Polar Storms on Jupiter (Rotating Convection)

Overview:

- Geophysical flows are often organized due by the effects of rotation. In particular, Coriolis forces often cause fluid motions to swirl around with a characteristic radius. This can lead to highly organized flow patterns in rotating systems, where, in comparable non-rotating systems, everything would be a turbulent disorganized mess!
- An exciting new example of such rotational organization are the honeycomb arrays of vortices situated around the poles of Jupiter.
- Deep oceanic convection, crucial to the global ocean circulation system, also occurs in the form of vortex arrays.
- Here we will make our own array of vortical (swirling) flows by spritzing dense food coloring atop a layer of rotating water. The slightly denser food coloring will sink. Coriolis forces will swirl the sinking fluid into a vortex array, similar, at heart, to what is seen at the Jovian poles.

Materials

- DIYnamics Technics Table
- Water
- Food Coloring
- Spray bottle
- Liquid soap (dish soap or hand soap)

Recipe

1. Place the LEGO motor next to the OXO Lazy Susan, taping the base to the table. The motor wheel should firmly contact the side of the Lazy Susan.
2. Fill the tank with 4 – 8 cm of water and add in a drop of liquid soap.
3. Start the LEGO motor and let the fluid spin up for about 10 minutes.
4. Spray food coloring on the surface of the water and then let the system evolve for a few minutes.
5. Observe the flow and discuss with your team.

Theory: Conceptual

Rotating fluid layers act like a fluid spinning top or gyroscope. They do not want to tip over. But the dense food coloring wants to sink down beneath the less dense water, which would cause the fluid to overturn – this is also called convection. ***But overturning is an anathema to a rotating tank of fluid!*** Internal frictional (aka viscous) forces in fluids become more important on smaller sized flow structures (for example, it is hard to suck fluid through a skinny straw). So convection can only occur in our tanks on a sufficiently small horizontal length scale –in a skinny enough straw– such that friction locally takes over.

The faster the rotation rate, the smaller the size of the convection cells in the vortex array. And since rotation causes flows to swirl, each little convection cell looks like a tiny swirling hurricane.

Theory: Advanced

Nobel prize winner S. Chandrasekhar was one of the first people to work on rotating convection. Chandra showed that the diameter D of the swirling convection cells varies as $D \simeq (\nu H/\Omega)^{1/3}$, where $\nu = 10^{-6}$ m^2/s is the water's viscosity, H is the fluid layer depth, and Ω is the angular rotation rate. Since the water's viscosity is fixed here, only changes in fluid layer height H or the tank's angular rotation rate Ω should change the spacing in the convective vortex array.

Discussion Question: By changing H or Ω, are changes in D observable?

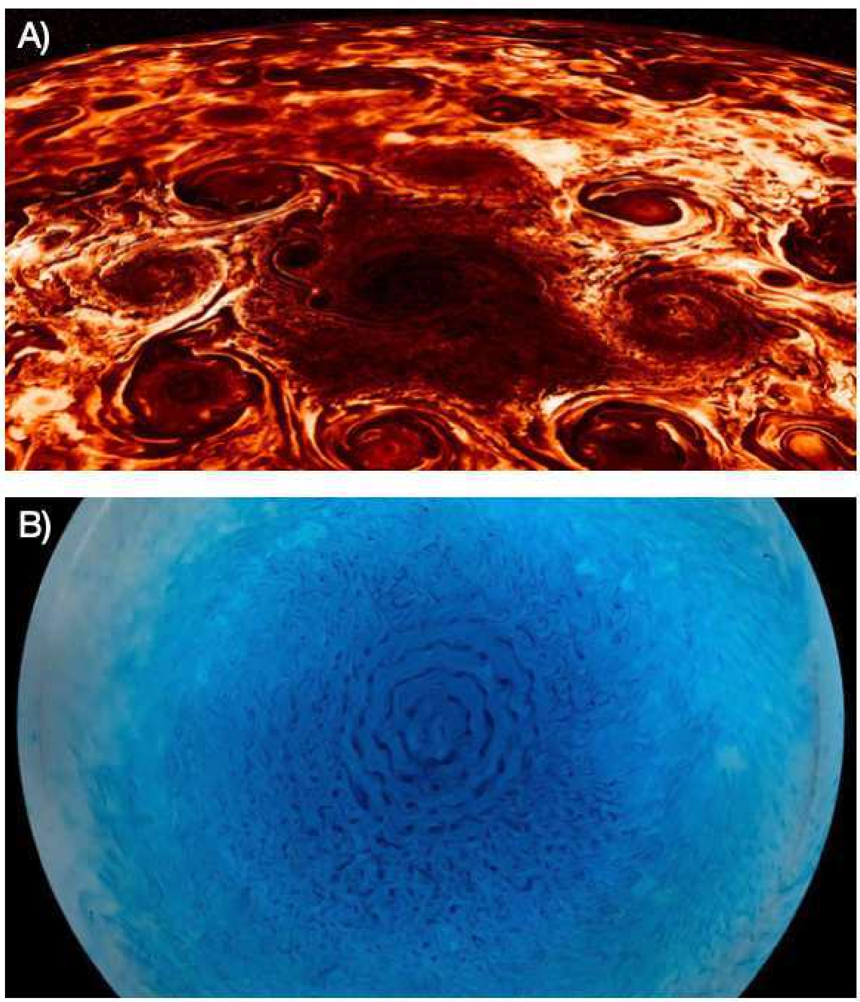


Figure 1: A) Oblique thermal image of Jovian polar cyclones. (Image: NASA's Juno mission) B) Rotating convective vortex array in a DIYnamics experiment (with a drop of radial shear).

Example video: `https://youtu.be/tOqODX3yUBo`

Taylor Columns

Overview:

- Taylor columns describe flow around an obstacle in rapidly rotating fluids. In a rotating tank, the fluid behaves like a spinning top. It stays vertically aligned along the direction of rotation—as if each column of fluid was an individual top.
- If an obstacle sits at the bottom of a non-rotating tank of fluid, a background flow will happily flow around as well as over the obstacle. In a rotating system, a weak background flow cannot deform the "fluid top" situated above the obstacle. Thus, the background flow deflects around the object at all heights! The flow above the object is then roughly locked in place forming a fixed column.
- These vertically-invariant columnar flows are called "Taylor Columns", and we can make them in our DIYnamics tanks.
- These "axialized" flows are essential to our understanding of, for example, large-scale atmospheric waves, deep ocean convection in the Weddell and Labrador Seas, and the axial alignment of the geomagnetic field by rotationally-aligned flows in Earth's molten metal outer core.

Materials

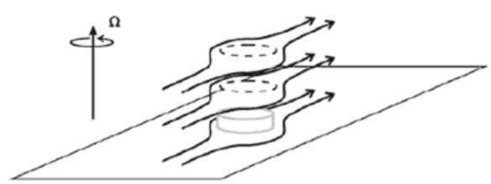
- DIYnamics Technics Table
- Variable power supply
- Water
- Plumbers putty
- Food coloring
- Bottle caps (aka obstacles)
- Paper dots (optional)
- Liquid soap (dish soap or hand soap)

Recipe

1. Connect the variable power supply to the LEGO motor. Place the LEGO motor next to the OXO Lazy Susan, taping the base to the table. The motor wheel should firmly contact the side of the Lazy Susan.
2. Fix the bottle cap with plumbers putty off center on the dry tank bottom.
3. Fill the tank with water, up to about 4 – 8 cm, and then place one drop of soap into the tank to break the surface tension.
4. Set the LEGO motor using the variable power supply to drive the tank at about 10 – 15 RPM, and let the fluid spin up for about 10 minutes.
5. Place a few drops of food coloring upstream of the bottle cap. Optionally, sprinkle paper dots on the water's surface.
6. Increase the rotation rate ($\lesssim 1$ RPM). This creates a background flow past the obstacle.
7. Observe the flow and discuss with your team. Does a clear Taylor Column form?

Theory (Conceptual)

In a rapidly rotating, fully spun-up tank of fluid, every column of fluid spins about the rotation axis, all with angular velocity Ω; the fluid is in solid body rotation. If nothing strongly acts on a given column of fluid, it will remain vertically aligned along the rotation direction. Each column of fluid will conserve its angular momentum. This is analogous to an iron nail aligned in a strong magnetic field. Unless its strongly perturbed, the nail remains aligned along the magnetic field direction. Taylor Columns do this too, but they align vertically in the direction of rotation.



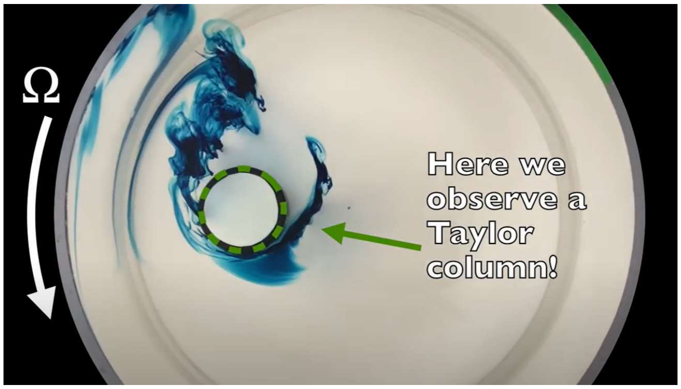


Figure 1: An oblique view of a Taylor column in a rapidly rotating fluid layer (left) and a top view of a food coloring wrapping around a Taylor column in a DIYnamics experiment (right).

Theory (Advanced)

Taylor columns can only form over an obstacle when the rotation time scale, $T_\Omega = (2\Omega)^{-1}$, is shorter than the flow time scale, $T_{flow} = D/V$, where D is the diameter of the obstacle and V is the typical flow velocity. This then predicts that Taylor Column formation requires

$$\frac{T_\Omega}{T_{flow}} = \frac{V}{2\Omega D} \lesssim 1\,.$$

Discussion Question: Can you test this prediction in the Lego Tanks by using obstacles with various D values? Or by varying V or Ω?

Example videos:
`https://youtu.be/KiBrKzykw08`; `https://youtu.be/7GGfsW7gOLI`

Atmospheric Circulation (Thermal Wind)

Overviews:

- Earth's tropical atmospheric circulation is organized into two large overturning cells, the Hadley cells, with east-west flow caused by thermal wind (since Earth is rotating and the Tropics are much warmer than the poles): flow is from east to west near the surface but west to east higher up.
- A rotating fluid with a large-scale temperature difference between the tropics and the poles will have flow along lines of latitude. These flows also vary with height.
- This change in the flow with depth in the fluid due to the rotation and temperature difference is called *thermal wind*. Thermal wind flows are ubiquitous in planetary atmospheres and oceans.
- If the rotation is fast enough, the steady thermal wind can become "unstable" and break apart into swirling eddies. This process is called *baroclinic instability*.

Materials

- DIYnamics Technics Table
- Variable power supply
- Empty can filled with weights (quarters)
- Ice
- Water
- Food coloring
- Liquid soap (dish soap or hand soap)

Recipe

1. Connect the variable power supply to the LEGO motor. Place the LEGO motor next to the OXO Lazy Susan, taping the base to the table. The motor wheel should firmly contact the side of the Lazy Susan.
2. Place the empty can in the center of the tank, and fill with weights.
3. Fill the tank with water, up to about 5 cm.
4. Place one drop of soap into the tank (this breaks the surface tension).
5. Start the LEGO motor and set it rotate the tank at around 3 to 5 RPM.
6. Allow the tank to spin for 10 minutes.
7. Add ice to the can.
8. Place a couple of drops of dye into the tank adjacent to the can. Observe what happens and discuss with all participants what they see.

Theory (Conceptual)

If a fluid that isn't rotating is warmer in one location than another, it will flow from the warmer to the cooler spot. But if the fluid is rotating, this flow gets turned 90 degrees. It also increases with height. The stronger the temperature difference, the faster the flow. On Earth, for example, the tropics are much warmer than the high latitudes, and this results in very fast flows from west to east in mid-latitudes several miles above the surface (the so-called "jet stream").

Theory (Advanced)

Thermal wind flow is analogous to the precession of a spinning top. When gravity attempts to pull over a spinning top, it pivots off to the side, precessing around its fixed bottom point. Here, gravity is trying to overturn the fluid layer by pulling the colder fluid down and out whilst raising the warmer fluid up and inwards (Figure 1, left). Instead of overturning, the fluid attached to the bottom of the tank stays roughly in place and the fluid at the top shears off to the side. Thus, the entire fluid layer 'precesses' sideways, creating a vertical shear flow that is analogous to solid precession of a top. Similar to a top, the slower the rotation rate, Ω, the faster the fluid precesses around the tank.

Discussion Questions: The typical thermal wind flow speed is

$$|V_{TW}| \simeq \frac{\alpha g}{2\Omega} \frac{\Delta T}{\Delta R} H$$

where $\alpha \simeq 2 \times 10^{-4}$ 1/K is water's thermal expansivity, g is gravity, ΔT is the temperature difference across the tank, ΔR is the gap width between the can and the edge of the tank and H is the layer depth. Can you estimate V_{TW} in your tank? Does it vary if you change $\Omega, \Delta T, \Delta R$, or H?

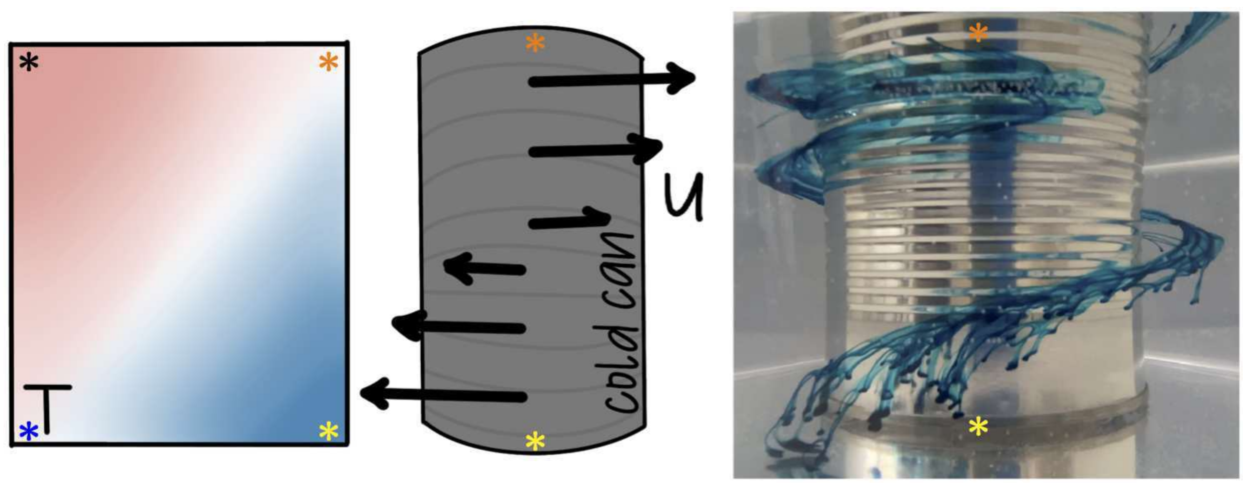


Figure 1: This cartoon (left) shows the radial temperature distribution in color with cold water near can and the bottom of the tank and warm water at the top and toward the edges. The black arrows (middle) show the resulting thermal wind shear. The image (right) shows the thermal wind flow visualized in blue dye in a DIYnamics experiment. Figure credit: Jordyn Moscoso.

Example videos: `https://youtu.be/jX5ppPQaea4`; `https://youtu.be/prZLcQZJkFs`

The Pacific Garbage Patch (Ekman Pumping)

Overview:

- A combination of wind and rotation (Coriolis) are responsible for determining the circulation of the "gyres" or huge wind-driven vortices in Earth's mid-latitude oceans.
- Coriolis deflected flow at the surface drives plastic and other trash in the ocean to aggregate in large masses, which have been named "garbage patches."
- We build an experiment with a rotating tank and clip fans to simulate the winds above the ocean surface to make a small "garbage patch."

Materials

- DIYnamics Technics Table
- Water
- Food coloring
- Paper dots
- Clip fans with power cords
- Battery
- Tape
- Liquid soap (dish soap or hand soap; optional)

Recipe

1. Place the LEGO motor next to the OXO Lazy Susan, taping the base to the table. The motor wheel should firmly contact the side of the Lazy Susan.
2. Fill the tank with water, up to about 5 cm.
3. Place one drop of soap into the tank (this breaks the surface tension)
4. Attach clip fans to the sides of the tank following the experimental sketch (the "wind" should be set up to blow in the direction opposite to the rotation of the tank). Turn the fans on.
5. Start the LEGO motor, and let the fluid spin up for 10 minutes.
6. Place a few drops of dye in the center of the tank, and paper dots on the surface of the water.
7. Observe the flow and discuss with your team.

Theory (Conceptual)

The behavior of fluids on rapidly rotating planets is dominated by rotation. At the surface of the ocean, friction, caused by the winds above the ocean, also becomes important. There, friction between the air and water, so-called wind-drag, balances the effects of rotation. Over the Pacific Ocean, the winds circulate clockwise, with the Trade Winds at the equator from the east, and the mid-latitude Westerly winds (from the west). Instead of following the winds, Coriolis deflects the water perpendicular to the wind. This then transports water, and any materials it contains, toward the center of the gyre forming large garbage patches.

Theory (Advanced)

Fluids in the interior of a domain often have very different dynamics than the boundary layers. The Ekman layer of a fluid is a layer of finite depth, given by the level at which the frictional stresses from a boundary eventually vanish. Inside this layer, there exists a balance of Coriolis force, pressure, and vertical viscous stresses induced by wind-drag. This experiment simulates conditions similar to the atmospheric winds over the Pacific Ocean: we investigate the impacts of surface frictional stresses from wind. The key force balance in this experiment is given by the following equation,

$$\underbrace{2\boldsymbol{\Omega}\hat{z}\times\mathbf{u}}_{\text{Coriolis force}} = \underbrace{A\frac{\partial\overline{\tau}}{\partial z}}_{\text{Wind stress force}} \tag{1}$$

where $\boldsymbol{\Omega}$ is the angular rotation rate, $\mathbf{u}$ is the fluid velocity, A is a coupling coefficient, and $\overline{\tau}$ is the surface wind stress. We set up this experiment so that the winds are in the opposite direction of the circulation of the tank, or anti-cyclonic. As a result of the balance of these forces, the bulk fluid transport is 90° to the right of the winds, given that the tank rotates counter-clockwise. This behavior drives convergence at the surface, downwelling into the interior, divergence at the bottom of the tank, and upwelling along the sides. With floating tracers, such as plastic, this creates convergent zones at the center of the gyre and results in the large garbage patches we see in the subtropical gyres.

Discussion Question: Then, if you flip your fans around, what happens to your garbage patch (and why)?

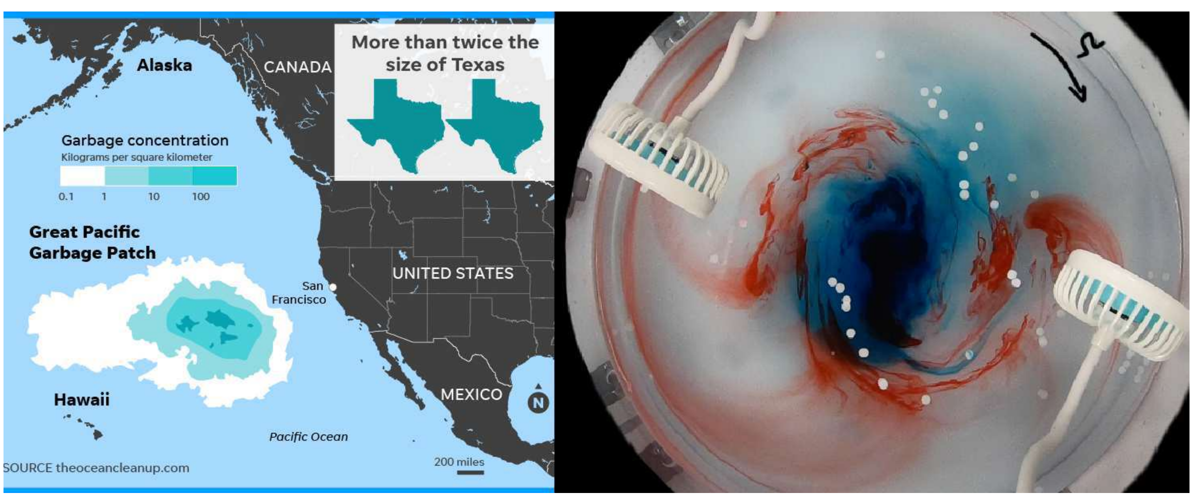


Figure 1: A photo of the location and size of the Pacific Garbage Patch (left), and a photo of an experiment of Ekman pumping in a DIYnamics experiment (right).

Example Video: `https://youtu.be/ojlbI9B0L9U`

How do midlatitude storms form?
(Baroclinic Instability)

Overview:

- Mid-latitude storms regulate the climate by transporting huge amounts of energy, heat, and moisture between the tropics and the poles.
- Here, we will set up such an unstable flow in a tank of water, and generate the associated unsteady swirling that resembles Earth's midlatitude atmospheric flow.

Materials

- DIYnamics Technics Table
- Water
- Food Coloring
- Empty can
- Weights (quarters)
- Ice
- Liquid soap (dish soap or hand soap)

Recipe

1. Place the LEGO motor next to the OXO Lazy Susan, taping the base to the table. The motor wheel should firmly contact the side of the Lazy Susan.
2. Place the empty can in the center of the tank, weighed down with quarters. You can rotate the tank manually to check the centering.
3. Fill the tank (not the can!) with water, up to about 5 cm.
4. Start the LEGO motor to spin the table and tank. The tank should spin at about 10 RPM, or faster.
5. Place one drop of soap into the tank (this breaks the surface tension)
6. Allow the tank to spin for about 10 minutes.
7. Carefully fill the empty can with ice, and pour a small amount of water into it.
8. Place a few drops of blue dye onto the surface of the water in the tank near the can, and a few drops of red dye near the outer radius of the tank.
9. Observe the flow and discuss with your team.

Theory (Conceptual)

If a fluid that isn't rotating is warmer in one location than another, it will flow from the warmer to the cooler spot. But if the fluid is rotating, this flow gets turned 90 degrees. The stronger the temperature difference, the faster the flow. Thus, in Earth's atmosphere where the high latitudes are much colder than low latitudes, the rotational effects generate so-called *thermal wind flows* that wrap around the globe along lines of latitude. These flows are very strong at high latitudes in wintertime. These thermal wind flows can spin out, like a car fishtailing on ice, and create huge midlatitude storms (this process is called *baroclinic instability*). In this experiment, the can full of ice causes the adjacent water in the tank to cool; this produces the required temperature contrast between inner and outer tank radii. Because the tank is spinning quickly, the horizontal flow that develops in the fluid is unsteady, so quickly breaks down into swirling motions ("eddies") that evolve with time. These act to mix the fluid between outer and inner radii of the tank, and are analogous to mid-latitude winter storms on Earth, which act to mix the atmosphere between lower and higher latitudes.

Theory (Advanced)

Baroclinic instability leads to the formation of baroclinic eddies. The energy of the motion in these eddies comes from the drop in the center of mass (potential energy) associated with cold, denser water moving diagonally downward, and warmer, lighter water moving diagonally upward. Thus, this can be thought of as a kind of "sloping convection," but note that the slopes are very shallow. The size of the eddies that result from this instability depend on the rotation rate of the fluid—the faster the rotation, the smaller the eddies. The rotation rate determines how quickly eddies of given sizes grow, which leads to certain sizes dominating.

Discussion Questions: Quantitatively, the baroclinic eddy radius varies as $R \simeq V_{TW}/(2\Omega)$ where V_{TW} is the thermal wind speed, leading to $R \sim \sqrt{H}/\Omega$. Does R change with H or Ω in your experiments? What happens if the baroclinic eddy radius exceeds that of the tank?

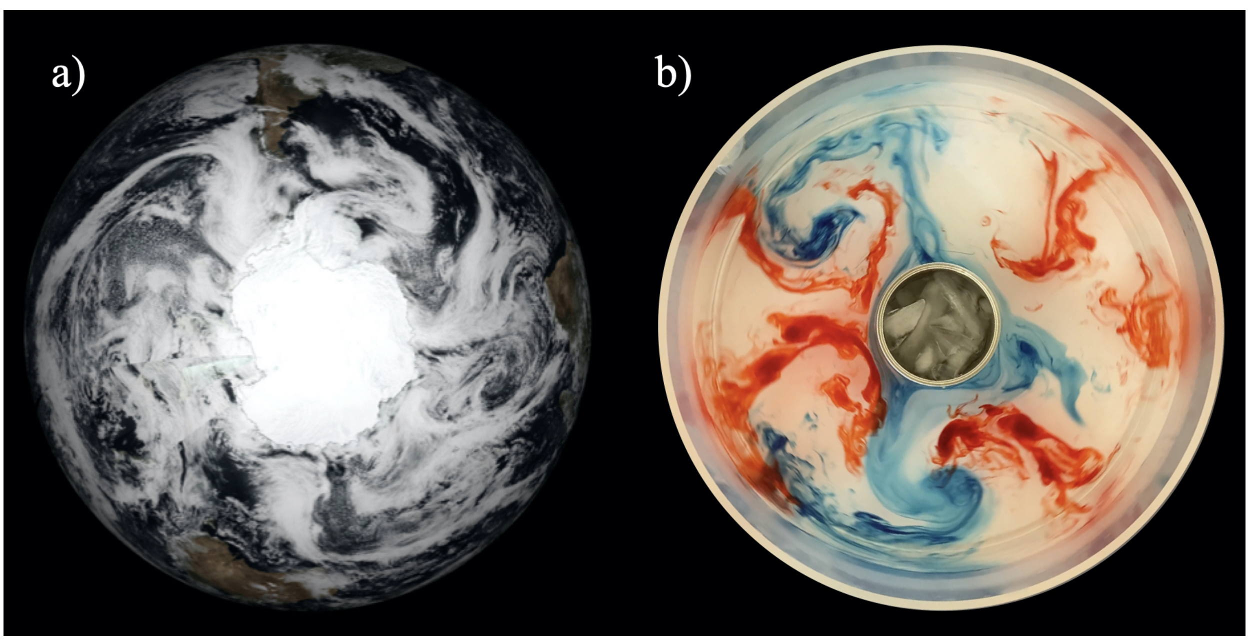


Figure 1: Baroclinic instability visualized a) in clouds streaming off of Antarctica and b) in food coloring in a DIYnamics experiment.

Example videos: `https://youtu.be/HTm3U8mfE1Y`; `https://youtu.be/mzTAc_Wu350`; `https://youtu.be/b4ARJls03YA`

Converging Flow near Earth's Surface (Ekman Layers)

Overview:

- On a non-rotating planet, air would flow directly inwards toward regions of low pressure in the atmosphere. Since we're on a rotating planet, Coriolis accelerations instead deflect those flows off to the right in the Northern Hemisphere, resulting in counterclockwise circulations.
- Friction (à la air drag) becomes comparable to the effect of rotation, Coriolis, near Earth's surface. Once they offset, pressure forces can then push fluid in toward the center of the low pressure system, instead of just circulating around it.
- This motion toward the center of the low pressure system creates fluid convergence near Earth's surface. At the center, the converging fluid has no where to go but up. In Earth's atmosphere, this leads to rising motions, tall clouds, and inclement weather.

Materials

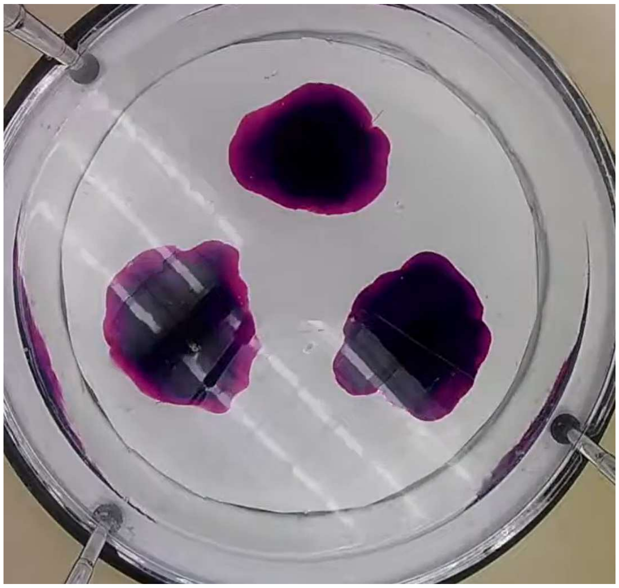
- DIYnamics Technics table
- Variable power supply and GFCI
- Water
- Salty food coloring/chia seeds
- Paper dots (optional; suggested camera in rotating reference frame)
- Liquid soap (dish soap or hand soap)

Recipe

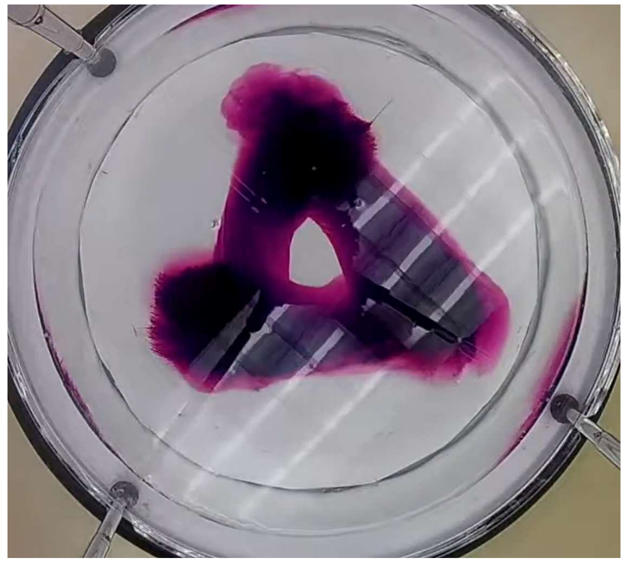
1. Connect the variable power supply to the LEGO motor. Place the LEGO motor next to the OXO Lazy Susan, taping the base to the table. The motor wheel should firmly contact the side of the Lazy Susan.
2. Fill the tank with water, up to about 5 cm and then add in a drop of liquid soap.
3. Plug in the variable power supply into GFCI and set the motor to rotate the tank counterclockwise at 5 - 10 rpm; let the fluid spin up for about 10 minutes.
4. Place three drops of dye in the mid-radius tank approximately in the pattern of a triangle (see figure for example).
5. Optional: place paper dots at the top surface and/or drop in chia seeds.
6. Use the variable power supply to slow down the motor, just a smidge.
7. Observe the flow, especially near the bottom, and discuss with your team.

Theory (Conceptual)

Fluids on rotating planetary bodies are dominated by rotation, which causes a turning of the winds, e.g., winter storms. After the fluid in the tank has spun up, reaching the same angular velocity as the lazy Susan, we slow the tank. The fluid is now traveling faster than the tank, which is analogous to the counterclockwise (cyclonic) motion seen around low pressure systems. In the atmosphere, the circulation around low pressure systems is formed by regional temperature variations; in the tank this is formed by mechanically changing the rate of rotation. At the bottom of the tank, the interaction of friction and Coriolis forces drives the fluid inward, similarly to what occurs in atmospheric low pressure systems. At the center, the fluid has nowhere to go, but up.



(a) Before slowdown; initial locations of the salty dye.



(b) After slowdown; shows rotational and convergent component near the surface.

Theory (Advanced)

In this experiment, we produce horizontal fluid convergence in the boundary layer below a cyclonic vortex. Above the atmospheric boundary layer, cyclonic vortices rotate counterclockwise in the Northern Hemisphere because they are in "geostrophic balance," which is where the pressure gradient force exactly balances the Coriolis force. Here we produce a counterclockwise rotating vortex mechanically by slowing down the counterclockwise rotation rate of the motor. In other words, the water in the tank has not yet adjusted to the new, slower rotation rate. In the boundary layer of the tank, the key force balance is given by the following equation, $2\vec{\Omega} \times \vec{U} = (1/\rho)\partial_z \vec{\tau}$, where $\vec{\Omega}$ is the vector rotation rate, $\vec{U}$ is the fluid velocity, ρ is the density, and $\vec{\tau}$ is the surface wind stress.

Discussion Questions: Can you see how thick the boundary layer is in the experiment? What would happen if we used a more viscous fluid (like a water-corn syrup mixture) in place of water? If you put chia seeds in your tank, where do they go?

† A cyclonic vortex is a low-pressure system rotating counterclockwise (N. Hemisphere).

⋆ The boundary layer is the fluid layer closest to the bottom surface where it "feels" friction.

Example video: `https://www.youtube.com/watch?v=ZdFOFROqVSO`