Friction in mid-latitude cyclones: More than Ekman pumping

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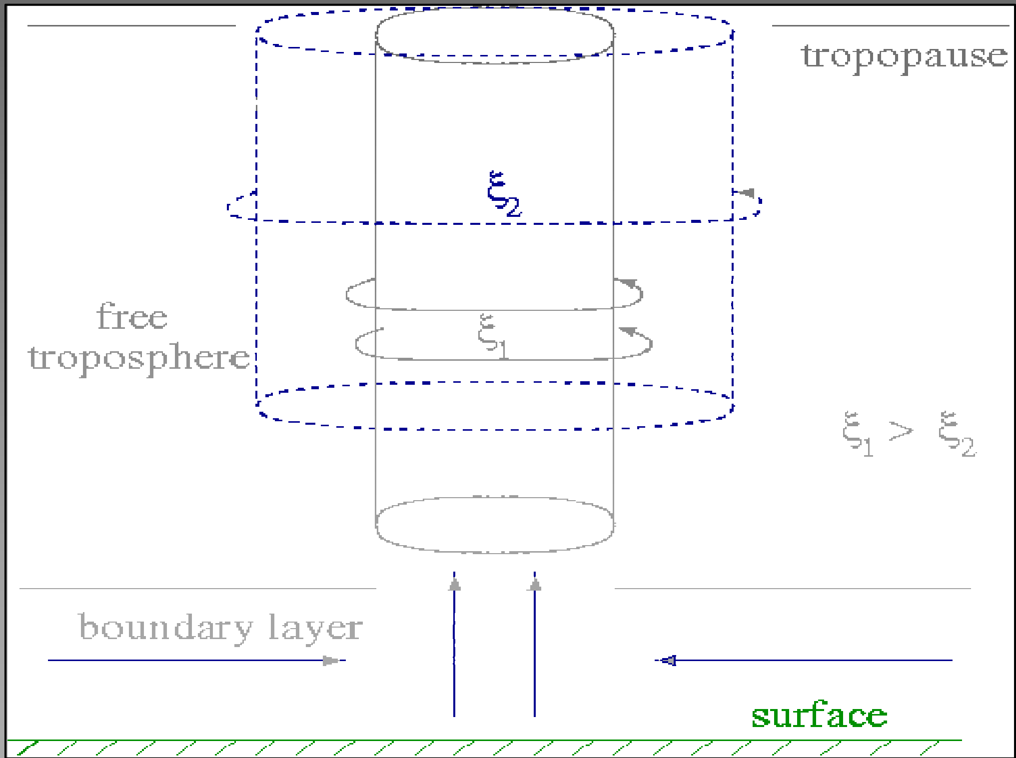
Motivation

- Increased surface roughness has improved skill in NWP forecasts:
  - Orographic roughness (Milton & Wilson 1996)
  - Ocean surface waves (Doyle 1995)
  - Stable flow around hills (Lott & Millar 1997)
- What is the mechanism?

Effect of friction on cyclones

- Baroclinic waves
  - Growth rate reduced by 50% (Valdes & Hoskins 1988)
  - Reduced eddy kinetic energy (Jones 1992)
- NWP forecasts
  - Improved surface winds and minimum pressure (Doyle 1995)
- But what is the mechanism?

Ekman spin down



Barotropic Vorticity Equation:

$$\frac{D_g \zeta}{Dt} = \zeta \frac{\partial w}{\partial z}, \qquad \zeta = f + \xi$$

But mid-latitude cyclones are baroclinic!

Potential Vorticity

$$P = \frac{1}{\rho} \underline{\zeta} \cdot \underline{\nabla} \theta$$

Natural generalisation of vorticity:

- Function of vorticity and temperature gradient
- Conserved under adiabatic, inviscid flow
- With balance condition, PV can be inverted

So: instantaneous PV

$\rightarrow$ instantaneous dynamics

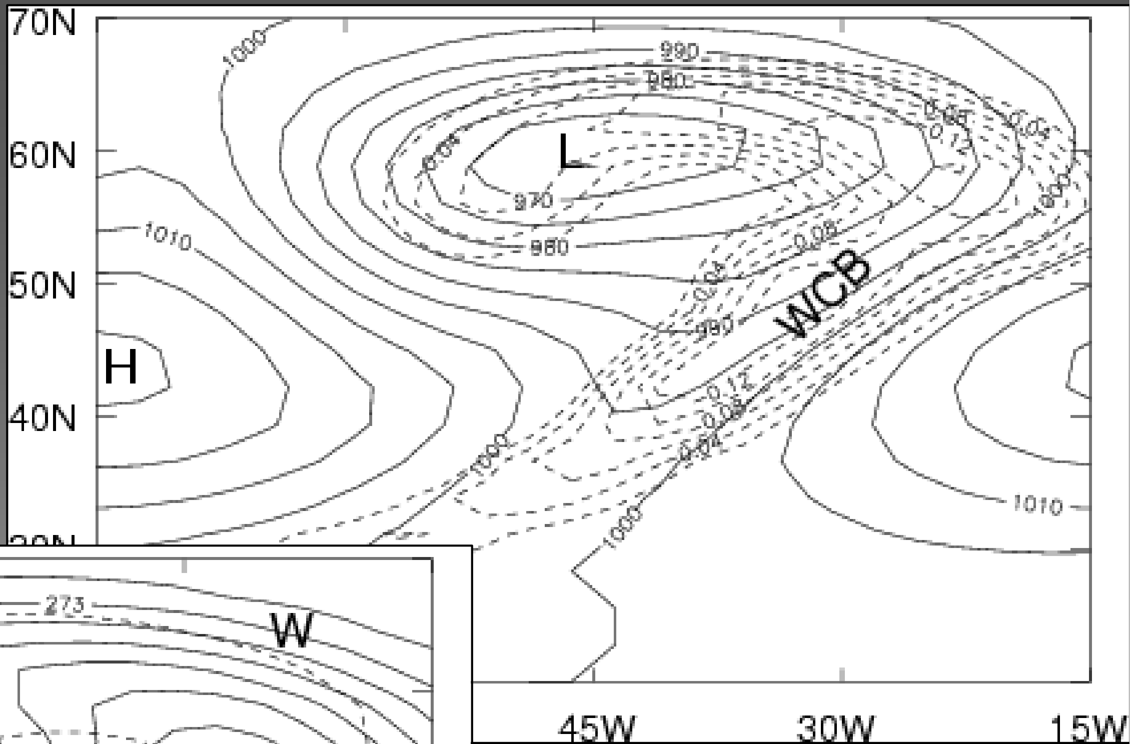
Outline of talk

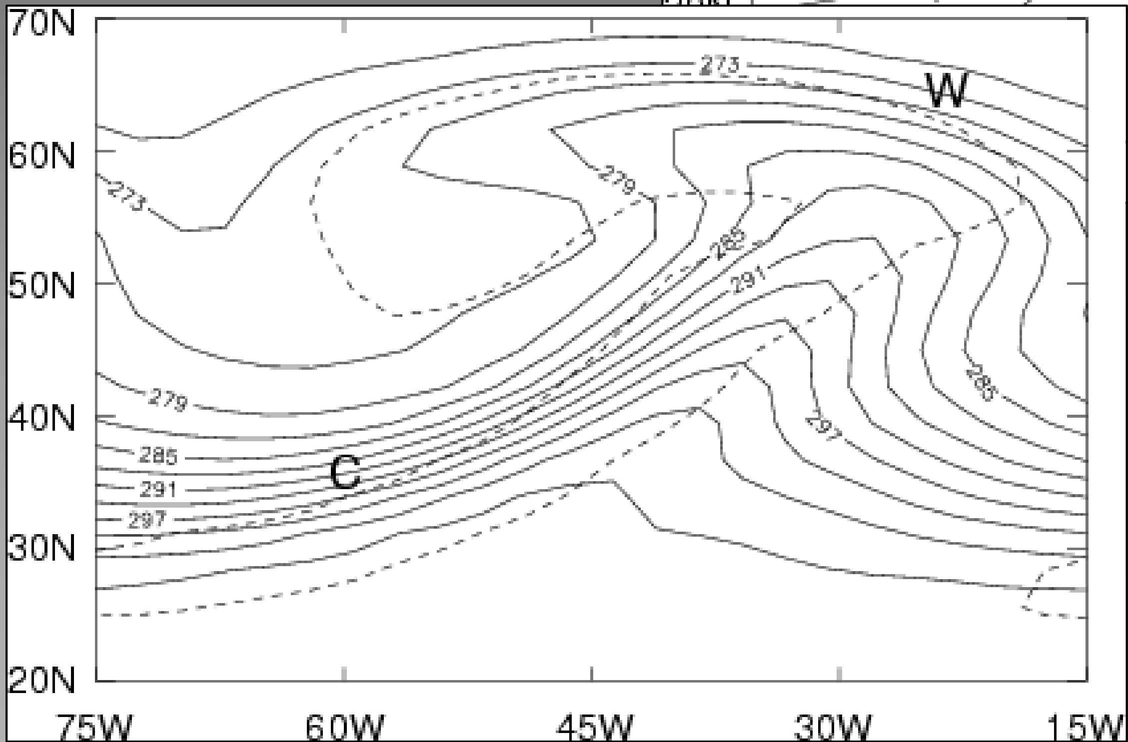
- PV view of baroclinic wave as model of mid-latitude cyclone
- PV with boundary layer friction
- Mechanisms for boundary layer generation of PV
- Mechanism for reduced baroclinic growth
- A case study
- Conclusions

Baroclinic lifecycle

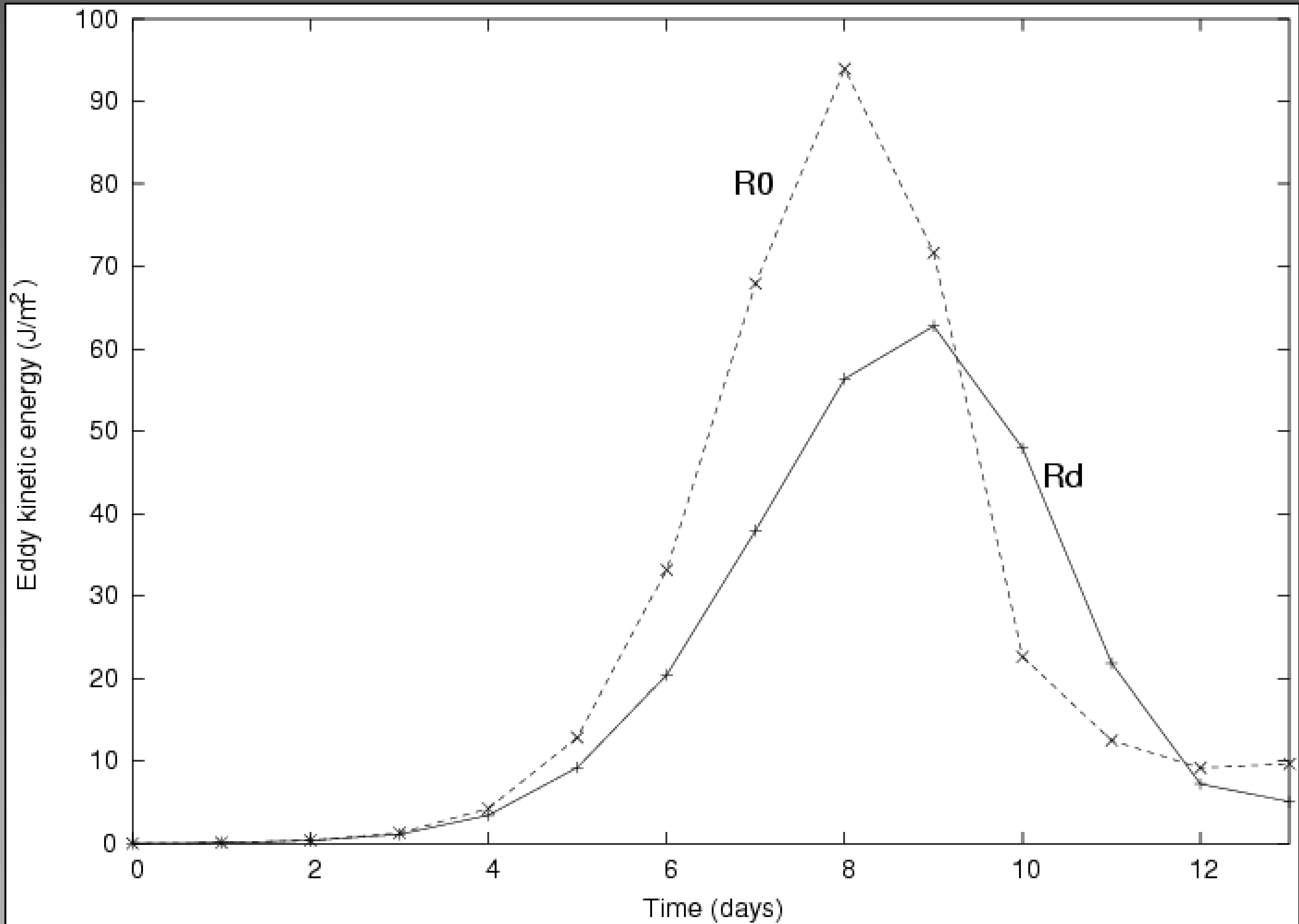
- Numerical simulations: Reading IGCM
- LC1 of Thorncroft et al:
  - Meridional temperature gradient
  - Perturb with wavenumber 6 linear mode
- Role of boundary layer friction:
  - R0: Inviscid, adiabatic simulation
  - Rd: Boundary layer representation

Life cycle at 8 days



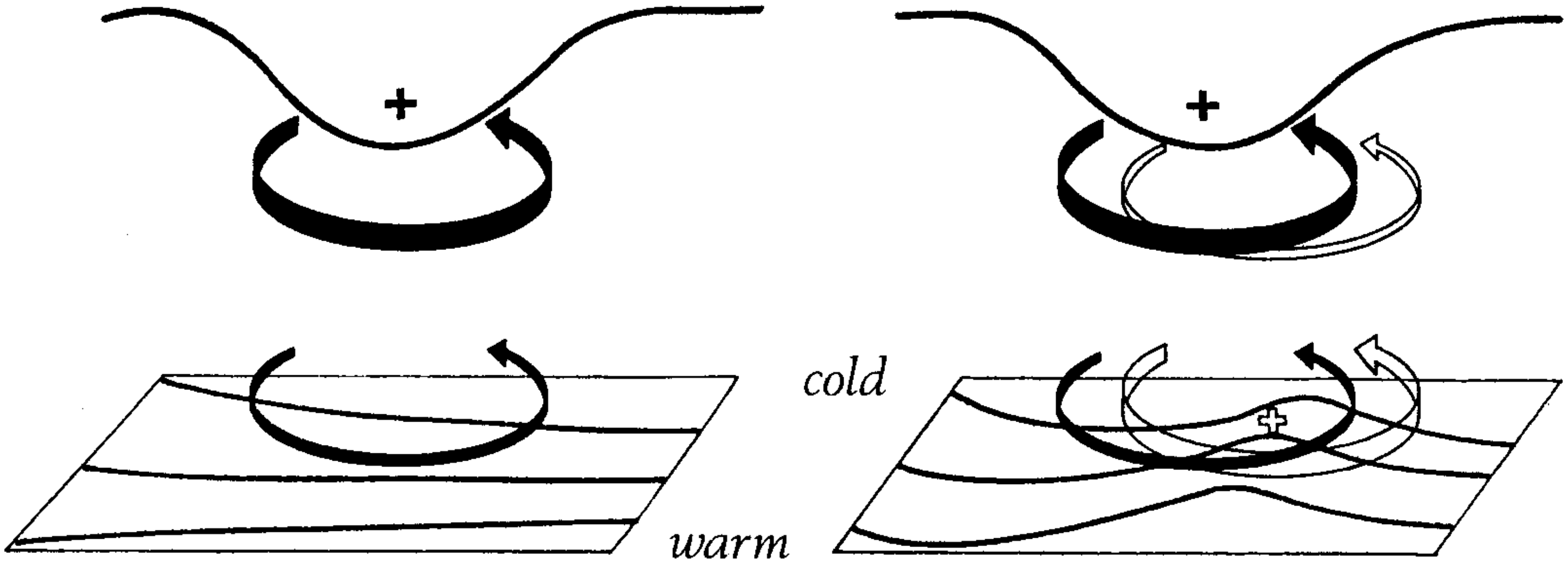


Bulk effect of friction



PV view of baroclinic instability

Hoskins, McIntyre & Roberts (1985)



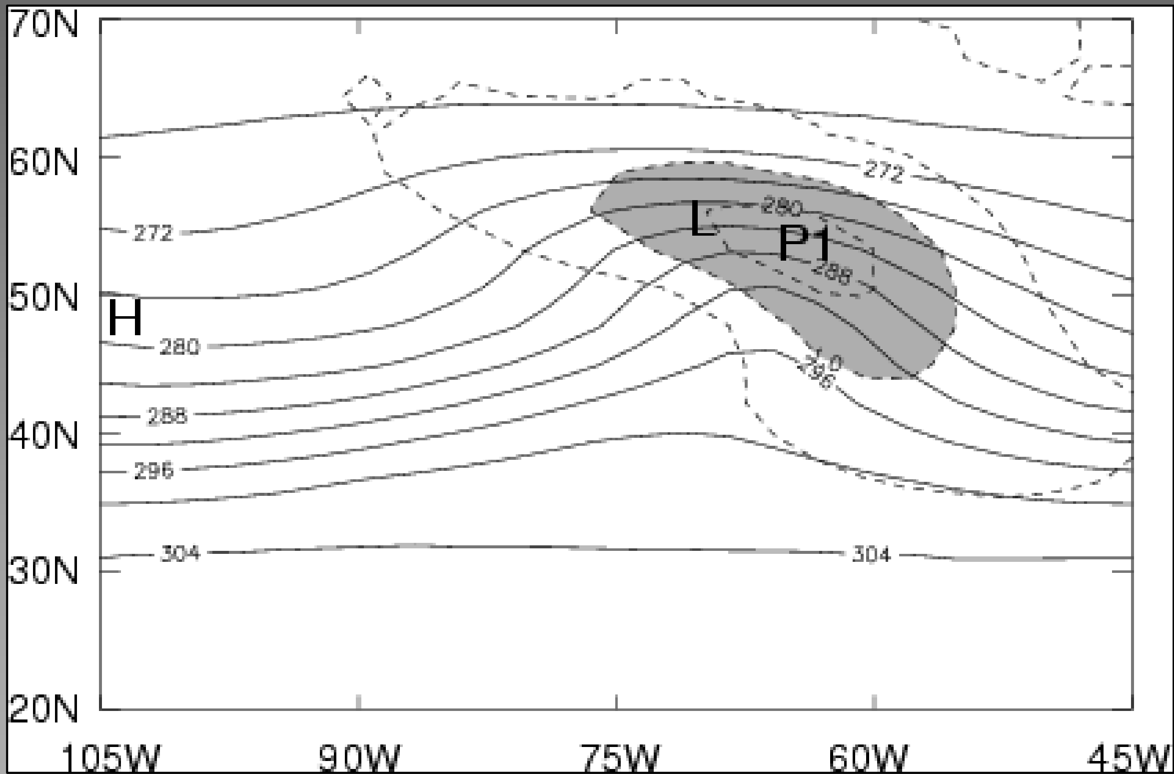
upper level influence on surface

surface level influence aloft

How does friction change this picture?

PV with boundary layer friction

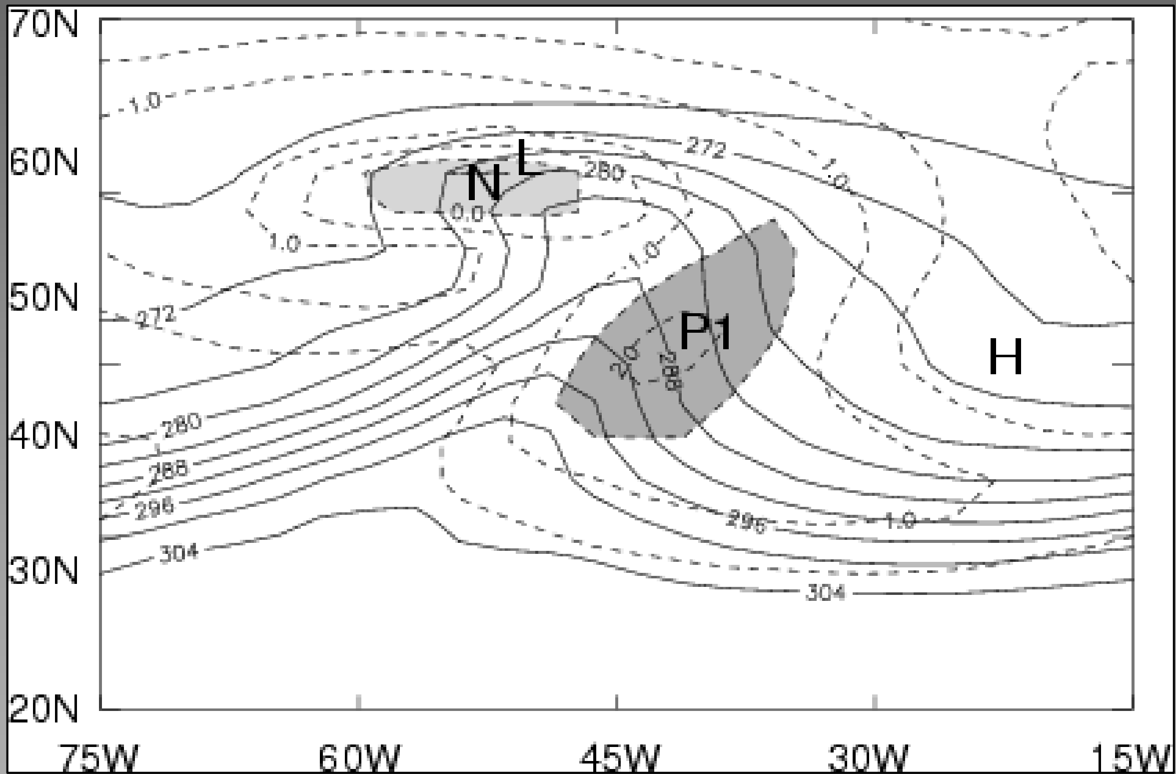
PV in frictional lifecycle I



Day 4

$$\sigma = 0.98$$

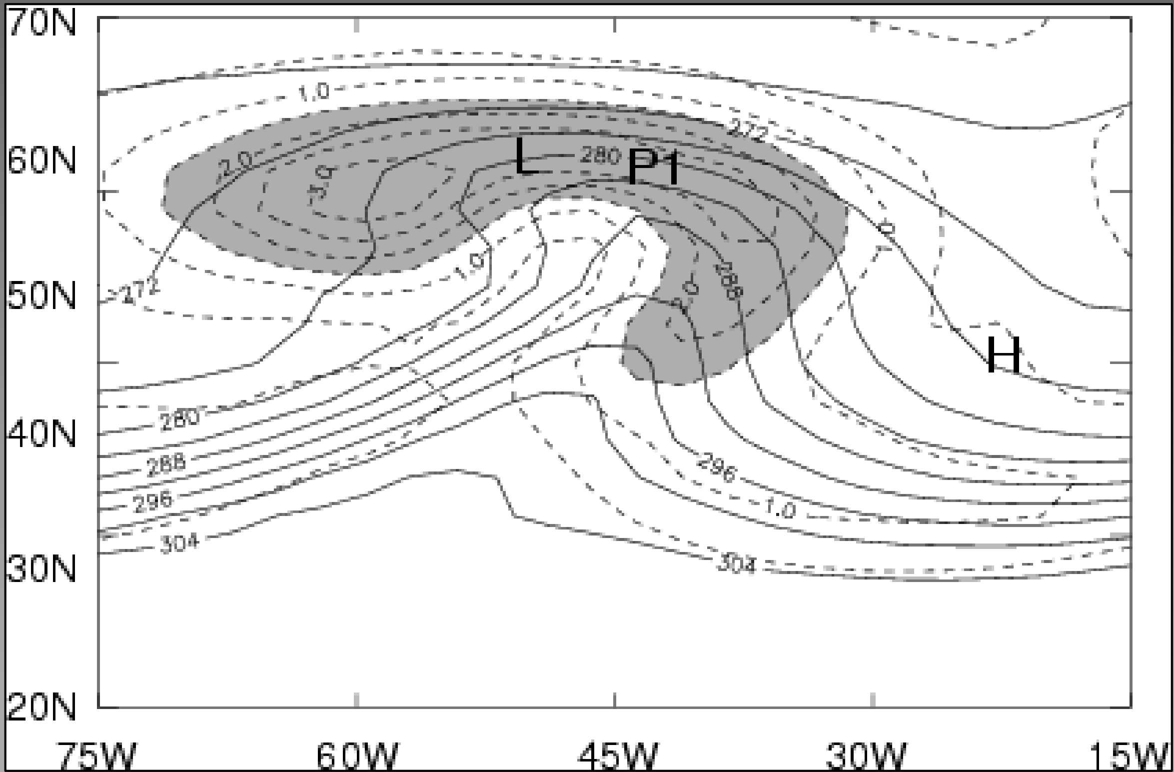
PV in frictional lifecycle II



Day 6

$$\sigma = 0.98$$

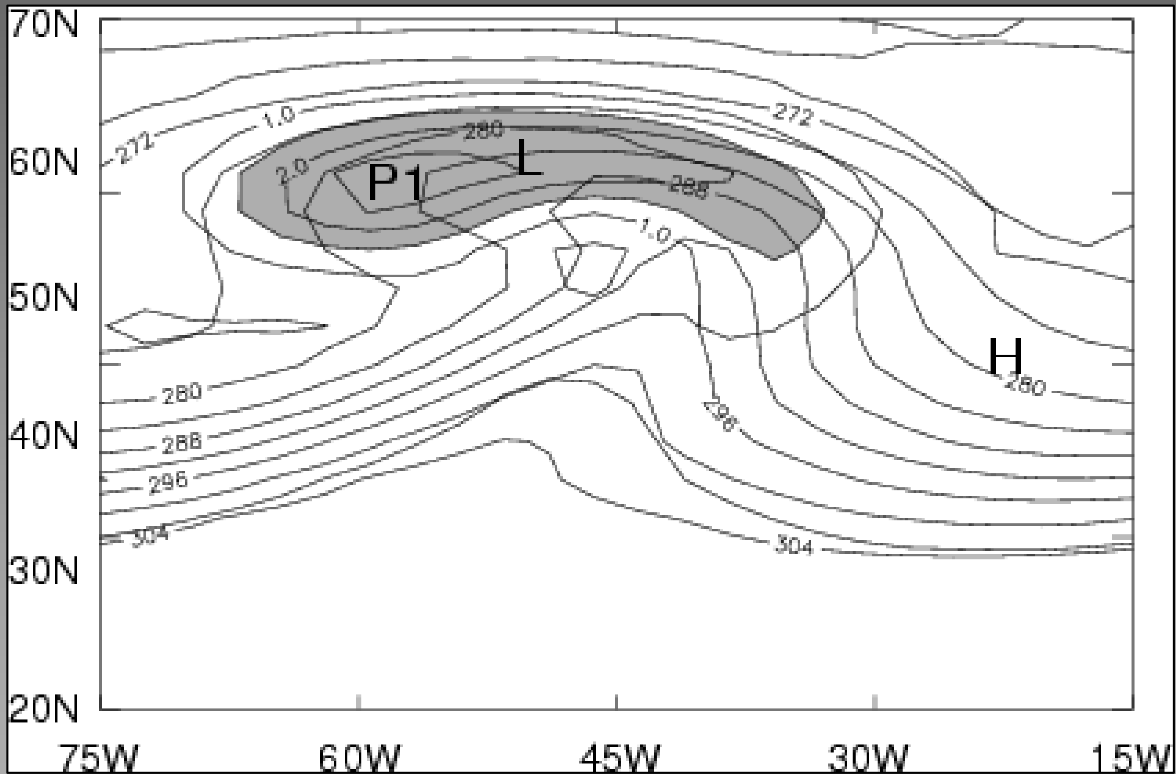
PV in frictional lifecycle III



Day 6

$$\sigma = 0.955$$

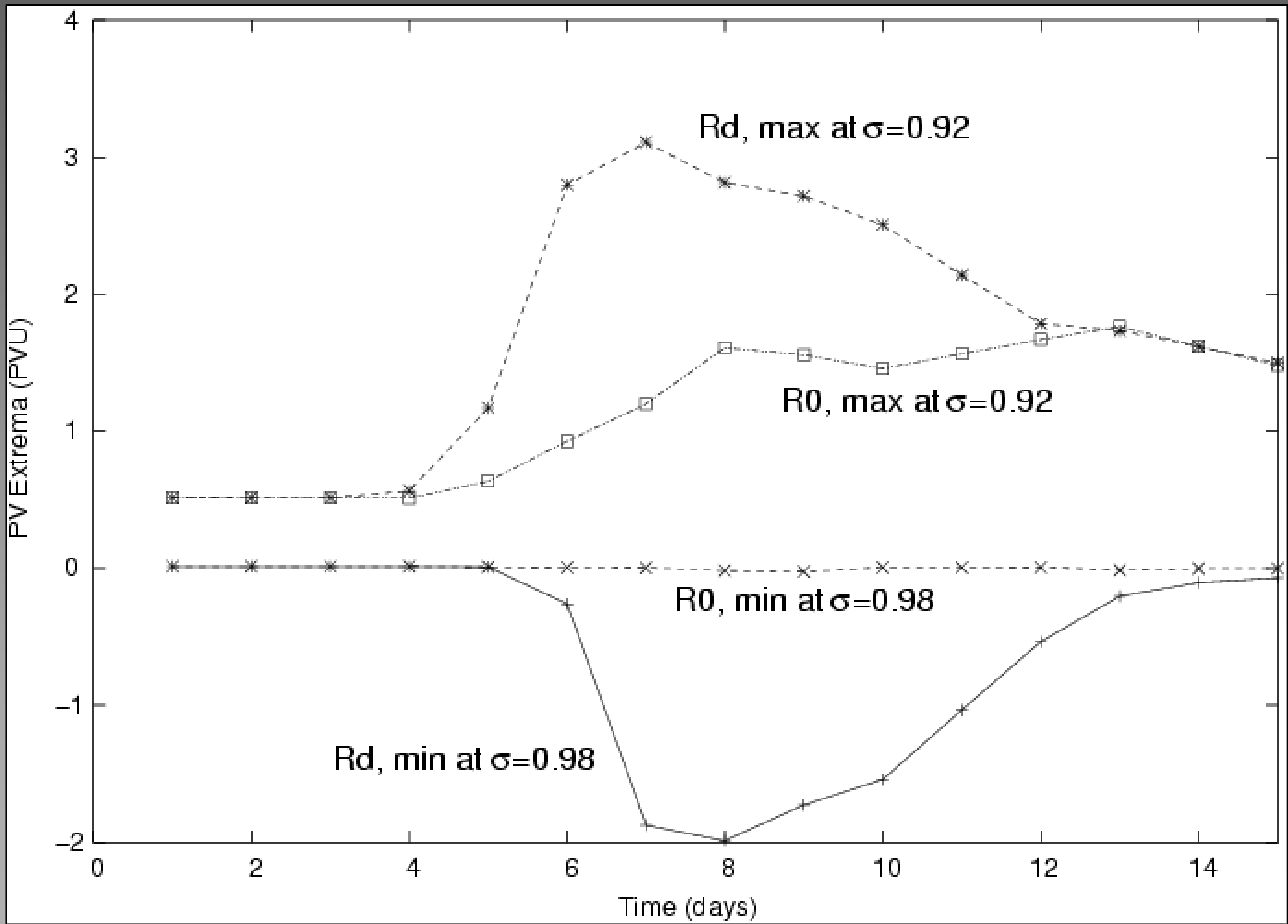
PV in frictional lifecycle IV



Day 6

$$\sigma = 0.92$$

Evolution of PV



Mechanisms for boundary layer generation of PV

Frictional generation of PV

Evolution equation for PV

$$\frac{DP}{Dt} = G = \frac{1}{\rho} \nabla \times F \cdot \nabla \theta$$

Depth integrated evolution

$$\frac{\bar{D}}{\overline{Dt}}[P] = [G] - F_h$$

$$[G] = [G_E] + [G_B], \quad F_h = \frac{1}{h} w_h P_h$$

Frictional generation of PV

Ekman generation:

$$\left[G_E\right] = -\frac{1}{(\rho h)^2}\Delta\theta\,\vec{k}\times\vec{\tau}_s$$

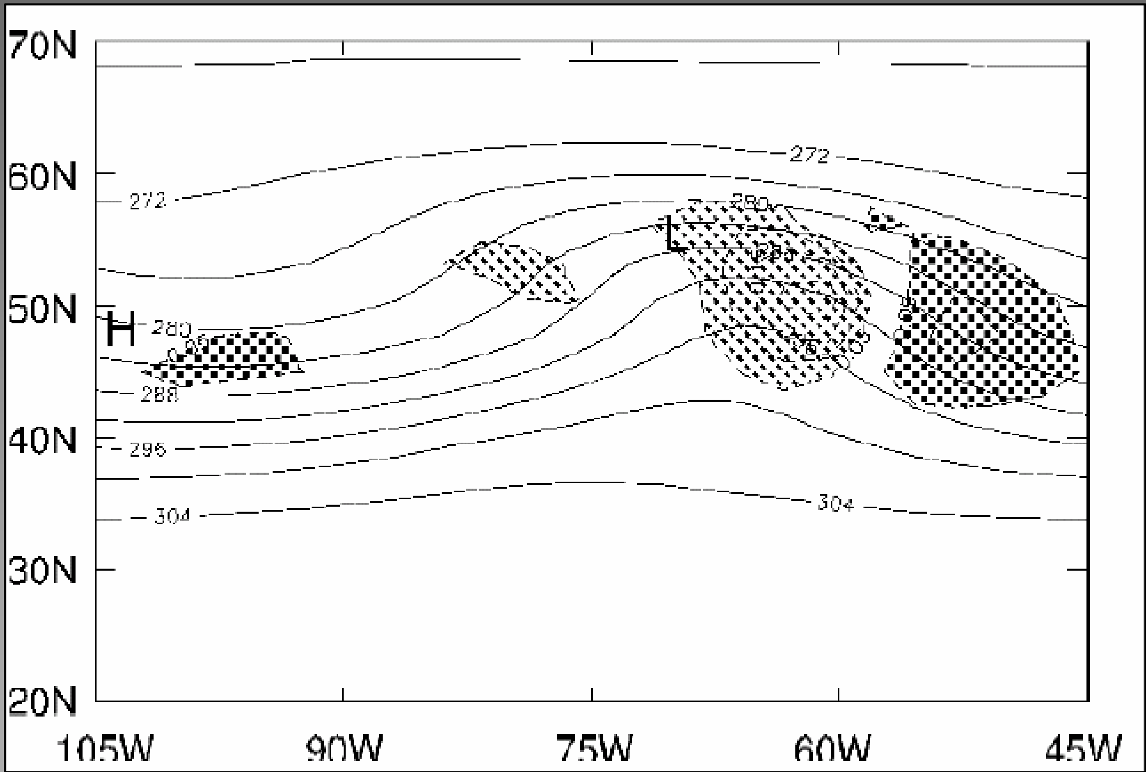
Baroclinic generation:

$$\left[G_B\right] = \frac{1}{(\rho h)^2}\vec{k}\times\vec{\tau}_s\cdot(\nabla\theta)_h \propto -\vec{v}_s\cdot\vec{v}_T$$

Ratio:

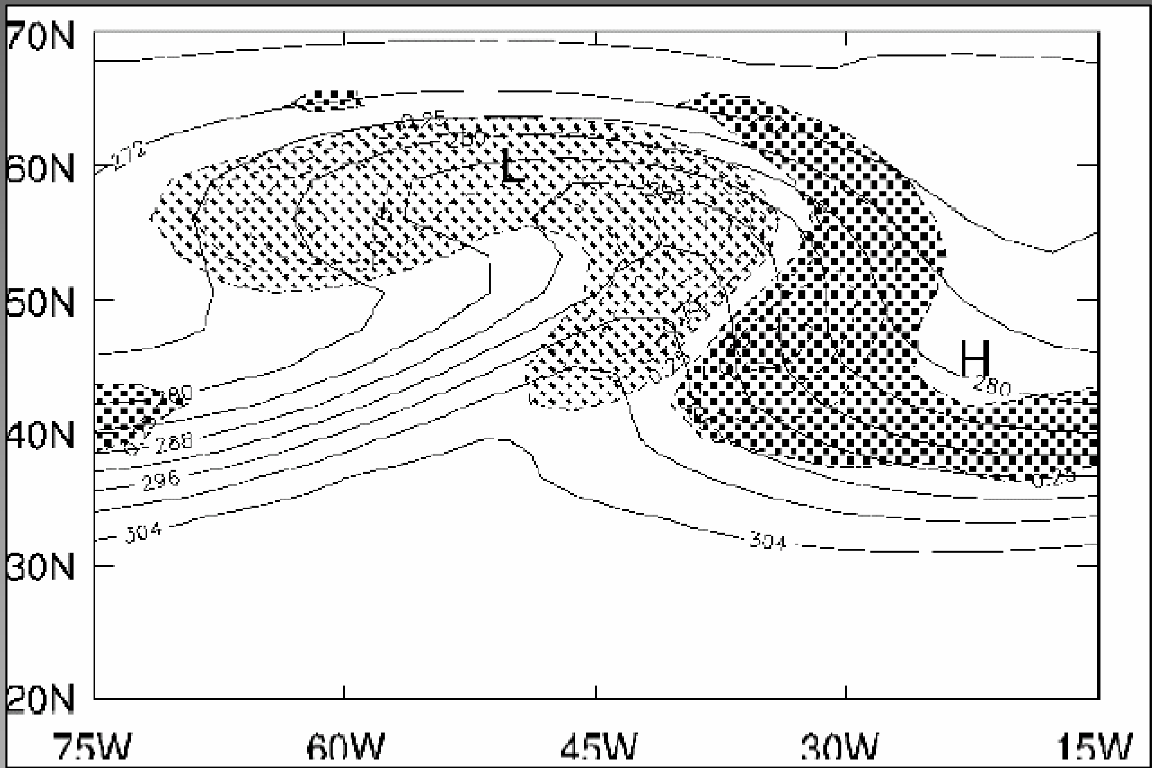
$$\frac{\left[G_B\right]}{\left[G_E\right]} \approx \frac{L\nabla\theta\big|_h}{\Delta\theta} \approx \frac{25K}{5K} = 5$$ But caution!

PV generation: Ekman



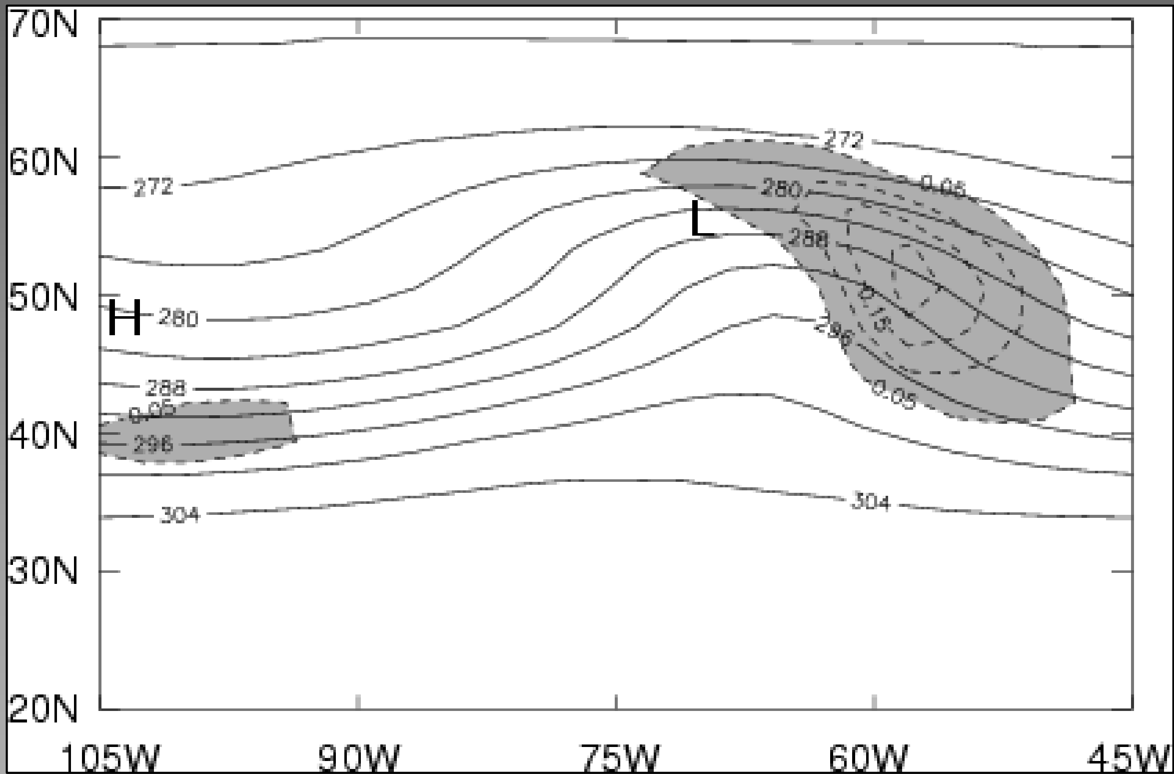
Day 4

PV generation: Ekman



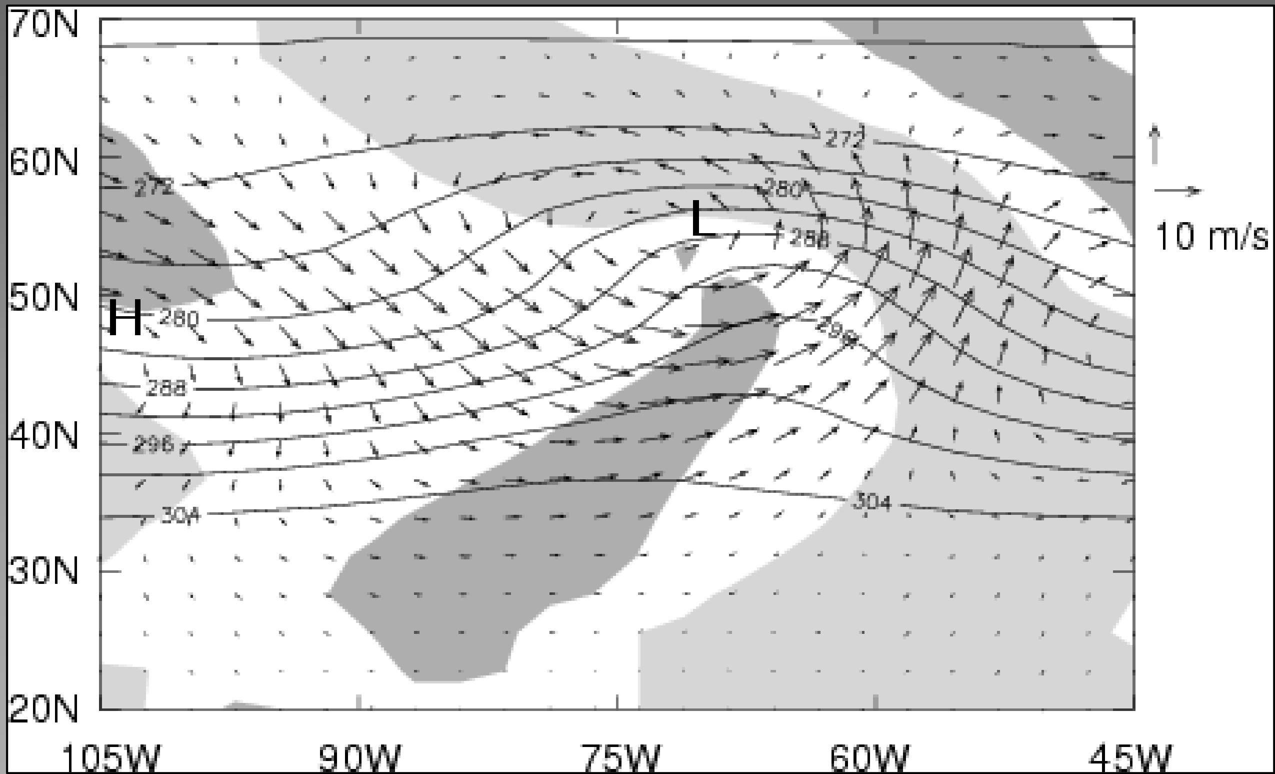
Day 6

PV generation: Baroclinic



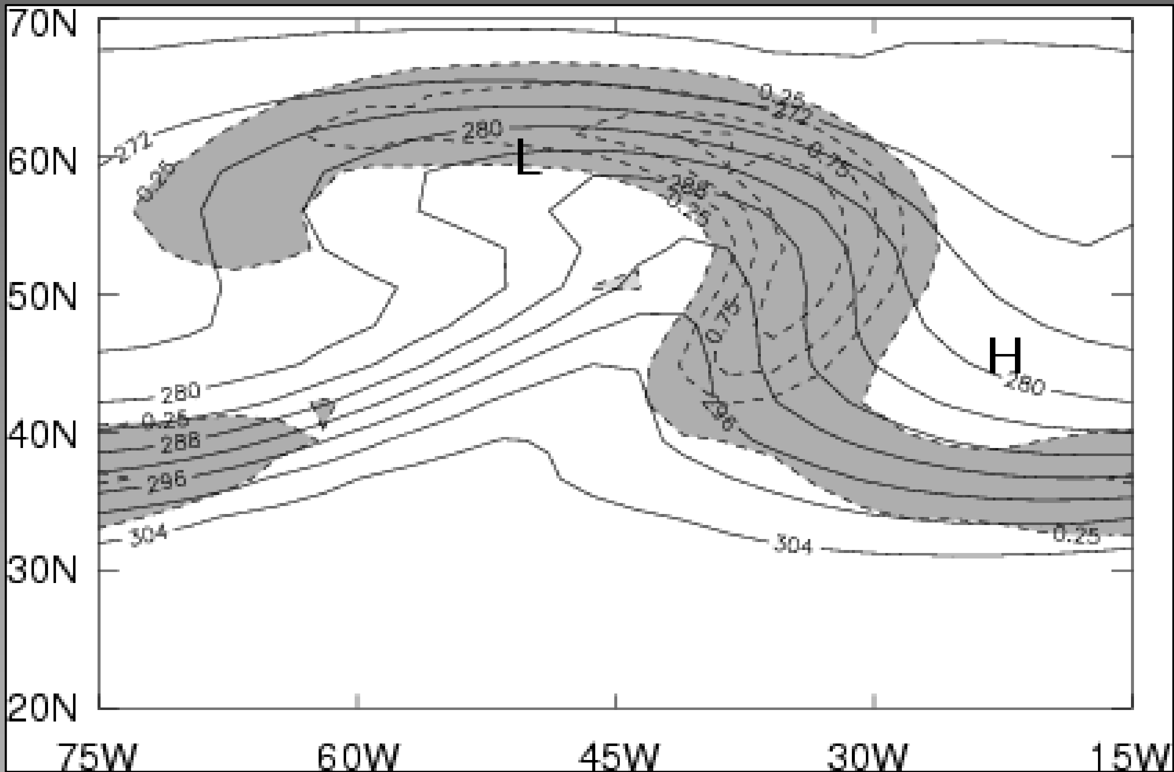
Day 4

PV generation: Baroclinic



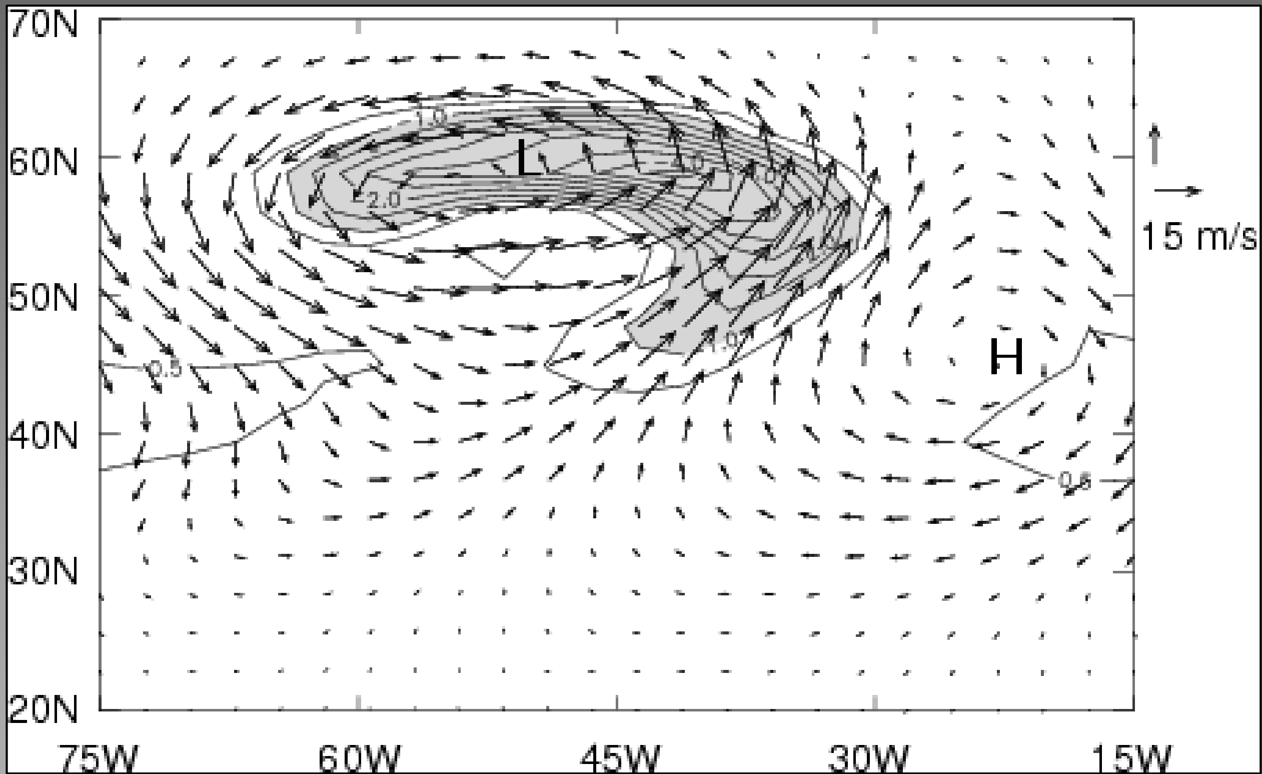
Day 4

PV generation: Baroclinic



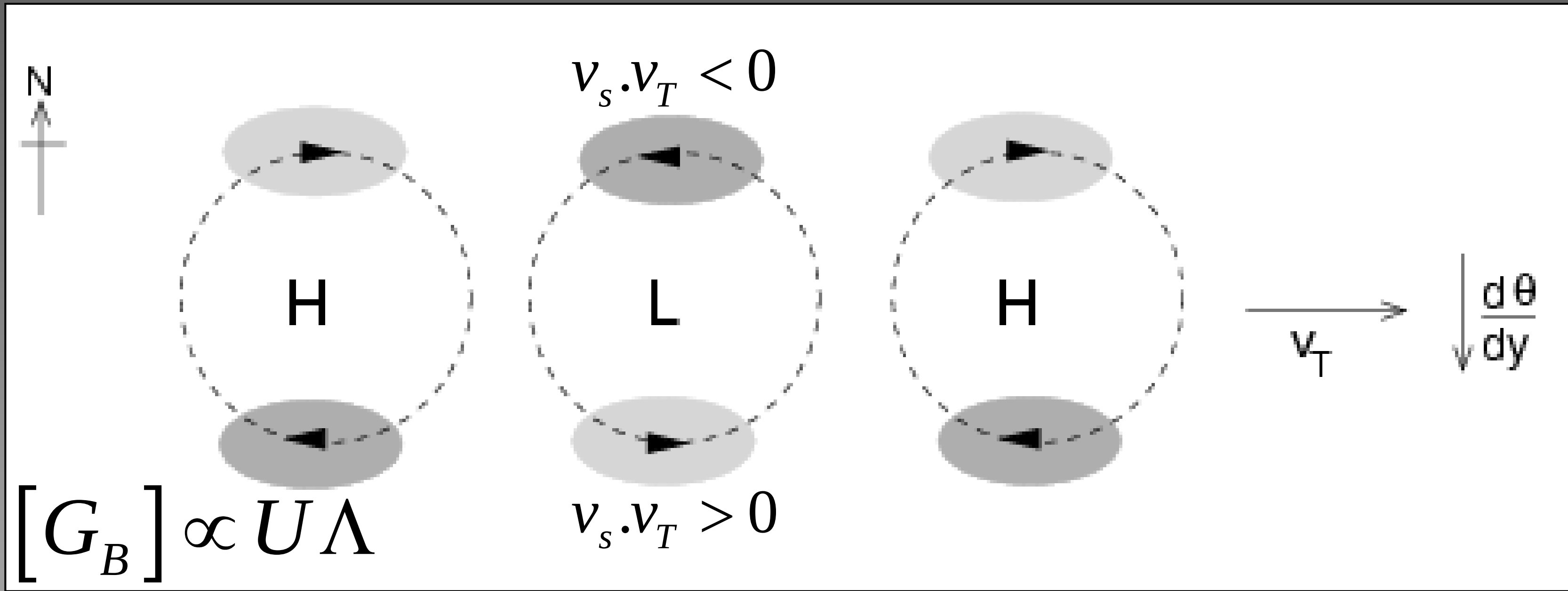
Day 6

PV flux out of boundary layer



Day 6

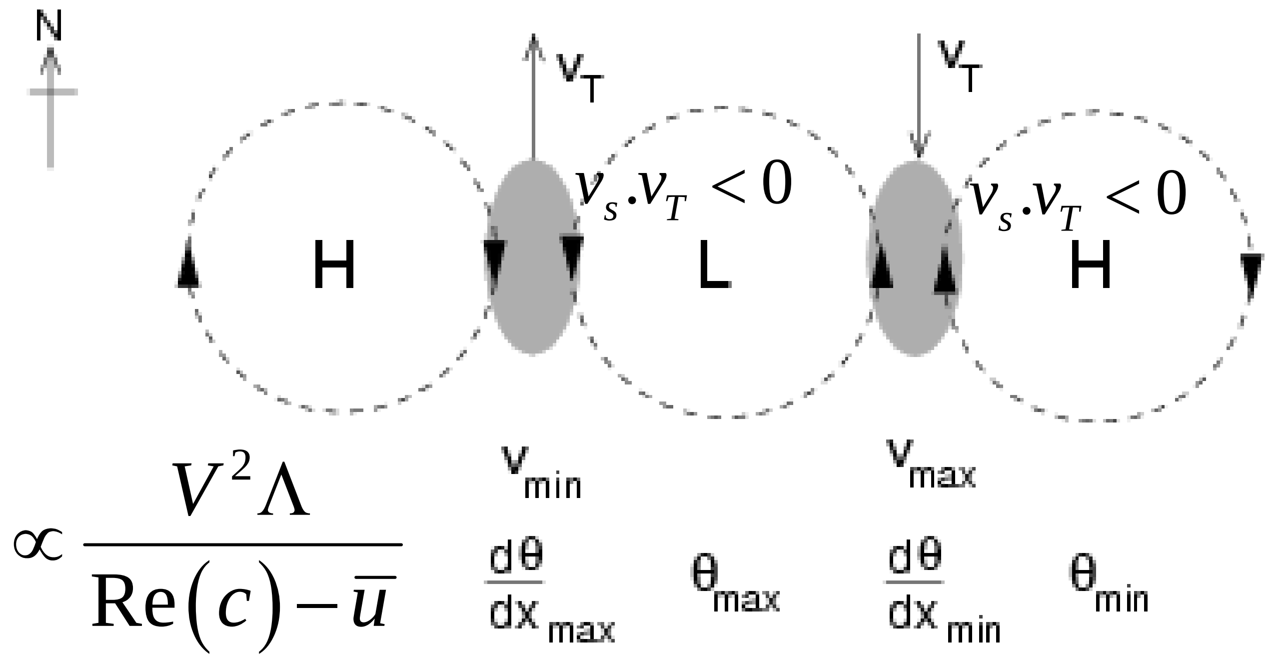
Baroclinic mechanism I



Meridional temperature gradient

Zonal wind perturbations

Baroclinic mechanism II

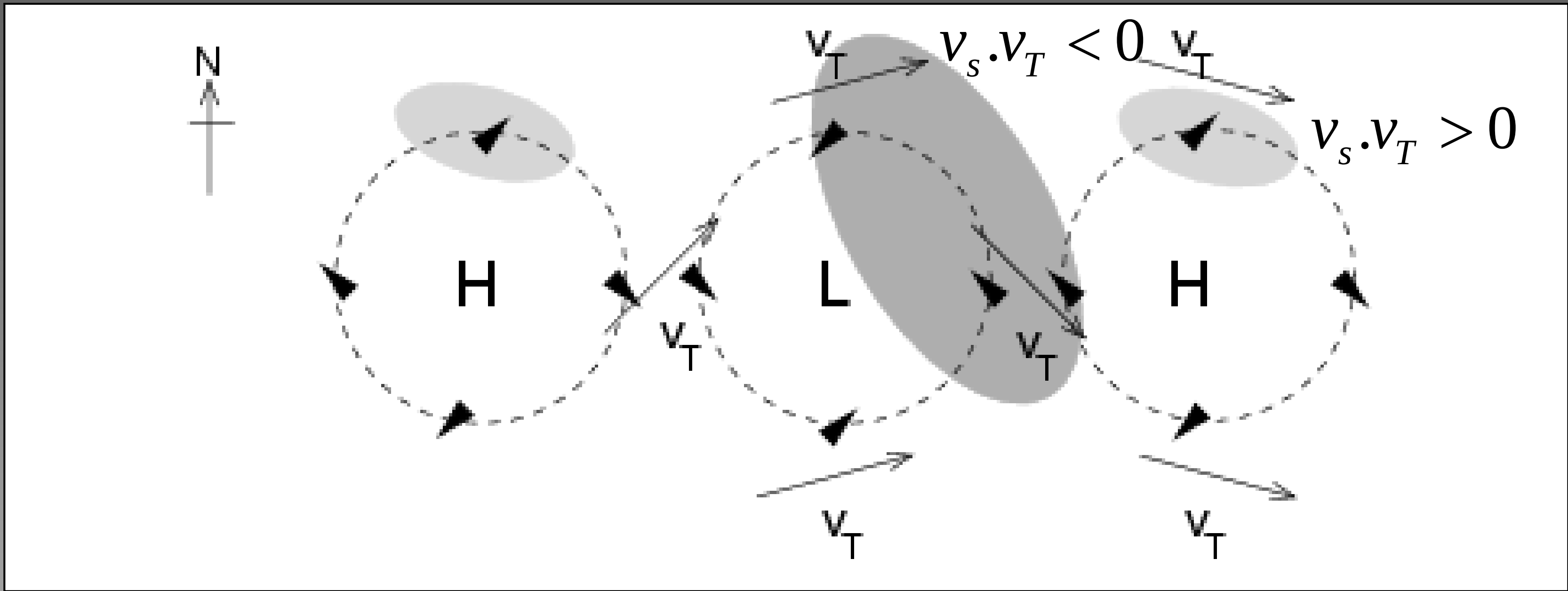


$$\left[G_B\right] \propto \frac{V^2 \Lambda}{\mathrm{Re}\left(c\right) - \overline{u}}$$

Meridional wind perturbations

Zonal perturbation temperature gradient

Baroclinic mechanism III

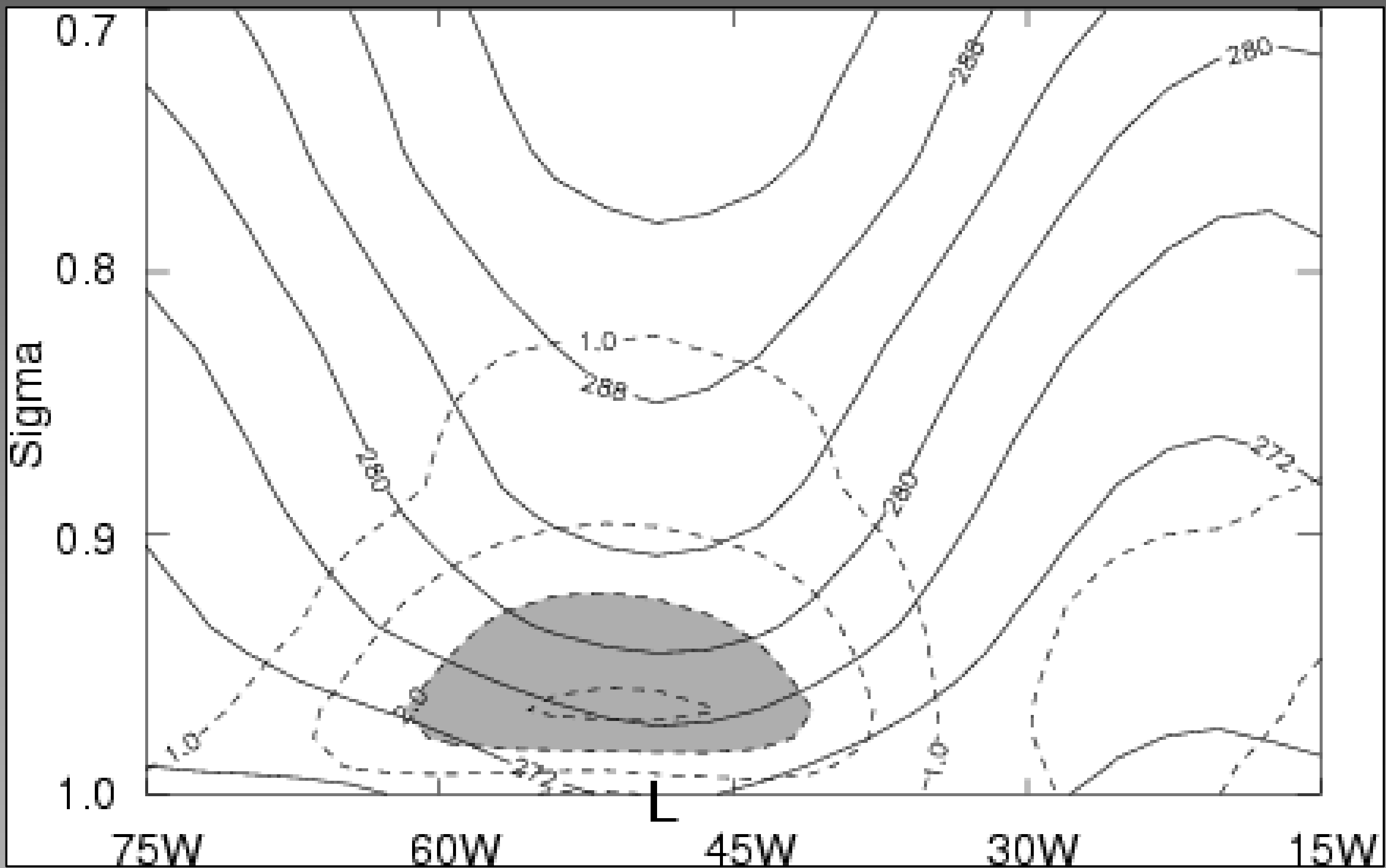


Frictional turning of surface winds

$\rightarrow$ **Primary generation: positive and NE of low**

Mechanism for reduced baroclinic growth

Reduction in baroclinic growth



Day 6

Increased stability

Reduced growth rate

Growth rate of Eady wave: $\sigma \propto \dfrac{1}{N}$

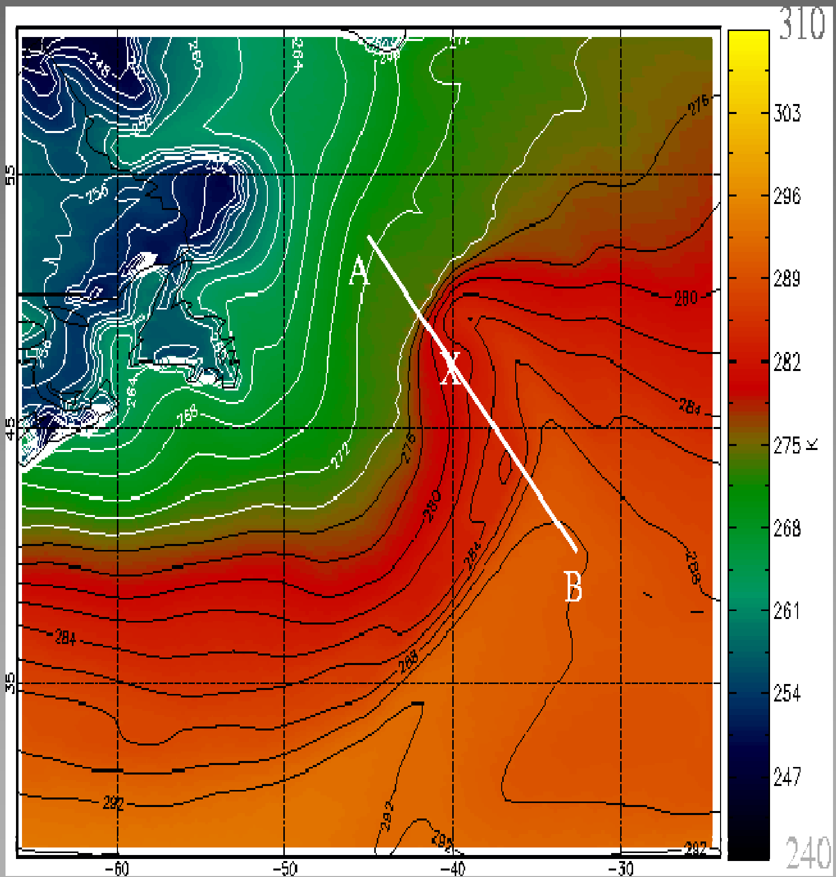
Use measured *N*:

- Growth rate reduced by 40%
- 25% due directly to reduced static stability
- 15% because Rossby radius increases so that wavenumber 6 no longer optimal

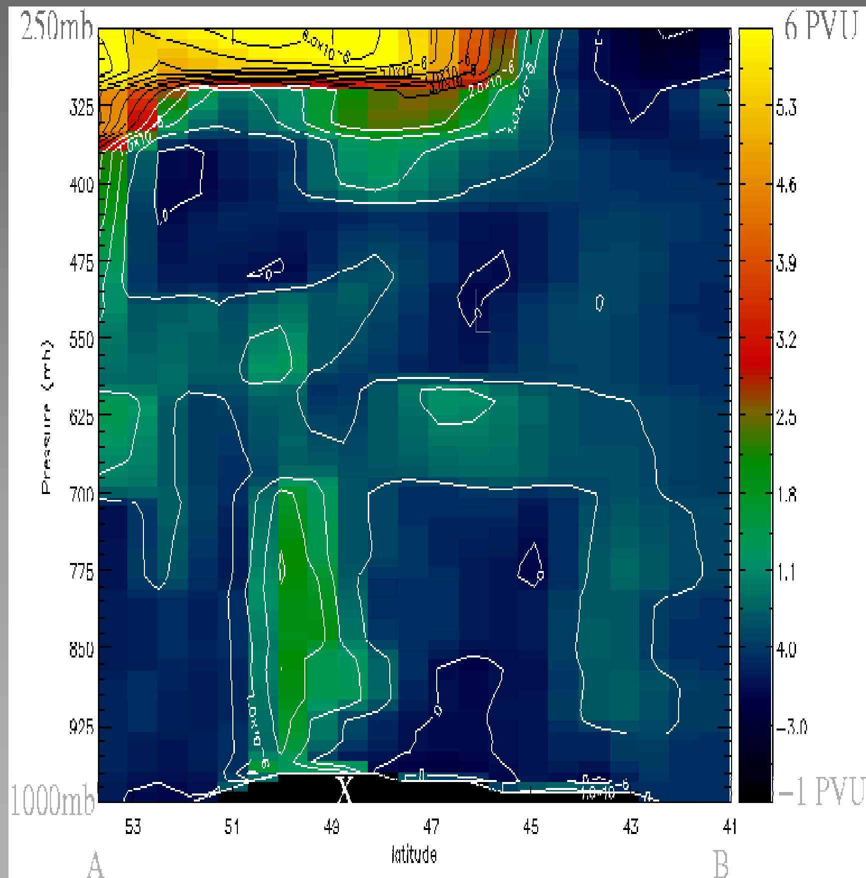
A case study

FASTEX IOP 15

FASTEX IOP15

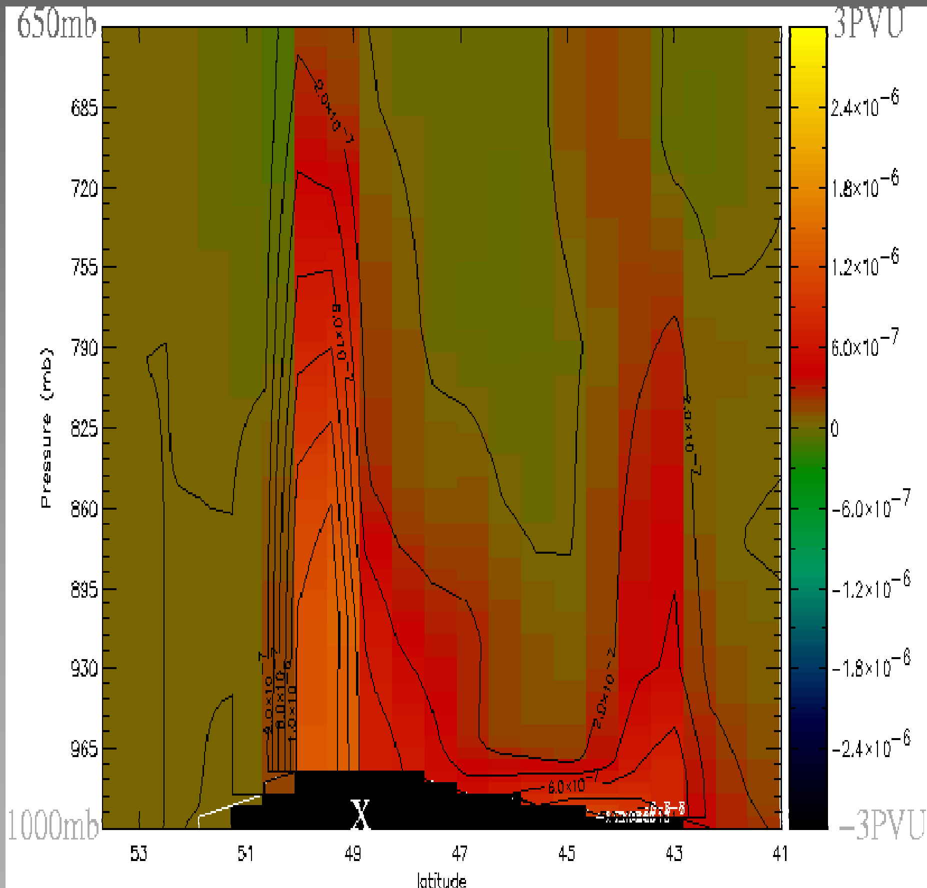


Temperature

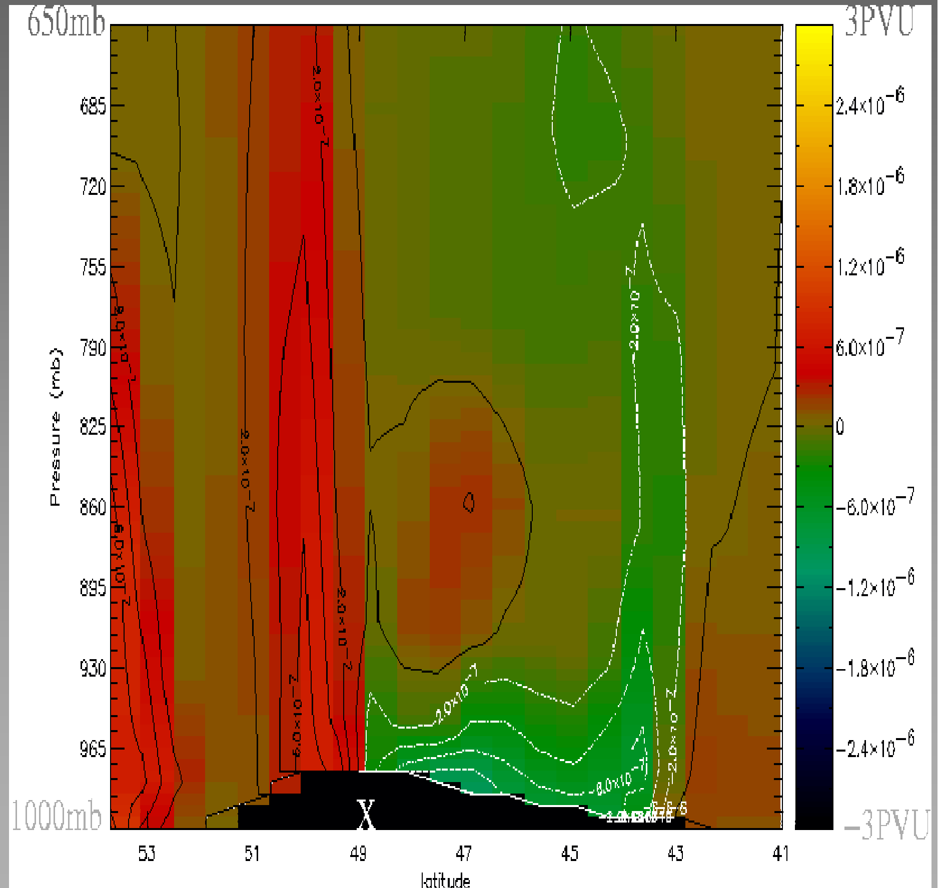


PV on cross section

PV generated by physics



PV from heating



PV from GB

Conclusions

Boundary layer friction generates PV through two mechanisms:

- Ekman generation: Weak
  - Destroys PV near low centre
  - PV remains near low centre
- Baroclinic generation: Strong
  - Generates PV NE of low - robust mechanism
  - PV fluxed out of boundary by warm conveyor belt

Conclusions

- Growth rate of baroclinic wave reduced
  - Baroclinically generated PV reduces static stability and so reduces coupling between upper and lower level PV
- Case study:
  - Latent heating: 2/3 PV from physics
  - Friction: 1/3 PV from physics