# Boundary Layer Processes in Midlatitude Cyclones

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## Abstract

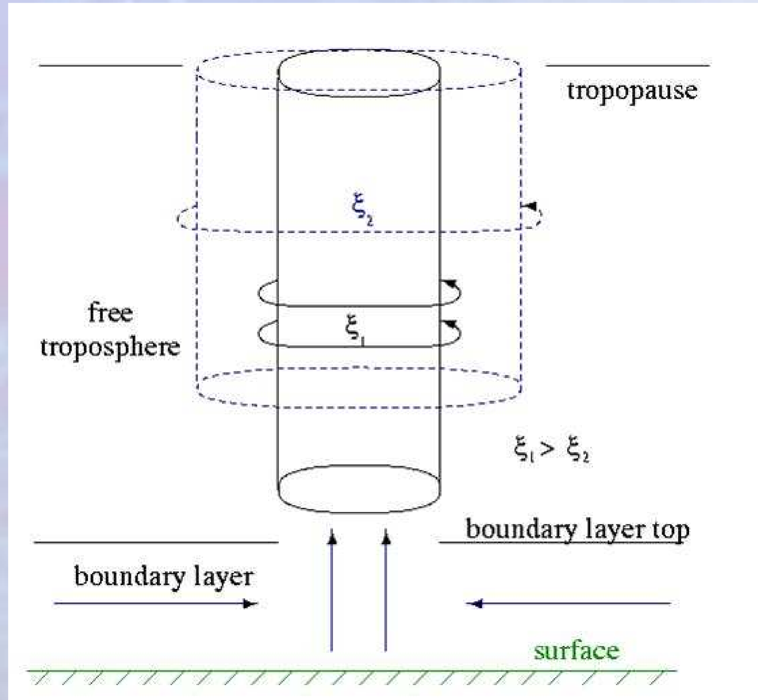
Idealised simulations in the Met Office Unified Model are used to study the frictional processes acting in the spin down of an extra-tropical cyclone. These dry simulations impose an upper-level trough onto a basic state baroclinic jet, spinning up into a cyclone over 3 days, utilising only the dynamics and boundary layer scheme.

The traditional Ekman pumping mechanism is compared to a new baroclinic mechanism based on potential vorticity (PV). Simulations show a PV anomaly, generated in the surface warm-sector, is advected along the warm conveyor belt and vented from the boundary layer. It appears as a static-stability anomaly above the low centre, damping the cyclone. Results suggest that both mechanisms are important, mutually reinforcing each other to enhance the spin down.

## 1 Ekman Pumping

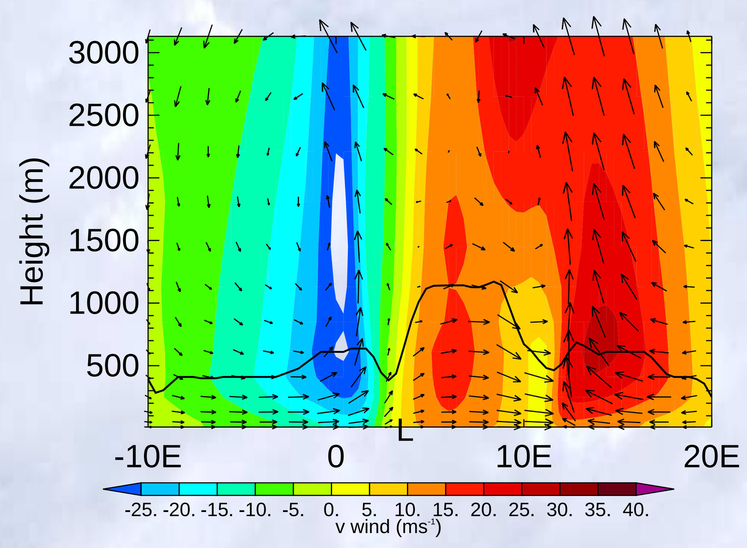
- Friction forces convergence of low level winds
- Continuity implies ascent above low centre

$$w_{\mathrm{Ek}} = \frac{1}{f_0}\boldsymbol{k}.\boldsymbol{\nabla} \times \boldsymbol{\tau}_{\mathrm{s}} \quad (1)$$



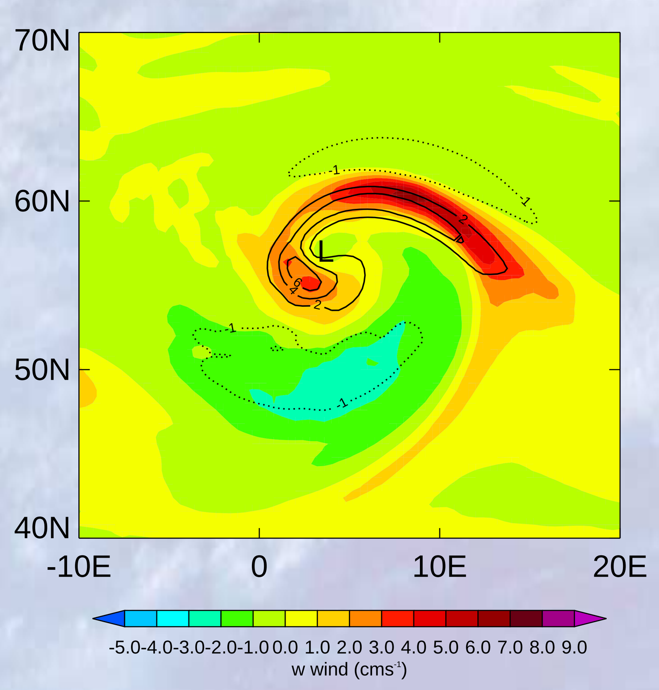

- Ascent reduces vorticity by vortex squashing in the interior
- Barotropic mechanism – what about temperature gradients and fronts?

## 2 Boundary layer winds




$x$-$z$ cross section through the low centre, showing $(u, w)$ wind vectors and the $v$-wind velocity (coloured). The thick black line represents the boundary layer top.

Behind the low centre ($-10$ – 4E), the flow looks like an "Ekman-type" circulation. However, ahead of the low centre, the flow is completely dominated by frontogenesis at 12E, and the warm conveyor belt flow ahead of this (12 – 20E).




Vertical velocity at the boundary layer top (coloured), and Ekman pumping velocity defined by Eq. 1 (contoured).

Ekman pumping helps with the low level ascent of the warm conveyor belt, but Eq. 1 over-estimates the vertical velocity around the low centre.

## 3 Potential Vorticity

Within the free troposphere, potential vorticity (PV) is conserved by adiabatic motions. However, within the boundary layer, frictional and diabatic processes can create or destroy PV.

$$\frac{D(PV)}{Dt} = \frac{1}{\rho}\left(\boldsymbol{\zeta}.\boldsymbol{\nabla}\frac{D\theta}{Dt} + (\boldsymbol{\nabla}\times\boldsymbol{F}).\boldsymbol{\nabla}\theta\right) \quad (2)$$

The terms on the right-hand side represent:

(I) Diabatic processes such as surface sensible heat exchange and latent heat release

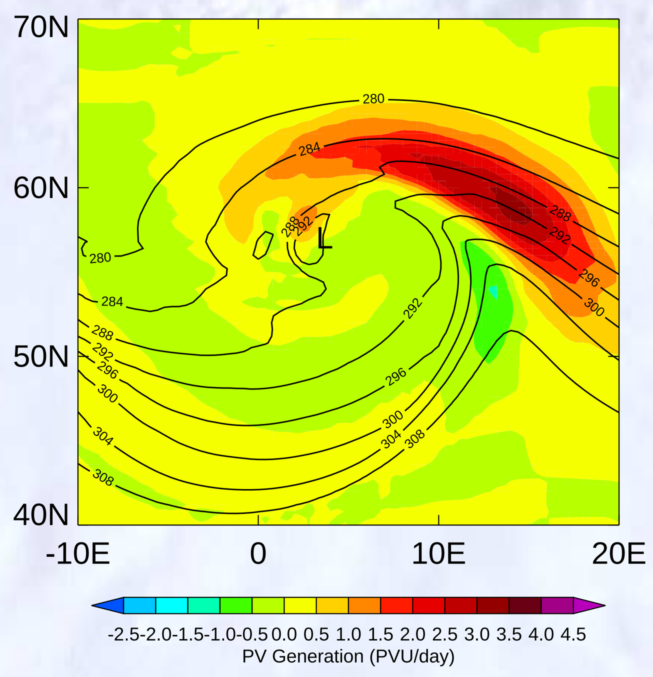
(II) Frictional processes such as Ekman destruction of PV and baroclinic generation of PV

### Baroclinic generation

Depth integration of Eq. 2 over the boundary layer gives rise to expressions for the creation/destruction of PV in the boundary layer (Adamson *et al.* , 2006). The following expression defines a baroclinic mechanism for PV generation:

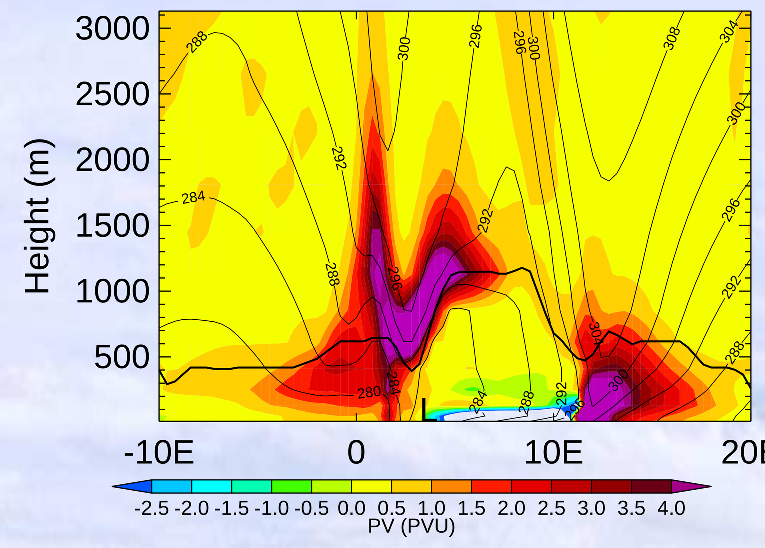
$$[G_B] = \frac{1}{\rho^2 h^2}\boldsymbol{k} \times \boldsymbol{\tau}_{\mathrm{s}}.\boldsymbol{\nabla}\theta_h \quad (3)$$

This generation, shown below, is colocated with the warm conveyor belt ascent (Section 2), and so is well placed for ventilation from the boundary layer.




## 4 A mechanism for spin down

Once generated, the PV is ventilated from the boundary layer on the warm conveyor belt. A branch of this turns cyclonically, leading to accumulation of PV above the low centre.




$x$–$z$ cross section showing the PV anomaly above the low centre.

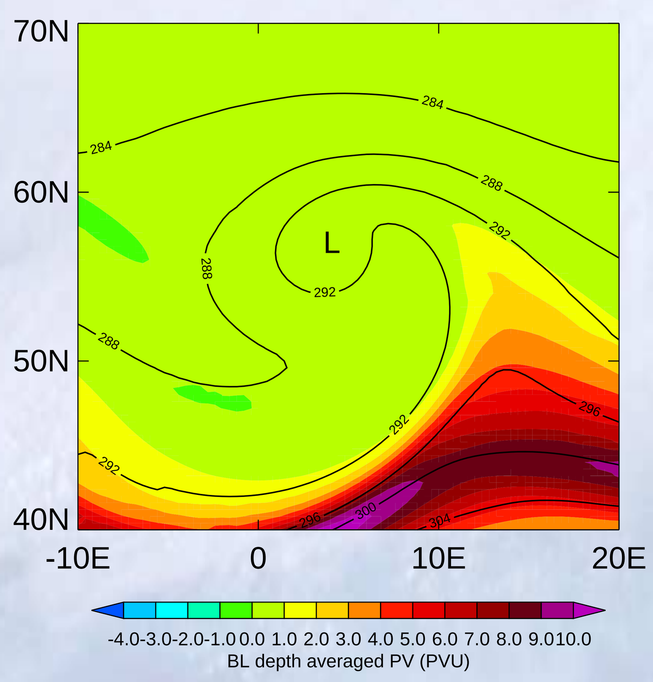
The PV accumulated above the low centre is confined in the vertical, but spread in the horizontal, in part due to Ekman circulation (Section 2). This shape is associated mainly with a PV anomaly of increased static stability. The increased static stability reduces coupling between the upper level trough and surface temperature anomaly, making their mutual reinforcement weaker.

## 5 Surface heat flux effects

- Eq. 2 suggests that surface sensible heat exchange will also be important for PV generation
- Hence the surface temperature (SST) distribution becomes important
- If a meridionally varying SST is imposed, with gradient matching that of the atmosphere at the initial time, then the effects are small (Plant and Belcher, 2007)
- However, if a meridionally uniform SST is chosen, the effects are large (Beare, 2007)

$$[G_H] = -\frac{\xi_h H_s}{\rho h^2} \quad (4)$$

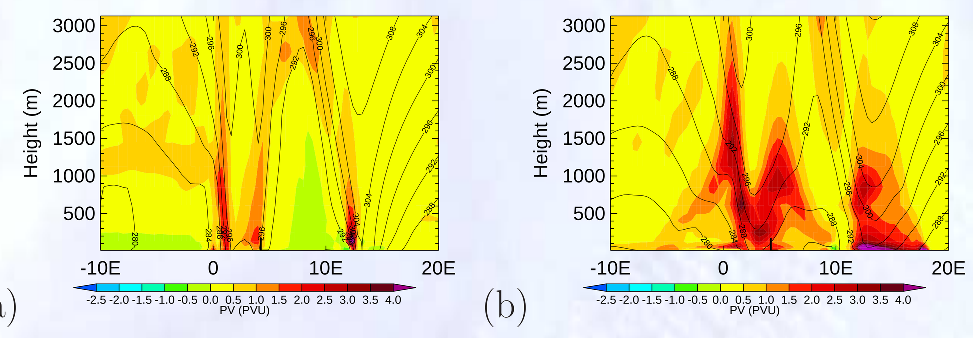
- Eq. 4 describes PV generation by surface heat flux effects, an effect which is maximised when $H_s$ is large and negative
- The figure below shows the accumulated PV at 48 hours under conditions of a meridionally uniform SST. Comparing to Sections 2 and 3 shows how this PV is not well placed for ventilation from the boundary layer (Boutle *et al.* , 2007)




- The constant SST leads to a more barotropic cyclone
- Very weak, poorly defined fronts
- Hence little baroclinic generation
- No PV anomaly seen above cyclone centre
- Spin down is mainly from Ekman mechanism

## 6 Importance of each mechanism

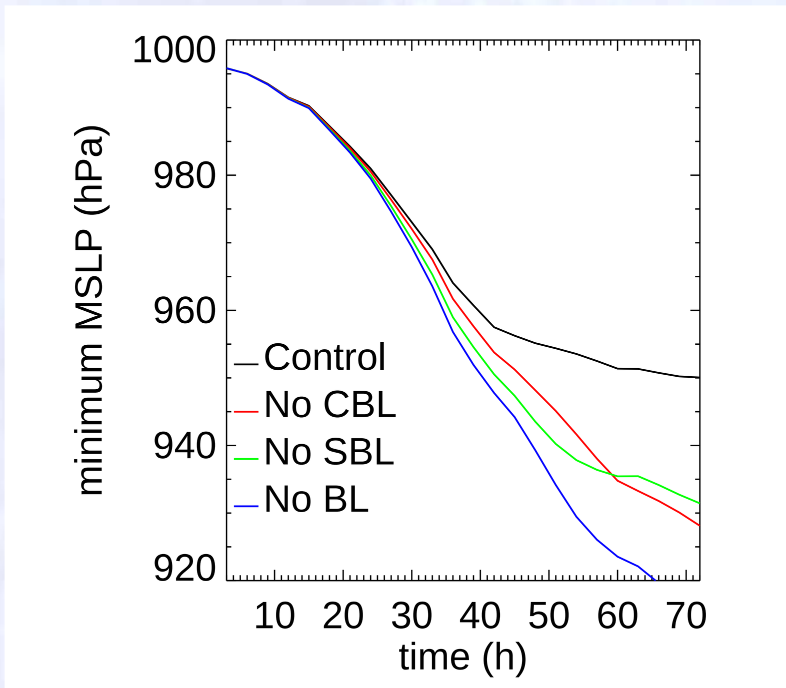
It is found that the PV is located mainly within the stable boundary layer (SBL), whereas the Ekman pumping is located mainly within the unstable boundary layer (CBL). Hence switching off the boundary layer scheme dependent on type isolates the two mechanisms.



(a) (b)

$x$–$z$ cross section showing PV for (a) No SBL (b) No CBL.

- No turbulence in the SBL totally removes the PV anomaly. All spin down here must be from Ekman processes
- No turbulence in the CBL removes most Ekman pumping, especially around the cyclone centre
- PV anomaly remains, but is lower in atmosphere and less well defined.




Similar size effect from stable and unstable boundary layers – suggests similar importance of each mechanism. However, it is not a simple linear process. Can be confident that the No SBL run is only the Ekman mechanism, but the No CBL run has distorted the PV mechanism.

## Conclusion

A new mechanism for the spin down of an extra-tropical cyclone is compared to the traditional Ekman pumping mechanism. Although we find evidence for the Ekman pumping mechanism, we also find evidence that a supporting PV mechanism can be of similar importance. The PV mechanism is strongly influenced by the degree of baroclinicity of the cyclone. Over constant sea-surface temperatures, the cyclone takes on a more barotropic nature, with weaker fronts and the Ekman mechanism dominating.

However, for a cyclone with strong fronts, baroclinic PV generation is large, and a well defined anomaly is clearly visible above the low centre. The two mechanisms are not independent, but rather the Ekman pumping supports the PV mechanism, assisting with ventilation of PV from the boundary layer, and controlling the shape of the PV anomaly to maximise its static stability contribution to the spin down.

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