Design and Construction of an Affordable Rotating Table for Classroom Demonstrations of Geophysical Fluid Dynamics Principles

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A rotating table was constructed on a limited budget. Demonstrations of fundamental concepts supplement graduate coursework in atmospheric dynamics, giving students the opportunity to experiment with parameters and gain insight into the phenomena being explored.

Rotating tanks have been in use for many years (e.g., Siemens 1866; Mallock 1896; Taylor 1921; Hide 1958; Fultz et al. 1959; Cenedese and Whitehead 2000) because of their ability to simulate geophysical fluid dynamical (GFD) phenomena, shedding insight on the sometimes complicated mathematics used to describe such processes. The devices come in a wide variety of sizes, from small record-player-type turntables with 10-cm-diameter tanks to the world's largest turntable with its 13-m-diameter tank at Grenoble, France (Sommeria 2001). Rotating table demonstrations and experiments have been and continue to be carried out at specialized GFD laboratories around the world, such as those at Woods Hole Oceanographic Institution, University of California at San Diego, Cambridge University, and several others. Useful results depend, of course, on the ability to establish dynamical similarity of the laboratory experiment with the geophysical phenomenon of interest.

Since there can be many dimensionless parameters (Rossby number, Richardson number, Ekman number, Reynolds number, Prandtl number, Froude number, etc.), precise dynamical similarity is not possible, and one must be satisfied with concentrating on just a few dominant parts of the total dynamics. Because they allow us to focus on the basic physics, laboratory experiments with rotating fluids can be very useful and can form an important part of our research tools, which also include observations, theory, and numerical modeling. Laboratory experiments with rotating fluids can also be an important part of educational programs in meteorology and oceanography.

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DOI: 10.1175/BAMS-84-12-1827

In final form 11 April 2003

HISTORY OF THE CSU SPIN TANK. In the fall of 2000, the Colorado State University (CSU) Department of Atmospheric Science decided to offer a group of graduate students the opportunity to design and construct a rotating table for classroom use. The device (the terms "rotating table" and "spin tank" will be used interchangeably) was funded by student tech-

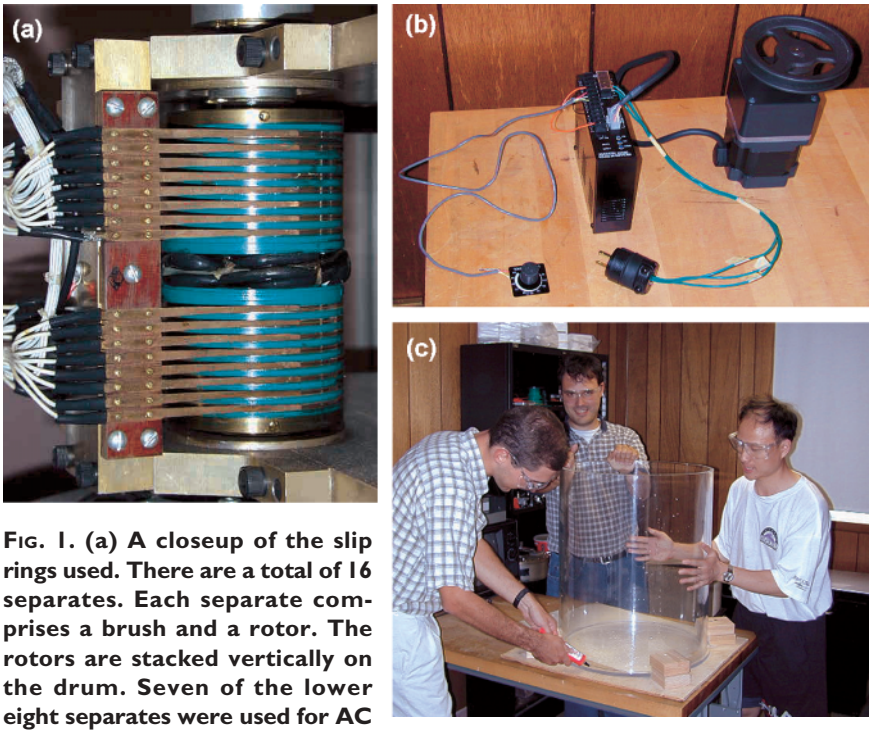

FIG. 1. (a) A closeup of the slip rings used. There are a total of 16 separates. Each separate comprises a brush and a rotor. The rotors are stacked vertically on the drum. Seven of the lower eight separates were used for AC power transmission. Two of the upper eight separates were used for analog video signal transmission. (b) The motor (and pulley wheel), controller, dial, and AC power plug. (c) Construction of the acrylic tank. The wooden jig can be seen at the base of the tank. A circle of adhesive was first applied to the circular base, then the tube was immediately, but carefully, placed on top of the plate.

nology fees, which are collected and used each semester for general improvement of the department's classroom facilities. Although a commercially available, research-quality rotating table can cost up to $100,000 (Australian Scientific Instruments 2000), that amount is not available to most universities' classroom budgets. However, many of the same experiments can be performed using a less sophisticated apparatus, significantly reducing cost. The project was formally identified as a practicum course to be held during the spring 2001 semester. It attracted the interest of five Ph.D. students and one M.S. student from various research groups within the department; W. Schubert, professor, volunteered to supervise the course and offered suggestions and direction at critical intervals during the project.

After 8 months of thought and work, the spin tank was completed and began classroom use to illustrate some selected principles in geophysical fluid dynamics. We wish to encourage other departments to build such an affordable device. In today's environment of numerical models, we are pleased to introduce a new addition to the often-forgotten realm of rotating tables.

DESIGN. At the onset of the practicum course, we were familiar with research papers that made use of rotating tables, but we lacked practical experience in construction and operation of any such device. Thus, we first contacted some experienced people—namely, P. Rhines at the University of Washington and R. Krishnamurti at the Florida State University, who brought some key issues to our attention. We needed to decide on the size of the tank, construction materials, range of desired rotation rates, motor type, etc., not to mention suppliers for all of the parts we would be buying or making during the project. In addition to those unknowns were several "knowns." We needed to build the entire apparatus for under $3,000 (class budget) and it had to be somewhat portable (it will be transported a few times each year).

A fundamental question to address was, "What principles of fluid dynamics do we wish to demonstrate?" The answer to that question would dictate tank size, tank shape, and demands on the motor. Those parameters had to fit within the budget. This practicum course focused on design and construction, leaving the more complicated demonstrations for future classes. We spent more than 1 month laboring over how we would build this device, what the allotted time should be for each phase, how sturdy or precise the components must be, and other details.

CONSTRUCTION. In mid-February 2001, we visited J. Hart and S. Kittelman at the University of Colorado's Geophysical Fluid Dynamics Laboratory (GFDL; see Hart 2000; Rhines 2002; Marshall 2003, for several examples of using a spin tank for classroom demonstrations). They not only had some great advice on tank construction and visualization, but they kindly donated to us a 1960-vintage Genesco turntable, which they had obtained through government surplus. The motor and electronics that once ran the turntable no longer functioned. The old components were antiquated and included giant variable resistors, transformers, and vacuum tubes, surrounded by a meticulously engineered maze of what seemed to be kilometers of thin red wire, intimidating even to an

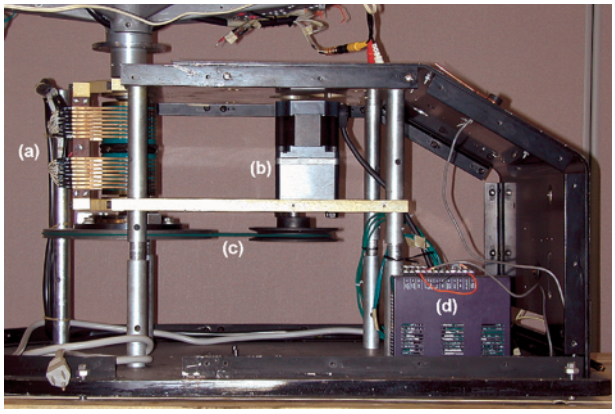

FIG. 2. A photograph of the inside of the apparatus. Key components are (a) the slip rings, (b) motor, (c) drive cord, and (d) motor controller. The dimensions of the base are 92 cm long, 40 cm tall, and 61 cm wide. The thick aluminum platter (partially shown at the top of the photograph) is 61 cm in diameter and extends 15 cm beyond the top of the base.

electrician. However, the mechanical parts of the turntable were very sturdy, well-machined, and in good working order. Thus, the apparatus was gutted and the remaining core (steel shell, structural supports, drive shaft, slip rings, turntable, and turntable bearings) proved to be a valuable starting point for the remainder of the project.

At this stage, the problem was essentially to select a new motor for the turntable. We chose a motor based on the range of torque it was able to supply, the dimensions, and cost. With the use of gear ratios, the motor (Fig. 1b) provided us with a maximum angular velocity of 3.0 rad s^{-1} and a maximum torque of 34.0 N m.

Slip rings are used to transmit electrical signals from the nonrotating frame to the rotating frame, and our design requirements were to deliver AC power and analog video signal. The slip rings used in this device comprise a drum with two stacks of eight separates (rotor/brush pairs), one above the other on the drive axle below the turntable (Fig. 1a). Two of the upper eight separates were designated for video signal transmission (positive and negative connections for analog video), and seven of the lower eight separates were designed for standard 120 V AC power transmission (three positive and three negative to accommodate household current, and one ground). Care was taken to leave enough physical distance between the "live" separates to reduce cross talk, electromagnetic interference, or electrical arcing. An alternative to slip rings would be to use battery-powered lights and camera, and a radio transmitter/receiver for the video signal. Although slip rings are fairly expensive and somewhat tedious to wire, they are a worthwhile investment because the power and signal passes through them with little noise or loss. The slip rings, drive cord, motor, and controller are clearly visible in Fig. 2.

Figure 1c shows the construction of the tank. The tube is a cylinder 50.8 cm in inner diameter and is 61.0 cm tall (capable of holding 124 kg of water). To construct the tank, we used a jigsaw to cut a circular piece of acrylic (55.9 cm in diameter) from a square sheet and the prefabricated tube was then glued to the sheet using an acrylic adhesive. All acrylic pieces were chosen to be 1.3 cm thick, which is amply rigid under the strains of handling the tank or filling it with water. Before gluing, we constructed a wooden support jig to assure proper placement during gluing and to secure the tank during the drying/curing stage. The assembled tank stood for 2 days beneath 20 kg of evenly distributed mass (cinder blocks on top of a piece of plywood) before disturbing it to ensure a complete and firm bond was made.

To the platter was attached a modular, removable superstructure made of aluminum rods and clamps to which lights and a small video camera were attached. Two rods were tapped and connected perpendicular to the turntable, and connected at the top by a rod of the same diameter. Clamp holders are used to assemble the superstructure and to hold the electric accessories. A standard AC power strip is secured to the turntable. The purpose for such a versatile superstructure is to allow flexible lighting and visualization options in the rotating frame. One setup is shown in Fig. 3, where the lights are placed on the side near the top of the fluid, and the camera is placed such that it can be pointed straight down into the

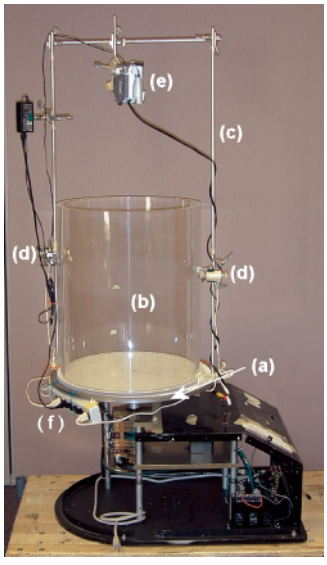

FIG. 3. A full view of the entire spin tank. The base (detailed in Fig. 2) supports the (a) platter, (b) tank, and (c) superstructure. Attached to the superstructure are (d) two small lights and (e) a video camera. (f) The standard AC power strip attached to the platter is also visible. The acrylic tank is 61 cm tall and 53 cm in diameter. The full apparatus, including the superstructure, is 177 cm tall and rests on a sturdy wooden cart with locking wheels.

fluid. We needed to solder standard RC audio/video jacks to the wires coming from the slip rings. Lighting is also tricky when dealing with a tube of acrylic filled with water, as finding an acceptable arrangement to minimize reflections takes a lot of patience.

For further details about construction materials, time line, specifications, and still and video files of the experiments, see McNoldy (2003). Without the inherited mechanical parts, the task would have been more difficult and would have involved a lot of time in the machine shop, but would still have been accomplished within the budget.

DEMONSTRATIONS. Here we present three geophysical fluid dynamics principles that are easily demonstrated with the apparatus described in the previous section: Ekman boundary layers, the Taylor–Proudman theorem, and barotropic instability. All are covered in the first-year graduate-level atmospheric dynamics courses at CSU. The experiments utilize a constant volume of a rotating, incompressible, homogeneous fluid (water) with a free upper surface.

Ekman boundary layers, Ekman pumping/suction, and spinup/spindown. Suppose our cylindrical tank has been rotating counterclockwise at a constant angular velocity for such a long time that the fluid within it has adjusted to a state of solid-body rotation. In other words, when viewed through the video camera in the rotating frame, the fluid is motionless. Now suppose the rotation rate of the container is suddenly, but only slightly, increased. Except very near the container floor and walls, the fluid is now in clockwise motion relative to the new rotation rate, which is denoted by Ω. How long will it take for the clockwise motion to disappear, that is, for the fluid to spin up to the new rotation rate? One might argue (erroneously) that spinup is a pure viscous diffusion process whose time scale can be estimated from the vertical diffusion of vorticity via the diffusion equation $\delta\zeta/\delta t = \nu(\delta^2\zeta/\delta z^2)$, where ζ is the initial relative vorticity and ν is the kinematic viscosity. We can estimate the magnitude of the left-hand side of this equation as $|\zeta|/\tau_d$ and the right-hand side as $\nu|\zeta|/H^2$, where τ_d is the diffusion timescale, and H is the mean fluid depth. Equating the magnitudes of the two sides, we conclude that the diffusion timescale is given by $\tau_d = H^2/\nu$. For the typical values $\nu = 1.0 \times 10^{-6}$ m^2 s^{-1} and $H = 0.15$ m, we obtain $\tau_d = 6.25$ h. Compared to the actually observed spinup time, τ_d is much too long. The actual spinup time of the fluid in the tank can be roughly determined by adding some dye just after the container rotation rate is suddenly increased. As seen from the video camera rotating with the container, the dye moves clockwise and eventually comes to a stop after approximately 5 min. Thus, τ_d is approximately 75 times larger than the observed spinup time.

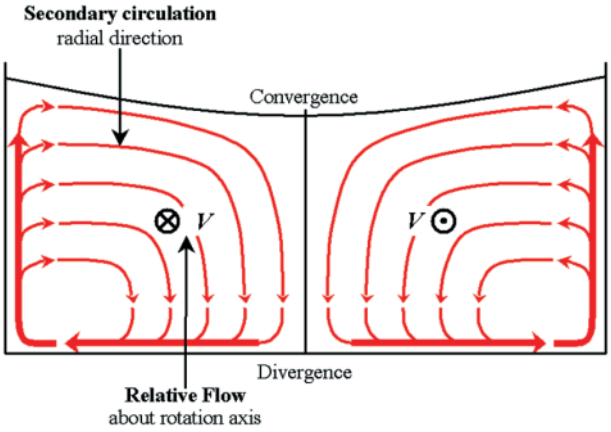

FIG. 4. Ekman pumping shown schematically through a vertical cross section. Relative motion is clockwise as viewed from above the tank. Thick arrows show the Ekman layer along the floor of the tank and the Stewartson layer along the wall.

The resolution of this discrepancy involves consideration of the Ekman layer and the associated secondary circulation. What actually happens during spinup is as follows. Within a few rotation periods after the sudden change of rotation rate, viscous layers are established along the floor (Ekman layer) and the walls (Stewartson layer) of the tank. The thickness of the Ekman layer is $O\{(\nu/\Omega)^{1/2}\}$. For $\Omega = 1.0$ s^{-1} and the value of ν given above, we obtain $(\nu/\Omega)^{1/2} = 1$ mm, so the Ekman layer is essentially confined to the lowest few millimeters of the container. In this shallow layer, after a few rotation periods, there is an approximate balance between the frictional, Coriolis, and pressure gradient forces, with a mass transport outward near the floor of the tank and upward along the walls (see Fig. 4). Due to mass continuity, the outward motion along the floor of the tank induces inward and downward motion through most of the fluid interior (i.e., boundary-layer suction). The suction at the top of the Ekman layer causes stretching of vortex tubes in the fluid interior. This stretching increases the relative vorticity and therefore returns the anticyclonic relative vorticity to zero—that is, it returns the fluid to a new state of solid-body rotation. The time required to reestablish a state of solid-body rotation via this process can be estimated by considering the vorticity dynamics or the absolute angular momentum dynamics of the interior fluid. The spinup time turns out to be $O\{E^{-1/2}(2\Omega)^{-1}\}$, where $E = \nu(2\Omega H^2)^{-1}$ is the Ekman number. For the values of ν, Ω, and H given above,

we obtain $E \approx 2.2 \times 10^{-5}$, so that the spinup time due to the secondary circulation is $\tau_s \approx 212(2\Omega)^{-1} \approx 5$ min.

In summary, there are three timescales: 1) the timescale to set up the Ekman layer, on the order of 10 s in our case; 2) the timescale to spinup the interior via Ekman suction at the top of the boundary layer and vortex stretching in the fluid interior, about 5 min in our case; 3) the timescale for diffusion through the total depth, about 6 h in our case. It is the first two timescales that are most relevant to understanding the actual behavior of the fluid in the tank.

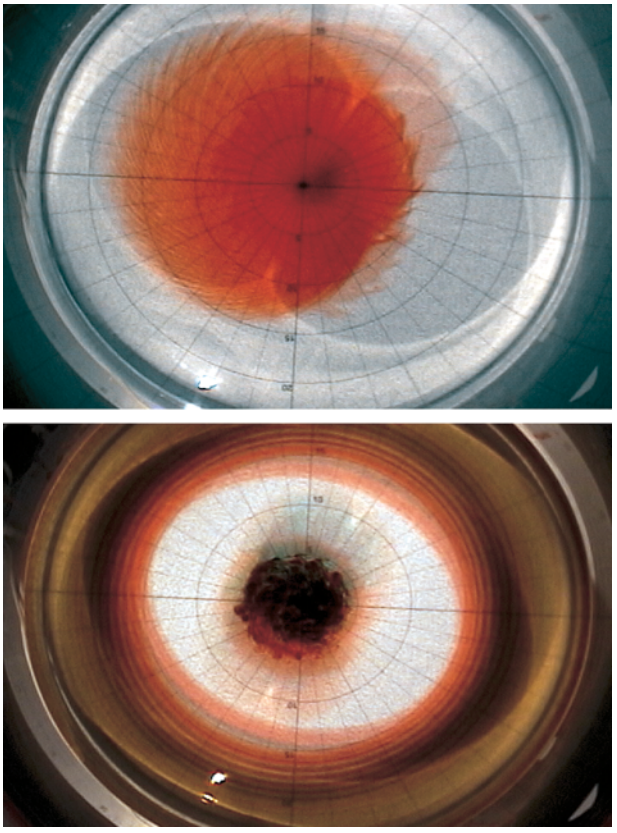

FIG. 5. Photographs from a demonstration of Ekman pumping. Red dye was added first, followed by green dye, both at the top surface. (top) The rapid outward motion along a shallow layer at the bottom of the tank (time scale is a few seconds). (bottom) The broad, diffuse return flow through the upper portion of the tank (time scale for the return flow to develop is a few minutes). Dark area in the middle of the tank is remnants of dye where it was initially added.

Figure 5 illustrates the Ekman pumping and resulting secondary circulation. The fluid is initially at solid-body rotation. Several drops of red food coloring are added to the fluid at the surface near the center of the tank. To produce a strong relative flow, the tank's angular velocity is suddenly accelerated. Immediately, the dye is drawn to the bottom of the tank, rapidly outward along the bottom, upward along the sides, and finally the dye moves inward through the bulk of the fluid. In our setup, the fluid achieves solid-body rotation again in approximately 5 min.

Greenspan and Howard (1963) presented an elegant mathematical analysis of the spinup problem. The three timescales discussed above are explicit features of their analysis. Very readable summaries of their work can be found in Greenspan (1968, 34–38) and Salmon (1998, 146–150). A review of spinup, including the stratified case, can be found in Benton and Clark (1974).

Taylor–Proudman theorem. The Taylor–Proudman theorem illustrates the powerful constraint that rotation can place on geophysical flows. The theorem states that, if the Rossby number is small, if friction can be neglected, and if there is no baroclinicity, then $\delta u/\delta z = \delta v/\delta z = \delta w/\delta z = 0$, where z is the coordinate parallel to the axis of rotation (i.e., the vertical coordinate). The small Rossby number and neglect of friction means that the horizontal flow components (u,v) tend to be geostrophic and horizontally nondivergent, and therefore that the thermal wind equations apply. The thermal wind equations relate $\delta u/\delta z$ and $\delta v/\delta z$ to density variations along the pressure surface (i.e., baroclinicity). Since there are no such density variations in a homogeneous fluid, then $\delta u/\delta z = \delta v/\delta z = 0$. With no vertical variation of the horizontal components u and v, it follows that a material line initially parallel to the rotation axis remains parallel to that axis as it moves around like a rigid column. This raises the following question: If we place a shallow obstacle at the bottom of the tank so that low-level flow is forced around it, will the fluid at all levels above the obstacle flow in an identical manner, as if there were a phantom obstacle extending through the whole depth of the tank (see Fig. 6)?

We tested this in our spin tank as follows. We first placed a shallow obstacle (a small unopened can of Friskies cat food) on the bottom of the tank, about two-thirds of the way out from the center of the tank (see Fig. 7). We then spun up the fluid to a solid body, counterclockwise rotation. After spinup, we slowly and slightly increased the rotation rate of the container, thus creating a weak (small Rossby number) clockwise flow relative to the new rotation rate. We

then dropped red dye on the water surface upstream of the obstacle, and observed the movement of the dye through the video camera rotating with the table. We used dye that is slightly more dense than water so that it sank and partially mixed, resulting in a red color over the entire depth of the fluid region upstream of the obstacle. The rather amorphous blob of red fluid upstream of the obstacle is seen in the top panel of Fig. 7. At a later time (Fig. 7, bottom), the red fluid is seen moving around the phantom obstacle, with no red fluid in the cylindrical region directly above the true obstacle. If the flow is observed from the side of the tank rather than from the top, one can see "Proudman pillars" of dye moving around the obstacle like rigid vertical rods extending the entire depth of the tank. This result was apparently very surprising even to Taylor (1923), who, as noted by Pedlosky (1987), stated that "the idea appears fantastic, but the experiments . . . show that the true motion does, in fact, approximate to this curious type."

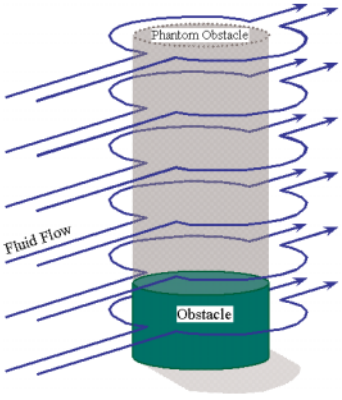

FIG. 6. The Taylor column shown schematically from an angle slightly above the obstacle. The blue arrows represent the relative flow around the obstacle and Taylor column.

Although detailed dynamical arguments leading to the Taylor–Proudman theorem are given in several textbooks (e.g., Pedlosky 1987, 42–45), it is our experience that most students do not truly grasp the concept until they see both the mathematical argument and the laboratory demonstration.

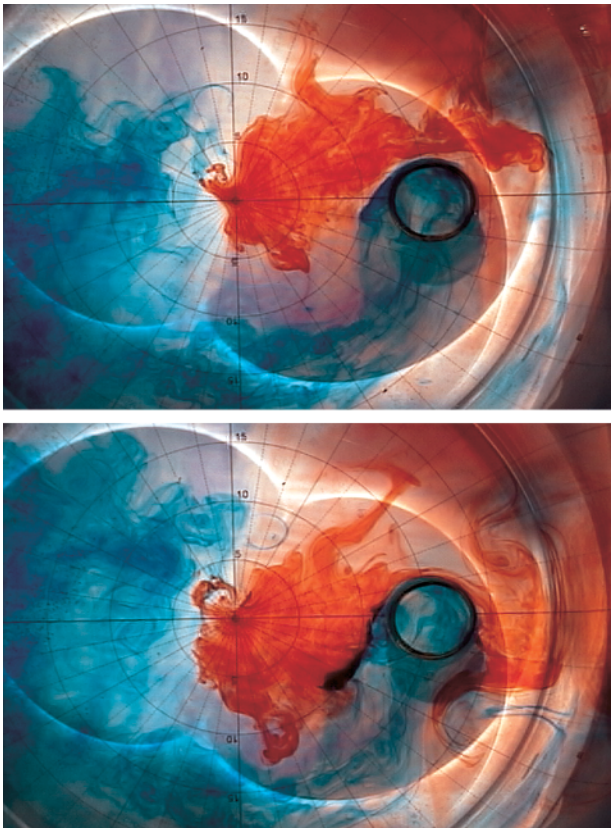

FIG. 7. Series of photographs from a demonstration of the Taylor–Proudman theorem. The fluid is approximately 5 times the depth of the obstacle. (top) Blue dye was initially added over the obstacle to check that solid-body rotation had been achieved and that the fluid was essentially two-dimensional through its depth. The rotation rate of the tank was then slightly increased, creating a relative flow around the obstacle. Finally, red dye was added "upstream" and the relative flow advected the red dye toward the Taylor column. (bottom) The blue dye remained over the obstacle and the red dye followed around the phantom column.

Barotropic instability. While experimenting with spinup and spindown, it is easy to produce flow instabilities. For example, near the end of the spinup process shown in Fig. 5, water containing red and green dye has moved radially outward along the bottom, up the side wall, and then radially inward a small distance through the remaining depth, stopping its inward radial displacement when spinup is complete. We end up with a banded pattern near the outer edge of the tank. Now suppose the rotation rate of the tank is abruptly and significantly decreased. The relative flow is now counterclockwise, with a large radial shear of the azimuthal velocity near the edge of the tank. In this region of large shear, barotropic instability (illustrated schematically by Fig. 8) begins to set in, as shown by the waviness in Fig. 9 (top). As this instability extracts increasing amounts of kinetic energy from the primary circulation, the waves continue to amplify, resembling the cresting and breaking of ocean waves, as shown in Fig. 9 (bottom). These eddies can rapidly mix the dye, leaving a featureless colored haze. This process can be repeated over and over until the water is too murky with dye to see these features. If the change in rotation rate is not large enough, the spinup time (see "Ekman boundary layers, Ekman pumping/suction, and spinup/spindown") will actually be shorter than the time required to set up the barotropic instability, and the aforementioned features will never be seen.

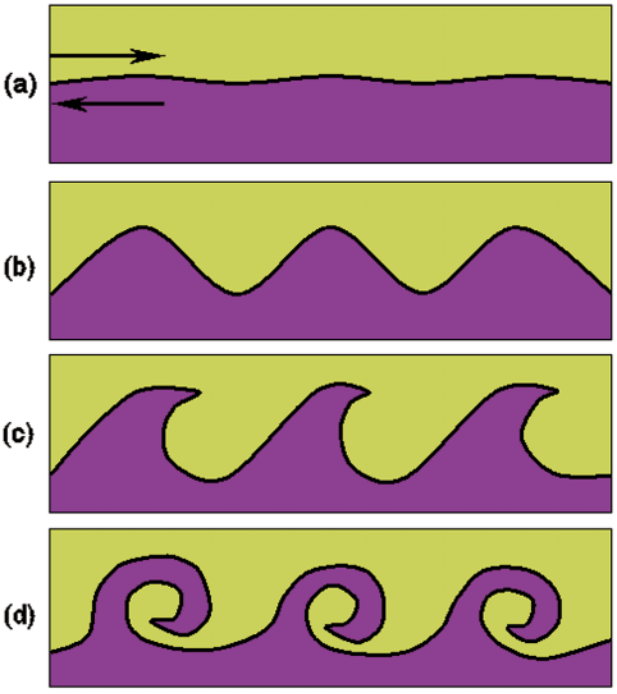

FIG. 8. A simplified schematic drawing of barotropic or shear instability. (a) A fluid experiences differential shear (horizontal shear in the atmosphere, and more precisely, radial shear in a tank). Assuming the instability criteria are met, the interface will become unstable, forming waves that (b) amplify, (c) crest, and (d) eventually break.

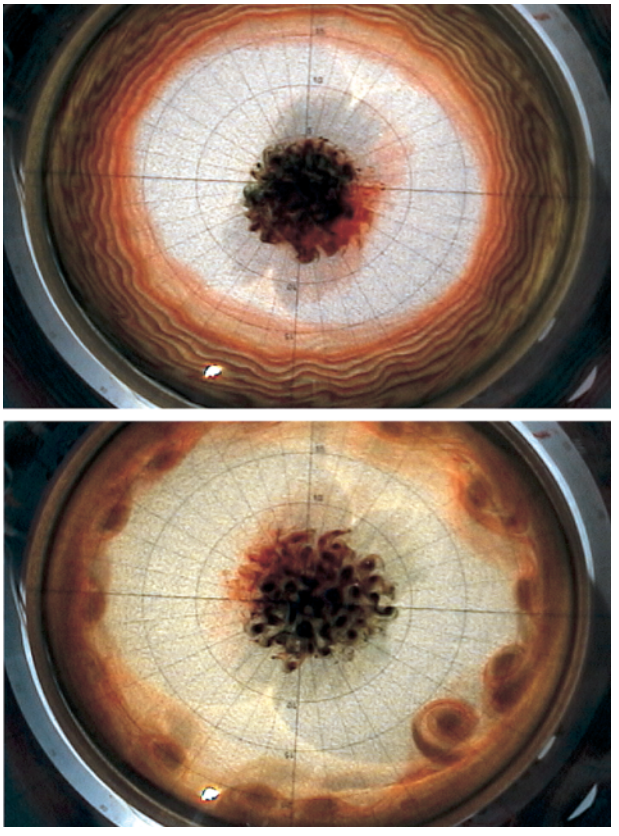

FIG. 9. (a) Barotropic instability and (b) wave breaking as a result of radial shear in an actual demonstration. Largest vortices are 5 cm in diameter and persist for several minutes. As in Fig. 5, the dark area in the middle of the tank is remnants of dye where it was initially added.

WHAT DOES THE FUTURE HOLD? A rotating table can be viewed as a basic facility on which many different types of fluid tanks and experiments can be mounted. We have given only three examples of the many experiments that can be performed. To get a feeling for the enormous possibilities, the reader is referred to J. Hart's (Hart 2000) and J. Marshall's (Marshall 2003) GFDL Web pages, where many classroom demonstrations are discussed. For example, Hart has shown that even baroclinic instability in a differentially heated annulus is within the realm of portable classroom demonstration.

In the near future for our device, we hope to improve visualization techniques, to demonstrate a wider range of fluid dynamics principles, and to precisely control the motor speed using a computer. Different tanks or additions to the current tank would allow Rossby waves, baroclinic instability, vortex merger, and thermal convection to be demonstrated. To show these principles as well as others, complications such as a wave maker, differential heating, concentric cylindrical tanks, stratified fluids, and various obstructions to the flow would be required. Although coming at a higher cost, improved visualization could be achieved by using small reflective particles and specialized lighting to trace out the flow (e.g., Greenspan 1968; Griffiths and Linden 1981; Sommeria 2001; Montgomery et al. 2002) rather than easily diluted food coloring. Other practicum courses, similar to the one responsible for the creation of the apparatus, will be held in the future with a goal of performing some of the experiments listed above.

DISCUSSION. We have demonstrated that it is not difficult to design and build an inexpensive rotating turntable with variable rotation rate and with an attached video camera. The completed apparatus fits within several constraints: 1) it is capable of demonstrating fluid dynamics principles relevant to graduate-level courses; 2) it was completed for under $3,000; 3) it is portable enough to be moved between classrooms; and 4) there are a variety of visualization options from the rotating frame, including live transmission to a television and recorded playback. The entire project took 8 months to complete, with six students each working an average of 1.5 h per week

on it. Although we benefited from the donation of some important turntable parts, including slip rings, the entire apparatus could still have been constructed within the budget (perhaps by choosing a smaller tank and a less powerful motor). A project as described in this paper would take significantly less time to complete for other departments using our experience as a guide.

The spin tank has been and will continue to be used in the classroom at CSU, utilizing the apparatus itself, or at least a video recording of the demonstrations, to complement and enhance the mathematical treatment of atmospheric dynamics. In September 2001, we presented the finished project at the weekly department seminar in front of a standing-room-only audience. Just weeks later, it was used in a classroom for the first time, with volunteer class members as operators and the tank creators as supervisors; student feedback was unanimously positive. It is hoped that future classes will continue to improve and build upon this work, allowing an increasing variety of fluid dynamics principles to be demonstrated.

In concluding, we would like to reemphasize the importance of combining laboratory demonstrations with mathematical derivations in the study of geophysical fluid dynamics. This view was clearly stated by Greenspan (1968) who begins a mathematically rigorous textbook with the opinion that "these demonstrations really give the subject life and their role in developing intuition cannot be overestimated."

ACKNOWLEDGMENTS. We thank John Davis and Brian Jesse at CSU for their help throughout the construction and testing phases of the project. We are grateful to John Hart and Scott Kittelman at CU for their advice and the gift of an old turntable that we used as the "backbone" of our table. Peter Rhines at UW and Ruby Krishnamurti at FSU were extremely helpful during the concept and design phases. We would also like to thank Michael Montgomery at CSU for his enthusiastic encouragement and for quickly incorporating the laboratory demonstrations into his atmospheric dynamics course. Finally, helpful comments from Jack Whitehead and an anonymous reviewer improved the manuscript.

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