General Circulation – Eddy Heat Transport

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Close to the equator, the primary method of atmospheric heat transport is by the Hadley Cell mechanism described by many of my classmates (here, here, and here). Hadley circulation is stable at low rotation rates; however, as rotation speed increases, the circulation breaks down.

As air parcels move from the equator to the poles, their velocity must increase due to conservation of angular momentum. Their circular path around the axis of rotation is decreasing in size, and to conserve angular momentum, as the radius decreases in size the velocity must increase. So, the Hadley circulation will eventually devolve from the neat cell to chaotic eddies.

Eddies in the Laboratory

Eddies are first studied in a tank in the laboratory. A rotating table is filled with water that is allowed to rotate with the table until it reaches solid-body rotation, at which point ice is placed in the center. To track the temperature changes, thermistors were placed prior to the tank being filled along the bottom and sides of the tank, and the movement of the water was tracked by using paper dots on the surface as well as two colors of dye.

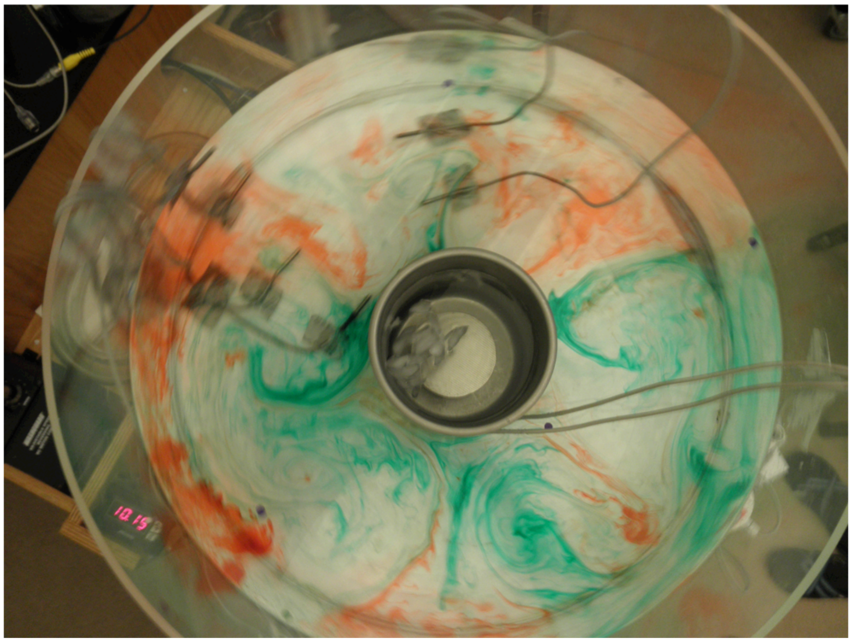

Fig. 1 An overhead view of the laboratory experiment. The red dye began at the edge of the tank, and the green dye began at the center.

When the table is rotated slowly, it forms a Hadley cell. Here, it is rotated at 10.17 revolutions per minute (1.07 radians per second), which is sufficiently fast to create instability.

The temperatures at different locations in the tank are shown in Fig. 2, below. Three of the thermistors were attached to the ice container, insulated from it so they were the same temperature as the water, not the ice. One thermistor was at the bottom of the tank in the middle, and two were attached to the warm side of the tank.

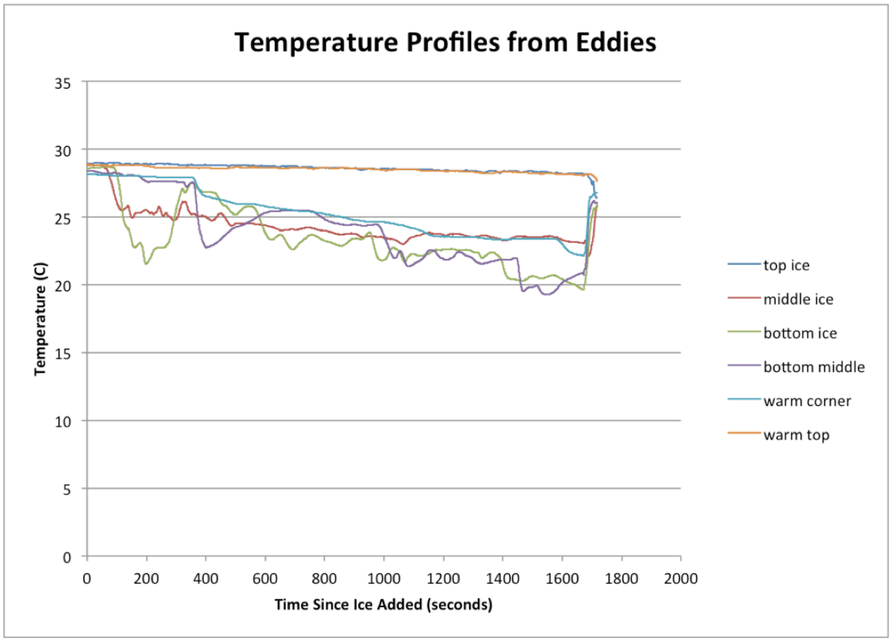

Fig. 2 The temperature over time at six locations in the tank.

The fact that the cold water does not mix evenly can be easily seen from the fact that the edge of the tank remains at essentially constant temperature. At the middle and center of the tank, the temperature gets generally colder as the ice melts, but oscillates as the cold and warm water swirl.

The cold water starts at the center of the tank, and swirls out in columns. Rather than mixing zonally, or directly along a meridian like a Hadley cell, heat is slowly distributed as columns of warm and cold water coil closer and closer.

Atmospheric Eddies

Eddies, mostly in the form of storm systems, are the primary mechanism of heat transport in the mid-latitudes. They are chaotic systems, which means they are extremely sensitive to initial conditions. Eddies are seen in the northern hemisphere primarily between 40-60°, on the boundary of the polar front.

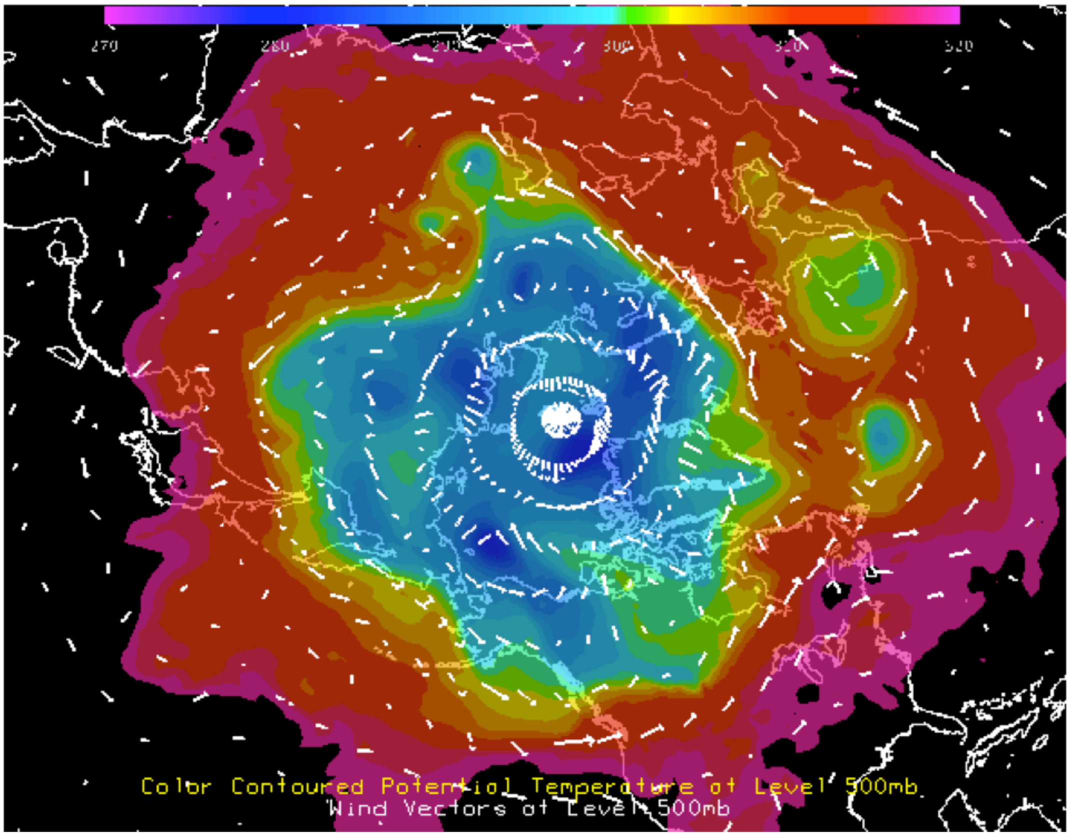

Fig 3 A potential temperature and wind map at 500 mbar.

Eddies are seen in Fig. 3 above in several places. They can be identified by their localized minima in temperature on the relatively warm outskirts of the front, with winds moving circularly around them.

Overall Meridional Heat Transport

The overall atmospheric heat transport to the poles can be calculated from data downloaded from the NCEP Reanalysis tool provided by NOAA. Transient heat flux data can be downloaded, then manipulated in MATLAB to be averaged vertically and zonally. This average can then be used to calculate the overall poleward transport at a given latitude using the equation

$$\mathcal{H} = c_p \int_{x_1}^{x_2} \int_0^{\infty} \rho \, \overline{v'T'} \, dx \, dz = 2\pi a \cos\varphi \frac{c_p}{g} \int_0^{p_s} \left[\overline{v'T'} \right] \, dp$$

which can be plotted for all latitudes to give a pole-to-pole profile of heat transport, seen in Fig. 4.

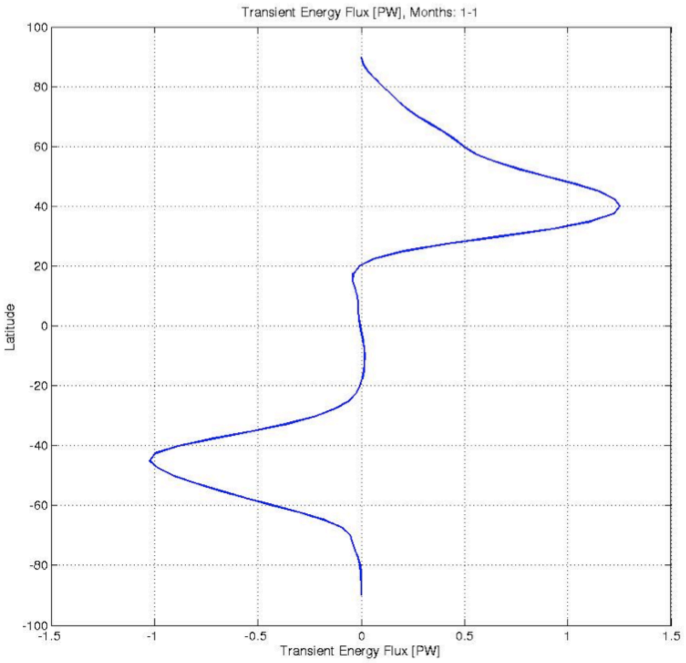

Fig. 4 The meridional heat transport, as calculated from transient heat fluxes.

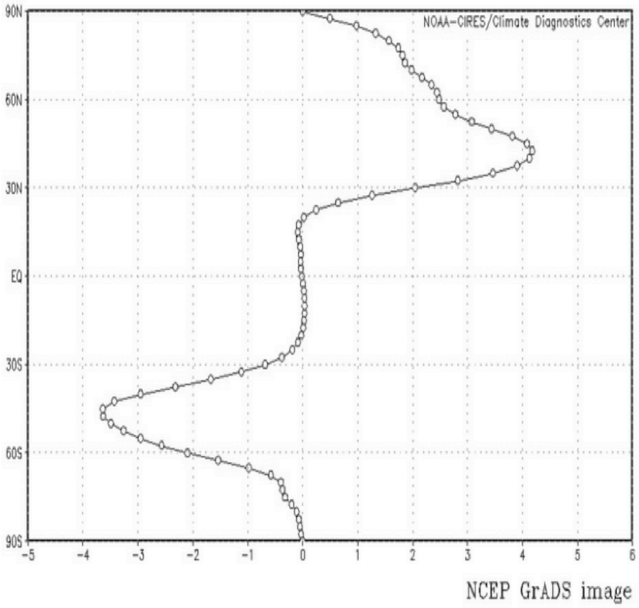

Fig. 5 The actual, observed meridional heat transport.

As expected, it shows the greatest transport around 40°, where eddies are most prominent. This can be compared to the actual, observed heat transport, seen in Fig. 5. The two clearly have the same shape, and deviate mostly in magnitude. The observed values are approximately three times the magnitude of the calculated values. This is likely because the observed values are taking into account multiple types of heat transfer, especially the latent heat involved in the transportation of moisture.