Boundary layer controls on extratropical cyclone development

R. S. Plant

(With thanks to: I. A. Boutle and S. E. Belcher)

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University of East Anglia

The University of Reading

Outline

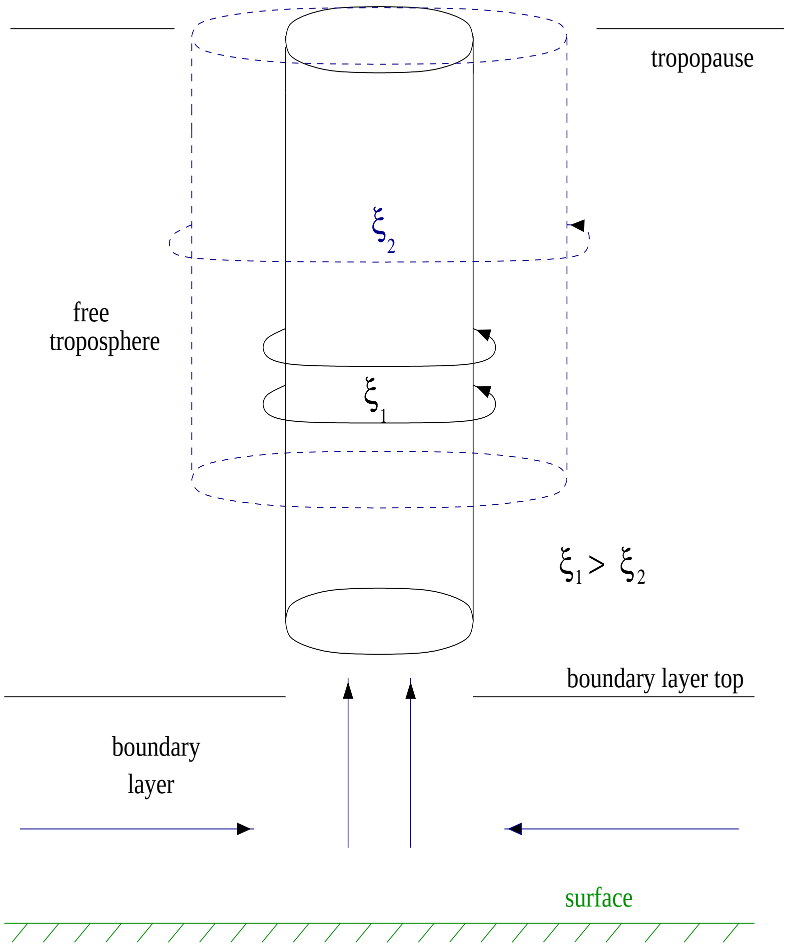
- Introduction and background
- Baroclinic wave simulations
- More than baroclinic instability
- The role of friction
- The role of boundary-layer moisture transport
- Conclusions

Introduction and background

Motivation

- Friction reduces growth rates of baroclinic waves by up to 50% (Valdes and Hoskins 1998)
- Improved surface winds and minimum pressure (Doyle 1995) from increased drag due to coupling with surface waves
- Precipitation and long-range moisture transport require evaporated moisture to be ventilated into free troposphere
- The boundary layer must mediate interactions with surface
- But what are the interaction mechanisms?

Role of friction: Ekman pumping



- Boundary layer convergence leads to ascent leads to spin-down of a barotropic vortex
- Barotropic vorticity equation,

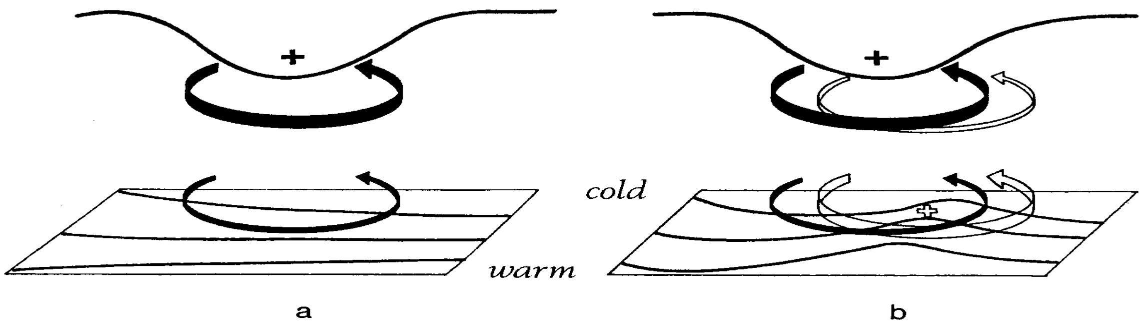
$$\frac{D\zeta}{Dt} = \zeta \frac{\partial w}{\partial z}, \qquad \zeta = f + \xi$$

Potential vorticity

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

- Natural analogue of vorticity for a baroclinic system
- Conserved for adiabtic, frictionless flow
- Given a balance condition, PV can be inverted to deduce the full dynamics
- Conversely, PV generation reveals action of friction or diabatic processes
- High PV must be associated with high stability (stratosphere) or high vorticity (usual in troposphere)

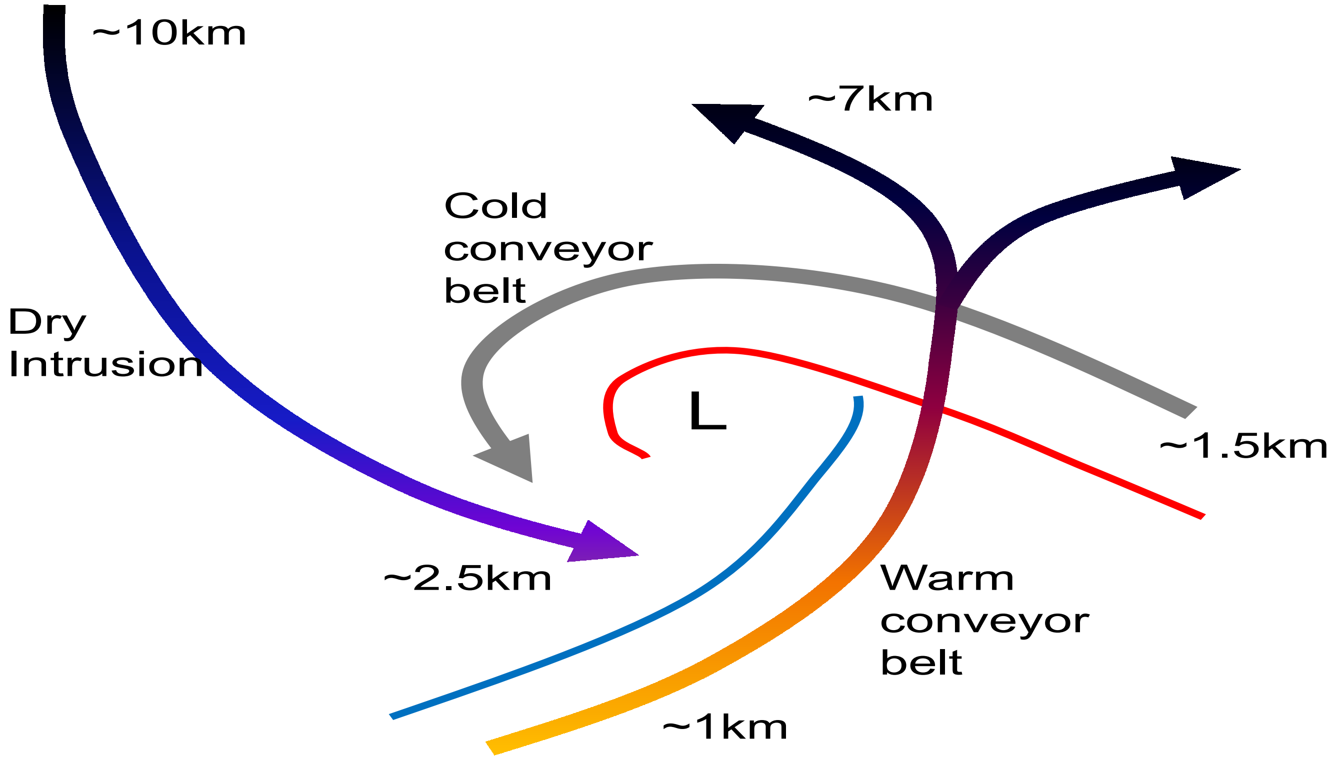
Baroclinic instability



- +ve anomaly of PV (eg descent of tropopause) implies a cyclonic circulation
- Warm temperature anomaly at surface equivalent to +ve PV anomaly (via the boundary condition for the inversion)
- Co-operative interaction of surface and tropospheric anomalies amplifies a baroclinic wave
- Strength of interaction governed by static stability

Main airflows

Main flows in a system-relative frame:

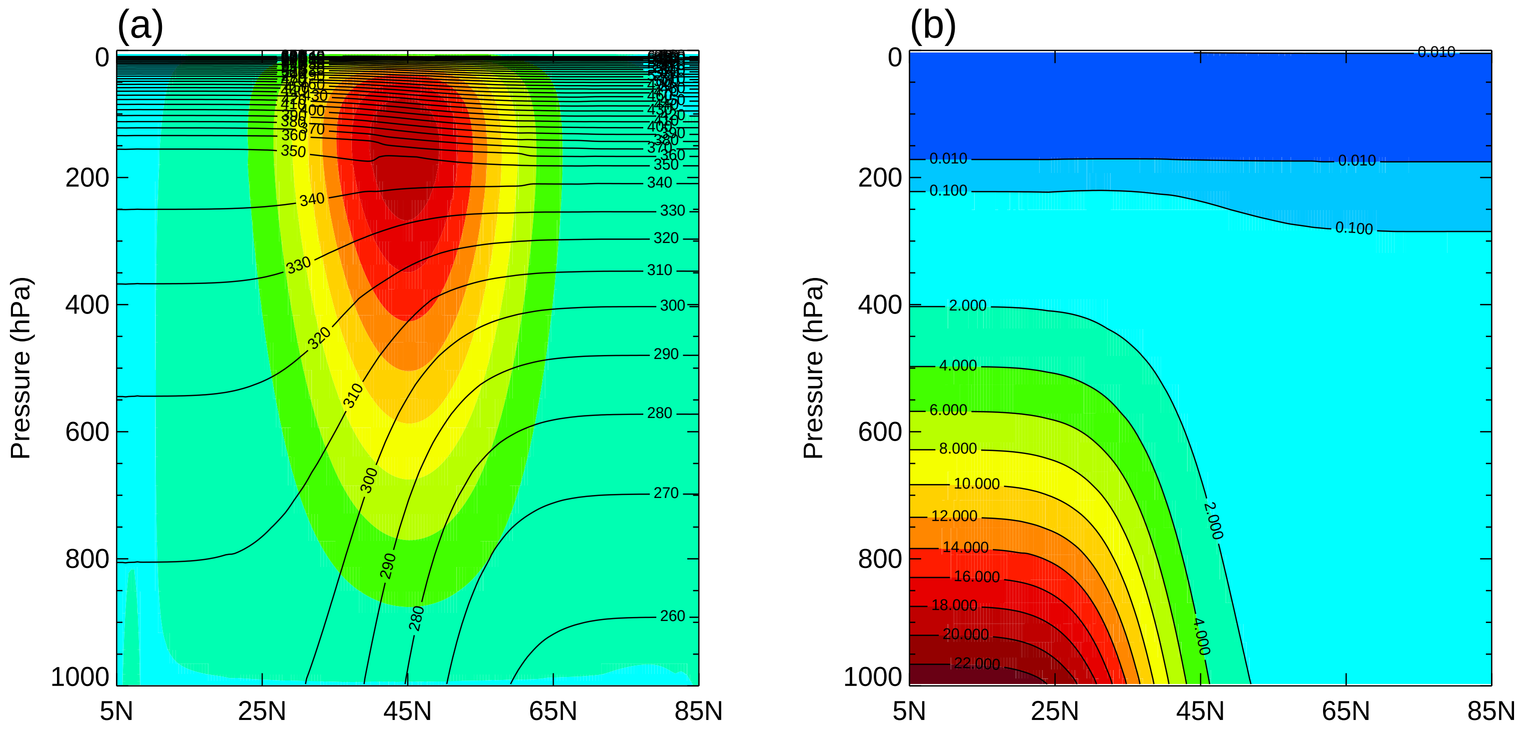


Baroclinic wave simulations

Simulation set-up

- Investigations based on simulations of real cases with Met Office Unified Model
- And also idealized simulations of “baroclinic waves” (most of the results today from these)
- These simulations are over ocean only
- Use a baroclinically-unstable initial state, which is zonally symmetric and based on the mean atmosphere in northern-hemisphere winter
- Start with small perturbation with wavenumber six
- Can be run with a dry atmosphere, and with or without a boundary-layer mixing scheme

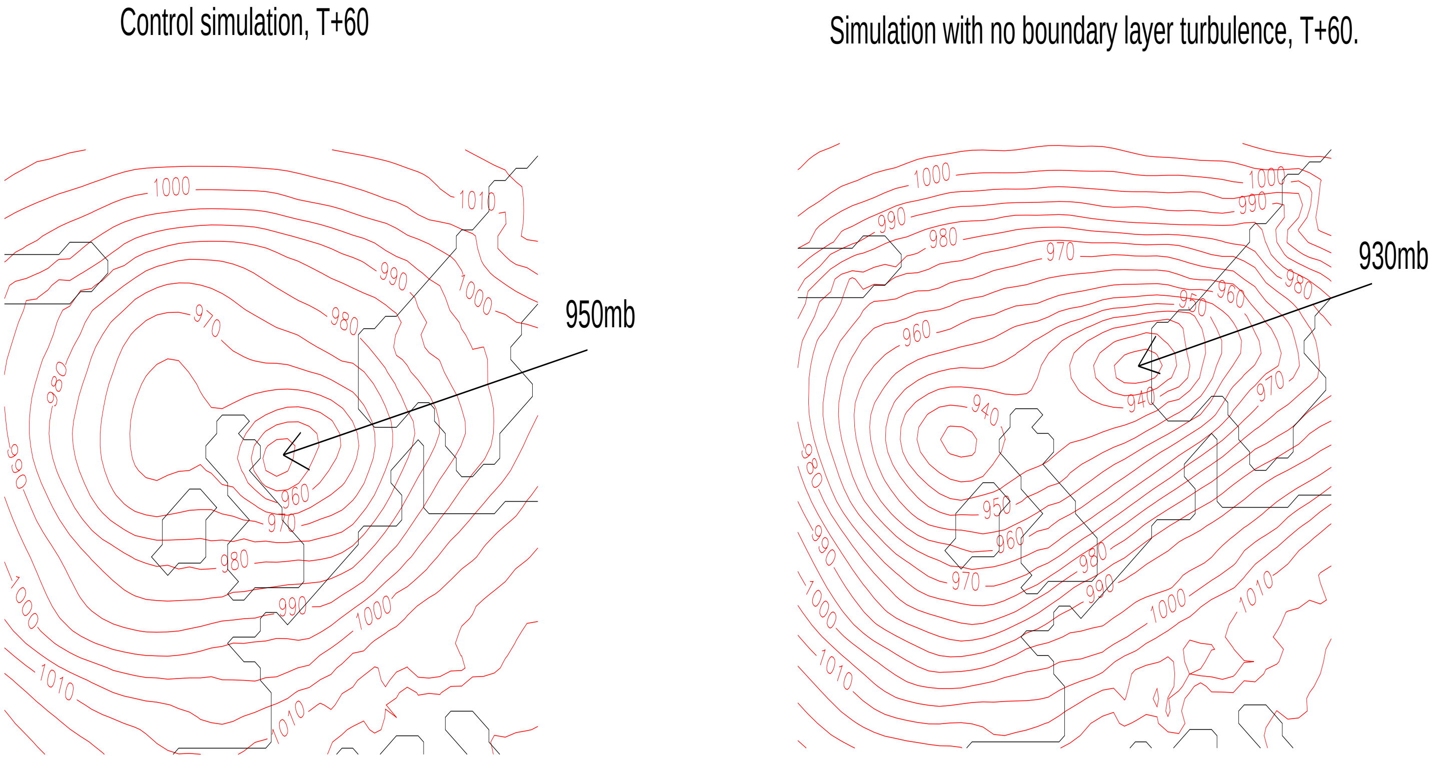
Initial conditions



Fixed SST equal to lowest-level atmospheric temperature in initial conditions

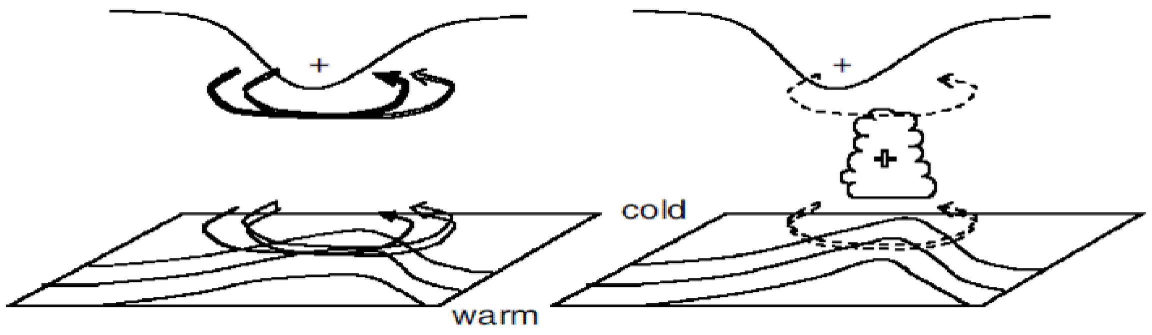
More than baroclinic instability

Effects of the boundary layer



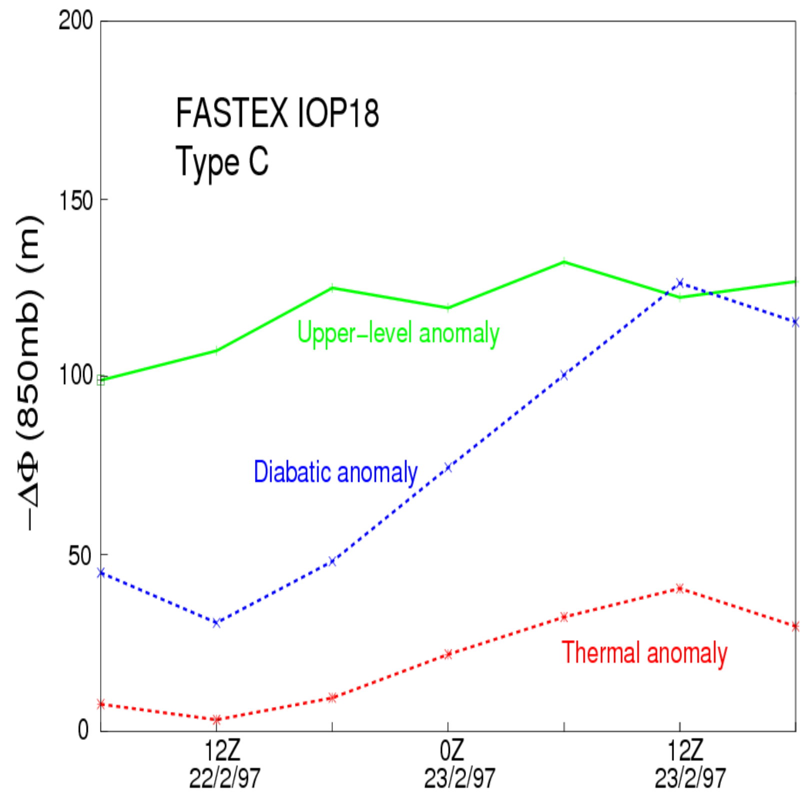
Simulations with (left) and without (right) boundary layer, of storm of 30/10/00

Latent heat release



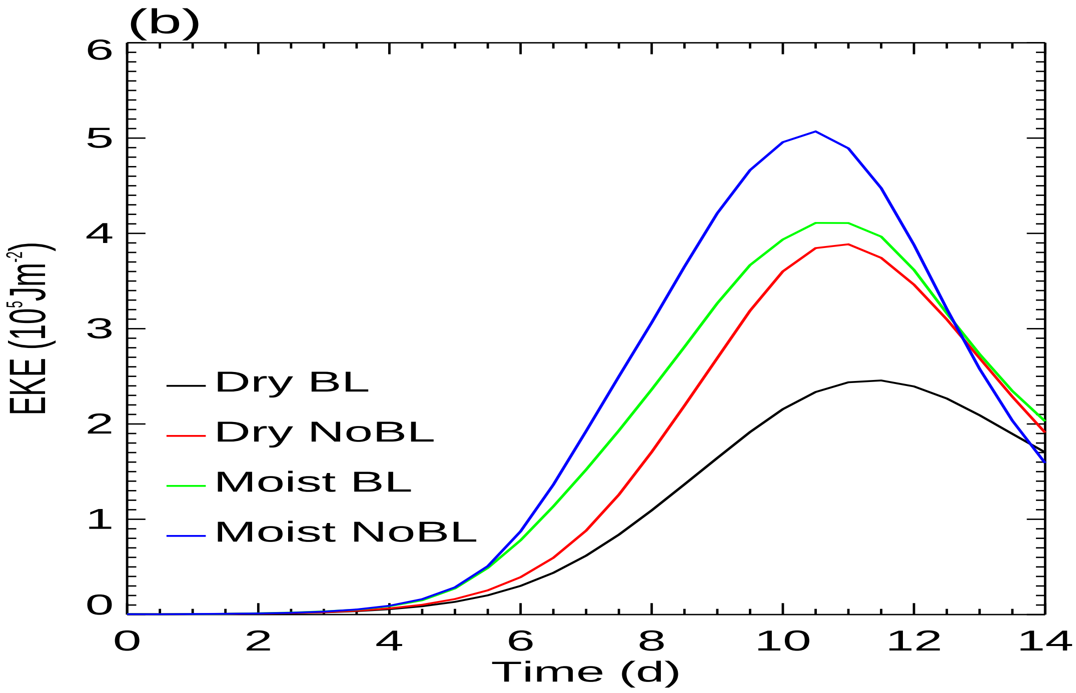
- Mid-level latent heat release produces +ve PV anomaly
- Associated cyclonic circulation enhances system development

Latent heating can dominate



- By inversion, can measure contributions to the circulation
- A diabatic PV anomaly drives the intensification
- Interacts constructively with tropopause feature
- System does not develop without latent heating

Diabatic and frictional effects



1. Does Ekman pumping explain the frictional effect?
2. How reliant is the latent-heating effect (and precipitation) on a boundary-layer moisture source?

The role of friction

Baroclinic effects

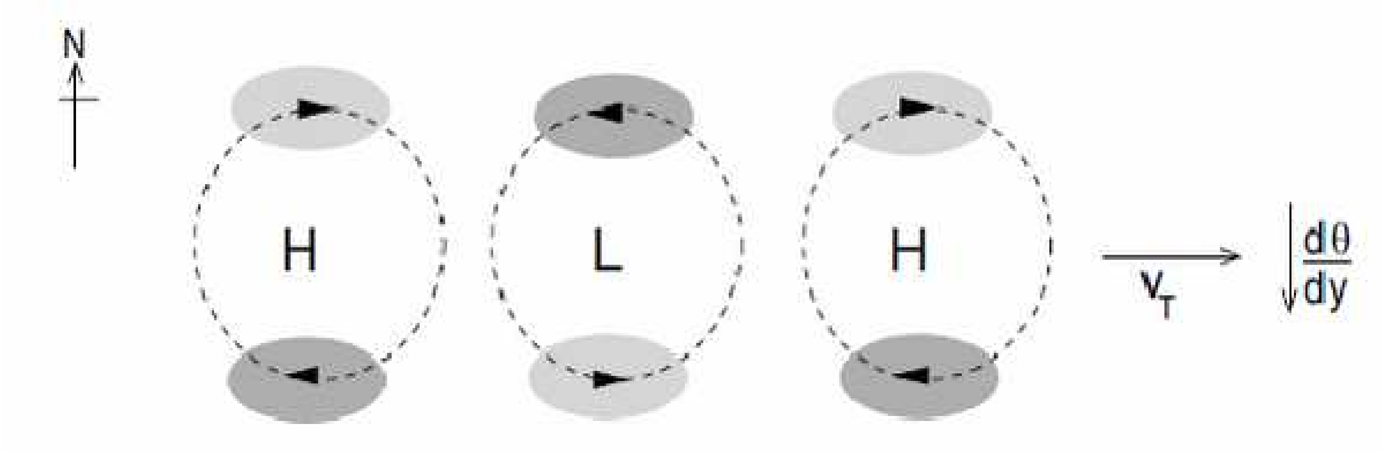
- Ekman pumping is barotropic mechanism, but cyclones are baroclinic!
- Evolution of PV due to friction,

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

- Consider evolution of depth-integrated PV, $[P]$ over boundary layer,

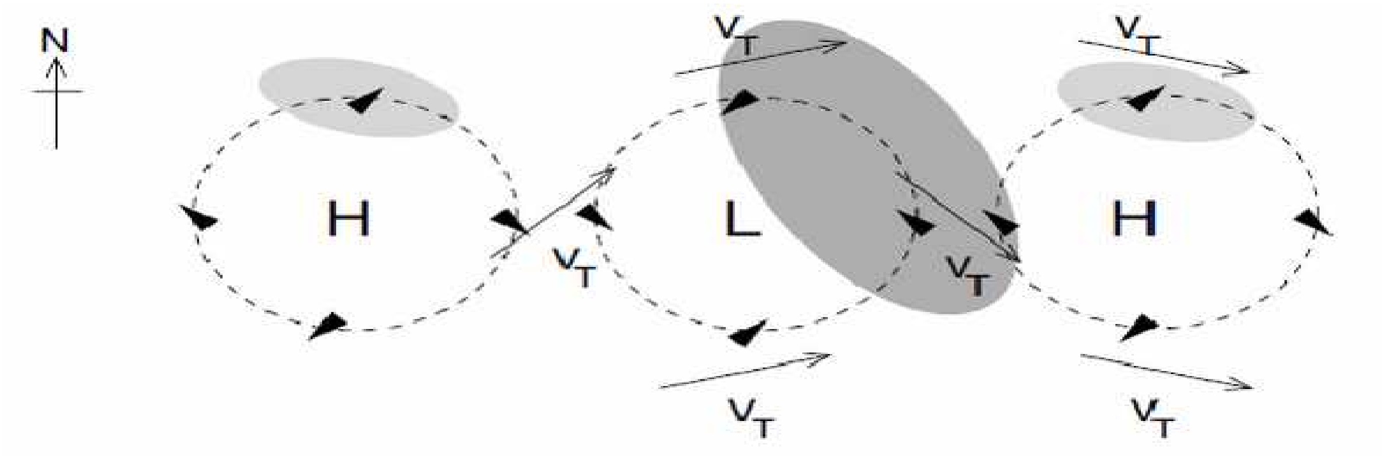
$$\frac{\overline{D}[P]}{\overline{D}t} = -(\text{term} \sim w_{\mathrm{Ekman}}) - \frac{1}{h} w_h P_h - (\text{term} \sim \underline{v}_{\mathrm{surf}} \cdot \underline{v}_T)$$

Baroclinic PV generation?



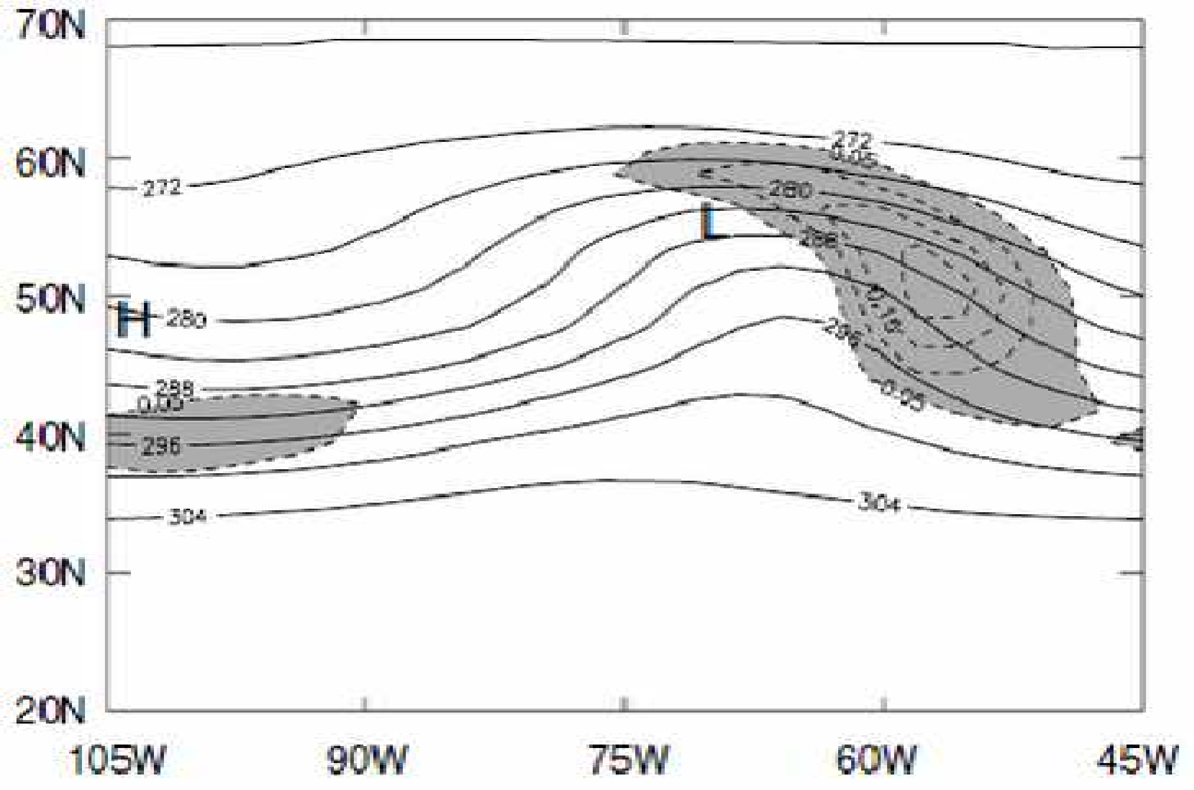
- NS temperature gradient in basic state, implies westerly thermal wind
- Cyclonic circulation implies frictional PV generation to the north of a cyclone (dark shading)
- and PV destruction to the south (light shading)

Baroclinic PV generation?



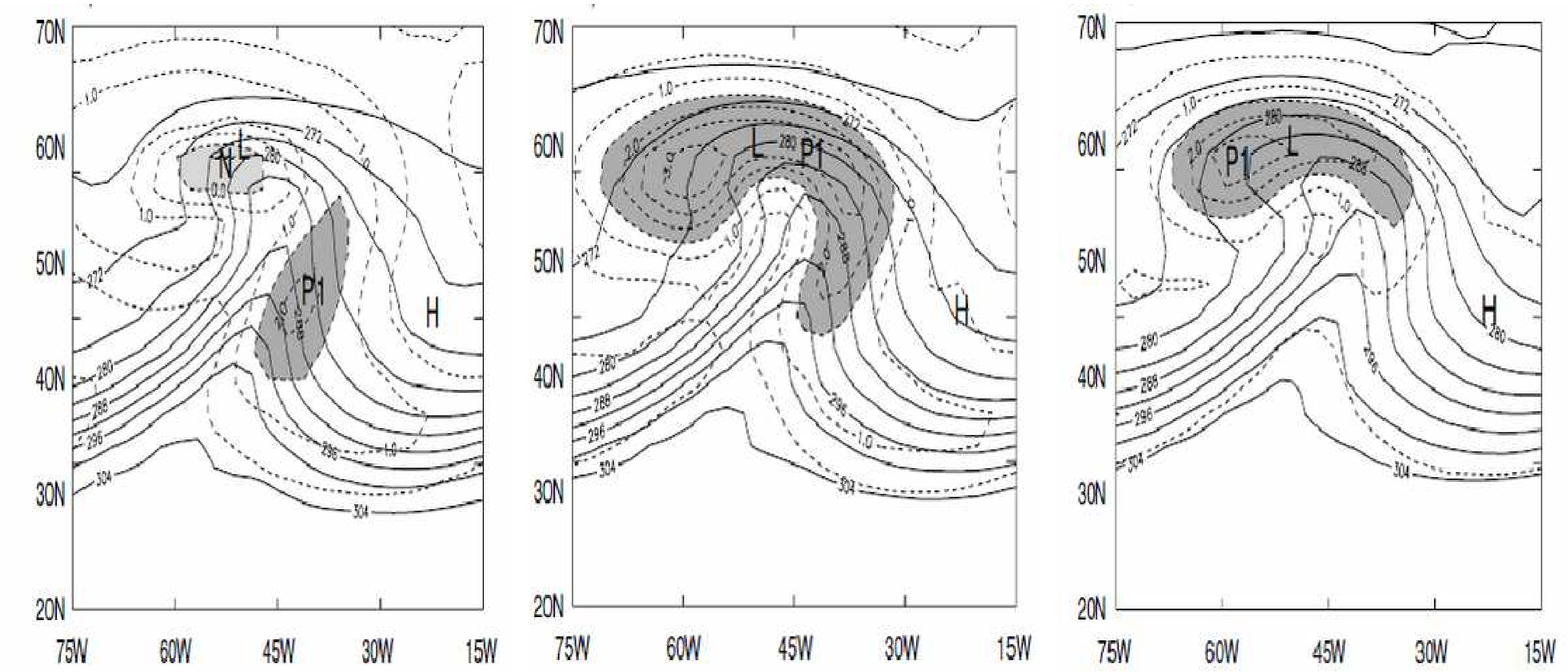
- Should also account for EW temperature gradients induced by the wave
- And frictional turning of the wind within the boundary layer
- Expect PV generation to the north and east of a cyclone

Baroclinic PV generation



Rate of PV generation at day 4 of a simulated dry baroclinic wave

Transport of generated PV

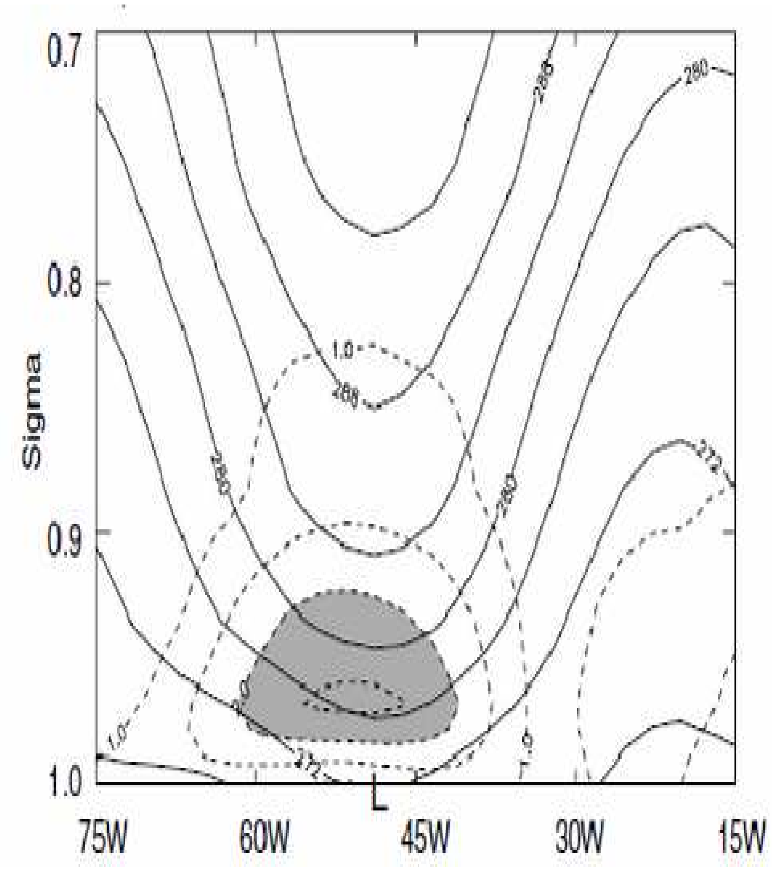


PV at $\sigma = 0.98$ (left), $\sigma = 0.955$ (centre) and $\sigma = 0.92$ (right) after 6 days of a simulated dry baroclinic wave

Transport of generated PV

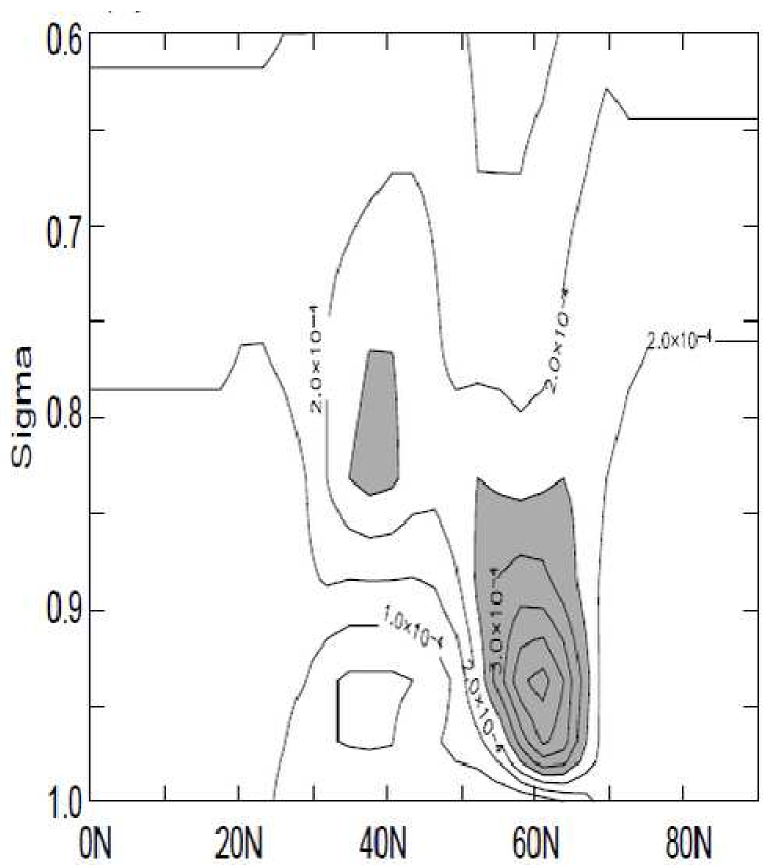
- Negative low-level PV in vicinity of low
  - generated by Ekman mechanism
  - remains localised
- Positive PV North and East of low:
  - generated by Baroclinic mechanism
  - advected out of boundary layer on warm conveyor belt

Effect on cyclone development



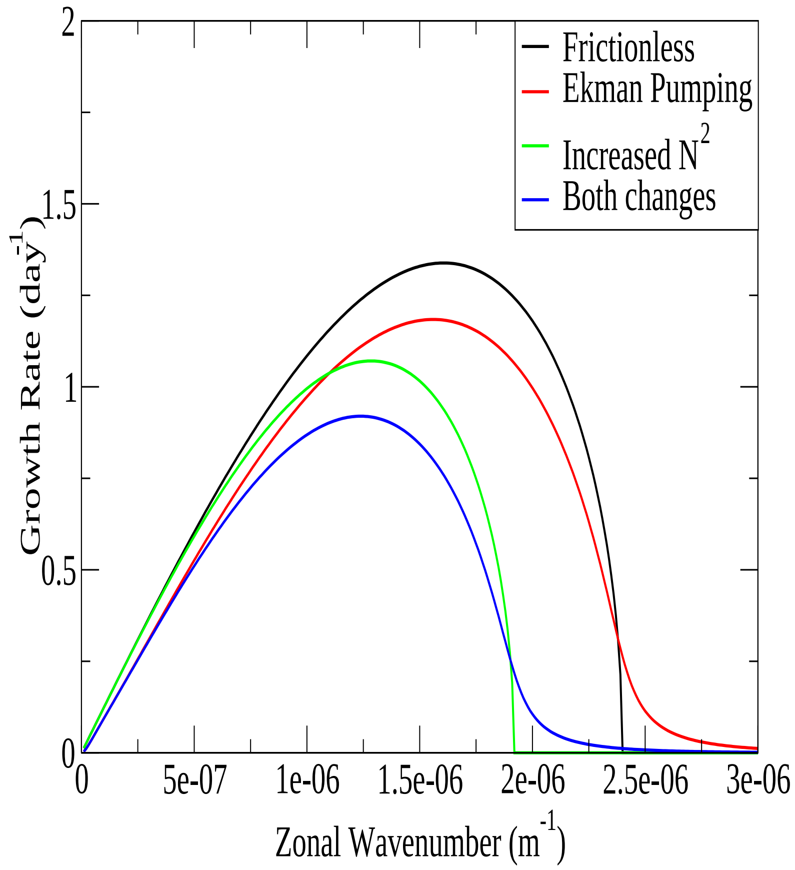
- Cross-section through low centre
- Thin PV anomaly, associated with enhanced static stability

Zonal-mean stability



- Mid-level feature associated with dry intrusion
- Baroclinic frictional effects increase low-level stability over the low centre
- Reduces the strength of coupling between tropopause-level PV feature and surface temperature wave

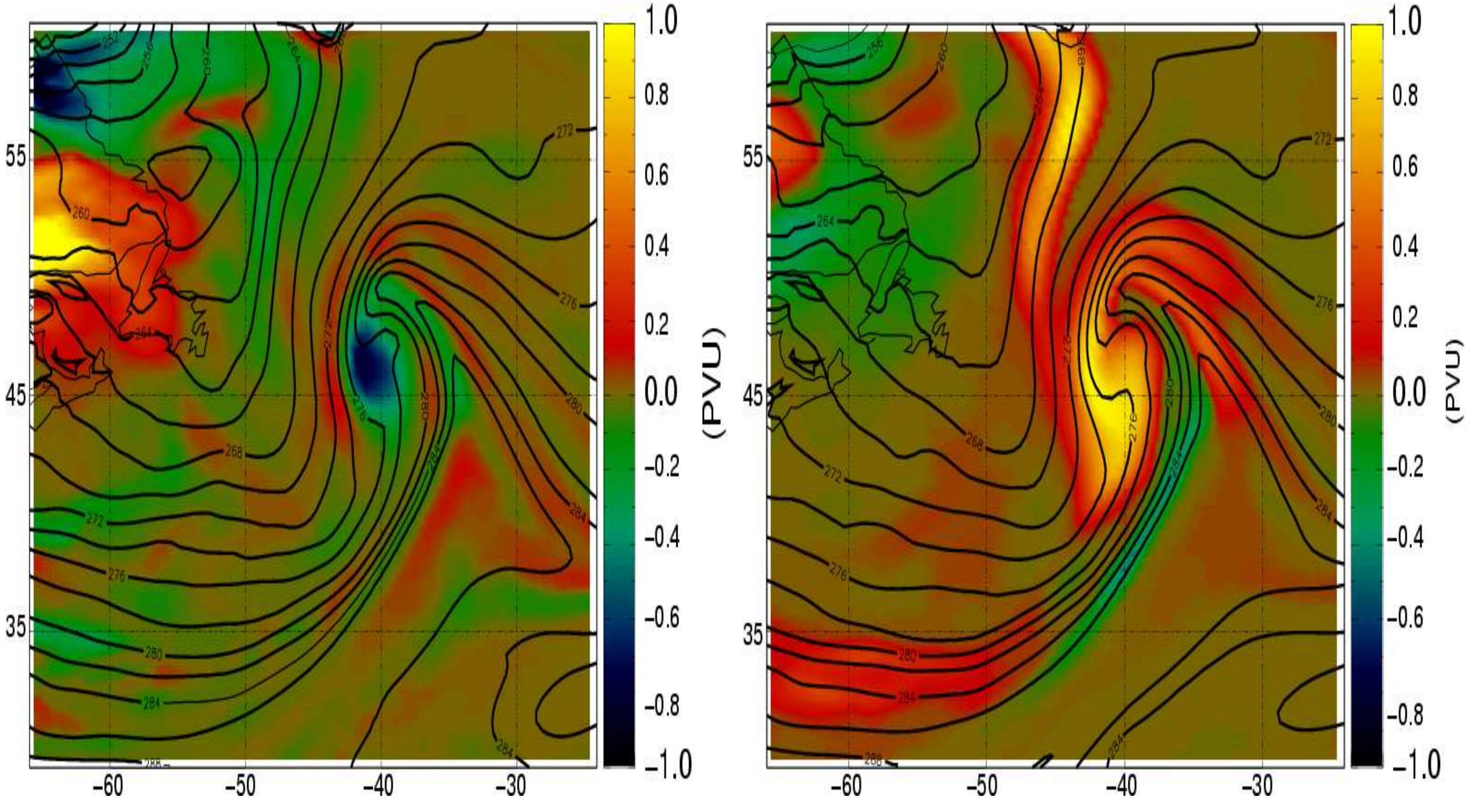
Comparison with Ekman effect



- Modified Eady model with Ekman-pumping included shows a reduction in growth rate
- Increased N^2 shows a similar level of reduction
- Both effects together can reduce growth rate by $\sim$ 50%

Effects of boundary-layer friction

PV attributed to frictional generation at T+24 in FASTEX IOP15



Barotropic term on 900mb. Baroclinic term on 850mb.

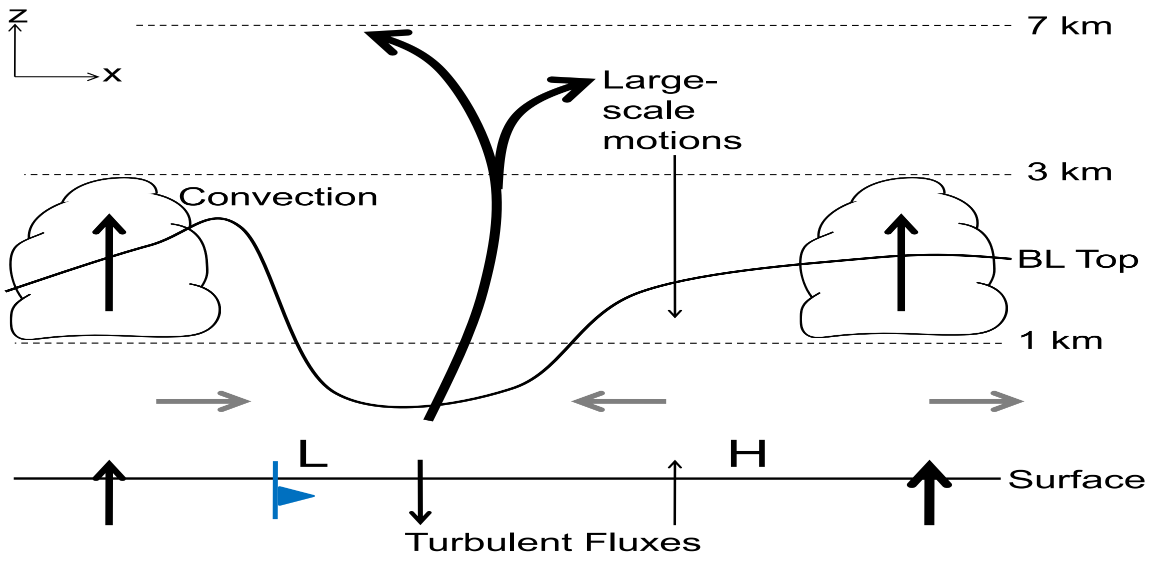
The role of boundary-layer moisture transport

Moisture source for a cyclone

- Precipitation occurs mainly in the ascending air on the warm conveyor belt
- In the WCB footprint area, boundary layer is stable (warm air moving over relatively cool surface) and evaporation is weak
- So where does the moisture come from?

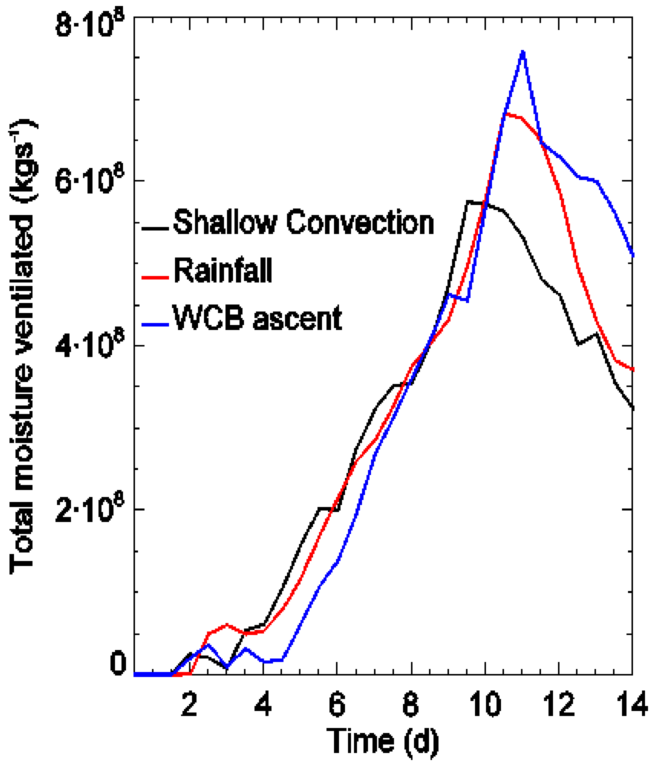
Moisture transport

Schematic based on boundary-layer moisture budget analysis:



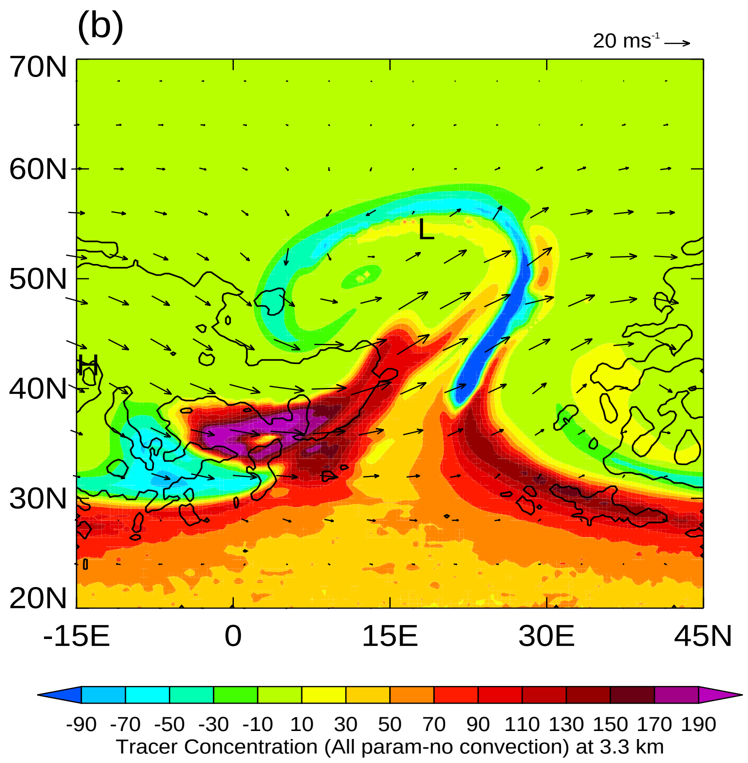
Divergence from high and convergence towards low within the boundary layer necessary to supply WCB with moisture

Ventilation mechanisms



- Warm-conveyor belt and shallow convection behind cold front ventilate similar amounts of moisture from the boundary layer
- Rainfall rate closely matches warm-conveyor belt ventilation: moisture is precipitated out quickly and efficiently

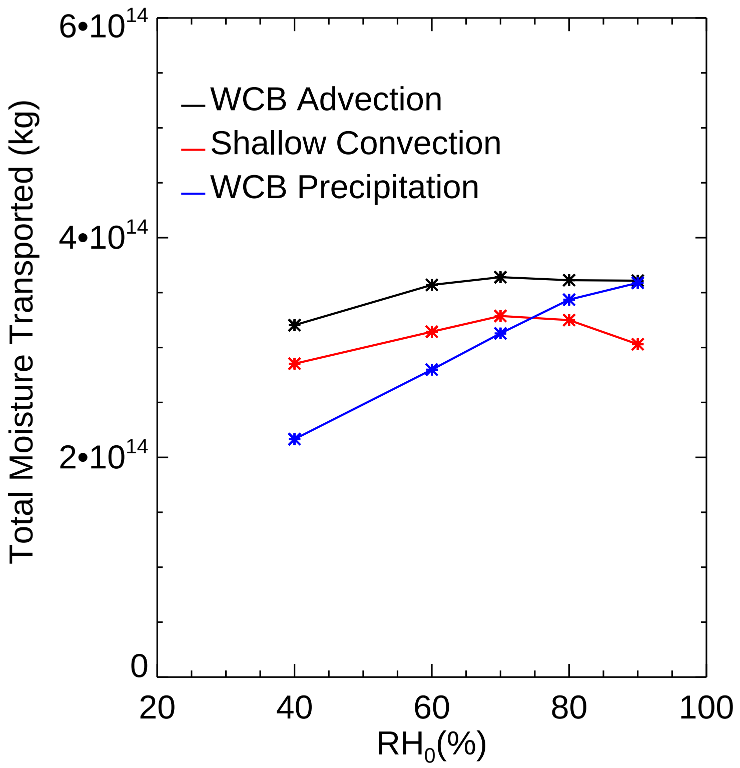
Convectively-ventilated moisture



Tracer difference at 3km

- Consider two tracers emitted at surface
- One of them is not passed through convection scheme
- Difference reveals that convectively-ventilated air is advected pole-wards and towards the cold front

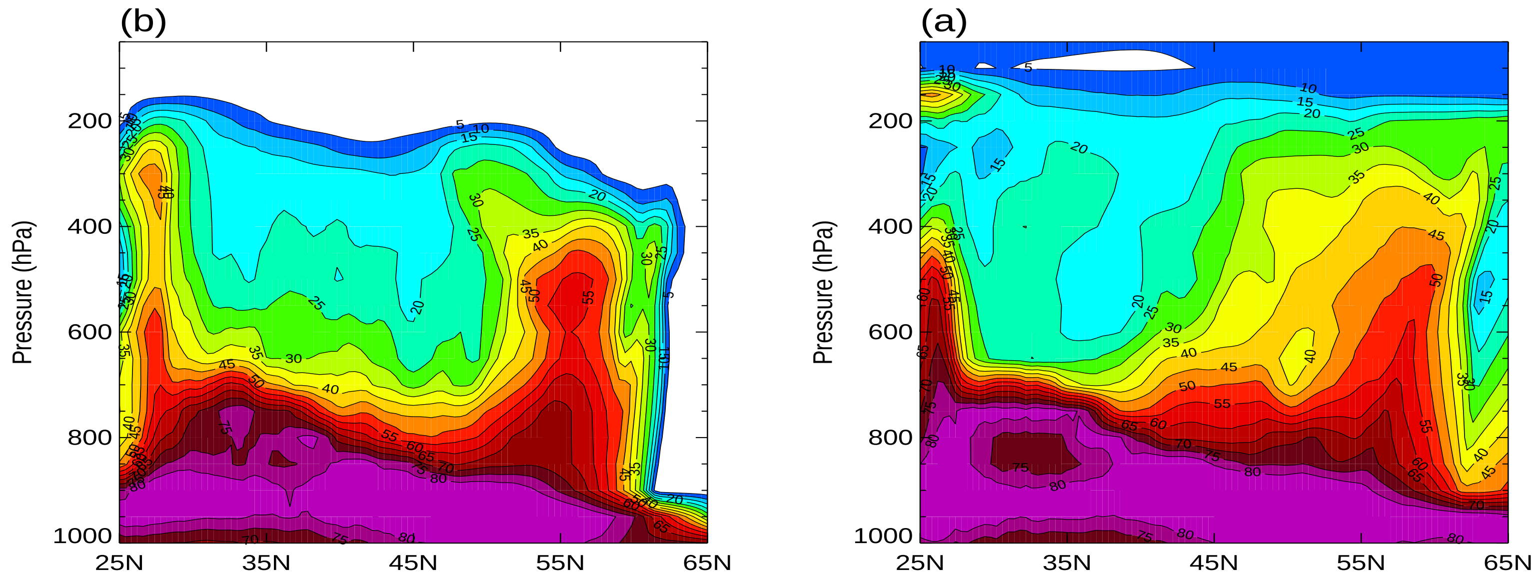
Initial moisture content



- Standard run has surface RH at 45N of 80%
- Rescale moisture content of atmosphere in initial conditions
- Little impact on total ventilation
- Less rain for low initial RH as some ventilated moisture retained in troposphere

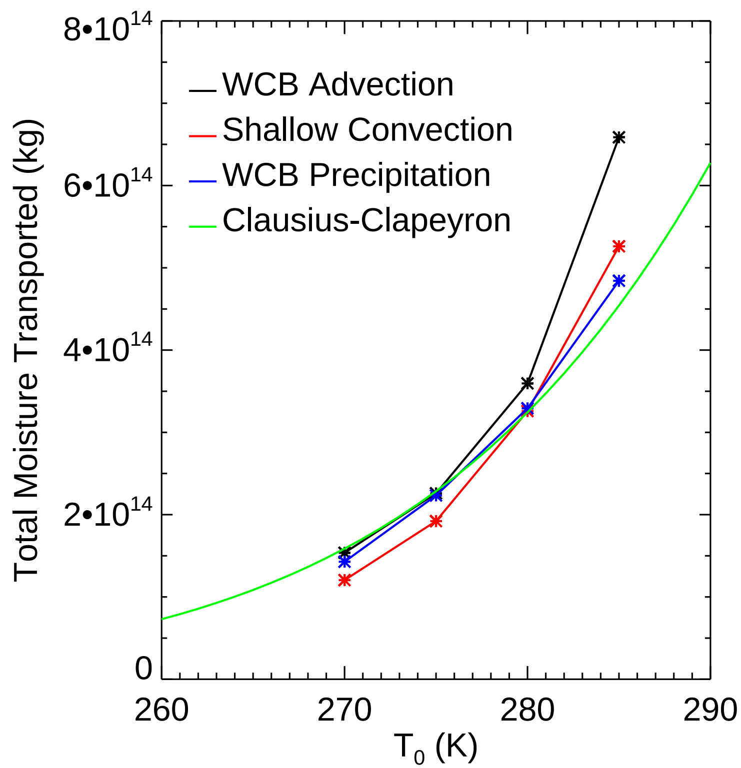
Final moisture content

Compare final states with no initial moisture (left) and standard initialization (right)



Climatological-mean mid-latitude moisture distribution can be regenerated in one wave lifecyle (14 days)

Scalings for moisture transport



- Scalings with changes in absolute temperature
- Like Clausius-Clapeyron based on temperature in the south, where main evaporation occurs
- But steeper because latent-heat release feeds back on system strength

Conclusions I

- Boundary layer friction dampens extratropical cyclones by two mechanisms:
  1. Ekman spindown: a barotropic mechanism the directly reduces cyclonic circulations
  2. Baroclinic PV generation and ventilation: an indirect mechanism that reduces the coupling between upper and lower levels
- Both mechanisms are robust

Conclusions II

- Moisture source for WCB precipitaion may be well away from cyclone
- Shallow convection is also an important means of moisture ventilation from the mid-latitude boundary layer
- Scalings can be developed for these ventilation processes
- Is it possible to develop a “bottom-up” analysis of changes to the water cycle in a changing climate?

Conclusions III

- Mid-latitude cyclogenesis is far from a dead, textbook subject
- Many important aspects of cyclones can only be understood by unravelling the interactions between large-scale, boundary-layer and moist dynamics