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Tabletop Atmospheric Rivers

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Strong atmospheric rivers (ARs) are characterized by the intense transport of water vapor in the atmosphere and, upon landfall, are associated with severe precipitation (Ralph and Dettinger 2011; Gimeno et al. 2014, 2016; Payne and Magnusdottir 2016; Payne et al. 2020; Cobb et al. 2026). ARs are long (~2500 km), narrow (~300 km) atmospheric streams that carry upward of 90% of the tropospheric water vapor flux across the midlatitudes (Zhu and Newell 1998), with volumetric flows similar to those of the world's largest rivers (Newell et al. 1992; Gimeno et al. 2014). Rainfall associated with ARs can be beneficial—often ending drought cycles in California—but can also be catastrophic by generating flooding events when strong and persistent ARs inundate a given locality (Ralph et al. 2006; Dacre et al. 2015; Dettinger et al. 2020). Furthermore, studies have shown that the frequency and intensity of ARs are likely to increase as a consequence of climate change, which can have broad-reaching societal impacts (Gimeno et al. 2016; Dettinger et al. 2020; Shields et al. 2023; Ryoo and Park 2023; Scholz and Lora 2024). As such, it is essential to be able to explain AR dynamics to a broad audience, from the general public to students in classrooms.

While many details of ARs remain under study, simple and fun rotating-tank experiments can offer accessible, hands-on insight into their basic behavior. Our so-called Do-It-Yourself Dynamics (*DIY*namics) Kits allow students to build their own experimental hardware in ~15 min and then carry out visually compelling experiments (e.g., Hill et al. 2018; Moscoso et al. 2023), including the formation of in-class wintertime storm and AR analogs (Fig. 1b). These tabletop experiments serve as an invaluable teaching tool, transforming complex concepts into engaging, inspiring, and visually compelling, active learning experiences. The efficacy of this approach was validated by Illari et al. (2009, 2017) and Mackin et al. (2012), who showed that in-class rotating fluid dynamics experiments inspire curiosity while demonstrating the governing physical processes, leading to measured improvements in students' conceptual gains. Moreover, the affordability of *DIY*namics Kits (less than $200) makes them accessible to a wide range of audiences, and their quick setup allows students to readily conduct side-by-side comparisons with neighboring experimental groups.

Figure 1a shows a NASA Giovanni image (made using MERRA-2 reanalysis data) of the atmospheric precipitable water content in the western Pacific on 4 January 2023. Dark blue

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(white) colors correspond to high (low) precipitable water content. The long, narrow dark blue band shows a powerful atmospheric river—a classic Pineapple Express. This AR funneled warm, humid air from near Hawaii to the U.S. West Coast, ultimately producing heavy rain and snow. Figure 1b shows a top-down, zoomed-in view from a *DIY*namics tabletop rotating-tank experiment. The curved, dark-red dye filament serves as an analog to an AR, closely mirroring the structure seen in the Fig. 1a precipitable water observations.

Figure 2 shows a top-down view of the LEGO Spike–based version of the *DIY*namics Kit used in the tabletop experiments presented here. Parts and construction directions for this Kit are given in the supplemental material of Moscoso et al. (2023). The Kit consists of a 36-cm diameter acrylic tank situated on an OXO kitchen rotary platform. The tank is filled with near-room-temperature tap water, roughly 5 cm deep. To simulate the strong effects of rotation on large-scale atmospheric dynamics, the rotary platform is spun at a constant rate by a drive wheel affixed to a variable speed LEGO motor that is mechanically coupled to the rim of the OXO platform. After allowing the fluid to spin up to the tank's rotation rate, food coloring or mica flakes are added to the water, allowing experimenters to visually observe the rotating fluid motions. (For parts and construction details of our most recent *DIY*namics Kits, see https://www.youtube.com/channel/UCnUHxOSVY4G4OFbF8XL1qUg.)

To produce a tabletop model of an AR, we turn to one of the oldest experiments in geophysical fluid dynamics: the rotating annulus. First made famous by the ground-breaking work of Raymond Hide (Hide 1958; Ghil et al. 2010), "Hide's annulus" consists of two nested coaxial cylinders on a rotating platform. The inner (outer) cylinder is typically held at a fixed temperature T_i (T_o). The cylindrically radial temperature gradient $\Delta T = T_o - T_i$ generates lateral buoyancy forces, which, interacting with the background rotation, can generate a vast array

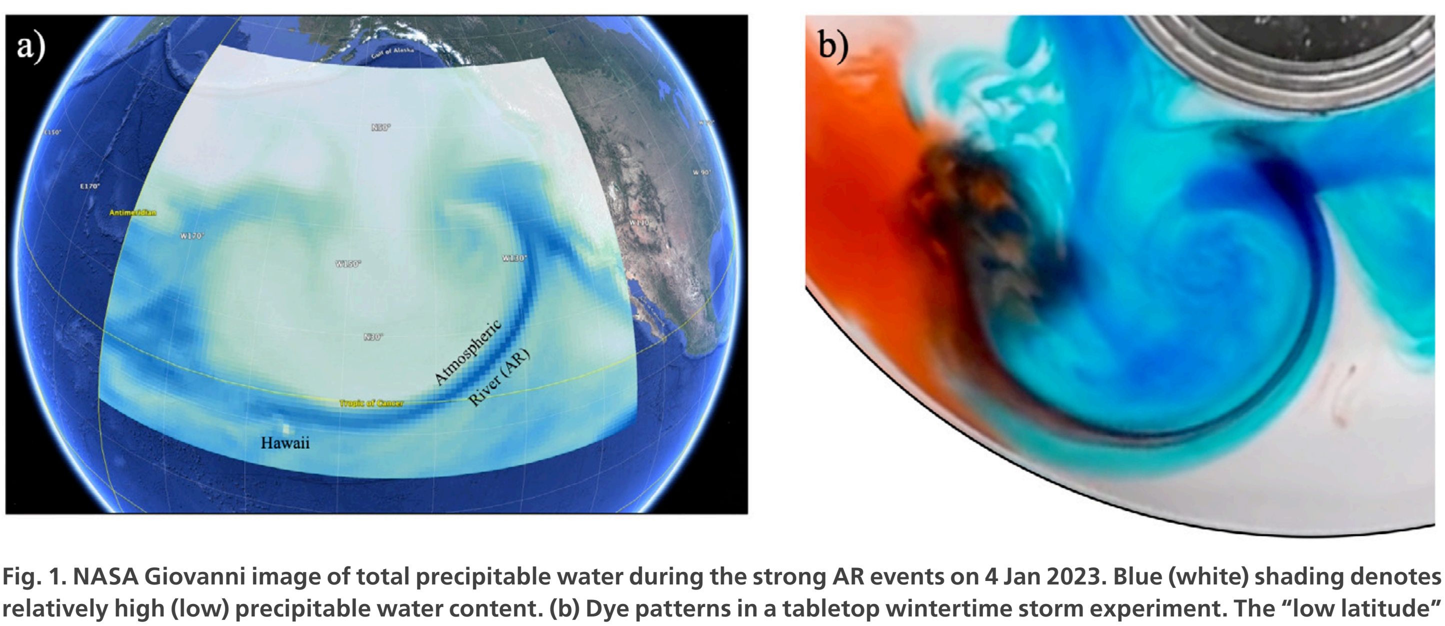

Fig. 1. NASA Giovanni image of total precipitable water during the strong AR events on 4 Jan 2023. Blue (white) shading denotes relatively high (low) precipitable water content. (b) Dye patterns in a tabletop wintertime storm experiment. The "low latitude" red dye is carried around the edge of the cold (blue) winter storm-like eddy, generating a scale model AR.

of geophysically relevant flows (e.g., Hide et al. 1977; McNoldy et al. 2003; Wordsworth et al. 2008; Illari et al. 2009; Scolan and Read 2017; Illari et al. 2017; Lonner et al. 2022; Harlander et al. 2023; Moscoso et al. 2023).

The AR experimental configuration shown in Fig. 2 represents another iteration of Hide's annulus. Its novelty lies in the fact that our low-cost experimental setup can be assembled and operated in roughly 30 min by learners from middle school onward. This makes it possible for students to conduct their own hands-on investigations across a wide range of conditions. In addition, because the Kits are built from a mix of LEGO components and common kitchen materials, they are both sturdy and hard to break. This robustness encourages exploration and creativity during in-class experimentation, which we have found often fosters student interest, agency, and confidence. Furthermore, the entire Kit fits in a shopping bag, greatly simplifying transport by outreach scientists.

The lateral temperature gradient is produced in our tabletop experiments by placing an ice-water-filled can at the center of the tank, as shown in Fig. 2 [see Figs. S3 and S4 in Moscoso et al. (2023) for quantitative measurements of ΔT]. Following Hide, the water in the tank is analogous to the air in the atmosphere because the dynamics of rotation and buoyancy controlling both the fluid in the tank and the air in the atmosphere are similar (without the effects of planetary sphericity, water vapor thermodynamics, or the compressibility of air). The can provides a cold source to the adjacent water and should be thought of as a proxy for the cold air mass that surrounds the wintertime poles (e.g., Nadiga and Aurnou 2008; Illari et al. 2017). Similarly, the water away from the cold can is a proxy for warmer, moist subtropical air.

Without rotation, the can cools the surrounding water, driving an overturning circulation where the cold water sinks and spreads radially outward along the tank bottom, and the

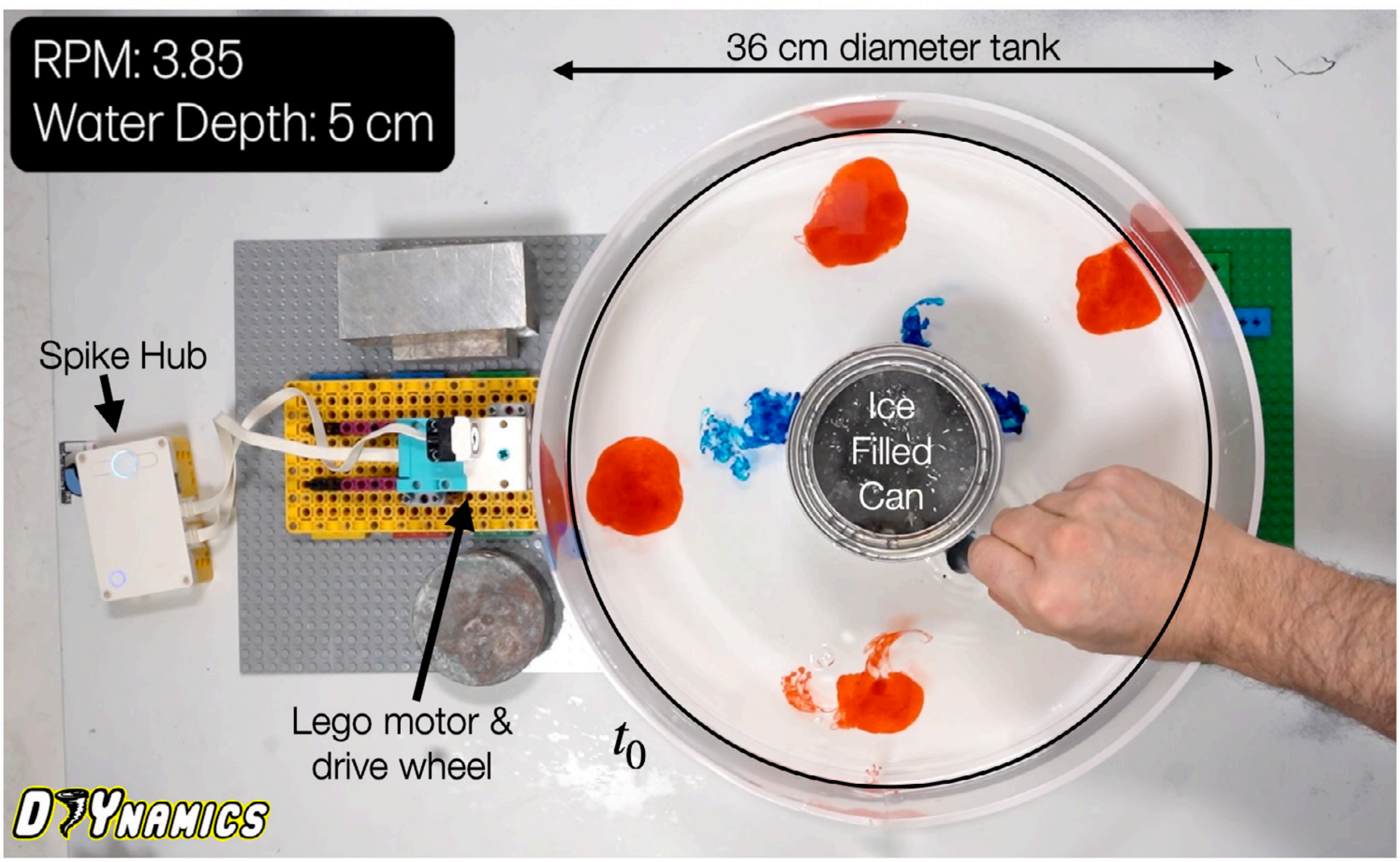

Fig. 2. Top view image of a *DIY*namics Kit acquired at time t_0 as we are putting in the last drops of red and then blue dye into the tank. Parts and build directions for our Kits can be found online (https://www.youtube.com/watch?v=JVKPCfq4ieQ&list=PLzrgmQpBPWiiDmXGBZZGNOv0Dmz1MZZSG).

warmer water nearer the tank's outer radius is transported upward and radially inwards (e.g., https://youtu.be/myaz1rX1szY?si=-HU8FznacuCrtClh in a channel geometry).

Rotation fundamentally changes this overturning flow: Instead of sinking and spreading outward, the cooled water forms a vertically sheared flow that circles the can (e.g., https://youtu.be/VR9OVlG_KTE?si=y-uZJqKe9qQhLIpX). This response arises from so-called thermal wind balance, in which buoyancy torques due to the horizontal ΔT are offset by the vertical shear in the azimuthal $\hat{\Phi}$ flow (e.g., Marshall and Plumb 2007; Illari et al. 2017; Moscoso et al. 2023). The resulting circulation is a tabletop analog of the wintertime subpolar jet stream. This circumferential flow frequently undergoes baroclinic instability, causing it to break apart into a number of swirling eddies (e.g., Holton and Hakim 2013; Illari et al. 2009; Moscoso et al. 2023).

The development of these vortical eddies is seen in the top-view images at times t_1, t_2, and t_3 of Fig. 3, acquired in a case rotating at ~4 rpm and with a water depth of 5 cm. These "polar

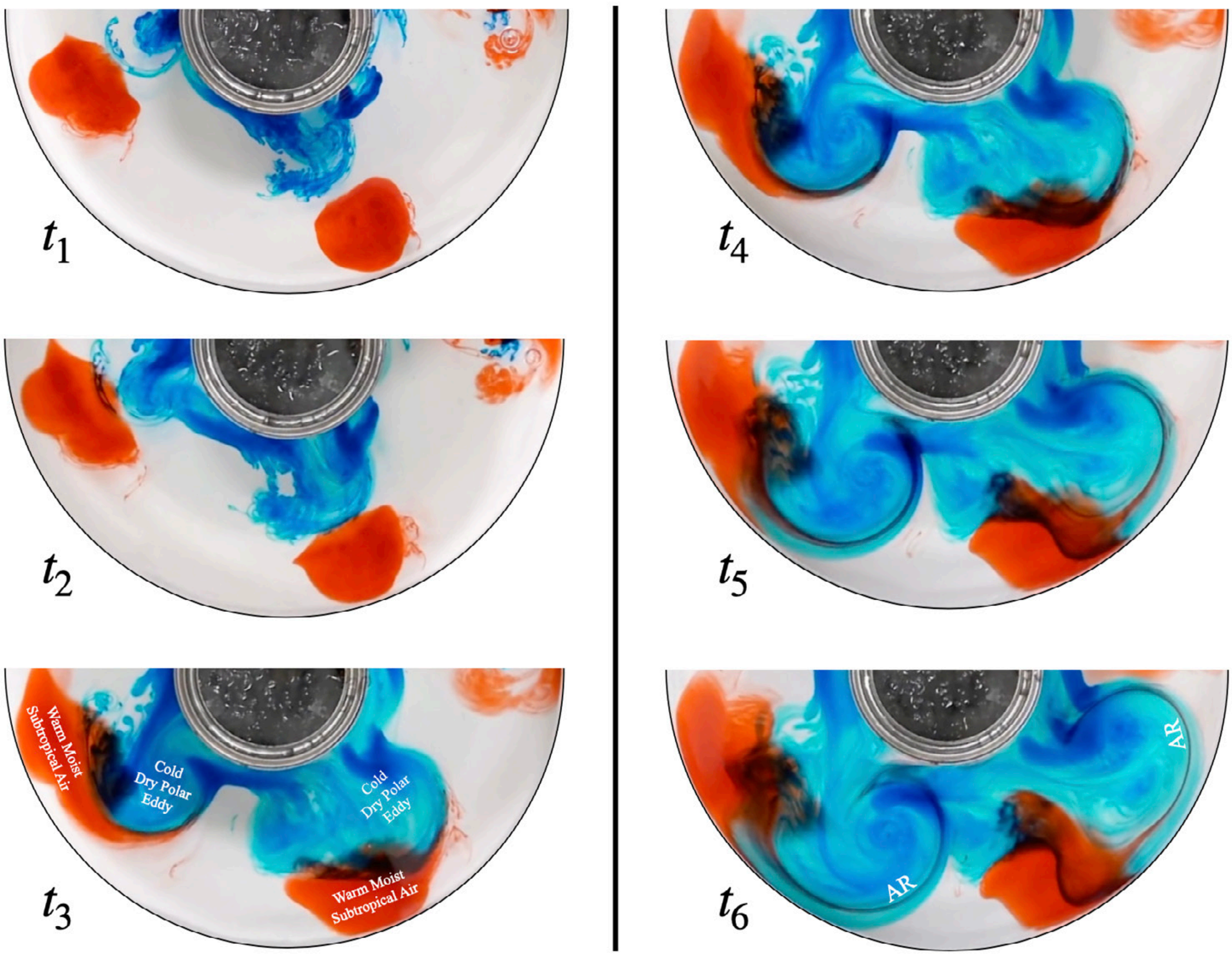

Fig. 3. Rotating annulus experiment carried out using a 5-cm-deep layer of approximately room temperature water that is rotating at close to 4 revolutions per minute (rpm). The water adjacent to the cold central can form rotating eddying structures when they spread away from the can (t_1 and t_2). When the edges of these polar eddies interact with the red-dyed water that represents warmer moist near-equatorial air, the red-dyed fluid is rafted around the rim of the eddy (t_3 and t_4), forming long, narrow arc-shaped filamentary AR-like dye structures that transport "equatorial" fluid to higher annular "latitudes" near the axially centered ice can (t_5 and t_6). The movie from which these still images were harvested can be viewed online (https://youtu.be/TseU9uLKIzQ?si=BDC5G0X5CmAPStTv and https://youtu.be/zj8wVDPwupk?si=ig_5eS0PDOKJu0LU).

eddies"—analogous to midlatitude wintertime atmospheric storm systems—are visualized in the pattern of the blue food coloring that was initially emplaced adjacent to the ice-filled can.

The interaction between the baroclinic eddies and the red-dyed water—our analogs for moist, low-latitude air masses—first appears in Fig. 3 at time t_3. Their interaction causes "equatorial" red-dyed water to become wrapped around the eddies, just inside their frontal boundaries. This wrapping persists in the subsequent frames at t_4, t_5, and t_6, where the dye is drawn out into a long, narrow filament tracing the rim of each of the two large "wintertime storm" eddies, as shown in detail in Fig. 4. Importantly, the red dye must be injected into the tank before the blue dye, so that it loses any injection-based inertia before interacting with the baroclinic eddies. Movies of the case shown in Fig. 3 are available online (https://youtu.be/TseU9uLKIzQ?si=BDC5G0X5CmAPStTv and https://youtu.be/zj8wVDPwupk?si=ig_5eS0PDOKJu0LU).

Figure 5 shows illustrations of troposphere (Fig. 5a) and tabletop (Fig. 5b) ARs and a schematicized cross-sectional view through an AR in Fig. 5c. As in the atmosphere, tabletop ARs form near the base of the tank along the frontal boundary between the warmer water and swirling baroclinic eddies (cf. Figs. 4 and 5c). Unabashedly mixing metaphors, the cold (blue), dry polar air mass subducts below the warm (red), moist subtropical air. The temperature gradient is strongest across the boundary between the air masses. This large local gradient drives a pattern of vertical wind shear ($\partial u_\phi / \partial z > 0$), forming a low-level jet (LLJ) that exists in thermal wind balance across the front and which is situated just above the nose of the cold polar air mass (Fig. 5c). It is this frontal LLJ that carries the moisture-laden subtropical air along the storm front, forming the atmospheric river. Thus, storm-bounded flows transport filaments of warmer fluid eastward and inward toward the tank's axis (i.e., around the edges of cyclonic storms and toward higher latitudes). These flows provide tabletop analogs of the ARs that dominate the meridional transport of water vapor in Earth's midlatitudes.

We argue here that Figs. 1, 3, and 4 demonstrate that tabletop ARs are similar to observed systems. We claim that this similarity is attributable to the fact that the governing dynamics are, to leading order, the same. Advanced undergraduates could test these statements

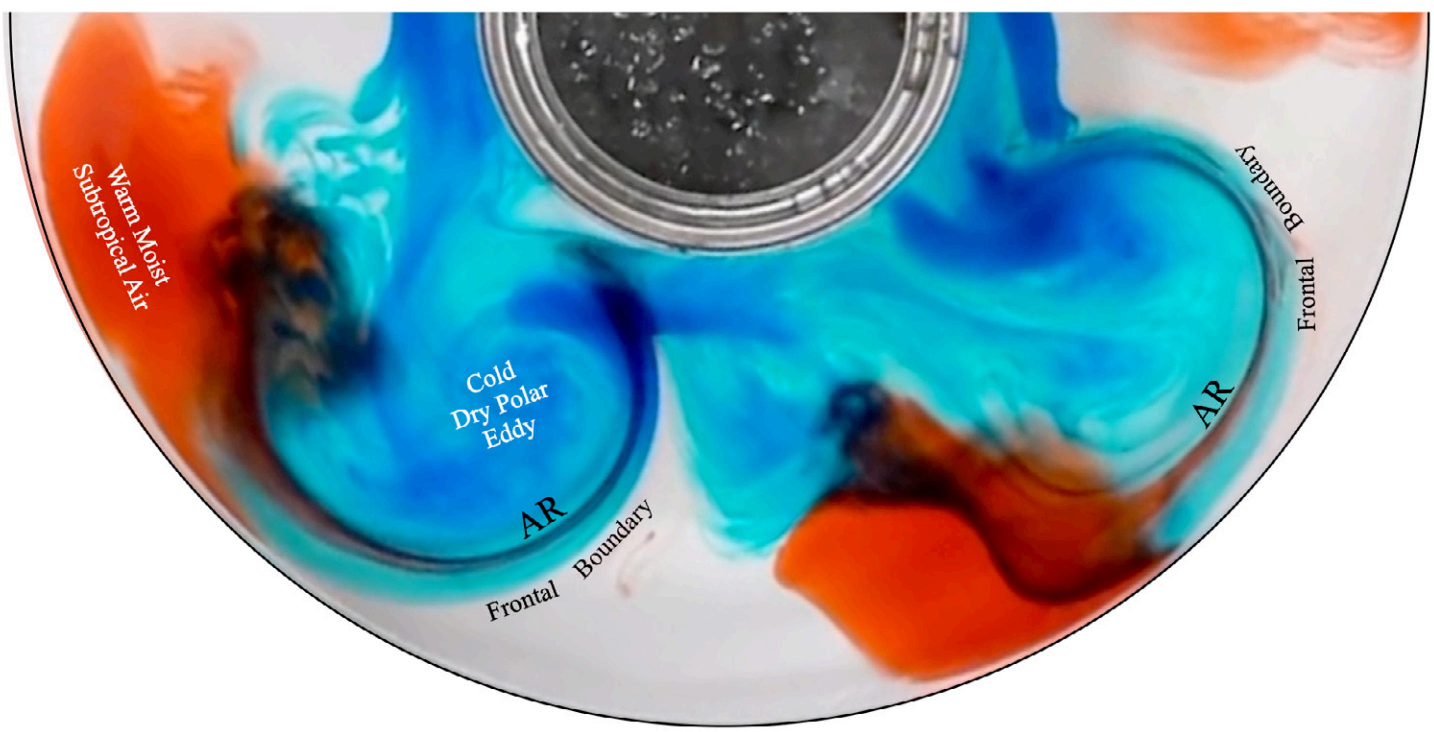

Fig. 4. Close-up t_5 image showing the red-dyed analog ARs that are drawn out just inside of the frontal edges of two neighboring wintertime storm-like eddies.

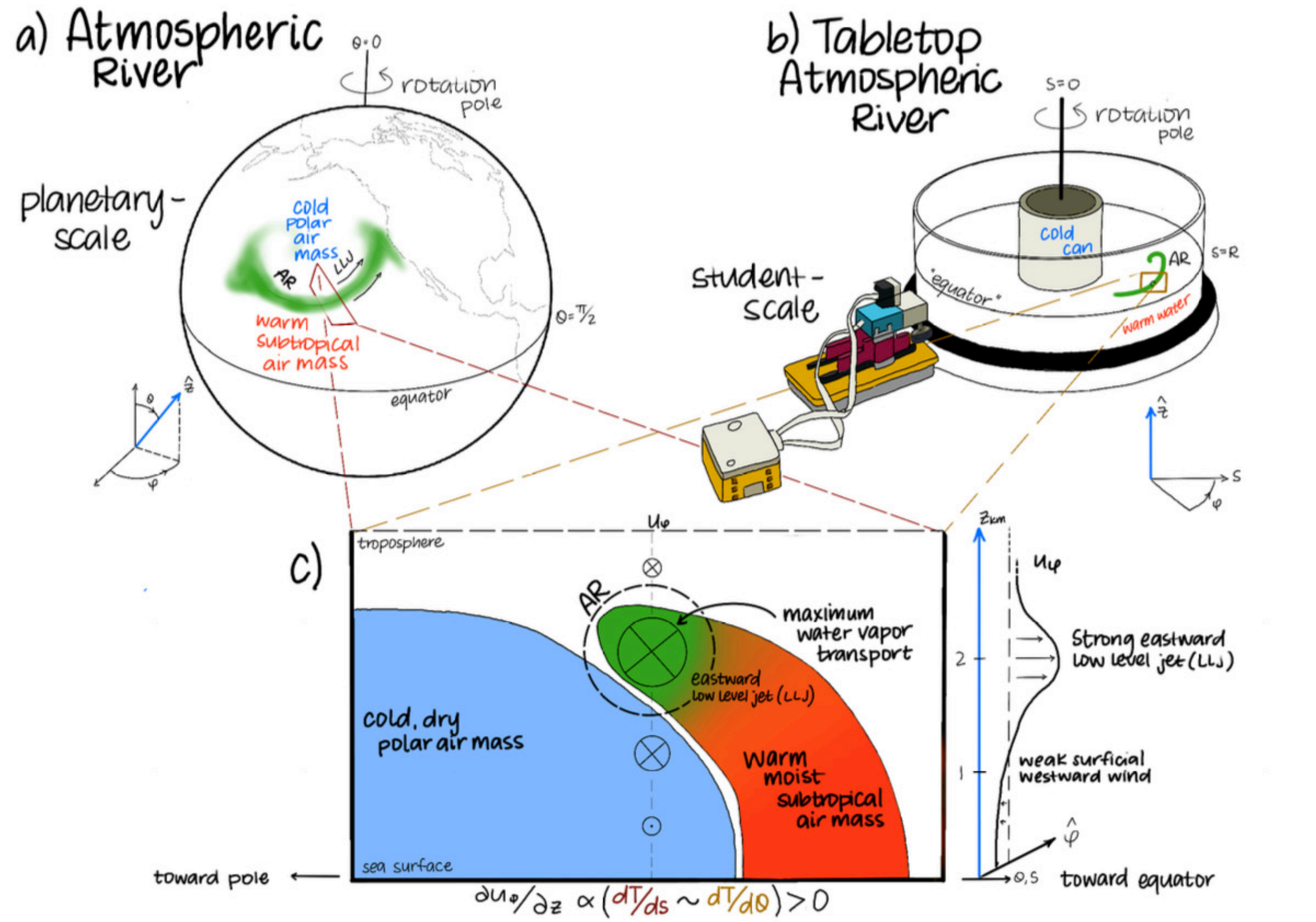

Fig. 5. (a) Sketch of the large AR (here denoted in green) formed on the edge of a wintertime storm in the North Pacific. (b) Schematic of a *DIY*namics rotating annulus experimental setup, in which analog ARs (green) also form. (c) North–south cross-sectional schematic of a wintertime storm's frontal zone. The cold (blue), dry polar air mass subducts below warm (red), moist subtropical air, leading to the formation of a LLJ flow situated near the frontal boundary of the cold polar air mass. [This is $\partial u_\varphi/\partial z > 0$ shear flow is denoted by the circles containing X's (dots) showing wind into (out of) the page, with circle size proportional to the magnitude of the wind velocity.] The LLJ transports the moist subtropical air around the storm's periphery, forming the AR. Approximately similar flows develop both in the wintertime atmosphere and in tabletop rotating annulus experiments.

experimentally by adding thermometry (e.g., Moscoso et al. 2023) and cell phone particle image velocimetry (e.g., Cierpka et al. 2021; Goushcha and Angira 2022) measurements to our *DIY*namics setups. Such quantitative experimental tests could be greatly bolstered with complementary numerical modeling using readily available open source tools (e.g., Burns et al. 2020; Ramadhan et al. 2020). In addition, the similarities in Figs. 1a and 1b suggest that state-of-the-art, research-level experiments (e.g., Harlander et al. 2023) can make important additions to the scientific AR literature.

Highly technical experiments are not, however, needed for students to investigate the systematics of tabletop ARs. A great deal can be learned simply by changing their tabletop experiment's rotation rate, ice mass, the fluid-layer depth, or tank diameter. Such changes alone allow students and teachers to address questions like "What would happen on a planet with a stable jet stream?" through lowering the rotation rate, or "What happens on a planet with a deeper atmosphere?" through changing the fluid-layer depth. Conversely, varying the amounts of ice or raising the water temperature provides a means to investigate how ARs respond to changes in the pole-to-equator temperature difference, occurring either seasonally or due to the longer-term shifting of global climate (e.g., Payne et al. 2020; Ryoo and Park 2023; Shields et al. 2023; Scholz and Lora 2024).

Hands-on tabletop experiments provide a unique, creative, and efficacious avenue of inquiry that allows user teams to experientially navigate the dynamics of real geophysical flows (Mackin et al. 2012). They also provide an immensely fun entry point into a broad range of discussions, including scale modeling and the concept of a scientific model; the differences between cylindrical and spherical dynamics; water vapor thermodynamics, precipitation dynamics, and orographic interactions. In any setting (e.g., Fig. 6), a rotating tank of water and a few drops of food coloring can go a remarkably long way!

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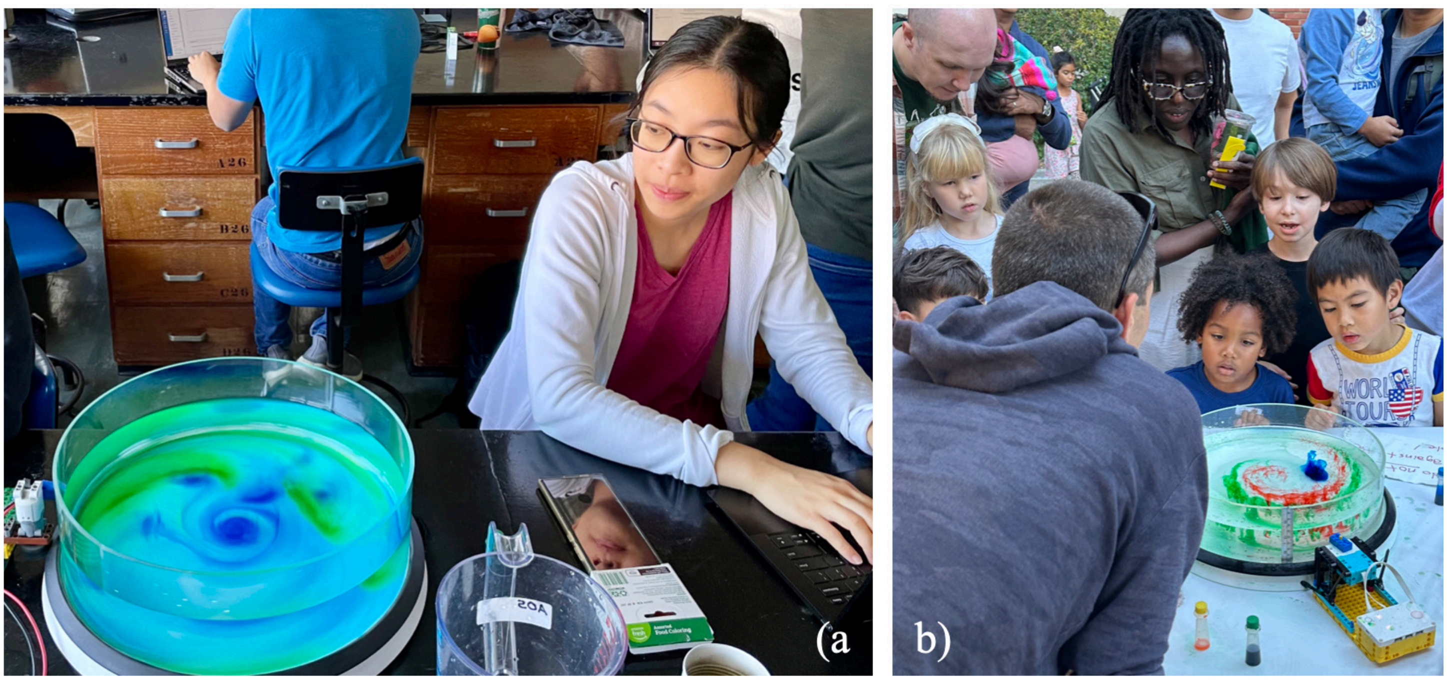

Fig. 6. Investigating rotating tabletop flows (a) in UCLA's Fall 2023 Marine Science Lab EEB 109L (Image: Dave Daversa) and (b) at the 2025 Exploring Your Universe outreach event.

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