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Journal
Bulletin of the American Meteorological Society, 99(12)

ISSN
0003-0007

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Publication Date
2018

DOI
10.1175/bams-d-17-0215.1

Peer reviewed

AFFORDABLE ROTATING FLUID DEMONSTRATIONS FOR GEOSCIENCE EDUCATION

The *DIYnamics* Project

Spencer A. Hill, Juan M. Lora, Norris Khoo, Sean P. Faulk, and Jonathan M. Aurnou

An ultra low-cost rotating tank platform made of LEGOs and a lazy susan has been developed and utilized for teaching elementary- through graduate-level students.

Planetary rotation fundamentally shapes large-scale atmospheric, oceanic, and planetary interior fluid flows, a fact that is generally second nature to geoscientists while unintuitive to students (Roebber 2005). Physical demonstrations using rotating tanks of fluid are a powerful pedagogical tool for illuminating these connections for students from the middle school (Illari et al. 2009) to university undergraduate (McNoldy et al. 2003) and graduate (Mackin et al. 2012) levels.

An invaluable resource for teaching with rotating tanks is the "Weather in a Tank" project (Illari et al. 2009, 2017). Its library of demonstrations (http://weathertank.mit.edu/links/projects) provides 15 demonstrations of different fundamental atmospheric and oceanic phenomena, each including how-to photos and written instructions, as well as a theoretical description and real-world examples. The Weather in a Tank website also details the physical components of the rotating tank platform used to execute these demonstrations (http://weathertank.mit.edu/apparatus). But the platform and a predecessor (McNoldy et al. 2003) require specialized equipment that must be custom ordered and assembled by experts, costing several thousand dollars. This is likely far beyond reach for many schools.

What is needed, we argue, is a demonstration platform that is easier to afford, acquire, and assemble. A useful analogy is the use of a *hierarchy* of complexity in atmospheric models (Held 2005; Bony et al. 2013; Jeevanjee et al. 2017). In this analogy (depicted in Table 1), the aforementioned rotating table platforms are akin to intermediate-complexity climate models run on university computing clusters. We aim to provide something akin to a shallow-water (e.g., https://github.com/PyRsw/PyRsw) or quasigeostrophic (e.g., Williams et al. 2009) model run on students' laptops.

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The abstract for this article can be found in this issue, following the table of contents.
DOI:10.1175/BAMS-D-17-0215.1

In final form 29 May 2018

To that end, we introduce Do-It-Yourself Dynamics (*DIYnamics*), an effort to develop and disseminate affordable, easy-to-build rotating tank platforms. We have created a rotating tank system built from household items that can be ordered online for well under $100 (https://diynamics.github.io/pages/table.html) and that can be assembled by novices in minutes (https://youtu.be/rvF6UAO8vPA). Accompanying videos and lesson plans enable instructors—even those previously unfamiliar with fluid dynamics—to use the demonstrations as part of an effective overall teaching module. The materials can be accessed through the *DIYnamics* website (https://diynamics.github.io), and they have been successfully piloted in multiple middle school classrooms, a joint undergraduate–graduate class, and public science outreach events.

THE *DIYNAMICS* TABLE. Table 2 lists the components of the *DIYnamics* rotating tank platform, and Fig. 1 shows the device fully assembled. The platform comprises a household lazy Susan as the rotating tabletop, a motor-driven wheel that spins the tabletop, a power supply for the motor, and a walled container that sits on the tabletop to hold the liquid (typically water). The motor and power supply consist of LEGO "Power Functions" products, and the motor wheel, axle, and motor housing are built from other LEGO pieces—see Fig. 2 for an example page from the instructions for assembling the motor housing.

The LEGO products provide several benefits. The power supply connects to the motor via rubber-encased wires that snap into place on either end and draws power from six standard AA batteries—making the table safe, reliable, and portable. The motor drives the table at a sufficiently steady rotation rate and with sufficient torque for all demonstrations attempted to date—up to ~3 gallons (~11.4 L) of water in a 16-in. (40.6 cm) diameter tank at roughly 25 revolutions per minute (RPM). The precise rotation rate can vary across motors, but for a given motor with sufficiently charged batteries, the rotation is steady enough that no "sloshing" or other physical artifacts of nonsteady rotation emerge during demonstrations. And, in our experience, the use of LEGO blocks makes the apparatus especially inviting to younger students.

Table 1. Summary of the analogy between the well-known hierarchy of numerical models of climate with the hierarchy we propose of demonstrations of atmospheric and oceanic phenomena, expressed in terms of three discrete levels of complexity. Note that the analogy is imperfect, in that the physical complexity of the phenomena is unlikely to differ appreciably across the rotating tank platforms (although the physical scale does), whereas in the computational hierarchy, both the actual simulated processes and the apparatus are simplified moving toward more idealized models. Items in brackets are examples in that category.

Level	Simulation model type	Simulation infrastructure	Demonstration infrastructure
Top	General circulation models Numerical weather prediction models [National Center for Atmospheric Research (NCAR) Community Earth System Model (CESM)][a]	Supercomputers [NCAR Cheyenne][b]	Research-grade rotating tanks [Rotating Magnetoconvection Projects (RoMag)],[c] [Coriolis platform][d]
Middle	Intermediate-complexity models [Gray-radiation moist (GrAM; Frierson et al. 2006)]	University computing clusters [UCLA Hoffman2][e]	Weather in a Tank
Bottom	Shallow-water models, "toy" models [Python Rotating Shallow Water (PyRsw)],[f] [Quasigeostrophic Model for Investigating Rotating Fluids Experiments (QUAGMIRE; Williams et al. 2009)]	Students' laptops	*DIYnamics*

[a] www.cesm.ucar.edu/models/.

[b] www2.cisl.ucar.edu/resources/computational-systems/cheyenne.

[c] http://spinlab.ess.ucla.edu/?page_id=861.

[d] www.louis.gostiaux.fr/spip.php?article6.

[e] https://idre.ucla.edu/hoffman2.

[f] https://github.com/PyRsw/PyRsw.

All parts can be purchased through a combination of online retailers; full ordering instructions are listed on the *DIYnamics* website (https://diynamics.github.io/pages/table.html). At the time of writing, they cost well under $100 in total before shipping charges (Table 2); those charges are in the range of ~$10 per retailer for domestic shipping and likely more for international shipping. Combined with other international fees (e.g., duties), outside the United States, it is likely that the components could be attained at lower cost through other sites. The entire kit weighs only a few pounds and fits easily into a grocery bag. Following along PDF and/or video assembly instructions (https://diynamics.ithub.io/pages/table.html), students are typically able to assemble the platform in well under one-half hour, sometimes in as little as a few minutes.

TABLE 2. Components of the *DIYnamics* rotating tank platform. (left to right) Table component, specific product used for that component, source from which the product was purchased, and cost at time of writing in U.S. dollars. Cost does not include shipping, which can be up to ~$10 per retailer for domestic shipping and appreciably more (along with customs fees, etc.) for deliveries outside the United States. The parts are separated into three categories, "core," "peripheral," and "optional," by horizontal lines. Core components are required, with these specific products highly recommended ($40.15 total); peripheral components are necessary or extremely helpful for most demonstrations, but the specific products used could readily be swapped out for alternatives ($16.46 total; $56.61 combined for core and peripheral); optional components provide additional functionality to the table but are not required for the demonstrations described here ($66.95 total; $123.56 combined for all components).

Category	Component	Product	Source	Cost (U.S. dollars)
Core	Rotating tabletop	OXO 16-in. lazy Susan	http://a.co/16P3tM1	$16.99
	Motor	LEGO Power Functions XL-Motor		$10.99
	Motor axle, wheel housing	Miscellaneous LEGO "pick a brick" pieces	https://diynamics.github.io/pages/table.html	$5.18
			https://shop.lego.com/en-US/LEGO-Power-Functions-XL-Motor-8882	
	Power supply	LEGO Power Functions Battery Box	https://shop.lego.com/en-US/LEGO-Power-Functions-Battery-Box-8881	$6.99
Peripheral	Tank	Gardener's Edge 12-in. plastic pot saucer	www.gardenersedge.com/12in-clear-plastic-pot-saucer/p/PTD-12	$1.99
	Nonslip pad	Regent jar gripper pad	http://a.co/8LXywUj	$6.99
	Food dye	Spice Supreme food colors	http://a.co/bAxjAMy	$5.49
	Dish soap	Gain Ultra liquid dish soap	http://a.co/ePPzSrl	$1.99
Optional	Infrared receiver	LEGO Power Functions IR Receiver	https://shop.lego.com/en-US/LEGO-Power-Functions-IR-Receiver-8884	$14.99
	Infrared remote	LEGO POWER Functions IR Speed Remote Control	https://shop.lego.com/en-US/LEGO-Power-Functions-IR-Speed-Remote-Control-8879	$12.99
	Tripod	Fotopro smartphone tripod	http://a.co/cmN3ik9	$25.99
	Duct tape	Duck brand duct tape	http://a.co/20kFXC9	$5.99
	Siphon	Tera Pump TRDP14 hand siphon	http://a.co/2WJokUT	$6.99

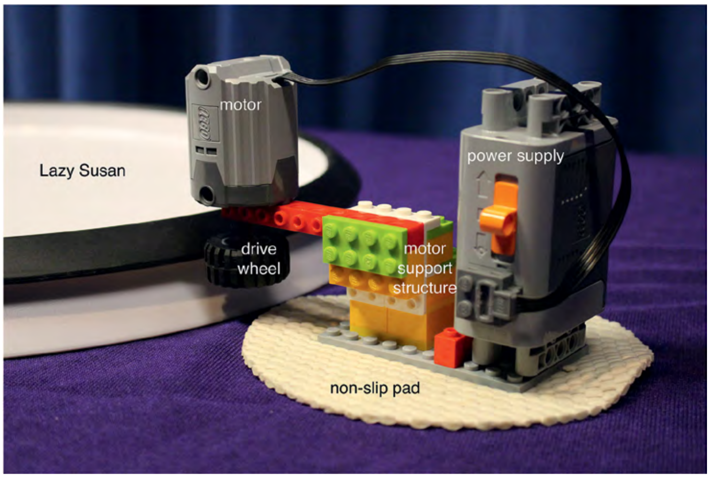

Fig. 1. Photograph of the *DIYnamics* rotating table platform with key components labeled. Video instructions are available online (https://youtu.be/rvF6UAO8vPA).

Optional components listed in Table 2 add additional functionality to the standard table configuration. An infrared remote and receiver enable varying the rotation rate by increments of one-eighth times the maximum value; this is useful in demonstrations of baroclinic instability (discussed further below and in the sidebar), as at the default rotation rate and typically used fluid depths, the eddy length scale is smaller than desired. A simple tripod and duct tape enable capturing video footage in the rotating frame using a cellphone camera. The footage can be streamed live to a computer or tablet via a video messaging application (e.g., Skype, FaceTime, or Google Hangouts) and/or recorded for subsequent viewing. This mitigates the drawback of a lack of power in the rotating frame. A hand siphon makes emptying full tanks less spill-prone.

The *DIYnamics* table's maximum tank diameter of 16 in. (40.6 cm) is comparable to the size of the standard Weather in a Tank platform (http://weathertank.mit.edu/apparatus). In our experience, students find demonstrations on the *DIYnamics* table engaging even with much narrower tanks, as little as 6 in. (15.2 cm). In addition, when the tripod is not being used, it is completely safe for students to lean all the way over the table or view it from the side from very close up, since no equipment sticks up that might strike a student as it rotates. This is not the case for conventional platforms, whose permanent (typically metal) arm holding the camera forces viewers to stay at a distance. In fact, we have found the opposite problem to emerge: excited younger students sometimes accidentally bump into the table, the solution being to use the disturbance to the fluid as an opportunity to teach about spinup and spindown processes.

DIYNAMICS DEMONSTRATIONS, LESSON PLANS, AND VIDEOS.

The *DIYnamics* table can be used to perform several engaging demonstrations. See the sidebar for a "recipe" for demonstrating baroclinic eddies (Nadiga and Aurnou 2008)—disturbances that feed off of meridional temperature gradients on rotating bodies and are a fundamental feature of Earth's midlatitude weather—and the *DIYnamics* YouTube channel for a companion instructional video that includes footage from the rotating frame (https://youtu.be/2tIVOK9wjI4).

An even simpler, hands-on demonstration especially useful with new students is to contrast rotating and nonrotating tanks side by side. Students drop food coloring into each tank (after a few minutes of spinup for the rotating tank; e.g., https://youtu.be/o-jV5Vf-bcw), observing that dye sinking through the nonrotating tank has complicated trajectories and gradually diffuses, while dye in the rotating tank simply sinks to the bottom with little horizontal motion. Instructional videos for both cases are available on the *DIYnamics* YouTube channel (https://youtu.be/oCgItK4arNM and https://youtu.be/5wJvRpiA38Q). This can be repeated adding mechanical stirring by

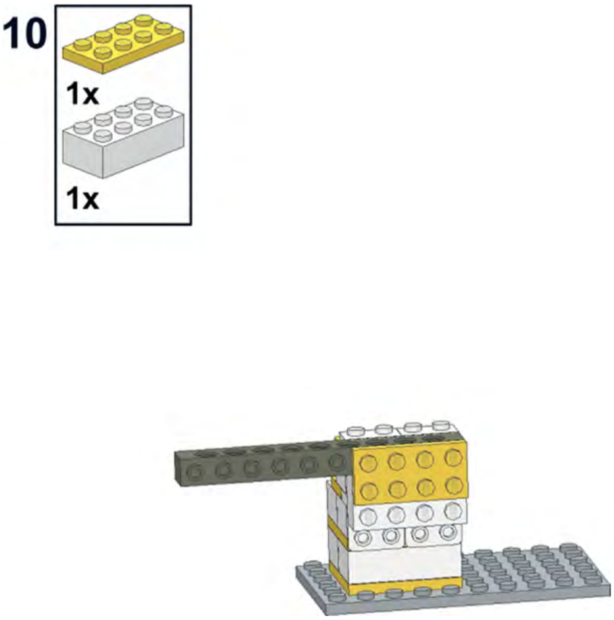

Fig. 2. Excerpt from the PDF assembly instructions of the LEGO-based housing for the motor and power supply (available at https://diynamics.github.io/pages/table.html). The instructions mimic those that come with official LEGO sets.

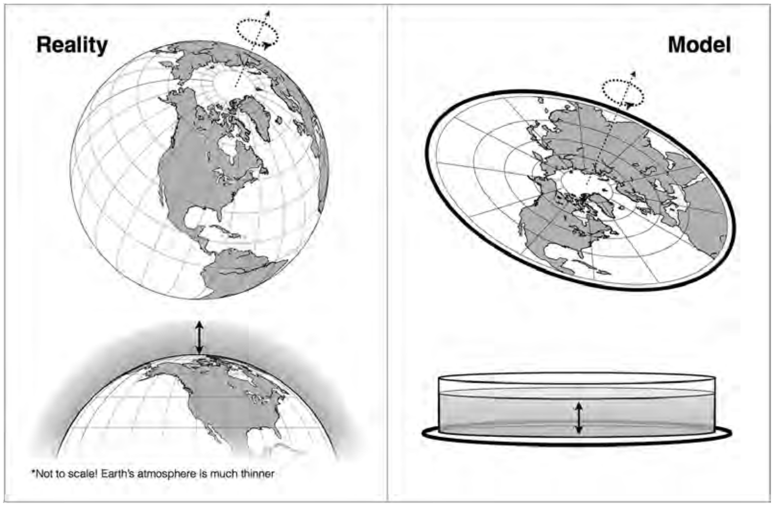

Fig. 3. Schematic used on the *DIYnamics* website and other materials. The graphical depiction of projecting the spherical Earth onto a flat surface helps students recognize the utility of a rotating tank of water as a model for planetary fluids. An analogous schematic was presented by Read et al. (1998).

having students briefly stir either tank with pencils after the dye is injected. Dye in the nonrotating tank mixes into a nearly homogeneous brown blob, while the rotating case generates persistent vortices and sharp gradients because of the axially aligned, gyroscopic nature of rotating fluids (Haine and Cherian 2013). If red and yellow dyes are used, the rotating case comes to resemble the surface of Jupiter, usually complete with a coherent red vortex that can serve as an analogy (albeit imperfect) to Jupiter's Great Red Spot.

We have incorporated these and other demonstrations into a lesson plan targeted at the middle school level that teaches the concepts of scientific modeling, convection, constraints on fluid motion and mixing due to rotation, and other topics (available at https://diynamics.github.io/pages/teaching.html). This document includes written text, photos, and schematics such as the one in Fig. 3 illustrating the connection between Earth's atmosphere and a small rotating tank of water [a predecessor to this schematic is available in Fig. 1 of Read et al. (1998)]. The existing lesson plans are targeted at middle school students but could be adapted to other audiences. For the sizable fraction of teachers with little background in fluid dynamics, these supporting videos and lesson plans are as important as the tables themselves: it is well documented that demonstrations, however fun, reliably improve learning outcomes only when the students are made to thoughtfully engage with the underlying concepts to be learned before, during, and after the demonstrations (e.g., Crouch et al. 2004; Mackin et al. 2012; Waldrop 2015; Feder 2017).

To provide teachers with an additional online resource to help explain the science, we have also created a video on baroclinic instability using a larger custom table and tank (www.youtube.com/watch?v=5bnmaYOFerk). It shows footage simultaneously from the rotating and nonrotating frames, the former captured wirelessly via a GoPro camera clamped onto the rotating tank. We have also produced a Spanish language version of this video (www.youtube.com/watch?v=b4f0plA3_Bg) and intend to produce additional foreign language videos and lesson plans in the future. These and all other videos are available on the *DIYnamics* YouTube channel (http://tinyurl.com/diynamicsvideos).

PAST *DIYNAMICS* OUTREACH EVENTS AND USE IN CLASSROOMS. We have used the *DIYnamics* materials to teach basic rotating fluid dynamical concepts in multiple classrooms and outreach events attended collectively by hundreds of students, all of which are described in posts on the *DIYnamics* blog (https://diynamics.github.io/pages/blog.html). These include presenting for seventh and eighth grade science classes at two middle schools in Los Angeles, California, in May 2017 (see Fig. 4); presenting to a public audience at the Sierra Nevada Aquatic Research Laboratory in June 2017; running a booth with continuously repeated demonstrations for attendees of the University of California, Los Angeles (UCLA), "Exploring Your Universe" science fair in October 2017 (www.exploringyouruniverse.org/); performing demonstrations as part of a "lab day" in a joint undergraduate–graduate class on atmospheric and oceanic fluid dynamics in April 2018; and running a booth at another science fair, at the El Marino Language Elementary School in Culver City, California, in April 2018.

One of the major benefits of the *DIYnamics* table compared to conventional platforms at these events has been the ability to simultaneously operate multiple tables—up to six *DIYnamics* table stations at once at events to date. This breaks otherwise large groups of students into smaller ones, enabling virtually all students to participate and, quite literally, get their hands wet. In written feedback, a teacher at one of the middle schools commented, "I *especially* loved that you were prepared for small group interactions and demonstrations so all the students could be front row at least once in the period." This is made possible by the ease of acquiring, transporting, setting up, and operating the *DIYnamics* table.

At the Exploring Your Universe event, we provided LEGO bricks and printed instructions for assembling the motor housing and connecting it to the motor and power supply. Around 20 young attendees successfully built the platform, which was then used to perform a demonstration for them and a larger audience. At the middle school and Exploring Your Universe events, we also demonstrated baroclinic instability with our larger tank and GoPro setup, streaming the rotating tank footage in real time onto a classroom wall or to a handheld tablet. The more recent El Marino science fair event featured demonstrations of baroclinic instability on the standard *DIYnamics* table (following the recipe in the sidebar), drastically increasing the ease of transporting our equipment.

Written assessments by teachers and students as well as informal assessments by teachers, students, and event volunteers indicate that the tables have been highly successful. One middle school student was surprised that "we can demonstrate the whole globe with a glass of water." Many students took pictures and videos of the demonstrations to share with their friends afterward. The tables' low cost enabled us to give one to each middle school, and, following our lesson plan, one teacher

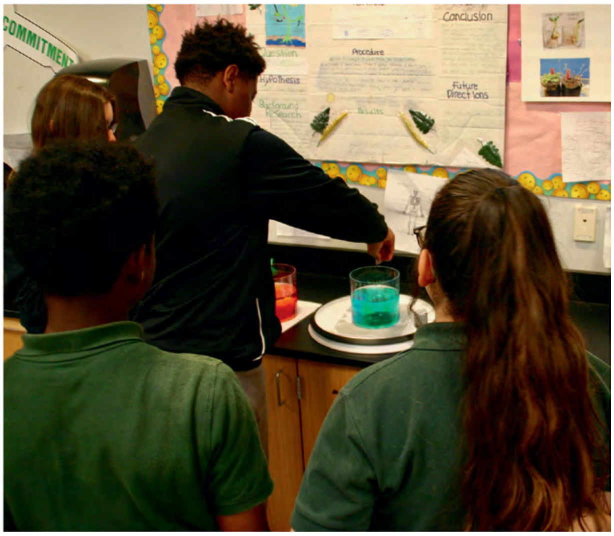

Fig. 4. A student at La Tijera K–8 Charter School in Inglewood, California drops dye into water spinning on the *DIYnamics* table as part of a demonstration comparing the behavior of dye in rotating and nonrotating tanks.

AN EXAMPLE DEMONSTRATION RECIPE USING

Here, we provide a "recipe" for demonstrating baroclinic instability using the *DIYnamics* table. A video-based version is available on the *DIYnamics* YouTube channel (https://youtu.be/2tIVOK9wjI4).

Required ingredients.

- All materials listed in the core and peripheral sections of Table 2
- Room temperature water, enough to fill the tank to ~1 in. (2.54 cm) from the top
- One 12-oz (340 g) can of tomato paste (or other substance), frozen

Optional ingredients.

- For reducing the rotation rate: the LEGO Power Functions IR receiver and remote (see Table 2)
- For recording footage in the rotating frame: the smartphone tripod listed in Table 2 and electrical or duct tape
- For contrasting solid-body rotation case: another 12-oz can, at room temperature

Directions.

1) If not done already, assemble the *DIYnamics* table following the instructions provided online (https://diynamics.github.io/pages/table.html and/or https://youtu.be/rvF6UAO8vPA).
2) Center the plastic tank on the lazy Susan tabletop. (It helps to mark the centers of each beforehand with a permanent marker.)
3) If the optional tripod is being used, extend the legs such that the tripod stands to a height above that needed for the phone's camera to capture the whole tank in video recording mode. Then use the tape to fasten the camera to the legs so that it points directly down onto the tank.
4) Fill the tank with the water, leaving roughly 1 in. (2.54 cm) between the water surface and the top of the tank.
5) Place the frozen can in the center of the tank. If rotating frame footage is being collected, turn on the recording/streaming now.
6) Turn on the motor and begin driving the table by placing the motor wheel directly in contact with the edge of the lazy Susan. If the optional IR remote and receiver are being used, use the remote to reduce the rotation rate by ~1/2 of the maximum.
7) If the can and/or tank are off-center, turn off the motor, recenter the can and tank as necessary, and then turn the motor back on.
8) Verify by eye that the rotation rate is generally constant, which requires that the wheel maintains steady contact with the table. If not, place a heavy object (e.g., a textbook) behind the combined motor and power supply apparatus, and/or try placing the motor at an angle with the lazy Susan rather than head-on.
9) Allow the system to spin up by having the table spin unperturbed for approximately 5 minutes. [For advanced students, this duration can be estimated using the time scale for one exponential spinup period τ as (cf. Greenspan and Howard

used it on a later date to demonstrate cellular rotating convection driven by evaporative cooling (Nakagawa and Frenzen 1955).

In April 2018, the *DIYnamics* tables and basic demonstrations of solid-body rotation and mechanical stirring were incorporated into a "lab day" of physical demonstrations in a combined upper-division undergraduate–graduate course at UCLA, "Introduction to Geophysics and Space Physics II: Oceans and Atmospheres," taught by

THE *DIYNAMICS* TABLE

1963) $\tau \simeq H/(\nu\Omega)^{1/2}$, where H is the depth of the fluid, ν is the kinematic viscosity, and Ω is the rotation rate. With the tank filled with ~2.5 in. ($H \approx 0.06$ m) of water ($\nu = 10^{-6}$ m^2 s^{-1}) rotating at ~25 RPM ($\Omega \approx 2.6$ s^{-1}), this yields ~37 s. So 5 minutes results in about eight exponential spinup periods, which is ample.]

10) Place a drop or two of dish soap into the tank. This breaks the surface tension that otherwise traps some of the food coloring in a thin surface layer, making it harder to see the dynamics of interest within the fluid interior. (The behavior below the surface will be the same with or without the soap.)
11) Place approximately five drops of blue dye in a circle roughly 1 in. (2.54 cm) from the can's edge, as evenly spaced as possible. If using the optional tripod, be careful not to knock into the tripod while putting in the drops.
12) Drop roughly the same amount of red dye in a larger circle, roughly 2 in. (5.1 cm) radially outward from the can's edge. Depending on the rotation rate and fluid depth, the red dye should be placed closer (faster and/or deeper) or farther (slower and/or shallower).
13) The dye should reveal eddies, typically a few centimeters in diameter (see top panel of Fig. SB1). As they move past each other, sharp fronts separating the red and blue dyes will emerge, as will large coherent vortices of either color. These are analogous to the winter storms and fronts in Earth's midlatitudes (e.g., bottom panel of Fig. SB1).

Optional supplement: Solid-body rotation. This is most effective if you have two tables and perform this side by side with the baroclinic instability, but the contrast can still be successfully made by performing them one after the other. Proceed as directed above, but use a can at room temperature rather than a frozen one or no can at all (video instructions available at https://youtu.be/oCg1tK4arNM). With no thermal contrast, there is nothing driving a radial circulation, and the system will simply end up in solid-body rotation—that is, with no fluid motions relative to the rotating tank. Food coloring of either color, being denser than the water, will simply sink to the tank bottom, with little horizontal motion. Note, after several minutes, evaporation at the surface may generate smaller-scale rotating convection cells (Nakagawa and Frenzen 1955; see also last bottom image of https://diynamics.github.io/blog/eyu-2017.html)

Additional supplement. Repeat, but with no rotation (video instructions available at https://youtu.be/5wJvRpiA38Q).

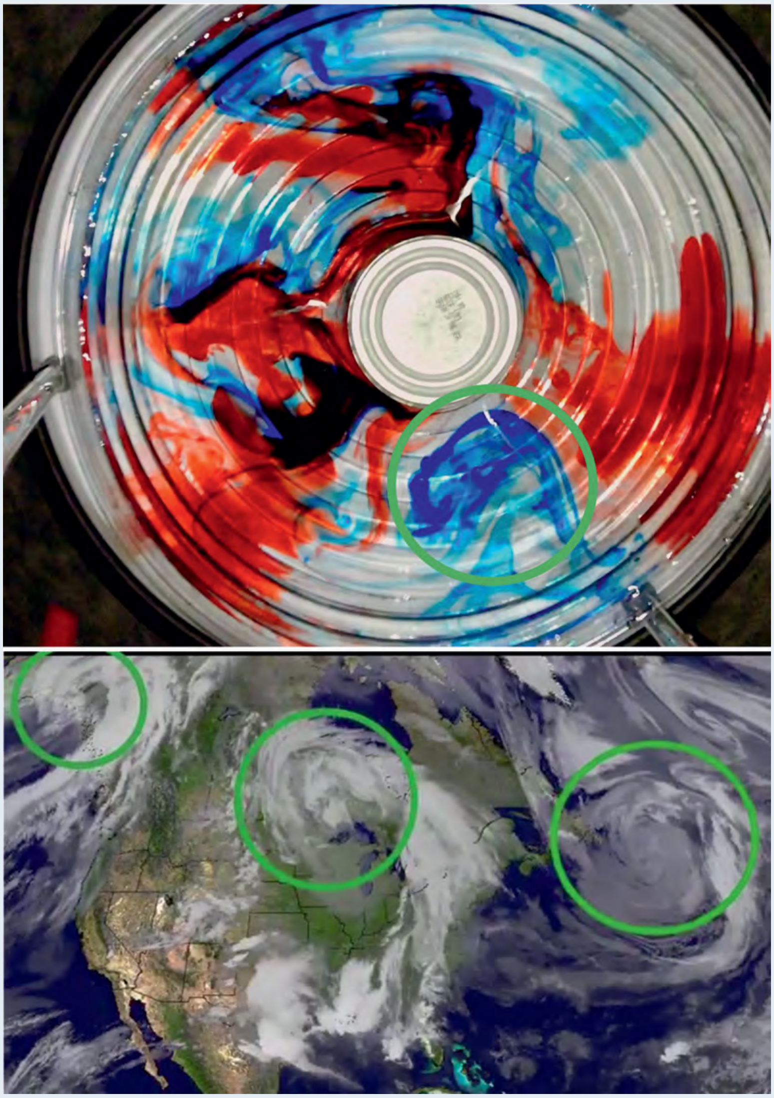

Fig. SB1. Baroclinic eddies (top) generated with the *DIYnamics* table following the sidebar recipe and (bottom) visible in satellite data of cloud cover. Both frames come from *DIYnamics* YouTube videos (https://youtu.be/2tIVOK9wjI4 and https://youtu.be/5bnmaYOFerk, respectively). Green circles focus the viewer's attention on the eddies of interest.

Professor Jonathan Mitchell. Our simple demonstrations supplemented demonstrations using more conventional equipment of radial inflow, the parabolic free surface of rapidly rotating water in a tank, and nonrotating convection in a stably stratified fluid. Provided the instructor possesses the requisite background knowledge, the demonstrations on the *DIYnamics* table can be directly adapted to this level by replacing appeals to the influence of rotation generally to specific concepts such as solid-body rotation, the Coriolis parameter, and the Rossby number.

THE FUTURE OF *DIYNAMICS*. There are many possibilities for additional demonstrations to perform on the *DIYnamics* table, including Taylor columns (Taylor 1921; www.youtube.com/watch?v=7GGfsW7gOLI), topographic Rossby waves, and other demonstrations from the Weather in a Tank online library (http://weathertank.mit.edu/links/projects). We will develop accompanying recipes, videos, and lesson plans as new demonstrations are perfected. Longer term, it will be important to more rigorously and quantitatively assess the pedagogical value of the *DIYnamics* materials (cf. Mackin et al. 2012).

However, based on the success of the existing *DIYnamics* materials in the teaching events to date, our primary focus is simply getting them into the hands of as many instructors as possible, from elementary school teachers to college professors. We encourage interested readers to visit the *DIYnamics* website (https://diynamics.github.io/) for more information and to contact us directly with questions and feedback.

ACKNOWLEDGMENTS. We thank Dr. Maurice Stephenson of La Tijera K–8 Charter School in Inglewood, California, for guidance in designing presentations for middle school audiences; Dr. Stephenson and Kenneth Howard of La Tijera and Jamie Ballard and Evelyn Chao of Ralph J. Bunche Middle School in Compton, California, for working with us to stage events at their schools; Jonathan Mitchell for allowing us to incorporate the *DIYnamics* demonstrations into his class at UCLA; Henry Gonzalez of UCLA for fabricating components for table prototypes; Raul Reyes for work on the baroclinic instability videos; event volunteers Chloe Whicker, Alex Arnold, Helen Parish, Ashley Shoenfeld, Katie Tuite, Ellen Hoppe, and Ashna Aggarwal; and Dr. Paul Williams and two anonymous reviewers for helpful comments on the manuscript. This work was supported by NSF Atmospheric and Geospace Science Postdoctoral Research Fellowships 1624740 (S.A.H.) and 1524866 (J.M.L.), NSF Geophysics Program Award 1547269 (J.M.A.), and the Straus Family Fund for Undergraduate Opportunity (N.K).

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