EAPS 53600: Introduction to the General Circulation of the Atmosphere
Lab 1: General circulation of the atmosphere in a tank
23 Jan 2020

In this lab, you will learn:

- How fluid circulations respond to temperature contrasts in the presence of zero, weak, and strong background rotation
- How these circulations are directly analogous to the dominant features of the general circulation of the Earth's atmosphere

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.

Group 1: executes set up of Exp 1, executes visualization of flow in Exp 3
Group 2: executes set up of Exp 2, executes visualization of flow in Exp 1
Group 3: executes set up of Exp 3, executes visualization of flow in Exp 2

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

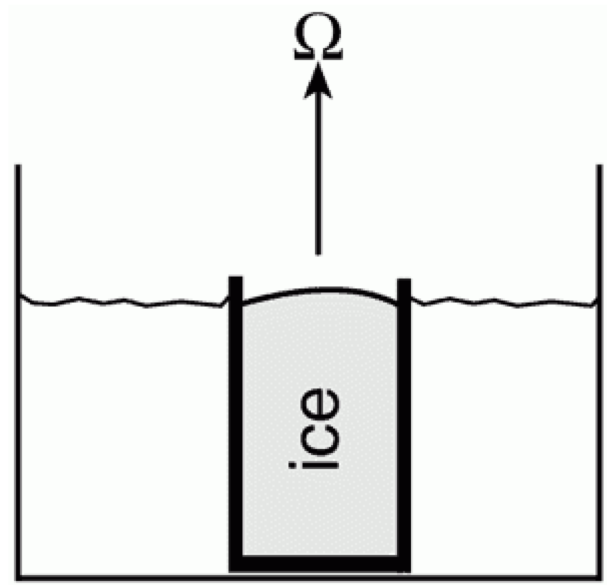
Rotating tank with full external water tank
Level
Bucket of at least 2 gallons of ice
Bucket of 1 gallon of cold water
Visualization materials:

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

Note:

- An ice maker is available in HAMP 2244 (EAPS Teaching Laboratory)
- The iPad IR camera code is 1869 (year of Purdue's founding). The app is "FLIR".

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: differential heating, no rotation

Here you will examine the fluid circulation response in the presence of a temperature gradient and in the **absence of background rotation**. In this experiment, you will place an ice-filled cylinder at the center of the fluid-filled tank at rest and examine how the fluid responds.

Hypothesis

E1.1) Propose a hypothesis for how you expect the circulation of 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 (ice) 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 circulation will respond in this manner.

Instructions

Setup:

1. Do not turn on the table's rotation.
2. Place the metal bucket with weight at the center.
3. Fill the tank with water up to the marked line.
4. Wait 5 minutes to allow fluid to settle. **Be very careful not to disturb the fluid in the tank.**
5. Add ice + cold water to the metal bucket. *Note: adding water greatly enhances the rate of heat transfer (conduction) between the warmer fluid and the cold ice in the bucket (air is a very poor heat conductor).*
6. Wait 10 minutes to allow fluid to respond to thermal forcing. **Be very careful not to disturb the fluid in the tank.**
7. Use the IR thermometer and IR camera to record the temperature difference radially across the fluid.

Notes:

- *For the visualization steps below, perform all the steps and take quick notes along the way, then answer the questions fully after all steps are complete. This will minimize the need to refill the ice and will reduce your time spent in lab.*
- *At each step, be sure to examine the fluid from above and from the side (inertial reference frame) as well as on the video screen (co-rotating reference frame).*
- *Take pictures or video using your phone!*

Visualize the temperature field using the IR camera. Note: you can take pictures/videos with the camera and save them for download later.

Visualize the flow #1: dye

- Add a few drops of red dye away from the center (warmer water) and green dye closer to the center (cooler water).

Questions:

E1.3) Describe the fluid flow as seen by the dye.

E1.4) In what direction does the fluid flow near the top? Near the bottom?

E1.5) Do the results prove or disprove your initial hypothesis?

Experiment 2: differential heating + slow rotation

Now you will test the fluid circulation response in the presence of a temperature gradient and **weak background rotation**. In this experiment, you will use ice to create a temperature gradient identical to Experiment 1, and the table will turn at a slow rotation rate (**1 rpm**).

Hypothesis

E2.1) Propose a hypothesis for how you expect the circulation of 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 (ice) 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 circulation will respond in this manner.

Instructions

Setup:

1. Set rotation to **1 rpm**. The number on the display is in units of 10 x rpm, but the minimum value it will read is 2 rpm (i.e. “20”). So you will have to determine this by hand!
2. Wait 5 minutes to let fluid adjust to solid body rotation with the tank.
3. If most/all of the ice is gone, add more ice. You may need to scoop out some of the water first. **Be very careful not to disturb the fluid in the tank, nor to hit the camera mast as it rotates.**
4. Wait 10 minutes to allow fluid to respond to thermal and dynamical forcing.
5. Use the IR thermometer and IR camera to record the temperature difference radially across the fluid.

Notes:

- *For the visualization steps below, perform all the steps and take quick notes along the way, then answer the questions fully after all steps are complete. This will minimize the need to refill the ice and will reduce your time spent in lab.*
- *At each step, be sure to examine the fluid from above and from the side (inertial reference frame) as well as on the video screen (co-rotating reference frame).*
- *Take pictures or video using your phone!*

Visualize the temperature field using the IR camera. Note: you can take pictures/videos with the camera and save them for download later.

Visualize the flow #1: potassium permanganate

- Use the metal spatula to drop in a few (~5-10) permanganate crystals at a single point halfway out from the center. This will dye the column of fluid in the vertical as well as the boundary layer at the bottom of the tank.

Questions:

E2.3) Describe the fluid flow as seen by the permanganate.

E2.4a) In what direction does the interior fluid flow?

E2.4b) How does the interior flow vary with height?

E2.4c) How does the fluid at the bottom flow?

Visualize the flow #2: paper dots

- Drop ~8 purple paper dots along a radial line from the cylinder edge to the outer edge.

Questions:

E2.5) Describe the fluid flow as seen by the paper dots in the co-rotating frame of reference.

E2.6) How does the flow at the top of the fluid vary as a function of radius?

Visualize the flow #3: dye

- Add three drops of red dye at different locations.

Questions:
E2.7) Describe the fluid flow as seen by the red dye, including any additional features not observed from the permanganate or the paper dots.

Visualize the flow: any other test you'd like to try in order to understand the flow? If so, describe 1) the purpose, and 2) the findings of your test(s).

Overall:
E2.8) Based on your tests, describe the circulation that emerged within the fluid. Draw a diagram of a cross-section through the tank radially from the center outwards, with the center of the tank (ice) 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. Does the flow appear to be smooth or turbulent?

E2.9) Which large-scale circulation in the Earth's atmosphere is this experiment analogous to? Describe the specific features in your laboratory experiment that are similar.

Experiment 3: differential heating + fast rotation

Now you will test the fluid circulation response in the presence of a temperature gradient and **strong background rotation**. This experiment is identical to Experiment 2, except the table will turn at a much faster rate (**10 rpm**).

Hypothesis

E3.1) Propose a hypothesis for how you expect the circulation of 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 (ice) 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.

E3.2) Explain why you believe the circulation will respond in this manner.

Instructions

Setup:

1. Increase rotation rate to **10 rpm**. The number on the display is in units of 10 x rpm.
2. Wait 5 minutes to let fluid adjust to solid body rotation with the tank.
3. If most/all of the ice is gone, add more ice. You may need to scoop out some of the water first. **Be very careful not to disturb the fluid in the tank, nor to hit the camera mast as it rotates.**
4. Wait 10 minutes to allow fluid to respond to thermal and dynamical forcing.
5. Use the IR thermometer and IR camera to record the temperature difference radially across the fluid.

Notes:

- *For the visualization steps below, perform all the steps and take quick notes along the way, then answer the questions fully after all steps are complete. This will minimize the need to refill the ice and will reduce your time spent in lab.*
- *At each step, be sure to examine the fluid from above and from the side (inertial reference frame) as well as on the video screen (co-rotating reference frame).*

Visualize the temperature field using the IR camera. Note: you can take pictures/videos with the camera and save them for download later.

Visualize the flow #1: paper dots

- If needed, add a few purple paper dots wherever you think would be interesting.

Questions:

E3.3) Describe the fluid flow as seen by the paper dots.

Visualize the flow #2: dye

- Add drops of dye at regular intervals around the fluid – use red dye farther out from center (warmer water) and green dye closer to the center (cooler water).

Visualize the flow: any other test you'd like to try in order to understand the flow? If so, describe 1) the purpose, and 2) the findings of your test(s). (Note the question below regarding eddy number.)

This is the final experiment, so you no longer have to worry anymore about the fluid turning too dark. This means that anyone can now try any more tests that might be of interest.

Questions:

E3.4) Describe the fluid flow as seen by the red and green dye. How are the red and green dyes each dispersing radially within the tank?

E3.5) You should observe eddies that have formed in the flow. Estimate:

- **The number of eddies there are around the circular tank – this is the *wavenumber* of the instability in the flow,**
- **The characteristic length scale (i.e. diameter) of an eddy**

Overall:
E3.6) Based on your tests, describe the circulation that emerged within the fluid. Draw a diagram of a plan (i.e. horizontal) view of the top of fluid. 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. Does the flow appear to be smooth or turbulent?

E3.7) Which large-scale circulations in the Earth's atmosphere is this experiment analogous to? Describe the specific features in your laboratory experiment that are similar.

Analysis and synthesis

Note: videos of successful execution of experiments 2 and 3 are available here:
Exp 2: http://ia600207.us.archive.org/10/items/MIT12.003F02/hadley.mp4
Exp 3: http://ia600207.us.archive.org/10/items/MIT12.003F02/eddies.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.

Experiment 2
A2) Compare and contrast the circulations found in Experiment 2 vs. Experiment 1. What are the key differences associated with the inclusion of weak background rotation?

A3a) For Experiment 2: The inclusion of background rotation imparts angular momentum to fluid parcels. Angular momentum per unit mass, M, is given by

$$\boldsymbol{M = rv}$$

where r is the radius from the axis of rotation and v is the tangential velocity. Because angular momentum is conserved in the interior flow, a parcel moving towards its axis of rotation (decreasing r) will begin to spin faster (increasing v) in order to keep M constant.

Use this concept of angular momentum to explain the variation of the flow with radius at the top of the fluid observed in your experiment. At what radius was the flow speed the fastest?

A3b) In a rotating system, horizontal temperature (density) gradients can exist at equilibrium in the presence of vertical wind shear (i.e. change in wind vector with height). This equilibrium is called Thermal Wind Balance, which in our cylindrical system is given by

$$\frac{dv}{dz} = \frac{g\alpha}{2\Omega}\frac{dT}{dr}$$

where v is the tangential flow speed in the rotating reference frame (i.e. as seen in the video screen), T is temperature, and Ω is the rotation rate. The constants g and α are, respectively, the gravitational acceleration and the thermal expansion coefficient of the fluid.

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 temperature gradient $\left(\frac{dT}{dr}\right)$. Is the warmer 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?

A3c) This experiment is analogous to the tropical Hadley cell in the Earth's atmosphere. Compare the circulation features you have observed in this experiment with the Hadley cell's zonal flow and meridional overturning.

<u>Experiment 3</u>

A4) Compare and contrast the circulations found in Experiment 3 vs. Experiment 2. What are the key differences associated with the increase in rotation rate?

A5a) For Experiment 3: The increase in background rotation causes the jet circulation around the tank to become unstable and breakdown into *eddies*; this breakdown is called *baroclinic instability*. "Baroclinic" simply refers to the existence of horizontal density gradients across the fluid.

Use this concept to explain the nature of the flow field observed in your experiment.

A5b) The length scale of an eddy follows the *Rossby deformation radius*. This length scale decreases with increasing rotation rate and increases with horizontal temperature contrast, i.e.

$$L_{eddy} \sim \frac{\Delta T}{\Omega}$$

What do you think would happen to the size of the eddies if you could do experiments with rotation rates over a range of values in between those of Experiment 2 and 3?

A5c) Energetically, these circulations develop within the fluid simply because the fluid is trying to reduce the horizontal temperature contrasts. Doing so requires transporting heat from warmer regions to cooler regions. On Earth, both the Hadley cell and the eddies try to

achieve this goal by transporting warmer air poleward and colder air equatorward. However, they do so in very different ways.

Based on your experiments, describe the nature of heat transport in the weak rotation cases (Exp 1 and 2) as well as in the strong rotation case (Exp 3). Where in the fluid are the warmer and cooler water being transported in each case?

A6) 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.