MIT *Weather in a Tank* Project Instructor Comments Regarding Benefits and Challenges to Using the Experiments in Classes and Student Reactions Fall 2007 Courses

Comments from Instructors are arranged by experiment. Universities involved in the project in Fall, 2007 included: Pennsylvania State University, University of Wisconsin, Madison, Millersville University, University of Massachusetts, Dartmouth, and Massachusetts Institute of Technology (MIT). Source: Instructor Logs, Fall, 2007

E1: Dye Stirring

Student Reactions

- I used the table for multiple demonstrations in a freshman physics seminar course (about 10-15 students). The students were very interested in the experiments. They were not shy about making predictions and participated in conducting them.

- Provided a focal point for visiting students. They asked many questions about fluids, etc. They were interested and paid close attention.

- I believe that the demos were convincing in that students could readily see that the rotation did impart stiffness (stability) to the fluid in the dye stirring demo.

- Interested. I believe it helped them get excited for the term, which was my goal with a first day demonstration.

- The students were just exposed to the derivation of the Coriolis force and Centripetal force for particle motion in a non-inertial frame of reference. Rotation was a major topic in the lecture for two week. Our TA conducted a demonstration of the stiffening of fluids due to rotation, and students were asked to go to the website to learn more. These are junior meteorology majors. They exhibited interest in the demo and asked related questions.

- Students really enjoyed the experiment and asked many questions. It was done on the first day of classes. The students are always asking me when the next experiment is going to happen. Good sign.

Benefits and Challenges in Using this Experiment

- For Dye Stirring: Hard to see that flow doesn't move over a barrier (hockey puck). But the stiffness of the fluid is apparent. For Ocean: Transience of the dye motion is a challenge. Have to look closely to see it.

- I do think the students enjoyed the break from straight lecturing. It was also rushed, so I did not have time after the demonstration to get feedback.

- Students found the demonstration helpful in visualizing surface and upper level circulation and features.

- Unfortunately, I presented the demonstration on Monday, was away on Wednesday (the next class) and explained it on Friday. So, I did not integrate the lecture content and the demo as well as I would have liked. The idea of rigidity and 2D nature of atmospheric flow is not easy to get across. I used Wallace and Hobbs to contrast estimates of vertical motion (observed) and what you get from scale analysis (former is smaller). I used this to motivate the demo. I think if I had done a non-rotating version of the experiment or asked students what their expectations of the outcome would be, that it would have worked better. I am getting my feet wet doing these experiments, so I don't expect it to work perfectly all the time.

E2: Fronts/Cylinder collapse

Student Reactions

- The experiment increased the motivation for students to think about thermal wind balance. The analogy to the jet stream was very useful too. After the class, many students stayed around the apparatus to check it out. I encouraged students to come to the front during class as the side view is important to see the cone shaped partial collapse.

- Students were intrigued that the balance of forces in the laboratory vortex was the same as observed in, for example, a hurricane. [This] helped explain how water masses maintain their structure for long timeframes.

- I used the experiment in support of an effort to challenge assumptions about the relationship of the internal pressure gradient and the density structure in the ocean. The goal was to bring out the importance of the surface height variations in setting up a baroclinic structure. I started by asking students to sketch how they thought the currents should go based on the dense fluid on the inside of the mound. The experiment then showed that the result is actually opposite their prediction, and then that the surface deviation in height is key. It was a very helpful support to this.

- Throughout the quarter, [we] worked on 6 projects-various topics- from geostrophy to baroclinic instability. Each includes a tank experiment. Two students performed the cylinder collapse this week. They spent time with equipment and apparatus. [We] did a first trial with good qualitative results--they will try again next week to get more quantitative estimates of the slope of the interface.

- The tank was used to demonstrate the formation of frontal boundaries. Students had completed a lecture component on why rotation is critical to the development and maintenance of frontal boundaries. The demonstration provided insight into the need for Coriolis force to turn the wind to the right in the northern hemisphere thereby maintaining the front.

- [The reactions were] generally very good. One student thought the cone itself was motionless, so I added some permanganate to visualize flow near the bottom. We saw a swirl in the opposite direction (an anticyclone), but did not have the time to discuss it until after the class with another student. I presented the demonstration today and gave qualitative explanations (based on PGF and Coriolis force) of the flow behavior. Friday I will go through the math of the thermal wind (I ran out of time).

<u>Benefits and Challenges in Using this Experiment</u>

- We tried both a cold pole and a warm pole case. The cold pole case worked much better. This was probably because it was easier to maintain the temperature gradient for the cold pole via ice. For the warm pole case, we used boiling water which, of course, did not maintain its temperature once poured into the metal cup.

- The overhead lighting in my large lecture hall is a big distraction and shows lots of rotating stars. So there is a "tension" between the lighting in the hall which is necessary to project on the screen and the reflection of the light bulbs. I think I need a light under the table to illuminate the table so that I can switch off the lecture hall lights completely. (2) The side structure of the fronts is very interesting, but could not be projected on to the big-screen. I called the interested students in groups so they could come by and see the side-view. This worked well. Many students stayed around afterwards to see the structure as well as the super rotating jet-stream. Students asked questions about what the "float particles" were. Unfortunately we had to leave the lecture hall rather quickly, because there was a business class starting in 10 minutes.

- The projection worked OK, but the classroom lights kept shining like stars on the screen. So overhead reflection is a problem in my lecture hall, but it still was "cool" to do it in a large lecture hall.

- The cart monitor was too small to be much use except for the people right at the front. I need to find a way to easily connect to the auditorium projector or the large monitor in our lobby. Otherwise, everything worked nicely.

- This is a nice experiment which illustrates balanced motion--simple in concept but brought to life through use of partial tracker.

- The setup and experiments made my "guest lecture" very interactive and easy for me, and a lot of fun for the students. We ended up being in the class for about 90 minutes.

- The students were very comfortable in taking the measurements and discussing errors. This is a good project for a lab course.

- I love this demo. It works so well and the connection to the atmosphere is pretty straightforward, particularly given the temperature and wind speed contour plots that are provided on the project website. Next time, I will definitely add the permanganate to show the anticyclone near the bottom. I realize that it gets a bit more complicated due to frictional effects, but I think this forces one to consider how the cylinder adjusts under gravity--the coriolis force turns the water to the right as it flows away from the center.

- The use of rotating fluid experiment in graduate teaching is very effective. Students are left in charge of the whole experiment. They seem to love getting their hands wet after so many theory classes.

E3: Ekman Layers

Student Reactions

- In the Ekman layer demo, which worked very well, students were interested in visual appearance of convergence/divergence in the Ekman layer. This is a large enrollment course of non-science majors.

- The demo seemed to generate more discussion beforehand than afterward. Following a colleague's advice, I asked what the students expected to see as a result of a decrease in rotation rate. Two or three students responded with different ideas. None mentioned convergence.

Benefits and Challenges in Using this Experiment

- I think this demo worked well. I explain it a bit differently than the web guide suggests. I simply make an analogy between the Coriolis force and the centrifugal force--both are outward in a low and both increase with velocity. Then I compare force balances aloft and at the bottom of the tank. I did not do the high pressure experiment because it is a lot less intuitive. That is, in a high, the centrifugal and coriolis forces point in opposite directions.

- The experiment worked very well, although I had to carefully level the table to eliminate distracting surface waves. The students were challenged by the experiment and my questions, but the equipment and the results in the tank were clear and unambiguous.

- The students were confused initially about what would happen when the tank rotation rate was changed. They had no idea how to think about what was likely to occur. Once they had seen the demonstration they could explain more clearly, and confidently, what happened. They began to see the connection to spin up/down covered in class, but they were still a little confused about the Ekman layer itself.

E4: General Circulation/Hadley

Student Reactions

- Student reaction was positive to both experiments (Hadley and General Circ). I used the class (50 min) to show and discuss both experiments. For the eddies part, I also used the movie on the lab guide website, as the experiment needed some more time, and we were reaching the end of the class. Both experiments worked quite well in illustrating the general circulation concepts, which is the chapter we covered this week.

Benefits and Challenges in Using this Experiment

- The primary challenge was visualization of the shear profile. It was much easier to see evidence of the shear profile from the side of the tank, rather than from the top. Thus, not all students (18 total) could view the experiment at the same time.

E5: General Circulation/Baroclinic Circulation

Student Reactions

- Student reaction was positive to both experiments (Hadley and General Circ). I used the class (50 min) to show and discuss both experiments. For the eddies part, I also use the movie at the lab guide website, as the experiment needed some more time, and we were reaching the end of the class. Both experiments worked quite well in illustrating the general circulation concepts, which is the chapter we covered this week.

E6: Taylor Columns

Student Reactions

- I used the rotating table for multiple demonstrations in a freshman physics seminar course (about 10-15 students). The students were very interested in the experiments. They were not shy about making predictions and participated in conducting them.

E7: Radial Inflow/Balanced Motion

Student Reactions

- We just completed a theoretical treatment of the momentum equations in natural coordinates. Cyclostrophic flow that results from a balance between the pressure gradient force and centrifugal force. The radial inflow with rotation experiment provided students with an excellent demonstration of this phenomenon. I followed up with a quiz (2 questions) that was directly related to the experiment.

Benefits and Challenges in Using this Experiment

- Students laughed because I had some trouble with this one--all my own fault. First, I could not get the projection working, which got me pretty flustered. So I had to present it on the cart's video monitor, which is dreadfully small for a class of 60. Then I could not find the paper dots! Anyhow, I did get some questions and discussion about the demo and about the gradient wind balance lecture, so I think it was a positive experience for the students.

- It is a very forgiving experiment. Because of the problems with projection, I did not have time to balance the table and center the bucket. Nevertheless, it worked quite well. I did not use particle tracking software, but I don't think it is necessary. The key, I found, was giving Ro as a ratio of two time scales: Ttable/Tparcel, where Ttable is the revolution time of the table and T parcel is the revolution time of a fluid parcel. The students could easily see that fluid parcels on the outside took a long time to make a loop compared to the table revolution. Similarly, the inner fluid parcels make many revolution in the time it takes the table to make one rotation.

E8: Parabolic Surfaces:

Student Reactions

- The concept being illustrated is simple but the students enjoy seeing the pronounced parabola at high rotation. The new turntable, which turns at higher rotation rates than the old table, enables the free surface to become strongly deformed.

- Students solve theoretically for standing waves at different rotation rates. The first attempt was not completely consistent with the theory.

Benefits and Challenges in Using this Experiment

- Getting solid body rotation to occur efficiently is a challenge.

E9: Inertial Circles

Student Reactions

- The students were impressed that the problem of a ball rolling around on a rotating parabola led to the equations of simple harmonic motion that they had studied in Physics classes. Thus the experiment seemed to help bridge between fields.

Benefits and Challenges in Using this Experiment

- It was only possible to carry on this experiment on our large rotating table. We will scale down for use on the portable table.

E11: Convection

Student Reactions

- The students saw the "2-layer" convection experiment in class. They noted several aspects (a) rising of the thermals plums (b) the stable layer at the top inhibiting the vertical movement and sideways spreading of the convection (c) Hadley cell arising out of the fact that one part of the heater does not have a heating element. The permanganate crystals worked great to visualize the flow. The students summarized their reactions in a few sentences on a sheet they handed in as they left the class. Most of the class got it right. A few students stayed afterwards to continue to watch the experiment. One student who did not stay for the entire demonstration and handed in their reaction later got confused and wrote that the circulation seen was due to "coriolis force."

E13: Ekman Pumping and Suction

Student Reactions

- There was initially confusion about which way the wind was blowing. We plan to add little streamers on the fans to illustrate this. Some students seemed to understand, particularly those familiar with a geostropic flow in the atmosphere.

- This was the first time I had made use of this experiment live in lectures - I was delighted at how it went. The experiment makes use of fans which blow air over the surface of the water in a circular tank on a rotating table. This represents the action of the wind. The experiment was devised in collaboration with another collaborator and students at the University of Massachusetts, Dartmouth in the summer of 2007. This real world example needs to be developed on the tankteam website.

- Students were pleased to find that theory and experiment were matching quite closely.

E14: Ocean Gyres

Student Reactions

- Students were surprised: Is that all that's going on? Is this real, not a simulation?"

Benefits and Challenges in Using this Experiment

- The ocean gyre experiment with the sliced cylinder was not very successful. The students could see how the setup related to the theory, but the flow pattern themselves, although revealing western intensification did not look very gyre-like. We need to work more on strategies to introduce the dyes.

E16: Source Sink

Student Reactions

- This was the first time I had used a new set-up of the experiment live in class. We use a pump to study source sink flow under rotational constraints in a tank with a sloping bottom to represent the spherical earth. I was pleased with how the experiment went. Several students gathered around inquiring about a hands-on lab class that another instructor is offering next semester. A good sign.

- The thermohaline experiment worked very well. The students seemed impressed and gathered around to watch with their interest piqued. The ocean gyre experiment was much less successful. I had to resort to showing the video.

Benefits and Challenges in Using this Experiment

- The flow rates are very low in the experiment and I did not anticipate how long it would take to set up interesting flow patterns. My timing was not perfect. I should have begun the experiment earlier with 1/2 hour of class to go.

- The experiment seems very robust - I carried out the cyclonic case which is easier to visualize. The connection with the data is also very tight. I showed patterns of Ekman pumping and suction and related it to the upwelling seen in the experiment.

E18: Rossby Waves/Frontal Waves

Student Reactions

- Students planned to study the waves which develop on PV (Potential Vorticity) fronts. Two regions of different shear were created by a co-rotating lid on the top of the tank. The waves develop on the interface and their propagation was analyzed and compared to theory. The students decided to use a laser PIV (Particle Image Velocimeter) method to measure the velocity field.

- In this second week of the project, the students decided to repeat the experiment and make a video of it.

Benefits and Challenges in Using this Experiment

- This second attempt of the Rossby waves experiment was more successful. The three female students had learned to be more careful in setting up the co-rotating lid and obtained quite beautiful standing waves.

- This (Frontal Waves) is not an easy experiment. It was particularly challenging because the students decided to use the PIV (Particle ImageVelocimeter) laser to measure the velocities. This requires an elaborate set up and careful management of the experiment.

- The experiment worked well and the velocity field, deduced with the laser PIV looked good. The students were proud of what they achieved and of the video they produced.

Others:

General Comment Regarding Lighting: [A colleague and I] brainstormed some ideas about lighting the theatre classroom. So we switched off ALL the lights in the classroom, and had one spot-light shining upwards away from the table. That worked much better, since it took care of all the reflection issues.

Comments from Noboru Nakamura - in fall'07 he taught an undergraduate laboratory course using rotating fluid experiments. He conducted the following experiments: Dye Stirring, Fronts, General Circulation, Taylor columns, Ekman layers, Radial Inflow. Student-led experiments: Rossby Waves, Karmann Vortices, Antarctic Coastal Current, Baroclinic Kelvin Waves.

<u>Student Reactions</u>

- Their eyes were glued to the "Fronts" experiment. I think they really got the essence of thermal wind and jets. Since we had a mixture of grad students (4) and undergrads (2), the level of understanding should vary. Nevertheless, they all seem to have gotten the gist of the experiments. Some grad students were motivated enough to design their own experiments. They also proved more motivated in developing mathematical theory to explain the observations, and they helped the two undergrads quite a bit.

<u>Benefits of experiments</u>

- It helped to develop a more empirical way of explaining fluids (as opposed to the math-based theory).

- Being the first time to teach a lab-based course, I made the first half as a mixture of demo and background lecture. I have more confidence now and perhaps will reduce the number of demonstrations and give the students more autonomy. This time I didn't have the oral presentations as part of the requirement. Next time I will.

- Petrolium jelly is easy to use in setting up the apparatus quickly, but a lot harder to clean up. If you have a lot of time for preparation, I would recommend a removable putty as an alternative. It's more difficult to achieve a perfect seal with putty, but much easier to clean up.

- Marshall and Plumb is a good background read, but it is a bit demanding as a required read for this course, particularly for undergrads. Perhaps a lab workbook of some sort (based on the web content) is more practical as a companion piece.

- The website was useful as it provided specific design based on the same equipment and ensured a consistent result.