Assignment 2 solutions

Martin Singh

1 Overview of the NCEP-DOE reanalysis

Figure 1 shows the distribution of temperature, potential temperature and zonal wind as a function of latitude and pressure calculated based on the NCEP-DOE reanalysis. The figure is constructed by extracting daily data on pressure levels from the years 2008-2017. These fields are then plotted as time and zonal means (using data from all seasons). Figure 2 shows the zonal- and time-mean wind at 10 m above the surface, also estimated by the NCEP-DOE reanalysis for the years 2008-2017.

2 Angular-momentum budget

Figure 3 shows the meridional flux of relative angular momentum $[\overline{F_M}] = R_e \cos\phi[\overline{uv}]$ divided into components associated with time- and zonal-mean flow, stationary eddies, and transient eddies. Here R_e is the radius of the Earth, ϕ is the latitude, u and v are the zonal and meridional velocities, respectively, and the overbar and square brackets refer to a time and zonal mean.

The flux of relative angular momentum may be used to construct an approximate momentum balance for a column of the atmosphere. In particular, by assuming friction acts as a linear drag on the boundary layer wind, we may relate the convergence of momentum in a column to the boundary layer zonal wind,

$$-\frac{1}{R_e^2 \cos^2\phi} \frac{\partial}{\partial \phi} \left\{ \int_0^{p_s} [\overline{F_M}] \cos\phi \, \frac{\mathrm{d}p}{g} \right\} = \frac{u_{BL}}{\tau_F} \frac{\Delta p_{BL}}{g}, \tag{1}$$

where p_s is the surface pressure, Δp_{BL} is the boundary-layer thickness, u_{BL} is the boundary-layer zonal wind, and τ_F is the timescale over which friction relaxes the wind to zero. The left hand side of (1) represents the zonal force per unit area of the atmosphere occurring as a result of the convergence of momentum into the column, and the right hand side represents the zonal force per unit area owing to boundary-layer friction.

Assuming u_{BL} is equal to the wind at 10 m above the surface, we may take τ_F to be a free parameter (that does not vary spatially) and estimate the two sides of (1). Figure 4 shows such an estimate, with $\tau_F = 0.3$ days (fitted roughly by eye). Given the typical timescales of the growth and decay of baroclinic cyclones (a few days) and the decay timescale of tropical cyclones that make landfall (a day or so), this timescale is a reasonable one for a rough estimate of the frictional timescale for large-scale flow in the atmosphere. Moreover, previous idealised studies using linear frictional damping in general circulation models (Held and Suarez, 1994) have used timescales of ~ 1 day, similar to, but somewhat larger than the timescale estimated here.

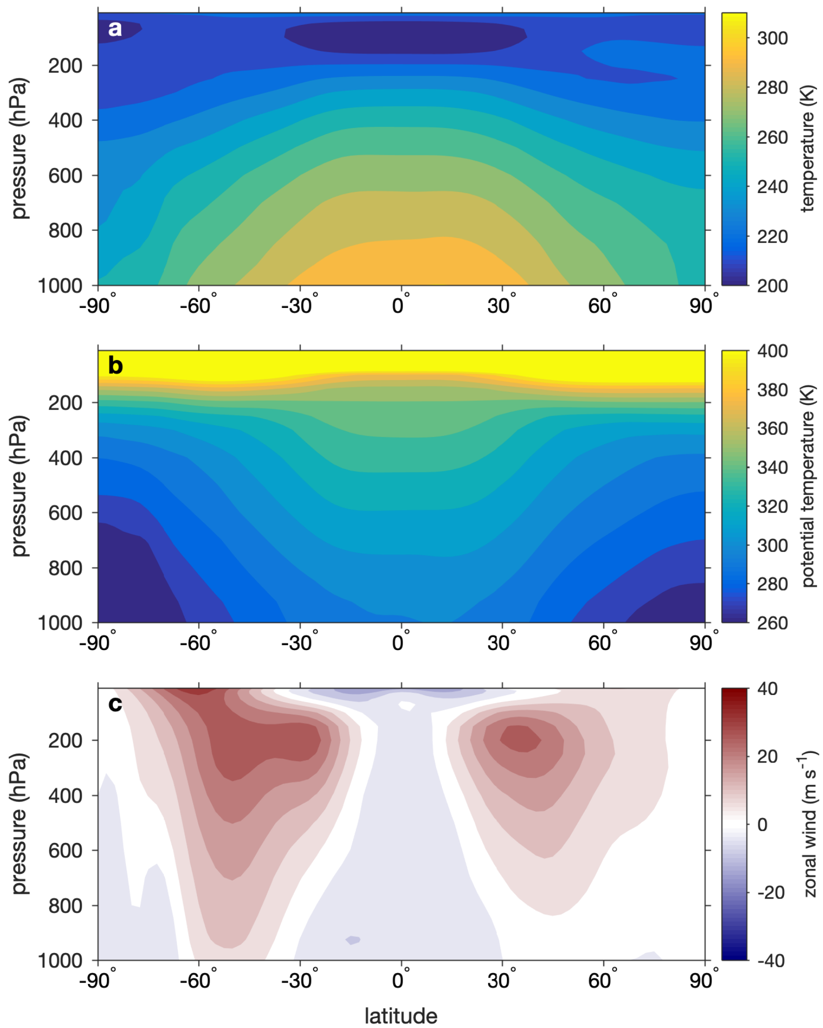

Figure 1: Zonal- and time-mean (a) temperature, (b) potential temperature and (c) zonal wind as a function of latitude and pressure according to the NCEP-DOE reanalysis for the years 2008-2017.

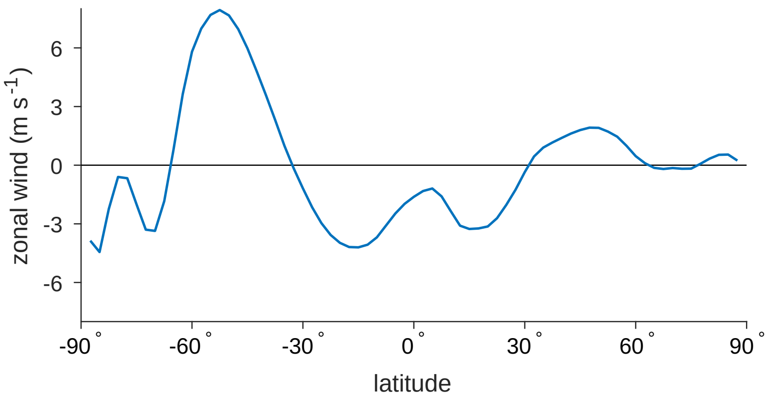

Figure 2: Zonal- and time-mean (top) zonal wind at 10 m above the surface as a function of latitude according to the NCEP-DOE reanalysis for the years 2008-2017.

3 Errors in the estimated angular-momentum budget

Estimates of the two sides of (1) are similar, particularly in the latitude range between 60°S and 30°N. outside these regions, however, the estimated can differ considerably, both in magnitude, and in some regions even in sign. There are a number of reasons that our estimated momentum balance does not close. These are outlined in the subsections below.

3.1 Errors in the estimation of drag

Our estimate of the momentum budget assumes that frictional forces are only present in the boundary layer, and that the boundary layer is of a fixed thickness of 50 hPa These assumptions are likely not accurate for Earth's atmosphere. Moreover, we have assumed here that friction acts as a simple linear drag on the boundary layer flow, and that this flow can be represented by the zonal wind at 10 m. In reality, the stresses in the atmosphere associated with friction are considerably more complex; often in numerical models a quadratic drag law is used to relate the near-surface flow to the surface stress.

Most importantly, however, we have assumed a constant value for τ_F across the globe, tuned to give a good match for the magnitude of the frictional force in the southern hemisphere extratropics. In reality, the relevant frictional timescale depends strongly on the underling surface; it is therefore onsiderably larger over land than ocean. This is one reason why the frictional force is underestimated in the northern hemisphere extratropics, where there is substantial land coverage.

Finally, we have also neglected form drag in deriving (1). Form drag is largest where there are mountains, and this may also contribute to the underestimate of the frictional force in the northern hemisphere.

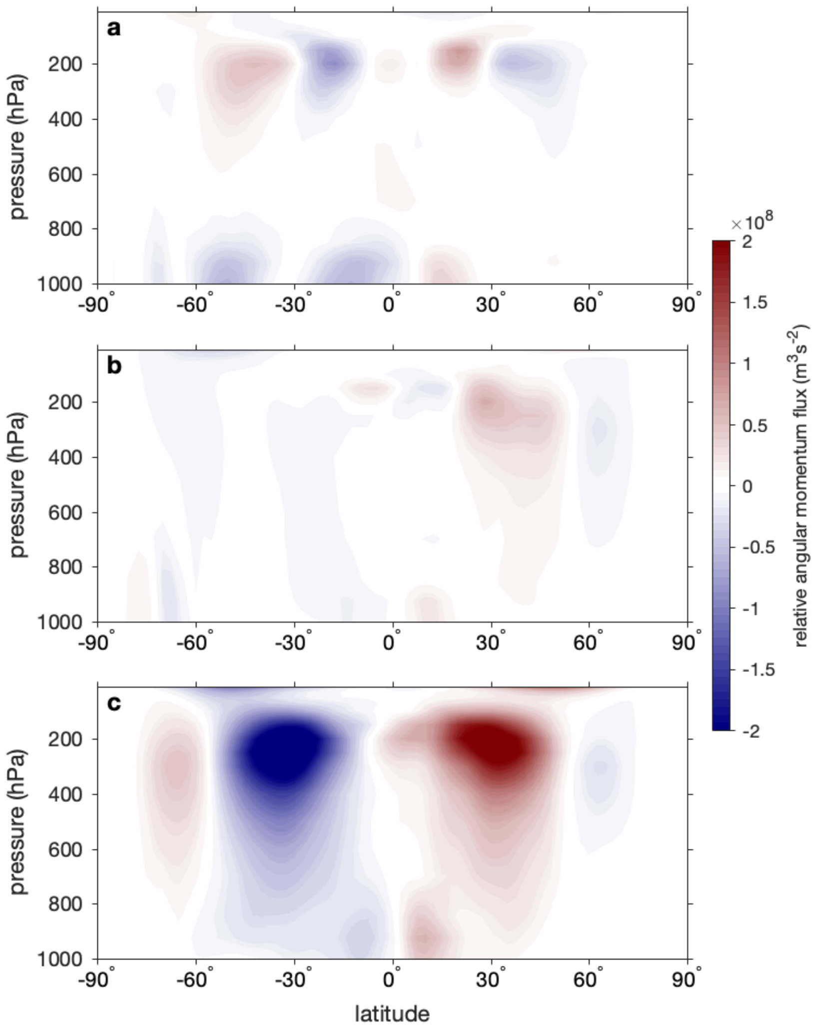

Figure 3: Meridional relative angular momentum flux produced by (a) zonal- and time-mean motions, (b) stationary eddies, and (c) transient eddies calculated based on the NCEP-DOE reanalysis using daily-mean data for the years 2008-2017.

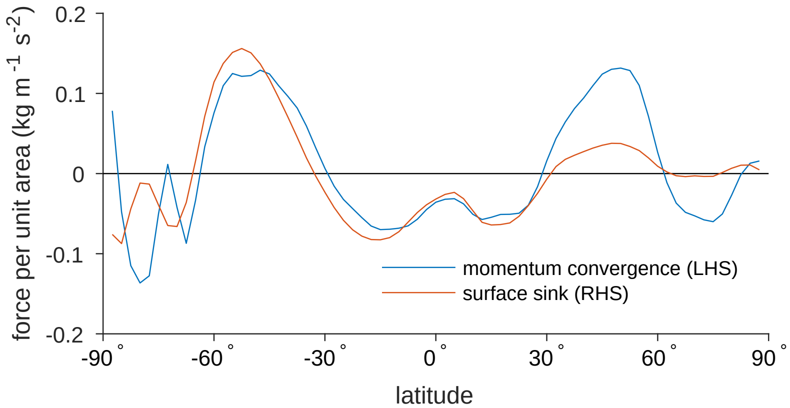

Figure 4: Zonal-mean zonal momentum budget for the atmospheric column as a function of latitude. Blue line corresponds to the convergence of momentum into the column [given by the left-hand side of (1)], and red line corresponds to the surface sink of momentum [corresponding to the right-hand side of (1)]. Data based on daily-mean winds taken from the NCEP-DOE reanalysis for the years 2008-2017.

3.2 Errors in the reanalysis

Another source of error in the budget is imperfections in the reanalysis data. It is well known that reanalyses do not typically have closed budgets of conserved quantities because of the nudging of the model solution towards observations. In our case, however, larger errors likely come about because of numerical errors in our calculation of the budget from numerical data. For example, our estimate of the left-hand side of (1) uses simple centred differencing for the meridional derivative; this is likely to be a different numerical scheme from that used by the reanalysis model itself to calculate advection and divergences.

Probably the largest issue, however, is the errors in our evaluation of the vertical integral in (1). We have taken the integral from 1000 hPa to the top of the atmosphere at all latitudes. But the 1000 hPa surface is often below the ground, particularly in mountainous regions, and these regions should not be included within an integral over the atmosphere. This is likely to account for a large part of the imbalance in our estimated budget in the high southern latitudes. The surface pressure over Antarctica is much lower than 1000 hPa at all longitudes, and thus our inclusion of this pressure level within the vertical integral adds spurious momentum fluxes to the estimate of the left-hand side.

References

Held, I. and M. Suarez, 1994: A proposal for the intercomparison of the dynamical cores of atmospheric general circulation models. *Bulletin of the American Meteorological society*, **75**, 1825–1830.