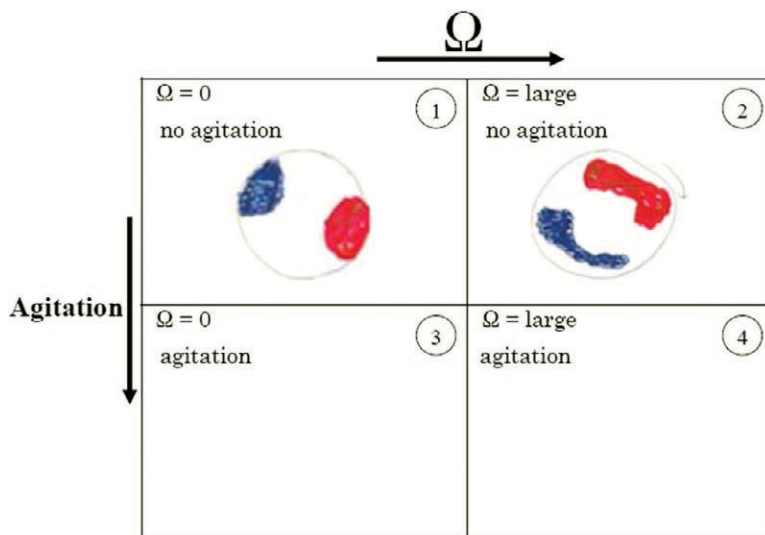


**FIG. 5. Dye-stirring experiment. Notice the qualitative similarities between the tracer patterns in the (left) dye-stirring experiment and the patterns evident in Jupiter’s atmosphere, such as (right) the Giant Red Spot. (False-color image from Voyager I, courtesy of Image Processing Lab at Jet Propulsion Laboratory, NASA)**



experiment is carried out, students are asked to make predictions by sketching what they expect to see happen, for example, with colored markers (see Fig. 6, right). Coauthor of this paper Amit Tandon reports, “This approach forces the class to be interactive, though many students do not like to make a prediction for the fear of being proven wrong. The positive part in our experience is that the students then have a stake in the outcome of the demonstration and get more interested in the results of the demonstration.” One of the educational benefits of making predictions is that it activates students’ prior knowledge of a phenomenon, whether theoretical or experiential, and prepares them to better understand the experiment, recognize important elements, and be prepared to identify relationships among variables. This approach can also help with the teaching of science to nonscience majors by demystifying the scientific method. Science-phobic students often do not realize that science is little more than ordering of facts taken by careful observation and the willingness to make sensible guesses that one tests with data!

Experiment 1 might seem trivial, but it provides a context to talk about how a tracer disperses in a fluid in the absence of advection—particularly useful for young students—in contrast with experiment 3 in which advection is at play. Experiment 2 focuses on solid-body rotation [a project in its own right (see Table 1)], a concept that is not immediately obvious to students. It offers the opportunity to discuss “frames of reference.” Students of all ages and backgrounds are surprised by solid-body rotation when first exposed to it. For example, Fig. 6 (right) shows a typical sketch provided by a student, in this case a first-year undergraduate science major. Most students conjecture—as in Fig. 6 (right)—that the dye will swirl out to the periphery following the rotation of the tank. We might have expected that middle- and high-school students were not familiar with the concept of solid-body rotation and frames of reference, but we were surprised to find that it was also not immediately obvious to college students, both undergraduates and graduate students. The obvious (strong) rotation of the tank leads students to believe that experiment 2 should be somehow more “energetic.” The fact that the dye is essentially motionless in the solid-body rotation



**FIG. 6. A  $2 \times 2$  matrix of experiments used in the dye-stirring experiment to introduce students to the effects of rotation on fluids, together with student sketches of what they expect to see happen.**

state seems paradoxical for some students who are thinking about energy.

Experiment 4 shows what happens when advection and rotation act together, spectacularly revealing the organized 2D nature of rotating fluids (see Fig. 5). We observe beautiful vertical streaks of dye falling vertically (Taylor columns); the vertical streaks become drawn out by the horizontal fluid motion into vertical “curtains” that wrap around one another. Students immediately see that dye “stirred” into the rotating body of water behaves in a very different manner from that in the nonrotating case (experiment 3). All students are fascinated and very intrigued by what happens, even more so when connections are made to natural phenomenon, such as flow patterns on Jupiter and the giant gas planets.

To help connect to real-world examples, a more quantitative analysis in terms of the Rossby number can also be carried out. This key parameter of rotating fluids gains a new life when computed with both experimental and real-world data. The use of such nondimensional numbers teaches students that we can draw meaningful parallels between the “small” rotating tank experiment over which they have total control and “large” real-world phenomena over which they have no control and are much more difficult to observe and study.

*Supporting Web materials and undergraduate textbook.* All experiments developed thus far (as listed in Table 1), together with the accompanying curriculum materials, have been collected in our project Web site

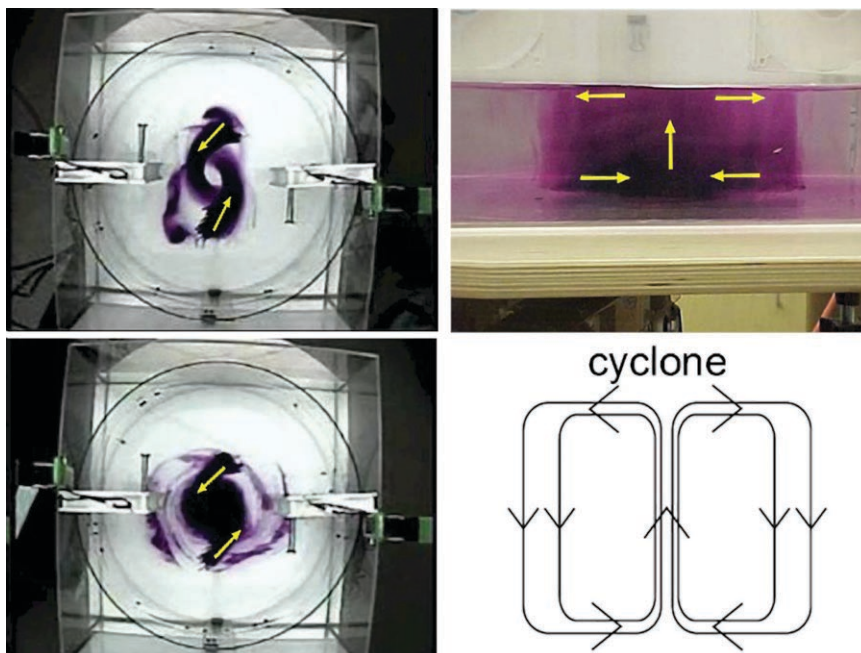
(<http://paoc.mit.edu/labguide>). The Web site has been critical in keeping all project materials and information organized and easily accessible. It contains detailed information about what apparatus is required, instructions on how to carry out the experiments, video of previously performed experiments, connections to relevant atmospheric or oceanographic data, some discussion of relevant theory, and suggestions to teachers. The Web site has been widely used by instructors and students at the collaborating universities, leading to constant improvements and updates of its content. To further improve this exchange of ideas, we have recently expanded it to a Wiki site with blog capabilities.

Our experiences in teaching undergraduates with laboratory experiments has influenced the new undergraduate textbook by John Marshall and R. Alan Plumb titled *Atmosphere, Ocean, and Climate Dynamics: An Introductory Text*, recently published by Academic Press. The book contains a detailed discussion of the dynamics of the atmosphere and ocean, interweaved with data and many examples of relevant laboratory experiments. The book is intended for undergraduate or beginning graduate students in meteorology and oceanography or anyone who wishes to get a “big picture” of what the atmosphere and oceans look like, how they behave on a large scale, and why.

**IMPLEMENTATION AND EXPERIENCE OF COLLABORATING UNIVERSITIES.** Each of the six universities chose to target specific courses

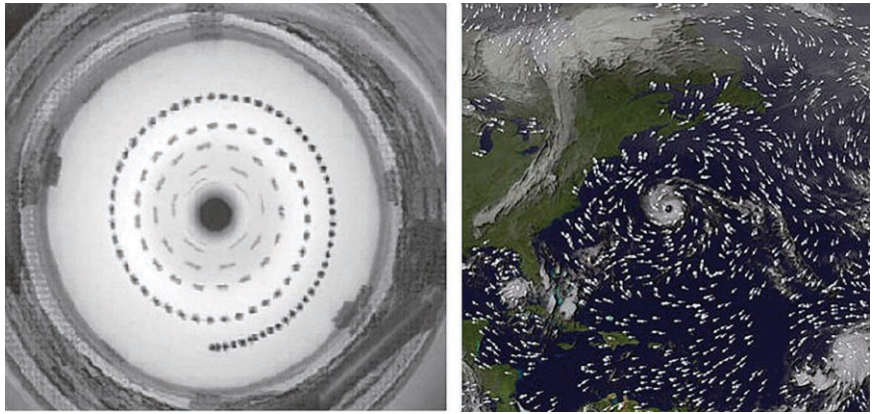
for exposing students to experiments: some were undergraduate courses for nonscience majors; others were undergraduate courses in atmosphere, ocean, or climate; and a few were more advanced atmospheric sciences courses for seniors or graduate students. A list of all the courses and instructors can be found on the project Web site (<http://paoc.mit.edu/labguide/assess.html>). To give an idea of the range of experiences and implementations, we present one example from each of the universities.

**UMass Dartmouth.** Under the leadership of professor Amit Tandon, rotating fluid experiments were used in both introductory and more advanced classes. Students were challenged to develop extensions or new ideas to demonstrate the concepts they had learned. One particularly fruitful project was initiated by physics undergraduates David Beesley and Jason Olejarz, who suggested and tried using computer cooling fans to demonstrate Ekman pumping and suction. To create the cyclone/anticyclone, two fans are attached to the edge of the tank. The wind-driven circulation is observed using a combination of potassium permanganate crystals and floating paper dots at the surface (see Fig. 7). A discussion about the Great Pacific Garbage Patch (Silverman 2007) before or after this demonstration can be very motivating. It is pleasing to report that the students wrote a paper on their work, published it, (see Beesley et al. 2008) and presented their ideas at an AMS meeting. The course of instruction begun under the Weather in a Tank project has now become an official physics laboratory at UMass Dartmouth and supporting laboratory space has been acquired.



**FIG. 7. Wind-driven cyclone/ Ekman suction experiment.** (left) Bottom circulation revealed at two successive times in the evolution of a cyclone driven by fans blowing air over the upper surface. Flow spiraling inward is revealed by potassium permanganate crystals resting on the bottom of the tank. (top right) Side view showing fluid rising in the core of a cyclone from the bottom all the way up to the surface. (bottom left) Schematic showing the ageostrophic overturning circulation in the cyclone.

*The Johns Hopkins University.* Professor Tom Haine used rotating fluid experiments both in introductory and more advanced undergraduate courses. His experience with an introductory course to a large (~100 students) class of nonscience majors is particularly illustrative. The balanced motion (radial inflow) experiment was used as a demonstration of the effect of rotation on fluid motion (Fig. 8, left). Parallels are drawn with the balance of forces in cyclones and hurricanes, using scatterometer wind data—see,



**FIG. 8. Balanced motion in the radial inflow experiment. (left) Trajectories of particles floating on the surface of a rotating fluid circling around and down a drain hole in the center. (right) Surface winds in Hurricane Erin from the SeaWinds instrument on the Quick Scatterometer (QuikSCAT) satellite, 10 Sep 2001.**

for example, winds from Hurricane Erin shown in Fig. 8 (right). Tom Haine says: “The experiment was very successful and gave unambiguous results. I made the connections to hurricanes/tornados, which seemed to be well-received.”

*University of Wisconsin—Madison (U. Wisconsin).* Professors Galen McKinley and Michael Morgan have made use of the following experiments: Taylor columns, fronts, Ekman layers, wind-driven circulation, abyssal ocean circulation, Hadley circulation, and baroclinic instability in atmospheric and ocean dynamics courses. Students were then invited to choose one of the experiments for more detailed exploration and were required to write a report about it. Students enjoyed the labs, as evidenced from U. Wisconsin student evaluation comments:

“This was one of the best parts of the class. Especially for visual learners.”

“It was good to actually get us doing our own experiments.”

*Millersville University.* Specializing in undergraduate education, professors Richard Clark, Todd Sikora, and Ajoy Kumar used the experiments in a variety of courses—from senior-level courses in climate dynamics, mesoscale and storm-scale meteorology, synoptic meteorology, and oceanography to junior-level courses in atmospheric dynamics and thermodynamics. A group of students became interested in expanding the fronts experiment by placing light fluid inside the central cylinder instead of (as in Fig. 3) heavy fluid. As professor Todd Sikora reported in his

weekly instructor log: “This was a great demo and the students enjoyed seeing the 4-D effects of the thermal wind relationship.” Professor Ajoy Kumar found the ocean experiments helpful not only in courses for oceanography majors but also in introductory non-oceanography courses. He reports his students saying: “Show us more hands-on experiments like these!”

*Pennsylvania State University.* Under the supervision of professors Sukyoung Lee, Ray Najjar, and Peter Bannon, experiments were successfully used as demonstrations in introductory courses to atmospheric/ocean dynamics. Furthermore, Lee built a graduate laboratory course around the experiments and found that the experiments were very successful in engaging the students and making their learning more active. Peter Bannon introduced the Weather in a Tank group to the Marsigli Density Current experiment (see also Gill 1982). When waters of two different densities meet, the denser water will slide below the less dense water, forming a density current. This is one of the primary mechanisms by which ocean currents are formed. It was first carried out in 1679 in the context of exchanging fluid to and from the Black Sea through the Bosphorous. It has been brought into the suite of experiments available to the project and is particularly useful in introductory classes.

*MIT.* Annual meetings at MIT, regular site visits plus personal exchanges, and direct experiences from various university settings have been very valuable to the project. The use of the web-based “instructor weekly logs” also helped in the monitoring of the project, as we now go on to describe.



**EVALUATION OF THE PROJECT.** *Description of students involved in the project.* Approximately 500 students, of which 55% were male and 37% were female, have been engaged in the experimental classes in the first two years of the project; no data were reported on gender for 8% of the students who participated. Figure 9 displays students by class level and major. The overwhelming majority (80%) of students were undergraduates; as few as 8% of the student participants were graduate students and only 8% were freshmen, most likely because the courses involved were *primarily* upper-level undergraduate courses that required some prerequisites.

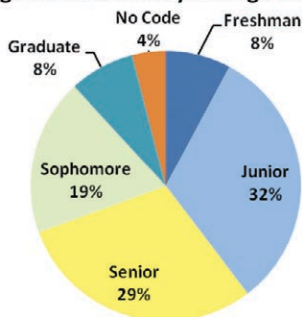
*Implementation of the project.* Both qualitative and quantitative methods are being used to assess the success of the Weather in a Tank project. To determine the extent to which the project was implemented as designed and the extent to which collaborators use and value the project experiments, Web site, and curricular materials, the evaluator gathers data each semester from collaborators, using the following instruments and protocols (see <http://paoc.mit.edu/labguide/assess.html>):

- Web-based weekly instructor logs: Evidence from collaborating professors about the number and type of demonstrations used, instructional learning benefits, student reactions, and other feedback on the experiments and equipment.
- Collaborator survey: Postsemester open-ended feedback from collaborators about their experiences with the project, including success with the equipment, the Web site, the level of project support, and suggestions for project improvement.
- Site visit reports: Information collected by the project director and coordinator during site visits with collaborators and students at each of the other five universities involved in the project.

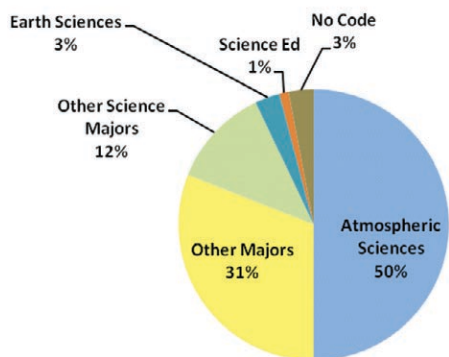
*Student outcomes.* To determine the extent to which students demonstrate gains in content knowledge as a result of engaging in the Weather in a Tank project, a pre/posttest was designed by the project staff and the evaluator and is administered to students at the beginning and end of each course term. The pre/posttest consists of 27 multiple-choice items, covering content related to climatology and meteorology. The pre/posttest is administered to a treatment group, who receive instruction using the Weather in a Tank experiments, and a comparison group of students, enrolled in appropriate courses at some of the same universities, who do not receive instruction. The treatment group consisted of 71% science majors (e.g., atmospheric sciences and physics) and 29% non-science majors (e.g., business management, education, and psychology); the comparison group consisted of 51% science majors and 49% non-science majors.

The following are two examples of questions from the pre/posttest test:

**Percentage of Students by College Level (N=467)**

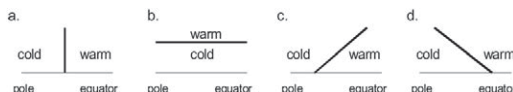


**Percentage of Students by Major (N=467)**



**FIG. 9. Charts displaying the percentage of students participating in the Weather in a Tank project by college level and major.**

1. Which answer best explains why it is hotter in the summer than in the winter?
  - (a) Earth is closer to the sun in summer than winter
  - (b) the sun burns more brightly in summer than in winter
  - (c) the Earth's spin axis is tilted toward the sun in summer
  - (d) the hemisphere experiencing summer is closer to the sun than in the winter
2. When cold air from the pole meets warm air from the tropics, the boundary between the two air masses looks most like:



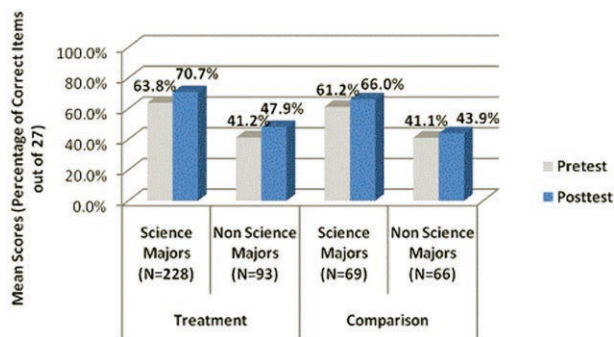
Preliminary results of the pre/posttest analysis after two years of experimentation (i.e., three iterations of the project in spring and fall 2007 and spring 2008 courses) indicate that the experiments had a positive effect on student learning. A statistical comparison of the pattern of performance of the science and nonscience majors revealed that both nonscience and science majors in the treatment group benefited, recording a 6.7 and 6.9 point gain, respectively (see Fig. 10), whereas such an improvement was not seen in the comparison group. Although the comparison group science and nonscience majors did realize gains of 4.8 and 2.8 points, respectively, they were significantly lower than the treatment group.

We believe that these preliminary results for the Weather in a Tank project are very promising, suggesting that all students (science and nonscience majors) learn readily and gain more from the laboratory-based approach and the Weather in a Tank curriculum. A more detailed statistical analysis of the data is ongoing and will be reported in the education literature in due course.

Results of the qualitative measures to date suggest that collaborating professors are very enthusiastic about the use of the experiments and curricular materials in their classes, commenting on the following benefits of the Weather in a Tank project:

- Contributed to a livelier, more engaged classroom experience;
- Assisted students in looking beyond the facts and making predictions;
- Prompted student engagement in questioning and interpreting data;
- Allowed for illustration of a point and opportunities to visualize a phenomenon;
- Enhanced instruction by allowing the development of more empirical explanations of weather events; and
- Encouraged students to conduct further inquiry into a theory.

**SUMMARY AND FUTURE PLANS.** As discussed in a recent article by Roebber (2005), there is a need to bridge the gap between theory and real phenomena. On the basis of a survey of undergraduates at the University of Wisconsin—Milwaukee, Roebber argues that the main drawback of current atmospheric science teaching is the lack of practical examples. He calls for “increased emphasis of physical examples and case studies within the existing curricular framework . . . , both for upper-level undergraduates and graduate students.” We believe



**FIG. 10. Student mean scores on pre/posttest scores in treatment and comparison groups by courses of predominantly science majors and predominantly nonscience majors.**

that appropriately chosen laboratory experiments and curricular materials, of the type described here, can provide an ideal mechanism to help bridge this gap.

We have emphasized the interplay of three elements: observations, experiment (model), and theory. In the rollout, the balance between these elements may vary according to the level, background, and interest of the students; however, we believe that the most effective pedagogy results when all three elements are present. This, of course, is how scientists work: they are motivated by real phenomena, and they attempt to explain/understand them in the context of fundamental laws, testing ideas in the framework of simplified models—whether they be laboratory, analytical, or numerical.

Our project seems to be having considerable influence, as gauged by the interest expressed by professors at other schools. We have also established an ongoing collaboration with a number of high schools: teachers are keen to use the rotating fluid experiments to bridge, for example, between the standard physics curriculum and that of the environmental sciences. For example, at the Monona Grove High School in Madison, Wisconsin, high school teacher Juan Botella is using a turntable in a new Weather and Climate class (see Fig. 2, bottom left). Furthermore, a highly successful workshop on the use of laboratory models in the teaching of weather and climate took place at the University of Chicago in June 2008 with the help of Professor Noboru Nakamura. More than 40 participants from universities and schools around the world exchanged ideas, with talks from invited speakers and numerous live demos (see <http://geosci.uchicago.edu/~nnn/postworkshop/index.html>).

Finally, one aspect of the project that we did not entirely anticipate, but with which we are delighted, is the great utility experiments have in outreach

activities—whether it be presentations to visiting dignitaries, school groups, prospective students, open houses, or others.

Our plans for the future are to expand the scope of Weather in a Tank to embrace simple numerical experiments to complement the rotating laboratory experiments. Ideas broached in the laboratory with real fluids can be explored in virtual laboratories where parameters can rather readily be changed. We firmly believe, however, that numerical laboratories alone cannot successfully replicate the visceral nature of the learning experience provided by real fluids. Nevertheless, when linked with laboratory experiments, great benefits are likely to flow by making a numerical connection in the context of Weather in a Tank.

We encourage all to get involved and to share with us their thoughts, expertise, and ideas.

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