Teaching with tanks: using GFD experiments in undergraduate education

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http://paoc.mit.edu/labguide/

An NSF-funded partnership with the Massachusetts Institute of Technology as lead institution, and five other universities (see author affiliations) representing diverse undergraduate programs in the physical sciences, has been exploiting the use of rotating and non-rotating tanks as a learning methodology for laboratory-based teaching of geophysical fluid dynamics.

Throughout the spring and fall semesters 2007, in senior level courses in climate dynamics, meso-and storm-scale meteorology, synoptic meteorology, and junior-level courses in atmospheric dynamics and thermodynamics, 2-D non-rotating and 3-D rotating tanks were incorporated into laboratory exercises as supplements to the theoretical treatment of fronts, Ekman layers, the Hadley circulation, baroclinic instabilities, western boundary currents, free convection, and thermohaline circulations.

Millersville 2-D tank used to demonstrate convection, frontal boundaries, and fluid stability

Portable rotating tank apparatus used to study the effects of rotation on geophysical fluid systems

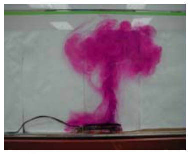
Students were expected to compare the fluid simulations with synoptic and climatological data available via the MIT “Weather in a Tank” web-site http://www-paoc.mit.edu/labguide/ as well as data acquired via Unidata’s Internet Data Distribution (IDD) system and rendered by their Integrated Data Viewer (IDV), 3-D visualization software that is uniquely suited to comparing 3-D tank simulations with real data and numerical output (see . http://www.unidata.ucar.edu/software/idv/).

EXPERIMENTS

Convection

Course: Atmospheric Thermodynamics:; Topic: Free Convection

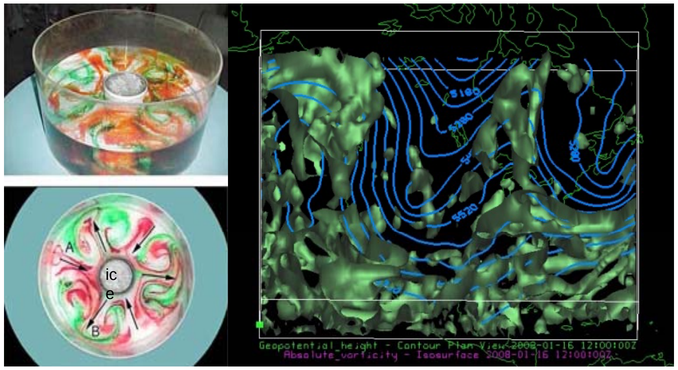
Tanks are excellent learning tools for simulating convection. Millersville has constructed a 2-D tank (shown above–left) that is used to study the nature of convection. A heating element is placed in the bottom of the tank, and layer stratification can be accomplished using salted and unsalted water. The tank provides students with the ability to visualize thermals as they rise from the bottom of the tank, entraining fluid as they rise. Parcels overshoot the level at which they become neutrally buoyant and brush the lighter fluid above, generating gravity waves on the inversion before sinking back into the convective layer beneath. The photos below shown a sequence in the evolution of convection in the 2-D tank.



Eddy regime (high rotation): Baroclinic instability of the thermal wind

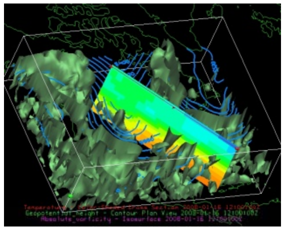
Course: Synoptic Meteorology; Topic: Baroclinic Instability

An ice bucket placed in the center of a rotating tank of water readily induces a radial temperature gradient analogous to that created on earth by differential heating, acting to warm the equator and cools the pole. If the turntable is rotated rapidly, an eddying circulation is set up analogous to the middle-latitude atmospheric circulation.



Formation of eddies in the general circulation created by a rapidly rotating turntable (left), and the geopotential height contours (blue) and vorticity fields (green isosurface) for a real (16 January 2008) synoptic scale baroclinic wave. The figure on the right was created in Unidata’s Integrated Data Viewer software.

More than just a comparison of pattern similarities, this tank experiment can be used to quantitatively determine the eddy Rossby Number. Tracking of paper dots using tracking software, one can measure characteristic horizontal current speeds u, the wavelength L, and the rotation rate Ω, to estimate the Rossby number, $R_o = u / 2\Omega L$. Typical surface current speeds are a few mm s^{-1} or so, Ω is 1.0 rad s^{-1}, and the eddy length scale is 10cm or so, yielding a Rossby number of 0.01. Thus the motion is close to geostrophic balance (except at the bottom and sides where friction becomes important).



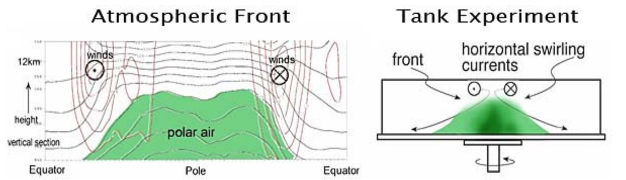
The figures above was created in IDV to show a cross-section of the atmosphere, which can be compared to the side view of the baroclinic structure produced in the tank (see top tank photo above).

Using the model output in IDV, one can visualize the thermal wind field and construct vertical cross-section contours of geostrophic wind and layer-average temperature to quantify the conditions for real baroclinic waves.

Using thermistors, students can measure the radial temperature gradient, and by monitoring the time that takes for the ice to melt, they can estimate the dm/dt.

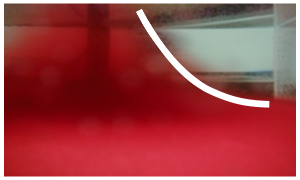
Fronts

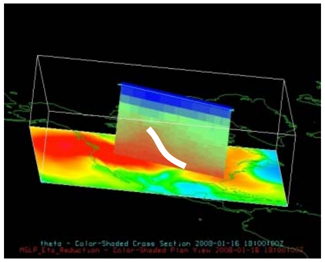
In the atmosphere, the transition between warm air in equatorial regions and cold polar air (shaded green in the figure, bottom left) is not gradual, but often occurs abruptly in mid-latitudes where equatorial and polar air masses meet. This transition region of sharp temperature gradient is known as the Polar Front. Weather is often associated with storms developing along the Polar Front. A rotating tank in which two bodies of water of differing densities are brought together can be used to study analogues of atmospheric fronts in the laboratory. Dense, salty water at the center of the tank (shaded green in figure, bottom right) can be thought to represent cold polar air, and the freshwater that surrounds it, warm tropical air.



Rotation is a key property in the maintenance of frontal surfaces. This can be readily observed using the rotating tank. A volume of salty water released in the center of a tank with NO rotation will quickly stratify. Apply rotation and the frontal structure is maintained. Margules formula can be used to estimate the frontal slope in both the tank and real atmosphere. Using the particle tracking software to estimate current velocities, with known densities of the salt water and unsalted water, the student can determine the slope of the frontal surface in the tank using Margules formula.

In the real atmosphere, with knowledge of the velocity field and a potential temperature cross-section, a student can determine the slope of the frontal surface and compare this to visual displays of frontal cross-sections as in the figure below.





Frontal surface generated in a rotating tank (above) and compared with a vertical cross-section of an atmospheric front on 16 January 2008 (right). The white curves highlight the similarities between the tank and real atmosphere

Assessment

Assessment tools have been developed to track the teaching procedures used in our project and determine how effective they are, especially the outcomes for students: 1) Student pre/post test of conceptual knowledge; 2) Log of instructor's equipment use in class ; 3) Rubrics for instructor use in evaluation of student writing and oral skills; 4) Survey of students impressions of the effectiveness of each laboratory experiment, its integration with observations, and its impact on their learning; 5) End of the semester survey of instructor impressions on the usefulness and impact on student learning. Early results suggest that students exposed to tank experiments do better on an evaluation metric than students in a comparison group.