PV Generation in the Boundary Layer

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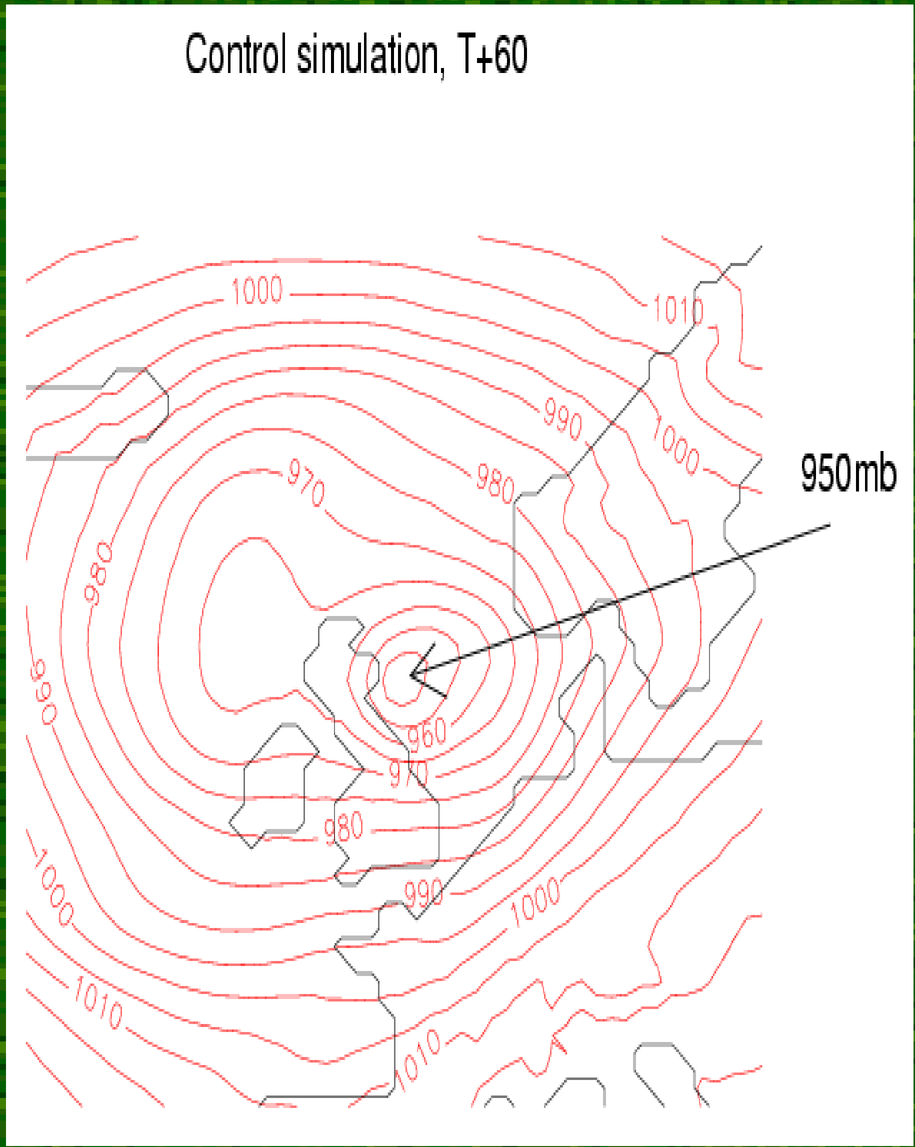
(With thanks to S. Belcher)

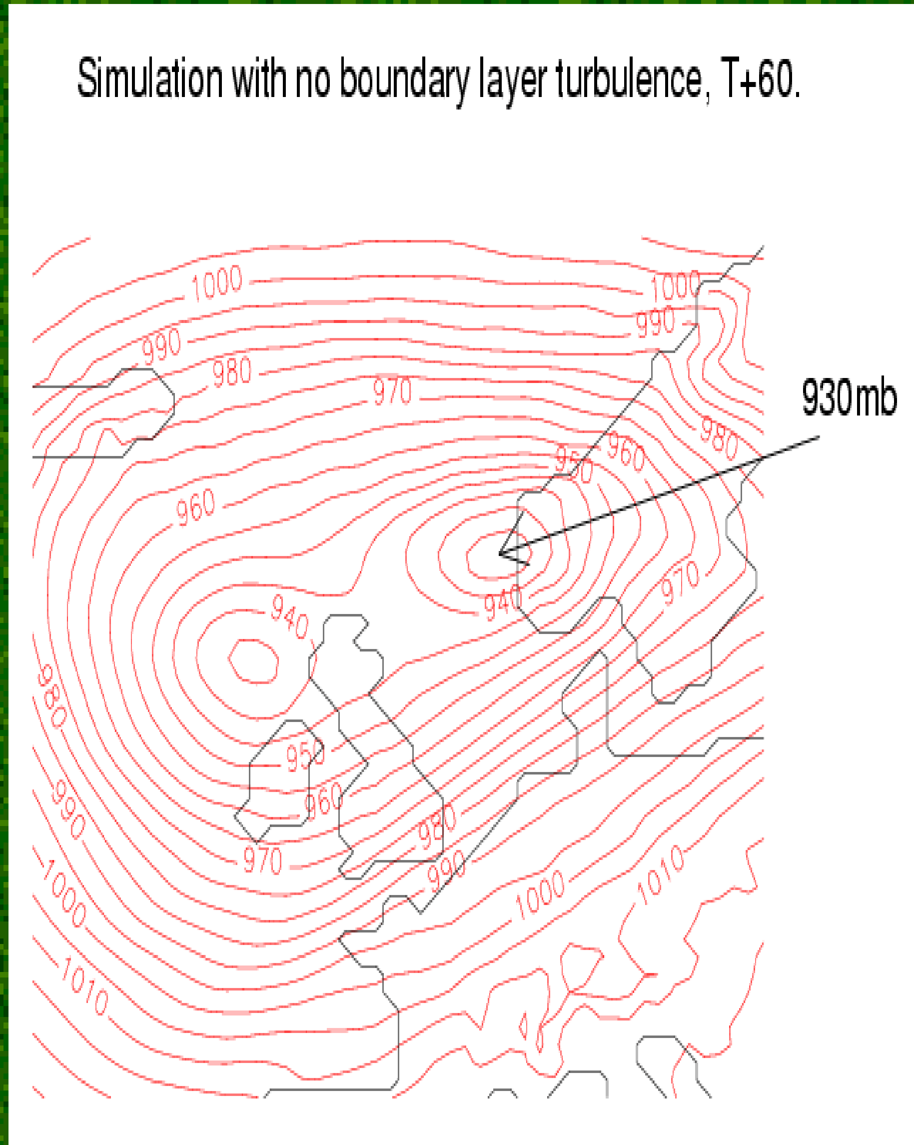
Introduction

- How does the boundary layer modify the behaviour of weather systems?
- Often regarded as a secondary effect.

But...

- The boundary layer is **often very active** within weather systems.
- Boundary layer processes are sometimes crucial.

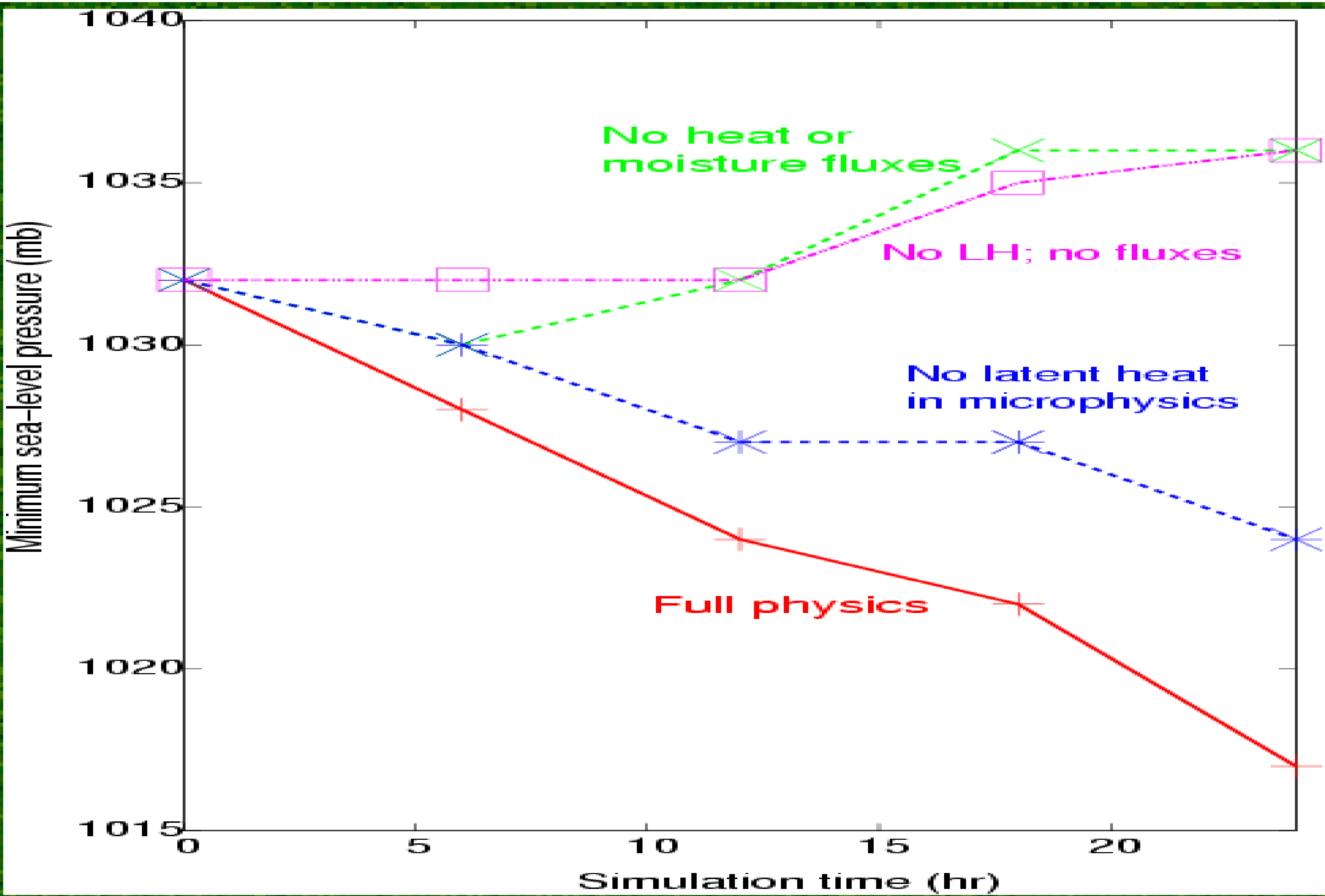




UM simulation of storm at 12Z on 31/10/00, with and without the model's boundary layer scheme.

Another Inviscid Example

- In a 24h cyclone simulation by Anthes and Keyser (1979):
  - With friction:
    - Minimum pressure of **978mb**
  - Without friction:
    - Minimum pressure of **955mb**
- A subtlety:
  - ~20% more precipitation with friction.
  - Stronger moisture convergence in boundary layer led to increased convection.



Minimum pressure of a system simulated by Uccellini et al (1987)

Interactions of Model Processes

- NB: Interactions between parameterized processes can be extremely important.
- Therefore: it is **dangerous** to try to determine the effect of a process by switching it on and off.
- The result may be…
    - a new, different and **highly unphysical** system,
- and not…
    - a perturbation of the system of interest.

How can we compare the actions of many interacting processes operating within a real system?

Outline

- What is PV anyway, and why do we care?
- Determining the integrated effects of model processes
- Results from UM simulations illustrating:
- Ekman pumping, and various other boundary layer mechanisms
- Conclusions

What is Potential Vorticity(PV)?

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

- A function of vorticity and the temperature gradient.
- Inversion:
  - Suppose there exists a relationship between the spatial distributions of wind and temperature. (Balance condition.)
  - With this and the PV, winds and temperature can be deduced.

$\Rightarrow$ Knowing the instantaneous PV means that we know the instantaneous state of the dynamics.

How does the PV evolve?

- PV is locally conserved in adiabatic, inviscid flow.

$$\rho \frac{DP}{Dt} = \underline{\nabla} \times \underline{F} . \underline{\nabla} \theta + \underline{\zeta} . \underline{\nabla} \frac{D\theta}{Dt}$$

- The PV field is:
  - advected by the total flow
  - modified by diabatic heating and frictional deceleration.

Constructing A Local PV Budget ….

A Local Budget

- Consider a variable V that is moved around by the flow.

$$V(\underline{r},t) = V_0(\underline{r},t) + \sum_i V_i(\underline{r},t)$$

- where:
  - V_0 is the advected form of the initial field, $V_0(t=0) = V(t=0)$
  - V_i is that part of the current V field due to the action of each parameterized "physics" process i.

Generation due to Process *i*

- To calculate the budget:
  - Increment V_i whenever the model "does i".
  - Advect V_0 and V_i whenever the model advects its prognostic fields.

- In the UM, sequential physics $\Rightarrow$

Increment from process i =
V just after i – V just before i

Generation due to a Subprocess

- We may want to subdivide process i into different sub-processes of interest.
- If the temperature and momentum changes for each subprocess are known, the tendency equation attributes the PV.

$$PV \text{ from boundary layer scheme} = \rho^{-1}\Big\{$$

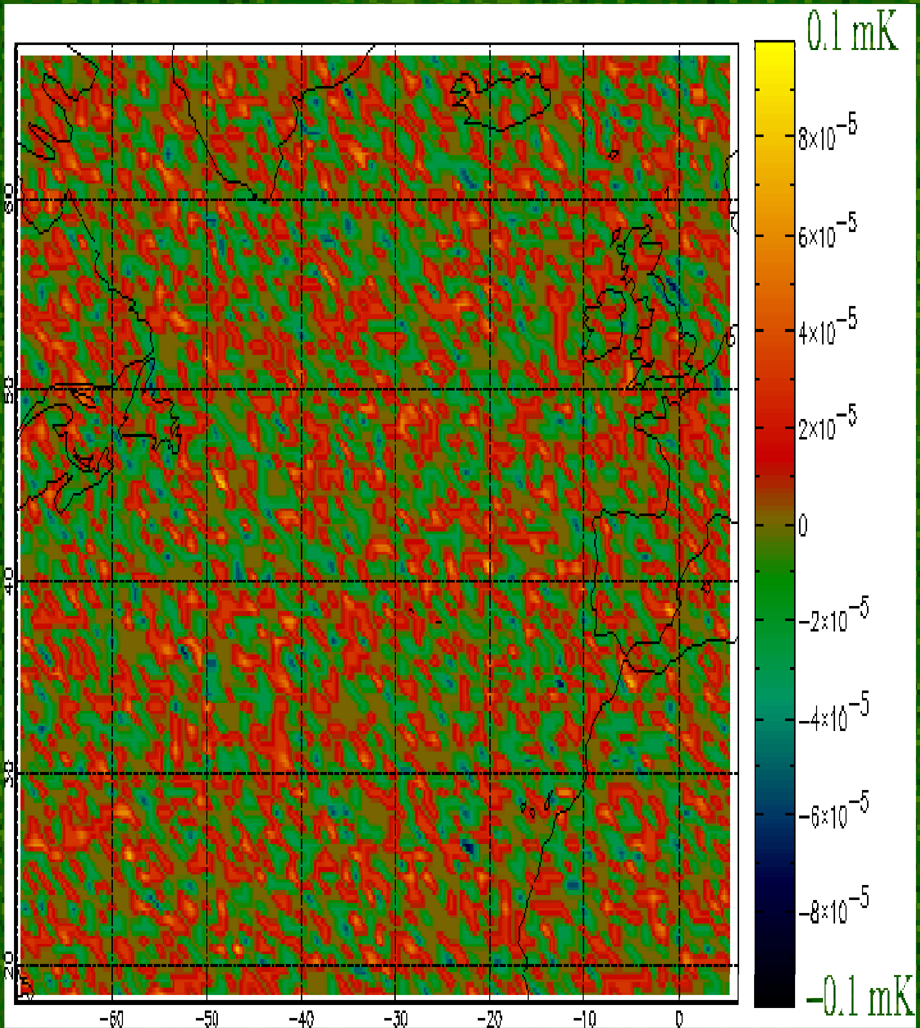
Barotropic friction	$\left(\underline{\nabla}\times\underline{F}\right)_z \dfrac{\partial\theta}{\partial z}\delta t +$
Baroclinic friction	$\left(\underline{\nabla}\times\underline{F}\right)_H \underline{\nabla}_H \theta\delta t +$
Heat fluxes	$\underline{\zeta}\cdot\underline{\nabla}\delta\theta_{\text{heat fluxes}} +$
Latent heating	$\underline{\zeta}\cdot\underline{\nabla}\delta\theta_{\text{latent heating}} \Big\}$

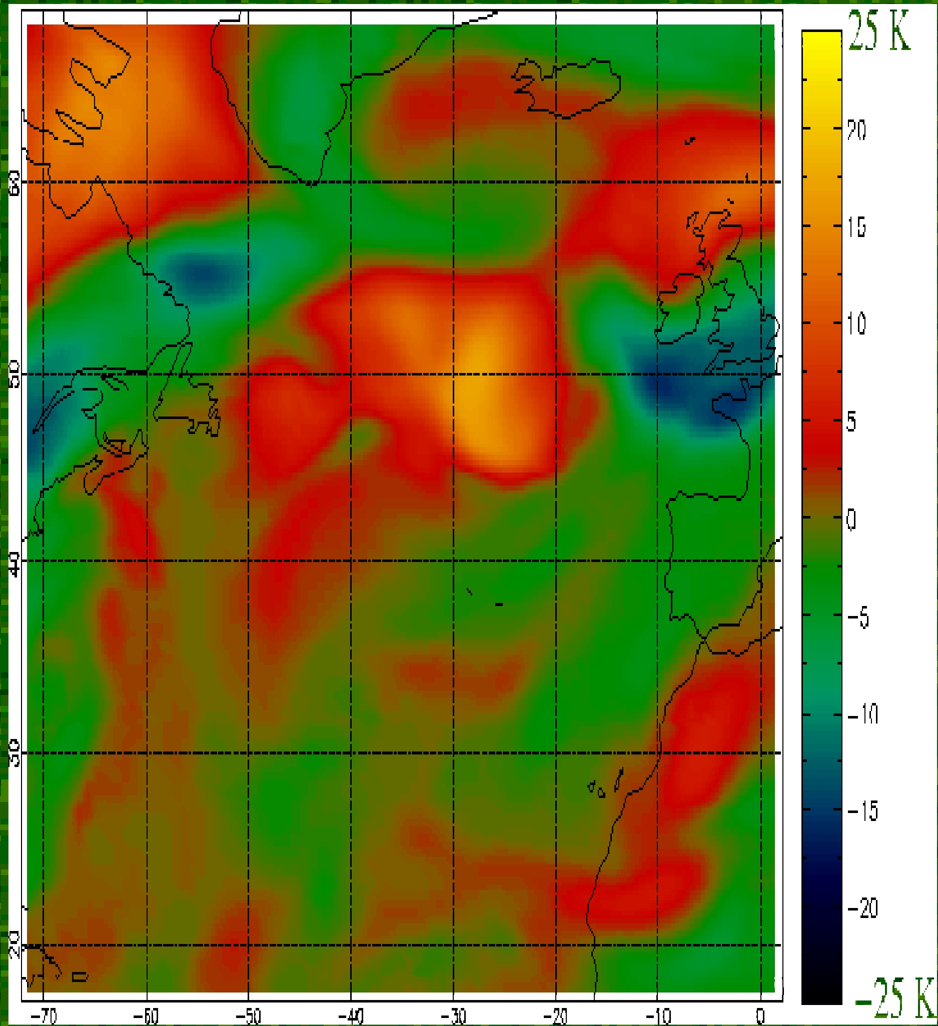
Dynamics

- If the model advection scheme acts as a linear operator on V then:

$$\text{advection of } V = \text{advection of } V_0 + \textstyle\sum_i \text{advection of } V_i$$

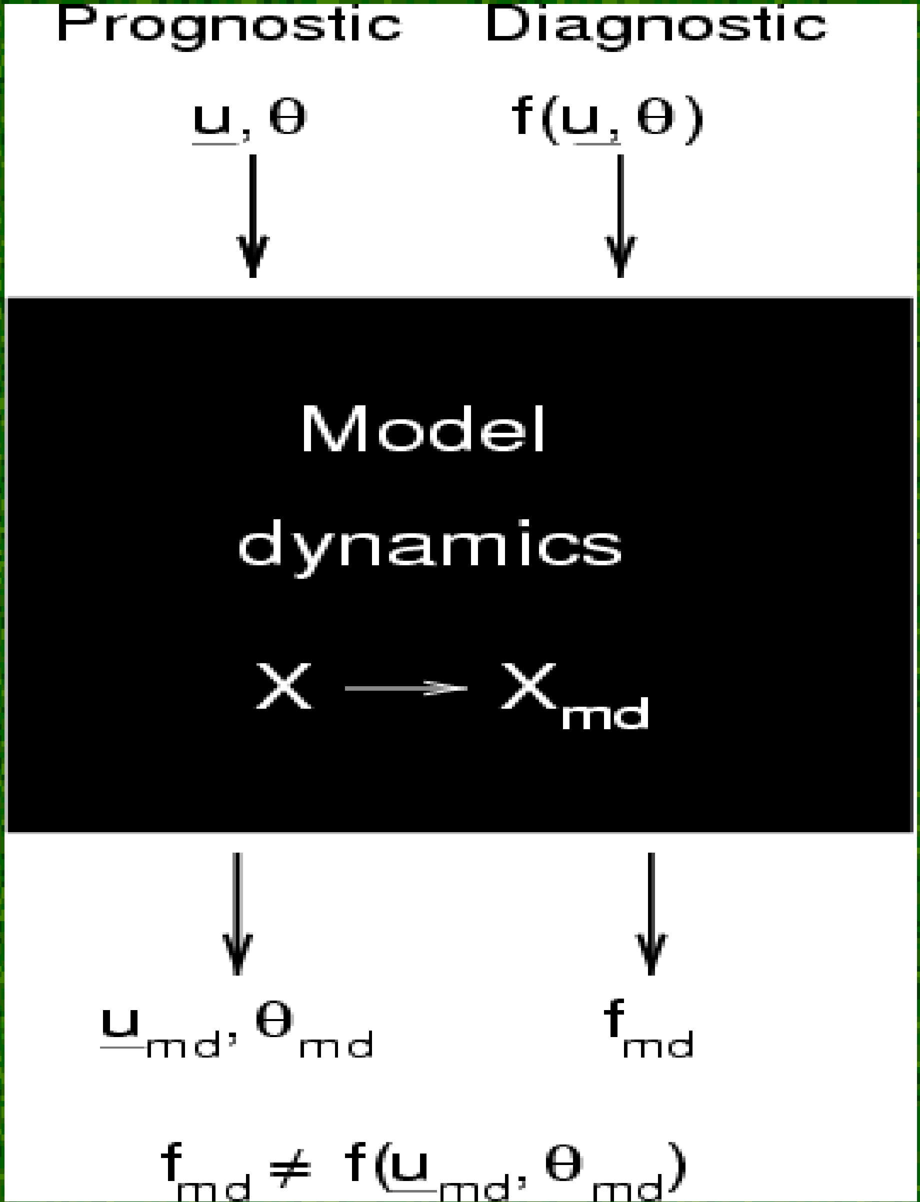
Error in Local Budget After 24h





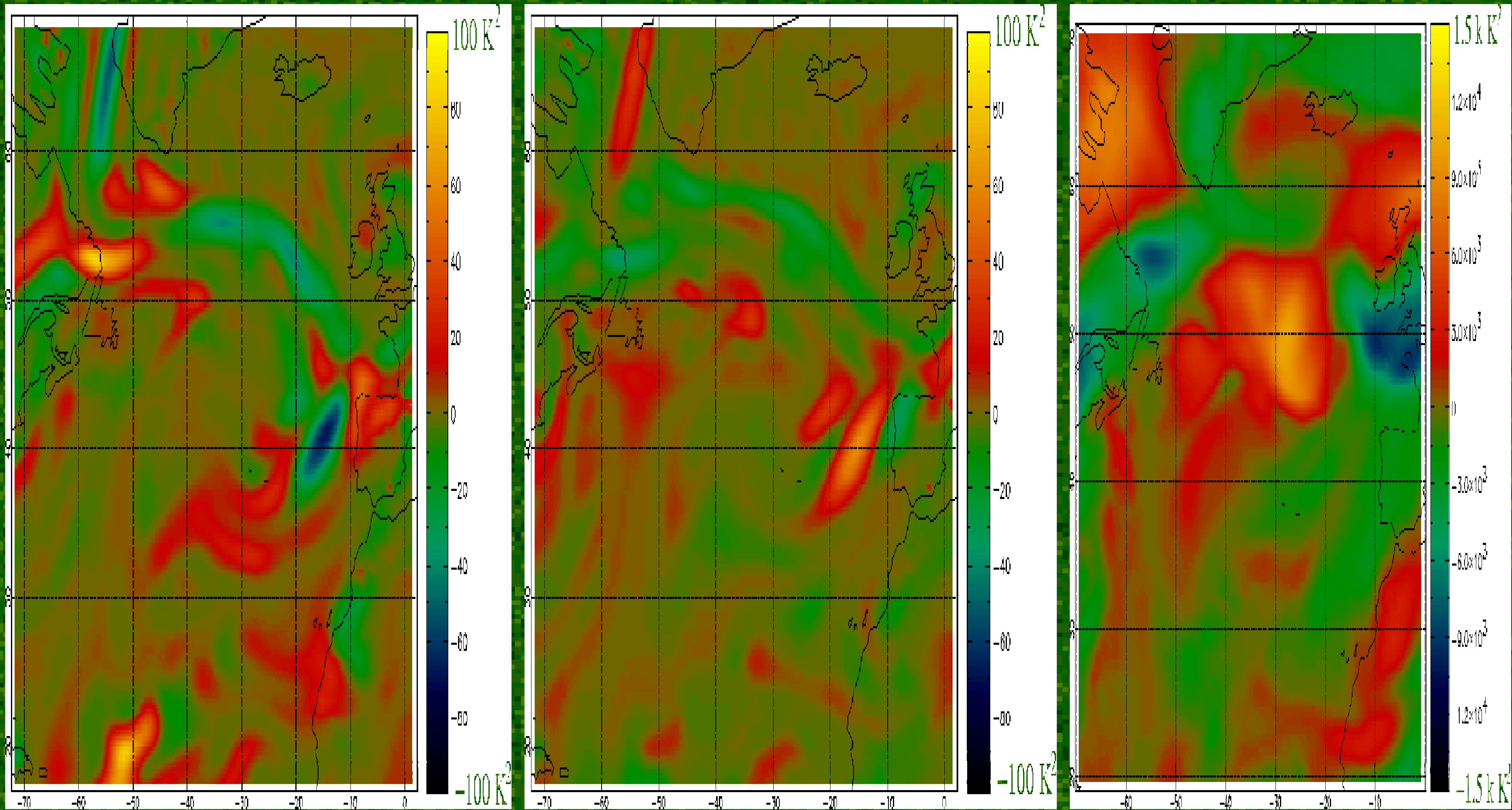
Full field – $\sum$ components of this field, for θ (LHS). Also, change in θ (RHS). On model level 10.

Error in Budget



- Error very small for prognostic variable, like θ.
- Error more significant for diagnostic variable, even very simple one like θ^2.

Error in Local Budget After 24h

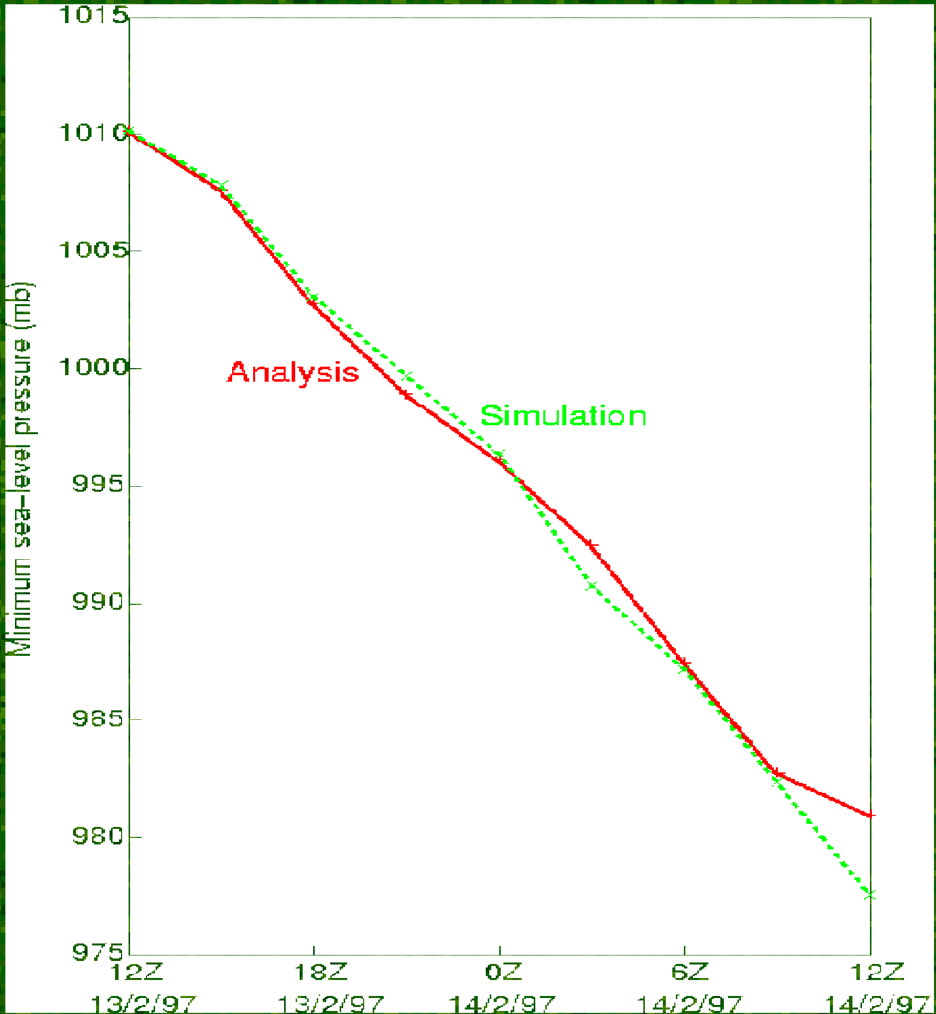


Full field – $\sum$ components of this field, for θ^2. On adjacent model levels 9 (LHS) and 10 (centre). Also total change (RHS).

An Example System…

FASTEX IOP15

- The development of FASTEX IOP15.
- A 24h simulation with the UM.

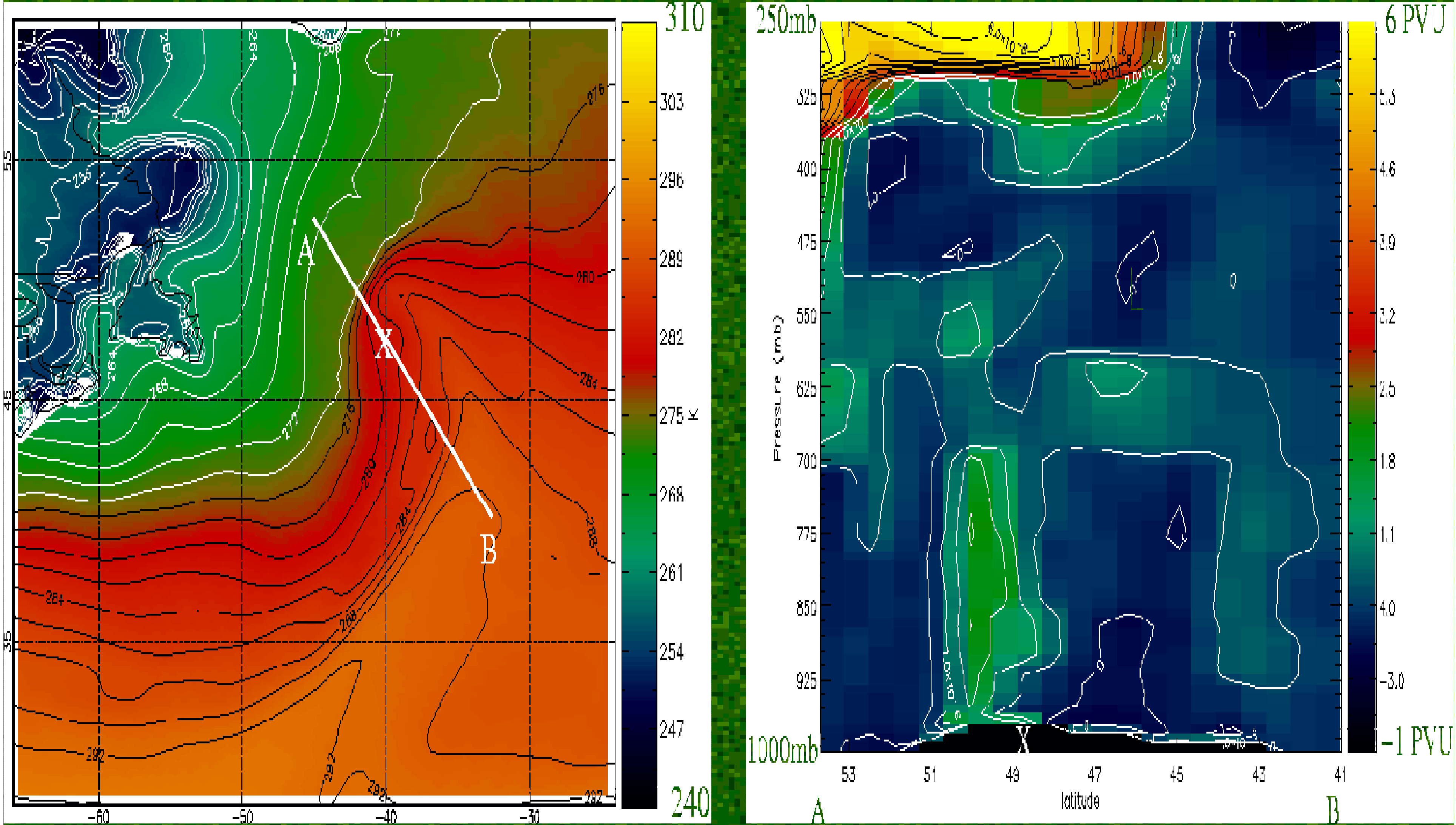


JCMM overview:

"Well-forecast and well-observed evolution"

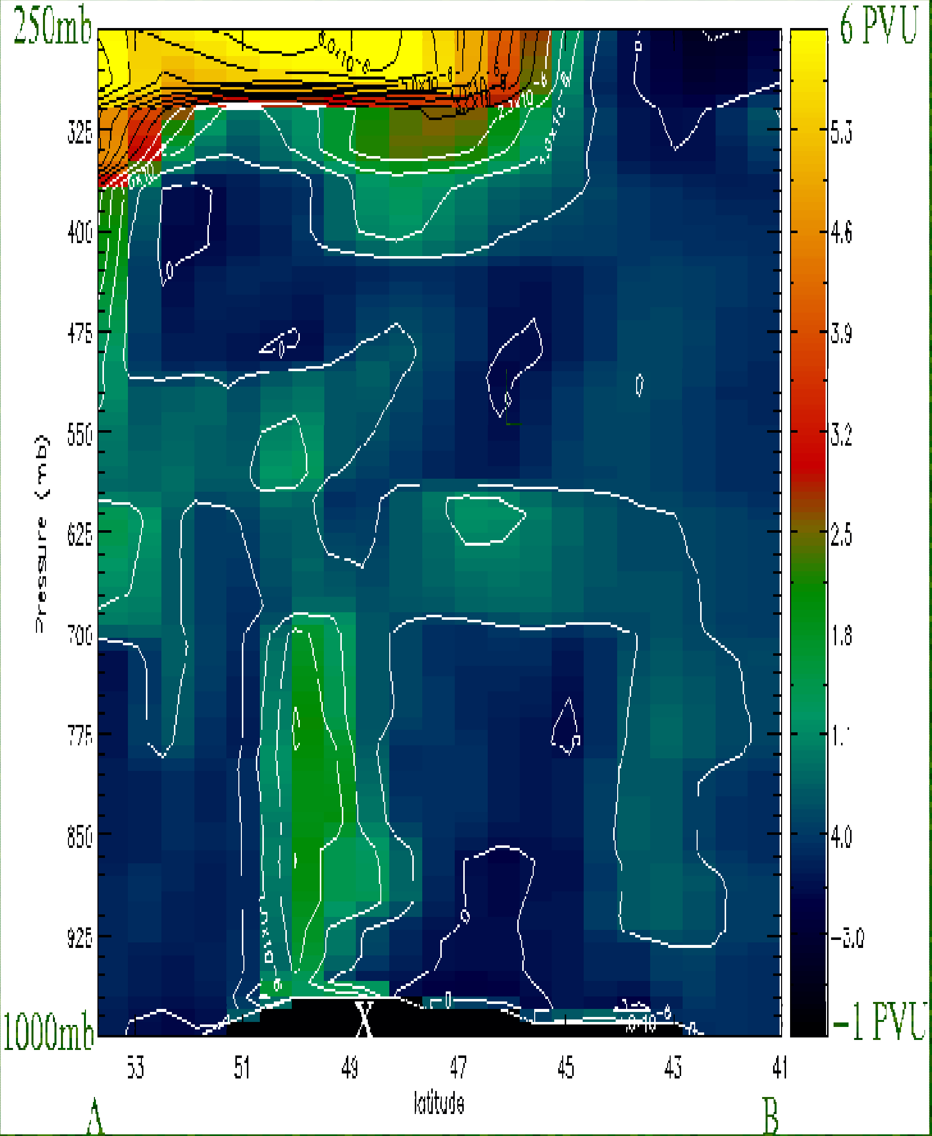
"Successive measurements along flow structure show very consistent patterns"

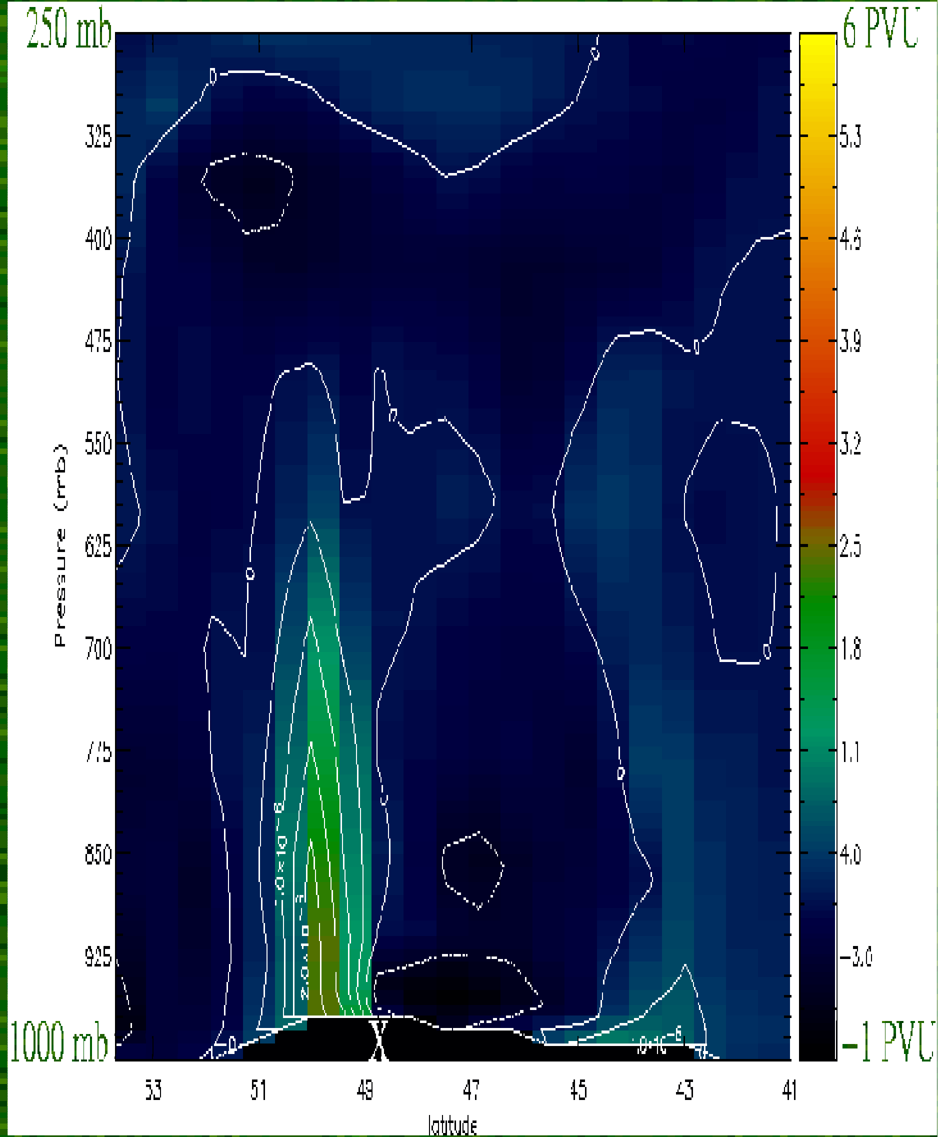
PV in IOP15



Temperature on lowest level (LHS) and PV X-section for IOP15, at T+24.

Action of Physics in IOP15



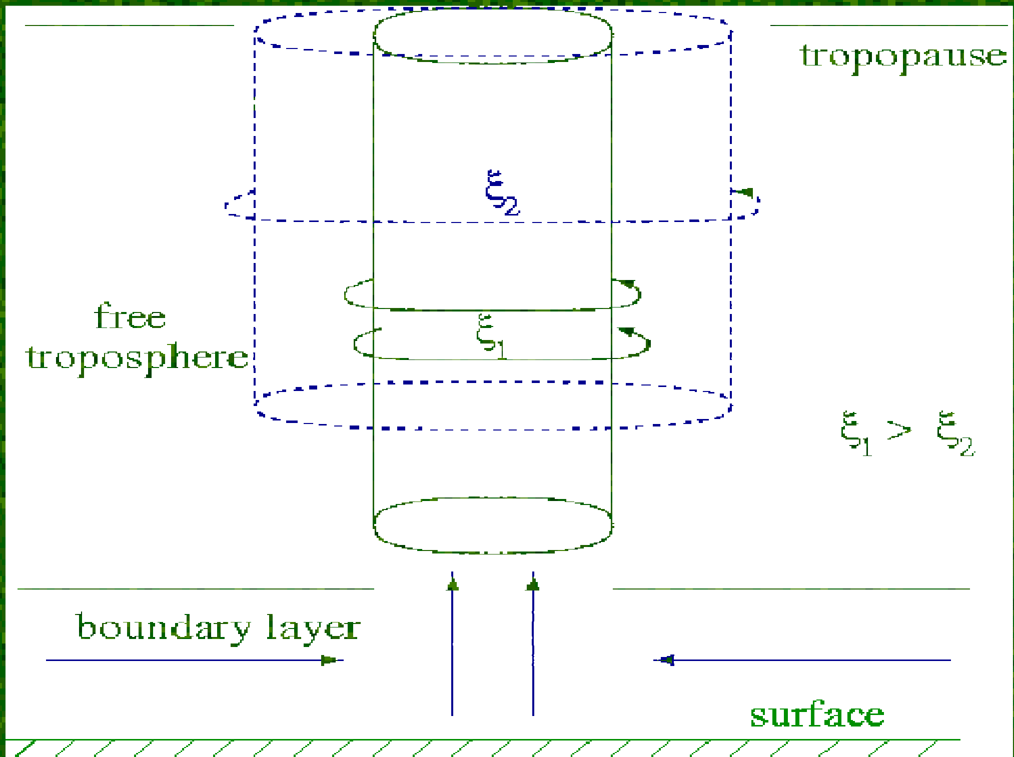


Full PV field (LHS) and that due to all physics, T+24.

Barotropic Friction

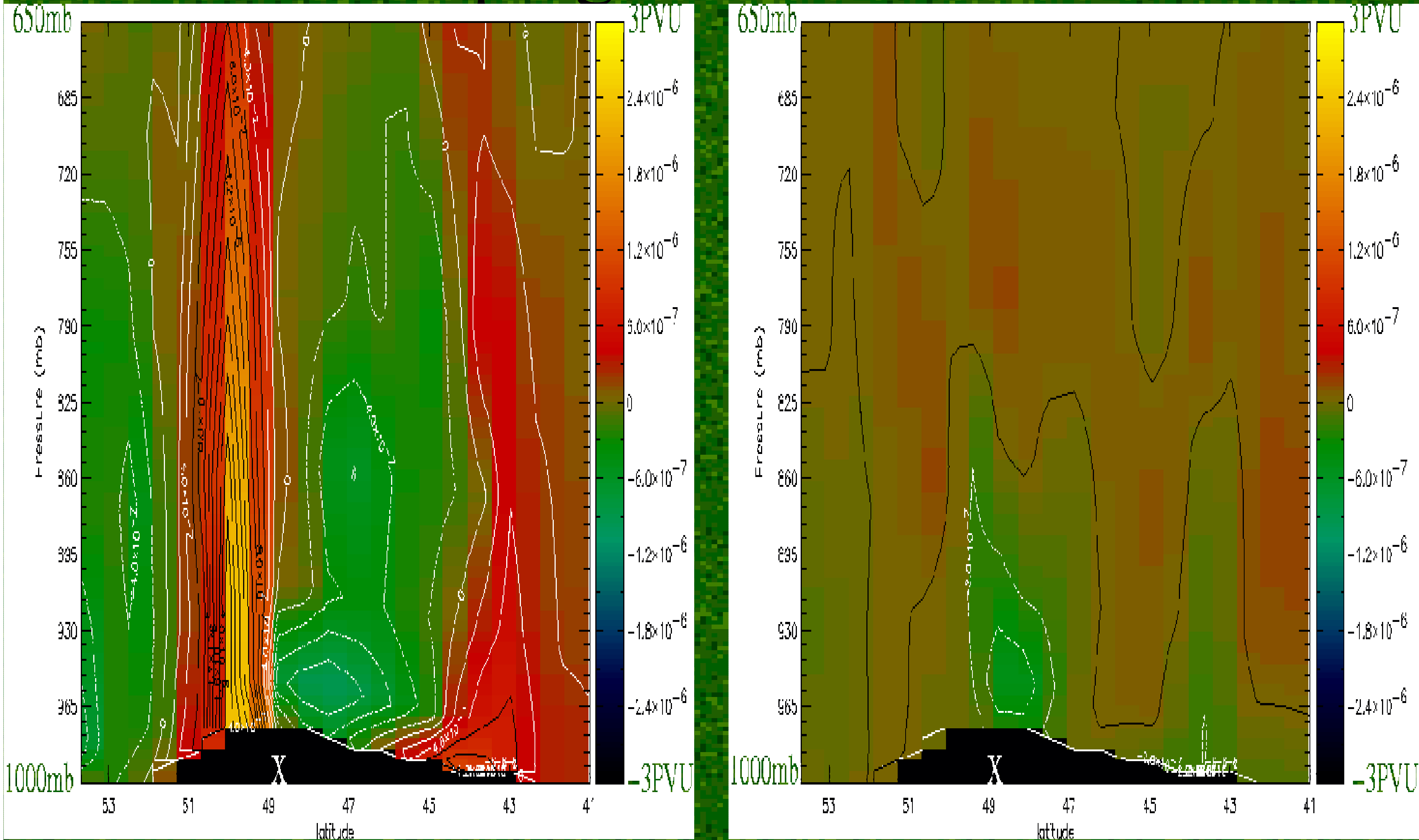
- Consider the barotropic frictional term $(\underline{\nabla}\times\underline{F})_z\partial\theta/\partial z$
- Averaging this over the depth of the boundary layer,

$$\frac{\overline{DP}}{Dt}=-\frac{fw_{Ekman}}{\rho h^2}\left[\theta(h)-\theta(0)\right]$$



Convergence over low ⇒ uplift ⇒ vortex tube squashing ⇒ spindown of cyclone

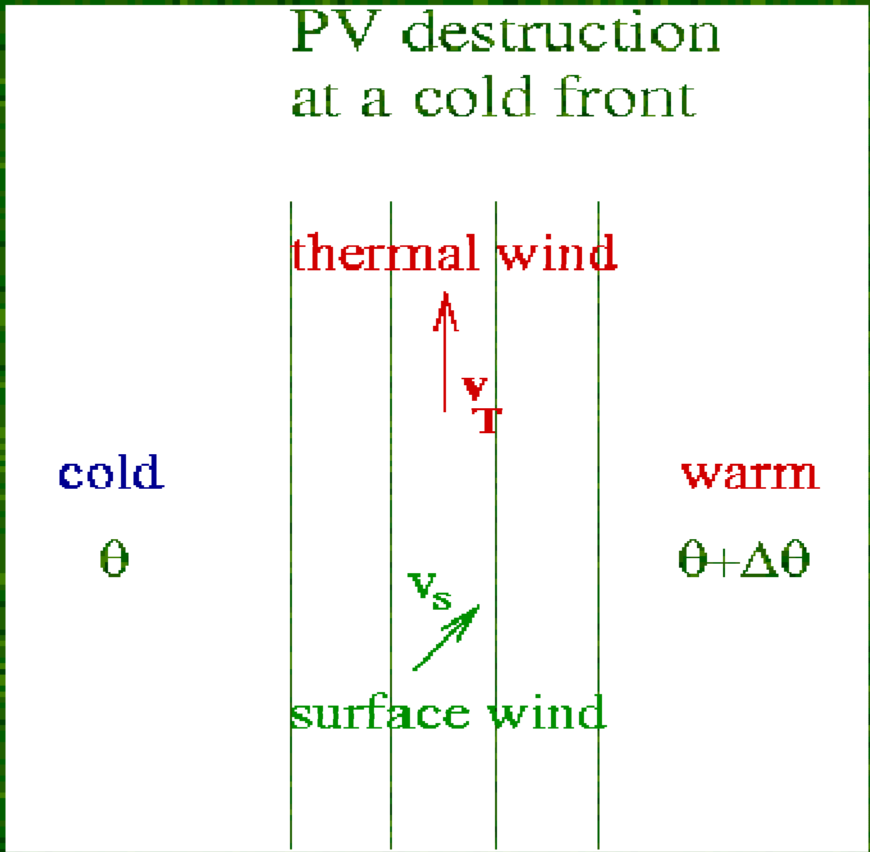
Ekman Pumping Contribution



PV due to all physics (LHS), and that due to Ekman pumping (RHS).

Baroclinic Effects?

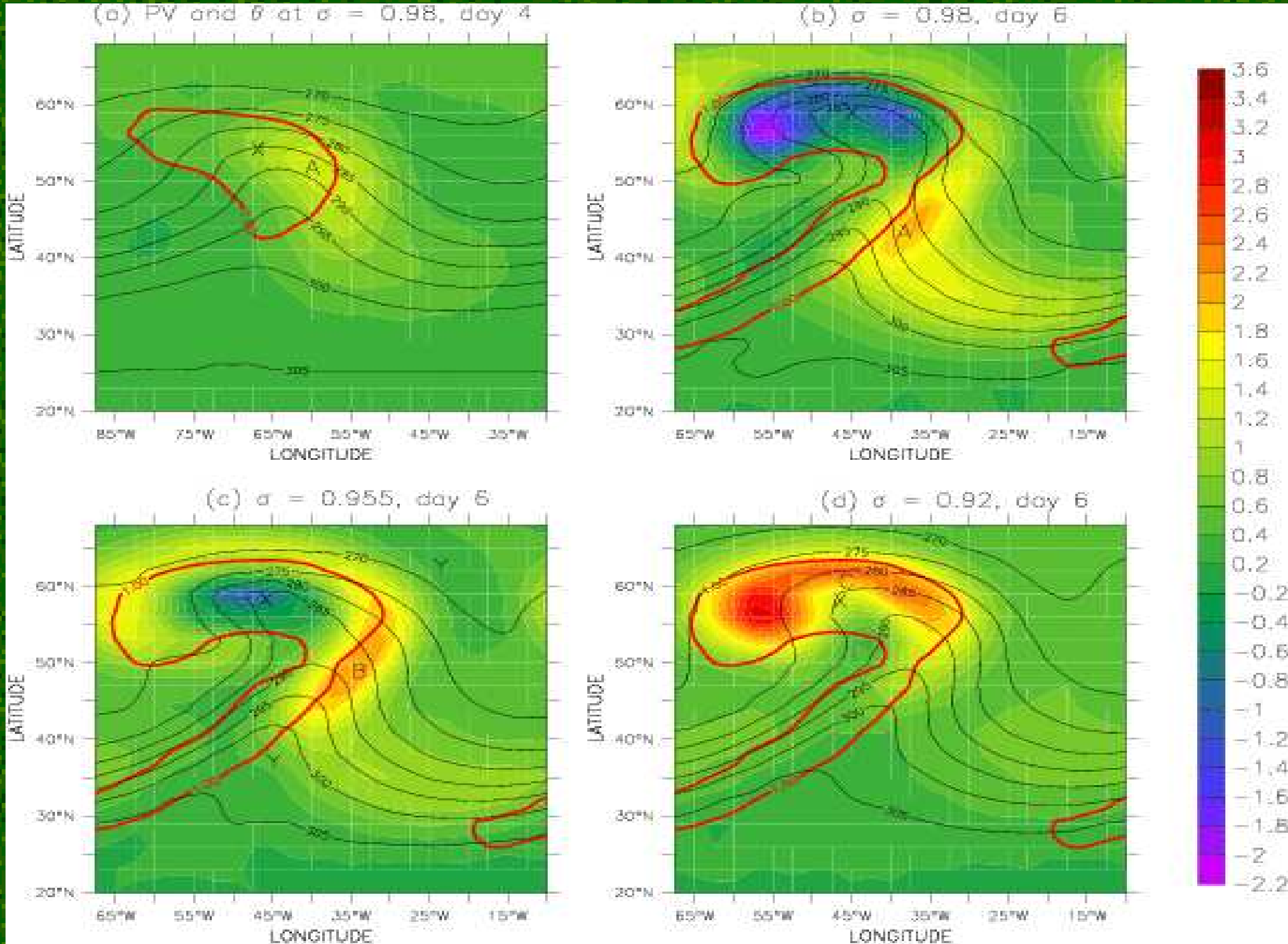
Averaging the baroclinic term... $(\underline{\nabla}\times\underline{F})_H\cdot\underline{\nabla}_H\theta$



$$\overline{\frac{DP}{Dt}} = -\frac{1}{\rho h^2}\underline{\tau}_s\cdot\underline{k}\times\underline{\nabla}_H\theta\,\Big|_{z=h}$$

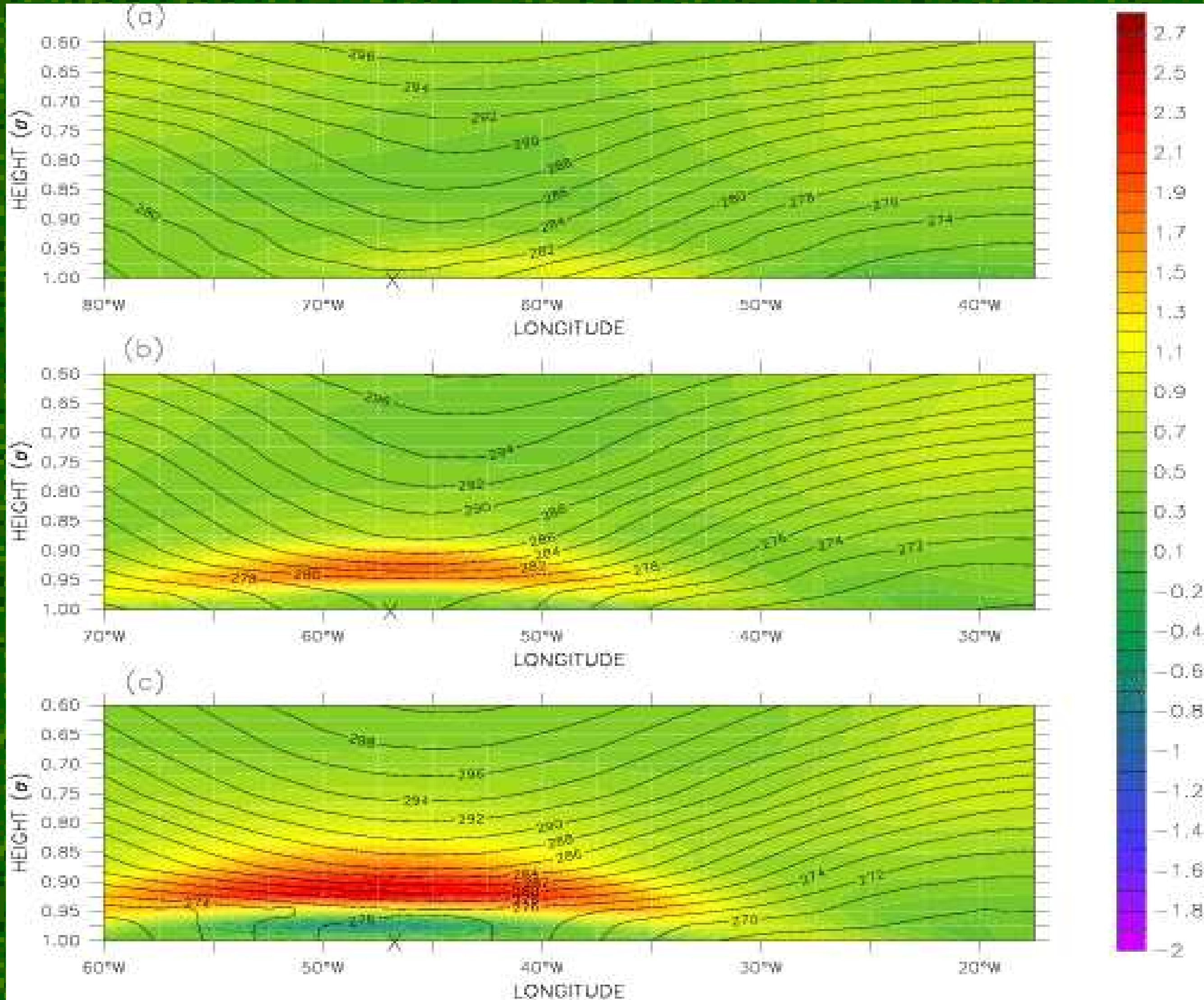
Destruction if surface wind has component parallel to thermal wind.

Also Seen in Baroclinic Waves



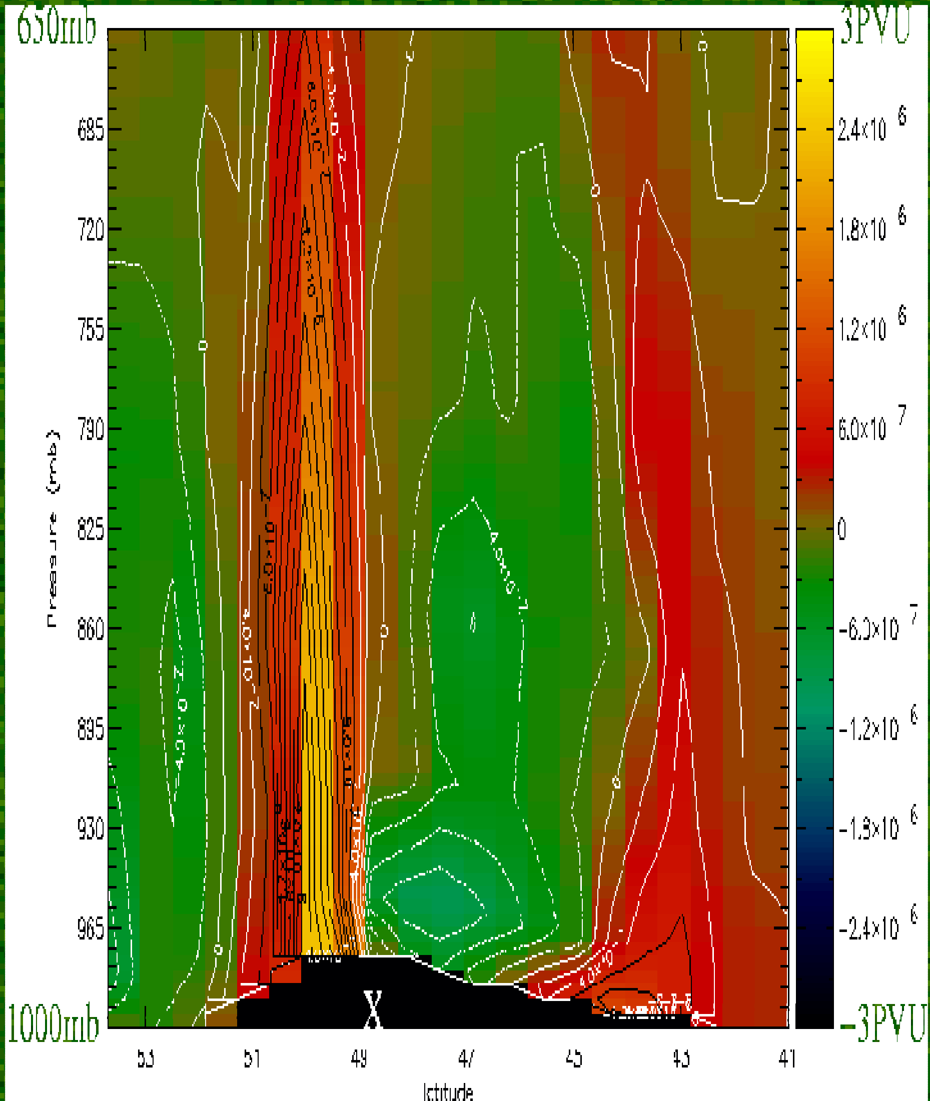
Adamson et al (2001): PV in frictionally-damped, dry baroclinic wave.

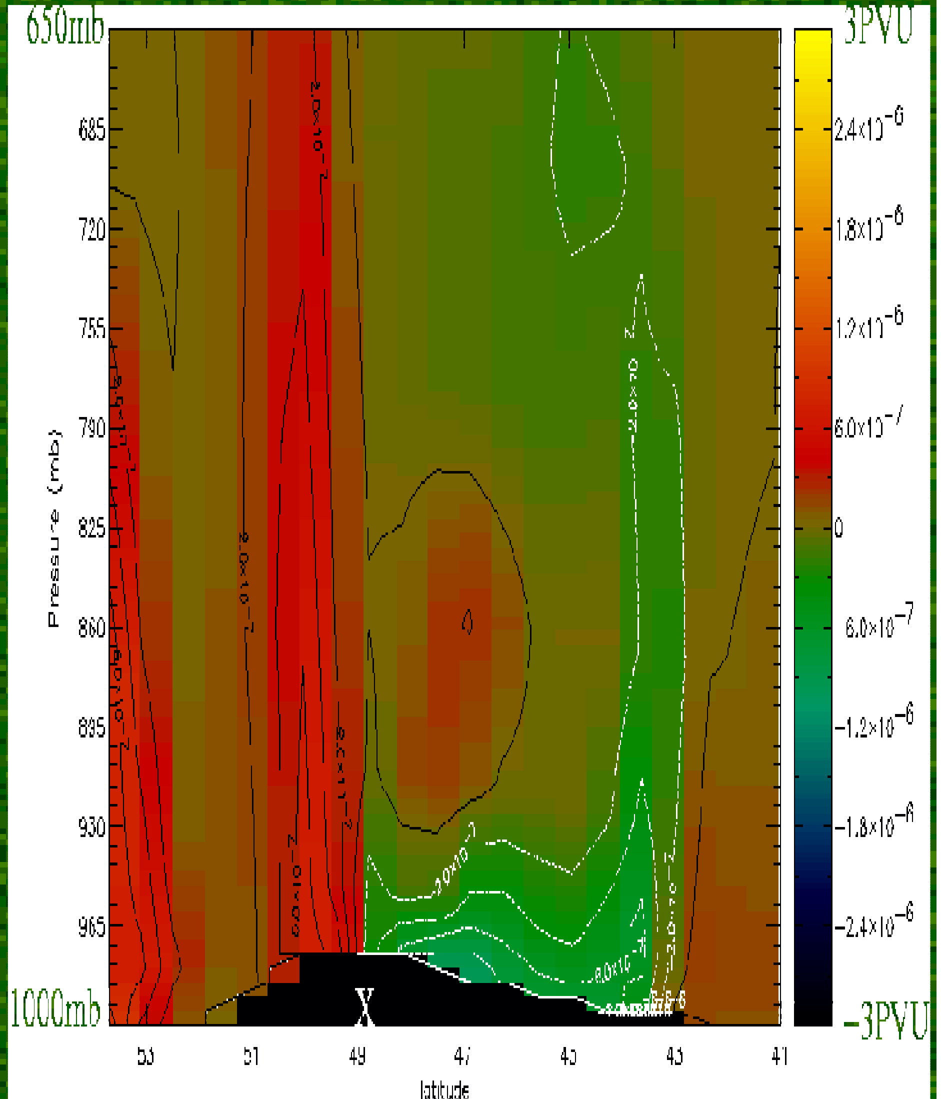
Does this Strengthen the Cyclone?



PV X-sections from Adamson, Belcher and Hoskins (2001)

Baroclinic Frictional Contribution



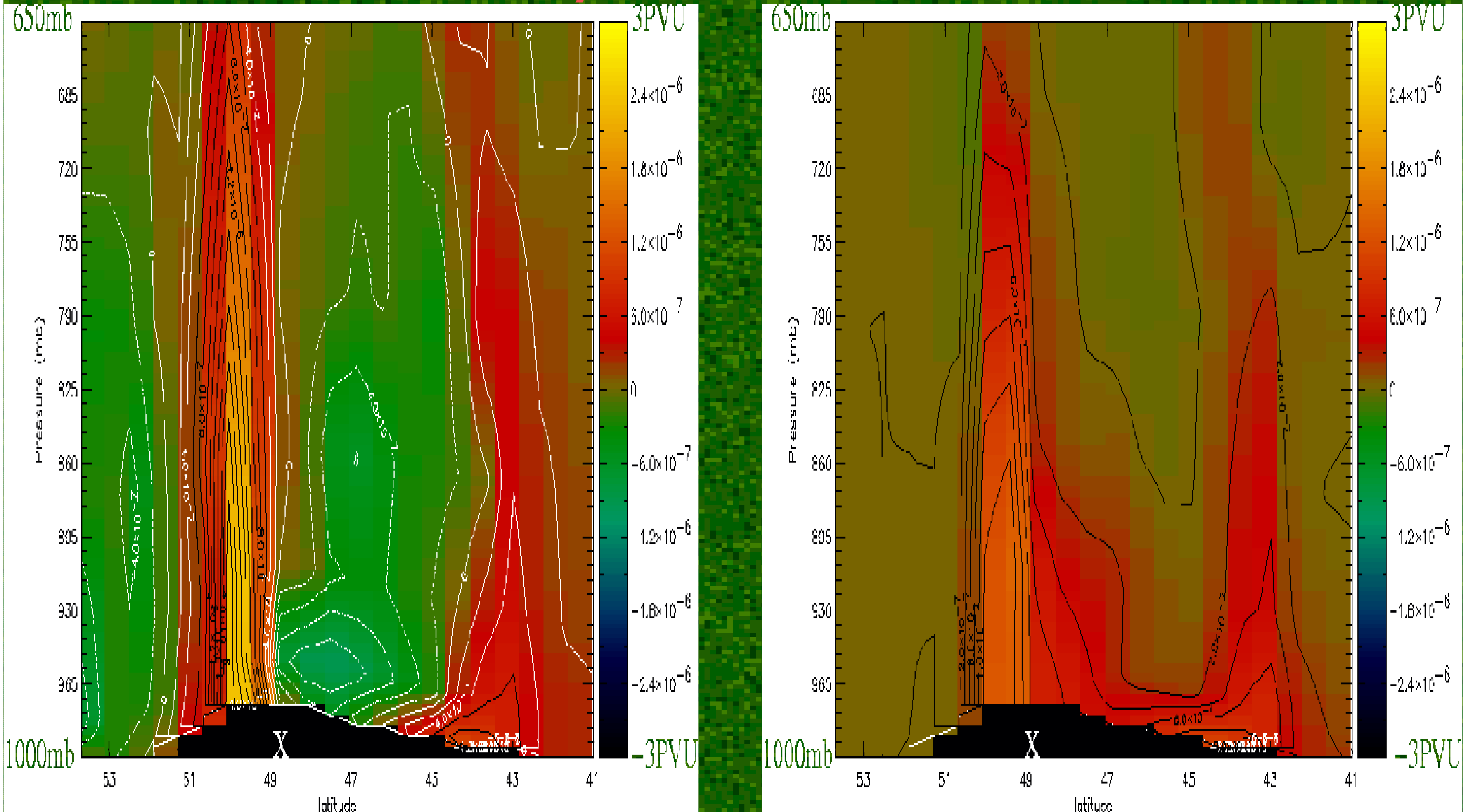


PV due to all physics (LHS), and that due to baroclinic frictional generation (RHS).

Heating Mechanisms

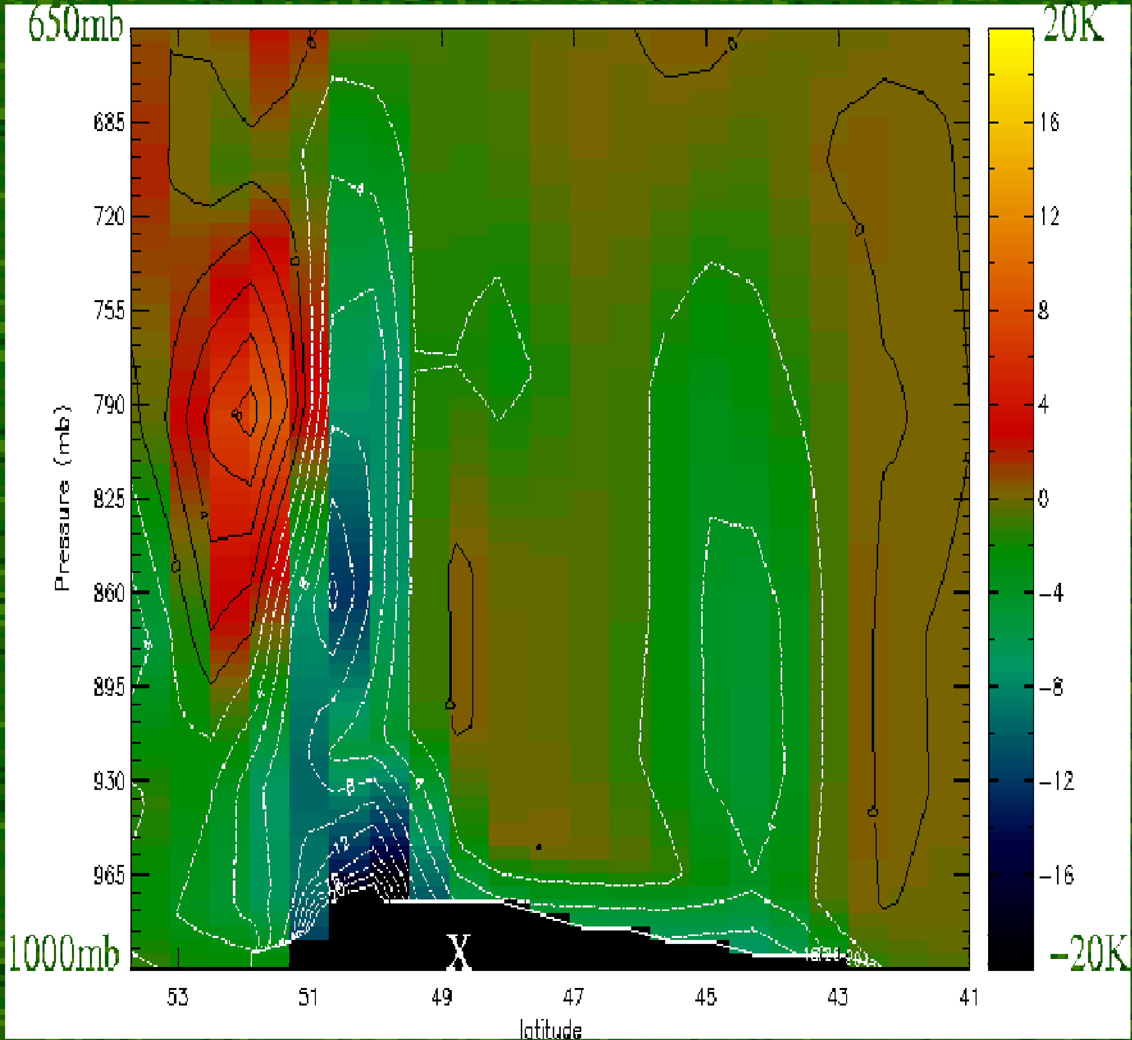
- Latent heating during motion attributable to the large-scale (resolved grid-scale) dynamics.
- Explicit precipitation scheme.
- LW and SW radiation.
- Convection.
- Heat fluxes in the boundary layer.
- Latent heating forced by boundary layer mixing.

LH due to Dynamics Contribution



PV due to all physics (LHS), and that due to latent heating from the dynamics (RHS).

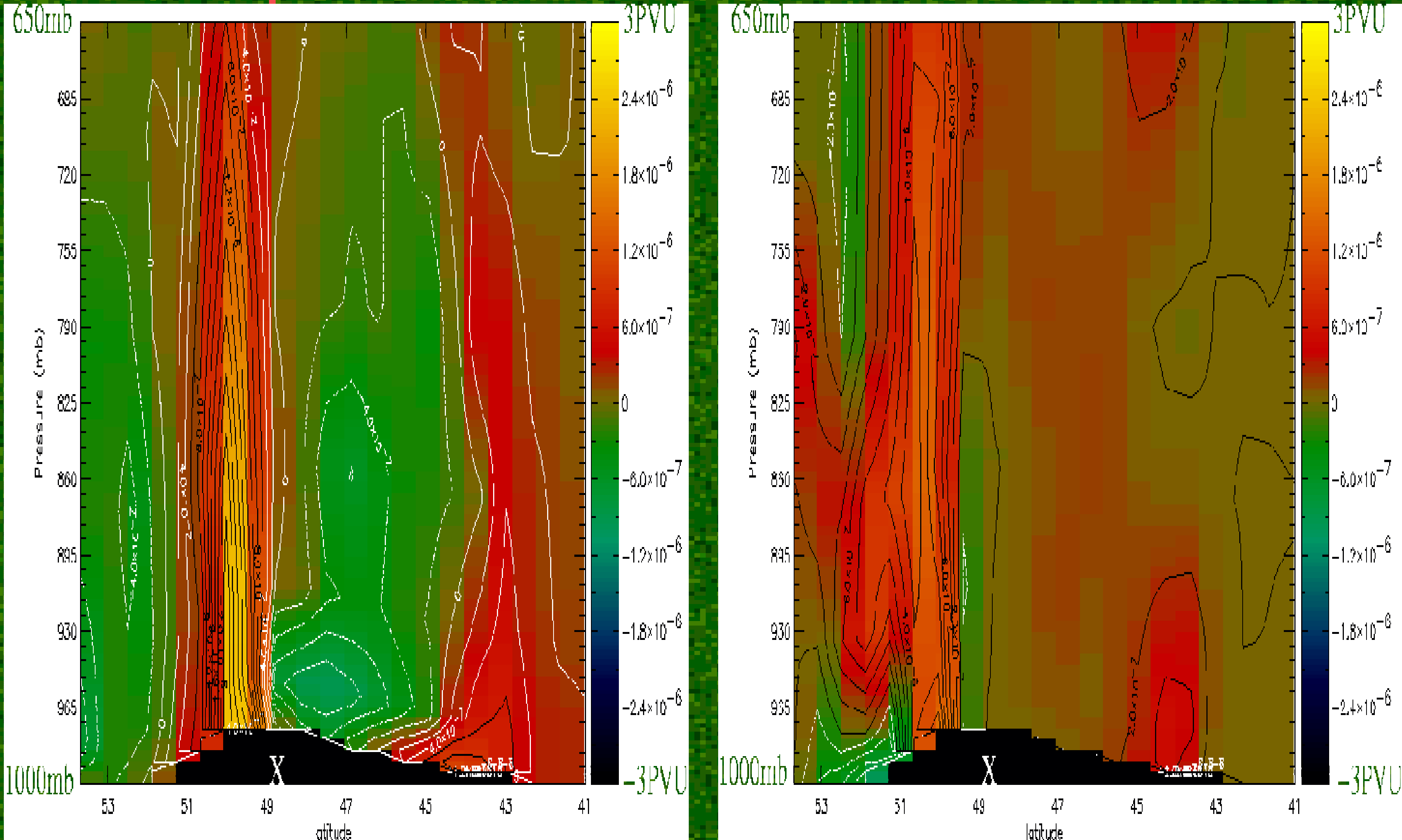
Precipitation Scheme



Production of rain, some of which evaporates close to the surface.

θ due to large-scale precipitation scheme.

Precipitation Scheme Contribution



PV due to all physics (LHS), and that due to large-scale precipitation (RHS).

Other Heating Processes

- As warm air passes over cooler sea, +ve heat fluxes destroy PV in region of cyclonic vorticity.
- Comparable with Ekman destruction.

- LW and SW radiation weak in general.
- Can sometimes see LW cooling at top of deep convective clouds.

- Convection is very much case dependent.
- May contribute strongly to +ve mid-level anomalies.
- Can sometimes see strong cancellations between PV generated in shallow convection in the cold air, and latent heating with the boundary layer scheme.

Conclusions (1)

- Model "physics" crucial for a good forecast of many systems.
- The physics processes often interact strongly.
- To understand the action of the physics:
  - switching physics on and off may not be a good idea
  - but a local budget of PV is appropriate.
- Ekman pumping is a barotropic, frictional process which destroys PV over a low.
- Baroclinic frictional processes tend to
  - destroy PV around cold front
  - generate PV at warm front: transported over low by WCB.

Conclusions (2)

- Diabatic PV generation typically 2 or 3 times larger than frictional generation.
- Latent heating due to the resolved-scale dynamics is the main diabatic effect in most cyclones.
- This is augmented by the precipitation scheme, which includes low-level evaporation.
- Convection also contributes, but its strength is variable.

Stochastic Physics

- A local PV budget provides a very quick way to see what physics is important.
- Looking at budget for the "perturbed physics" runs could be used to determine how parameterized processes interact.