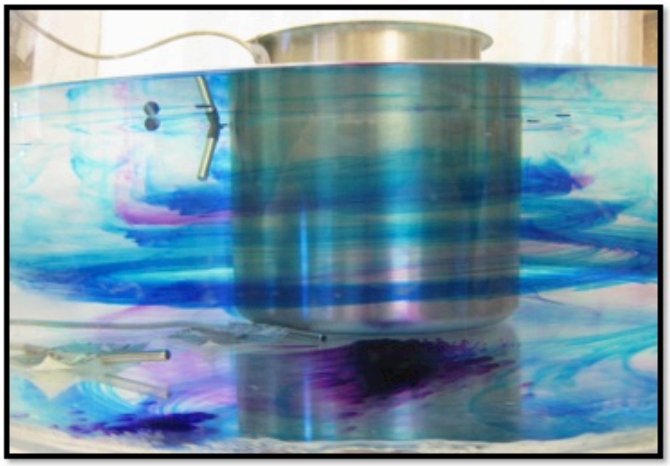
12.307

Lab 4

General Circulation

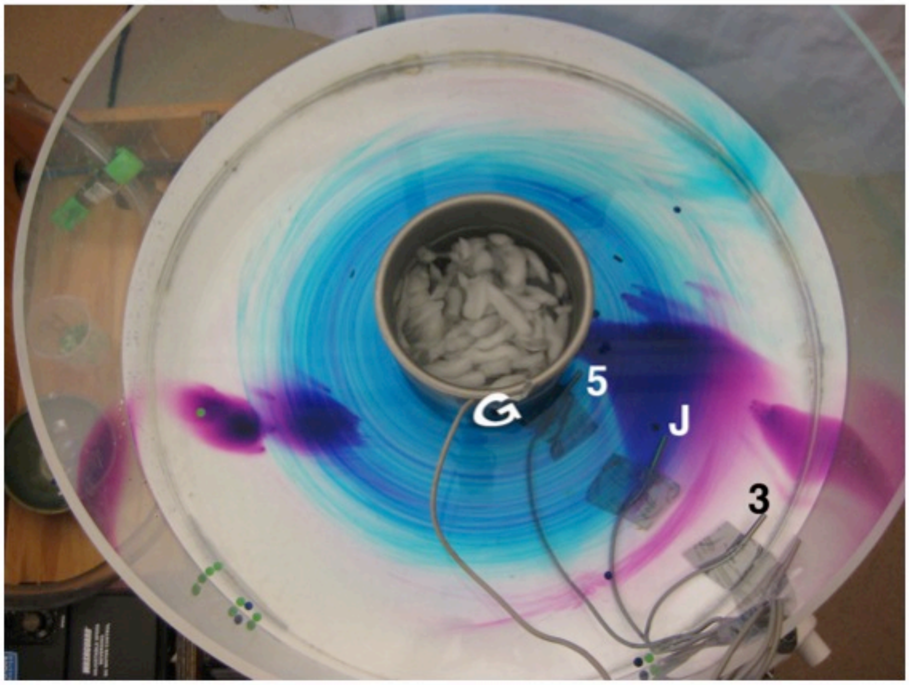


Aimee Harrison

Michelle Slosberg

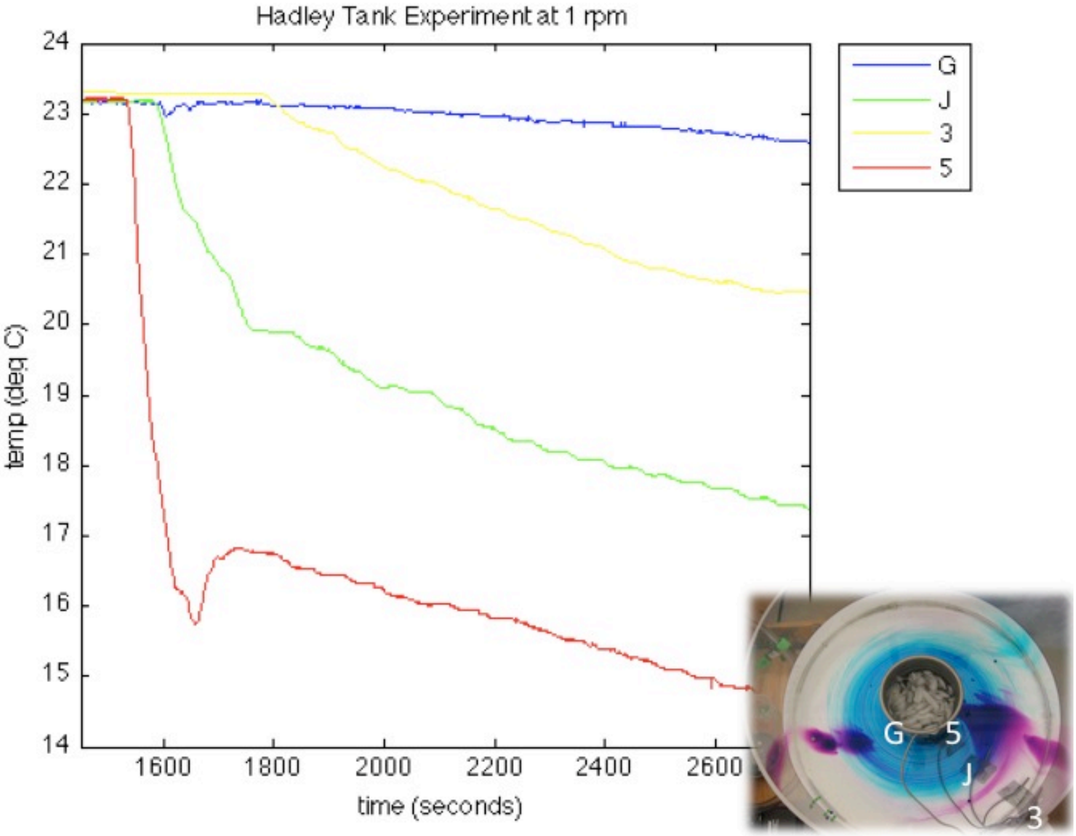
Aimee and Michelle worked on this project together but Aimee focused on the eddies section and Michelle focused on the Hadley cell section.

Hadley Cell Experiment



The first tank experiment was analogous to the Hadley cell and also showed associated thermal winds. This image shows the setup of the first experiment. The tank was filled with water and spun up to solid body rotation at 1 rpm (0.10 rad/s). Once the tank spun up the bucket in the center was filled with 1000 g of ice and water to fill in the gaps. Prior to spinning, three temperature sensors, labeled 5, J, and 3 in the image, were arrayed radially outward from the ice bucket. The fourth sensor, G, was taped near the top of the bucket. It did not touch the ice bucket but was placed near the bucket and near the surface of the water. Blue dye was injected to observe thermal wind and potassium permanganate crystals tracked motion at the bottom of the tank. Floating paper dots allowed motion at the surface to be tracked with the particle tracker.

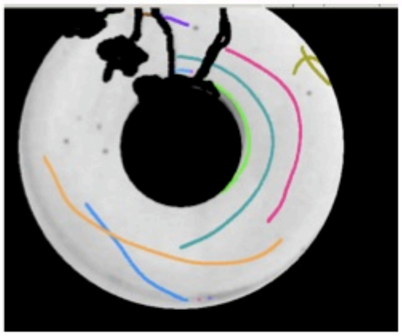
Over time a cone of cold water developed near the center of the tank, as can be seen in the introductory image.



Temperature sensor data for the Hadley Cell experiment. As predicted, temperatures decreased as distance from the ice in the center of the tank increased. The tmeperature at sensor G, which was at the top of the water near the center, remained mostly constant and relatively warm. Even though the sensor was near the ice bucket the cold plumes of water sank to the bottom before spreading to the temperature sensor. As a result the water in this region stayed at its initial temperature.

Thermal Wind

$$\frac{\partial u}{\partial z} = -\frac{g\alpha}{2\Omega}\frac{\partial T}{\partial r}$$



$\Delta z = 0.15m$

$g = 9.8m/s^2$

$\alpha = 2*10^{-4}K^{-1}$

$\Omega = 0.10rad/s$

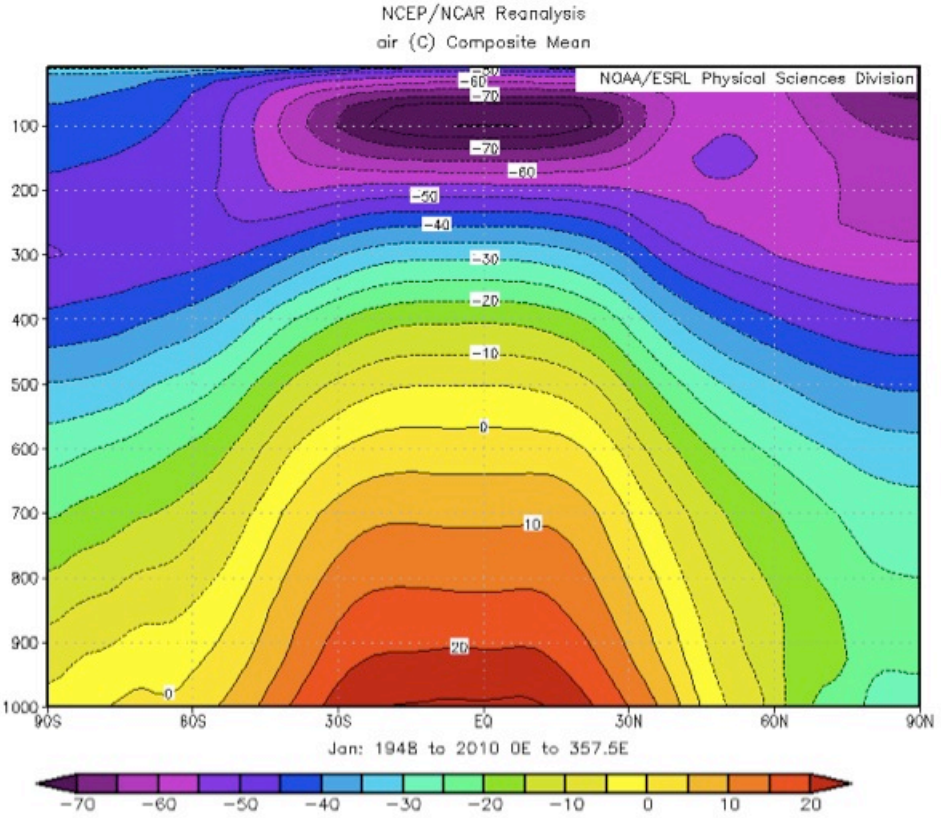
$\Delta T = 8.5K$

$\Delta r = 0.69m$

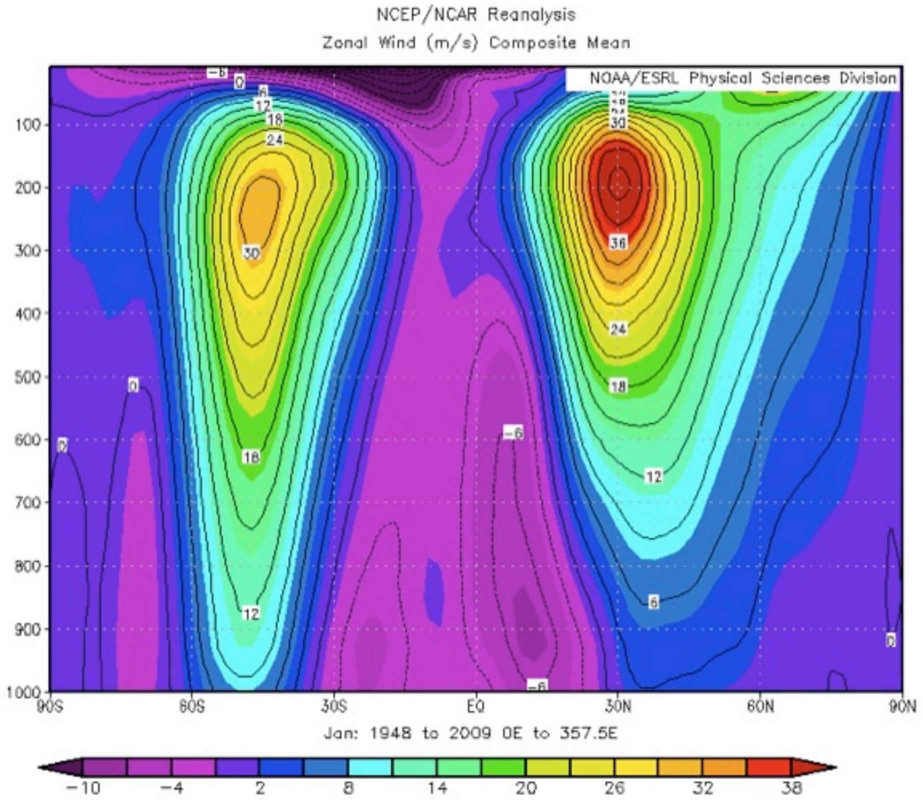
$$\Delta u_{calc} = -0.02m/s$$

$$\Delta u_{measured} = 0.003m/s$$

Thermal winds were observed to develop in the tank along frontal surfaces so the thermal wind equation was applied. Velocity of particles at the surface was measured with particle tracking softward (tracks are pictured in the upper right corner). The calculated average theoretical velocity was determined by using the values given. The two velocities are only one order of magnitude apart. Additionally, some measured velocities were on the same order of magnitude as the calculated value. This similarity implies that the system has thermal winds.



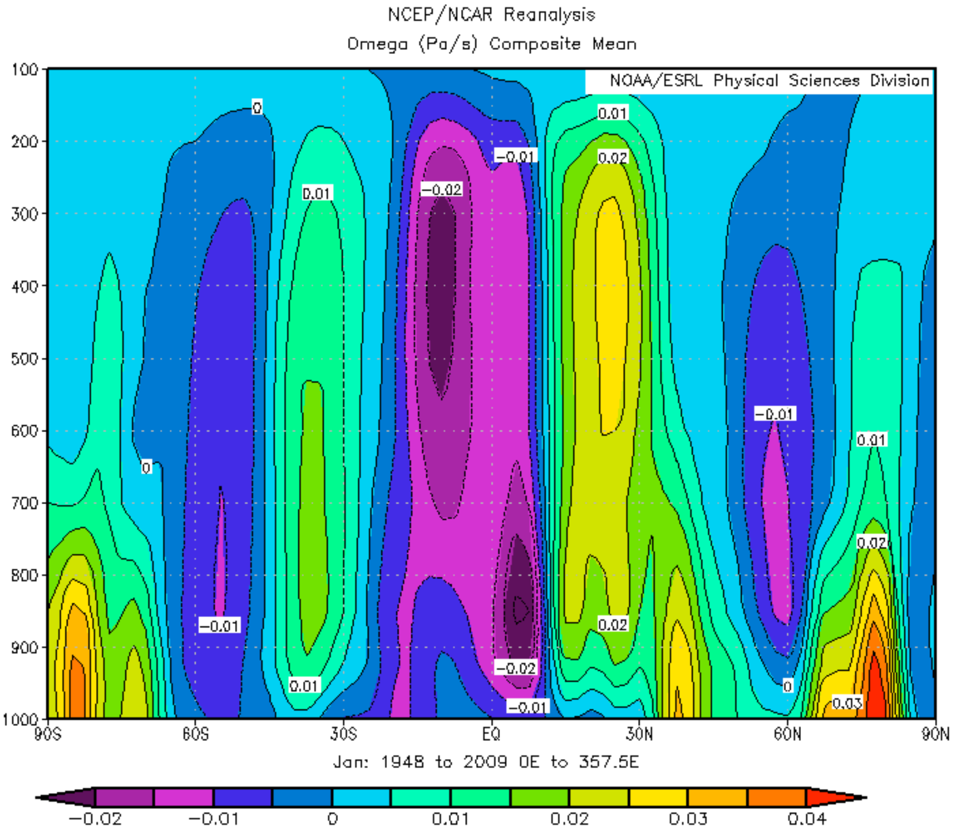
Differential heating of the Earth causes the poles are much colder than the equator. Due to transfer of heat by Hadley circulation at low latitudes, though, the region from about 25S to 30N is observed to have very constant temperature profiles. Steep temperature gradients at mid-latitudes will be discussed in more detail with the zonal wind data.



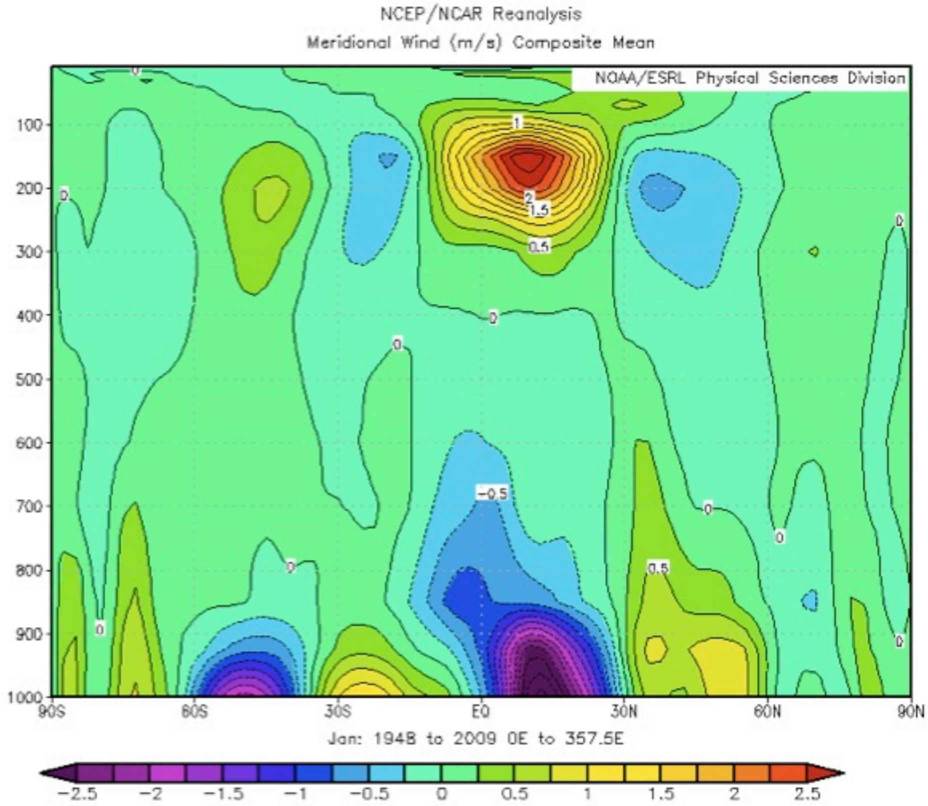
Zonal winds in the atmosphere were observed. The steep temperature gradients noted in the previous image are associated with fronts and strong zonal winds. Atmospheric behavior and around the fronts can be modeled using the thermal wind equation for the atmosphere, which is given in pressure coordinates by,

$$\frac{\partial u_g}{\partial p} = \frac{R}{fp}\left(\frac{\partial T}{\partial y}\right)_p .$$

As shown by the thermal wind equation, the temperature gradients observed in the atmosphere are associated with winds. The observed zonal winds, plotted above, are strongest at mid-latitudes, in the same locations as the steepest temperature gradients in the previous image.

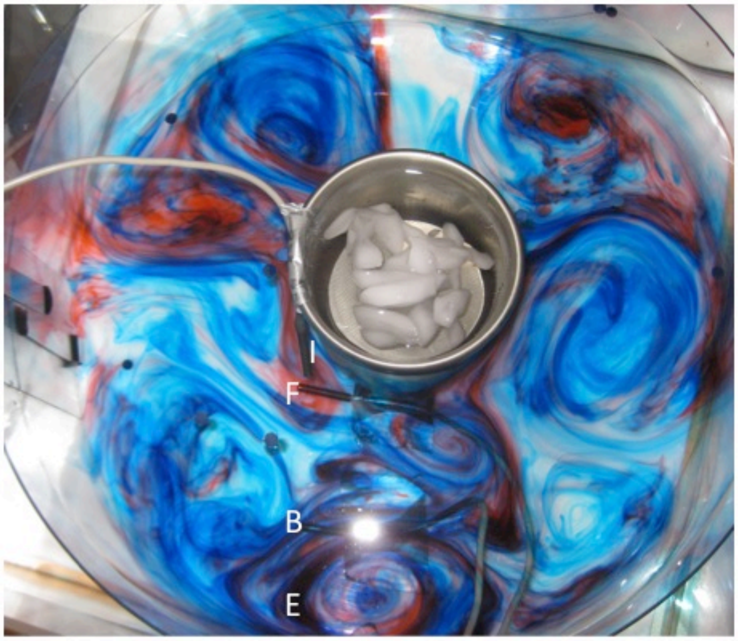


Due to transfer of heat by Hadley circulation at low latitudes, the region from about 25S to 30N is observed to have very constant temperature profiles. Plots of omega, which is a measure of vertical velocity expressed here in Pa/s are shown. The plots show upwelling (negative ω values) near the equator where air is warmest and downwelling towards the outer extents of the Hadley cell at mid-latitudes. The upwelling center shifts between very low latitudes in the northern and southern hemispheres depending on the seasons, centering in the hemisphere where it is summer.



Meridional winds represent horizontal transport in the Hadley cell. Meridional winds travel along north-south lines away from the equator at higher elevations and towards the equator at low elevations in the summer hemisphere and the opposite in the winter hemisphere.

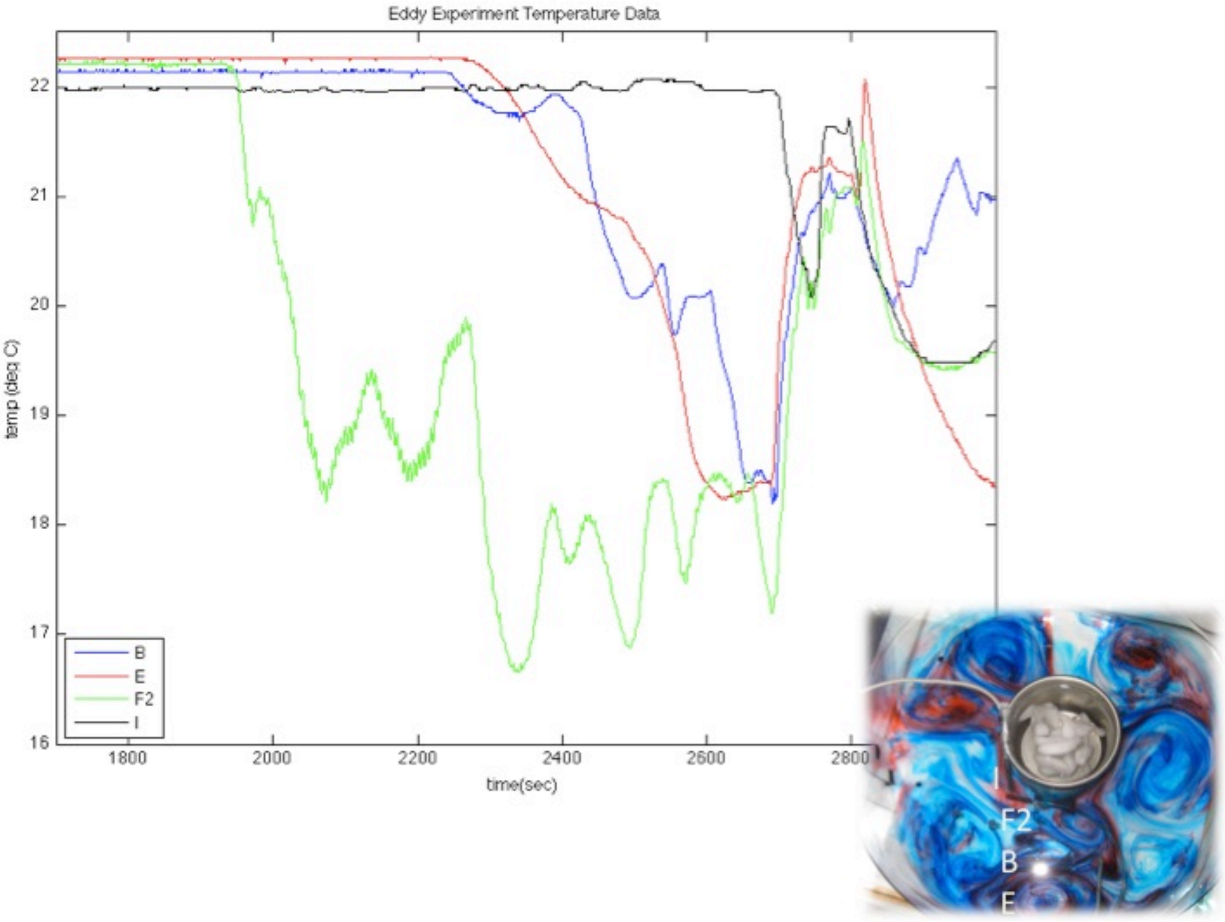
Eddy Experiment



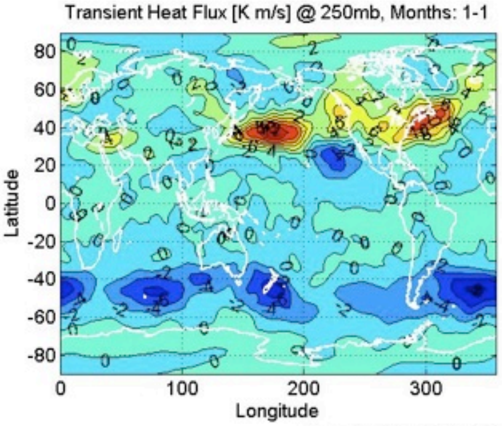
The second part of the lab experiment simulated eddies. Eddies are formed from barometric instabilities. At high rotation rates, Coriolis forces are so strong that they overpower pressures from temperature gradients, and so thermal wind no longer applies. Instead, heat is transported in parcels along sloping pressure surfaces, longitudinal currents (eddies).

The setup for this experiment was very similar to the Hadley cell experiment. An ice bucket was placed in the center with one temperature sensor near the top. The rest of the sensors were arranged radially outward on the bottom of the tank. The tank was spun up to 10 rpm and when the water reached solid body rotation ice was added to the bucket. Floating paper dots showed surface motion and dye was injected to observe motion throughout the water. Eddies developed around the tank as seen in the image above.

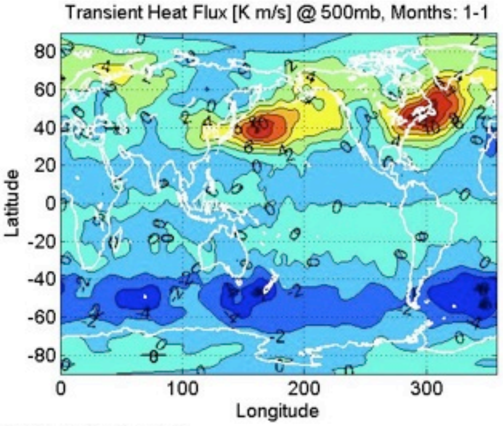
By considering the average diameter of these eddies (~0.0634 m) and the average speed of the particles in eddies (~0.0031 m/s), tracked using ParticleTracker, the Rossby number of these eddies was calculated to be 0.002. Because this Rossby number is extremely small, it indicates that at high rotation rates, Coriolis forces dominate motion of the particles in this tank.



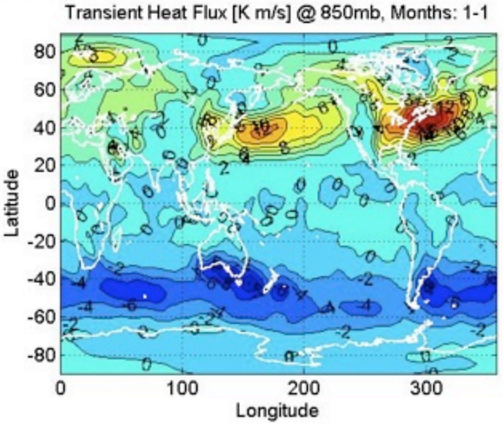
Temperature sensor data from the eddy experiment is shown above. Like in the Hadley cell experiment, the sensor near the top of the water remained at constant temperature for most of the experiment. The two outer radial sensors (B and E) cooled at about the same time since they were near eachother and the eddy circulation occurred quickly. The variations observed at each sensor are due to the swirling eddies transporting heat in the individual cells. The convergence of the lines at about 2700 seconds indicates the emptying of the tank.



Transient Heat Flux [K m/s] @ 250mb, Months: 1-1

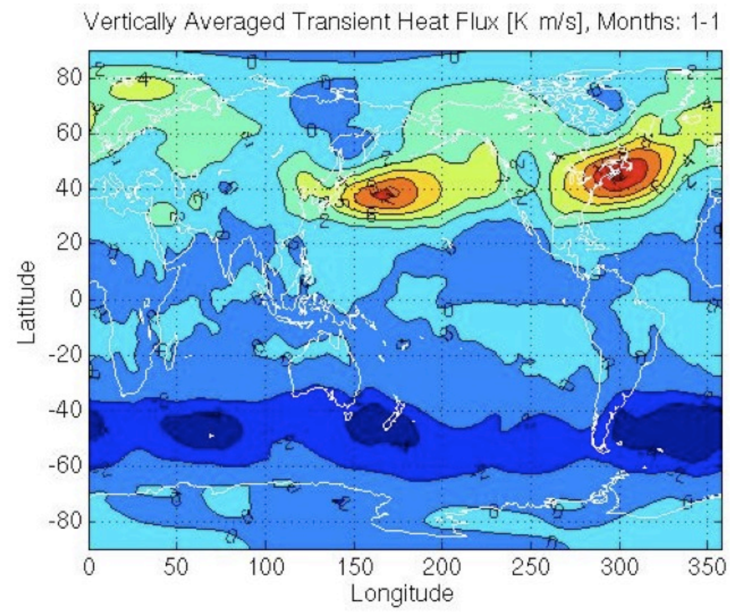


Transient Heat Flux [K m/s] @ 500mb, Months: 1-1

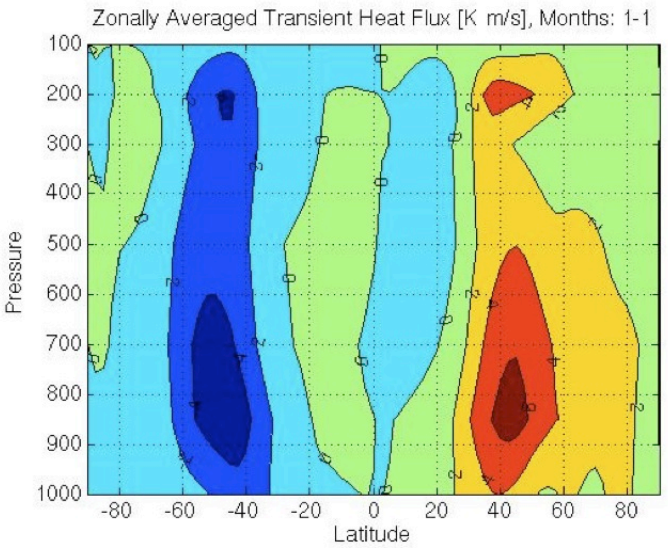


Transient Heat Flux [K m/s] @ 850mb, Months: 1-1

Eddies provide a mechanism for heat transport in the turbulant middle latitudes on Earth. By calculating the monthly mean vT for a region, the image above was produced which shows how heat is being transported across the globe. From this plot of the averaged heat transport, it is observable that heat is transported from the subtropics to the poles in circular currents and that these currents are stronger at higher elevations.



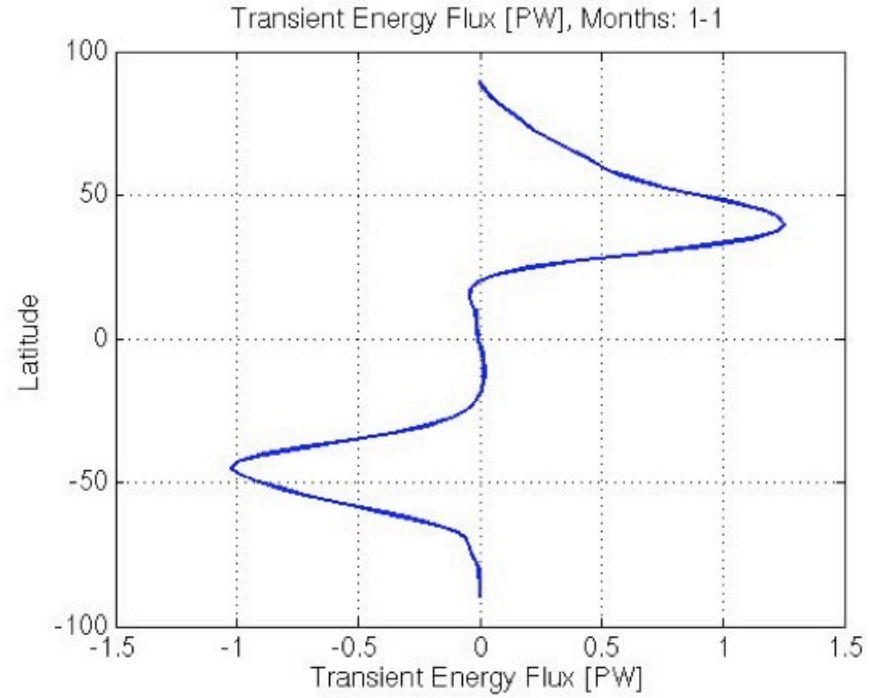
From this image of the vertically averaged heat transport, we can observe the same pattern described above only averaged throughout all pressure surfaces.



This figure displays the longitudinally (or zonally) averaged heat flux. Such values were calculated from the formula:

$$\left[v'T'\right] = \frac{1}{x_2 - x_1} \int_{x_1}^{x_2} vT \, dx$$

From this image we can observe that eddies transport heat from the Northern Hemisphere to the Southern Hemisphere.



From this plot displaying both zonally and vertically averaged heat transport across different latitudes, we can see that energy flux occurs in opposite directions in northern and southern hemispheres, carrying heat from the equator to the poles, peaking in transport aroun the subtropics, where eddies occur. Furthermore we can observe that in January, heat transport is occurring at nearly equal rates in both hemispheres.