Boundary layer dynamics in extra-tropical cyclones

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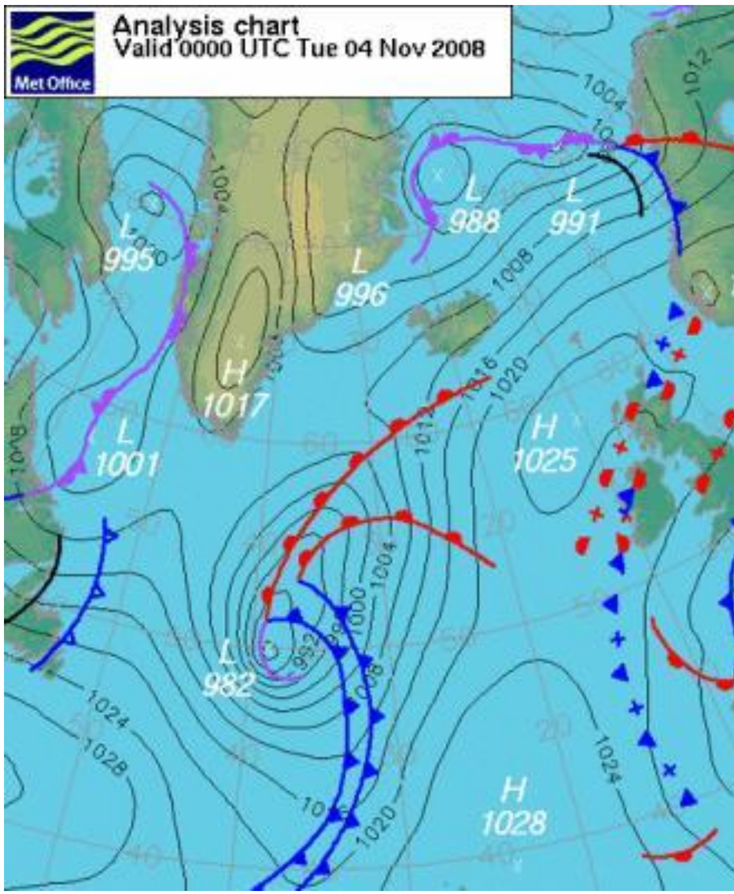
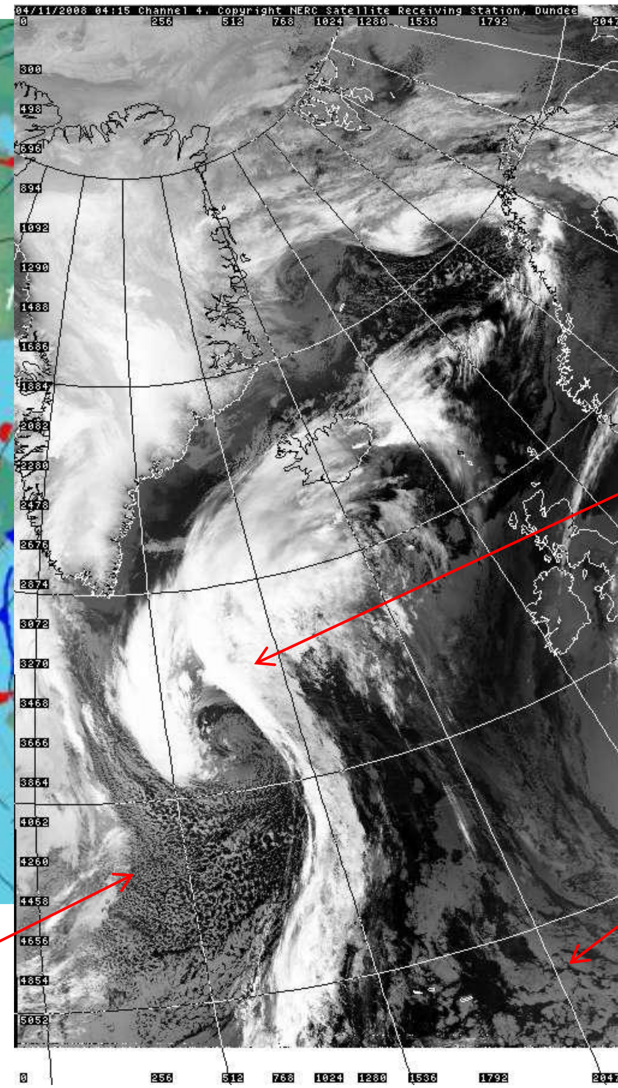
Is this a boundary-layer turbulence problem?





Warm Conveyor Belt Cloud

BL Top Cloud

BL Top Cloud

Aim:

"To understand and quantify the water cycle in extra-tropical weather systems"

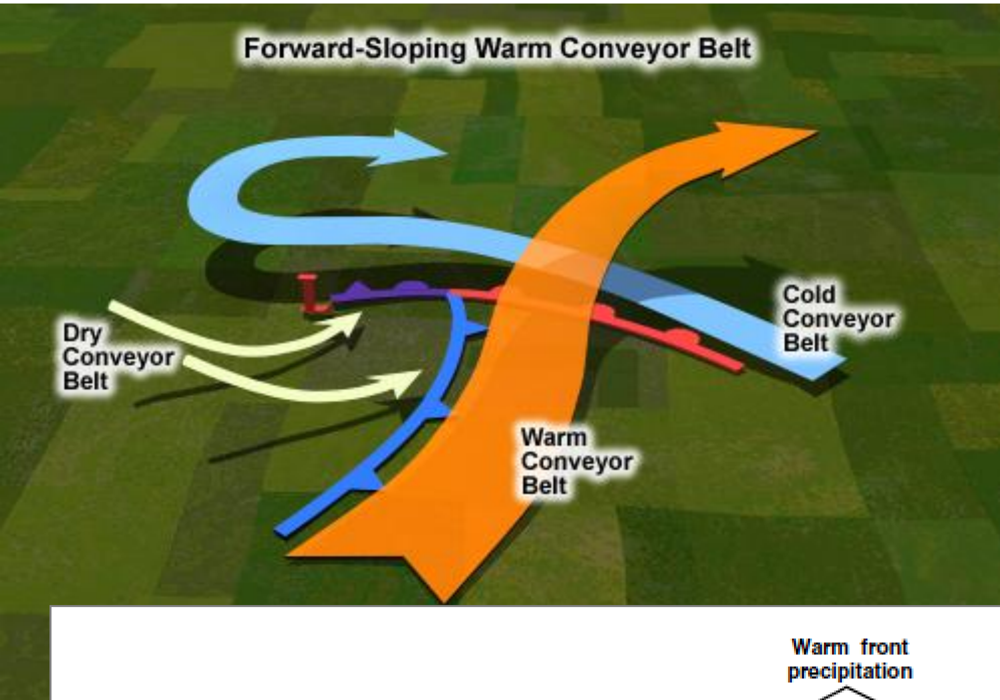
T-NAWDEX

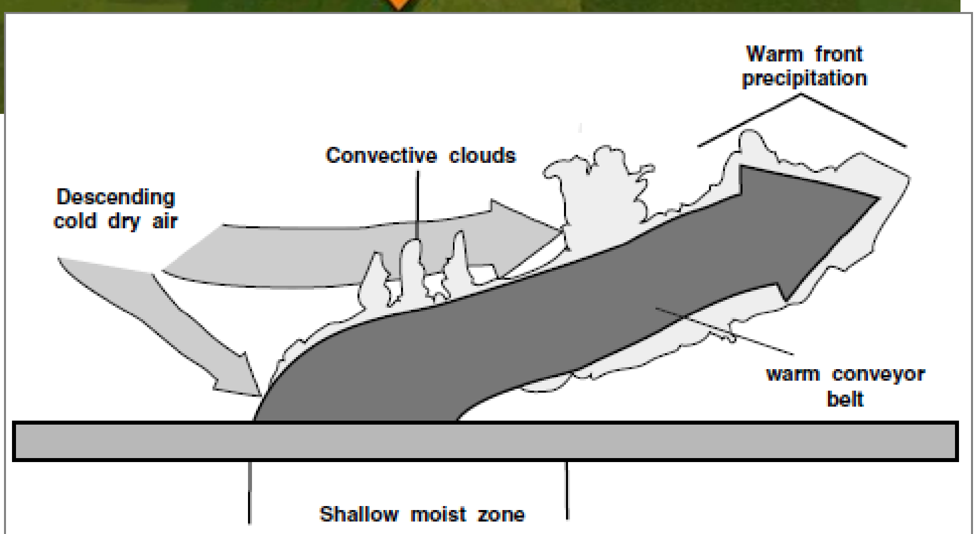
- "Do WCBs in the models start off with the correct humidity and temperature structure?"
- "Is the representation of turbulence correct along the WCB?"

NERC Changing Water Cycle theme

- "Develop an integrated, quantitative understanding of the changes taking place in the global water cycle."

Conceptual cyclone models





- Warm conveyor belt (WCB) ascends ahead of cold front and over warm front, from <u>near-surface</u> to ~300hPa
- Primary source of cloud and rain within cyclone (eg. Summer 2007 floods)

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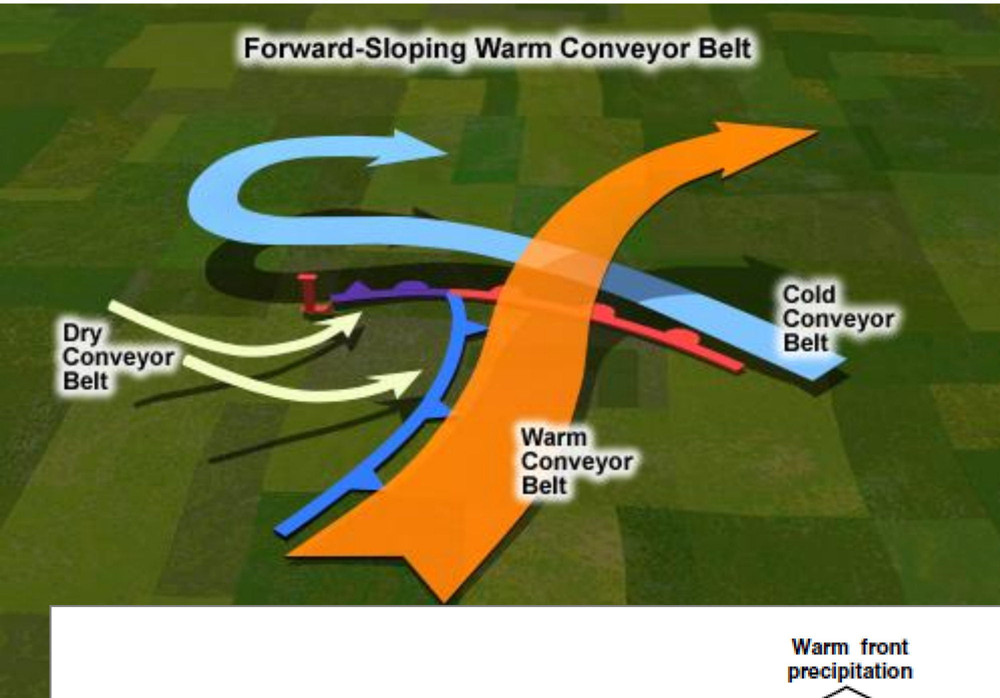
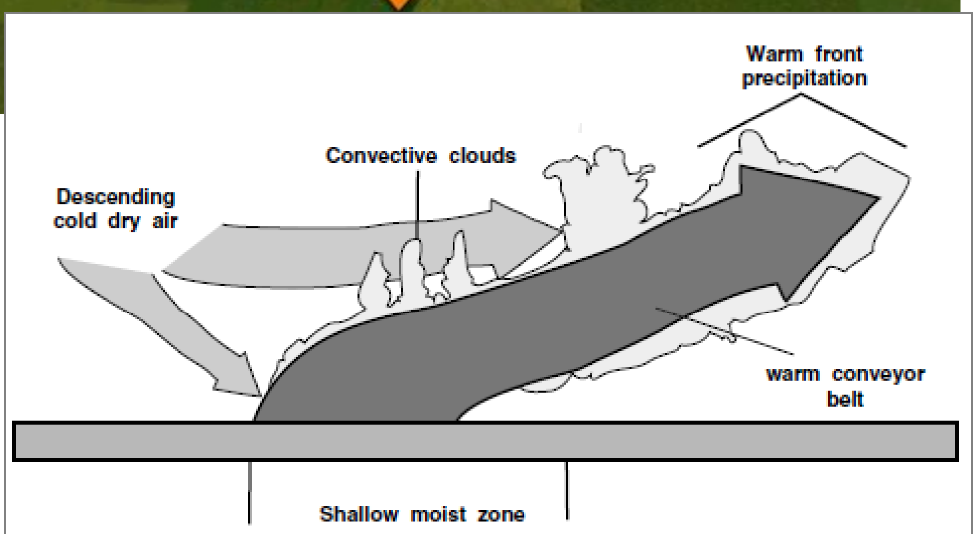
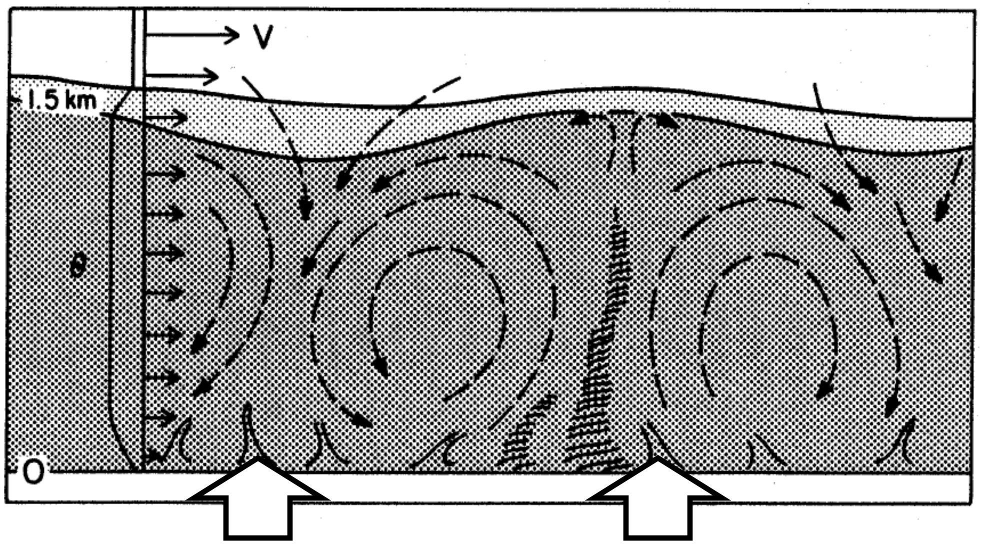
Conceptual cyclone models

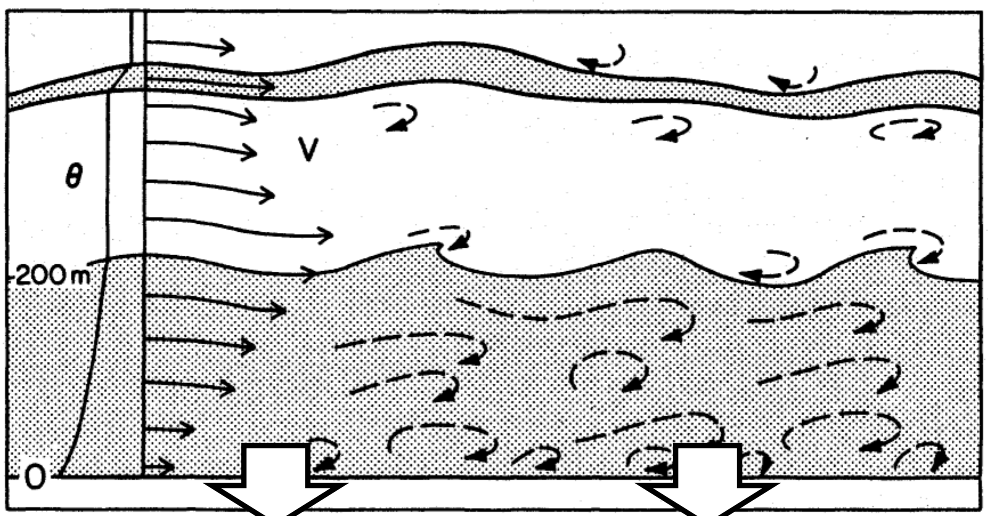




- Large-scale, cyclone driven, airflows are well understood – what is happening in the boundary layer?
- Moisture outflow from WCB often linked to forecast “busts” – knowing the inflow might help!

The atmospheric boundary layer

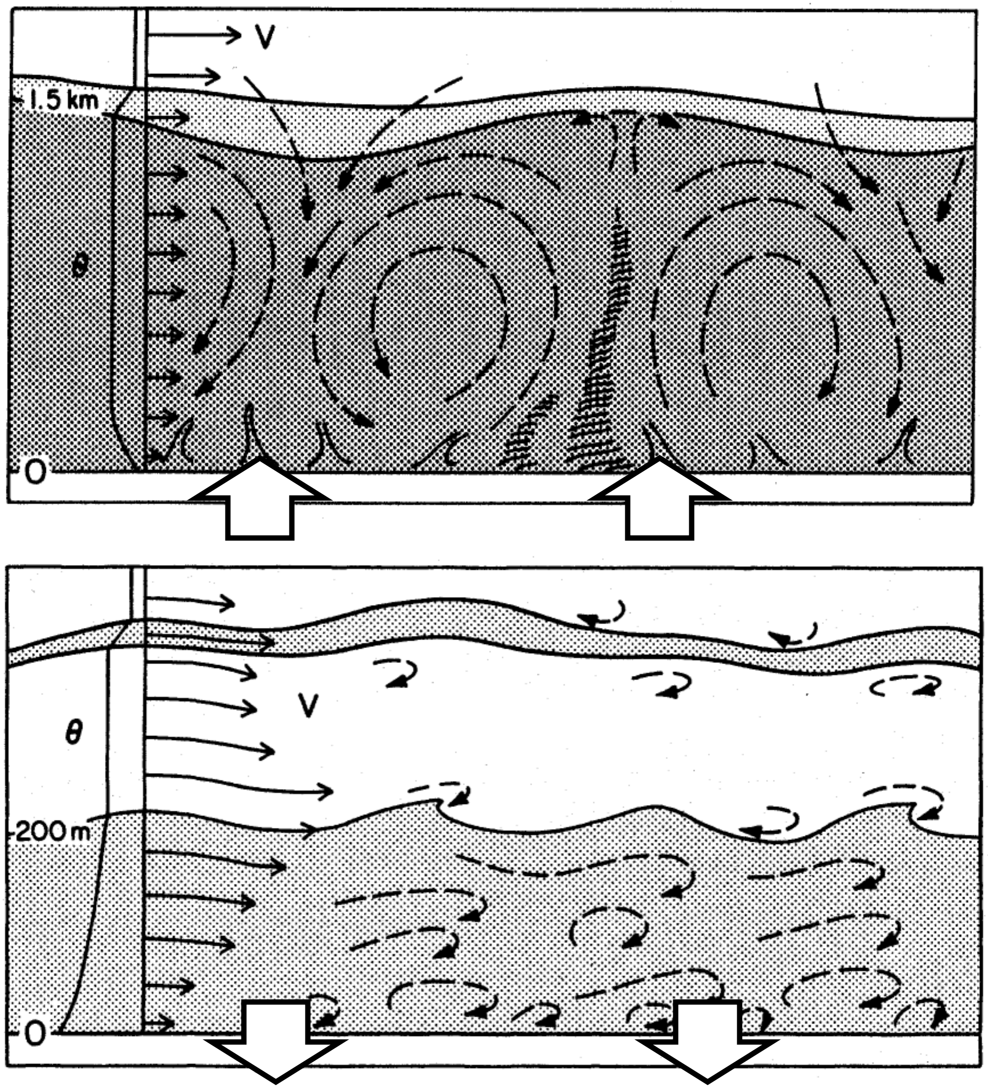




- <u>Unstable</u> – surface warmer than atmosphere, surface fluxes positive (daytime)

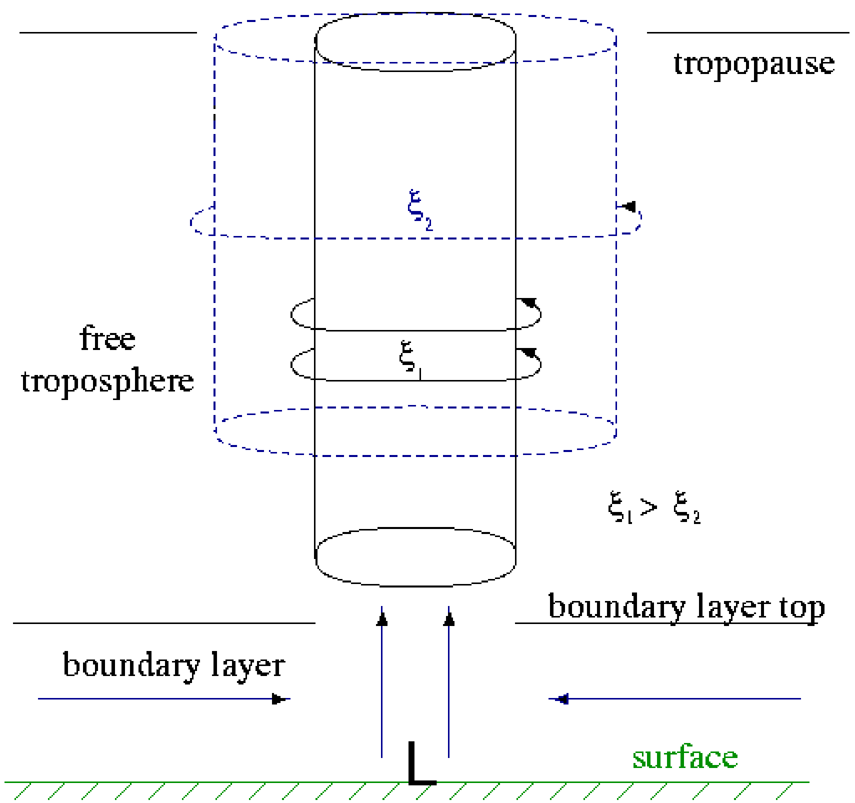
- <u>Stable</u> – atmosphere warmer than surface, surface fluxes negative (night-time)

The atmospheric boundary layer



- Previous studies show very different impact of fluxes on cyclone development
- Lack of clear mechanism how surface fluxes are communicated to cyclone above

Cyclone/BL coupling



- Ekman pumping normally cited as the mechanism
- Doesn’t look like the conceptual models presented
- What is the effect of moisture here?

Objectives

- Develop a framework in which to understand cyclone / moisture / boundary layer interaction
- What is the source of warm-conveyor belt moisture?
- Develop conceptual model of moisture transport in the cyclone boundary layer
- Quantify how moisture is transported by cyclone and boundary layer – vertically and polewards.
- What factors control the moisture transport?

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Outline

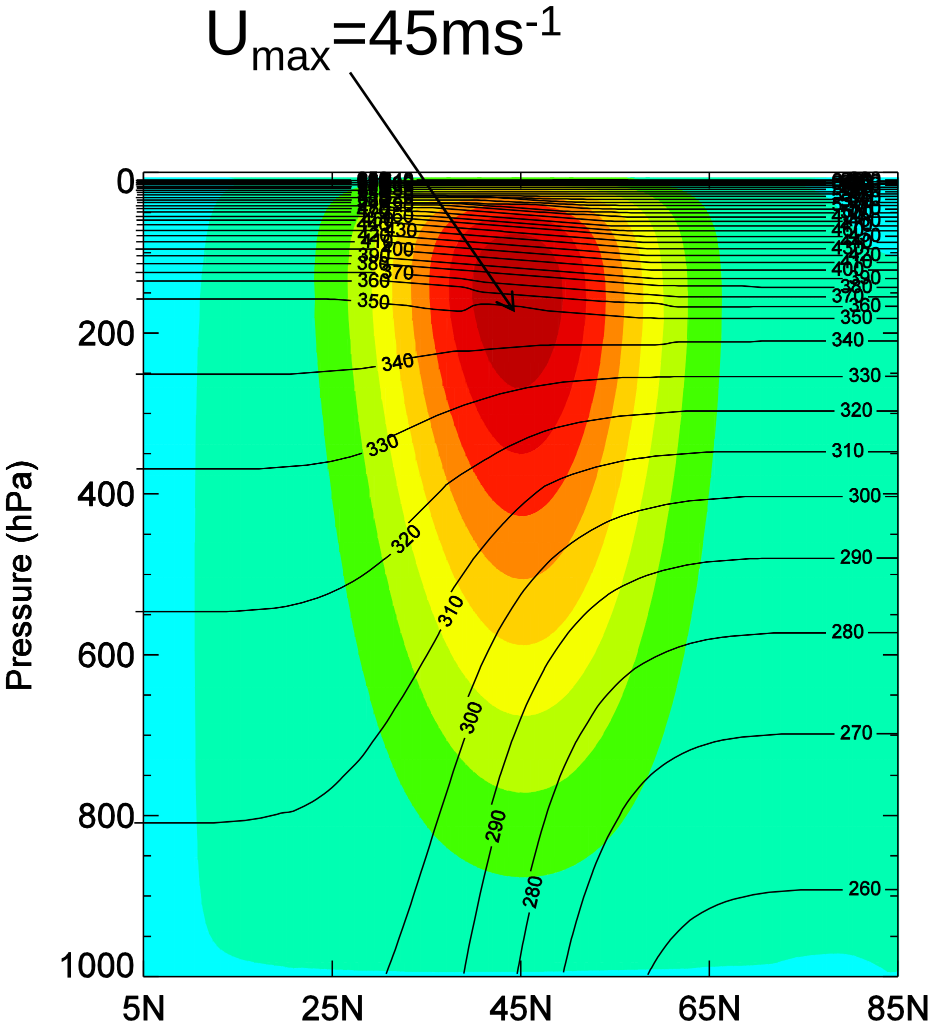
- Development of idealised cyclone simulations in the Unified Model
- Structure of the boundary layer under mid-latitude cyclones
- Moisture transport within & ventilation from the boundary layer
- Factors controlling cyclone moisture transport

A full physics idealised cyclone

- Met Office Unified Model (MetUM) is used in Idealised mode
- 0.4° horizontal resolution (~44 km grid squares)
- 38 vertical levels with a well resolved boundary layer
- Boundary-layer scheme of Lock et al. with nonlocal mixing in CBL & cumulus/stratocumulus decoupling
- Mass-flux convection, mixed phase microphysics, large-scale cloud
- Sea-surface with fixed temperature

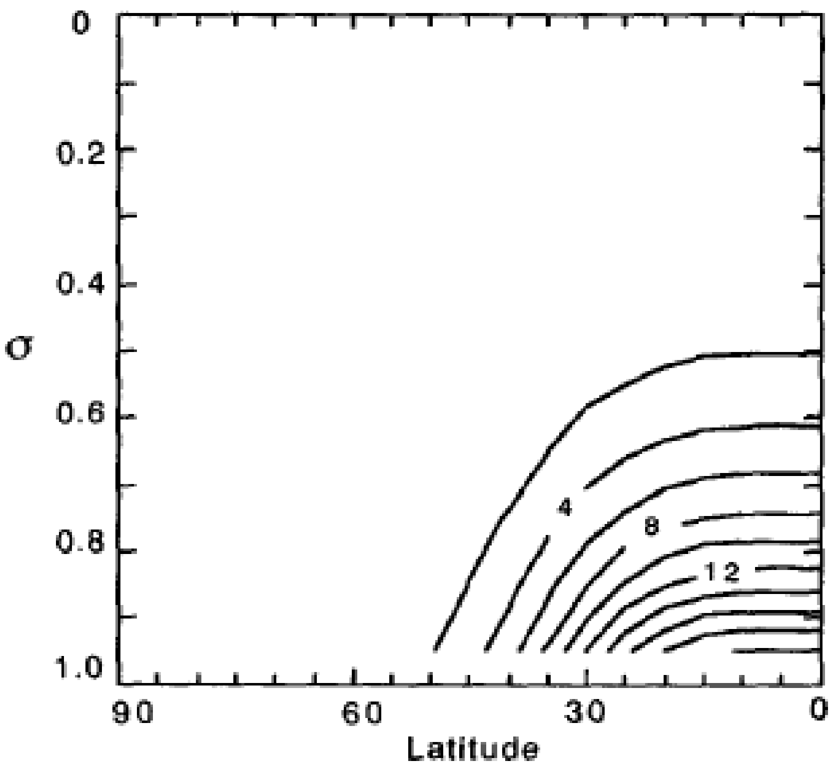
Initial Conditions

- North-South temperature gradient in thermal wind balance with a westerly jet
- Represents the wintertime condition of the storm track
- Based on LC1 initial condition (Thorncroft et al. (1993))



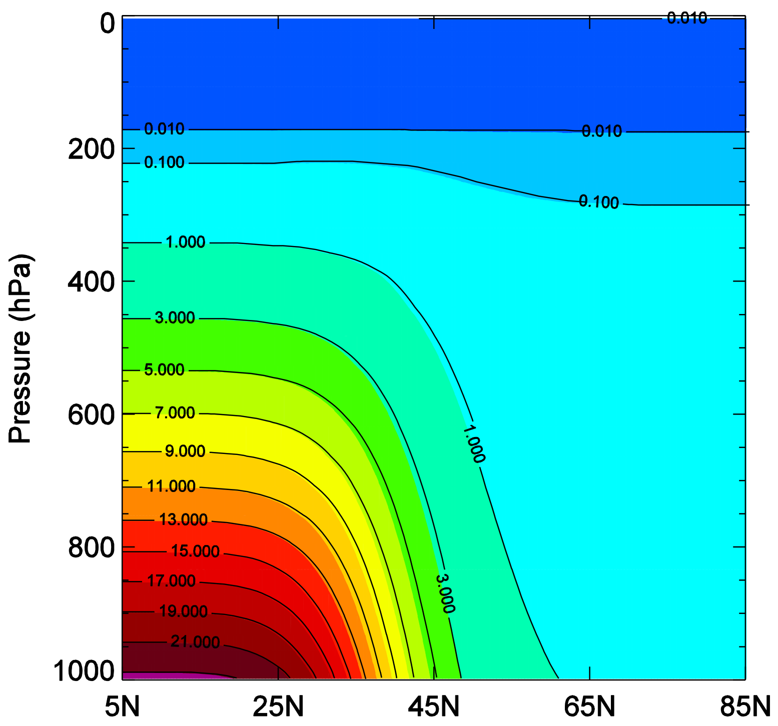
Initial Condition Specific Humidity

Gutowski et al. (1992):

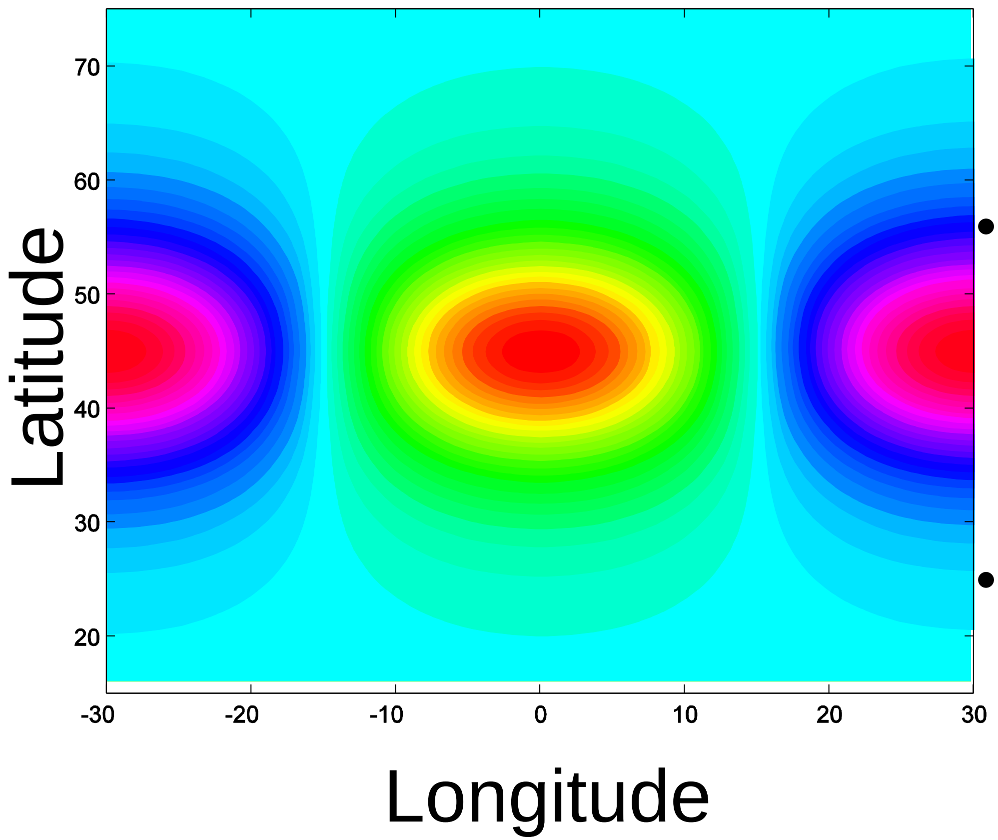


Simplified NH Climatology

Ours:



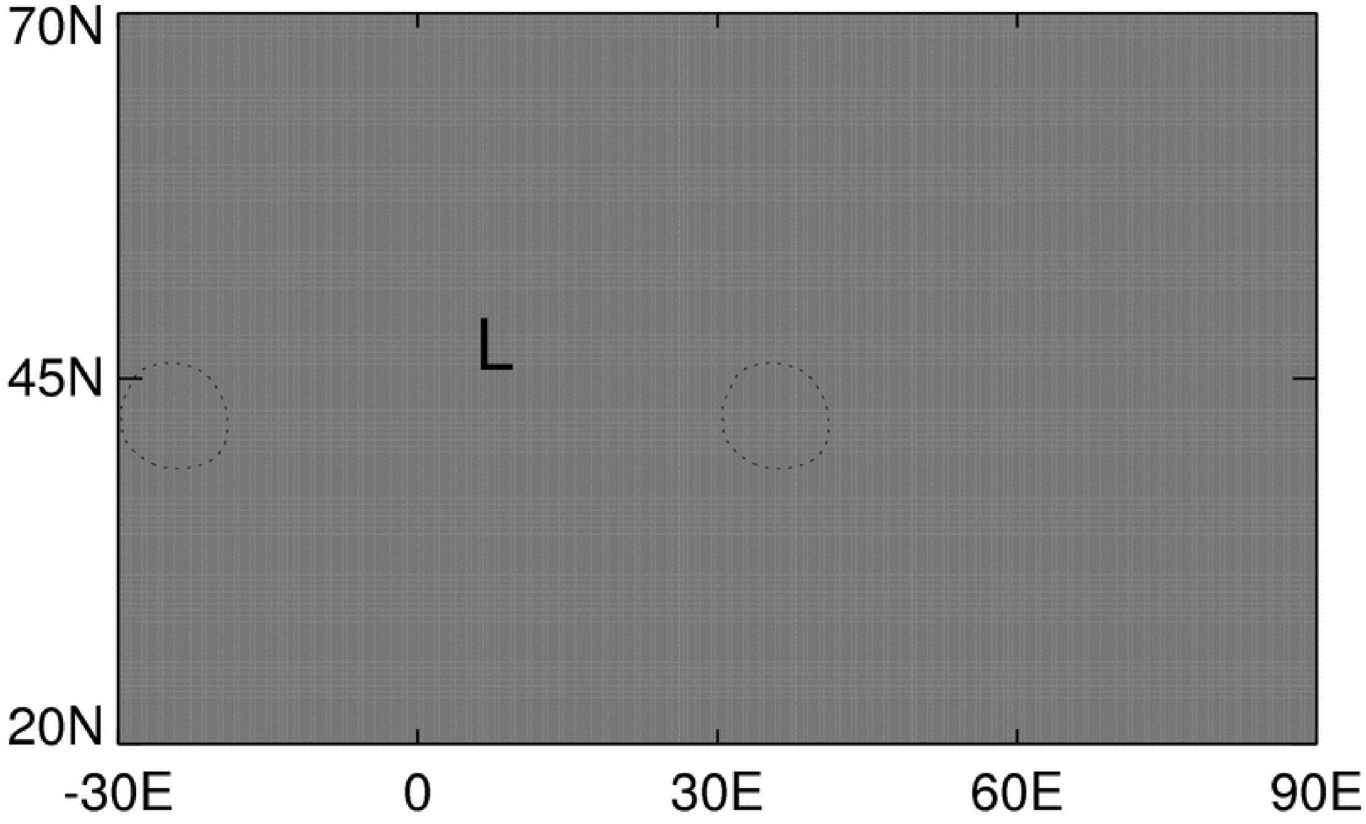
Triggering Cyclogenesis



$$T'(\lambda,\phi) = T_0 \cos(m\lambda)[\text{sech}(m(\phi - \hat{\phi}))]^2$$

- Initial state is well-balanced, but baroclinically unstable
- Perterb temperature field to generate normal-mode type growth of baroclinic wave
- $m=6$, $T_0=1$K as in Polvani and Esler (2007)

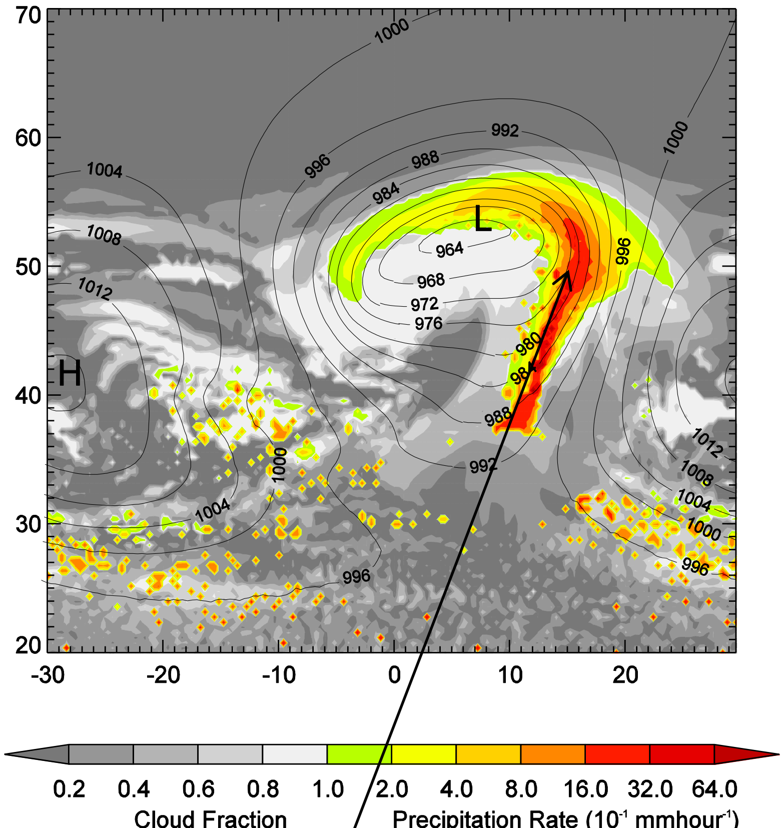
Life cycle



Cloud Fraction and Rainrate over 14 days of the lifecycle

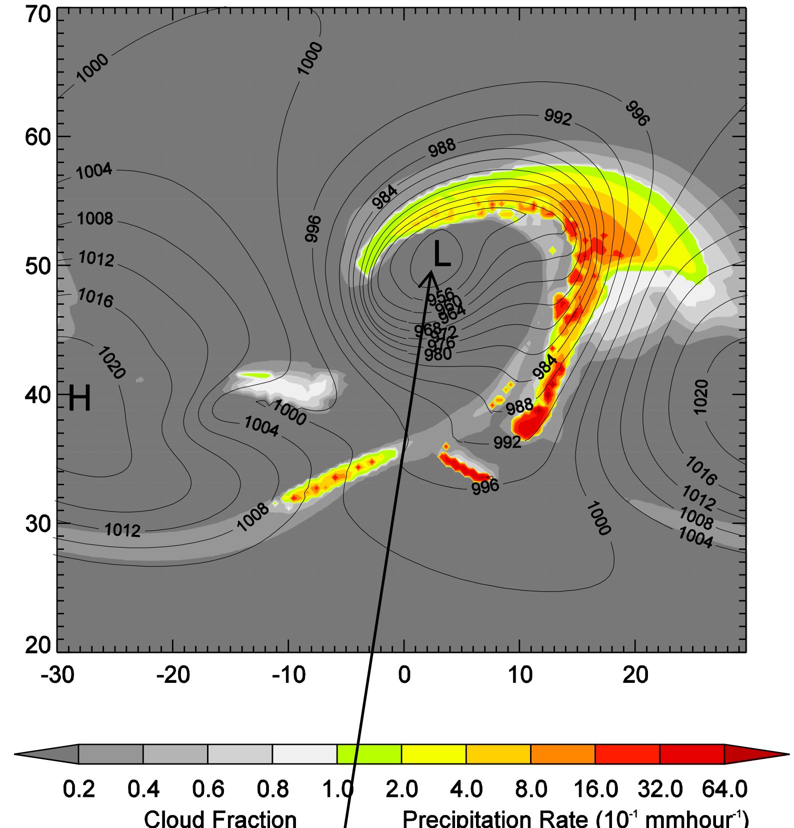
Impact of boundary layer

With BL Scheme



More precipitation

Without BL Scheme



More intense system

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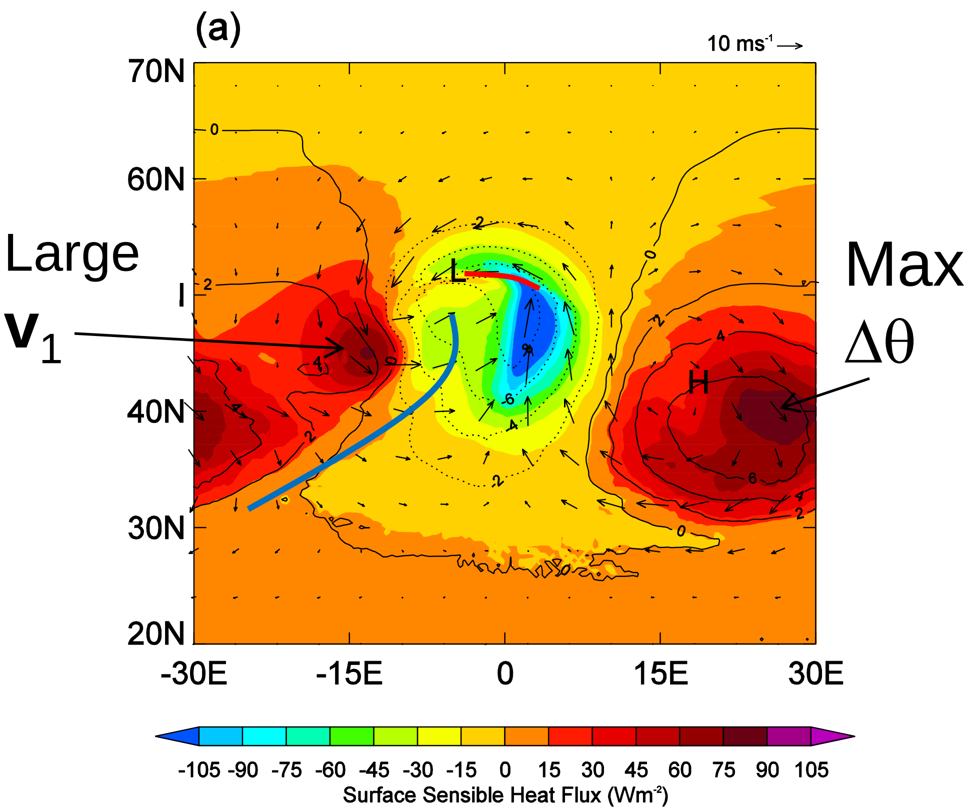
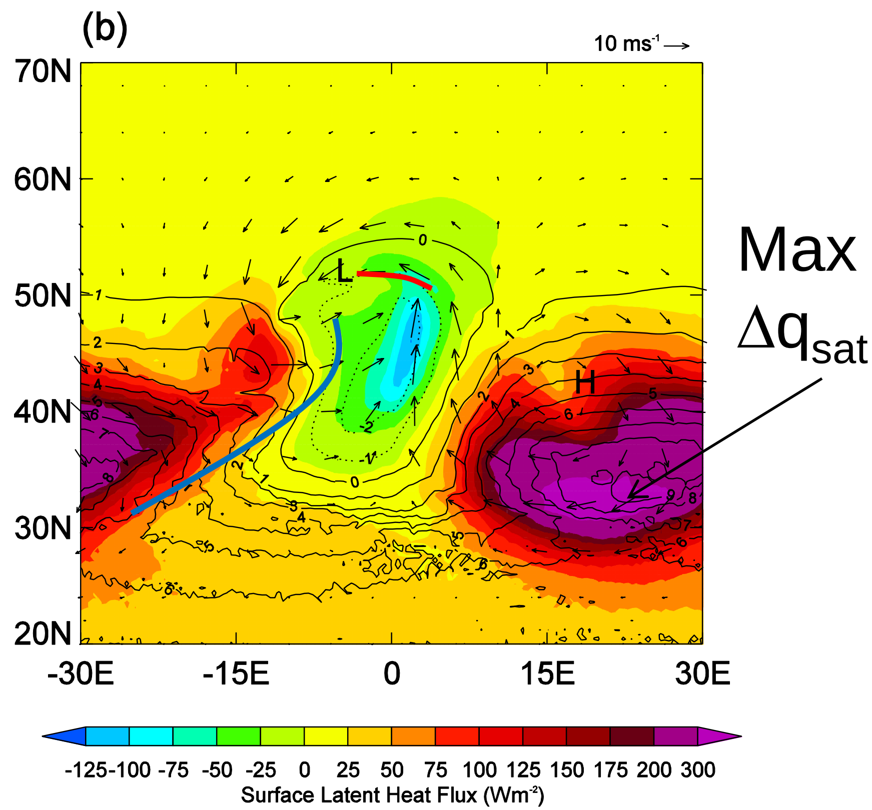
Surface Fluxes

Surface Sensible Heat:



$$H_s = \rho C_p C_H \left|\mathbf{v}_1\right| (\theta_s - \theta_1)$$

Surface Latent Heat:



$$\lambda E = \rho \lambda C_H \left|\mathbf{v}_1\right| (q_{sat}(\theta_s) - q_1)$$

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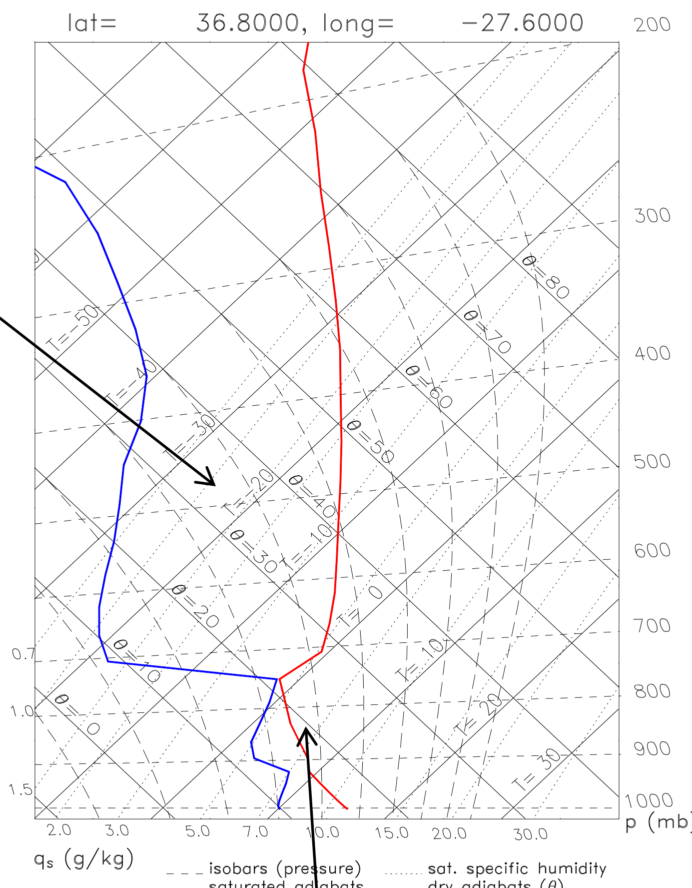
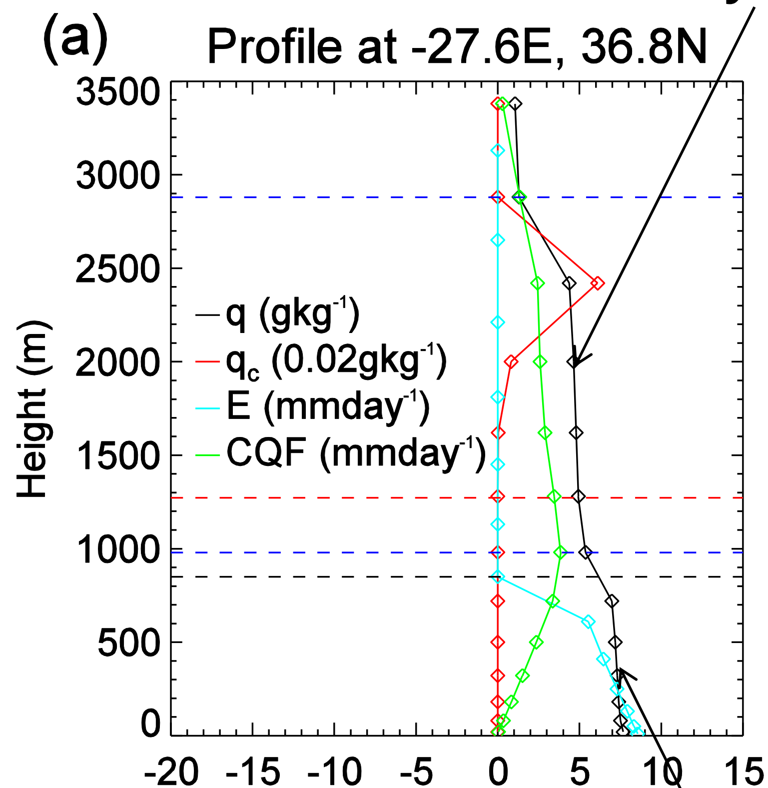
Post cold front boundary layer

Dry air aloft



Some CAPE for convection

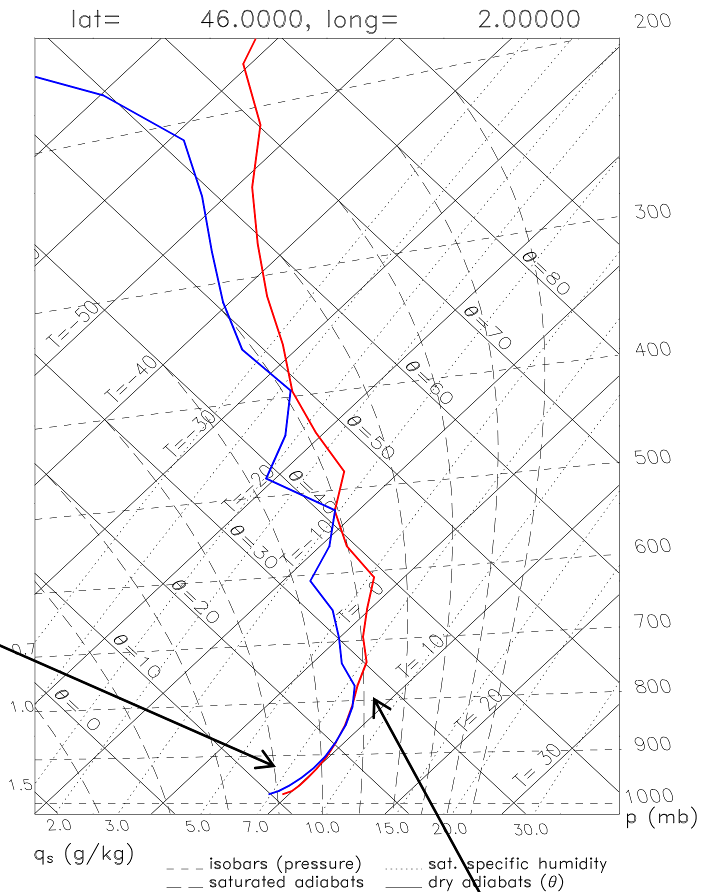
Well-mixed cloud layer

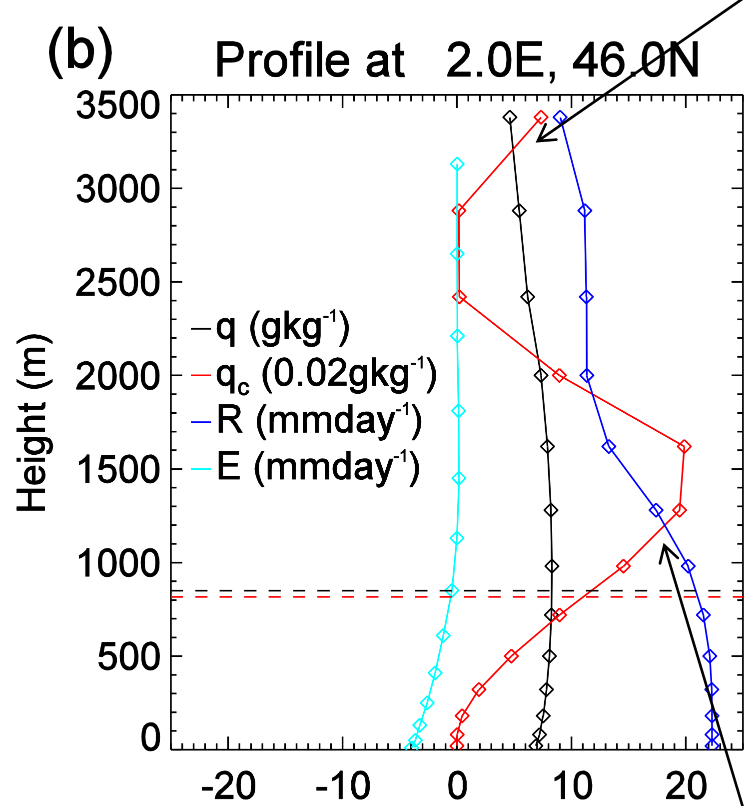


Well-mixed sub-cloud layer

WCB boundary layer

Higher precipitating cloud





Stable BL

Very saturated profile

BL(?) cloud, enhancing precipitation

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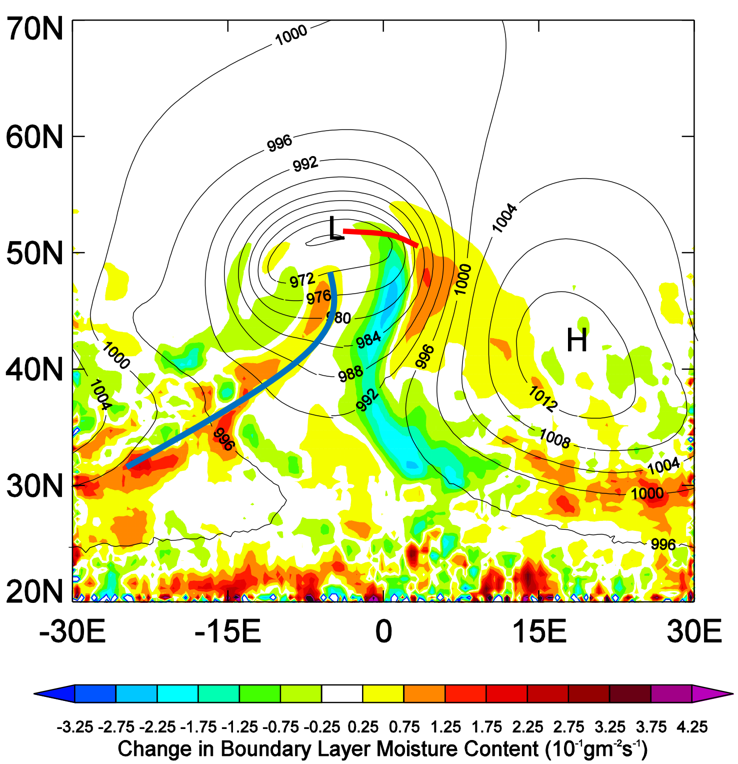
Boundary-Layer Moisture Budget

$$\frac{\partial}{\partial t}\widehat{\rho q} = (\rho q)_h \frac{\partial h}{\partial t} - (\rho q)_h \mathbf{u.n} - \nabla_2 . \widehat{\rho q \mathbf{v}} - (\rho \overline{w' q'})_h + (\rho \overline{w' q'})_0 + \hat{S}$$

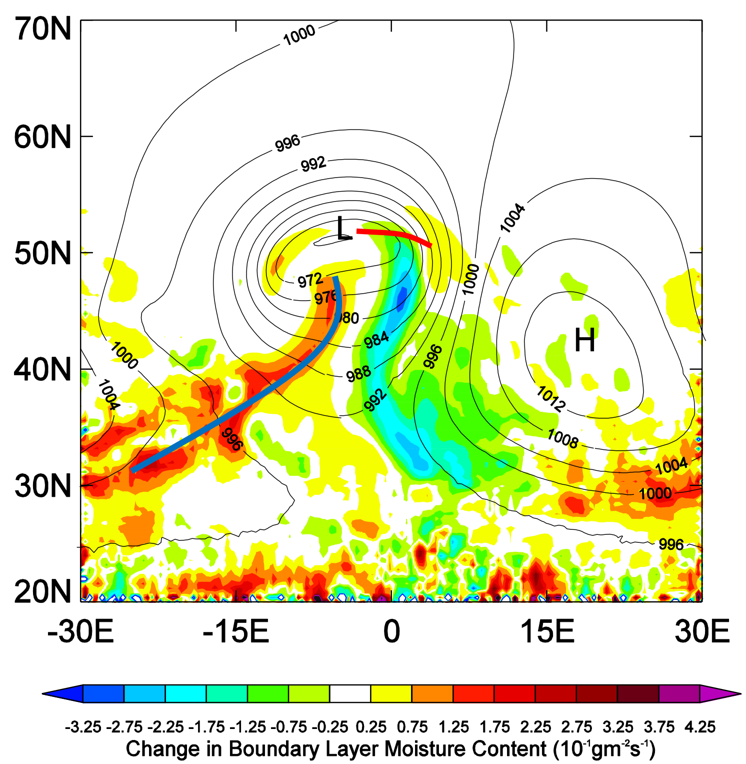
- Rate of change of total moisture in boundary layer
- Eulerian change in boundary-layer height
- Advection across boundary-layer top
- Horizontal divergence within the boundary layer
- Net vertical transport by boundary-layer turbulence
- Source and sink from microphysical processes

Budget Terms

Total change:



BL height change:



Mainly eastward propagation of cyclone forcing change

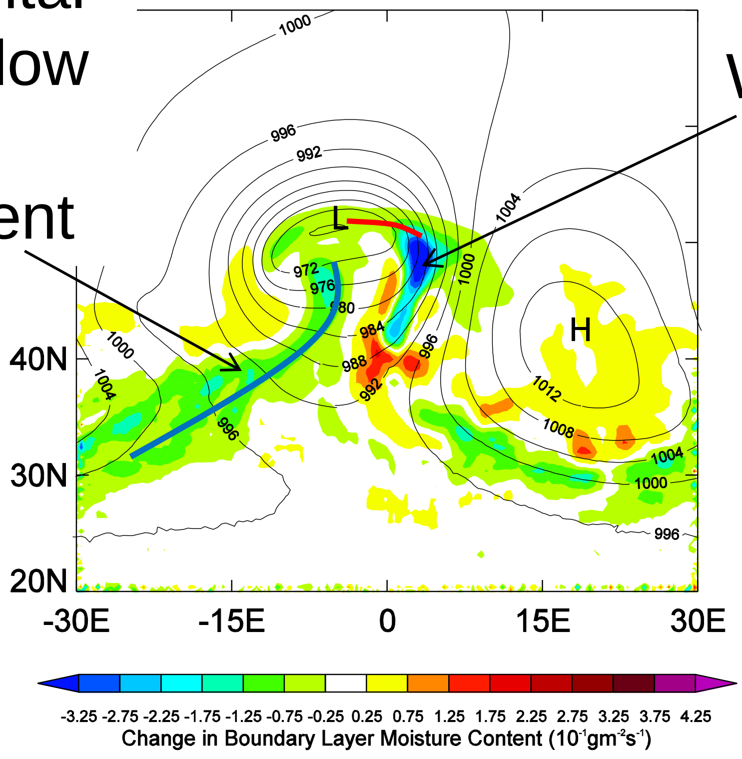
Flow across BL Top

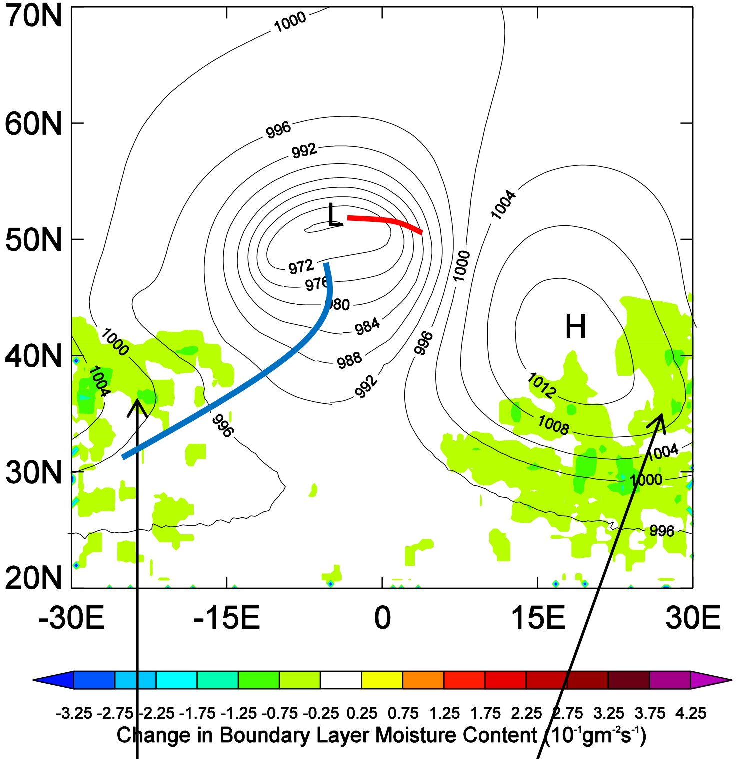
Large scale advection:

Cumulus Convection:

Frontal outflow and ascent

WCB

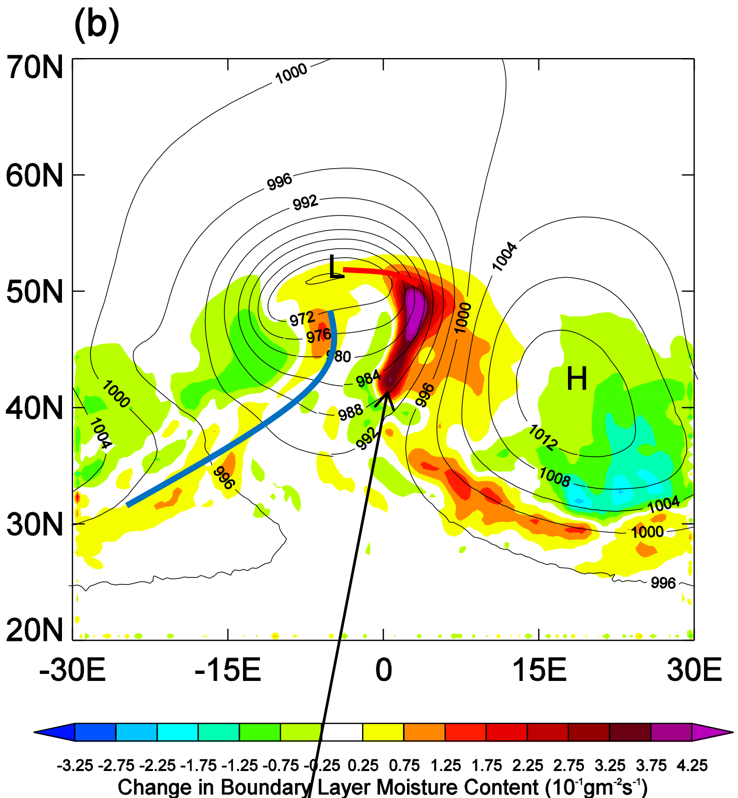




Large amount of ventilation

Movement and sources

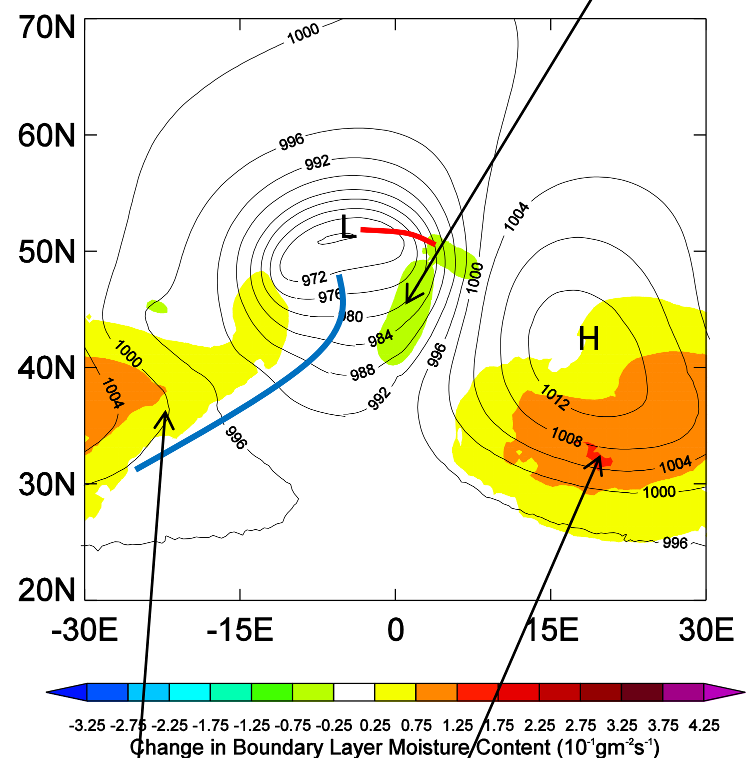
Divergence in BL:



WCB source

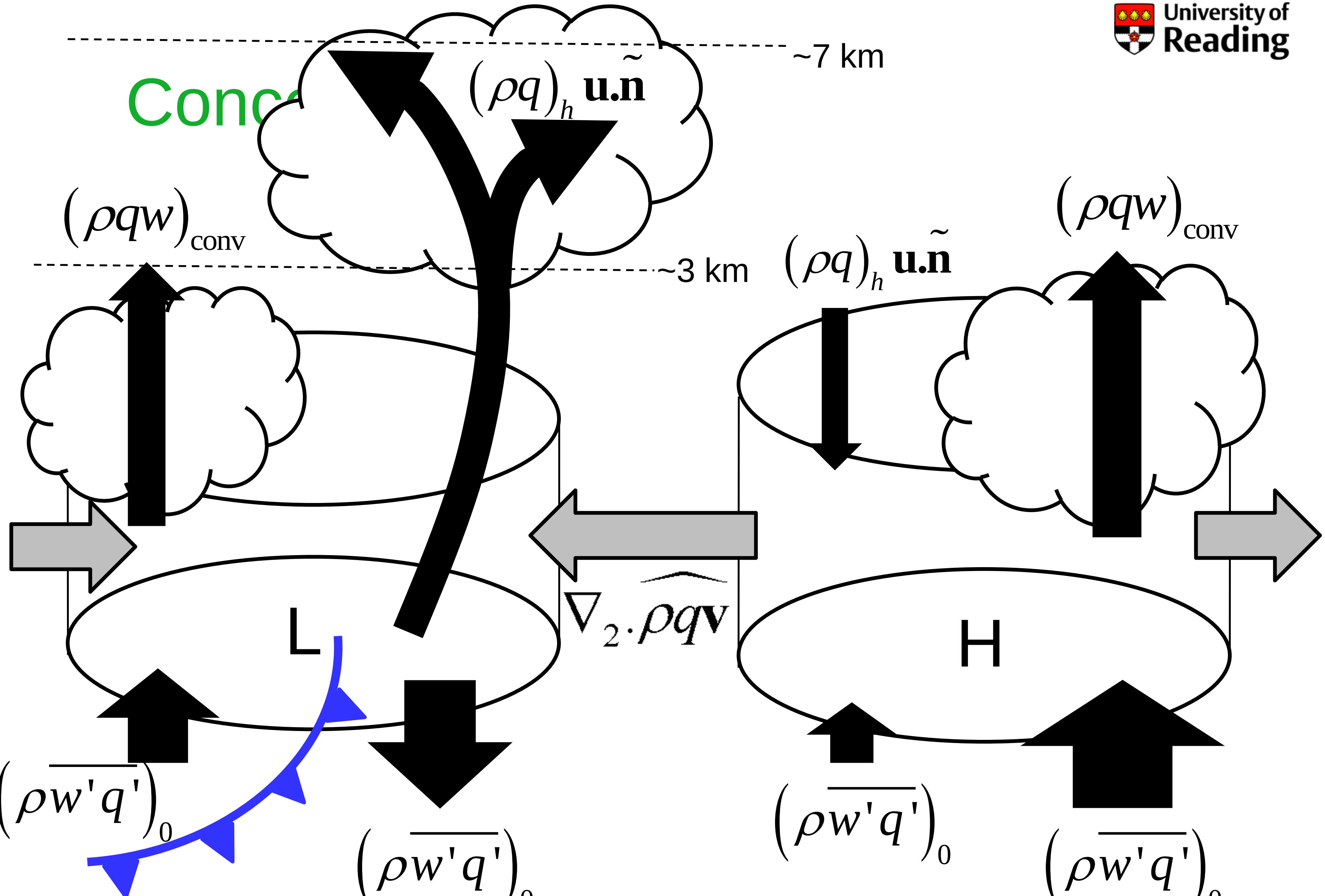
Turbulent Flux:

Negative λE



Evaporation is main input

Conc

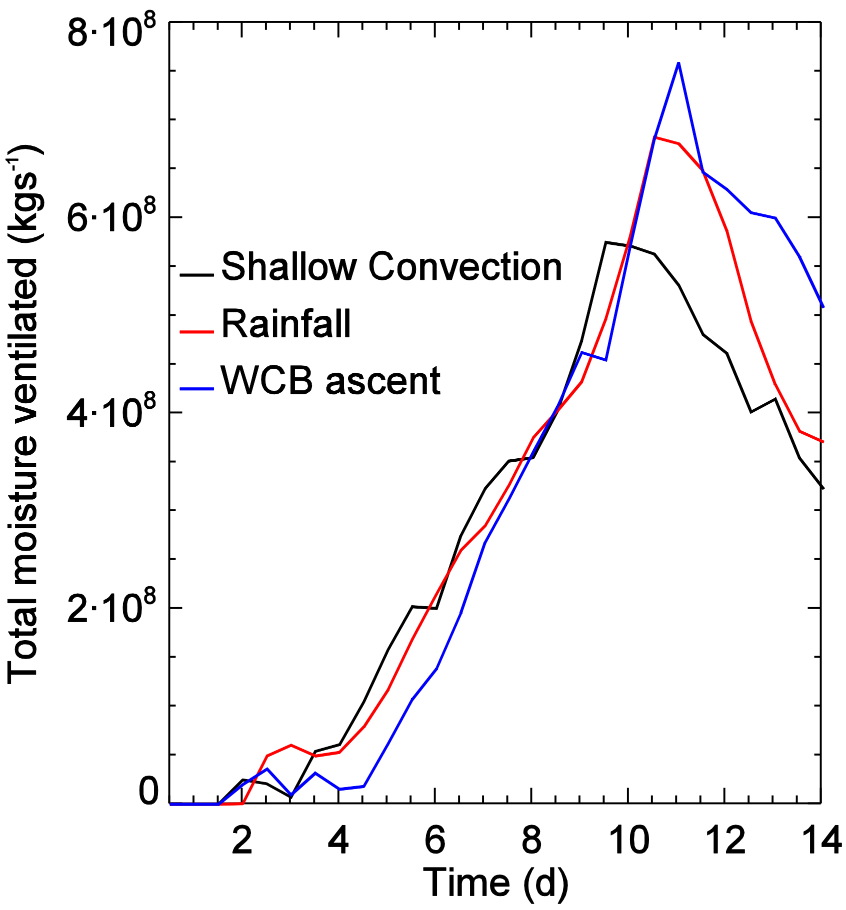


~7 km
$(\rho q)_h \, \mathbf{u.\tilde{n}}$
$(\rho qw)_{\text{conv}}$
~3 km
$(\rho q)_h \, \mathbf{u.\tilde{n}}$
$(\rho qw)_{\text{conv}}$
L
$\nabla_2 \cdot \widehat{\rho q \mathbf{v}}$
H
$(\rho \overline{w'q'})_0$
$(\rho \overline{w'q'})_0$
$(\rho \overline{w'q'})_0$
$(\rho \overline{w'q'})_0$

Ventilation of Moisture

- Warm-conveyor belt and shallow convection can ventilate similar amounts of moisture from the boundary layer

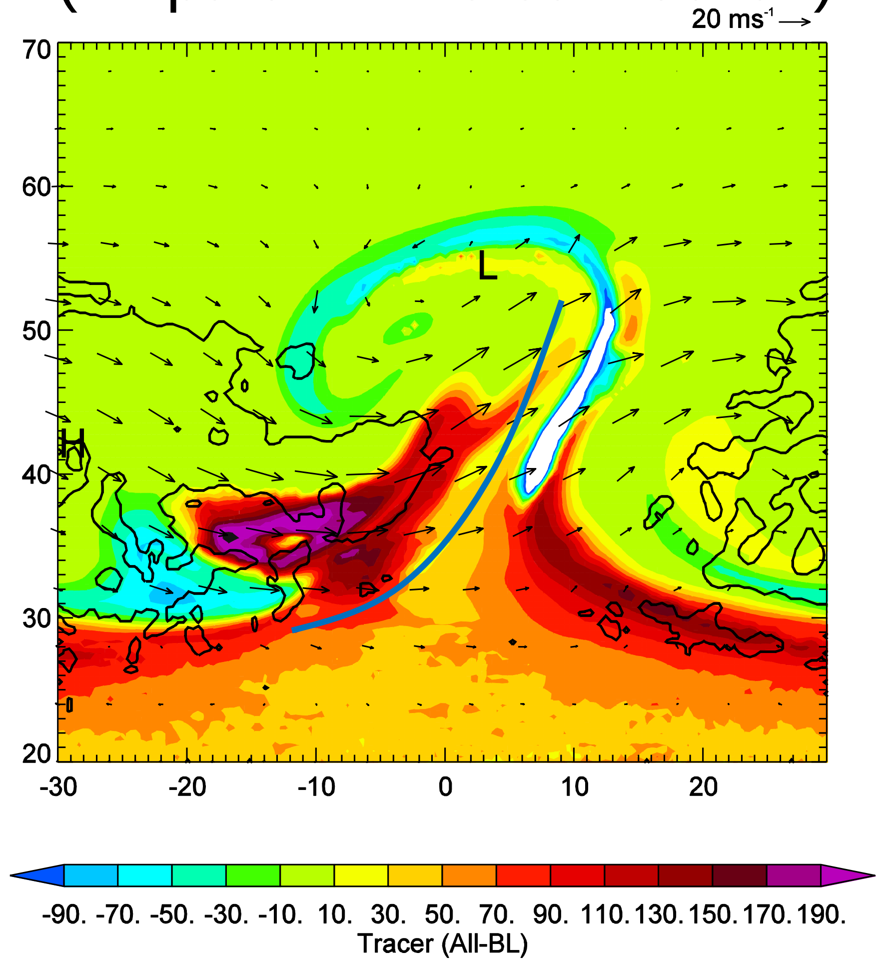
- Rainfall rate closely matches warm-conveyor belt ventilation – moisture is precipitated out quickly and efficiently



Transport in Troposphere

- 2 tracers emitted at surface and passed through different parameterisations.
- Tracer passed through Convection scheme gets advected with background flow towards cyclone cold front and poleward

Tracer difference at 3km – (All param – no convection)



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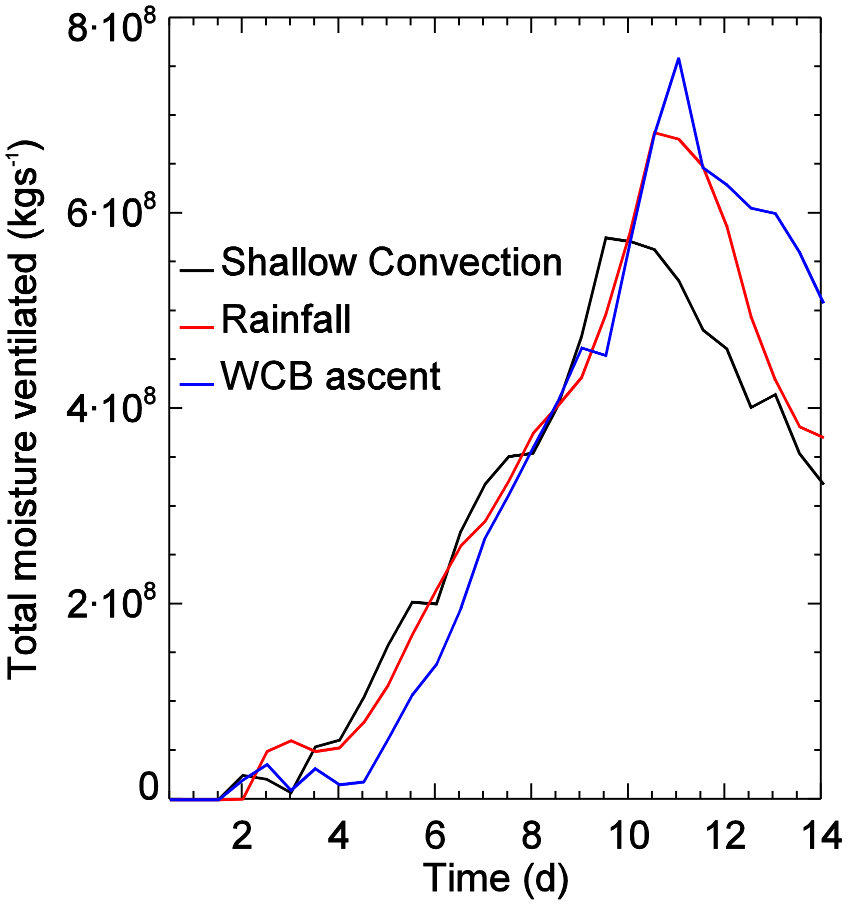
Factors controlling moisture transport

- Is similarity in convective/advective ventilation a coincidence or a robust feature?
- What drives the ventilation – large scale features or boundary layer processes?

- Integrate over life cycle to get a single quantitative measure of ventilation

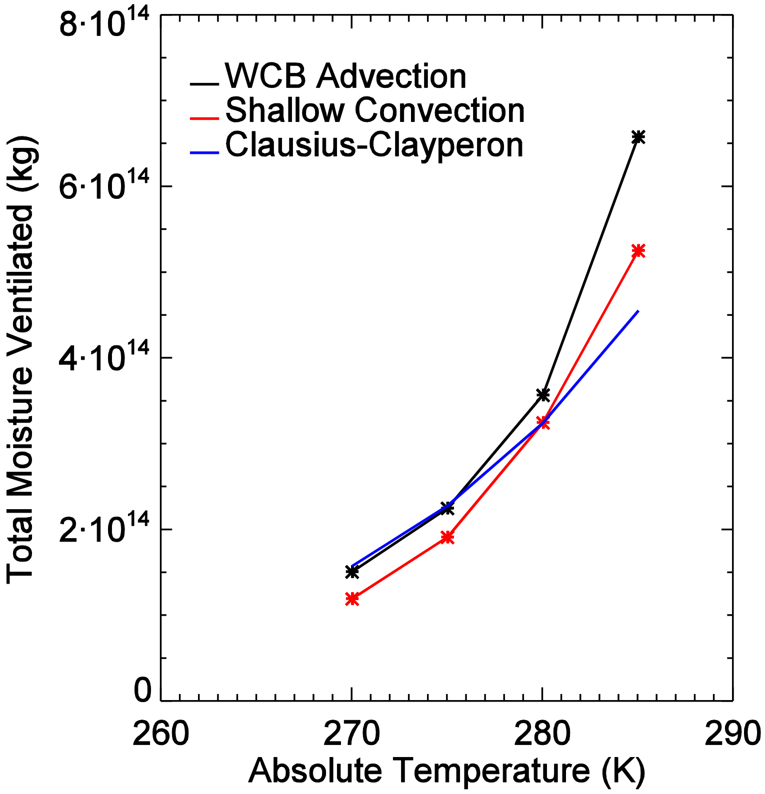


Absolute temperature

- Ventilation =

$$\iint q_h w_h \, dA \, dt$$

- q_h changes with temperature according to Clausius-Clayperon
- But, positive feedback at high temperatures, increasing w_h
- Both processes scale in the same way



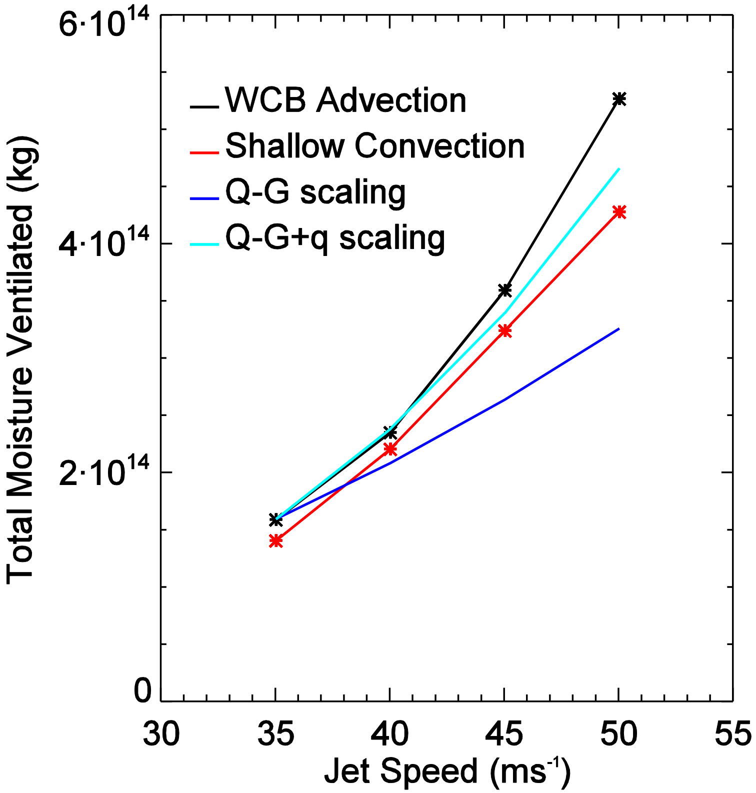
Black = advective
Red = convective

Meridional temperature gradient

- Ventilation =

$$\iint q_h w_h \, dA \, dt$$

- $w_h \sim U^2$ for a passive tracer based on quasi-geostrophic theory
- But, increased temperature to south of domain => $q_h \sim U$
- Again, both processes scale in the same way



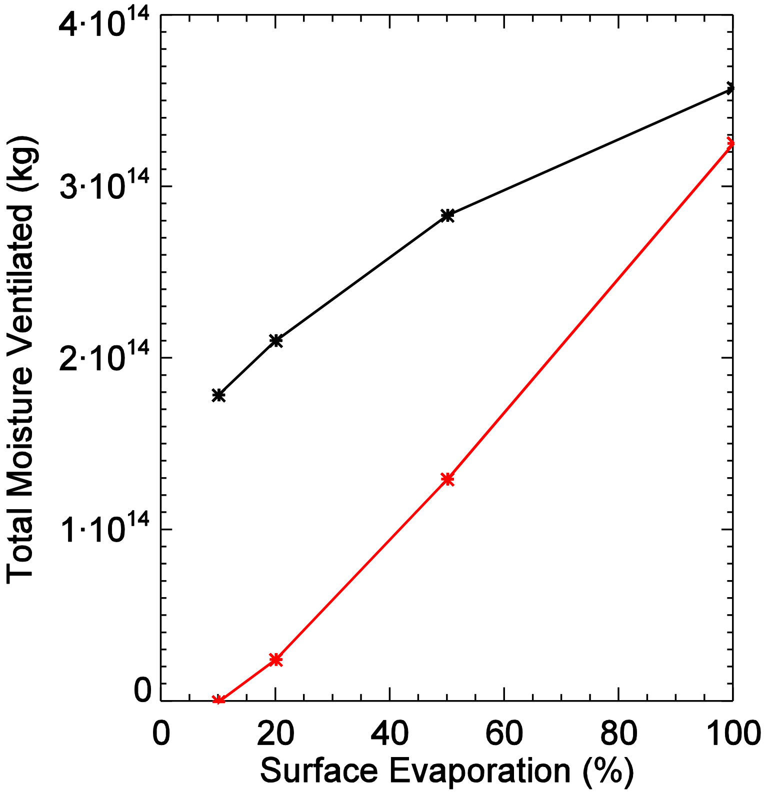
Black = advective
Red = convective

Surface evaporation

- Ventilation =

$$\iint q_h w_h \, dA \, dt$$

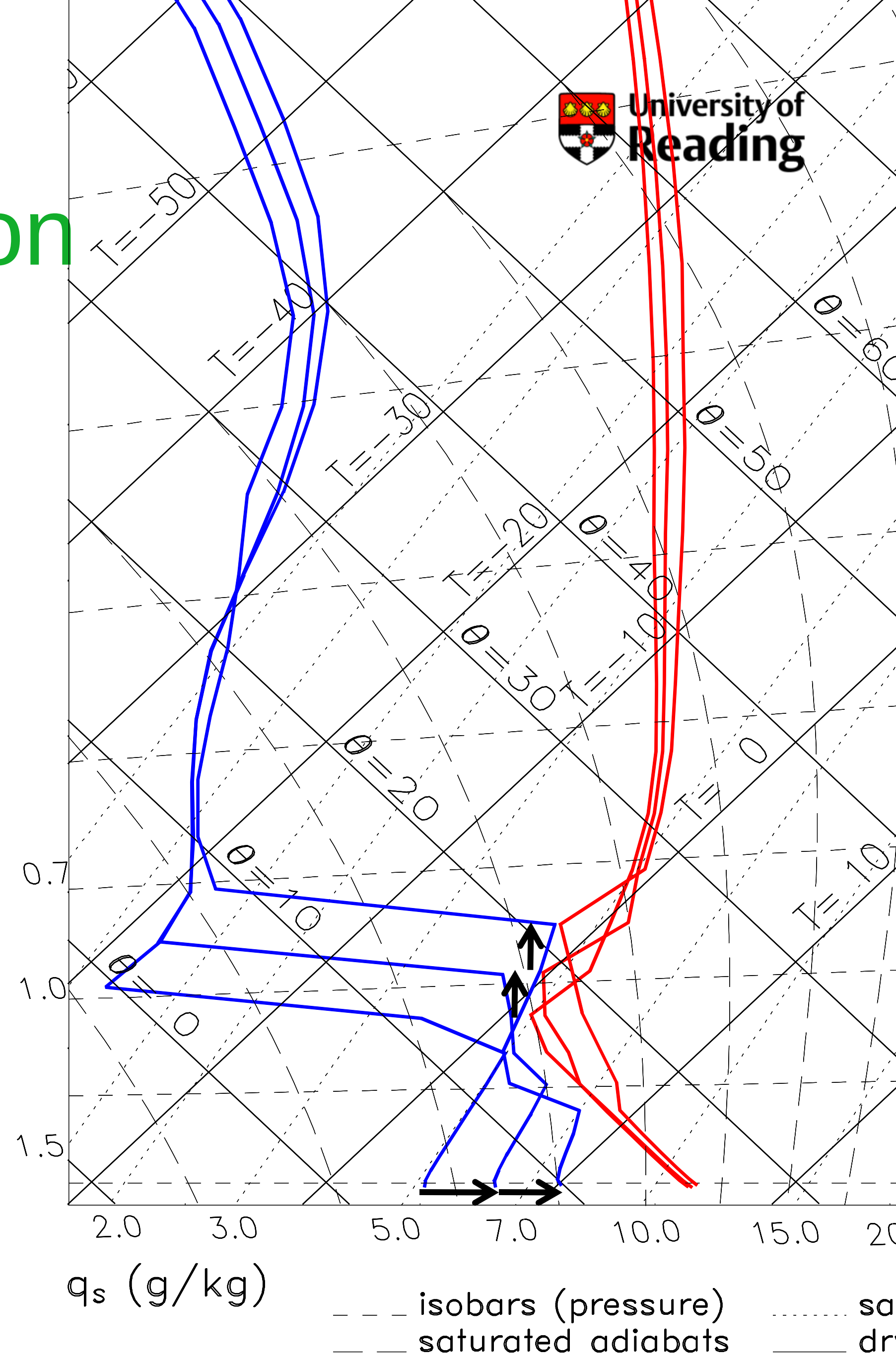
- q_h scales almost linearly with evaporation
- Feedback process in the convective ventilation
- Once convection is triggered, the cloud layer grows deeper, increasing w_h



Black = advective
Red = convective

Triggering convection

- Dew-point increases with surface evaporation
- Lowers lifting condensation level
- Triggers convection which deepens convective mixed layer
- Increased updraft speeds (w_h) enhance ventilation further



Summary and Conclusions

- Developed new idealised cyclone model with complete treatment of physical processes – lots of possibilities for other uses here!
- Demonstrated that the moisture source for warm-conveyor belt precipitation lies well away from the cyclone
- Shallow convection adds a new pathway for ventilation and transport from regions with large surface evaporation – consequences for pollution ventilation

Summary and Conclusions

- Shallow convection equally important for ventilation and contributes to poleward moisture transport – boundary layer & convective process are important in the global water cycle
- Ventilation by WCB is dominated by large-scale features
- Ventilation by shallow convection also closely linked to the boundary layer structure – requires knowledge of surface energy balance