Boundary layer ventilation by weather systems

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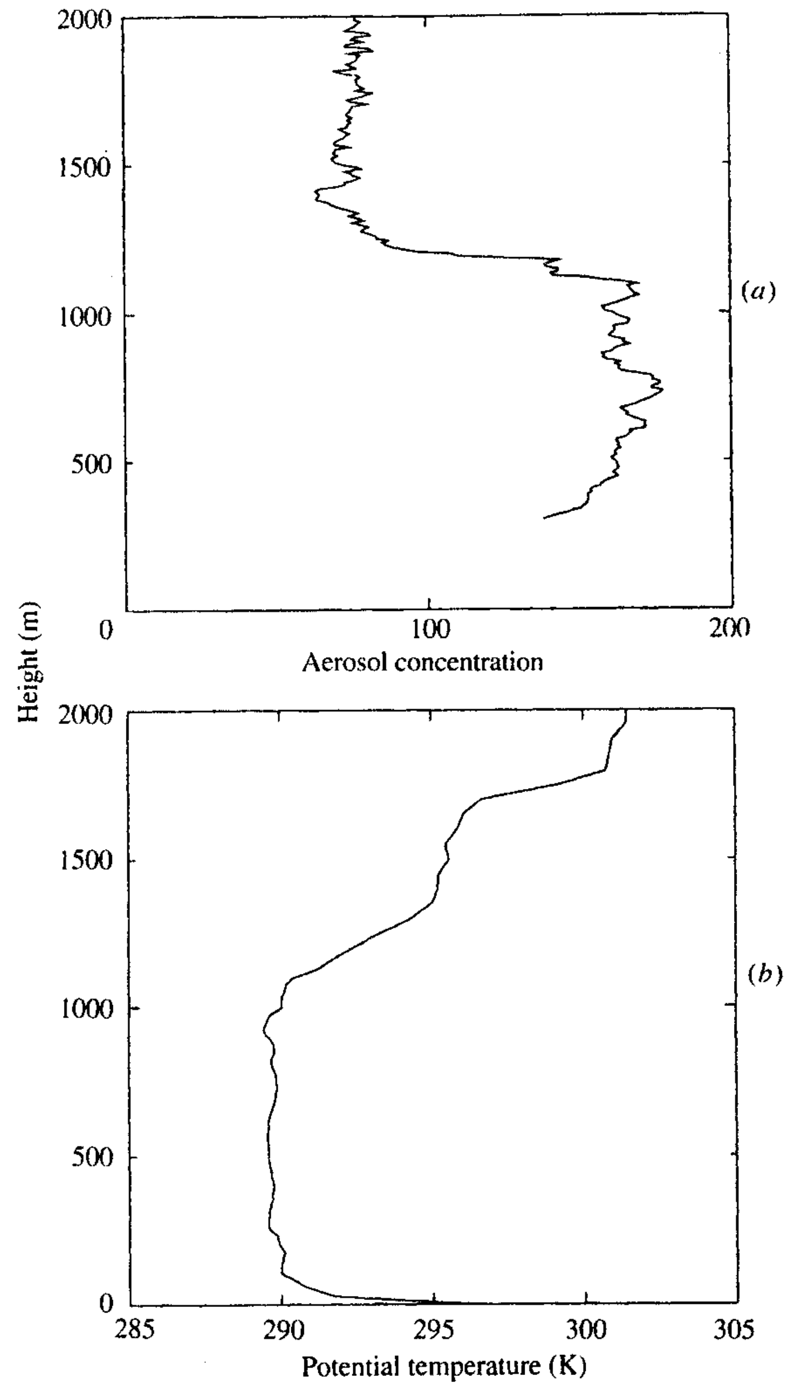
Motivation

- Most emissions at surface
- Easily mixed through depth of boundary layer
- BL inversion a strong barrier to further vertical mixing
- Surface concentrations determined by:
  - Source strength
  - Boundary layer depth
  - Rate of ventilation of boundary layer
- Case studies
  - Ventilation rate varies
  - 20% - 70% mass ventilated

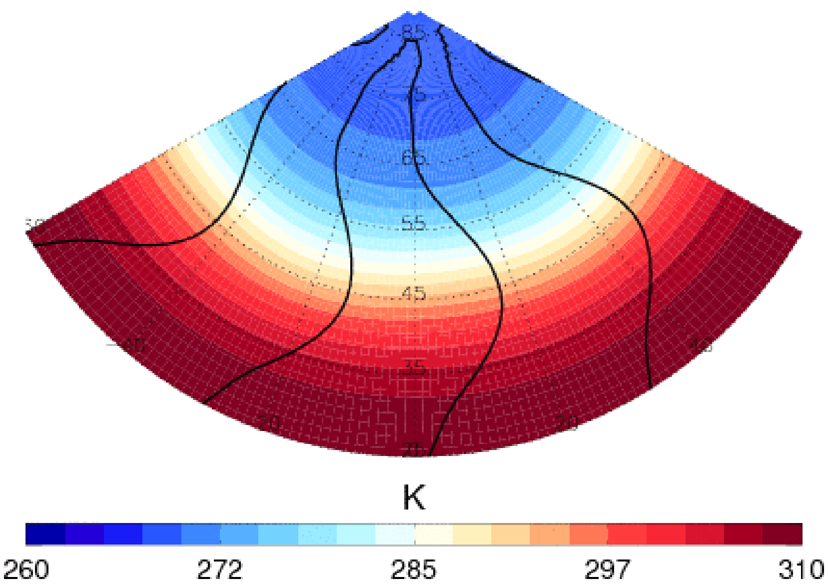


Idealised simulations

- Simulate idealised weather systems
- Use Met Office Unified Model in idealised channel configuration or IGCM
- **Dry simulations**
- Include Boundary-layer scheme
- Constant strength source at surface, across the whole domain

$$\frac{DC}{Dt} = \nabla.\vec{F}$$

$$\vec{F} = F_s \quad \text{at } z = 0$$

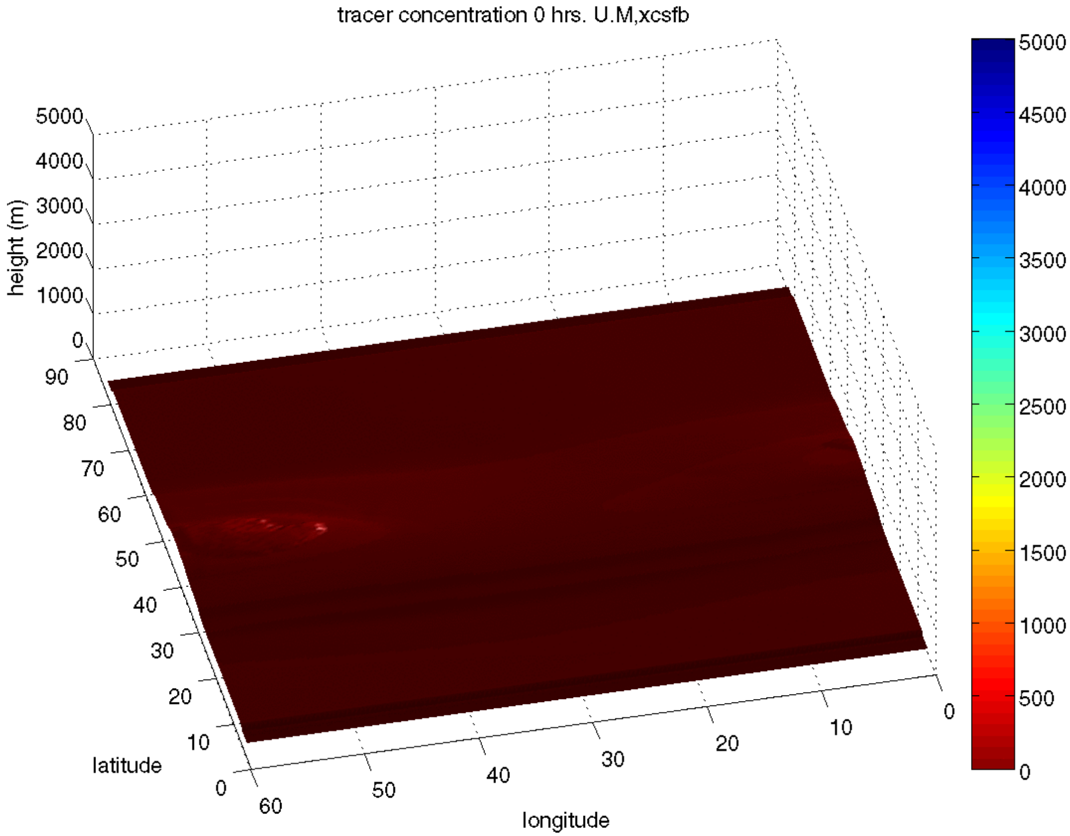


Lines: Surface pressure
Contours: potential temperature at 1km
Each frame is 1 day apart

Transport into free troposphere

Three phases:

- Vertical BL mixing
- Horizontal transport within BL
- Ventilation by warm conveyor belt



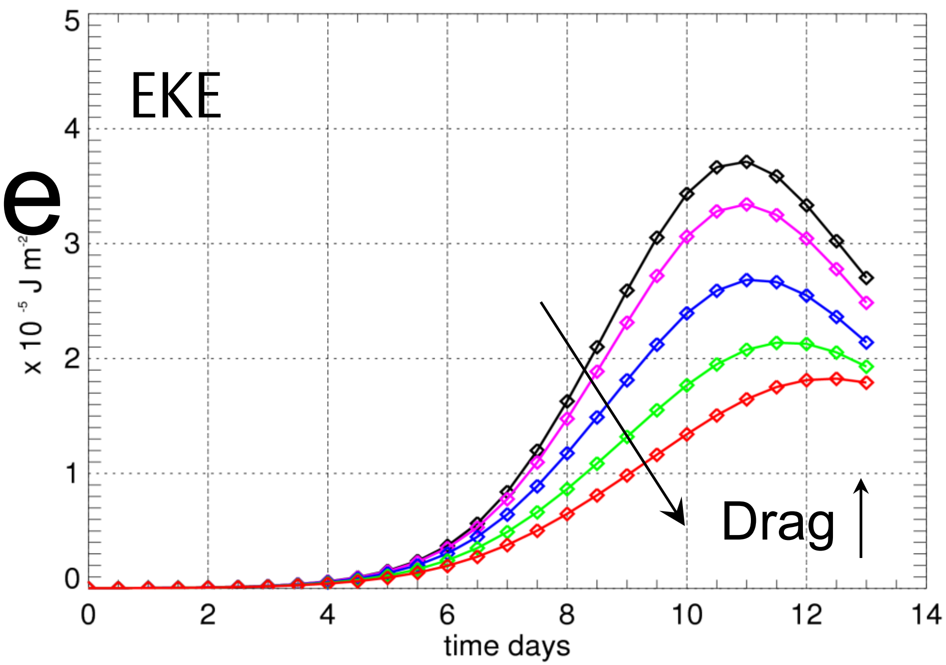
Isosurface of tracer concentration. Colours show the height of the surface

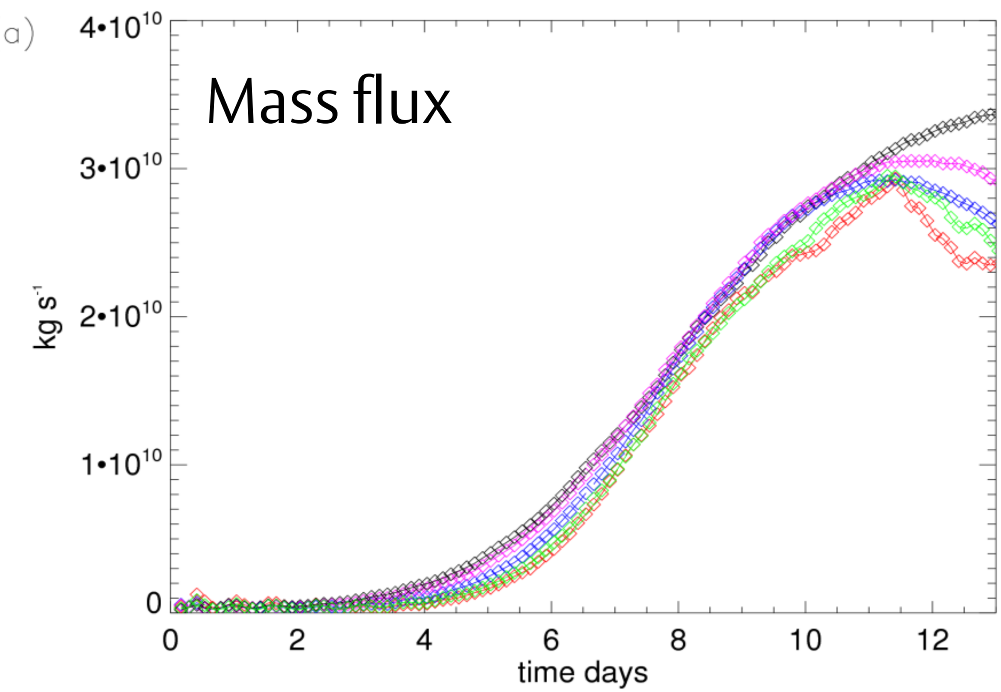
What controls ventilation rate

- The amount of turbulent mixing within the boundary layer?
  - Pollutants need to be mixed up to near the top of the boundary layer for ventilation to occur
- Horizontal transport within the boundary layer?
  - Convergence and divergence within B.L.
  - Only certain regions of the boundary layer are ventilated
- The large scale vertical motion associated with the cyclone?
  - Final step in ventilation
  - Most important?
- Numerical experiments:
  - Role of boundary layer convergence: vary drag coefficient
  - Role of large scale flow: vary weather system strength

BL convergence

- Cyclone energy sensitive to BL drag
- Ventilation mass flux is not





$Cd = 0$

$Cd = 0.1 \times 10^{-3}$

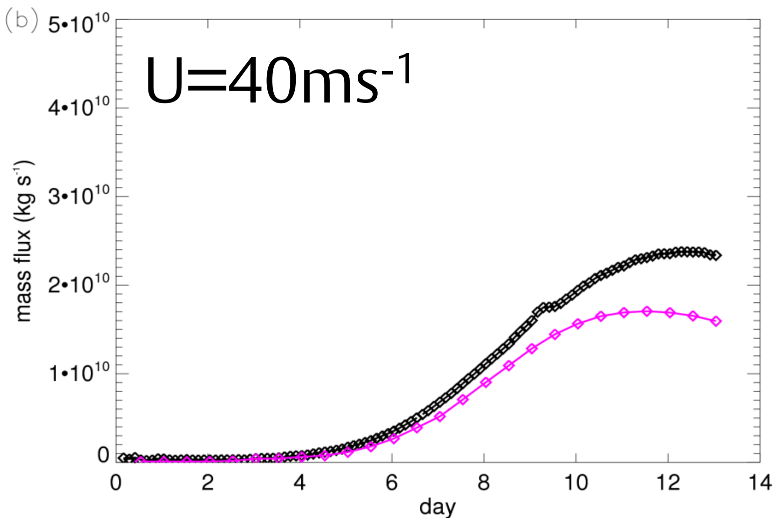
$Cd = 0.56 \times 10^{-3}$

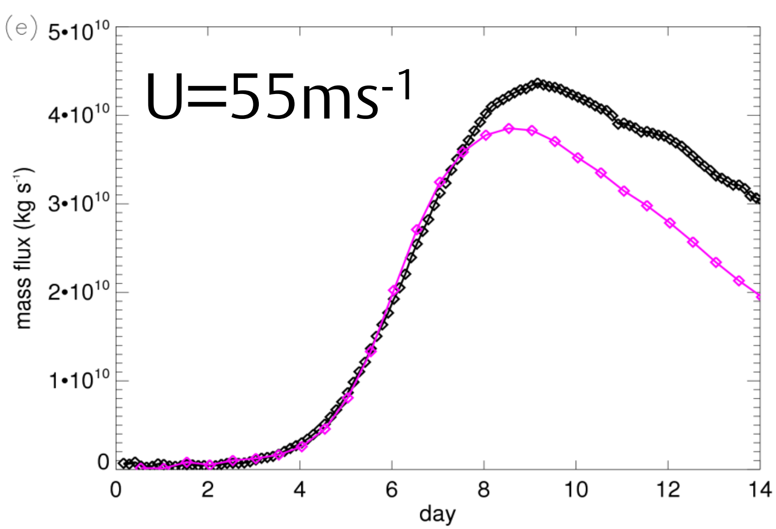
$Cd = 2 \times 10^{-3}$

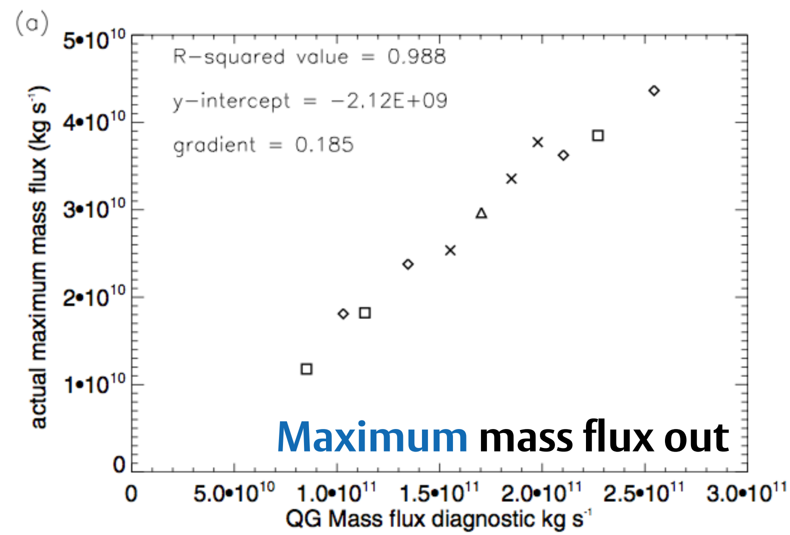
$Cd = 5 \times 10^{-3}$

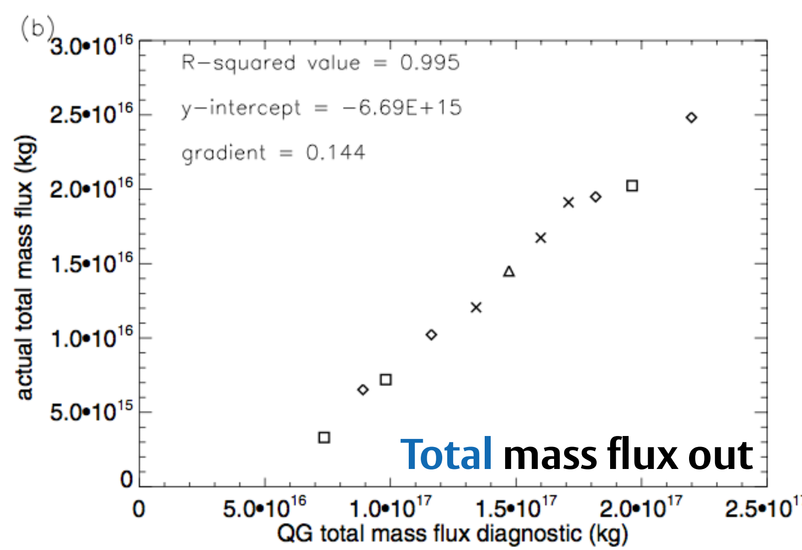
Role of large scale flow

$$w \propto \frac{-v_g f \, {\partial u_g}/{\partial z}}{2N^2}$$

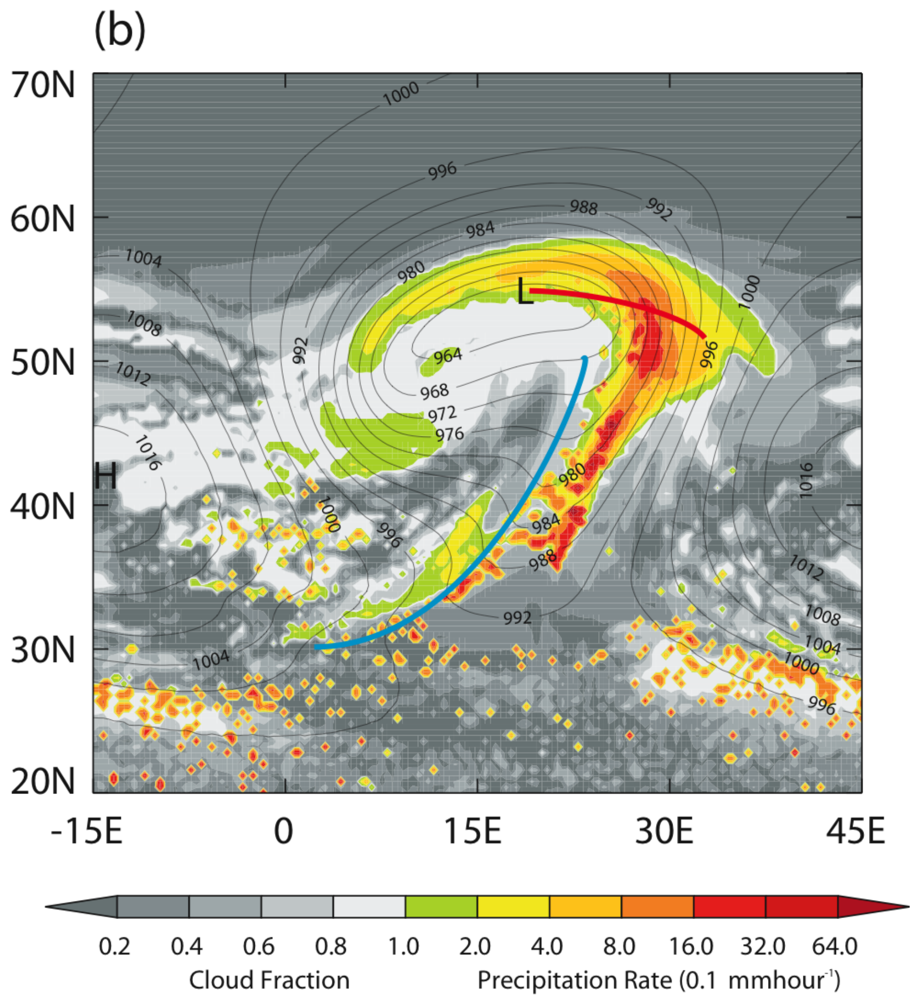


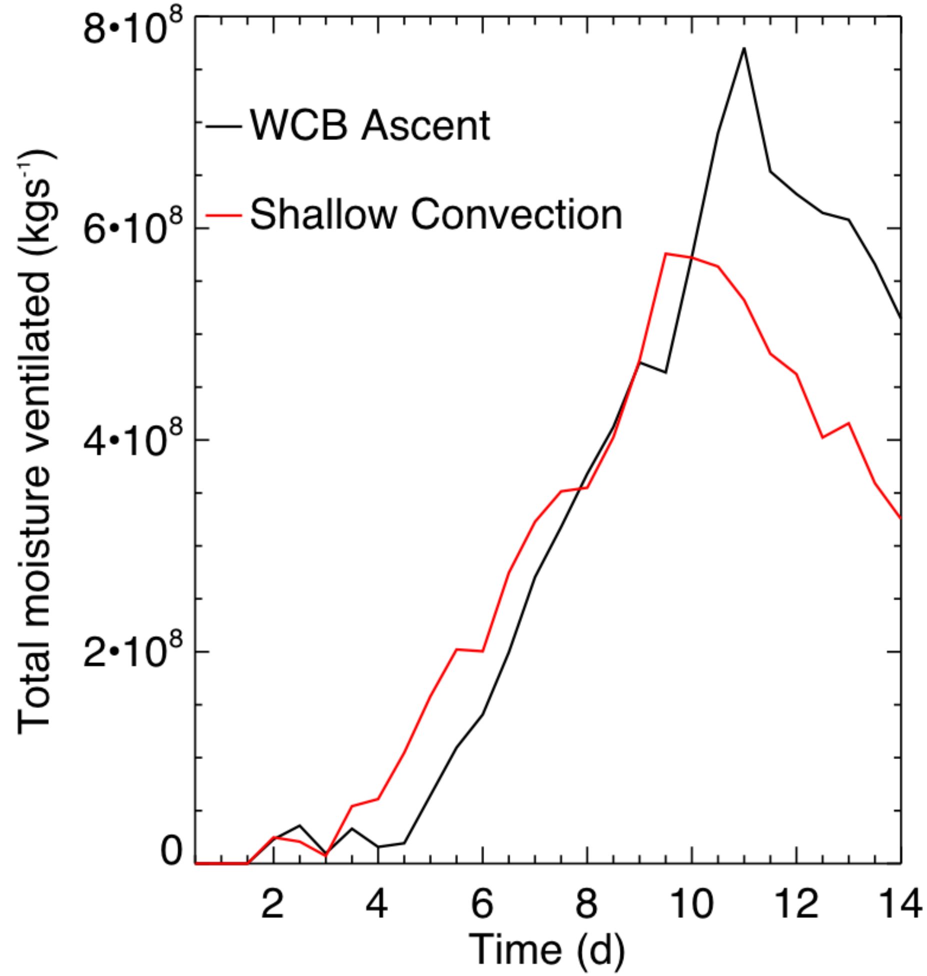






Moist lifecycles





The sting:

moist convection as effective as large scale ventilation

Conclusions

- BL top acts as barrier to vertical transport
  - Comparable to strat-trop exchange
- Mid-latitude weather systems ventilate boundary layer
  - Large-scale vertical WCB motion is the dry control
  - Re-analysis products sufficient to capture WCB
- Moist lifecycles:
  - New pathway through convection
  - Convection gives comparable ventilation as WCB
  - More delicate to represent in models

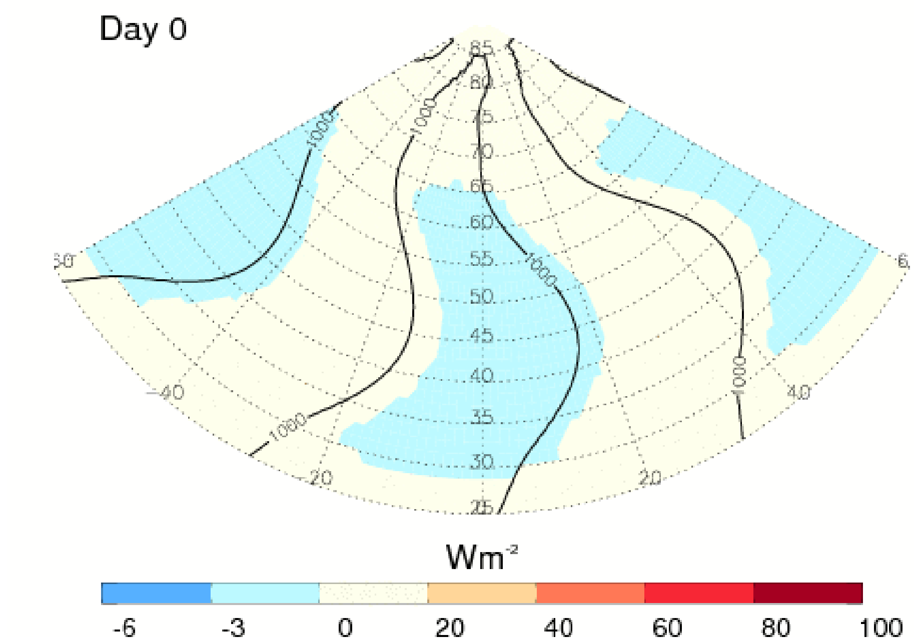
Conclusions

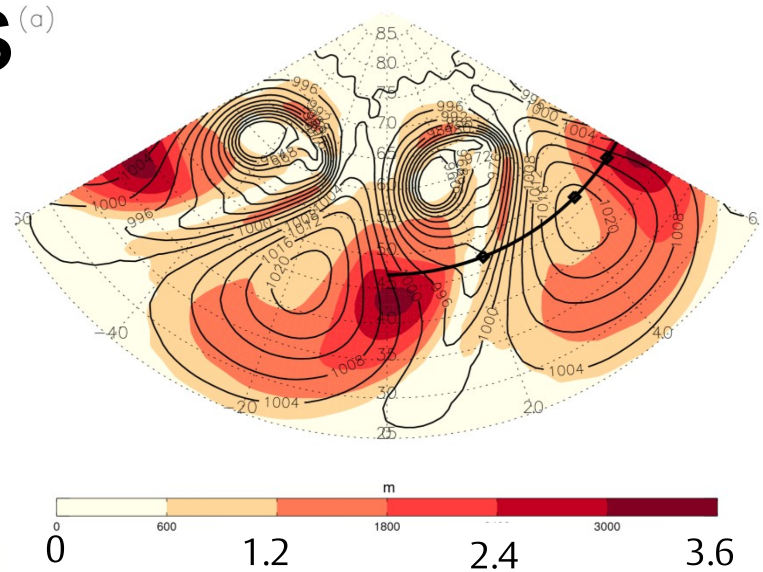
- Pathways for boundary layer ventilation:
  - Diurnal cycle of BL
  - Transport through inhomogeneous BL
  - Convection:
    - case specific
    - Fast: 3 hours up to 5km
  - Conveyor belts:
    - Reliable: all cyclones
    - Slow: 12 hours to 5km

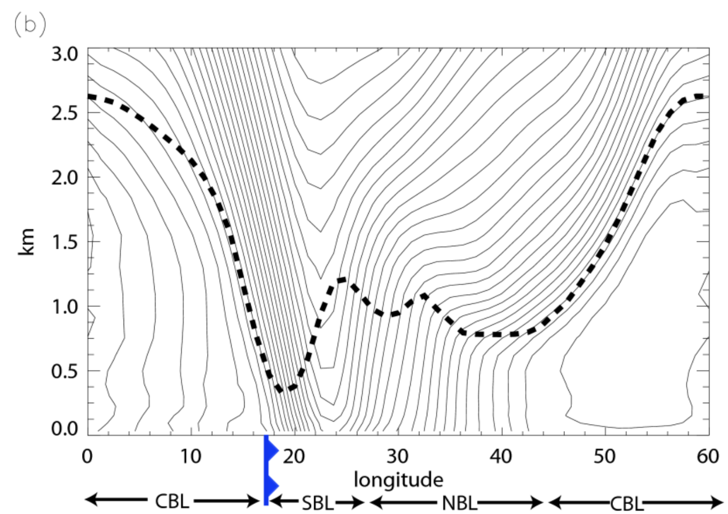
Further questions

- How does the chemistry care:
  - Time scale for ascent?
  - Height of destination?
  - Passage through clouds?
  - When do trajectories fail?

B.L. charateristics







- Fluxes drive by thermal advection
- Deepest boundary layers are co-located with maximum heat fluxes
- Large change in boundary layer depth across cold front

Boundary layer mass budget

- Integrate continuity over the B.L depth:

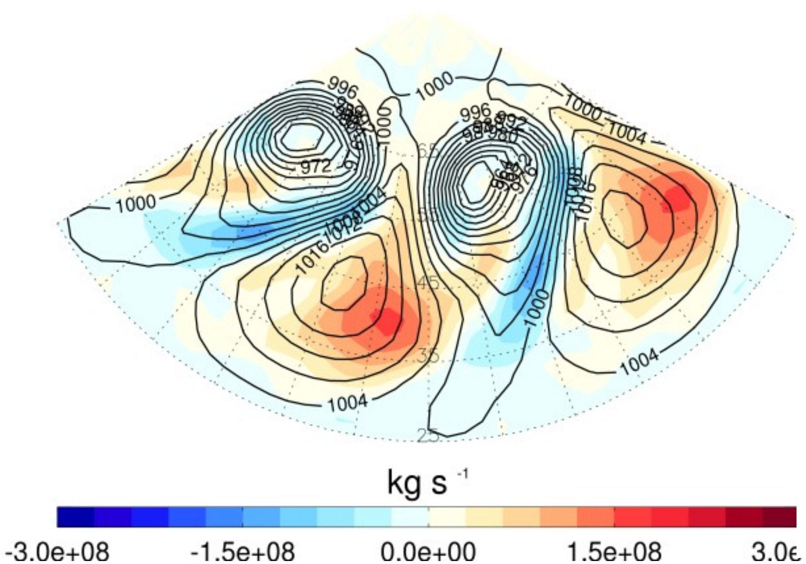
$$\frac{\partial \tilde{\rho}}{\partial t} = \rho_h \frac{\partial h}{\partial t} + Convergence - \rho_h (\underline{u}.\underline{n})_h$$

Changes in B.L depth

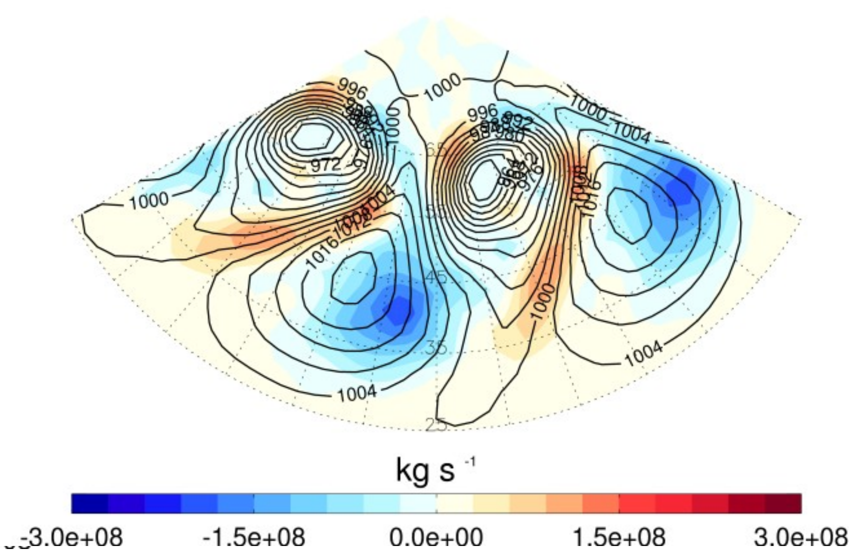
Transport within B.L.

Synoptic ascent/descent

Synoptic



Convergence

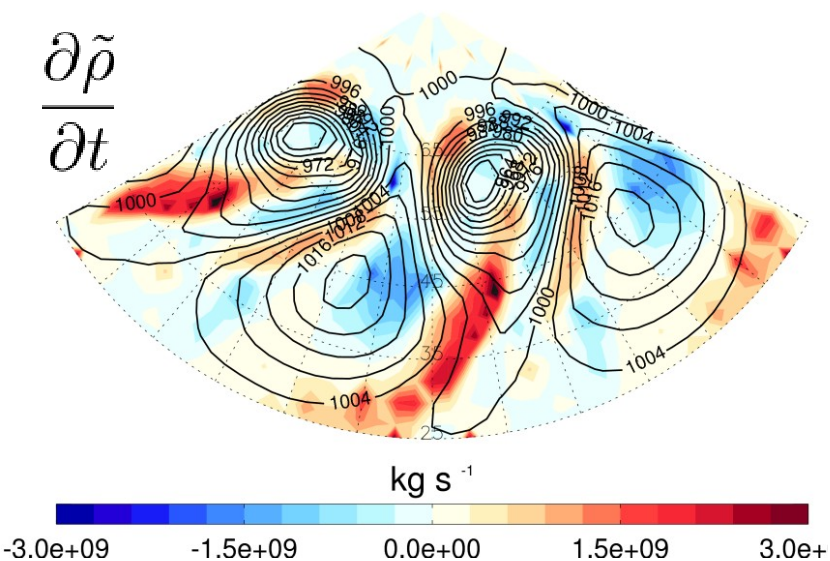


Boundary layer mass budget

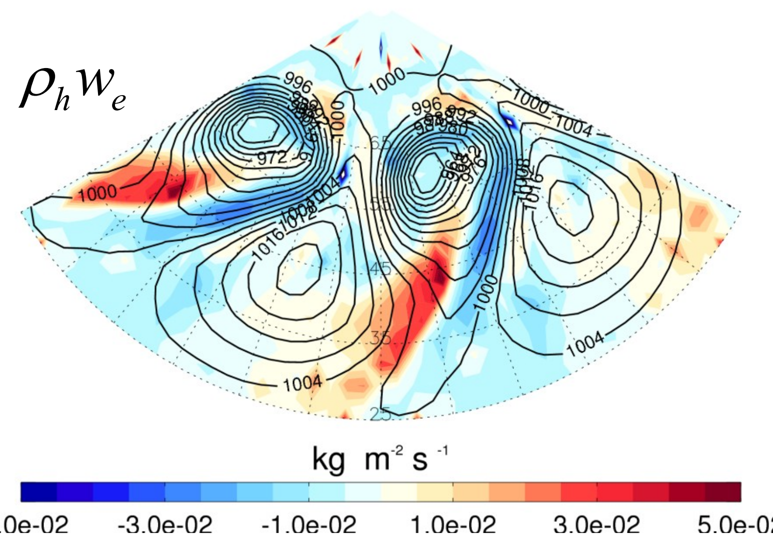
- But B.L depth can change due to the surface heat flux, which leads to entrainment into the boundary layer
- OR due to the large-scale vertical motion (subsidence) pushing down the theta contours
- Combine to form an 'entrainment' velocity

$$w_e = \frac{\partial h}{\partial t} - (\vec{u}.\vec{n})_h \qquad \frac{\partial \tilde{\rho}}{\partial t} = \rho_h w_e + \tilde{C}_h$$

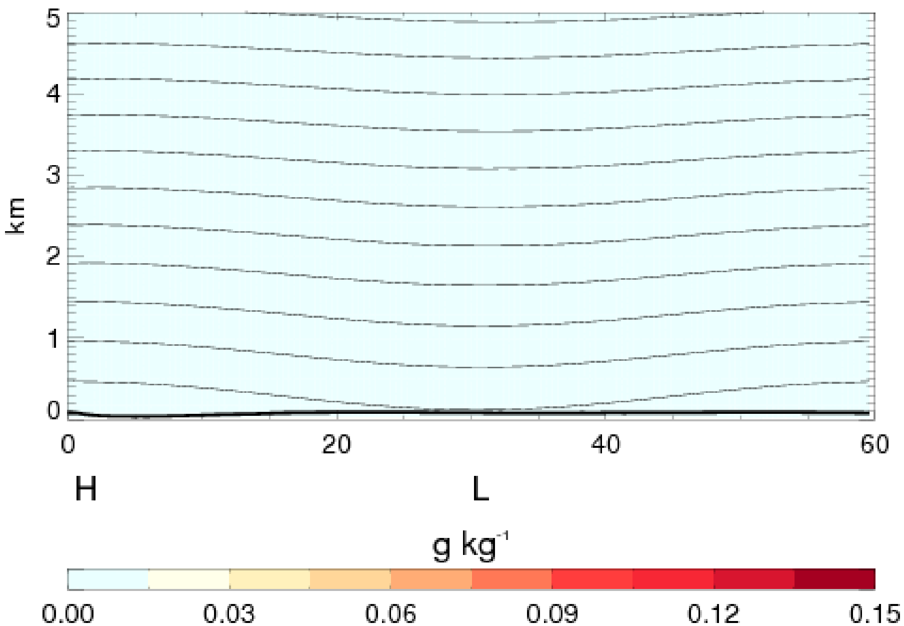
$\frac{\partial \tilde{\rho}}{\partial t}$



$\rho_h w_e$



Transport of tracer in the B.L.



X-Z cross section. Potential temperature (contours), tracer concentration (colours) and B.L depth (black line)

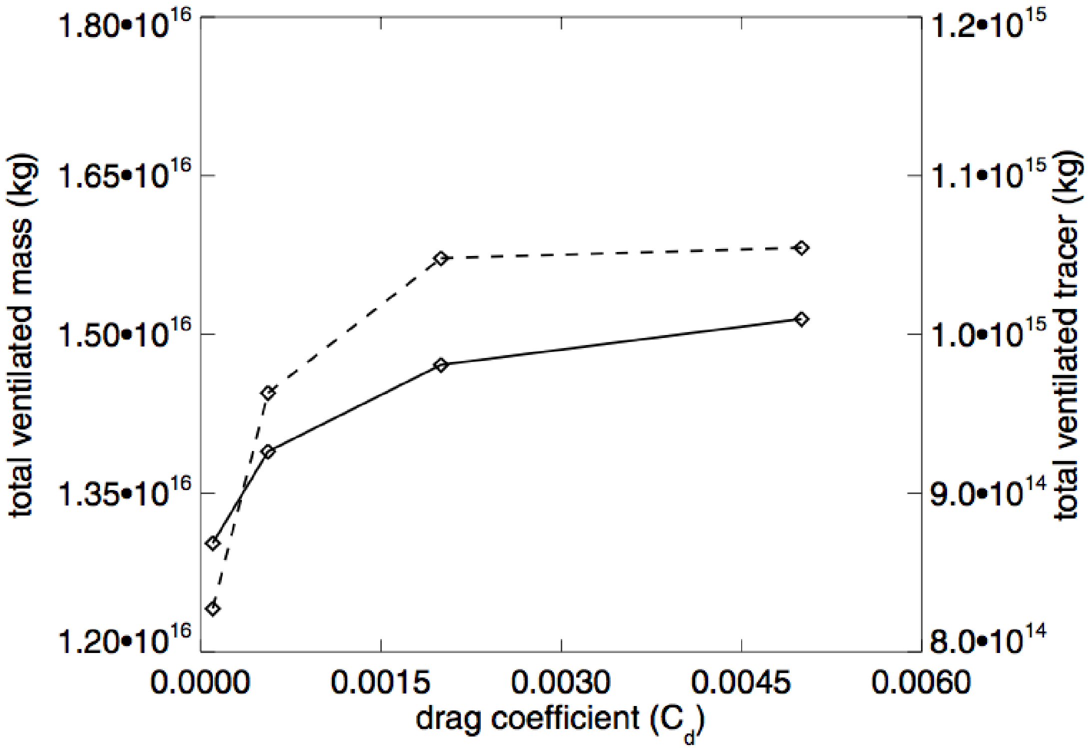
Tracer is mixed vertically by turbulent mixing .

- More mixing in high pressure region
- Little vertical mixing in low pressure region

Tracer is also transported horizontally within the B.L.

- Convergence towards low centre
- Divergence out of high pressure

Mass ventilated



- Surface type has little affect on mass ventilated
- When ‘no’ friction acts, reduced mass ventilated
- No tracer in the correct regions
  - conveyor belt footprint areas or the mid to upper regions of the B.L