A Tabletop Demonstration of Atmospheric Dynamics

Baroclinic Instability

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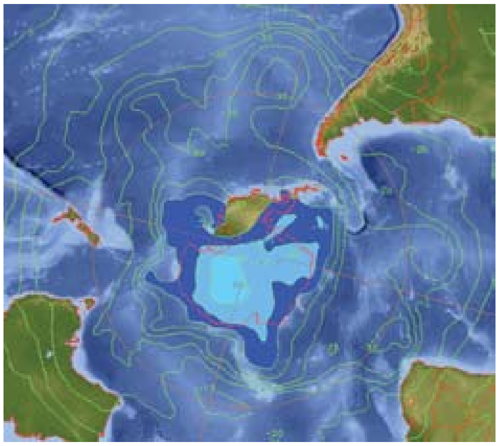
PURPOSE OF ACTIVITY

Here we study a fundamental instability mechanism of the atmosphere that affects us very directly in terms of mid-latitude winter weather. We provide a hands-on demonstration of this instability using a setup that can be put together at home and at minimal cost. Increased sophistication that can be achieved with institutional support will aid in further quantitative analysis, but the fundamental appreciation of the phenomenon is well achieved in the simple setup described here.

Students learn how a combination of rotation and buoyancy (density contrasts) underlies this instability mechanism. We naturally anticipate that when a dam breaks, gravity causes the water to flow outward. Students will learn how this behavior fundamentally changes when the system is rotating sufficiently fast. The experiment also serves as an accessible introduction to large-scale dynamics in the atmosphere.

a



b

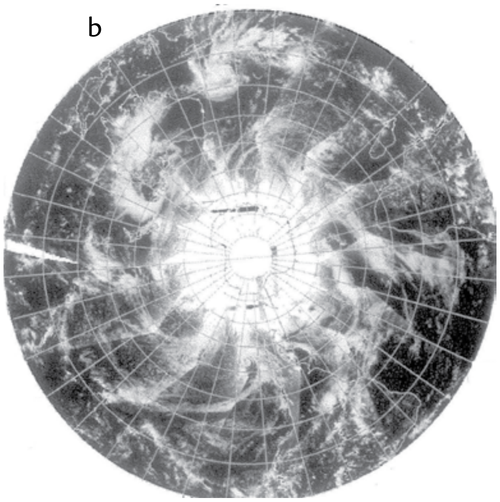


Figure 1. (a) The distribution of temperature in the southern-hemisphere atmosphere in winter at midlevel in the troposphere (temperature in degrees Celsius on the 500 millibar pressure surface at 1200 GMT on 25 August 2008; map from http://www.atmo.arizona.edu). A cold air mass is shown in blue and light blue, centered over Antarctica. The surrounding temperature field is shown via light green line contours. Because of rotation, the cold Antarctic air mass does not simply respond to gravity by settling and flowing outwards and below warmer lower latitude air . Instead, rotational effects give rise to an azimuthal "thermal wind flow" that circulates around the cold air mass. The thermal wind can, however, become unstable and develop meanders (visible in green line contours). (b) NASA image showing tropospheric clouds over Antarctica that trace out a pattern of meanders that are qualitatively similar to those in panel a.

AUDIENCE

This activity can be conducted with groups ranging from middle-school science classes through graduate classes in fluid dynamics. Components of this laboratory exercise have been used in undergraduate and graduate classes on geophysics and fluid dynamics at the University of New Mexico, Albuquerque, the University of California, Los Angeles, and the Los Alamos Summer School.

BACKGROUND

In Earth's atmosphere, a cold dome of air forms over the pole in winter (Figure 1a). Because cold air is denser than warm air, this relatively dense polar cap of air might be expected to settle, under the force of gravity, and spread radially outwards to lower latitudes (e.g., Figure 2). However, because of Earth's rotation, this does not occur (Figure 3).

Instead, a Coriolis force deflects flow to the right of its intended path in the northern hemisphere: $\vec{F}_{Coriolis} = -2\vec{\Omega} \times \vec{u}$, where $\vec{\Omega}$ is the planet's angular rotational velocity vector and $\vec{u}$ is the fluid's velocity vector (Holton, 1992). Thus, when a mass of fluid attempts to settle, the Coriolis force deflects the flow (Figure 3b), that is, the Coriolis force effectively opposes the gravitational settling force. Cold, dense fluid attempting to spread outwards at the base of a cold air mass is deflected clockwise, whereas warmer air attempting to converge toward the rotation axis is deflected counterclockwise. Such a vertically sheared atmospheric flow that circulates around the edge of the dense polar air mass is called a "thermal wind" (Holton, 1992; Cushman-Roisin, 1994; Vallis, 2006). The Coriolis force associated with the thermal wind largely balances the gravitational settling force and thus prevents the dense column of air from settling, in contrast to the nonrotating case (compare Figures 3 and 1a with Figure 2).

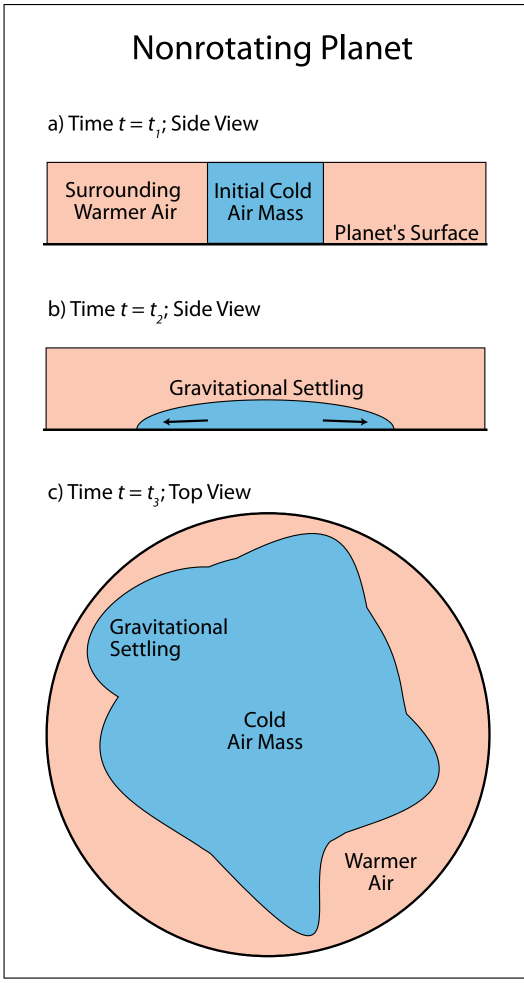


Figure 2. Sideview schematics of the settling of an atmospheric dome of cold air on a nonrotating planet. Time increases down the page such that $t_1 < t_2 < t_3$. For reasons of simplicity, the boundary of the cold air mass is shown to be smooth. In reality, the boundary tends to be highly corrugated and contorted and the associated flow turbulent.

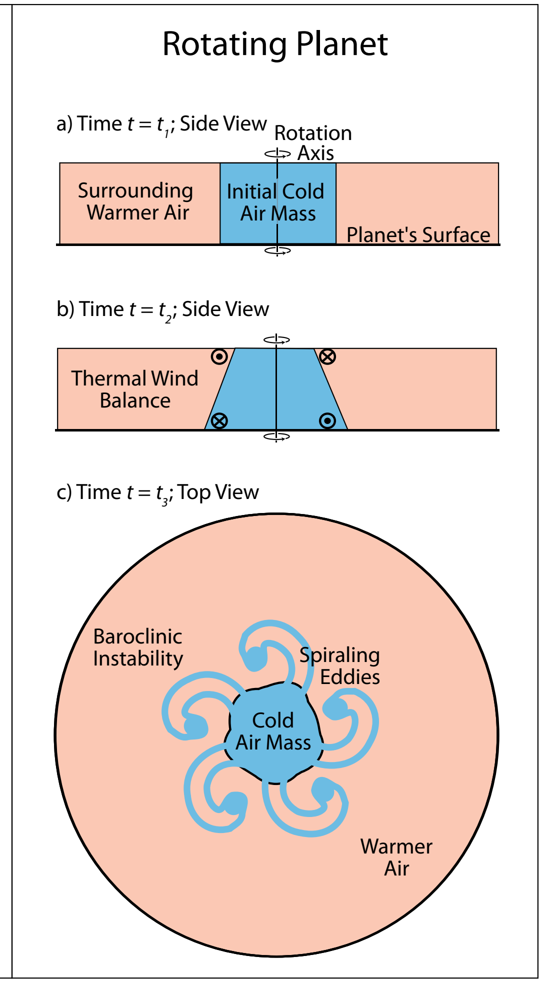


Figure 3. Schematics of the settling of an atmospheric dome of cold air on a rapidly rotating planet. The cold air mass does not spread out indefinitely, as in Figure 2. Instead, a "thermal wind" flow develops that is able to support the air mass (b). This thermal wind is not stable. It breaks apart via a process called baroclinic instability (c). Time increases down the page such that $t_1 < t_2 < t_3$.

The denser the polar air mass, the higher the thermal wind speeds must be in order to generate a sufficiently strong Coriolis force to balance the greater gravitational settling force. For sufficiently dense air masses, the thermal wind can become "unstable"—that is, minor perturbations to the system can grow with time and consequently lead to major changes—through a

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process called baroclinic[1] instability (Figures 3 and 1a; e.g., see Holton, 1992; Cushman-Roisin, 1994; Vallis, 2006). This complex process produces a number of large-scale spiraling eddy structures that tend to propagate away from the poles and toward lower latitudes. In so doing, and with the addition of moist physics (physics of water vapor), they produce strong winter storm events such as snowstorms and blizzards. These eddies serve to horizontally mix up the cold dome of air over the pole (e.g., Figure 3b), which in effect transports heat poleward and makes the higher latitudes warmer.

In this baroclinic instability process, part of the gravitational potential energy stored in the dome of cold polar air is converted to kinetic energy in the form of the eddies. The kinetic energy of these eddies is eventually dissipated, allowing the system to settle down to a state of lower energy (Valllis, 2006). Interestingly, the kinetic energy of the eddies is felt in the form of strong winds and gusts that accompany the wintertime storm systems. In summary, while heavier air sinks without much fanfare in a nonrotating system, the process of equilibration is far more dramatic in a rotating system.[2]

Baroclinic instability is also an important dynamical process in the atmospheres of the giant planets and in Earth's ocean. For example, intense wintertime storms can cool localized regions of the ocean surface. These cooling events produce regions of locally cold, dense ocean water. These localized regions of dense ocean water tend to break apart via baroclinic instability processes, which disperse the cold fluid around the ocean basin in the form of baroclinic eddies (Marshall et al., 1998; Vallis, 2006; Marshall and Plumb, 2007). In other settings relevant to the ocean, wind-driven gyres in ocean basins give rise to western boundary currents such as the Gulf Stream and the Kuroshio current. These western boundary currents and their extensions are active sites of baroclinic instability as well (Vallis, 2006). It has also been proposed that atmospheric baroclinic instabilities release energy that drives the powerful zonal jets observed on the giant planets (Ingersoll, 1990).

Figure 4. Photograph of the experimental setup. A vinyl record player is used as the rotating table. The planter, with a hole cut in its bottom, accommodates the spindle of the record player and is centered by hand along the axis of rotation. The shallow pan is then hand centered on the planter. Water is used in the shallow pan as the working fluid.

RESEARCH QUESTIONS

1. How is the settling of a colder fluid different in a rotating system compared to that in a nonrotating system?
2. How are these differences dependent on (1) the rotation rate, (2) the rotation direction, (3) the location of the cold mass of fluid, and (4) the temperature difference between the cold fluid and the surrounding warmer fluid?
3. In rotating experiments, is the thermal wind observable? Does it qualitatively agree with the flow shown in Figure 3b? How does the thermal wind change if the rotation rate of the system is increased, decreased, or reversed?
4. In comparison to nonrotating systems, does rotation tend to inhibit or enhance mixing?

MATERIALS

1. A vinyl record player (see Figure 4)
2. A plastic planter
3. Two wide, flat-bottomed, shallow circular pans (e.g., found at grocery or kitchen-accessory stores)
4. A piece of rigid, transparent acrylic sheet that can be placed over the shallow pan as a cover (e.g., found at home-improvement stores)
5. Food coloring
6. Water
7. Two small dead weights, such as 3/8-inch steel hex nuts
8. Two small paper cups (3 oz)
9. Wood shavings, talc, or used tea leaves
10. Access to a freezer
11. A still or video camera

[1] A flow is termed baroclinic if surfaces of constant density are inclined (clinic: turned) with respect to surfaces of constant pressure (baro).

[2] For reasons of simplicity and in order to focus attention on the process of baroclinic instability, we eschew considerations of turbulence here. While such considerations of turbulence can be explored in the present setup, they are best studied separately.

ACTIVITY

Experiment 1: The Nonrotating Case

1. Freeze about 1.5 oz of water along with a small dead weight, such as a 3/8-inch hex nut, and some dark food coloring in each of the two 3-oz paper cups. Because ice floats on water, the dead weight is included to make the ice block sink and stay put at a particular location in the container of water.
2. Place one of the flat-bottomed, wide, shallow containers on the tabletop. Add room-temperature water to about 4-cm (~ 1.5-in) depth and allow five minutes for random motions to die out. Place one of the cylindrical weighted blocks of colored ice in the center of the container.
3. Completely cover the top of the container with a clear sheet of acrylic, which isolates the fluid layer from air currents in the room.
4. The ice block begins to melt because of the warmer surrounding water in the container. The latent heat required to melt the ice is extracted from the water immediately surrounding the ice, which cools the surrounding water. This is the experimental analog of the cold, dense air mass that forms in the polar atmosphere in wintertime.
5. The cold annulus of water surrounding the ice block gives rise to a large-scale flow, which is easily visualized by the food coloring that leaks out of the ice block into the surrounding water. Without rotation, the cold, dyed water forms a gravity current that spreads radially outwards from the ice block. An example of such a flow is shown in Figure 5a.
6. Observe the spreading pattern of the dyed water. Have the students take still images and videos. Also have them use their time-keeping devices (wristwatches, cell phones) to determine how long it takes for the dyed water to spread to the edge of the container. Variations include introducing the dye into the ambient water in the center of the container just before placing the ice block in the water. (This was done in Figure 5a.)

Experiment 2: The Rotating Case

7. Assemble the rotating tray setup shown in Figure 4. Drill or cut out a hole in the center of the bottom of the plastic planter. By hand, center the hole on the spindle of the vinyl record player. Hand center the second flat-bottomed, wide circular pan on the open top of the planter. Add room-temperature water to about 4-cm (~ 1.5-inc) depth. Place the acrylic sheet atop the circular pan in order to enclose it.
8. Set the record player on its slowest possible setting (typically 16 or 33 rpm). The water in the container will spin up to the rotation rate of the container in approximately 10 to 15 minutes.
9. Once the water has spun up, carefully remove the acrylic sheet cover while the record player continues to spin. Place the cylindrical weighted block of colored ice in the center of the wide circular pan. Replace the acrylic sheet cover.
10. Similar to the nonrotating experiment, an annulus of cold fluid forms around the ice block. However, in the rotating

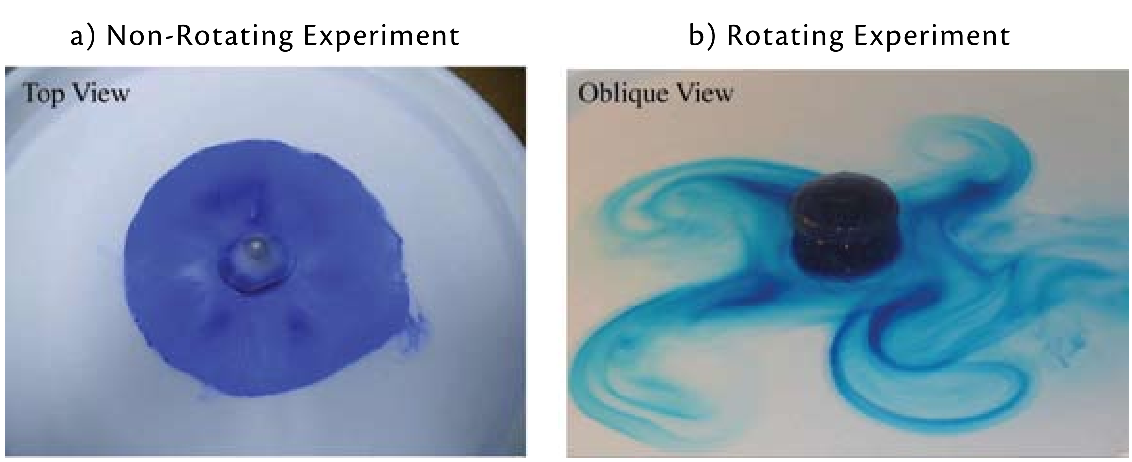

Figure 5. Photographic images of visualization of the flow in (a) the nonrotating experiment and (b) the rotating experiment when the rotation is at 16 revolutions per minute. The blue dye helps visualize the flow of the cold water. In the nonrotating case, the cold water flows outwards but otherwise exhibits little structure. In the presence of rotation, the process of baroclinic instability gives rise to the distinctive multiple spiral-arm structure.

case, the cold annulus of water gives rise to a large-scale flow that circulates around the ice block. Sprinkling small buoyant particles, such as talc or pencil shavings, on the surface of the water allows the students to visualize and measure the speed and direction of this flow. In the atmospheric context, this large-scale flow is qualitatively analogous to the polar jet stream that is familiar in mid-latitude winter weather forecasts.

11. If students wish to estimate the thermal wind at the bottom of the tank, used tea leaves can work rather well, and a co-rotating video camera will simplify such measurements. (See Figure 7.13 in Marshall and Plumb, 2007, for an alternative method.)
12. After a few minutes, the thermal wind flow becomes *baroclinically unstable*: a number of dyed spiral arms extend outwards from the annular region surrounding the ice block. Figure 5b shows a snapshot of such a growing baroclinic instability. For the conditions of the experiment, five spirals develop around the periphery of the ice block. Careful observation of the spiraling structures from different angles should convince the students that the instability and the resulting spiral structures serve to carry the cold annulus of water outward and below the warmer, ambient water.
13. Have the students take still images and video. Using their time-keeping devices, have students measure the time it takes for baroclinic eddies to transport dyed fluid to the edge of the container. How does this time compare with the time taken for the colored liquid to arrive at the edge of the container in the nonrotating case? Also have students compare the extent of mixing of the colored fluid at fixed times in the rotating and nonrotating cases. It will be observed that the extent of mixing is significantly less in the rotating experiment. Thus, rotation typically acts to inhibit mixing processes in fluid systems.

GENERAL COMMENTS

1. Assuming the ice blocks have been frozen and the rotating tank has been set up prior to class, this activity can be carried out over the course of one lab period (1–2 hours).
2. This activity allows students to investigate qualitative aspects of the baroclinic instability process in hands-on experiments. Similar "desktop" experiments can now be performed on computers as well. In such cases, the physics of the system is represented by an appropriate set of equations that are solved on a computer. The advantage of performing such studies on a computer is the ease and relatively low cost with which various measurements can be made.
3. The food coloring used in these experiments helped us visualize the flow. In other words, if there were no food coloring, the flow would be very similar, but we would not be able to *see* it. Methods such as this are called "flow visualization techniques" and are common in fluid dynamics experiments. Such techniques, however, do not allow for accurate measurements of the flow itself. That requires more sophisticated experimental techniques, such as particle image velocimetry (e.g., Adrian, 1991). In this technique, the fluid is seeded with particles that move with the flow while minimally disturbing it. These particles are then tracked across a sequence of images to obtain an estimate of the velocity field.
4. For images and movies of polar weather patterns, have students visit the GOES Web site (http://goes.gsfc.nasa.gov). Compare these images and movies of Earth's atmosphere to those acquired in the rotating experiments. Related experiments, along with a more detailed theoretical treatment ideal for undergraduates, are described in Chapters 7 and 8 of Marshall and Plumb (2007).

POSSIBLE MODIFICATIONS

1. Further experiments can reveal more about thermal wind and baroclinic instability. For instance, other experiments can be carried out using different rotation rates of the record player. Changing the rotation rate will alter the speed of the thermal wind flow as well as the number of spiral arms that form during baroclinic instability. (See Chapters 7 and 8 in Marshall and Plumb [2007] for theoretical background.) In particular, professional DJ turntables, such as the Stanton T120 (about $350), have sliding pitch controllers that allow significant variations in the turntable's rotation rate, from roughly 16 rpm to 120 rpm. In addition, these turntables can reverse their direction of rotation, which will flip the direction of the thermal wind as well as the direction of the spiraling arms.
2. One of the best perspectives for viewing the fluid dynamics is from within the rotating frame. Ideally, one would record movies with a camera situated on the record player. A cost-effective way to do this is via a wireless security camera. In classes at UCLA, Swann MicroCam models III and IV (costing about $100) have been used with good results.

Students gain more information and intuitive comprehension of the system by viewing from within the rotating reference frame as well as from a stationary viewpoint.

3. Lastly, instructors can make other modifications to generate the density contrast achieved here by the melting of ice (e.g., see Marshall and Plumb, 2007). For instance, placing a (waterproof) heater at the base of the fluid layer can generate warm, low-density fluid, which will also generate a thermal wind that can become baroclinically unstable.

WRAP-UP

Our first experiment explored how fluids of differing temperatures (and, therefore, densities) mix within a nonrotating system. This served as a control for our next experiment—an experiment in which a single controlling variable was altered; differences in the outcomes of such a pair of experiments are attributable to the variable that was altered. In the second experiment, we introduced rotation and obtained dramatically different results, suggesting that rotation fundamentally alters how fluids of differing temperatures mix.

In the nonrotating experiment, the cold, dyed fluid sank and then spread laterally across the bottom of the tank. In the rotating system, the flow circulated around the ice block. This is an example of the so-called thermal wind, which is characteristic of extra-tropical atmospheric flows. This flow eventually broke apart into a number of spiraling arms through the process of baroclinic instability, as it does in the atmosphere when the thermal wind is strong enough. In Earth's atmosphere, additional physics can result in further development of these arms into winter storms that can eventually break off and migrate to lower latitudes.

Finally, inexpensive, tabletop experiments such as these demonstrate to students that fundamental characteristics of a system as large and complex as the atmosphere can be reproduced and studied rather easily.

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ADDITIONAL ONLINE RESOURCES

http://goes.gsfc.nasa.gov/
http://spinlab.ess.ucla.edu/movies.html
http://web.mit.edu/fluids/www/Shapiro/ncfmf.html
http://www-paoc.mit.edu/labweb