Project description

1 Overview

Geoscientists play vital roles in many challenges facing America, from managing water resources in drought-stricken watersheds to forecasting hurricane landfalls in a warming world. Demand for degree-holding geoscientists is increasing, for those with professional degrees especially, as these challenges amplify and interconnect in the 21st century (e.g. *Perkins*, 2011). But growth in geoscience degrees conferred is not keeping pace (e.g. *Wilson*, 2019). Recognizing this, the geoscience community has a long-standing goal of expanding and diversifying the pool of students pursuing geoscience-related degrees and ultimately geoscience career pathways (e.g. *Velasco and de Velasco*, 2010). A recent emphasis has been on recruiting and making the geosciences more hospitable to underrepresented minority (URM) populations, spurred by decades of low proportions (even compared to other STEM disciplines which are themselves insufficiently diverse) of URM geoscience students and professional geoscientists (e.g. *Bromery*, 1972; *White et al.*, 2013). Past studies have identified exposure to the geosciences in K-12, which occurs rarely compared to many other STEM disciplines, as a positive influence in attracting students to the geosciences (e.g. *Miranda et al.*, 2021). Further, hands-on, active experimentation by students has been noted as critical to igniting curiosity and the understanding necessary to ask and address their own questions (e.g. *Kastens et al.*, 2013).

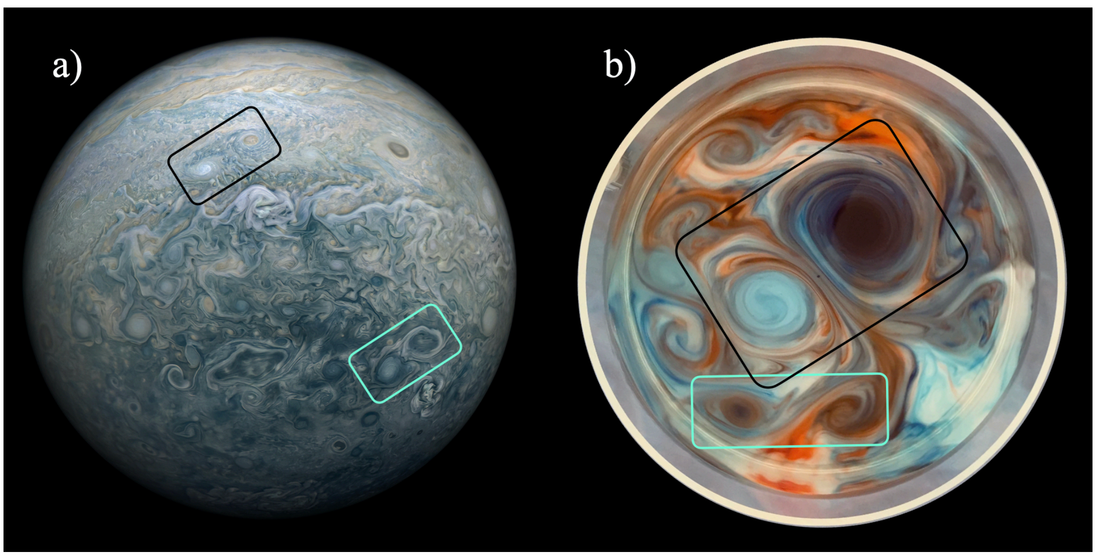

Figure 1: a) Turbulent cloud patterns in Jupiter's rapidly rotating weather layer (Image: NASA Juno Mission). b) Flow structures visualized with blue and red food coloring in a stirred tank of rotating water. The camera is looking down from above the DIYnamics Kit's axis of rotation. The black and cyan boxes compare similar flow structures in the two systems.

With NSF-AGS Postdoctoral Fellowship funding (PI Hill) and an NSF-EAR Geophysics Program award (Co-PI Aurnou), our group established the Do-It-Yourself Dynamics, or DIYnamics, Project five years ago to expand student interest in geophysical phenomena using hands-on experiments that demonstrate fundamental planetary processes (Figure 1). Our approach is built around a simple experimental apparatus, the DIYnamics Kit, that students construct themselves out of familiar household objects. Students then use the assembled Kits to create analog models of fundamental and visually striking planetary fluid dynamical phenomena such as mid-latitude winter storms and the swirling wind patterns on Jupiter. The Kit consists of a clear, cylindrical container of water sitting on a Lazy Susan, rotated at a constant rate by a motor assembly made out of toy Lego pieces (*Hill et al.*, 2018). (All components of the Kit are purchased from retailers such as Amazon and Lego; the DIYnamics organization does not sell the Kits

Figure 2: DIYnamics experiments a) at La Tijera Middle School, Inglewood, California (part of an interactive presentation nearly identical to that described in the text at Ralph J. Bunche Middle School in Compton, CA); b) in an upper-level oceanography class (Image: Marianna Linz, Harvard University); c) in a graduate-level atmospheric dynamics class (Image: Alex Gonzalez, Iowa State University); and at UCLA's 2017 Exploring Your Universe public science fair. Notice students in (a) using their cellphones (with teacher permission!) to take photos and videos of the experiments.

or profit from them.) This is a do-it-yourself but still highly functional version of so-called rotating tank platforms, which have a storied history in planetary fluid dynamics (e.g. *Taylor*, 1921). And in the last decade, rotating tanks have been formally evaluated to be an effective teaching tool for undergraduates in courses in atmospheric science, oceanography, or both — especially for introductory courses (*Mackin et al.*, 2012).

However, the rotating tanks used in that study are based on a dated, intricate design (*McNoldy et al.*, 2003), must be operated by the instructor, and are too expensive (~$5000) to be acquired by most schools. Prior to the DIYnamics Kit, these were the only rotating tank platforms widely used in teaching and outreach to our knowledge, making them impractical to most high schools and colleges, particularly under-resourced ones. This almost surely contributes to an overall lack of awareness — let alone use — of rotating tank-based teaching that we have found informally among educators outside select departments of a few well-endowed research universities.

In contrast, the DIYnamics Kit provides an affordable, accessible system that has the potential to be disseminated broadly throughout the educational continuum. It has been used in diverse settings within geoscience learning ecosystems (GLEs) across the U.S., including university courses, museums, public science fair events, and interactive presentations at URM-serving K-12 schools (*Hill et al.*, 2018) (Figure 2). And the informal responses we have received on these from both students and teachers have been highly positive, in line with *Mackin et al.* (2012). In a virtuous cycle, these successes have spurred more uptake of the Kits by other university groups, who then share their experiences, suggestions, and videos through the DIYnamics website, blog, YouTube channel, or Twitter, leading to further improvements of the Kits and supporting materials, growth of the DIYnamics community, even more motivation among DIYnamicists, and even more interest by the broader community. In other words, a Community of Practice (CoP; e.g. *Kastens and Manduca*, 2017) on rotating tank-based teaching has emerged (though we are the first to describe it as such here).

Two crucial missing elements to date have been (1) awareness of and training in rotating tank-based teaching among high school and college science educators beyond the existing DIYnamics CoP, and (2) the full inclusion of non-specialist educators into the DIYnamics CoP — especially those from predominantly URM-serving high schools and colleges. Addressing these will require a coordinated, multi-year, multi-institutional effort beyond what could be achieved through the ad hoc efforts (despite their successes) otherwise sustaining the community. We therefore seek GEOPAths funding of a collaborative project among Lamont-Doherty Earth Observatory (LDEO), UCLA, and the City College of New York (CCNY), centered on professional development workshops for educators in hands-on rotating tank-based teaching, and with a strong emphasis on URM-serving institutions, as a means of increasing interest in the geosciences and ultimately geoscience career pathways. We have the following specific objectives:

1. Develop in Year 1 a professional development workshop that trains high school and college educators in using DIYnamics Kits to teach core concepts of weather, climate, ocean currents, and planetary fluid dynamics.
2. Execute the three-day workshop each summer of the project at a broader STEM education-focused conference such as the Earth Educators' Rendezvous (EER), in Years 2 and 3 incorporating feedback from past participants and lessons learned from preceding workshops.
3. Work with a subset of workshop participants each year to implement a rotating tank-based teaching unit with the DIYnamics Kit, which incorporates material on related geoscience career pathways, into their classrooms or other venue within their local GLE in the subsequent school year.
4. Build out the existing DIYnamics CoP to welcome, support, and learn from workshop participants and other non-specialist newcomers to rotating tanks via efforts such as new and/or revised online resources and regular networking activities.

1.1 Background

The DIYnamics Kit is shown in various settings in Figures 2 and 3. The LEGO products provide several benefits. The LEGO 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 14-in. (36 cm) diameter tank at roughly 25 revolutions per minute (RPM). Importantly, the basic kit costs roughly \$50, with all the necessary parts available to order online via the LEGO site and Amazon. With parts in hand, it can be built in class in under 15 minutes. And, in our experience, the use of LEGO blocks makes the apparatus especially inviting to students. More broadly, the "DIY" (do it yourself) aspect is fundamental to the Kits: by physically assembling the model apparatus themselves, participants take ownership in it while developing problem-solving skills in engineering their optimal set. In this way, these DIY rotating tank models can be used to teach to students the entire iterative process of scientific modeling (*Kastens et al.*, 2013), including building the model, an advantage over other "runnable" models that come to students pre-assembled.

To concretely illustrate the overall teaching procedure using rotating tanks, we describe here the procedure for the simplest experiment, on rotating vs. non-rotating fluids. It teaches the most fundamental but otherwise counterintuitive properties of planetary fluid flows — a necessary starting point from which other, more involved experiments can be built out that model other engaging weather, oceanographic, climate, and planetary interior processes such as hurricanes, the atmospheric polar vortex, and the Great Pacific Garbage Patch (*Marshall and Plumb*, 2008). Students begin by adding drops of food coloring in a few locations of a non-rotating tank, observing the dense dye sink but also move horizontally and mix (Figure 4a). Then, they repeat the procedure in an identical tank, except that it is rotating on the DIYnamics Kit. The dense dye again sinks but does *not* spread horizontally — forming visible columnar structures instead (Figure 4b). The experiment demonstrates the organizing, gyroscopic effect of rotation, as most students are familiar from a spinning top (e.g., *Haine and Cherian*, 2013). Students and instructors

Figure 3: a) Image from the LEGO-based drive system from one of the DIYnamics Project's library of online videos. b) Experiment showing spiraling flow patterns similar to middle to high latitude atmospheric observations on Earth.

then discuss the columnar structures that emerge in the atmosphere, oceans, and interior fluids of rotating planets (once every 24 hours for Earth) and the ways in which the spinning tank of water is a useful analog thereof. In particular, the columnar dye structures are analogs to the rotationally aligned flows in Earth's molten metal core (Figure 4c) that create pole-aligned geomagnetic field, which makes a familiar compass work and protects us from the constant stream of ions bombarding the Earth called the solar wind.

One prior study evaluated the effect of rotating tanks in geoscience courses. *Mackin et al.* (2012) demonstrated that hands-on active rotating fluid dynamics experiments increased both instructor and student engagement and improved student learning outcomes in undergraduate oceanography classes. This study was carried out as part of the pioneering "Weather in a Tank" project funded by NSF (*Marshall and Plumb*, 2008; *Illari et al.*, 2009; *Haine and Cherian*, 2013; *Illari et al.*, 2017). Twelve professors at six universities carried out in-class experiments using the custom-designed and fabricated 'WiaT' apparatus. Approximately 900 students took part in pre- and post-testing assessment of learning gains via multiple choice tests concerning ocean, atmosphere, and climate science and online surveys of student perceptions. One student wrote, "The experiments clarified misconceptions; SEEING phenomena was far more real than 'proving' with equations" (*Mackin et al.*, 2012). Overall, the proof-of-concept testing in this study showed that analog experiments performed on the WiaT apparatus led to statistically significant positive learning and attitudinal increases, especially in introductory classes.

Informal written feedback on past DIYnamics outreach evinces the potential value of the teaching with the Kits in exposing and exciting students about the geosciences. At Ralph J. Bunche Middle School in Compton, CA, a predominantly URM and historically disadvantaged neighborhood of Los Angeles, the instructor provided us anonymous responses from approximately 40 students following a set of 1-hour, interactive presentations that we conducted with two seventh grade science classes (Figure 2a). The affordability and portability of the DIYnamics Kits enabled us to bring five whole Kits, splitting classes of approximately twenty into much smaller groups where each student could literally get their hands wet. In addition to demonstrating interest in the scientific concepts, many were expressly curious to know more about careers in science. A few examples of their questions directed toward the DIYnamics presenters included forward-thinking inquiries about careers in sciences: "[W]hy did they choose to study this? [...] [W]hat helps them study this and not give up?" "I would ask them how their experience in college was like." "I like the hands on experience, [...] being able to get in there and experience it."

1.2 Need For Workshops

Our work to date demonstrates the potential effectiveness of using hands-on rotating tanks in the classroom as a means to attract students to geoscience and to introduce educational and career pathways.

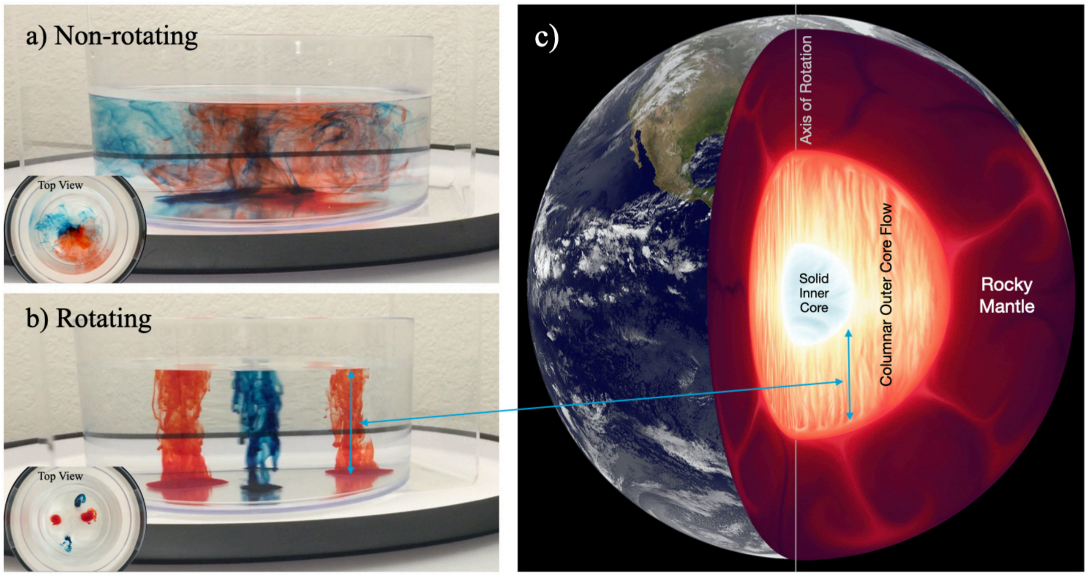

Figure 4: a) Contemporaneous sideview and topview (inset) images obtained after adding red and blue food coloring to a tank of non-rotating water. The food coloring sinks and efficiently mixes into the surrounding water. b) Sideview and inset topview images obtained after adding food coloring to a tank of rotating fluid. Each drop of dye becomes wrapped up in a vertically-aligned, swirling column, analogous to a spinning top. c) Rapid rotation in Earth's liquid iron outer core also leads to axially-aligned flows, with overlain arrows emphasizing the correspondence with the rotating tank in (b). These core flows generate Earth's global-scale magnetic field (not shown), which, controlled by the fluid motions, aligns near to Earth's axis of rotation. Hence magnetic compasses point North-South. (Image: Jonathan Cheng, University of Rochester)

However, at this stage we see an imperative to recruit and train teachers in the optimal use of this analog modeling platform (Figure 5) and to determine best practices for each educational setting. Further it is essential that we formally assess the effectiveness of this approach in increasing students' knowledge and interest and, importantly, determine its role in the recruitment and inclusion of URM students.

The creation of DIYnamics workshops will bring together instructors at a setting such as the annual Earth Educators' Rendezvous. These professional development workshops will introduce the use of DIYnamics kits as an educational tool for high school and introductory college science classes and will provide training in operating the DIYnamics Kits and in relevant geoscience principles, such as atmospheric and oceanic applications. Over three days educators will lead sample classes and will contribute to the creation of lesson plans relevant to each instructor's classroom environment and to the unique interests of each classroom of students. Ultimately we anticipate those plans will be shared and disseminated. Significantly, we will initiate the assessment of the workshop sessions, which will allow us to refine and improve upon them with each iteration.

Through initial exploratory recruiting via the project team's own professional networks of contacts, we have already found strong interest in the workshops at both the high school and college levels and including URM-serving institutions. Each of the following educators have provided a Letter of Support to formally express their intention to participate in the first workshop and to advertise the workshop among their colleagues: Charles Ichoku, Professor of Earth and Environmental Sciences, Howard University; Kunio Sayanagi, Associate Professor, Department of Atmospheric and Planetary Sciences, Hampton University; Professor Peggy McNeal, Assistant Professor, Department of Physics, Astronomy & Geosciences, Towson University; and William Robertson, Science Teacher, Stone Ridge School of the Sacred Heart (a Catholic girls school serving Grades 1-12 in Bethesda, MD). This accounts for four of the twenty participant slots. Based on these commitments by educators spanning both the high school and college levels and including two HBCUs, we are confident we will be able to meet our Year 1 workshop recruiting target of 20 science educators from a diverse range of high schools and colleges, including a significant portion from predominantly URM-serving institutions.

1.3 Organizational structure and timetable

The project personnel will be divided into the following groups:

1. Project Team: PI Hill, Co-PI Aurnou, Co-PI Turrin, and Co-PI Booth
2. Workshop participants: High school science teachers and college and university instructors who wish to implement rotating tank-based teaching into their courses.
3. In-class Implementers: Co-PI Booth and a subset of workshop participants who elect to work with us over the subsequent school year to perform pre- and post-surveys of their students regarding the influence of the rotating tanks.
4. External Evaluator: Kathleen Mackin

The project timetable is as follows:
Year 1: Establish logistics of the summer workshop (with intended venue EER); develop workshop content; recruit 20 workshops participants, especially targeting teachers from URM-serving colleges and high schools; execute workshop; recruit In-class Implementers group from workshop participants; make plans and begin work on making existing DIYnamics CoP's activities, website, and resources welcoming and useful to workshop participants and other non-specialist newcomers.
Year 2: Work with In-class Implementers to implement a rotating tank-based unit and accompanying geoscience career-related materials into their classroom and/or other venue of their local GLE; pre- and post-tests of their students regarding the influence of rotating tanks on learning outcomes and their geoscience educational and career plans; continued DIYnamics CoP development strongly informed by feedback from workshop participants; modify workshop materials incorporating participant feedback from the Year 1 workshop; plan, recruit for, and execute the workshop for 40 instructors.
Year 3: Work with the In-class Implementers from Year 1 and Year 2 to implement rotating tank experiments in their GLEs and assess their students; further revise workshop materials; plan, recruit for, and execute the workshop for 40 participants; make final modifications to workshop materials following the workshop; disseminate the finalized workshop materials and assessment results online, at geoscience meetings, and in the literature.

1.4 Populations targeted and recruiting

Our target population includes (1) teachers of upper-level high school physics, environmental science, and potentially other courses in which a rotating tank unit could usefully be incorporated into the curriculum, and (2) instructors at community colleges and universities that teach entry-level courses in Earth science, climate science, or any other general education-style course in which a rotating tank unit could usefully be incorporated into the curriculum. We will recruit instructors at both the high school and college levels from across the United States, but with a particular emphasis on predominantly URM-serving institutions. We expect the participant pool of our workshops to be diverse in its makeup, with a mixture of high school and colleges represented, and in the student bodies served by those schools.

Having participating educators from both upper-grade high school science courses and entry-level college courses serves multiple purposes. First, this is a critical transition period where high school students make life-changing decisions about their educational and career pathways as they enter adulthood. For first and second year college students, it is a time for selecting their field of study and thus shaping their future career pathways. Second, the level of technical detail that is plausibly taught to students

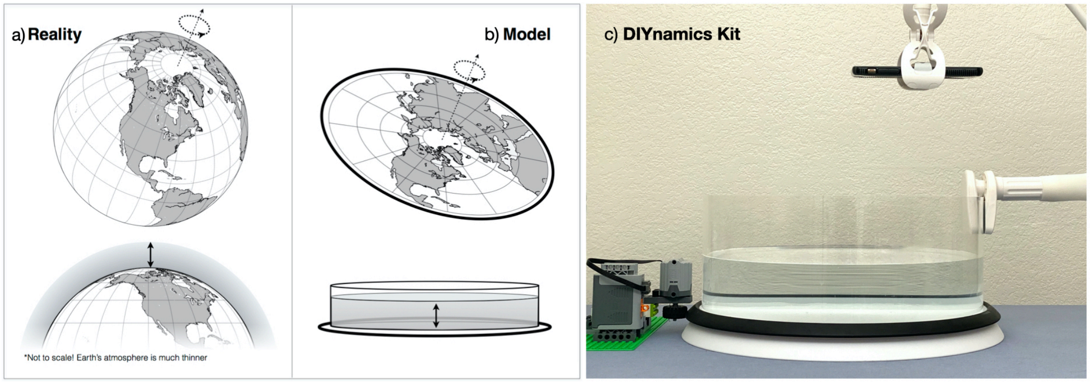

Figure 5: Schematic used on the DIYnamics website and other materials. The graphical depiction of projecting a) the spherical Earth onto b) a flat surface used to help explain to students the utility of a rotating tank of water as an analog model for planetary fluid systems. c) Sideview of the DIYnamics Kit, with cell phone attached to the tank via a gooseneck clamp.

in either setting will be comparable. Third, bringing together high school and college instructors will enable exchanges and learning about the critical high school/college transition from new angles for the participants and the project team.

A considerable portion of our project budget is devoted to paying in full for each participating instructor's travel, lodging, DIYnamics kit, and other costs associated with attending the workshops. This is vital to recruiting a diverse array of instructors from a diverse array of high schools and colleges. Otherwise less materially privileged instructors and instructors from the under-resourced high schools and colleges of our particular emphasis will be less able to justify attending.

In the spring of 2021 PI Hill will present an overview of DIYnamics and rotating tanks in Earth2Class, a teacher professional development program and well-received venue for high school students that brings them together with Lamont scientists to learn about cutting-edge research investigations. In addition to recruiting participating high school teachers for the workshops, PI Hill will engage Earth2Class attendees in a discussion about curricular fit at the upper high school level. Michael Passow, director of Earth2Class, has provided a Letter of Support.

2 Project Design

2.1 Workshop design

The workshop design concept is presented in this subsection. The full workshop materials will be created in Year 1 by the whole project team, making particular use of Co-PI Turrin's expertise in running educational workshops and relying on published literature on workshop best practices (e.g. *Miller and Kastens*, 2018); in particular, surveyed members of the geosciences educational community have noted their interest in workshops that provide tools they can use immediately (*Kastens and Manduca*, 2017)

The intended venue for the workshops is the annual Earth Educators' Rendezvous (EER) run by the National Association of Geoscience Teachers (NAGT) and the Science Education Resource Center (SERC) at Carlton College. Workshops are selected by competition, with the submission process occurring in the fall preceding the summer EER. We will have conversations with EER conveners about our intended workshop in the months preceding to get their feedback, which we'll incorporate in order to make our application maximally competitive. If not selected to EER, the annual conferences of the National Science Teaching Association and the Geologial Society of America are worthy alternatives we would pursue.

Each workshop participant will be provided with a complete kit: the rotating lazy Susan base, the LEGO motor and other bricks, batteries, one or more tanks, food coloring, assorted other peripherals, and a canvas bag in which all the materials (which combined weigh no more than a few pounds) can easily be carried. Although EER workshops consist of three, half-day sessions, we have budgeted for all participants to attend the full five day EER conference, in order to be able to attend other sessions of interest and connect with others in the broader geoscience education community.

We envision running the Year 1 Workshop by directly engaging the instructor participants with exercises in inquiry-based pedagogy, focussed on one canonical experiment on each day of the workshop. Each day we will begin with an informal welcome discussion. Following this, geophysical observations and associated science questions will be presented. Participants will then form small groups in which to carry out their experimental inquiry, each with their DIYnamics Kit in hand and guided in their set-up by workshop leaders only where necessary or requested. After setting up the Kits and running experiments, all participants will gather together, with each small group presenting their experimental observations, open questions that have emerged, and proposed explanations to the day's science questions.

The next part of each day's workshop will feature sub-group dialogues focussing on how to best incorporate rotating tank experiments into instructors' specific course curricula. We believe that participants will know best the precise role that rotating tanks can serve in their GLE. To provide a starting place, we will share some of the different contexts in which DIYnamics materials have been used in the past — including formally included as labs in university courses; public science outreach events, museums, and events at K-12 schools. From these past use cases, their impressions of the tanks through the workshop so far, and their own intimate knowledge of the needs, capabilities, and histories of their own GLEs, they can decide on how best to introduce the materials. We suspect that some will come up with new uses beyond what we have done, based on the same occurring often with university instructors that have used DIYnamics materials and shared their findings with us.

An important component of each day will be explicitly linking rotating tank models to career and educational pathways in meteorology and other geoscience disciplines in which geophysical fluid dynamics are relevant (including atmospheric science, climate dynamics, oceanography, planetary science, space physics and solar physics). There are numerous high-quality career pathways in these fields not just in academic research but in operational capacities, both in the public and private sectors. Towards this end, we will present an array of career paths near the end of each day's session, opening up this discussion for input from all participants.

Finally, assessment survey links will be distributed to all participants and organizers, to be filled out at or after the end of each day's session. Year 2 and 3 workshops will take into account the findings of these assessments and modified accordingly.

The workshop will train participants in a core sequence of three experiments, one per day: rotating vs. non-rotating fluids (described briefly above), mixing in rotating fluids, and break-up of Earth's polar vortex. These topics build upon one another. On the first day, we will focus on the essential process of how a tank of fluid comes into equilibrium with its rotating container, and why this is a good analog model for fluids on a rotating planet. On day two, we will consider what controls the essential morphologies of fluid structures observed in planetary fluid layers. We will investigate this by experimentally studying mixing (aka, turbulence) in non-rotating and then rotating tanks of water. On day 3, we will focus in on atmospheric polar vortices, as have now been found on Earth, Jupiter and Saturn. Experimentally, we will simulate how latitudinal temperature gradients in Earth's atmosphere cause the polar vortex to break apart, generating miserable weather with its visitations to mid-latitude cities.

Investigating Earth's Magnetic Field by Creating a Rotating Fluid Gyroscope. We will first discuss Earth's magnetic field. Generated by flows in Earth's liquid iron outer core, the geomagnetic poles tends to remain closely aligned with our planet's axis of rotation. To provide a basic understanding of this phenomenon, we will focus on Day 1 on understanding the gyroscopic qualities of rotating fluids. First though observations will be made of the behaviors of dye tracers (e.g., food coloring) in non-rotating tanks (Figure 4a). This non-rotating case will provide a benchmark against which participants will compare all our other observations. Next, we will consider how the fluid in a spinning tank comes to discover it is rotating, and over what time it takes for it to reach the state of 'solid body rotation', where the fluid moves in lockstep with the rotating tank. Geophysical flows are all near to this solid body state: they are well aware that the planet they are situated upon, or in, has been spinning for billions of years. Thus, to create an accurate analog model we must first allow us system to reach this state. Finally, we will add food coloring to the equilibrated rotating, tanks of water. The fluid in the rotating system is (formally) analogous to a gyroscope (*Haine and Cherian*, 2013): When perturbed, the fluid motions remain largely aligned with tank's rotation axis (Figure 4b). Thus, it is hard to tip the fluid over, similarly to a spinning top. Instead, the dye tends to form highly elongated, swirling columnar structures, that stretch out along the direction of the tank's axis of rotation. We will then return to our considerations of flow in Earth's core and consider how rapidly rotating, axially-aligned flows (Figure 4c) can act to generate our axially-aligned global magnetic field. Finally, we will discuss different ways in which the Earth's magnetic field likely affects the lives of the participants' students and geoscience career pathways that relate to Earth's magnetism.

Investigating Cloud Patterns on Jupiter via Mixing Experiments. The second day's topic will focus on understanding the types of flows that observed by the Juno spacecraft currently in orbit around Jupiter (*Sayanagi et al.*, 2013). To investigate this, we will first review classic flows that develop in these geophysical systems. Then DIYnamics Kits will be set up and filled with room-temperature water. We will add food coloring to non-rotating and then rotating tanks of water, similar to day 1's activity. By stirring the fluid, it will be possible to experimentally investigate how mixing differs in systems when the gyroscopic effects of rotation are included (Figure 1). The experiments will be compared to images of turbulent flow structures in planetary atmospheres. We will also discuss turbulent mixing structures in oceans, subsurface oceans on icy moons (e.g., *Kivelson et al.*, 2000; *Soderlund et al.*, 2014), and in planetary cores (e.g., *Aurnou et al.*, 2015; *Guervilly et al.*, 2019). We will then discuss different ways in which these turbulent mixing structures influence life on Earth, for example through mixing of nutrients in the ocean and pollution in the atmosphere. Finally, we will discuss geoscience career pathways that relate to these processes.

Investigating Earth's Polar Vortex by Adding a Centralized Cold Patch. The third day's experiment will add in two more another important physical ingredients: temperature and material density. By thermally perturbing the density field in our rotating tanks, the group will seek to model the instability of the wintertime polar vortex (Figure 6a). A brief explanation of the polar vortex phenomenon will be given, discussing how the polar vortex tends to go unstable in the depths of winter, generating strong cold spells to the midlatitudes, while warmer weather is often observed in neighboring higher latitude regions.

Participants will be asked to to set up their experimental systems in order to model the break up of the polar vortex. The goal will again be to work as a collaborative group towards an inquiry-based understanding of the polar vortex instability process (Figure 6b). Further, experiments will first be carried out first without rotating their tanks, and then afterwards including rotational effects. As on days 1 and 2, we will seek to accomplish this via multiple breakout groups in which all the participants are asked to compare and contrast their different experimental findings. Here, different sub-groups will be given a different number of ice cubes to use in making their polar cold patches. This will allow us to qualitatively investigate how the strength of the cooling affects the behavior of cold polar air masses. We will then discuss the relevance of the polar vortex has to students — those in the midwest and northeast will be keenly aware of the winter storms and intense cold and warm fronts associated with undulations and breakups of the polar vortex. Finally, we will discuss geoscience careers that relate to polar vortex dynamics, including operational meteorology, research meteorology, climate services, climate science research, and planetary science research.

2.2 Creating a DIYnamics CoP that welcomes, supports, and learns from newcomers

We will use the CoP model of *Kastens and Manduca* (2017) as a guiding framework to ensure that the DIYnamics CoP builds the capacity of both individual community members and the overall community with time. In this framework, when instructors are empowered to apply what they learn from the CoP within their local GLE, they and their students are likely to generate ideas for improvements to the CoP materials (in this case the Kits, experiments, videos, and other supporting materials). By establishing trusted means of communication to share these back to the community, these improvements can be incorporated into published materials and ultimately ratchet up the community's capacity.

To build and support our network of high school and college instructors using rotating tanks in their local GLE, we plan to leverage the DIYnamics organization's active CoP. The DIYnamics community GitHub site, blog, and YouTube channel provide an initial information base for new users of rotating tanks. At the time of writing there are 30 blog posts by 11 unique authors showing how rotating tanks are used in a variety of settings, including middle school classrooms, undergraduate and graduate classrooms, museums, and public science outreach events. In addition, our 'DIYnamics Team' YouTube channel is currently home to 26 DIYnamics videos, showing a variety of experiments and how to set up them up. The channel has 104 subscribers and 8,459 views of its videos at the time of writing.

DIYnamics community members communicate with one another via a Slack organization with channels devoted to different topics. We host a monthly "All-Hands Virtual Meeting," where team members volunteer to share their recent efforts, such as new demonstrations, new videos or animations, advances in platform design, forthcoming or recently completed events or courses, and new software tools. PI Hill and Co-PI Aurnou lead the meetings, and the atmosphere is always one of earnest engagement —

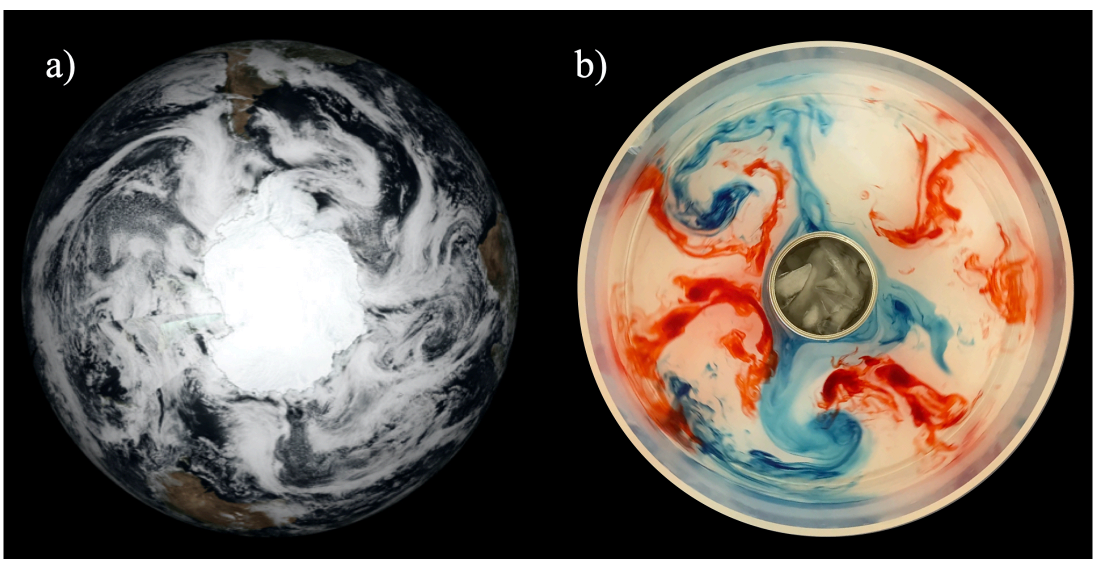

Figure 6: a) South hemispheric cloud patterns in March 2017 (Image: NOAA Suomi satellite). b) DIYnamics Kit image showing flow structures in an experiment with strong cooling near the pole of rotation (similar to that of the wintertime Earth). Even though their scales are greatly disparate, the same essential fluid dynamical processes generate the flow patterns in both systems.

with vigorous discussion, suggestions, questions and comments on the presented materials — but in an extremely supportive, almost celebratory atmosphere. The result is team members gaining directly actionable tools and/or advice on how to improve what they have done, affirmation of their work by trusted colleagues, expressions of gratitude for what they've done, and expressions of excitement for what they'll do next.

We plan to expand the ∼1.5-hour All-Hands Virtual Meetings into an All Hands Virtual *Morning* hosted once a month by this proposal's project team. The Morning will be broken up into a Development Hour, where we discuss recent Kit developments; Curriculum Hour where rotating tank curricula are the topic of focus; and then Operational Hour where all are invited to troubleshoot how best to work or modify the experiments and how to optimize student's in-class experiences. All developers, instructors and DIYnamics Kit users will be encouraged to take part in these sessions, as is the case now. We believe that DIYnamics' open community of practitioners will provide ample support to workshop participants and any additional newcomers.

2.3 Introducing rotating tanks into the GLEs of workshop participants

As detailed in the Participant Recruitment, Selection, and Mentoring Plan, at each workshop we will recruit a subset of participants to work with us over the forthcoming school year, forming the In-Class Implementers personnel group. Co-PI Booth will also act as an In-Class Implementer in Years 2 and 3 of the project. Booth will also introduce rotating tank-based instruction using the DIYnamics Kit in one or more of his courses in Year 1 (which courses Booth will be teaching in each year has not yet been set). Booth's proximity at CCNY to PI Hill and Co-PI Turrin will enable Hill and/or Turrin to sit in on some of Booth's teaching sessions with the Kits, in order to see firsthand what works well and what needs improving. Booth will also thoroughly document all of his experiences with the Kits throughout the project duration, reporting them regularly back to the remainder of the project team. This likewise will enable tweaks and other course corrections. Booth's hybrid role as both Co-PI and participant will be extremely valuable, ensuring at least one In-Class Implementation in each year and enabling more detailed feedback and monitoring than can reasonably be asked of volunteer participants.

External Evaluator Mackin and PI Hill will lead on coordinating with the volunteer In-Class Implementers on scheduling of the DIYnamics unit and administering the student assessments, as detailed in the Evaluation Plan. The pre- and post-tests will include a learning component, designed following that of *Mackin et al.* (2012), as well as questions on the students' awareness of and interest in geoscience career pathways. In addition to these formal assessments, we will request feedback from the instructors, shared with us and, if they are willing, with the broader community. The latter could occur through the aforementioned virtual All-Hands monthly CoP events. Assessments and other feedback will be synthesized and analyzed at the end of each term, and all lessons learned will be documented and used to modify the materials for forthcoming In-Class Interventions and workshop sessions.

3 Project Personnel

As detailed in the Participant Recruitment, Selection, and Mentoring Plan, this project works more directly with educators than with their students, and the relationship among project staff and participating instructors will be less one-directional than a traditional mentor/mentee relationship. Instead, in the CoP model, project staff and participating educators will learn from one another. Nevertheless, as a mentoring pool the project staff is diverse in several ways that will be conducive to connecting with the diverse array of participants we will recruit. It includes early-career (Hill), mid-career (Aurnou, Booth), and late-career (Turrin) professionals; research scientists (Hill), educational programming specialists (Turrin), and university professors (Aurnou, Booth); employees of an Ivy League university (Hill, Turrin), a highly competitive public research university (UCLA), and a predominantly URM-serving public university (CCNY); and institutions from coast (UCLA) to coast (LDEO, CCNY).

PI Spencer Hill has advised 7 undergraduate students since 2013 and is currently advising 2 Columbia undergraduates. Two of the past advisees, co-advised with Co-PI Aurnou, worked on the DIYnamics project. One of them, Norris Khoo, developed the original design for the DIYnamics table in 2017 and has worked on the project for research credit or in a paid capacity since. PI Hill organized the first DIYnamics events, comprising eight 1-hour presentations by DIYnamics team members over three days at two middle schools in the disadvantaged Ingelewood and Compton neighborhoods of Los Angeles. Hill has since helped organize and/or participated in numerous science outreach events, taught three guest lectures, and led a peer-reviewed paper (*Hill et al.*, 2018) all based on the DIYnamics materials. Hill co-founded DIYnamics with Aurnou and others, co-directs DIYnamics with Aurnou, and has overseen its expansion to include students and instructors across the U.S. and in Europe using rotating tanks in their own GLEs in a diverse range of settings including university classrooms, museums, and science outreach events both for the general public and for K-12 students.

Co-PI Jonathan Aurnou Prof. Jonathan Aurnou (Co-PI) is the director of the Simulated Planetary Interiors Laboratory (SPINlab) in UCLA's Department of Earth, Planetary and Space Sciences. Aurnou is experienced in geophysical and planetary fluid dynamics; working with 9 Ph.D. students and over 60 undergraduates and 30 researchers to date, Aurnou has built advanced laboratory and theoretical models of natural fluid systems (e.g. *Aurnou et al.*, 2015, 2020) as well as the do-it-yourself fluid dynamics kits (*Hill et al.*, 2018) that form the focus of this project proposal. In addition to his research and outreach efforts, Co-PI Aurnou has been serving the geoscience community via 8 years as Vice-Chair and Chair of International Union of Geophysicists and Geodesists' Study of Earth's Deep Interior (SEDI) organization (2010 - 2018) and 5 years as Chair of Computational Infrastructure for Geodynamics' Geodynamo Working Group (2014 - 2019).

Co-PI Margie Turrin As Director of Educational Field Programs at Lamont, Turrin dedicates the majority of her time to working with high school, undergraduate, graduate students, and high-school teachers on research & education projects. She is currently Co-PI on two NSF grants, one an NSF INCLUDES project developing opportunities for URM in tiered high school and undergraduate summer research experiences, and another on immersive team research experiences for high school students and developing ethics in research. She co-leads the JEDI committee for the International Thwaites Glacier Collaborative focused on improving diversity in polar sciences. Turrin has a grant from NYS to develop culturally responsive curriculum around the Hudson River, serves on the regional diversity committee for the NY/NJ Harbor Estuary Education Committee, and is on the advisory committee for the Lamont Secondary School Field Research Program that annually provides 65 URM high school and undergraduate students with summer research opportunities. She is actively involved in national and regional teacher professional organizations and runs workshops and training sessions for teachers regularly. For over a decade she co-ran a faculty boat-based summer professional development program on the Hudson River, and for close to two decades she has run a large-scale field based program for schools throughout the region on estuary sampling and data-sharing. She currently coordinates research opportunities for undergraduates, teachers, and high school students out of the Lamont Hudson River Field Station.

Co-PI James Booth James Booth is an Associate Professor and Deputy Chair in the Earth and Atmospheric Sciences Department at City College of New York (CCNY). As Deputy Chair, he mentors undergraduates and graduate students, working to help them learn geoscience and plan their futures. The students are often first-generation college students, and most are from underrepresented minority groups. Through his teaching, Professor Booth has built many strong bonds with students that have led to his writing over 20 graduate school application referrals during his 7 years at CCNY. Professor Booth leads a research group that is as diverse as the student body at CCNY, and he mentors his students in science and life. Many of his former undergraduate trainees went on to have successful graduate careers, and his graduate students have graduated into jobs at the EPA, or are collaborating with national government labs. Professor Booth has also developed an interactive climate-science related program with one middle school in the Harlem neighborhood near CCNY.

External Evaluator Kathleen J Mackin, Ph.D. brings twenty-five years of experience serving federal, state, and local education entities and universities. As a researcher, Dr. Mackin has performed large-scale studies in diverse program settings, employing mixed-method evaluation strategies and designing unique technology-based approaches to data collection and management. In the past ten years Dr. Mackin has conducted evaluations for four NSF-funded projects that are relevant to this project. Dr. Mackin served as evaluator for the NSF-funded project with MIT, *Weather in a Tank: Exploring Laboratory Experiments in the Teaching of Meteorology, Oceanography, and Climate* (*Illari et al.*, 2009; *Mackin et al.*, 2012). This evaluation examined the efficacy of using laboratory fluid experiments to enhance the teaching of meteorology and climatology with undergraduate students. Recently, Dr. Mackin served as evaluator for two NSF-funded projects conducted at Millersville University, Department of Earth Science: *GEOPOD: GEOscience Probe of Discovery* and the SEGUE project which was conducted in collaboration with The National Center for Atmospheric Research Earth Observing Laboratory (NCAR/EOL) and the COMET program. The SEGUE project resulted in the production of ten online learning modules related to instrumentation and measurement in the atmospheric sciences for undergraduate and graduate students. Dr. Mackin evaluated the NSF-funded STEM Teaching Fellowship/Master Teaching Fellowship program of the Center for University, Schools, and Community Partnerships (CUSP) at the University of Massachusetts, Dartmouth. This evaluation examined the success of the CUSP's partnership with high-need middle and high schools in the region to strengthen STEM teaching and learning.

4 Institutional Profiles

Lamont-Doherty Earth Observatory is a research laboratory of Columbia University for earth and environmental science located in Palisades, New York. Much of the modern understanding about the composition of the solid Earth, the interactions of the oceans, ice caps, and atmosphere, past and present ecologies, and the prospect of climate change are underpinned by research done by Lamont scientists. Nearly 200 Ph.D. level researchers work and teach there, and 80-90 graduate students are involved in research. Since 2016, LDEO has established an Office of Education and Outreach, with the purpose of leading and facilitating all educational research, programming, and outreach initiatives at the Observatory and strengthen a centralized role in bringing Earth Science research to a wide variety of audiences. The Office combines pedagogical research, authentic learning opportunities, and cutting-edge science and data to train and prepare a new generation of scientifically literate citizens.

The **University of California, Los Angeles** is one of the world's top-ranked public universities, and has placed atop US News and World Report's list of top US public Universities for the past four years running. Co-PI Aurnou is situated within UCLA's Department of Earth, Planetary and Space Sciences, with long-lived expertise in plate tectonics, planetary mission science, internal dynamics, cosmochemistry and space physics. Within this multi-institutional project, UCLA will continue to test, build and improve our DIYnamics outreach experimental kits; develop movies of our experiments; test out our materials in outreach and classroom settings; and seek to make connections with URM-serving CC's and college in the LA Basin.

City College of New York is part of the City University of New York. It is located in Harlem, and all five boroughs of NYC are well-represented by CCNY students. According to the U.S. News ranking, CCNY is #17 nationally in Top Performers on Social Mobility and in Campus Ethnic Diversity. City College has both an Earth and Atmospheric Sciences and an Environmental Engineering program. These programs have 20–40 new students per year, many of those majoring in these subjects come from underrepresented cultural backgrounds. These students are ready to diversify the academy.

5 Broader Impacts

The activities proposed in this project are strategically aligned with NSF's broader impact goals of broadly expanding student pathways into geoscience and STEM fields. They are also well aligned with the Next Generation Sciences Standards, such as HS-ESS2-4 ("Use a model to describe how variations in the flow of energy into and out of Earth's systems result in changes in climate." cf. Figure 6b). Thus, our project will ultimately serve students in upper level high schools, community colleges, liberal arts colleges and universities by building up an instructor base that is empowered to teach geoscience topics via active, inquiry-based, student-focussed rotating tank experiments. In addition, the classroom-based development of curricula and detailed information on careers related to our rotating fluids experiments will lead to an array of classroom experimental and curricular products that have the potential to broaden participation in geoscientific STEM fields and seeks to address the low percentage of college students choosing geoscience as their major field of study.

6 Results from prior NSF support

Spencer Hill: AGS-PRF-1462544, "Advancing Understanding of Monsoons by Bridging Gaps among Disparate Theoretical Perspectives." 9/1/16 - 8/31/18. $172,000. **Intellectual Merit**: PI Hill demonstrated via analytical theory, idealized model simulations, and comparisons to observational data that the poleward extent of the cross-equatorial Hadley circulation ascending branch is fundamentally set by the extent over which the radiative-convective equilibrium climate that would exist absent any large-scale circulation would be symmetrically unstable. **Broader Impacts**: PI Hill organized and executed numerous science outreach events, co-founded the DIYnamics organization to disseminate rotating tank outreach materials, created the DIYnamics website, blog, and Youtube channel, penned multiple blog posts, created multiple explanatory videos, and lead-authored a peer-reviewed paper on DIYnamics. PI Hill mentored three undergraduate students at UCLA (two working on DIYnamics) over a combined 5 academic quarters. **Publications**: *Hill* (2019); *Hill et al.* (2019, 2018, 2020a,b). **Research products and their availability**: All DIYnamics materials are freely available from the DIYnamics website (whose underlying source code is also freely posted on Github) and Youtube channel.

Jonathan Aurnou: NSF EAR Geophysics Program Award #1853196, "Phase V: Development of the Core Fluid Dynamics Laboratory at UCLA." 2/1/19 - 1/31/22. $702,610. **Intellectual Merit** The Co-PI's Simulated Planetary INteriors Laboratory (SPINLab) group has carried out a wide range of laboratory, numerical and theoretical studies relevant to planetary fluid dynamics. Recent experiments provide fundamental laboratory data characterizing and quantifying multi-scale planetary-style convective turbulence. This data is necessary to benchmark and validate advanced theories of planetary core flows and to build predictive models of turbulent planetary dynamo generation in liquid metals. Thus, our results are useful to models of Earth's core and other planetary dynamos, fluid turbulence, solar and stellar convection zones, as well as oceanic and atmospheric dynamics. **Broader Impacts**: This work continues expanding the realm of experimental-theoretical simulations of planetary core processes, involving new aspects of flow fields (e.g. vorticity data) and exploring new experimental geometries that have not been previously interrogated. Further, the SPINLab provides training in laboratory experimentation, numerical and theoretical modeling to graduate students, undergraduates and postdoctoral researchers. The award also provides funding for the expansion of our outreach efforts, in particular the development of our do-it-yourself experimental toolkits. **Publications**: *Horn and Aurnou* (2019); *Mound et al.* (2019); *Aurnou et al.* (2020); *Vogt et al.* (2021). **Research products and their availability**: Data and publications are made available according to the project's Data Management Plan.

Margaret Turrin: NSF INCLUDES #1649310, $299,995,000 (10/01/2016-09/30/2018) "Early Engagement in Research: Key to STEM Retention." **Intellectual Merit**: This INCLUDES pilot established a network of organizations in the Lower Hudson region to provide high school students from groups underrepresented in STEM with geoscience research opportunities. Partner organizations included academic institutions, local environmental non-profits, high schools and organizations with field locations. The group organized into regional clusters that piloted summer research programs with shared parameters including tiered mentoring with undergraduates, common assessments, field and lab research, culminating in a shared poster session. **Broader Impacts**: Turrin co- chaired AGU session on Geoscience Learning Ecosystems; Turrin co-chaired session Earth Educators Rendezvous on building a Community of Practice. **Research products and their availability**: The project is currently under a NCE with final evaluation underway and publications to follow. Data will be available through Columbia Commons and publications. Conference Abstracts: *Lev et al.* (2017); *Turrin et al.* (2018); *Robles et al.* (2019).

James Booth: NSF PREEVENTS Program Award #1854773, $268,070, "PREEVENTS Track 2: Collaborative Research: Geomorphic Versus Climatic Drivers of Changing Coastal Flood Risk." 6/1/2019 – 5/31/2022. **Intellectual Merit**: This project, part of a collaboration on improving our theoretical understanding of coastal flooding, derives statistical relationships between physical properties of tropical and extratropical cyclones and the characteristics of coastal flooding. The CCNY team is focused on historical extreme storm surge events for coastal cities along the eastern seaboard. We have developed a new metric for extremes based on their duration, which has direct links to societal impacts. We then identified the anomalous atmospheric circulation patterns that generate long-duration surge extremes. We have determined specific circulation regimes in which extreme surge is more predictable. **Broader Impacts**: The research being developed will improve the field of coastal flood forecasting by providing weather forecasters a better idea of how the path and strength of the cyclones can influence the strength and duration of storm surge. The project has provided a research opportunity for 4 students (one graduate student, two undergraduate student, and one high school student) in a STEM field. Three of the four students are under-represented minorities. **Publications**: In preparation. **Research products and their availability**: None to report yet.

7 Conclusion

We expect the proposed work to increase adoption of rotating tank-based instruction into multiple GLEs in various communities throughout the country, including some of predominantly URM communities. This will be accomplished through instructor training and DIYnamics Kits provided via professional development workshops and by properly establishing the DIYnamics Community of Practice as a source of resources and support to workshops attendees and other instructors otherwise new to rotating tanks. The project will also produce the first formal evaluations of how this proven effective pedagogical tool influences geoscience pathways of students at both the high school and collegiate levels. Together, these constitute substantial advances in pursuit of the IUSE goals of "connecting education research to practice, building institutional capacity for preparing the professional geoscience workforce, and broadening participation in the geosciences" as well as the IUSE:GEOPAths primary goal to "increase the number of students pursuing undergraduate and/or postgraduate degrees through the design and testing of novel approaches that engage students in authentic, career- relevant experiences in geoscience."

The combination of PI Hill's and Co-PI Aurnou's experience through DIYnamics in simplifying rotating tanks and expanding their use from the university to secondary levels (*Hill et al.*, 2018), Co-PI Turrin's extensive experience in broadening geoscience participation and in professional development workshops, Co-PI Booth's extensive experience in teaching geosciences in a predominantly URM-serving university, and External Evaluator Mackin's extensive prior experience in evaluating rotating tank demonstrations (*Illari et al.*, 2009; *Mackin et al.*, 2012) make the project team uniquely well-suited for this work.