Virtually Enhanced Fluid Laboratories for Teaching Meteorology

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VIRTUALLY ENHANCED FLUID LABORATORIES FOR TEACHING METEOROLOGY

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A virtually enhanced "Weather in a Tank" laboratory illustrates how fundamental principles of rotating fluid dynamics shape the observed structure of atmospheric circulation.

The general circulation of the atmosphere is extraordinarily complex, comprising many interacting components. Yet, it has an underlying beauty and order that reflects the controlling influence of Earth's rotation and differential heating. At the Massachusetts Institute of Technology (MIT), and in collaboration with other universities (see Illari et al. 2009), we have explored an approach to teaching meteorology that combines observations with key fundamental theoretical concepts but that is enlivened and illuminated by carefully chosen rotating laboratory experiments. The importance of laboratory experiments in understanding atmospheric fluid dynamics has been long recognized (Hide 1966; Ghil et al. 2010). Persson (2010), for example, stresses how laboratory experiments can help in communicating the nonintuitive nature of geophysical fluids.

In "Weather in a Tank" (Illari et al. 2009; Mackin et al. 2012), the general circulation of the atmosphere emerges from the "mix" of two key planetary "ingredients":

1) differential heating of the atmosphere (i.e., cooling of polar latitudes relative to the equator) and
2) rotation of Earth.

The first ingredient is intuitively understood and part of common knowledge. However, the second is known to be important but often not well explained, or the details are glossed over. Teachers often believe that rotational effects can only be demonstrated by complex mathematics beyond the grasp of many students, particularly in introductory classes (see the discussion in Mackin et al. 2012).

In Weather in a Tank the combined effect of rotation and differential heating is illustrated using simple laboratory experiments in which a can of ice in the middle of a rotating tank of water represents the pole–equator temperature difference and the rotating turntable represents the rotation of Earth (see Fig. 1). A "three-legged stool" approach is followed in which

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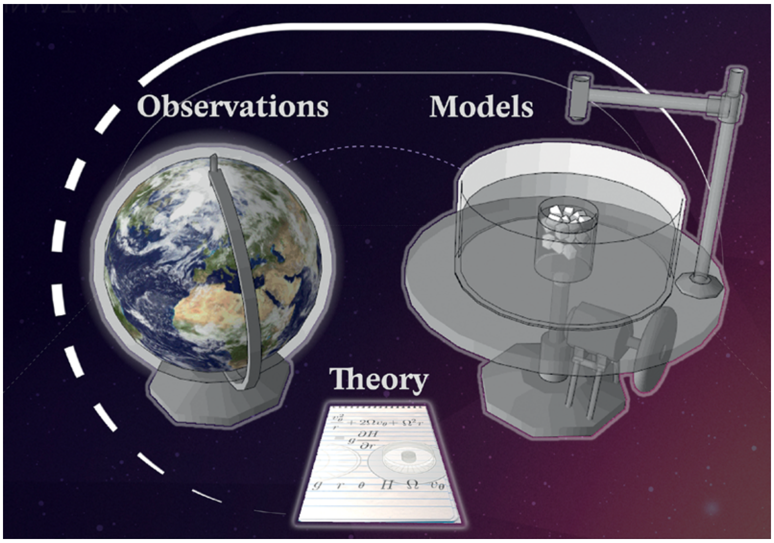

Fig. 1. The three-legged-stool approach to teaching the fundamentals of atmospheric dynamics at the heart of the Weather in a Tank project. On the right is a representation of a turntable apparatus with corotating camera, viewing a circular tank of water with a can of ice in the middle.

fluid experiments are used together with real-time observations and relevant theory (Fig. 1). Students are encouraged to explore the same phenomenon from a number of aspects and become accustomed to moving between observations, theory, and laboratory abstraction. The simplification required to set up laboratory experiments demands that complicating details be removed to reveal the essence of the underlying processes at work. This is a truer analog, we believe, of how research scientists work and, most importantly within the present context, is also very effective pedagogy. Experiments capture the interest of many, if not all, students irrespective of their background knowledge or sophistication in mathematics and physics. They are also great "fun" and particularly useful in outreach to nonscientists and the public in informal educational settings such as museums and libraries.

This use of laboratory experiments combined with real-world phenomena and relevant theory has proved very effective in teaching the nonintuitive nature of rotating fluids in undergraduate courses. Over the past several years many colleges have adopted the curriculum and the related equipment. A comprehensive guide to the Weather in a Tank experiments and how to obtain the apparatus can be found in Illari and Marshall (2006). For a quantitative assessment of the impact of the Weather in a Tank curriculum on student learning, see Mackin et al. (2012). Despite the increasing use of laboratory experiments in teaching meteorology, we are acutely aware that many teachers and students do not have access to suitable apparatuses and so cannot benefit from them. However, the digital world of online education provides the possibility of reaching out to a vast audience of "distance" learners. How can we make a laboratory experience available to such an audience? Thus far, virtual laboratories available to the educators in meteorology are mainly composed of computational modules or educational games; see, for example, the virtual laboratories from UCAR (2012). Here, instead, we describe a "virtually enhanced" laboratory that is very effective in getting across a flavor of the experiments and bringing them to a wider audience. In the pedagogical spirit of Weather in a Tank, we focus on how simple underlying principles, illustrated through laboratory experiments, shape the observed structure of the large-scale atmospheric circulation.

Our paper is set out as follows. In the next section we describe the teaching method we advocate and the role that real and virtual laboratories can play in it. We then present a particular example focusing on the Hadley regime of the tropical atmosphere. Virtually enhanced annulus experiments are presented, available through an accompanying website described in the appendix that renders digital recordings of laboratory experiments, allowing features of the circulation to be viewed from different angles. Real-world applications of the Hadley circulation are presented using advanced graphics [Integrated Data Viewer (IDV) by Unidata (2012)] to highlight connections to the laboratory experiment. Later, we argue that the availability of virtually enhanced experiments could allow students to benefit from a laboratory experience even though they may not have access to a real laboratory. Finally, we outline some of our future plans.

TEACHING METEOROLOGY USING VIRTUAL LABORATORIES.

We begin by briefly describing three closely related fluid experiments used in our undergraduate courses at MIT to teach students about the general circulation of the atmosphere and the underlying dynamical principles that cause it. This will give the reader a flavor of the pedagogical approach advocated here and the central role that laboratory experiments play in it.

The setup in the three experiments is the same and comprises a circular tank of water at the center of which is a can containing a mix of ice and water (Fig. 1). The melting ice extracts heat from the surrounding water at the center of the tank, inducing differential cooling and a circulation, the first ingredient mentioned at the start of this paper. The only difference between the three experiments is in the second ingredient, the rotation rate Ω of the turntable on which the circular tank sits.

We carry out the following experiments in turn:

1) nonrotating, $\Omega = 0$—this is used as our control experiment;
2) low rotation, Ω = small [less than one revolution per minute (rpm)], an analog of the circulation of the tropical atmosphere, the Hadley circulation;
3) high rotation, Ω = large (order 6 rpm), an analog of midlatitude weather systems (see the section on the weather regime below).

Experiments 2 and 3 involve the use of a rotating turntable with a corotating camera (see Fig. 1), which may not be available to the teacher. However, the first experiment can be easily carried out in any classroom on a solid bench using readily available equipment, including an ice can, water tank, colored dyes, etc. The "virtual laboratory" could then be used to illustrate the two rotating experiments.

The sequence of three experiments can be presented in one (~1.5–2 h) class. Even better, perhaps, they can be broken up into extended activities spread over several classes with related discussions of the laboratory experiments, theory, and study of observations.

We have found it to be very useful to introduce the experiments to the students through the use of a matrix (Fig. 2) printed on a sheet of paper that lays out the experiment in a logical order. Before the experiment is carried out, students are encouraged to sketch on the matrix what they think will happen, and share and discuss their predictions with the class. The experiment is then performed before returning to a discussion of student predictions within the context of what actually happened, and why. Relevant theory [e.g., the thermal wind relation, Ekman layers,

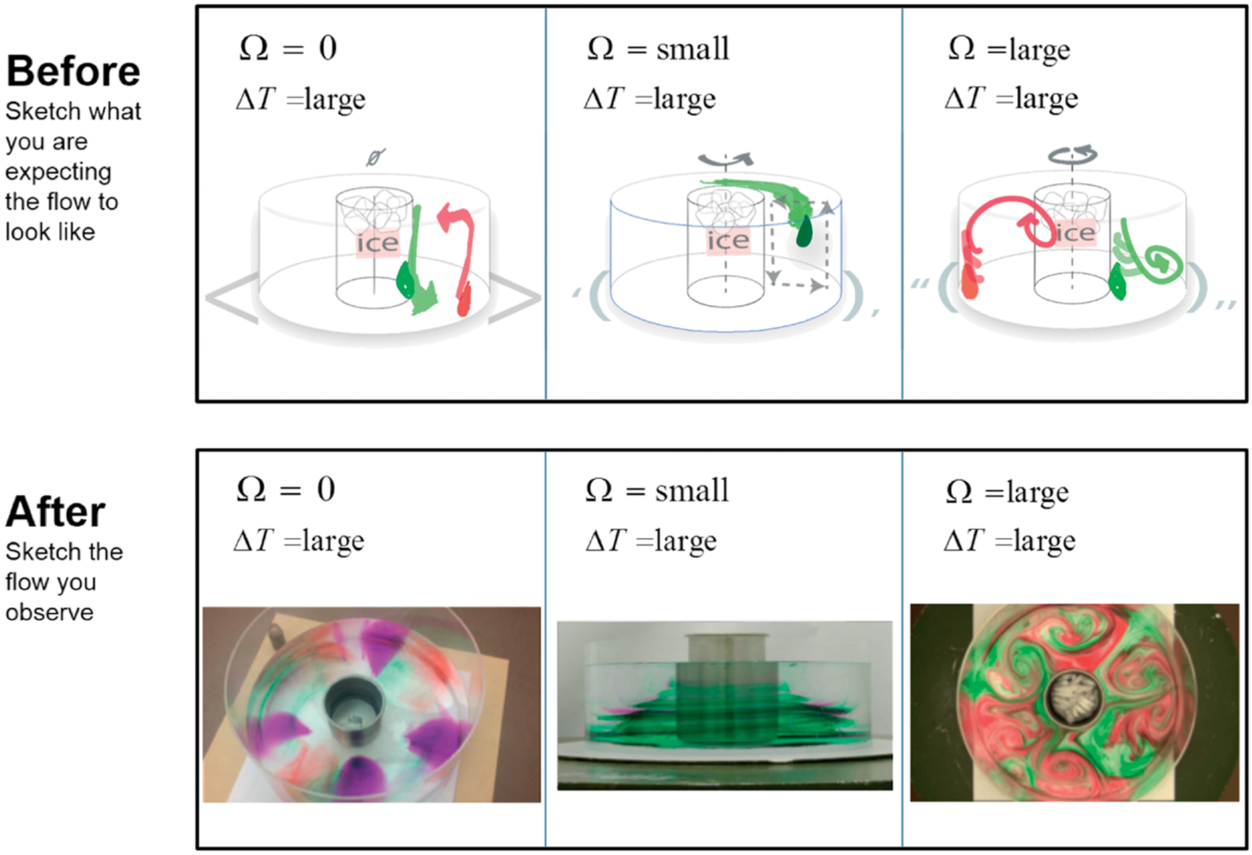

Fig. 2. Matrix used in teaching the general circulation. Three experiments are carried out in which a radial temperature gradient is induced through use of an ice can, placed at the center of a cylindrical tank of water. The only difference between them is that the rotation rate Ω of the tank is different (Ω = 0, small, large).

conservation of angular momentum as described in Marshall and Plumb (2008)] is developed and/or reviewed to help constrain and inform speculations about what did or did not happen. Finally, meteorological observations are explored in a manner that makes the connection to the laboratory experiments clear.

EXAMPLE OF PEDAGOGY: HADLEY CIRCULATION.

Laboratory experiments. To give the reader a concrete example, we now describe laboratory experiments that pertain to the Hadley circulation, real and virtual manifestations, associated theory, and exploration of relevant meteorological observations.

Nonrotating. An initially resting tank of water is differentially cooled by filling a can at its center with a mix of ice and water. The system is not rotating and thus represents our "control" experiment. It is very simple yet encourages students to think about the effect of thermal contrast: where does the cold water in contact with the ice can move and what are the consequences for the "general circulation" in the tank?

The resulting circulation can be easily visualized by using dye (food coloring) and permanganate crystals, as shown in the photograph in Fig. 2 (bottom left). The permanganate is particularly useful in indicating flow at the bottom since it sinks in the water column, whereas dye is more nearly neutrally buoyant and reveals flow interior to the fluid. Cold water sinks near the ice can and flows radially outward (the pink streaks), inducing water on the periphery to rise at the edge of the tank. To conserve mass, surface waters must move toward the ice can, thus completing the overturning circulation. The resulting circulation is axisymmetric with predominantly radial (inward and outward) flow. Students are generally "comfortable" with this circulation and can readily rationalize what they see happening. But, now, what happens when we add rotation?

Slowly rotating. The setup is exactly the same as the nonrotating case except that now the tank of water sits on a turntable that is rotating very slowly, here at only 1 rpm. The scene is viewed from above via a corotating camera, as indicated in Fig. 1. Even though the turntable completes only one rotation in a full 60 s, the circulation is strikingly different from the nonrotating experiment. Rotation imparts a "winding effect" on the fluid, as revealed by the corkscrew patterns of the green dye streaks seen in Fig. 3. Flow at the top is cyclonic (in the same sense of rotation as the tank) but flow at the bottom is anticyclonic, as revealed by the pink permanganate streaks (Fig. 3, top right).

This circulation pattern is a surprise to almost all students and few are able to predict it. Our mind has difficulty in visualizing and anticipating the effects of rotation. This is perhaps not surprising in view of the fact that Hadley himself did not fully appreciate the effect of rotation on atmospheric flows (see Lorenz 1967; Marshall and Plumb 2008).

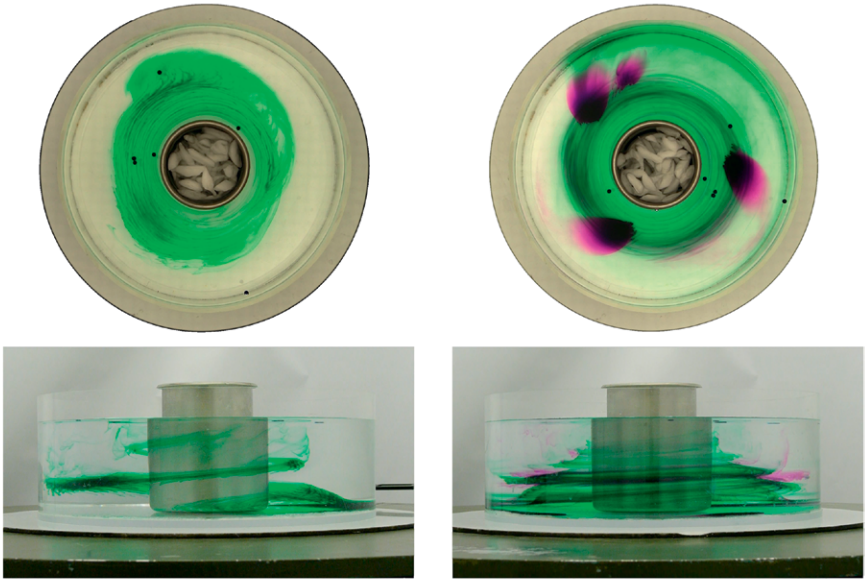

Fig. 3. The low-rotation "Hadley" experiment. (top) Overhead view of the evolving azimuthal circulation at (left) early and (right) later times. The pink plume on the right emanates outward in a clockwise loop from crystals of permanganate dissolving at the bottom of the tank. They indicate the sense of the flow near the bottom. (bottom) Side views of the green dye streaks being tilted over into an anticlockwise corkscrew pattern (left) early and (right) later in the experiment.

In summarizing and reviewing student sketches and observed circulation patterns, we introduce angular momentum principles to rationalize the features of the corkscrew zonal circulation. As in the nonrotating experiment, water in the outer region of the tank is displaced by cold waters flowing outward along the bottom, away from the ice can at the center. It rises and subsequently moves inward at the top surface. But now with rotation, contracting rings of fluid associated with inward flow conserve their angular momentum and thus speed up, generating upper-level zonal flow, which has the same sense of rotation as the tank (i.e., cyclonic). This flow is analogous to the upper-level atmospheric westerlies, as will become apparent later when meteorological data are analyzed (see the section titled "Connections to the observed Hadley circulation").

On reaching the ice can, the water is cooled, descends, and moves outward along the bottom. Rings of fluid expand and begin to circulate in the opposite direction of the turntable, as expected from conservation of angular momentum. As can be seen from the pink streaks in Fig. 3 (top right), flow at the bottom is anticyclonic (opposite to the sense of rotation of the tank). The bottom flow is directly analogous to the easterly (trade) winds of the low-latitude Hadley circulation. The accompanying video of the experiment, found on the project website (http://lab.rotating.co), provides views from the camera above the tank and from another camera viewing the side of the tank.

In summary, the circulation of the low-rotation experiment is not intuitive. Many students have difficulty visualizing what is going on and it is not easy to anticipate the impact that rotation has on the fluid.

Virtually enhanced Hadley example. The experiments described above have been recorded, put through a process of virtual enhancement using animation software, and presented for viewing over the web. The capture process involves recording from different angles using top and side cameras in corotating and laboratory frames. By combining all of the views together using specialized programs such as Rhinoceros 3D, it is possible to reconstruct and enhance the 3D structure of the evolving dyes. Multiview images of the experiment from two different cameras (top view from the corotating camera above and side views from the camera in the laboratory; see Fig. 4) are processed to produce line contours, which are turned into volumetric meshes, and finally fully rendered surfaces as shown in Fig. 5. More discussion of the rendering process is provided in the appendix. The fully rendered surface looks very realistic and can be viewed from different angles. Students can readily see what is going on in three dimensions, thus gaining a more complete perspective of the effect of rotation on the fluid motion. The enhancement of the video, and the ability to view it over the web, gives students a vivid impression of the experiment, even though they may never have had the benefit of a first-hand experience. The experiment comes alive as in a Pixar

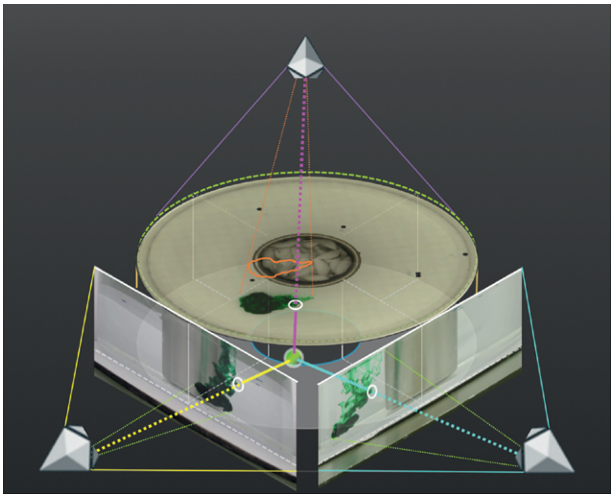

Fig. 4. Views from three mutually perpendicular camera angles provide a spatial fix on the dye plume as it evolves and deforms with the fluid flow. Overhead lineaments are coordinated with side views of tracer extents, enabling the 3D structure of the plumes to be reconstructed.

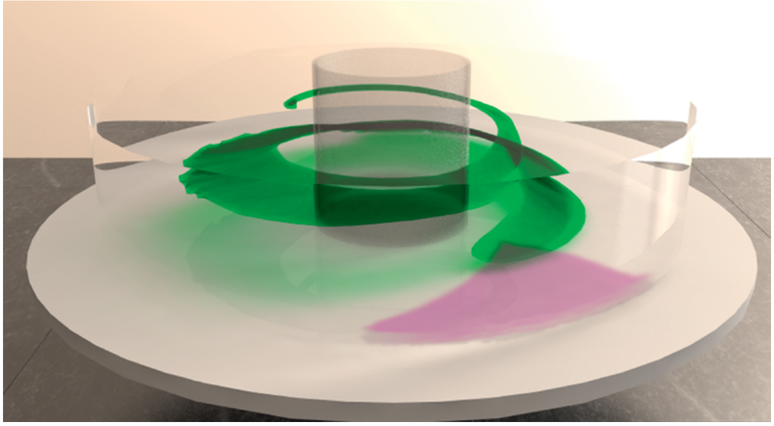

Fig. 5. Rendered (virtual) view of the Hadley experiment showing the "winding up" of green dye plumes by the cyclonic (anticlockwise viewed from above) flow in the thermal wind balance with the radial temperature gradient. The evolution of the anticyclonic (clockwise) flow at the bottom is revealed by the pink plume. The geometric surfaces created by the multiangle views in Fig. 4 have been given visual-perceptual properties, which resemble real dye surfaces. The final image is continuous without obstruction of the tank and ice can used in the experiment.

movie! The fly-by animation from digitally enhanced, merged video loops is available for viewing (http://lab.rotating.co/#/flyby).

The accompanying website (http://lab.rotating.co) allows one not only to inspect prerecorded experiments but is also designed to give one a feel for how and what it is like to carry out the experiment. Moreover, data on flow speeds and temperatures are provided, enabling one to quantitatively check dynamical balances that one expects to pertain, as we now go on to explain.

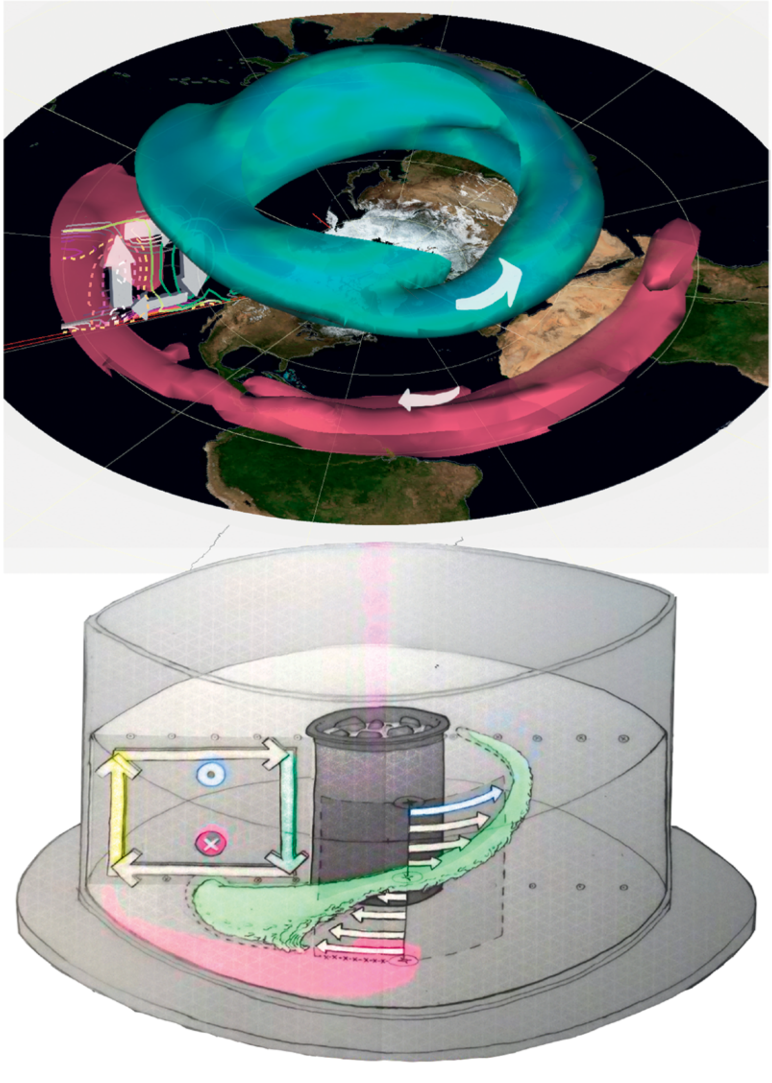

FIG. 6. (top) Climatological winter mean circulation, showing upper-level westerlies (cyan isosurface of $u = 30$ m s^{-1}) and low-level easterlies (pink isosurface of $u = -10$ m s^{-1}). The meridional section on the left-hand side shows the zonally averaged overturning circulation at low latitudes; vertical and meridional wind directions are marked by white arrows. (All fields are plotted using IDV software.) (bottom) A schematic diagram of the laboratory Hadley circulation, showing similar features to the observed climatology: the green streak of "westerlies" and the pink plume of "easterlies" (cf. with Fig. 5).

Associated theory. The Hadley experiment provides an excellent tutorial for exploring the "thermal wind" relation, the theory leg of our stool. As described above, the radial temperature gradient (induced by the ice can and decreasing "poleward") supports zonal motions in the tank, the nature of which depends, inter alia, on the rotation rate. When weakly rotating ($\Omega \lesssim 1$ rpm), we see the development of the thermal wind in the form of a strong "eastward" (i.e., superrotating) flow in the upper part of the fluid, which can be revealed by paper dots floating on the surface. At these low rotation rates the flow is stable to baroclinic instability and laminar motion is observed, as seen in Fig. 5, for example. At higher rotation rates the flow breaks up into eddying motions analogous to synoptic systems, as described in the section on the weather regime below and discussed in detail in section 7.3.1 of Marshall and Plumb (2008).

For an incompressible fluid in cylindrical geometry (with radius r increasing outward), the thermal wind relation is

$$\partial u / \partial z = -1 / (f \rho)(\partial \rho / \partial r), \qquad (1)$$

where f is the Coriolis parameter, ρ is the density, and u is the azimuthal speed of the current. Since ρ increases toward the center of the tank, because the water is cold there ($\partial\rho/\partial r < 0$), then, for positive f, $\partial u/\partial z > 0$. Since u is constrained by friction to be weak at the bottom of the tank, we therefore expect to see $u > 0$ at the top, with the strongest flow at the radius of the maximum density gradient. As we have seen, dye streaks clearly show the thermal wind shear (Fig. 3), especially near the cold can, where the density gradient is strong.

On the website that accompanies this article, data are presented on the flow speeds (by tracking particles) and temperature gradients (from thermistors deployed in the tank) existing in the Hadley experiment enabling the thermal wind relation, Eq. (1), to be quantitatively checked (http://lab.rotating.co/#/thermalw).

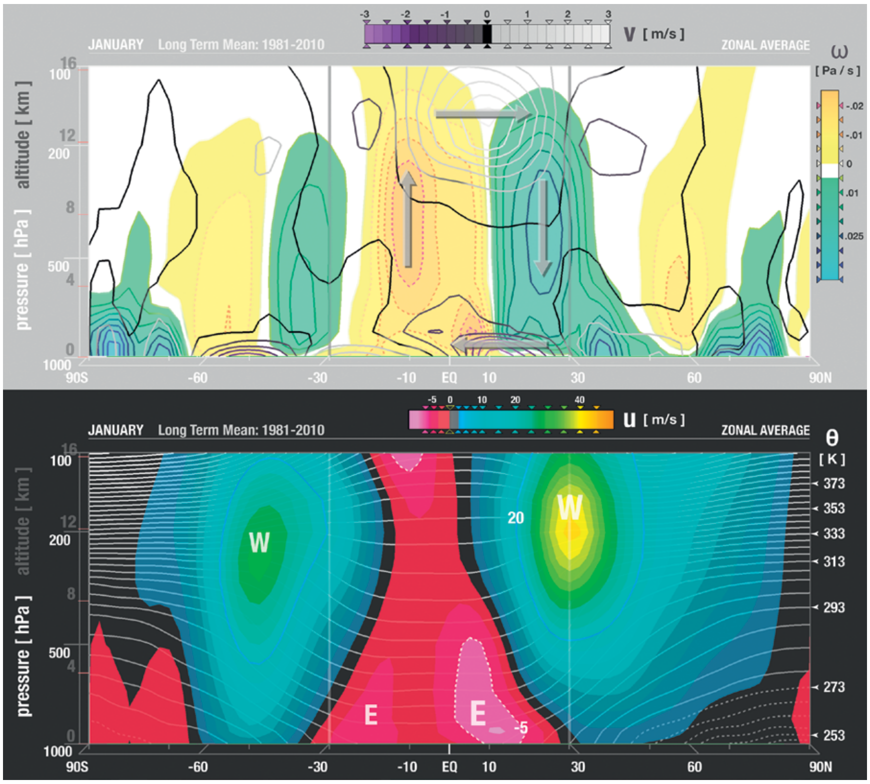

Fig. 7. The observed mean meridional circulation during Jan (from NCEP–NCAR Reanalysis 1). (top) Zonally averaged meridional wind (scale on top) and vertical wind (scale on side) are contoured (and colored) and the sense of the flow is indicated by arrows. (bottom) Zonally averaged potential temperature (scale on left-hand side) and zonal wind (scale on top). Westerly winds are blue–green and easterlies are red–pink. All fields are plotted using IDV software.

Connections to the observed Hadley circulation. Along with the laboratory experiment we have produced graphical displays using IDV that enable one to present meteorological observations in a manner that emphasizes connections to the fluid experiments. Students are encouraged to carry out exactly analogous calculations from meteorological data to check the thermal wind in action for atmospheric flows. Indeed, the jet observed in the laboratory experiment is directly analogous to the creation of the subtropical jet by the Hadley circulation, as we now discuss.

In Fig. 6 (top) National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis climatological winter-mean [December–February (DJF)] data are used to map the main features of the Hadley circulation and strengthen the connection between the real world and the tank experiment. IDV is a powerful graphical package, giving us the tools to go beyond the usual horizontal and vertical sections and explore the 3D structure of the atmosphere. The cyan picks out the tubular surface corresponding to westerly winds aloft. The pink tube highlights easterly winds near the surface. The Arctic ice cap is clearly visible at the surface over the pole. Superimposed is the Northern Hemisphere wintertime Hadley circulation with the meridional and vertical components of the wind indicated by the arrows. The rendering of the data in this way (Fig. 6, top) makes the connection with the laboratory experiment (Fig. 6, bottom) much more immediate and compelling.

To further emphasize the main features of the observed meridional circulation, zonally averaged fields are plotted separately in Fig. 7. Figure 7 (bottom) shows the potential temperature (θ, in K) and zonal wind (u, in m s^{-1}) in January. In the troposphere, the maximum warmth is found south of the equator, consistent with the winter radiative forcing. The north–south potential temperature gradient is small in the tropical region, whereas it is large in the midlatitudes; this is the polar front, marking the edge of the dome of cold polar air. By thermal wind arguments there are strong westerlies at upper levels (in the midlatitudes), with weaker easterlies in the lower troposphere (at low latitudes). Figure 7 (top) shows the vertical and meridional winds. Vertical velocities are large in the tropical band with air rising where it is warm (south of the equator) and sinking where it is colder in the Northern Hemisphere (around 30°N). Meridional winds are directed poleward at upper levels and equatorward at low levels, consistent with rising close to the equator and in the subtropics. Arrows mark the sense of the overturning circulation in the tropical regions. Meridional winds tend to be large in the tropical band and small everywhere else—a clear signal of the Hadley circulation confined to the tropical belt.

Figures 6 and 7 together give a summary of the general circulation and illustrate the main features of the Hadley cell in the tropics. Using the above material, the connection between the laboratory flows and the observed Hadley circulation can be made clearly evident.

THE WEATHER REGIME. *Baroclinic instability of the thermal wind.* Following our matrix of experiments shown in Fig. 2, students are encouraged to compare and contrast the low-rotation Hadley experiment with exactly the same laboratory setup but now rotating much more rapidly (Ω is large) as shown in Fig. 8 (top). This illustrates dynamics typical of the midlatitudes. The difference is striking: at a higher rotation rate the axisymmetric circulation of the Hadley regime breaks down. The flow becomes turbulent and more chaotic; tongues of cold and warm fluids intermingle, sliding one on top of another (Fig. 8, middle). The analogy to the midlatitude weather systems is very evident by visually comparing with Fig. 8 (bottom), showing the 850-hPa temperature over the Northern Hemisphere for a typical wintertime day. Tongues of warm air move north toward the pole, while the opposite is true as cold air is moving south toward the equator, equilibrating the pole–equator temperature gradient. A video of the high-rotation experiment together with the observed temperature field can be found online (http://lab.rotating.co/#/eddies).

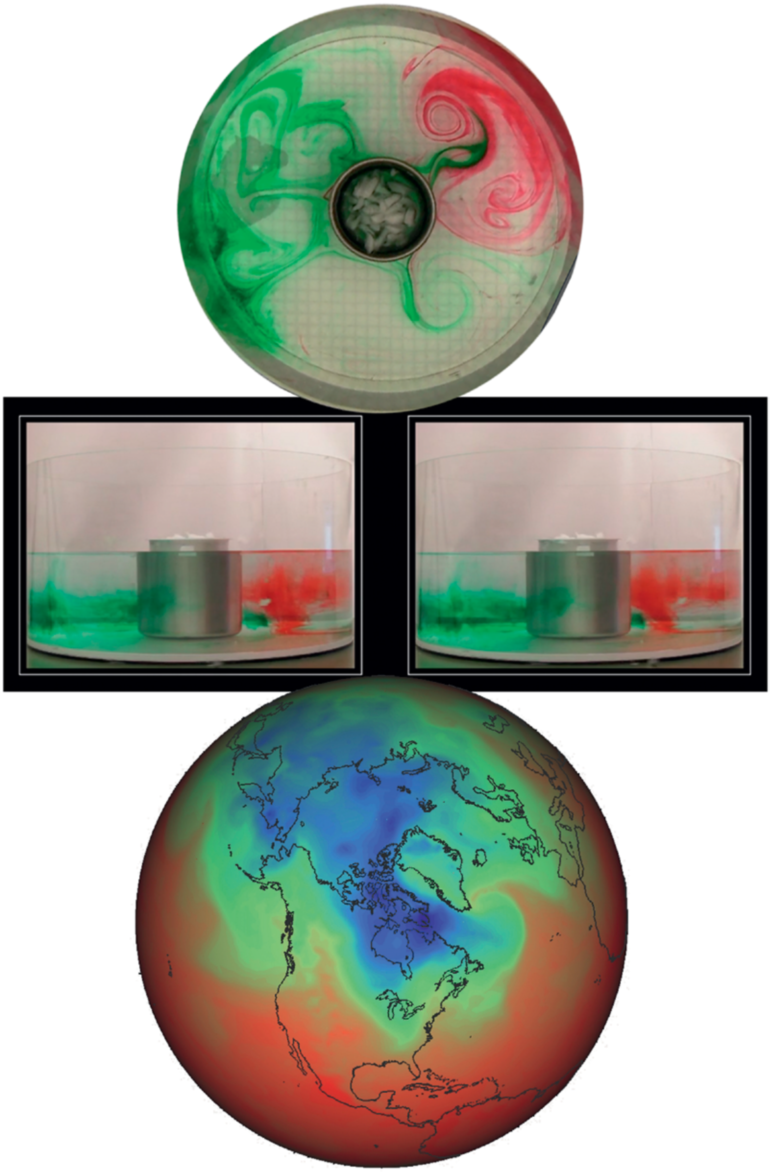

Fig. 8. The high-rotation experiment showing baroclinic instability: (top) view from the corotating camera showing turbulent eddies transferring fluid from the warm (red) edge of the tank to the cold (green) inner can with ice; (middle) side views of the whole tank, showing the colder green water sliding under the warmer red water and mixing laterally and vertically—evident in 3D by crossing one's eyes; and (bottom) 850-hPa temperature on a typical winter day over the North American sector, showing a burst of cold Arctic air being advected south over Canada and the United States, while a tongue of warm tropical air is advected north.

The contrast between the low- and high-rotation experiments helps one grasp the importance of rotation in shaping weather regimes. Students are amazed to see that the complexity of weather systems can be readily captured by such a transparent rotating fluid experiment with an ice can in the middle and an appropriate rotation rate. Indeed, experiments such as these, known as "annulus" experiments, were fundamental to our understanding of the general circulation of the atmosphere: see Hide (1966) for a comprehensive discussion of relevant laboratory experiments and Lorenz's (1967) classic review of the general circulation of the atmosphere.

DISCUSSION AND FUTURE PLANS. As demonstrated in the Weather in a Tank approach to teaching weather and climate (Illari et al. 2009; Mackin et al. 2012), we believe that student learning is enhanced by being exposed to simple rotating fluid analogs of meteorological (and oceanographic) phenomena. However, we are aware that not everyone has access to rotating turntables, hence the emphasis here on virtually enhanced experiments that can provide a flavor of the true laboratory. Indeed, we have noted in teaching that the availability of a virtually enhanced laboratory can deepen understanding by helping students to gain a 3D perspective of the phenomenon studied. This is particularly appropriate when studying the general circulation of the atmosphere, whose regimes are rather complex and difficult to unravel. The availability of virtually enhanced movies and snapshots can help the students appreciate the essence of the phenomena. The virtual laboratory can also be used in conjunction with "live" experiments, enabling students to replay and explore again both in and out of class. It is also a valuable and highly effective means of reaching out to larger audiences.

In conclusion, we would like to contrast the approach presented here with other explorations of digital learning in meteorology. Often the virtual laboratory is presented in a gaming context (typically in introductory courses) or a set of computational simulations (in more advanced courses). Indeed, the University Corporation for Atmospheric Research (UCAR) list of virtual laboratories (http://scied.ucar.edu/games) is dominated by games or simple computational exercises. For example, there are several virtual tornadoes:

- the early work of Gallus et al. (2006), developing a virtual tornadic thunderstorm, combining data collection and analysis;
- the more recent and very realistic experience provided by the Cube theater/laboratory, where one steps into a virtual recreation of a tornado that hit Oklahoma in 2013 (Carstensen 2015); and
- the Geopod game (Yalda et al. 2012), designed to give a 3D virtual experience to meteorology majors. Geosciences Probe of Discovery (Geopod) makes use of IDV graphics' flying simulation capabilities and encourages students to "dive in" and analyze a variety of atmospheric data. Evaluation of student learning showed that the technology was not only visually compelling, but also helped students deepen their understanding of meteorological concepts.

Such examples demonstrate that technology can indeed give exciting experiences to students. The approach presented here is perhaps a little more conservative, rooted as it is in the "tradition" of the laboratory exploration of simplified systems in the spirit of geophysical fluid dynamics. Nevertheless, the artful use of laboratory visualization together with the use of 3D graphics of the real phenomena, as made possible by IDV software, can perhaps give new life to these classic experiments and enthuse a new generation of online students, helping them to understand the world around them at a deeper level.

ACKNOWLEDGMENTS. This study was made possible in part by NSF support through AGS-1338814 (FESD type 1: The impact of the ozone hole on the climate of the Southern Hemisphere).

APPENDIX: CONSTRUCTING THE VIRTUAL FLUID LABORATORY.

Rotating fluid experiments present a 360° rolling view to laboratory observers with each complete rotation of the system. This driving action shapes the dynamic forms of Weather in a Tank as well as makes them opportune subjects for digital capture and virtualization. Here, we outline the processes used to create an enhanced animation from video recordings as described in the section titled "Virtually enhanced Hadley example" in the main article.

Building a viewing tool. Footage of the experiment from multiple cameras is combined into a synchronized multiview video. Imagery for a selected tank angle is cued into a 3D modeling environment to create a viewing tool for photogrammetric reconstruction of the fluid forms.

CAMERA SET. The setup of cameras for recording rotating fluid experiments is illustrated in Fig. A1 (left):

- "A" is the camera on-axis overhead, corotating with the turntable;
- "B" is the camera on a tripod in the fixed frame of the laboratory, capturing the vertical structure of the whole system as it turns; and
- "C" is an additional camera affixed to the turntable, providing a single viewpoint that can be used to check the consistency in camera B's capture.

SYNCHRONIZED IMAGERY. Viewing frames from the various cameras are aligned and scaled to be consistent with one another, as illustrated in Fig. A1 (middle). Here the experiment is sampled at a rate of 12 frames per rotation.

FLUID ZOETROPES. The views from around the system over the course of one period can be used to create a virtual corotating viewing tool, similar to the cylindrical image sequence inside a zoetrope (see Fig. A1, right). (Software used: Adobe After Effects » Max/ MSP Jitter » Rhinoceros 3D.)

Animation tools. Information about the evolution of dye streaks in the corotating frame is analyzed with selected view-angle observations from the laboratory frame to build up a 3D animation of the fluid flows.

MAPPING EVOLVING DYE PLUMES. We use a modeling technique similar to "rotoscoping," in which live footage is traced over to produce a realistic animation. The overhead features of the dye (Fig. A2, left) are traced into a closed 2D contour. This creates an initial curve matching the observed extent of the dye form, which is then traced back in time until the dye returns to the initial droplet.

The edges of the stretching 2D dye contour are given depth using elevation data from the tripod camera. A top view together with a pair of perpendicular side views allows us to triangulate the vertical structure of the evolving dye plume.

SURFACE VOLUME MESH. In this phase we move from animated line contours to surfaces: the 3D contours in Fig. A2 (left) are surfaced, thickened, and turned into a closed mesh, as shown in Fig. A2 (middle). This mesh provides the basis for rendering other properties.

PHOTO-REALISTIC RENDERING. The geometric surfaces created by the multiangle modeling in Fig. A2 (middle) can be rendered to resemble real dye surfaces. In our case, the turntable, tank, fluid media, dye tracer, and can of ice are rendered separately and overlaid into coaxially nested systems. Some materials' parameters may be modified to reduce the effects of refraction, which usually distort the image. The final product can be seen as a continuous form without obstruction from the original vessels, as shown in Fig. A2 (right). The layer-based animation and rendering can then be staged using dynamic views: in the laboratory, corotating with the tank, or even in the flow, moving in sync with a prominent fluid feature, for example, the superrotating jet at the free surface. The enhancement allows points of views that would otherwise be available only through complex camera setups. For

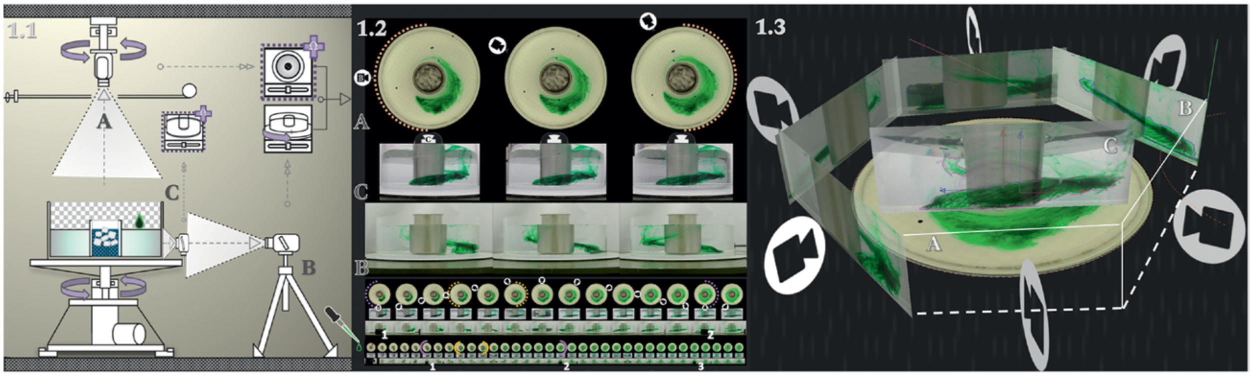

FIG. A1. Variable-angle video from (left) a turntable experiment in the laboratory that is (middle) sampled at a regular frequency subdividing the rotation period and then (right) mapped to frames linked to time points of view in the animation environment.

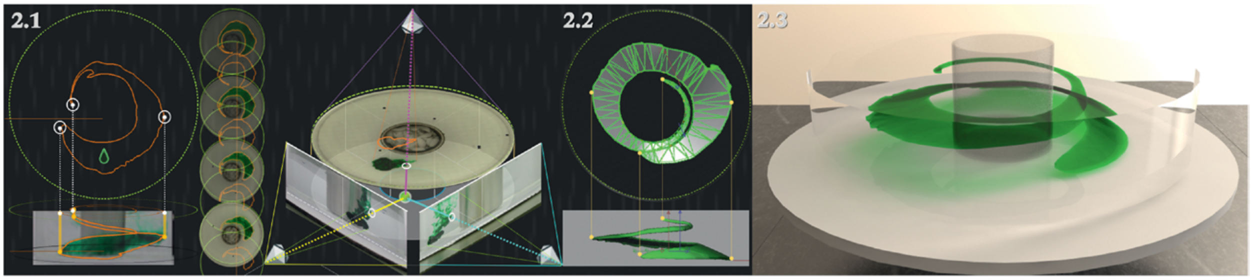

FIG. A2. (left) Projections of extracted features from overhead and side views combine to map the volume of fluid containing dye. (middle) The interpolated contour bounding the evolving dye plume is surfaced, (right) to produce a visualization of the circulation pattern.

example, see the animation online (http://lab.rotating.co/#/flyby). (Software used: Max/MSP « » Rhinoceros 3D + Bongo + V-Ray)

Website. Real movies, virtual movies, and observations of the Hadley cell are organized into a coherent story on the project website (http://lab.rotating.co/).

Utilizing the virtual laboratory. The website provides a "public view" into the laboratory and can be used in various contexts:

- web-based presentations for large classes or audiences at meetings, where the scripted animations can be used instead of the real experiment, when the use of a turntable is not practical;
- classroom environment, where students can export the virtual models to a specified coordinate system for analysis and interrelation with world observations or their own run of the experiments; and
- stand-alone mode, where the virtual rendering of the experiment can be replayed, skipped back, and studied at great length to "research" the real behaviors of the fluid.

The website brings together the rotating fluid experiment and the real world with a comprehensive discussion of the climatology of the Hadley cell, as visualized with IDV (see http://lab.rotating.co/#/world). Three-dimensional plots of the Hadley cell from climatological data (NCEP–NCAR Reanalysis 1) show close analogies to the low-rotation tank experiment.

Navigation of the website. Visitors to the virtual laboratory will arrive with differing intents, time constraints, and levels of familiarity with the material or laboratory methods. In consideration of this, we have devised a streamlined experience for Weather in a Tank watchers along the top (progressing by right arrow/left swipe), while elaborations on a subject are folded in below (discoverable through a downward arrow/upward swipe). We recommend a first pass through the main stream at the top before making a second pass to review and explore in depth. Jumps across sections are possible through use of the menu.

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