Barotopic and Baroclinic Frictional Damping of Cyclone Development

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Action of friction

Frictional processes are not often considered in any detail in studies of cyclone development. However, they are undeniably important. This can be demonstrated with a simple, if rather extreme, example. We have performed T+72 simulations with the UK Met Office unified model of an intense storm over the UK on 30th October 2000. The control, in reasonable agreement with observations, gave a minimum mean-sea-level pressure of 949mb at midnight. However, with fluxes of momentum and heat are switched off, the pressure falls to just 921mb.

Frictional processes can be thought of in terms of changes to boundary layer potential vorticity (PV). Assuming that the surface-layer stress decays linearly across the boundary layer, then:

$$\frac{D}{Dt}\langle PV\rangle = \frac{-1}{\rho h^2}(f\Delta\theta w_e + \underline{\tau}\cdot\underline{k}\times\underline{\nabla}\theta_h) + \dots$$

where the Dirac brackets denote a vertical average over the boundary layer. The first term on the right-hand-side represents barotropic damping by friction, and the second is baroclinic generation of PV. (Other terms represent diabatic and orographic processes.)

Barotropic damping of PV

The mechanism usually assumed for frictional damping of a cyclone is the spindown of a barotropic vortex by Ekman pumping (Figure 1). Frictional convergence in the boundary layer over a cyclonic system implies an uplift at the top of the layer. This leads to squashing of the vortex tube in the free troposphere and hence to spin-down of the cyclonic vorticity.

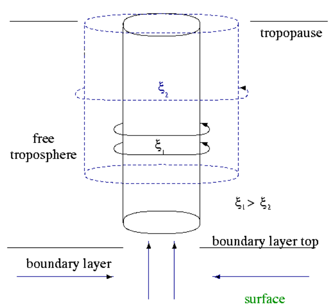

Figure 1. Schematic illustrating barotropic spindown of a cyclonic vortex due to Ekman pumping.

Baroclinic PV generation

Figure 2 shows the baroclinic PV generation when the surface stress acts in the opposite direction to the thermal wind. The 3d flow within the cyclone is important in determining both the sign and magnitude of this term. Thus, one might expect that the relative significance of baroclinic PV production would vary from case to case, according to the low-level flow and the strength, location and orientation of fronts.

Baroclinic generation can lead to significant positive anomalies of PV. Suprisingly then, friction generates PV! We are studying baroclinic effects of friction using numerical simulations of frictionally-damped baroclinic waves and full-physics simulations of some real cases.

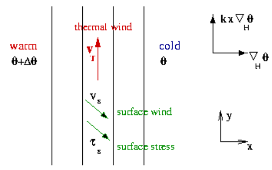

Figure 2. Schematic illustrating baroclinic generation of PV.

Damping of baroclinic lifecycles

Figure 3 shows the PV at day 6 in a simulation of a baroclinic wave.

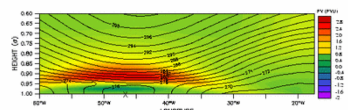

Figure 3. Vertical cross-section of PV through a frictionally-damped, numerically-simulated baroclinic wave. The contours are of potential temperature.

Barotropic damping leads to a negative PV anomaly over the low centre, where the vorticity is high. Positive, baroclinically-generated PV is formed near the cold front and carried along the front and upwards through the boundary layer by a warm conveyor belt (WCB) flow. The WCB terminates with a W2 flow, transporting this PV towards the low centre and forming a positive anomaly just above the boundary layer. Figure 4 illustrates the flow.

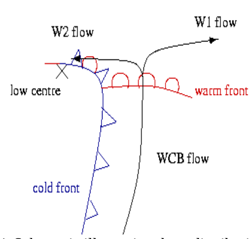

Figure 4. Schematic illustrating the redistribution of baroclinically-generated PV by a warm conveyor belt flow.

The baroclinically-generated PV anomaly enhances the vorticity at the occluded front. Nevertheless, the cyclone is considerably damped: the anomaly is short and squat and so is associated with an anomaly of static stability. This increased stability immediately above the boundary layer reduces the coupling between upper and lower levels, thereby reducing the growth of the system.

Some real cases

We are currently examining barotropic and baroclinic frictional processes in real cases. We compute the PV generated by the boundary layer scheme and other processes at each timestep. This information is used to increment the model's tracer fields, which handle advection of the generated PV. Thus, we derive a tracer field that at any given time represents the current location of PV that has been produced at earlier times.

Our investigations confirm that both the barotropic and baroclinic generation terms contribute to the PV in real systems. However, both their formation and the evolution are strongly case dependent. We conclude with a couple of examples.

Figure 5 shows the PV attributed to the boundary layer scheme at T+18 in a simulation of FASTEX IOP4. There is little baroclinicity in this case, so the PV is mainly negative due to Ekman pumping. Interestingly though, anomalies of low or negative PV are not observed in the full PV field due to cancellations with PV that is generated by the convection scheme.

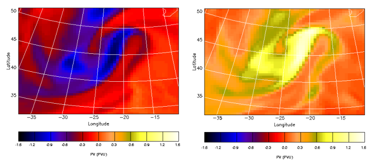

Figure 5. PV at 950mb generated by the boundary layer (left) and convection (right) schemes in a simulation of FASTEX IOP4. The time is 18Z on 17/1/97, at T+18.

By contrast, in the IOP14 system, there are important contributions from both the barotropic and baroclinic generation terms (Figure 6). Here the baroclinically-generated PV evolves differently to that in the baroclinic wave described above. In this case, the steering level is higher, relative to the end of the WCB. So, PV generated along the cold front is carried initially by the WCB but is then advected by a W1 flow (Figure 3), moving downstream relative to the low centre (Figure 7).

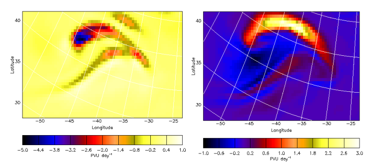

Figure 6. Rates of generation of PV due to barotropic (left) and baroclinic (right) frictional processes in FASTEX IOP14. The time is 18Z on 12/2/97.

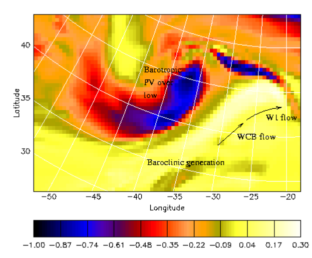

Figure 7. PV at 900mb generated by the boundary layer scheme in a simulation of FASTEX IOP14. The time is 6Z on 13/2/97, at T+18.

The bottom line

Boundary layer friction significantly changes PV and influences the development of cyclones.

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