EAPS 53600: Introduction to the General Circulation of the Atmosphere
Lab 2: Geostrophic Adjustment
13 Feb 2020

In this lab, you will learn:

- How a fluid at rest responds to an imposed horizontal density gradient
- How background rotation affects this response – i.e. "**geostrophic adjustment**"

For each experiment, you will first make a prediction about what you think will happen. Then after the experiment you will answer questions describing what happens. Your prediction will not be graded, so don't worry about being wrong.

Please answer your lab questions on separate paper.

You will split into groups. Since we have only a single rotating table, all groups will have to work together, but each section of the lab will be led by a different group.

Notes:

- **Talk with each other and share with each other what you think will happen. Group work is highly encouraged in this lab!**
- **If you are unsatisfied with the outcome of an experiment you are encouraged to repeat it, as well as to try other experiments if interested. The tank + materials will remain available.**
- **For the lab report**
    - **You are welcome to work together just as you did for the lab itself -- including sharing photos, discussing calculations, ideas, etc. Obviously its hard for 10 people to all take the same photo from the same spot, so those types of materials should be shared with everyone. If there are any issues on this front let me know.**
    - **Be as detailed and quantitative as possible, particularly when it comes to calculations. For example, if you are estimating a slope, you should be very clear how you arrived at the value and show the evidence for this value from the experiment itself if possible (e.g. a photo with annotation). Your report should be *reproducible* -- i.e. if you handed the report to someone they should be able to go back and redo all of your methodological steps and calculations based on what you wrote.**

Materials list

Rotating tank with full external water tank
Level
Vaseline (small tub)
~3” diameter open metal cylinder (i.e. bottom cut out)
Small bucket/cylinder (to store high-density fluid)
Stirring device (to mix in salt)
1 metric scale
Salt (2 cups)
Measuring tape
Fluid pump + tube
Calculator
Visualization materials:

- In situ:
    - Two colors of dye
    - Potassium permanganate crystals
    - Paper dots
- Remote sensing:
    - Your smart phone (for pictures/video)

Introduction

The transition from warm equatorial air to cold polar air is not gradual, but occurs rather abruptly in mid-latitudes where tropical and polar air masses meet at the **polar front**, collocated with the mid-latitude jet stream (Fig. 1). Everyday weather is often associated with undulations of this frontal surface.

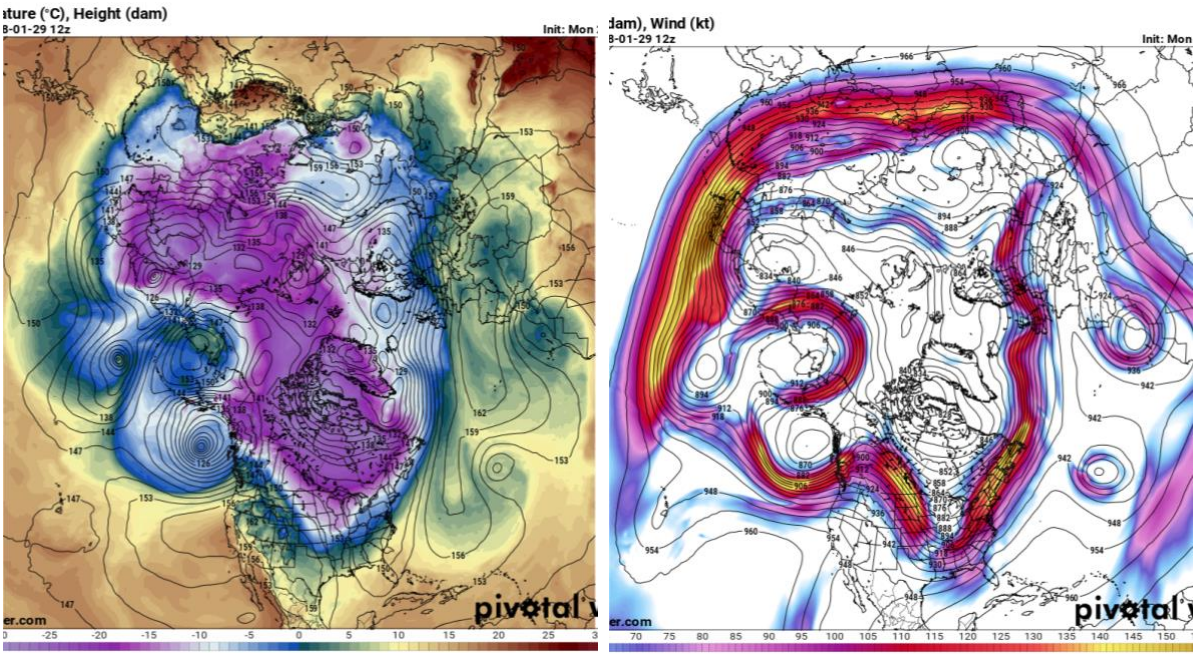


Figure 1. Northern hemisphere (left) 500 hPa temperature (color, [$_o$C]) and height (contour, [dam]), and (right) 300 hPa wind speed (color, [kt]) and height (contour, [dam]) on January 29 2018 12Z from the GFS model.

A conceptual diagram and an example from atmospheric data of the 3D structure of this frontal surface in the vicinity of a cold front is shown in Figure 2.

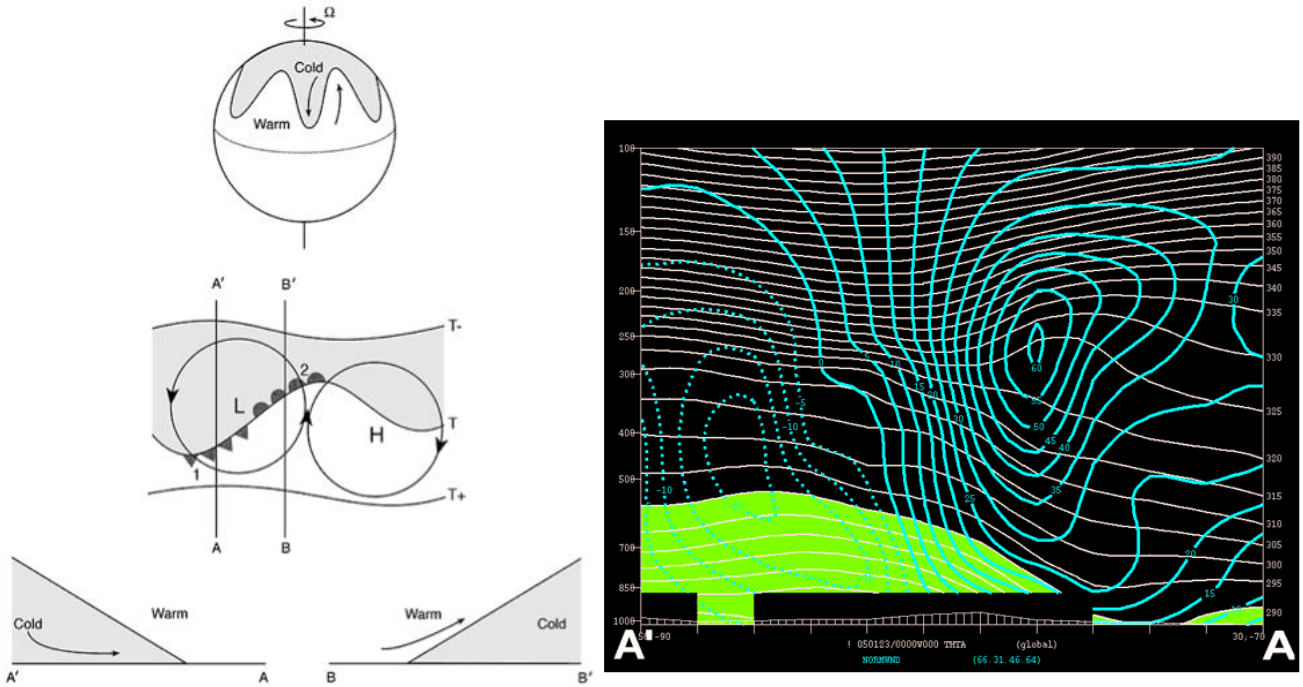
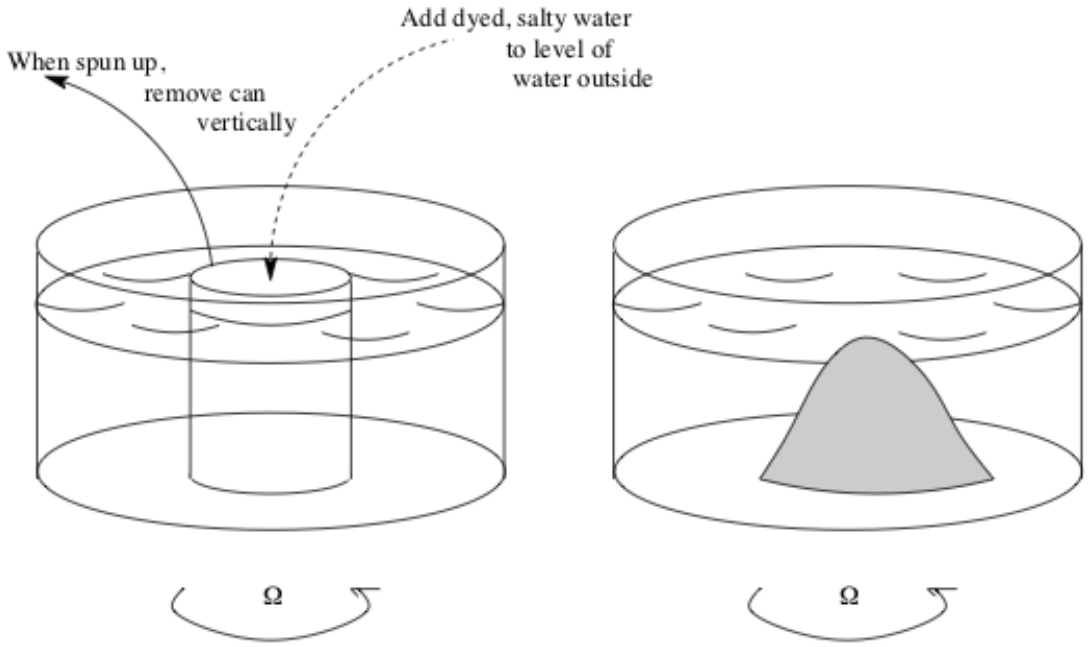


Figure 2. Left: diagram of low and high pressure systems along the polar front separating cold air (gray) and warm air, with vertical cross-section diagrams of vertically-sloped frontal surface separating high density fluid (e.g. cold air) from low density fluid (e.g. warm air) near the surface. Right: vertical cross-section across cold front on 23 January 2005 from atmospheric data showing normal wind speed (blue contour, [m/s]) and potential temperature (white contour, [K]); green denotes dome of colder (denser) air.

Rotating tank apparatus



Tank: 16” side length.
Video screen: displays view of fluid in the co-rotating reference frame (i.e. rotating with the table). This is analogous to our view of our atmosphere on the rotating Earth.

Do not touch the table or camera mast when in motion.
The motorized wheel should be <u>disengaged</u> from the tank (by setting the acrylic block beneath the motor) at all times unless an experiment is in progress.

Experiment 1: horizontal density contrast, no rotation

Here you will examine the fluid circulation response in the presence of a horizontal density contrast and in the **absence of background rotation**. In this experiment, you will place use a cylindrical barrier to separate denser fluid at the center of the tank from lighter fluid in the rest of the tank at rest and examine how the fluid responds.

Predictions

E1.1) How do you expect the fluid to respond? Draw a diagram of a cross-section through the tank radially from the center outwards, with the center of the tank on the left. To illustrate azimuthal flow (i.e. in direction of rotation), use standard physics notation of (x) for into the page and (o) for out of the page.

E1.2) Explain why you believe the fluid will respond in this manner.

Instructions

Prepare high density fluid: **(GROUP 1)**

1. Fill small bucket with a volume of water required to fill the cylinder to a height of 10 cm water.
2. Measure mass of salt, add, and stir. Repeat until reaching saturation.
3. Add green dye – enough to give a deep green color.
4. Calculate the density of the salty water. (You may do this later if needed.)

Prepare tank: **(GROUP 2)**

5. Rub generous amounts of Vaseline along thin base of hollow cylinder
6. Place can dead center and press down for at least 10 seconds to create strong seal
7. Apply Vaseline liberally along base edge to create 100% seal – **significant leaks will require you to restart the experiment**.
8. Using the pump, add water to the tank outside of the cylindrical barrier to a height of 10 cm.
    - CAUTION: BEFORE turning on the pump, one person should hold pump tube securely in the desired position. If water is spilled onto the table, the table must be shut down and dried off and the experiment restarted.
9. Check for significant leaks (i.e. more than just a small pool) across the barrier. If one exists, the water must be removed, the tank dried, and the experiment restarted.

Experiment: **(GROUP 3)**

10. Add the denser dyed fluid at the center of the tank (same height as surrounding).
11. Once the fluid has settled (20 seconds), pull the cylindrical barrier rapidly and firmly straight upwards while causing the least disturbance possible to the fluid itself.

Visualize by eye / photos: **(ALL GROUPS)**

Questions:

E1.3) Describe the initial transient response of the fluid immediately after the barrier was removed.

E1.4) Describe the final state of the fluid (i.e. after 10 seconds). Draw diagrams (horizontal, vertical cross-section) depicting the distribution of dense vs. light fluid and any circulations that may have formed. Use standard notation for flow into the page (circle with cross inside) and out of the page (circle with dot inside) when necessary.

Experiment 2: horizontal density contrast with rotation

Now you will test the fluid circulation response in the presence of a horizontal density contrast and in the **presence of background rotation**. You will repeat Experiment 1 but with the table rotating at a rate of 15 rpm.

Predictions

E2.1) How do you expect the fluid to respond? Draw a diagram of a cross-section through the tank radially from the center outwards, with the center of the tank on the left. To illustrate azimuthal flow (i.e. in direction of rotation), use standard physics notation of (x) for into the page and (o) for out of the page.

E2.2) Explain why you believe the fluid will respond in this manner.

Instructions

Prepare high density fluid: **(GROUP 2)**

1. Fill small bucket with a volume of water required to fill the cylinder to a height of 10 cm water.
2. Measure mass of salt, add, and stir. Repeat until reaching saturation.
3. Add green dye – enough to give a deep green color.
4. Calculate the density of the salty water. (You may do this later if needed.)

Prepare tank: **(GROUP 3)**

5. Rub generous amounts of Vaseline along thin base of hollow cylinder
6. Place can dead center and press down for at least 10 seconds to create strong seal
7. Apply Vaseline liberally along base edge to create 100% seal – **significant leaks will require you to restart the experiment**.
8. Using the pump, add water to the tank outside of the cylindrical barrier to a height of 10 cm.
    a. CAUTION: BEFORE turning on the pump, one person should hold pump tube securely in the desired position. If water is spilled onto the table, the table must be shut down and dried off and the experiment restarted.
9. Check for significant leaks (i.e. more than just a small pool) across the barrier. If one exists, the water must be removed, the tank dried, and the experiment restarted.

Experiment: **(GROUP 1)**

10. Add the denser dyed fluid at the center of the tank (same height as surrounding).
11. Begin table rotation
    a. Twist silver knob to disengage transparent block and rotate transparent block from under motor – this will connect the rotating wheel to the table. **Once this is done, do not attempt to manually turn the table.**
    b. Using the gold knob, gradually (over 60 seconds) increase the rotation rate to 15 rpm (150 on the dial)
    c. Check for significant leaks. If one exists, the experiment must be restarted.
12. Wait 10 minutes for fluid to adjust towards solid body rotation.
13. Pull the cylindrical barrier rapidly and firmly straight upwards while causing the least disturbance possible to the fluid itself.

Visualize the flow: **(ALL GROUPS)**

- Take photos
- Use paper dots to visualize the surface flow.
- Use potassium permanganate to visualize the interior flow.

Measurements: **(ALL GROUPS)** *You will compare your measurements against theory in the post-lab analysis.*

- Calculate the slope, $\frac{\partial z}{\partial r}$, of the interface that emerges. (*Take a picture*.)

- Calculate the velocity of the azimuthal flow, v , (i.e. swirling flow, as seen in the co-rotating reference frame) at the top of the fluid.
- Calculate the radial distance from center that the dense fluid shifts after adjusting to steady state.

Questions:

E2.3) Describe the initial transient response of the fluid immediately after the barrier was removed.

E2.4) Describe the final state of the fluid (after 10 seconds). Draw diagrams (horizontal, vertical cross-section) depicting the distribution of dense vs. light fluid and any circulations that may have formed. Use standard notation for flow into the page (circle with cross inside) and out of the page (circle with dot inside) when necessary.

Analysis and synthesis

Note: videos of a version of Experiment 1 and a successful execution of Experiment 2 are available here:
https://www.youtube.com/watch?v=Ak9CBB1bTcc&t=62s
http://ia600207.us.archive.org/10/items/MIT12.003F02/cylinder_collapse.mp4

Questions:
A1) Do you think each experiment was conducted successfully? (see videos above if needed) Discuss any errors that may have been introduced during the execution of the experiment. If needed, take this into consideration as you answer the questions below.

A2) Compare and contrast the final state of the fluid found between the two experiments. What are the key differences associated with the inclusion of background rotation?

A3) Use the concept of angular momentum conservation to explain the variation of the flow with radius at the top of the fluid above the front observed in Experiment 2.

Thermal wind balance defines an equilibrium state in which horizontal density gradients are collocated with vertical wind shear. This state arises due to the combination of geostrophic and hydrostatic balance. In our cylindrical system, thermal wind balance is given by

$$\frac{dv}{dz} = -\frac{g}{f\rho_0}\frac{d\rho}{dr}$$

where v is the azimuthal (i.e. swirling) flow speed in the rotating reference frame, ρ is density, and f is is the Coriolis parameter for the system (i.e. 2Ω). The constants g and ρ_0 are, respectively, the gravitational acceleration and the mean density for the entire fluid.

A4) Use this equation to explain <u>conceptually</u> the relationship between changes in flow speed with height $\left(\frac{dv}{dz}\right)$ and the radial density gradient $\left(\frac{d\rho}{dr}\right)$. Is the denser fluid located to the left or the right of the wind shear (i.e. the direction of the jet)? How does this compare with the jet stream in the Northern Hemisphere on Earth?

The slope of the interface between two fluid layers in geostrophic and hydrostatic balance (i.e. thermal wind balance) is given by Margules' relation

$$\tan\gamma = \frac{f}{g'}(v_2 - v_1)$$

where f is the Coriolis parameter for the system (i.e. 2Ω), $g' = g\left(\frac{\rho_2-\rho_1}{\rho_1}\right)$ is the reduced gravity (where g is the gravitational acceleration), subscript 1 corresponds to the lighter fluid and subscript 2 corresponds to the heavier fluid (i.e. $\rho_2 > \rho_1$), and γ is the angle of the frontal surface as shown in the figure below.

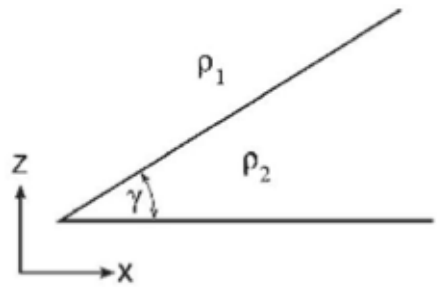


***Figure 4. Diagram for Margules' relation*.**

A5) Calculate the slope predicted by the theory above and compare the result with your measured slope. Discuss possible reasons for discrepancy.

Alternatively, this sloping interface may be thought of in terms of the distance over which the dense fluid shifts outward in the form of a gravity wave before "feeling" the effect of rotation. This length scale is called the Rossby deformation radius, given by

$$L_{Rossby} = \frac{\sqrt{g'H}}{f}$$

where g' is the reduced gravity, H is the depth of the fluid, and f is the Coriolis parameter.

A6) Calculate the Rossby deformation radius for the fluid and compare the result with your measured radial displacement. Discuss possible reasons for discrepancy.

A7) Based on your experiments and analysis above, draw diagrams depicting the outcome you would expect if you reran the experiment under the following scenarios. For each, provide a brief quantitative explanation of your reasoning.

1. **Rotation rate halved to 7.5 rpm**
2. **Rotation rate doubled to 30 rpm**
3. **Density difference doubled**
4. **Zero density difference**
5. **Fluid depth doubled**
6. **Salty water outside the cylinder, fresh (i.e. non-salty) water inside the cylinder**

A8) Compare the features you have observed in Experiment 2 with the polar front and mid-latitude jet stream in the Earth's atmosphere discussed in the Introduction of this lab.

A9) Invent one new experiment that you think would be fun to try out. 1) Propose a hypothesis, 2) Propose a set of experiments to test your hypothesis, and 3) Propose an analysis methodology to evaluate your hypothesis in your experiments.