Rotating Fluids

Modeling Geophysical Fluid Dynamics and Climate

For Teachers and Students

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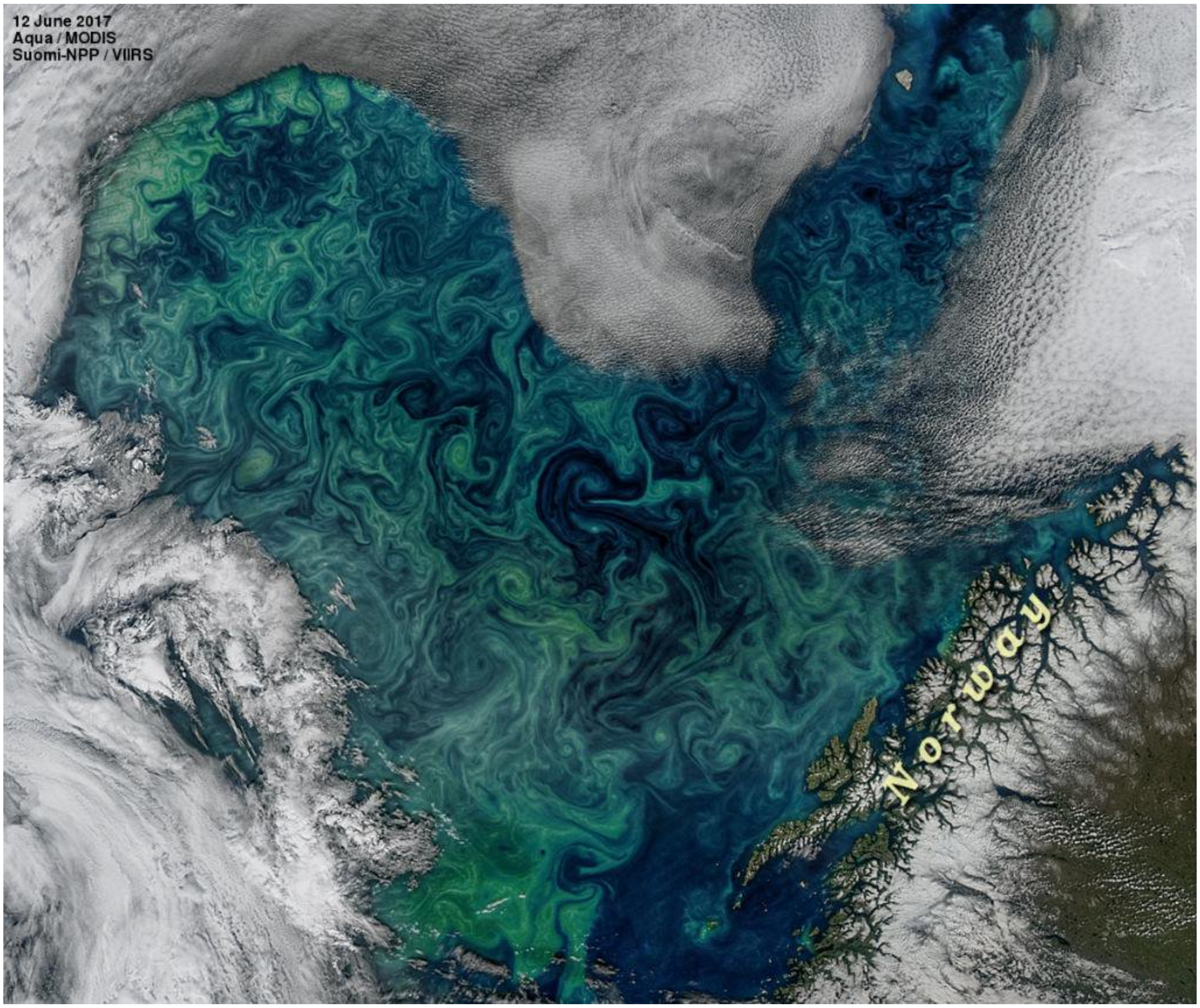
Experiments adapted from UCLA SPINLab outreach efforts
(http://spinlab.ess.ucla.edu/)

Background

Fluids are everywhere on our planet. The water in the ocean, the air in the atmosphere, and even the molten rock and metal deep beneath the Earth's surface are *all* fluids: any liquid or gas is, by definition, a fluid.



In this image taken from a satellite, you can see the swirling eddies in the ocean off the coast of Norway. The different colors in the ocean come from blooms of phytoplankton, tiny sea creatures that get moved along with the currents. From https://twitter.com/NASAOcean/status/874944513789317123

It doesn't seem like it to us, but since the planet is always rotating, these fluids are *always rotating* too, resulting in ocean currents, atmospheric circulations, and swirling liquid metal at our planet's core that generates Earth's magnetic field. The same is true on other planets and moons, since they are all spinning too!

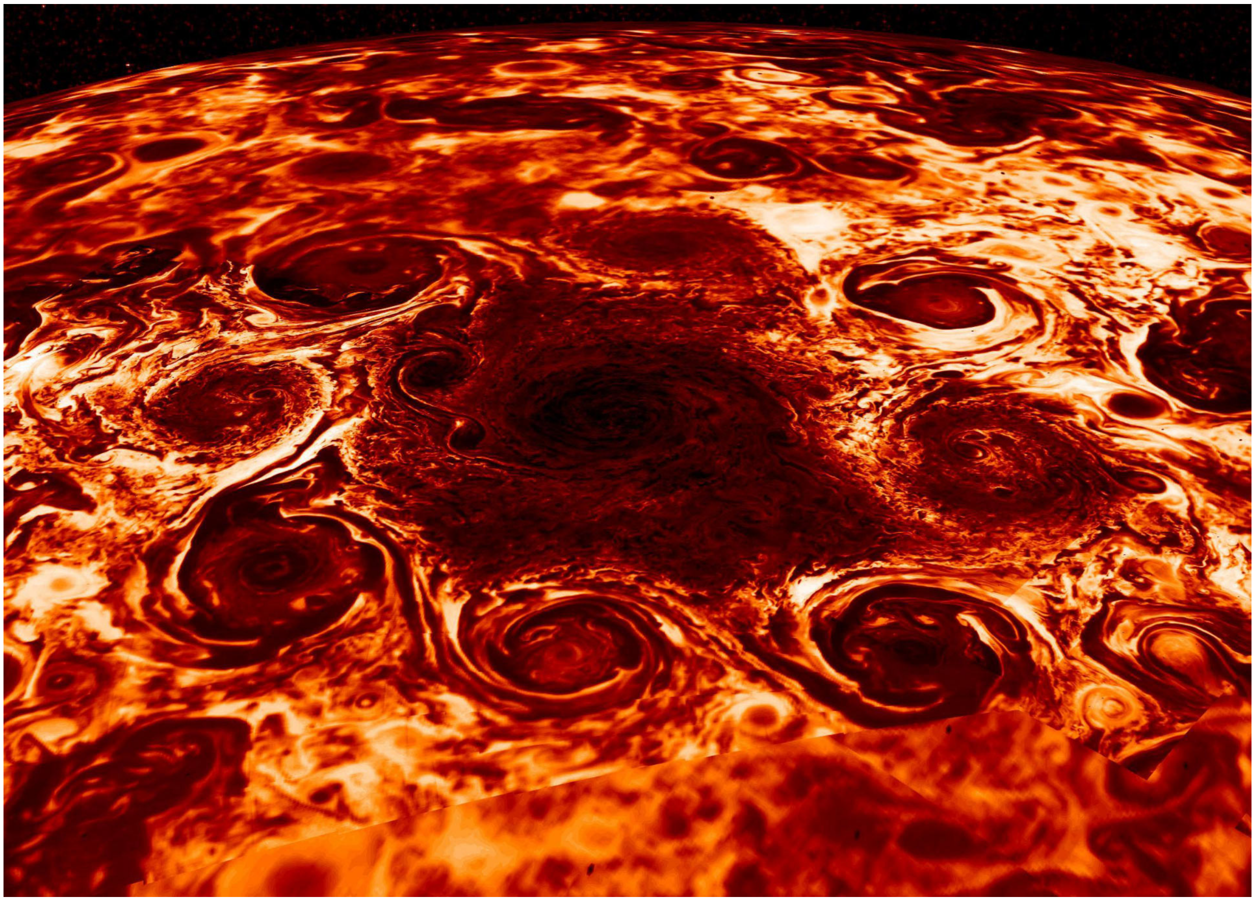


Image from the Juno spacecraft of the "vortex crystal" at Jupiter's north pole. Jupiter's massive size and fast rotation rate combine to create tons of amazing atmospheric circulation features such as these. From https://apod.nasa.gov/apod/ap180308.html

As a result, it is important for us to understand the impact of rotation on fluid motions, which we call **geophysical fluid dynamics**! Let's break that down:

- **geo***:* Earth (or another planet)
- **physical***:* Relating to the branch of science called "physics", which is the study of how real-life objects in our universe behave
- **fluid*:*** any gas (like the atmosphere) or liquid (like the ocean or molten metal in Earth's core)
- **dynamics**: how things move around

Together then, *geophysical fluid dynamics* refers to the behavior of moving fluids on a rotating planet.

Students using a rotating tank of water to model geophysical fluid dynamics at UCLA's Exploring Your Universe.

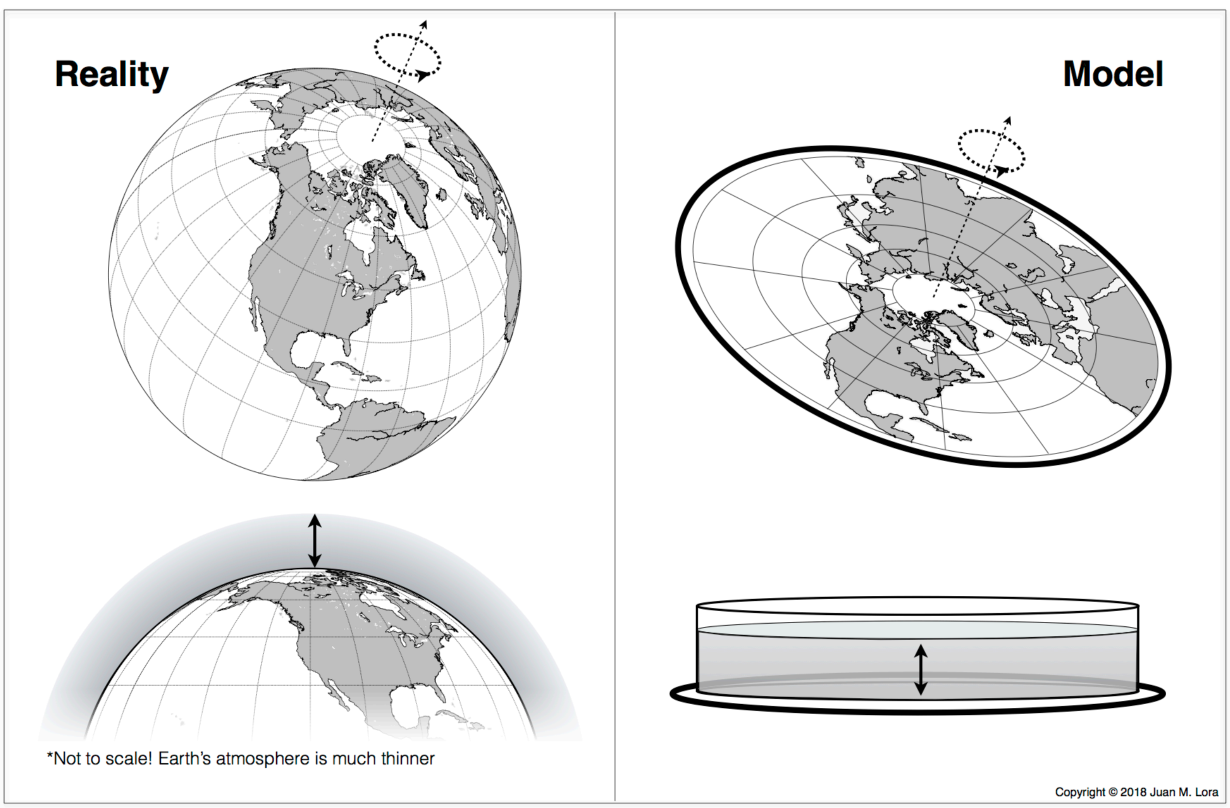
In these laboratory examples, we **model** geophysical fluid dynamics using a rotating tank of water. Models help us describe and test our scientific understanding of phenomena we see in nature. Here, the tank represents the planet, and the water in the tank represents the atmosphere (or the ocean, or the planet's core).

Models, though, are rarely perfect—and ours isn't either. Take a moment to ask yourself:

1. What does our model properly capture about the natural world?
2. What does our model *not* capture about the natural world? What are the major differences between our model and the atmosphere itself?

There are many answers to these questions, but one major difference between our model and the real world is **scale**, or the representation of size. The actual Earth is huge, but a rotating tank is small enough to sit on a desk. So the tank can't exactly reproduce all of our observations of nature. Think about the following:

1. The Earth's radius is approximately 6370 km. What is the horizontal scale of our tank model?
2. The depth of the **troposphere**—the part of the atmosphere where weather happens—is roughly 10 km. What is the vertical scale of our water model?

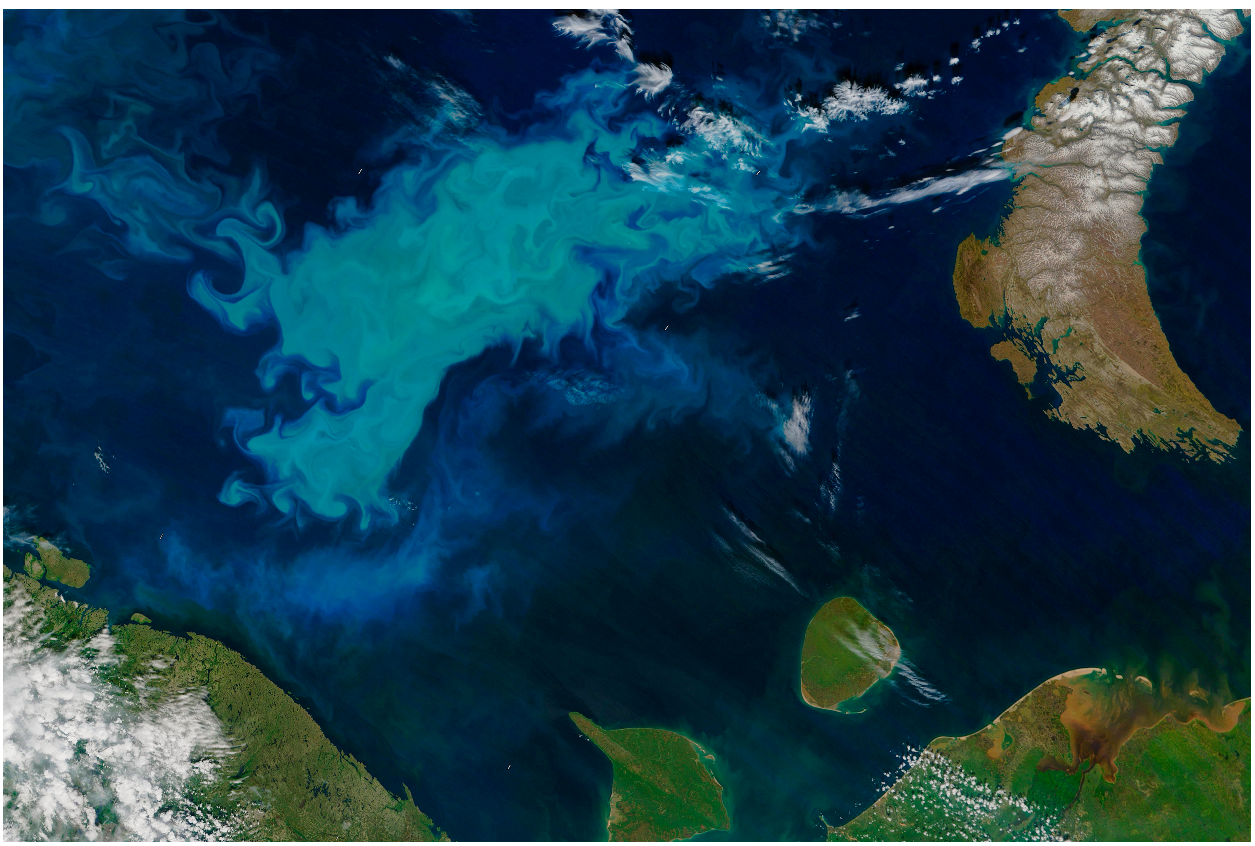


Our model also allows us to investigate the ways that fluids (like air, water, etc.) transport material. One way this happens is through **diffusion**, where particles of the transported material move from regions of high concentration to low concentration within the fluid. Another way is **advection**, where the fluid itself *carries* the particles with it as it moves. We can observe these modes of transport using colored food dye as a **tracer** for fluid motions. A tracer is simply something that gets transported by the fluid. Ocean currents, for example, are fluid motions that can be traced and are visualized in this video:

https://svs.gsfc.nasa.gov/3827

Understanding the fluid motions of our world is of great importance to scientists and engineers across the world. Research institutions and governments invest lots of money, time, and effort into studying geophysical fluid dynamics. Before we go further, take another moment to ask:

1. Why do you think it would be important for us to study the behavior of geophysical fluids?
2. Can you recall a time in your life when geophysical fluids affected *you*? (Hint: all of the weather we experience occurs in the atmosphere, a geophysical fluid.)



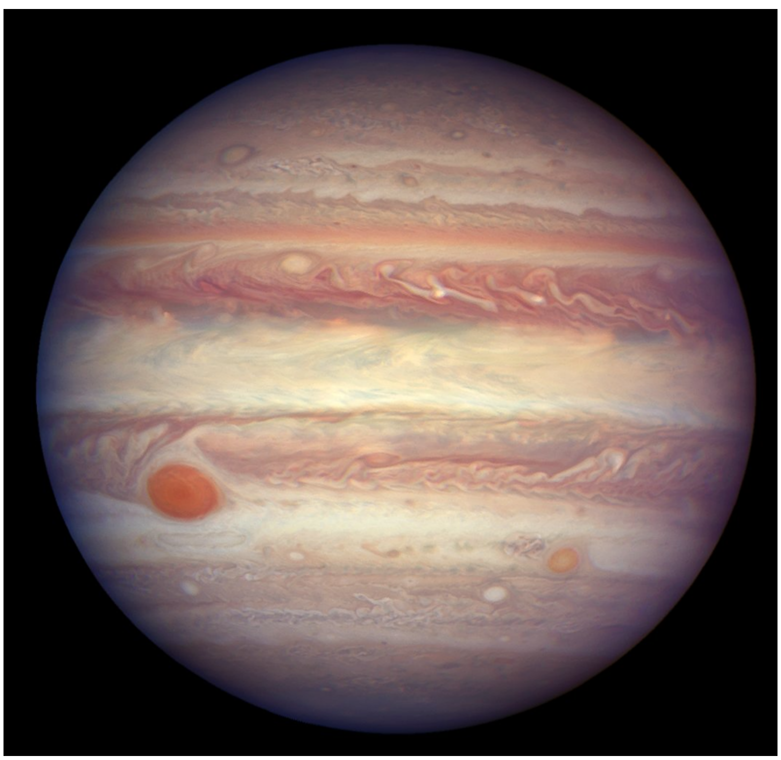
Phytoplankton bloom from the Barents Sea in the North Atlantic Ocean captured by a satellite in 2016 (https://earthobservatory.nasa.gov/NaturalHazards/view.php?id=88316).

Fluid motions in the atmosphere and ocean have a major impact on our planet's **climate**, and the **life** that inhabits it. Winds in the atmosphere determine temperatures and precipitation by carrying heat and moisture across large distances, creating distinct ecosystems for life. Ocean currents draw up nutrients to the surface, spawning plankton blooms that sustain large marine ecosystems.

For all of Earth's history, changes in these kinds of oceanic/atmospheric currents and circulations have led to corresponding changes in climate that disrupt ecosystems and even drive biological evolution. We refer to such climates of the ancient past as ***paleoclimate****.* Earth's modern climate is currently undergoing a period of very fast changes, so understanding paleoclimate can help us to predict where our climate system may be headed.

Beyond the atmosphere and ocean, fluid motions (molten rock and metal) inside of our planet also impact life. Motions of extremely hot liquid iron in the Earth's core generate Earth's magnetic field, which protects us from the harmful particles released by the Sun.

Lastly, our model helps us study not just Earth's atmosphere, but also atmospheres on other planets. The massive storm systems and swirling clouds observed on the gas giants of the Solar System (Jupiter, Saturn, Uranus, Neptune), such as Jupiter's Great Red Spot, are examples of fluid motions driven by rotation. Models similar to the ones we use in this lab can help us learn more about these features and effectively study faraway planets that we can't physically go to ourselves.



*The bands and storms of Jupiter, including the Great Red Spot. (*https://www.spacetelescope.org/images/heic1708a/ *)*

Experiments

When doing rotating tank experiments, we have to let the tank rotate for some time so the water can properly *spin up*. When the tank first starts rotating, the water on the outside is going faster than the water near the center because **friction** from the tank walls is pulling it along. The first experiment demonstrates this.

Experiment 1: Spinning Dye Curtain

1. Begin rotating the tank.

2. After a minute, before it's spun up, drop in a *streak* of dye from the center of the tank to the outside edge (rather than a single blob of dye in the center).

> **a.** Before doing this: what do you think will happen to the streak of dye? How do you think it will behave differently from just a single blob?
>
> **b.** What do you observe happening to the streak?
>
> **c.** How would you explain your observation?

Looking from the side, you can see that the dye forms curtains, or sheets.After a few minutes of rotating your water-filled tank, all of the water will be rotating at the same speed. The more water you have and the bigger your tank, the longer it takes to spin up!

Photo from the spinning dye curtain experiment. Video is available on the DIYnamics YouTube channel: https://youtu.be/dn_bjnc2a80

Experiment 2: Rotating Columns

1. In a non-rotating tank of water, drop a single blob of dye and observe.

a. First, before dropping it, what do you think will happen to the dye?

b. Now after you've dropped it, how would you describe the movement and structure of the dye in the tank?

2. Now begin rotating a tank of fresh water, wait a couple minutes for the water to spin up and then, as before, drop in a single blob of dye and observe.

a. Before doing so, what do you think will happen this time?

b. Now how would you describe the movement and structure of the dye?

c. Do you notice a change from the non-rotating experiment? If so, how would you describe it?

3. Pump up the speed of the tank and wait a couple minutes for it to spin up. Drop in a single blob of another color dye and observe.

a. Before you drop it, how do you think the dye will behave?

b. Now after you've dropped it, do you notice a change in the movement and structure of the dye as compared to the more slowly rotating experiment?

b. What can you conclude about the effect of rotation on the movement and structure of the dye?

In non-rotating experiments, the dye moves fairly quickly in all directions and has little structure. The transport is dominated by diffusion. However, rotating dye moves more slowly and forms vertical columns—the faster the rotation, the smaller the radius of the columns. In this case, diffusion is limited, and the rotation organizes the flow into columns.

Physical analog: *This experiment provides an effective model for planetary interiors. In planetary interiors of rotating planets, fluids form* columns *that are aligned with the axis of rotation. These columns can create circulating electric currents that generate magnetic fields.*

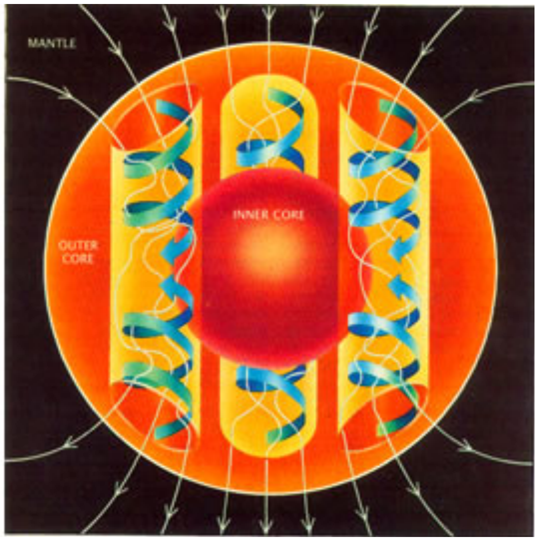


Illustration of Earth's core. Planetary rotation forces the liquid iron outer core into columns that help generate Earth's magnetic field. (https://www2.usgs.gov/faq/categories/9782/2738)

Experiment 3: Vortices

1. In a non-rotating tank, spray in fine dye patches with spray bottles, if available. Then, with differently colored dyes, add in a couple more blobs. Using *one or two* strokes of a pen or a finger, mix the colors.

a. Before doing so, what do you think will happen to the colors?

b. Now after you've mixed the colors, what do you observe?

c. How would you explain your observation?

2. Refill the tank with clean water now. Begin rotating the tank and wait a few minutes for the water to spin up completely.

3. As before, spray in fine dye patches with spray bottles if available and a couple more blobs with differently colored dyes. Now mix the colors with *one or two* strokes of a pen or finger.

a. Again, before mixing, ask yourself what you think will happen?

b. Now after you've mixed the colors, what do you observe?

c. What do you notice when you observe from the *side* of the tank?

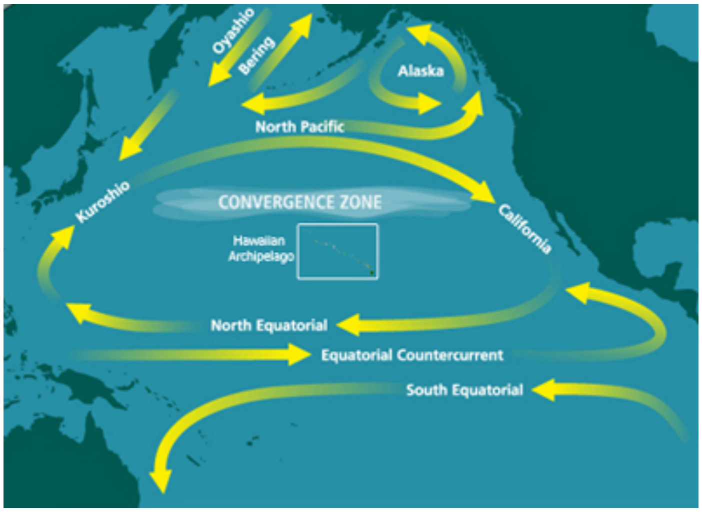
d. Can you draw connections between this experiment and Experiment 1?

e. What might your observations represent in the natural world?

You may observe swirling patterns from the colored dye. These are called **vortices** (plural of **vortex**), or **eddies** (plural of **eddy**). They show up readily in rotating fluids. In this model, we generate vortices *mechanically*, meaning we physically stir the fluid to create the turbulence. But vortices can also be generated by other sources of turbulence – hurricanes, for example, are large weather systems in the tropics that are the result of rising hot air in a rotating atmosphere.

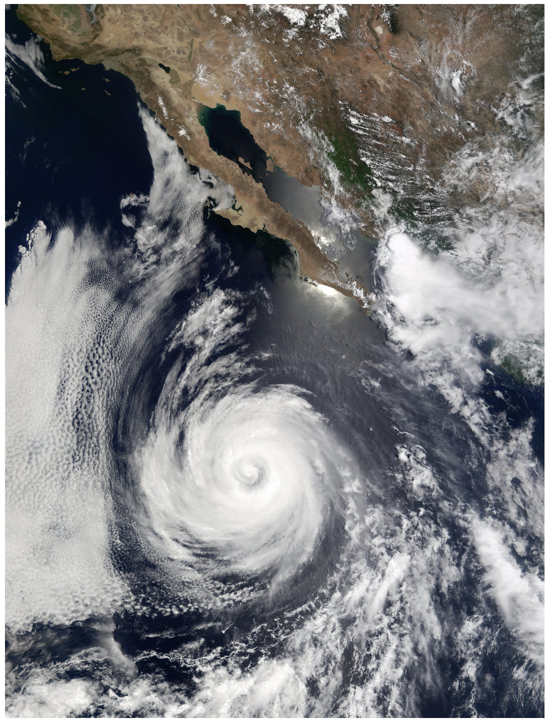
Physical analog: *Vortices are typical in stirred fluids and are a fundamental component of turbulent flow in the atmosphere and oceans. Major storms and ocean gyres are examples of vortices driven both thermally and mechanically.*

Vortices also occur in the ocean, where they are commonly called **gyres** if they're large. Ocean gyres concentrate nutrients to promote plankton blooms, but they can also concentrate trash: The Great Pacific garbage patch is the result of a gyre in the Pacific Ocean that spans from Asia to the American west coast and is known for the high concentrations of plastics and chemical sludge gathered at its center by ocean currents.



The North Pacific Gyre and other ocean currents stirred mechanically by winds and continental boundaries (https://marinedebris.noaa.gov/info/patch.html*). For a demonstration of the garbage patch in a rotating tank similar to the one we're using, check out this YouTube video:* https://youtu.be/yP6eG9iXmKc

Note: Tornadoes develop from large storms, but their rotation is not due to planetary rotation.



Hurricane Douglas moving away from the Baja California Peninsula in 2002 (https://earthobservatory.nasa.gov/NaturalHazards/view.php?id=9989).

Bonus Round: Convection

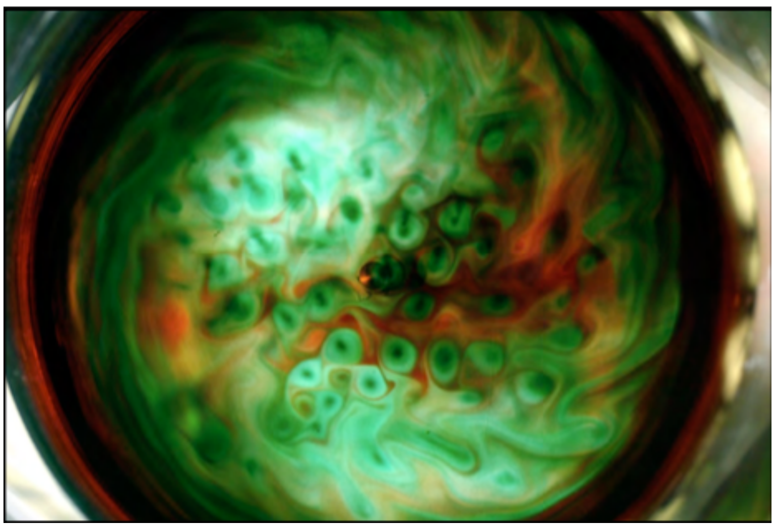
In doing the previous experiments, you might have noticed small swirls on the surface of the water forming a honeycomb-like pattern.

1. If you missed them, perform Experiment 3 in bright sunlight.

    a. How would you describe the surface as compared to the same experiment run without sunlight?

    b. What do you think is causing the patterns that you see?

    c. What do you think your observations might represent in the natural world?



These tiny, organized swirls are the result of **convection**. Heat, from the sun's energy, is responsible for these small vortices: The heat evaporates the water at the surface, which *cools* the surface water. Because colder material is more dense, the surface water then sinks, while the water beneath rises. This convection is a form of stirring, so it too forms vortices under the influence of rotation.

Physical analog: *Convection is enormously important for transferring heat in the atmosphere and ocean, as well as within the Earth's interior where it helps drive plate tectonics. This experiment shows tiny, upside-down versions of hurricanes!*

<u>Terms:</u> **geophysical fluid dynamics, model, scale, diffusion, advection, friction, vortex/eddy, gyre, convection**