Hadley Cells in a Rotating Differentially Heated Annulus

Introduction

The thermally driven rotating annulus has been used in many different experiments, I will be using it to try and simulate atmospheric circulation due to differential heating from the equator to polls and observing how the rotation and thus Coriolis force affects it.

Thermal imbalance on the earth stems from the fact that the earth is a sphere that is incident on what is essentially a plane of incoming radiation. This means that the higher in latitude you are on the earth the less concentrated the incoming radiation is, thus the equator and lower latitudes experience higher solar radiation than the polls. Further, the outgoing longwave radiation from the earth is more equally distributed meridionally leading to an even larger difference between the equator and polls. This disequilibrium would lead you to believe that energy would be transported to higher latitude by large convective motion. George Hadley theorized that a single large thermal circulation cell would rise at the equator and transport warm air to the poles at altitude where it would cool and descend to return to the equator along the surface. This is not what happens in our atmosphere. The circulation that Hadley envisioned only reached to approximately 30 degrees before it cools and descends. This is due to the Coriolis force as well as that a single circulation cell from equator to pole would be baroclinically unstable. The development of midlatitude cyclones and anti-cyclones provide transport of heat through a horizontal circulation. These weather systems are strong enough to reverse the meridional circulation in the vertical plane causing the formation of indirect cells called Ferrel cells.

Another consequence of a meridional temperature gradient is the development of vertical wind shear or thermal wind. This is where the zonal wind increases with altitude and is responsible for the easterlies near the equator.

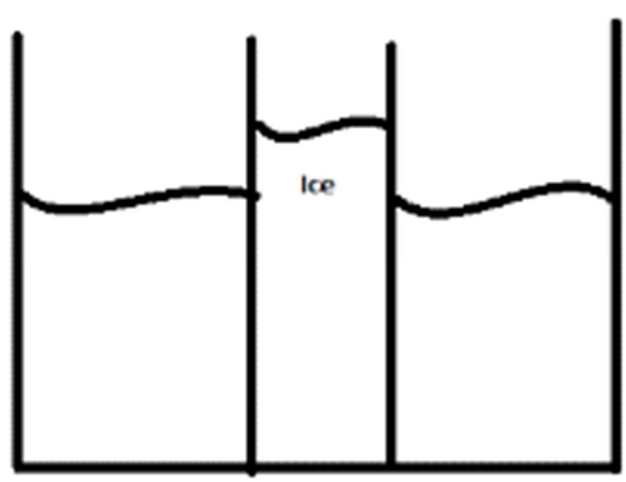
One of the issues faced in climate science is that we cannot reproduce global phenomenon on a one to one scale. This experiment will allow for a better understanding of how the large-scale processes in the atmosphere can be simulated in a simple lab environment. The simplicity of the setup will also shed some light on what variables can or cannot be omitted when considering the reproduction of global circulation using a much smaller model.

While this experiment has been done before, many of the more current papers are investigating more complex phenomena (Read and Young, 2015; Randriamampianina and Crespo del Arco, 2015), I am trying to provide a simple yet still accurate method in which to observe large-scale atmospheric circulations. This was originally done by Hide (1958), I will be trying to reproduce the results using a more simplified setup other than the video camera. An experiment by Scoland and Read (2017) provided a more accurate heating and cooling profile for the atmosphere to help simulation vigorous convection about at the upwelling and downwelling location but this small addition would be beyond the scope of my experiment but can still be considered.

The main parameter controlled during this experiment was the rotation rate of the tank. The temperature difference between the centre and the outside of tank were recorded but were not varied. I expected a single Hadley cell to be produce at a slow enough ration rate and as I increased the rotation rate for the Hadley cell and thermal wind to become baroclinically unstable. This should cause eddies to form in the midlatitudes equivalent of the tank. Higher rotation rates would also be tried to try and develop further convection cells in the tank.

Procedure:

A rotating table with a tank of 56cm diameter was used to observe the flow at rest and at different ration speeds with radial thermal forcing. A tin can of 15.5cm diameter was placed in the center of the cylindrical tank and filled with ice water and some lead. The tank was then filled with water from the tap to a depth of 15cm. Two temperature probes were place in the tank, one close to the tin can in the centre and one by the outer edge of the tank, at a depth of about 5 cm from the bottom of the tank. The tank was then put in motion at whichever angular speed was being observed and let to sit for about 20 minutes to achieve solid body rotation and a stable circulation. Once solid body rotation was achieved ink and dye were used to observe what circulation patterns had developed and the size of these patterns. These were observed for no more than 10 minutes and the water was changed between each experiment.



Conditions will be observed at rest initially and dye will be used to observe the movement of a parcel of water, in this initial set up I will expect that a large convective circulation cell will develop due to the differential heating causing a density gradient within the fluid. Next, I will observe the circulation while rotating the table at low rate, I don't expect this to affect the flow significantly as I don't think the Coriolis force will be strong enough to cause enough zonal flow to break the thermally driven circulation. I will continue to increase rotation rate of the tank until the large thermal circulation cell is broken and hopefully an indirect cell will develop. I am hoping to find an equilibrium that will allow for three circulation cells, two direct and one indirect, as is observed on earth in the atmosphere but due to the size restrictions of the tank this may not be possible.

Results:

The very first run was done at a speed of 5rpm with a water depth of 5cm. This was done mainly as a proof of concept and to verify that all the equipment would work together well for other portions of the experiment. However, there was still some useful observations to be made. As seen in Figure 1, the ink that was place at the centre of the tank has begun to move radially towards the outside of the tank but has developed into an eddy which is indicative of the Coriolis force being strong enough to disrupt the flow even at this lower rotation rate.

The second run was done at 18rpm and with a depth of 15cm of water. This was to verify that the eddy observed preciously was indeed due to the rotation of the tank as opposed to another phenomenon. As seen in Figure 2, there is also an eddy that has developed from ink travelling away from the centre of the tank towards the outside, this eddy is much closer to the centre of tank as opposed to the previous run which correlates with the increase in rotation speed.

The third run was done at 1.15rpm and with 15 cm of water. At this speed some interesting things developed. The permanganate crystals that were placed in the tank moved radially towards the edges of the tank and did not develop into eddies as in the previous two attempts. The flow along the bottom was deflected quite strongly in a cyclonic motion initially but after some time the flow seemed to begin to deflect in an anticyclonic motion. The ink that was placed in the midlatitude equivalent moved radially towards the centre of the tank then back to the outside of the tank repeatedly as it slowly propagated in a cyclonic direction. Both flow patterns can be clearly seen in Figure 3.

The fourth run was done at 1.21rpm with 15cm of water. This lead to some very nice patterns that were observed. The permanganate that was placed in the midlatitudes moved towards the edges on the tank as expected and deflected anticyclonically as it moved radially. The ink placed in the midlatitudes started to circulate cyclonically around the tank with very little radial motion, viewed from the side it can be seen that the flow is faster near the surface and slows with depth as seen in Figure 4. Both the cyclonic motion of the ink and the radial motion of the permanganate is clearly visible in Figure 5.

The fifth run was performed at 10rpm with 15cm of water. In this run the eddies in the midlatitudes were clearly visible with ink inserted at the surface whereas the permanganate turned into a bit of a mess. Multiple eddies from several different ink blots can be seen in Figure 6.

The last run was performed at rest with 15cm of water. The permanganate moved radially outward and was not deflected at all while the ink in the midlatitudes still rotated around the centre of the tank however did so in an anticyclonic motion as seen in Figures 7 and 8.

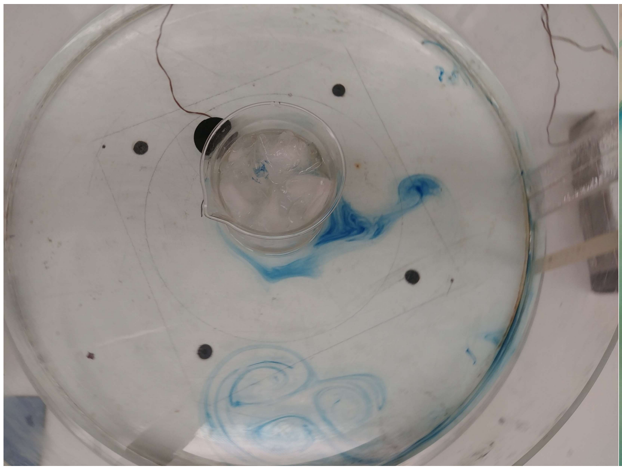


Figure 1 5rpm

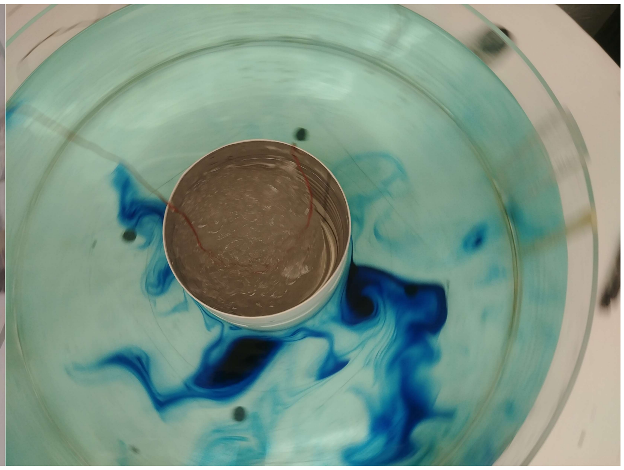


Figure 2 18rpm

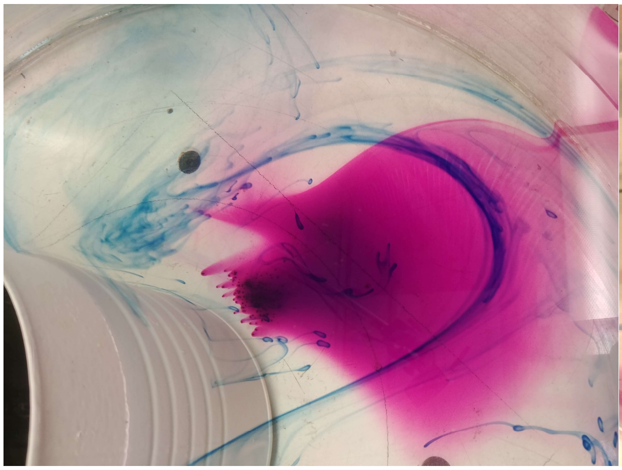


Figure 3 1.15rpm

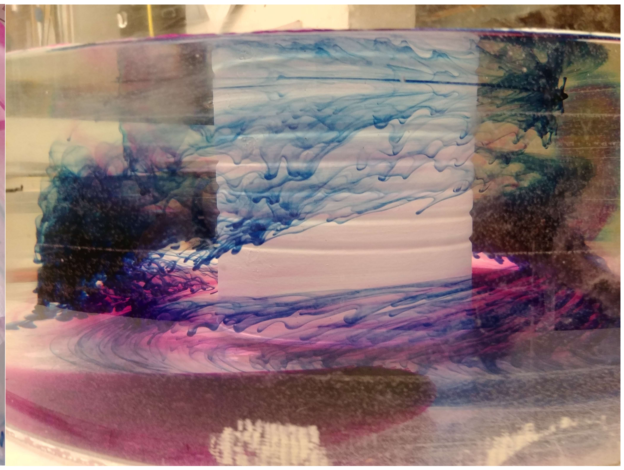


Figure 4 1.21rpm

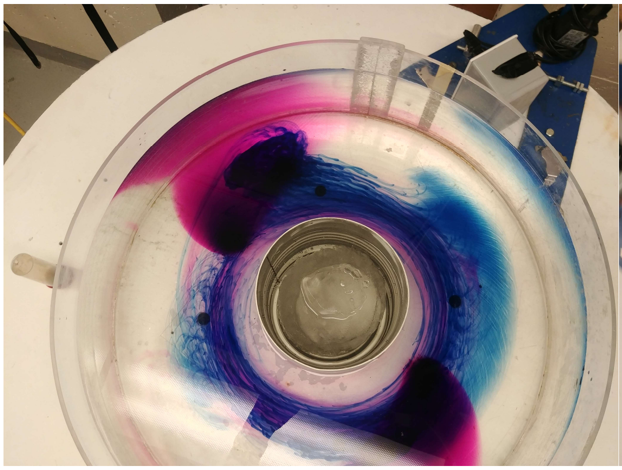


Figure 5 1.21rpm

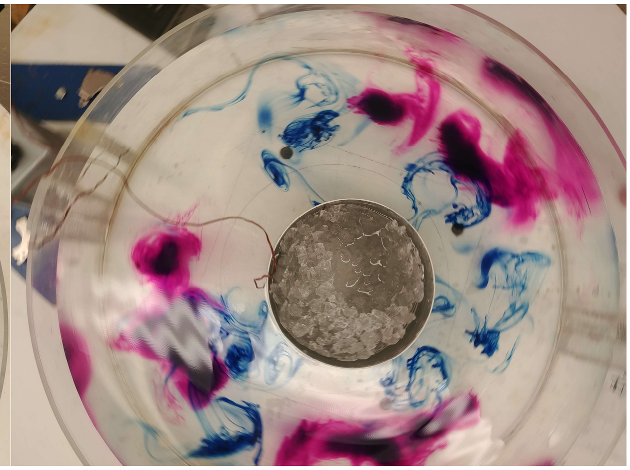


Figure 6 10rpm

Figure 7

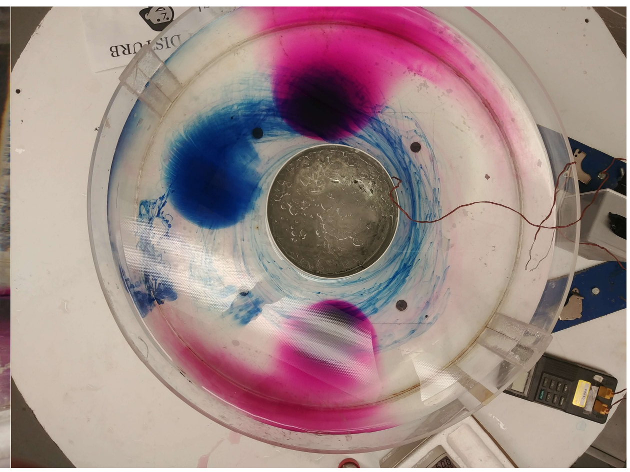


Figure 8

Discussion

The first run showed that even at 5rpm there are baroclinic instabilities and the second at 18 merely confirmed this with the eddy forming much closer to the tank than previously. This shows that at rpm higher than 5 a single circulation cell in not stable in a tank with 56cm diameter.

The third and fourth runs were done at closer rpm, 1.15 and 1.21 respectively, and gave some results that were more expected. The third and fourth runs showed the permanganate behaving as expected with no eddy forming, this suggests that the Coriolis force at this rotation speed is low enough for a single Hadley cell to be baroclinically stable. However, in the third run the ink that was place in the water behaved quite differently from the fourth run. This difference is most likely due to the placement of the ink. In the third run it was place near the center of the tank while in the fourth it was place more in the midlatitudes, this indicates that there would possibly be very different surface flow that I had not considered in the setup of this experiment. The fourth run gave a very good example of the thermal wind as the ink was sheared so much that it moved around the tank and came back on top of itself as can be seen in Figure 4. This shows that the meridional temperature gradient while only a difference of 1.5 degrees across 20cm was enough to produce quite a strong vertical wind shear.

The fifth run at 10rpm showed clearly the baroclinic instabilities in the midlatitudes due to the Coriolis force, the ink place in the centre of the water column developed into very strong eddies showing that at 10rpm the Coriolis is quite strong and has no problems making the flow unstable away from the edge of the tank.

The last run at rest gave steady flow at the bottom towards to outside which would be expected with no Coriolis force. The thermal wind was still present as would be expected as the only parameter that it relies on is the meridional temperature gradient.

The main sources of error from this lab would be the unstable temperature gradient. The observations were restricted in time due to the heat sink not being countered by anything other than the ambient room temperature and the initial temperature of the water in the thank itself. If the experiment is left too long then the water in the tank itself will become homogeneous in temperature and no longer thermally driven. To avoid this and allow processes to go on for longer the outside of the tank could be wrapped in coils of wire to heat the outside of the tank and provide a constant and variable temperature gradient. This would allow for the observation of the change in thermal wind with the change in temperature gradient. Use of a thermal camera could also be used to observe the flow of warmer and cooler water.

Conclusion

When trying to produce a single Hadley circulation cell and thermal wind in a differentially heated rotating annulus with a diameter of 56cm the rotation speed must be near to or slower than 1.2rpm. At higher rotation rates the flow will become baroclinically unstable and eddies will form in the midlatitudes of your tank. At 10 rpm the eddies are the most clearly visible with large formations spanning half the distance from the centre to the edge of the tank. At higher rpm the eddies become much smaller and more irregular.

Ref:

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