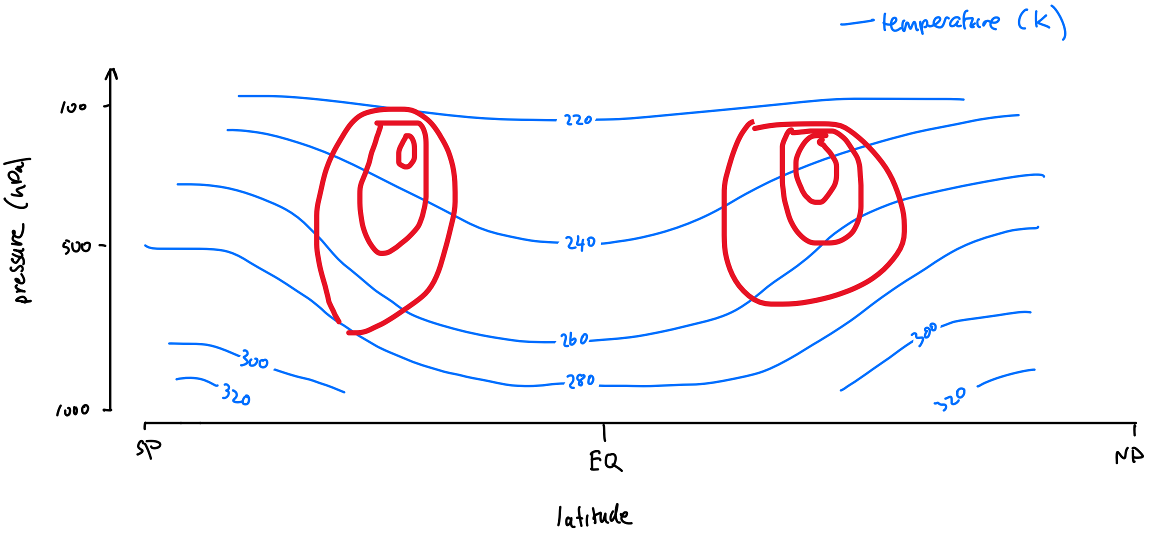
General circulation of the atmosphere

Problem set 3

Problem 1.

Sketch the zonal-mean zonal wind associated with the temperature distribution below.



Explain how you arrived at your answer.

Thermal wind balance tells us that vertical gradients in the zonal wind are related to meridional gradients in temperature. In both hemispheres, when temperature increases towards the pole, the wind becomes more easterly with height. Assuming that the surface winds are weak, the distribution above therefore produces Easterly winds at upper levels, strongest in the regions where the lines slope the most. The sketch above gives a rough estimate of this wind – red contours represent Easterly (East to west) zonal wind.

Problem 2.

We have derived an equation for the zonal-mean meridional flow in the upper troposphere which may be written,

$$f[\overline{v}] = \frac{1}{R_e \cos^2\phi}\frac{\partial}{\partial\phi}([\overline{uv}]\cos^2\phi) + \frac{\partial}{\partial p}([\overline{u\omega}]). \qquad (4)$$

This equation relates the upper tropospheric meridional flow to the flux divergence of angular momentum (by both eddies and the mean flow).

On the other hand, in the Held & Hou model of the Hadley Cell, the strength of the cell (which is related to the strength of the meridional flow in the upper troposphere) was determined using the thermodynamic balance.

Discuss how this difference in our perspective arises. How is (4) satisfied in the (axisymmetric) Held & Hou model? What happens to (4) when eddies are important?

In the Held & Hou model, there are no eddies, so the only contribution to the right-hand side is from the mean flow. This model requires air within the Hadley Cell to conserve its angular momentum above the boundary layer. This places a strong constraint on the zonal wind distribution such that (4) is automatically satisfied for any distribution of [v]. In this case, (4) does not tell us about the Hadley Cell strength, and we have to appeal to thermodynamics.

When eddies are important, the right-hand side of (4) is dominated by the eddy component. In this limit, eddies determine [v] and hence the overturning circulation, and the overturning cells can only respond to forcing by changing the eddy fluxes.

Problem 3.

The schematic below shows the eddy-momentum fluxes in a hypothetical atmosphere as a function of latitude (*x*-axis) and height (*y*-axis). Arrows give the value of the zonal- and time-mean eddy momentum flux at a given latitude and height up to the tropopause (arrows to the right give northward fluxes, arrows to the left give southward fluxes). Assuming quasi-geostrophic scaling is valid (except very close to the equator), sketch the corresponding overturning streamfunction (on the same axis) and the corresponding zonal-mean surface winds (on the axis below).

Arrows represent $\overline{u'v'}$, northward eddy momentum flux.