Pollution transport by weather systems:

Interactions between boundary layer and synoptic scale processes

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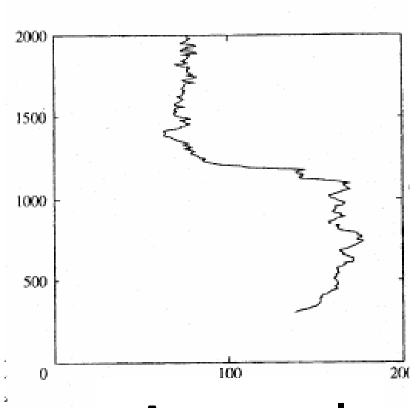
Outline

- Motivation
- Mechanisms for boundary layer ventilation
- Experiments with Reading IGCM
- Results
  - Synoptic structure of idealised weather systems
  - Boundary layer structure on synoptic scales
  - Transport within the boundary layer
  - Transport out of and above the boundary layer
  - Mass and tracer budgets of the boundary layer
- Ongoing work with the Idealised Unified Model

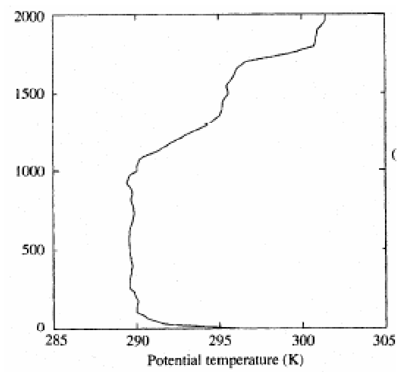
Motivation

- Pollution is mainly emitted near the surface and can be trapped by an inversion
  - Affects human health
  - Affects vegetation
  - Corrodes buildings

- Dry deposition only occurs in the boundary layer



Aerosol



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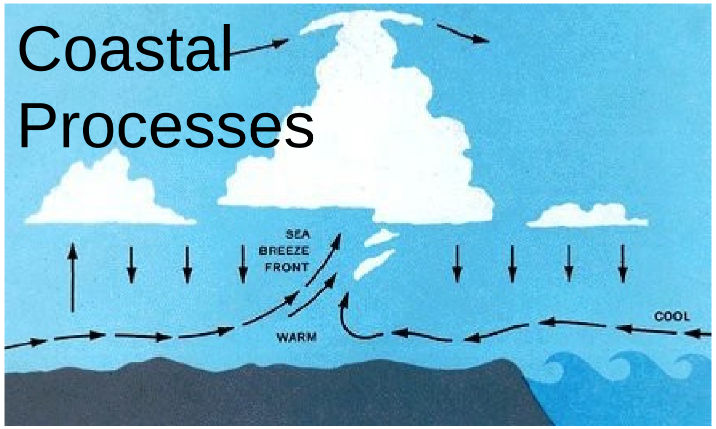
Garrett

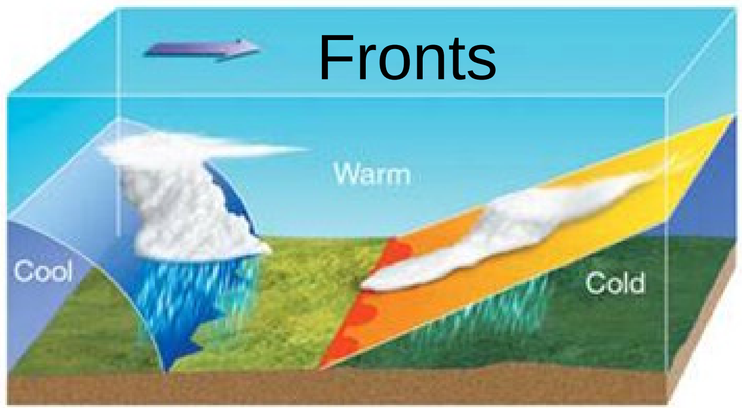
Pollution in the free troposphere

- At upper levels particles affect the radiation budget
- Chemical reactions are often strongly linked to temperature
- Can be transported large distances

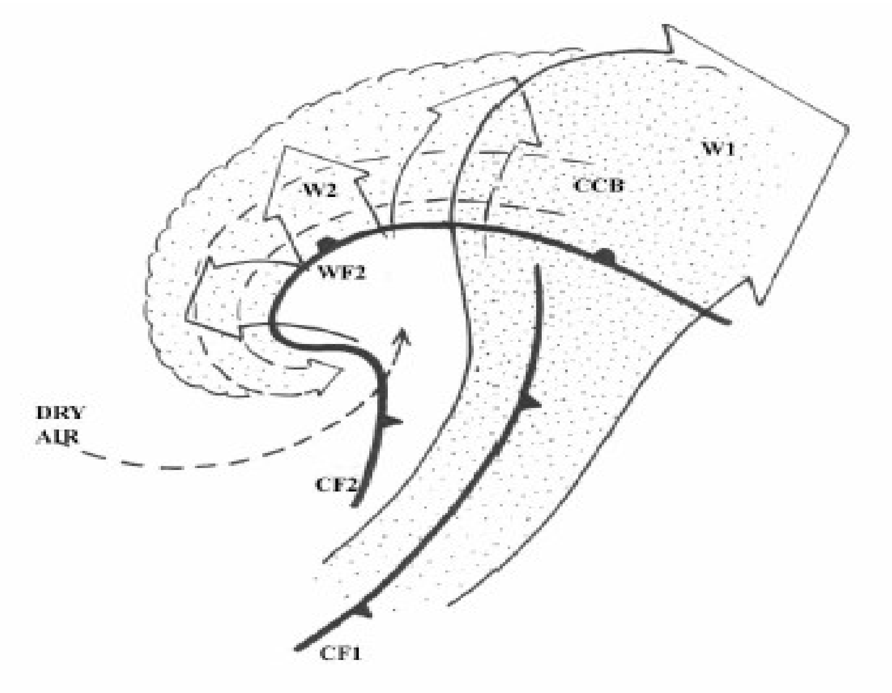
May 4th 2001
SeaWiFS, NASA

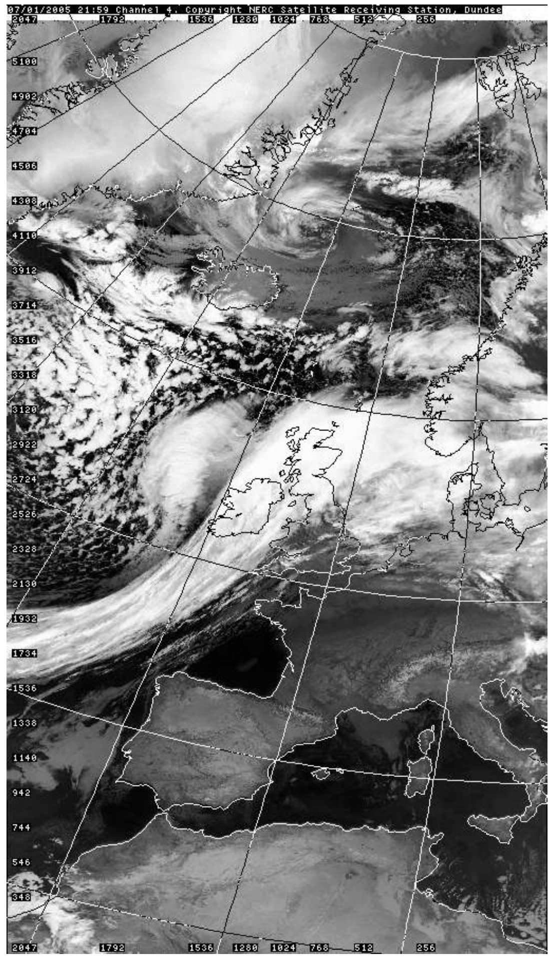
How can pollution be ventilated out of the boundary layer?





Airflows in cyclones





Case study approach

	Advection	Advection Plus Turbulent Mixing	Advection Plus Convection	All
May (case1)	28	39 (+11)	49 (+22)	52 (+24)
January (case 2)	30	38 (+9)	47 (+18)	52 (+23)
July (case 3)	22	36 (+13)	36 (+13)	41 (+18)

Donnell et al (2001)

Agustí-Panareda et al (2005): *"68% of the total mass is in the free troposphere during the final day"*

Table 1. Percentages of the ABL passive tracer in the FT, above 4 km and above 6 km in the area of the WCB.

day / hour	FT [%]	> 4 km [%]	> 6 km [%]
3/8, 00 UTC	21.4	3.4	1.5
3/8, 12 UTC	30.4	10.3	4.7
4/8, 00 UTC	49.7	21.4	9.8
4/8, 12 UTC	70.1	45.2	26.5
5/8, 00 UTC	66.3	41.3	21.2
5/8, 12 UTC	64.2	38.9	18.4

Kowol-Santen et al (2001)

"The processes that lead to transport in the free troposphere are well understood but our ability to quantify the magnitude of transport needs to improve " United Nations interim report: Hemispheric transport of air pollution 2007

Case Study approach

- Case studies are all different and are very complex
  - Need to take a step back
  - Perform idealised studies
- Focus has been on transport once pollutants are in the free troposphere

Questions to answer

1. How are pollutants transported **in** the boundary layer?

2. How, where, and how efficiently are pollutants ventilated **out of** the boundary layer?

3. Where are pollutants transported **to** in the free troposphere?

4. What controls the amount of boundary layer ventilation by cyclones?

Reading Intermediate Global Circulation Model (IGCM)

Standard Reading IGCM DRY, T85 Spectral Model	+	Additional vertical levels. 39 levels 10 below 1km	+	Complex Boundary layer scheme	+	Tracers

= A suitable idealised model for boundary layer ventilation studies

Boundary layer scheme

- Based on the ECMWF parameterization
- Calculates turbulent fluxes of heat, momentum and tracers at all model levels
- Surface fluxes
  - Bulk aerodynamic formulae
  - Stability dependence calculated using Monin – Obukhov theory
- Outer layer fluxes
  - 1^{st} order closure mixing length (K-theory)

$$H_s = \rho c_p C_H |V_s| (\Delta\theta)$$

$$C_H = \frac{\kappa^2}{\left[\ln\left(\frac{z}{z_{0h}}\right) - \Psi_h\left(\frac{z}{L}\right)\right]^2}$$

$$H = \rho c_p k_h \frac{d\theta}{dz}$$

$$k_h = l_h^2 \left|\frac{d\underline{v}}{dz}\right| f_h(Ri)$$

Tracers

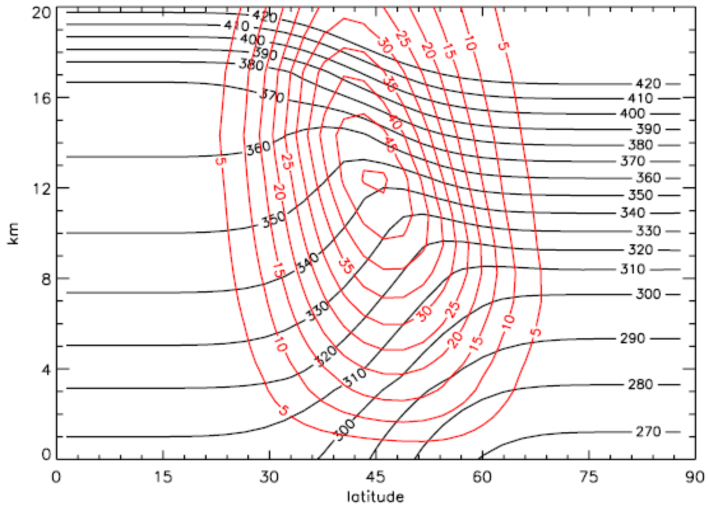
- To represent pollutants use a passive tracer
  - Acted upon by resolved winds and turbulence diagnosed by the boundary layer scheme

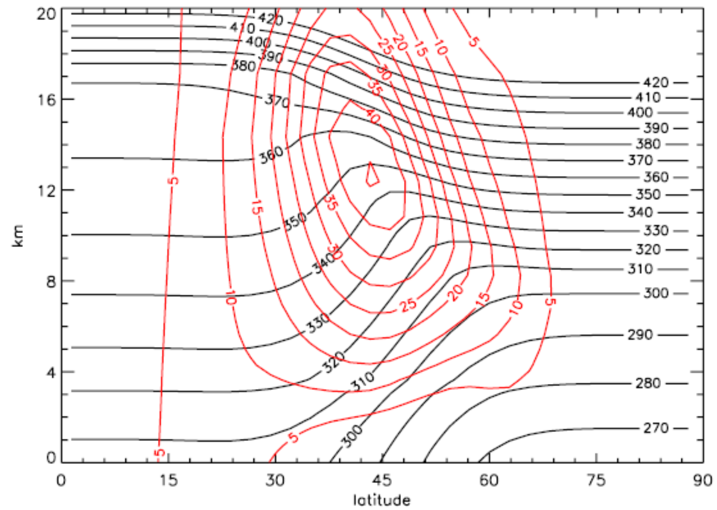
- Initialise with a uniform concentration at the lowest model level
  - $C = 1 \text{kg kg}^{-1}$

- No sources or sinks of tracer
  - Mass is conserved to within 1%

Synoptic Structure

Initial conditions



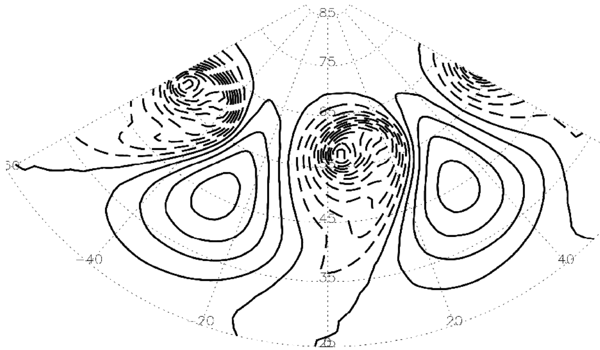


left: LC1, right: LC2. Black lines potential temperature (C.I. 10K), Red lines zonal wind speed (C.I. $5ms^{-1}$)

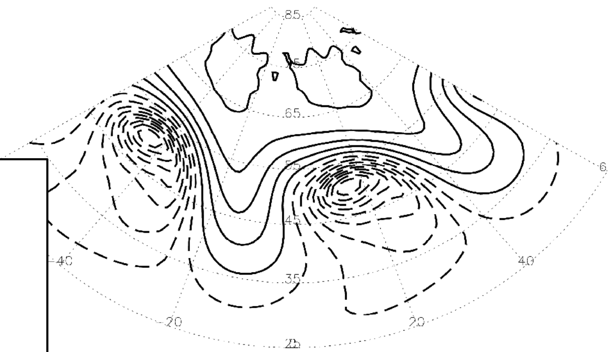
- Initialise two baroclinic lifecycles, LC1 and LC2, by adding a normal mode to an unstable background state

Mature LC1 and LC2

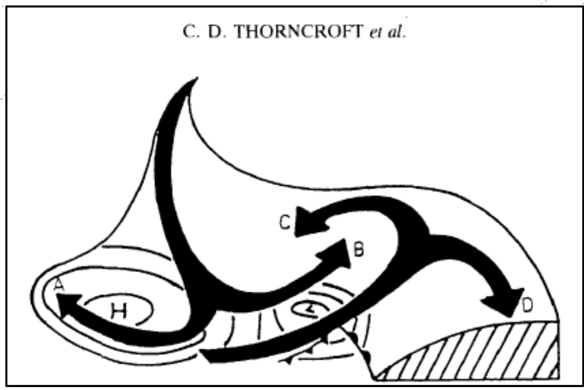
LC1 Day 6



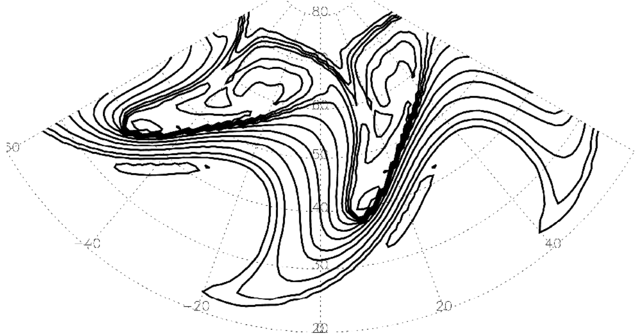
LC2 Day 6



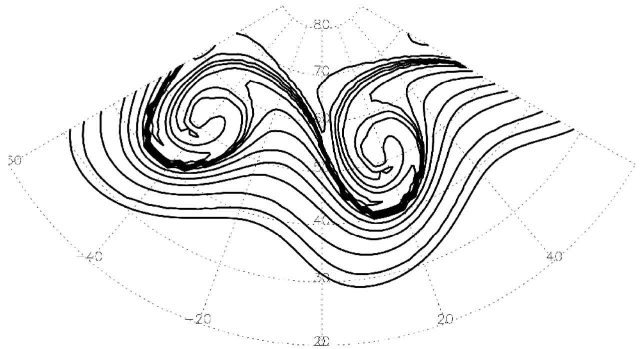
Surface pressure



LC1 Day 9



LC2 Day 9

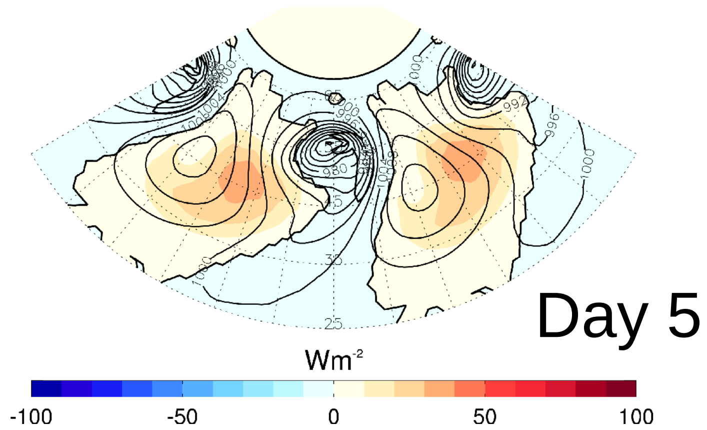


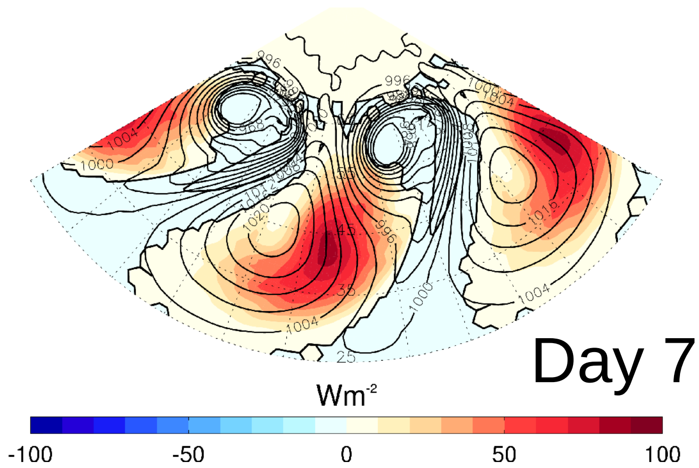
Theta on PV=2

Boundary layer structure

Surface heat fluxes

- Proportional to temperature difference between the surface and atmosphere
- Low level thermal advection
- Increase as intensity of lifecycles increases
- THE DRIVING FORCE of the boundary layer structure





Boundary layer depth

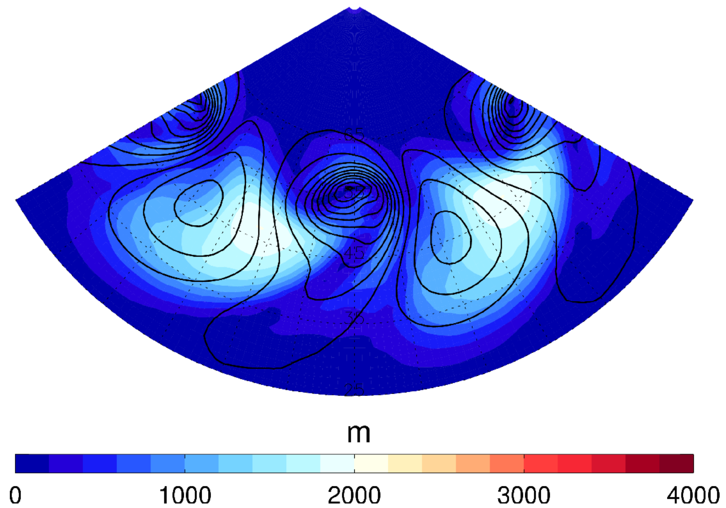
- Critical Richardson number method based on that of Troen &Mahrt (1986) $\longrightarrow$ $$Ri_b = \frac{(g/\theta_s)(\theta_z - \theta_s)\Delta z}{(u_z{}^2 + v_z{}^2)}$$

- Additional term to account for dry thermals in unstable boundary layers $\longrightarrow$ $$\theta_s = \theta(z_s) + b\frac{(w'\theta')_0}{w_m}$$

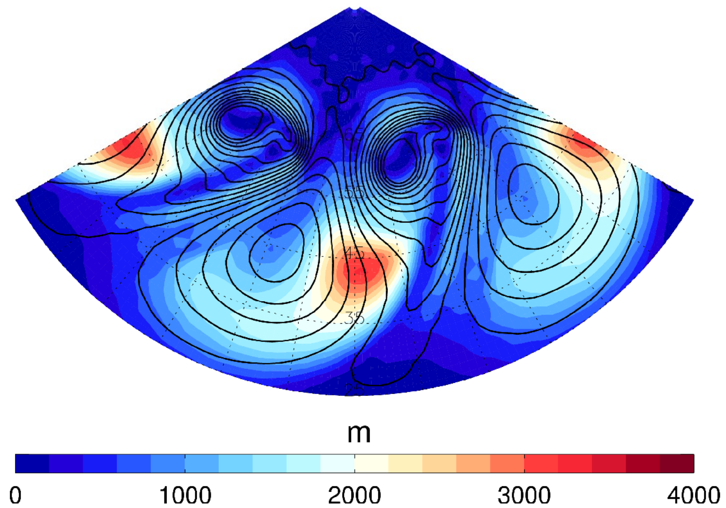
- W_m is related to thermal turnover time $\longrightarrow$ $$w_m = \frac{U_*}{\phi_m}$$

Boundary layer depth

LC1 Day 5



LC1 Day 7



Deepest in the regions of largest heat fluxes

Determines the volume within which pollutants initially mix

Stability

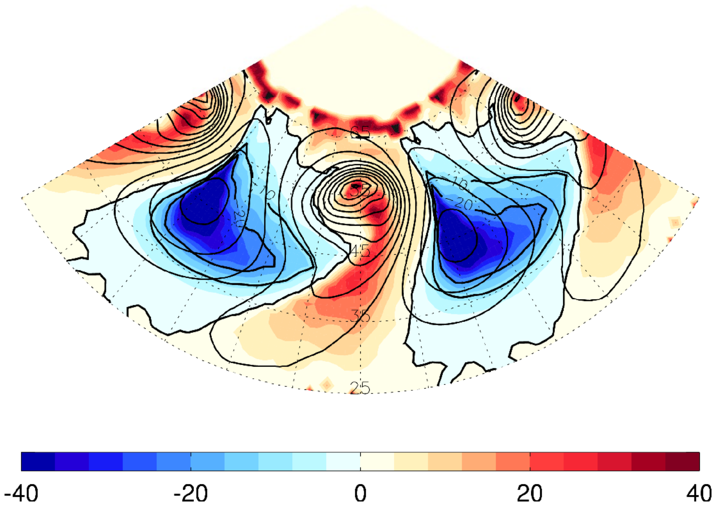
$$\text{Obukhov length} = L = \frac{-u_*^{\;3}}{\kappa\left(\dfrac{g}{\theta_0}\right)\left(\dfrac{H}{\rho c_p}\right)}$$

Heat flux	L	h/L	Stability
Large +ve	Small -ve	-ve large	Very unstable
Large -ve	Small +ve	+ve large	Very stable
0	infinity	0	neutral

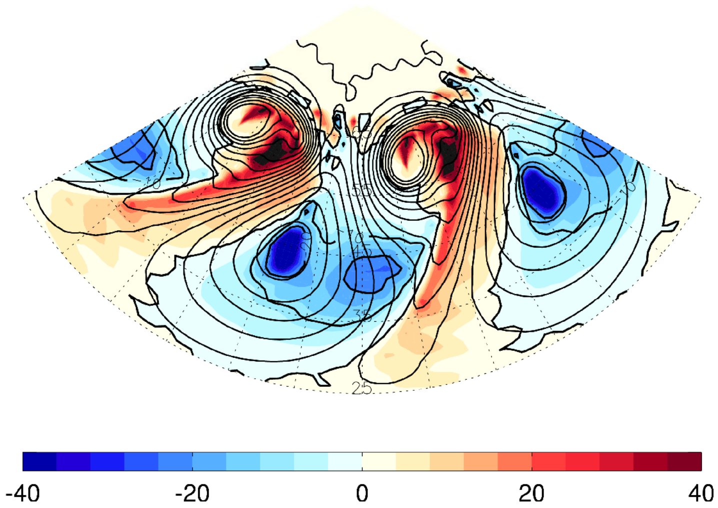
h/L characterises the bulk stability of whole boundary layer

Stability (h/L)

LC1 Day 5



LC1 Day 7



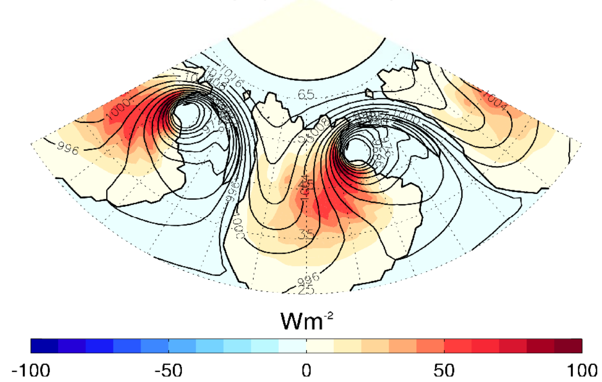
Cyclonic regions are stable

Anticyclonic regions unstable

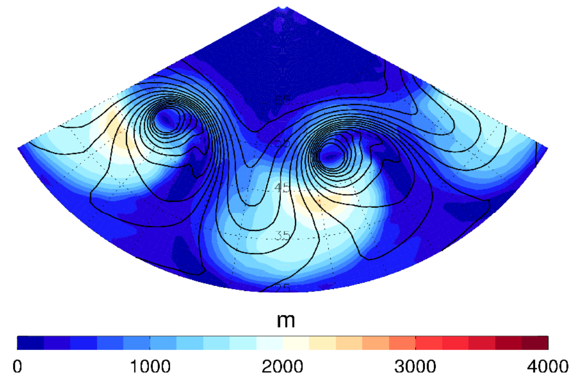
Describes the amount of mixing in the boundary layer

LC2 boundary layer structure

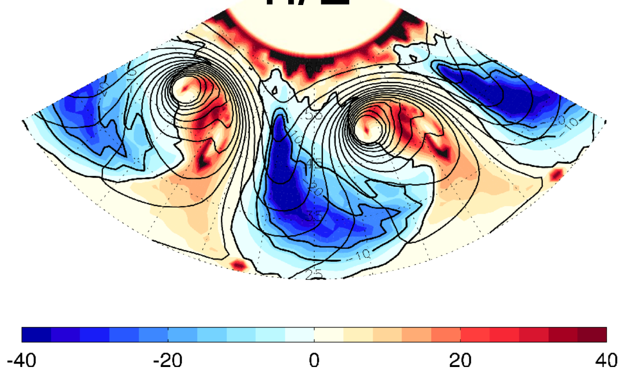
Heat Flux



Depth



h/L

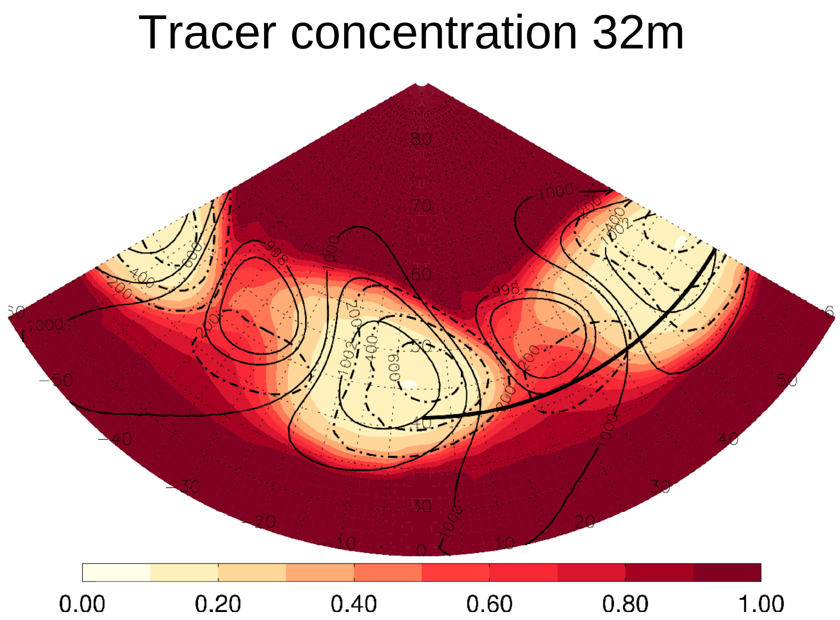


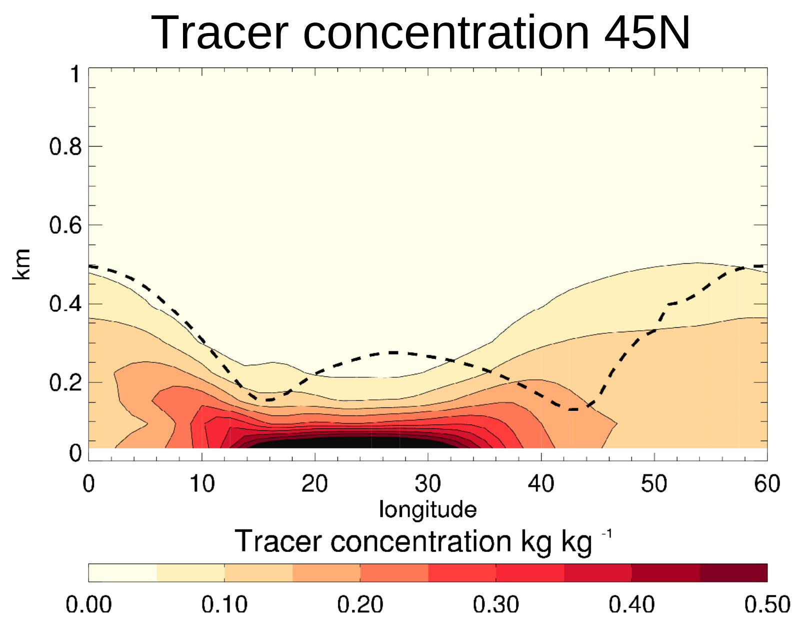
The same patterns are observed as in LC1 in relation to the synoptic features

Boundary layer structure is strongly coupled to the synoptic-scale forcing

Tracer transport within the boundary layer

LC1 day 2 Tracer transport in B.L





Depleted in anticyclones

Weak synoptic forcing

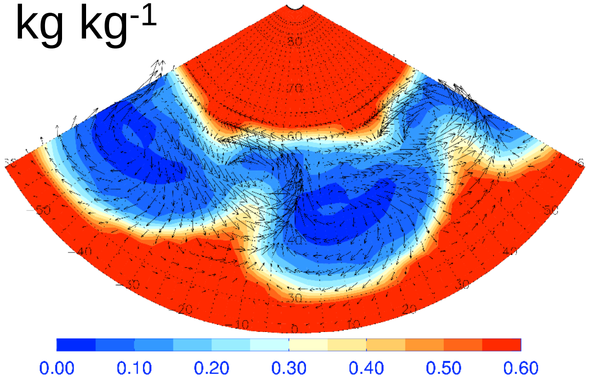
Strong vertical gradients in cyclonic regions.

Well mixed in anticyclonic regions

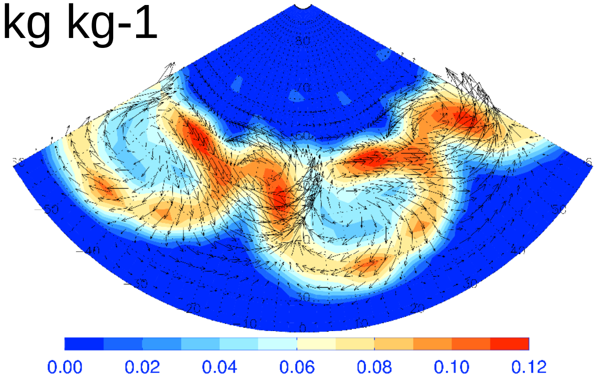
Vertical transport due to turbulence

LC1 Day 4

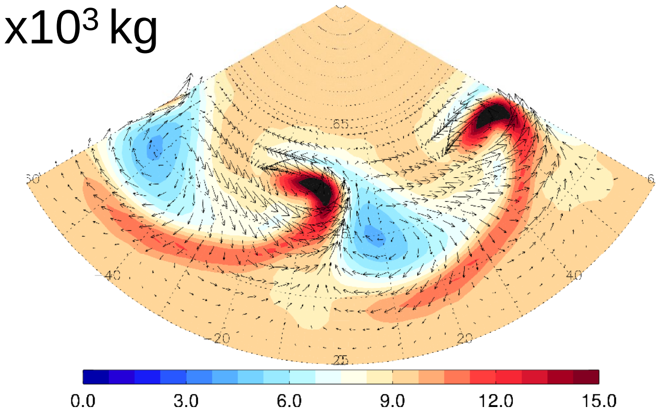
Tracer concentration 32m
kg kg^{-1}



Tracer concentration 400m
kg kg-1



Depth integrated tracer mass
x10^3 kg



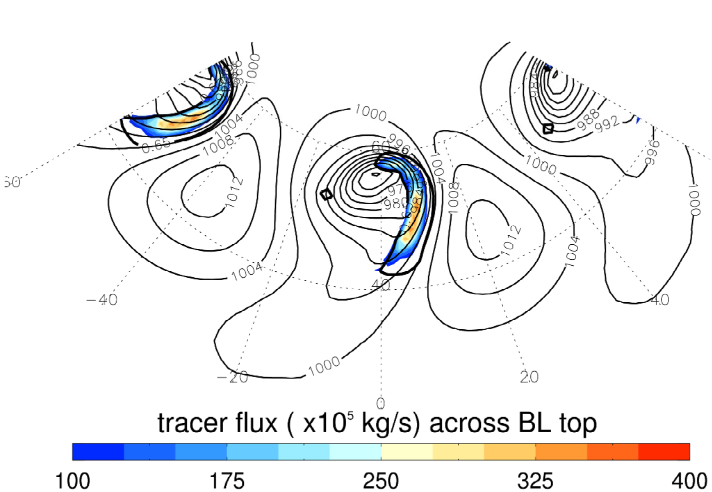
Tracer is forced into the convergent cyclonic regions

Ekman type motions lead to long range horizontal transport within the boundary layer

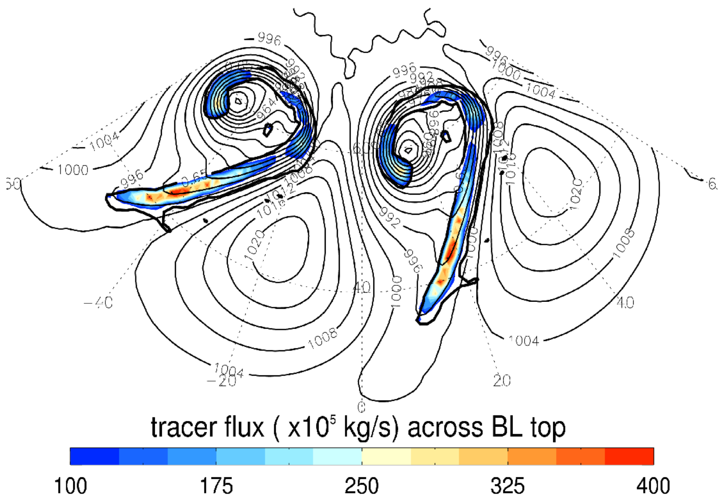
Transport out of and above the boundary layer

Ventilation regions LC1

Day 5



Day 7

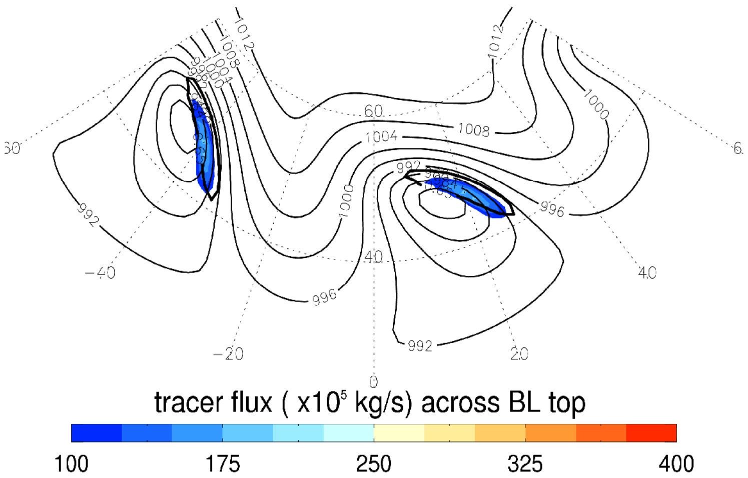


Tracer flux (x 10 ^{5} kg s^{-1}) out of the boundary layer

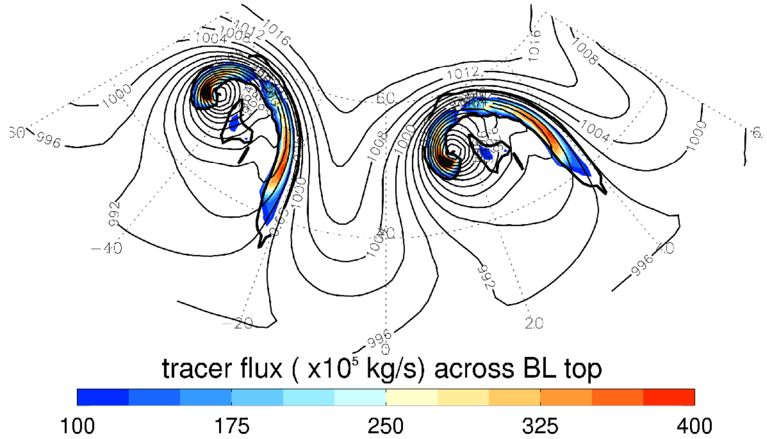
0.65 cm s^{-1} vertical velocity contours on the boundary layer top

Ventilation regions LC2

Day 5



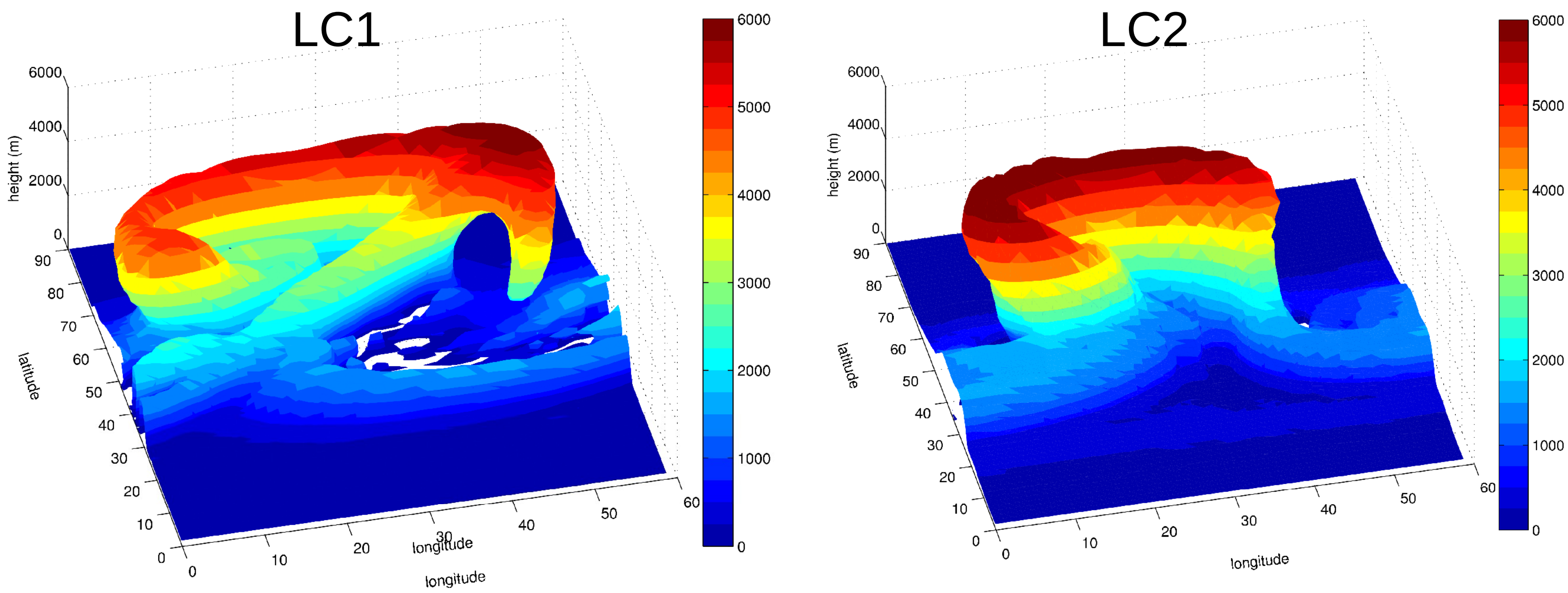
Day 7



Tracer flux (x 10^5 kg s^{-1}) out of the boundary layer

0.65 cm s^{-1} vertical velocity contours on the boundary layer top

Transport in the troposphere

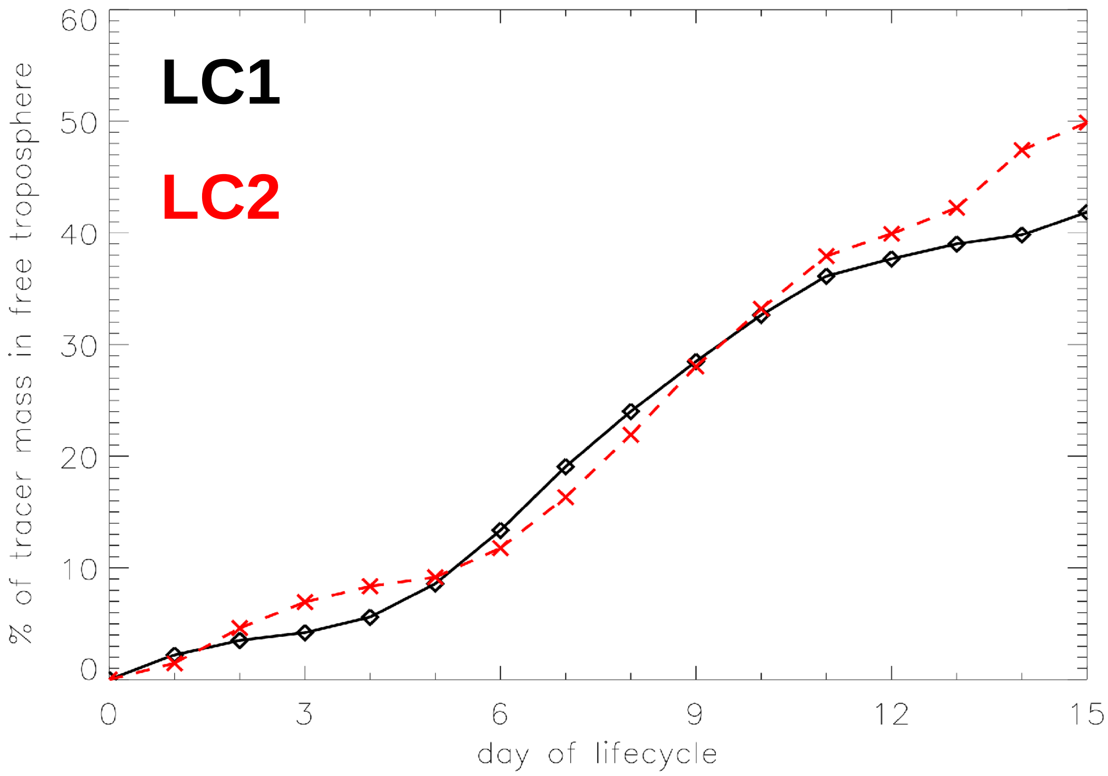


The 0.02 kg kg^{-1} tracer surface after 7 days.

Colours show the height of the surface

Very different spatial distributions

Boundary layer ventilation rate



Both ventilate a surprisingly similar amount

The **RATE** of ventilation is also similar

Mass and tracer budgets of the boundary layer

Boundary layer mass budget

- Starting from the continuity equation:

$$\frac{\partial \rho}{\partial t} + \nabla.(\rho \underline{u}) = 0$$

- We can integrate over the B.L depth to obtain a mass budget equation for the boundary layer:

$$\frac{\partial \tilde{\rho}}{\partial t} = \rho_h \frac{\partial h}{\partial t} - \frac{\partial (\widetilde{u\rho})}{\partial x} - \frac{\partial (\widetilde{v\rho})}{\partial y} + (u\rho)_h \frac{\partial h}{\partial x} + (v\rho)_h \frac{\partial h}{\partial y} - (w\rho)_h$$

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

In terms of density as we have cancelled through by grid box area

Changes in B.L depth

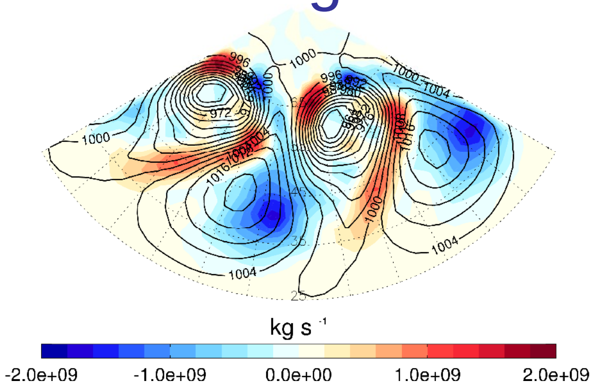
Synoptic ascent

Physical meanings

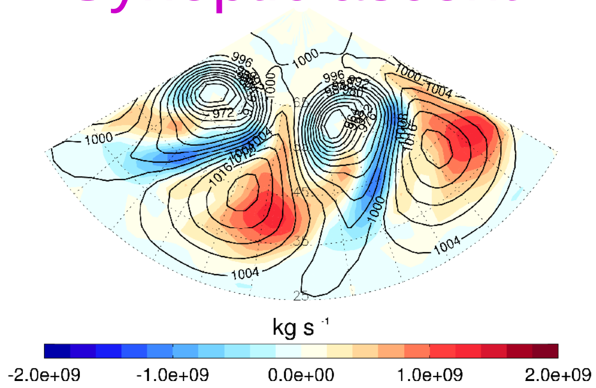
- Convergence: how mass is transported within the boundary layer
- Synoptic ascent: how mass is exchanged between the boundary layer and free troposphere
- Changes in B.L depth: how new mass is entrained into the boundary layer due to increasing depth. No transport across the boundary layer top.

Mass budget terms

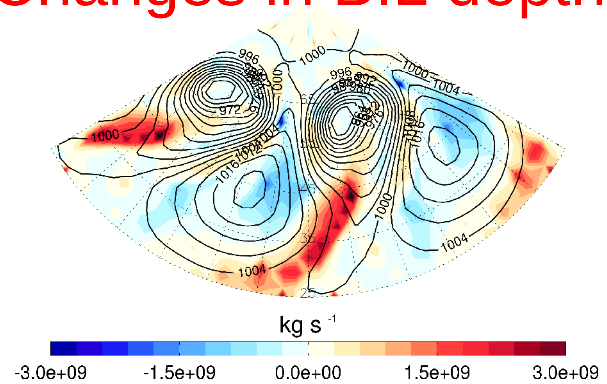
Convergence



Synoptic ascent



Changes in B.L depth



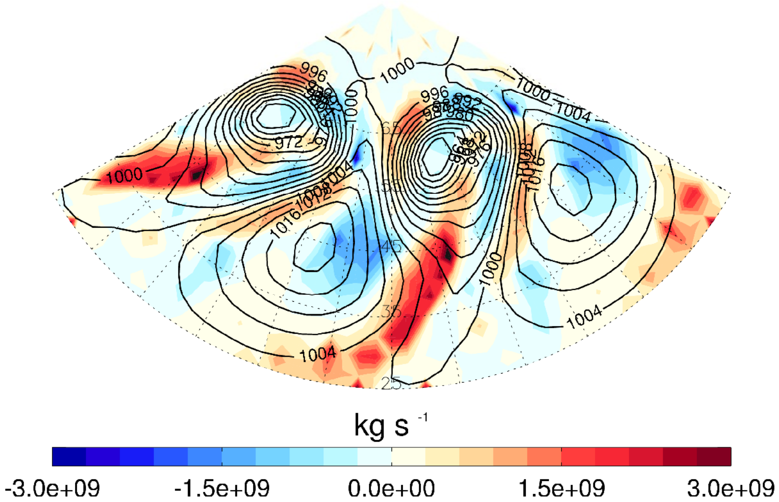
Note different scale here

Convergence and synoptic ascent cancel giving no net change, but describe how mass is transported through the boundary layer

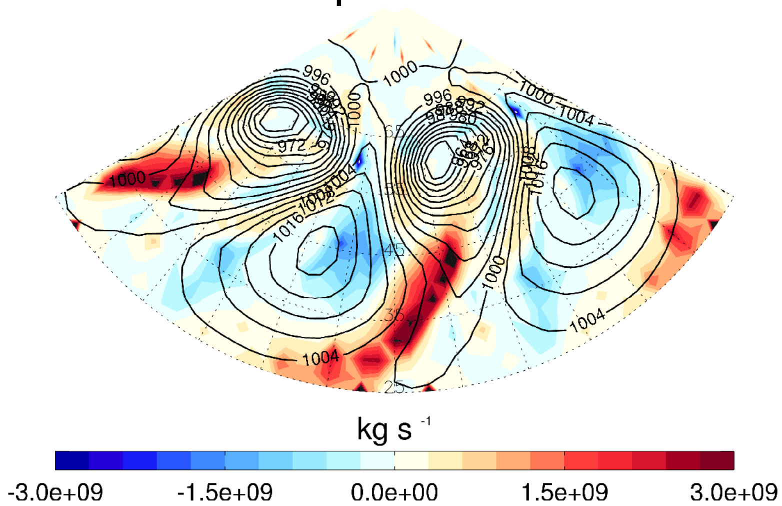
Boundary layer depth increases behind cold front

Total change of BL mass

Calculated from individual terms



Direct output from model



Net change in boundary layer mass is dominated by changes in the boundary layer depth

Tracer Budget equation

$$\frac{\partial \widetilde{\rho_A C}}{\partial t} = (\rho_A C)_h \frac{\partial h}{\partial t} - \frac{\partial (\widetilde{u \rho_A C})}{\partial x} - \frac{\partial (\widetilde{v \rho_A C})}{\partial y}$$

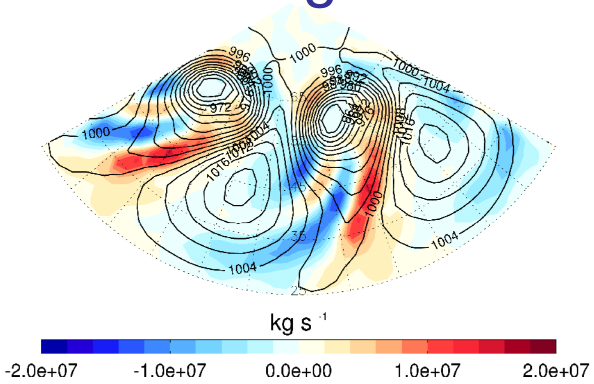
$$+ (u \rho_A C)_h \frac{\partial h}{\partial x} + (v \rho_A C)_h \frac{\partial h}{\partial y} - (w \rho_A C)_h - (\rho_A \overline{w' C'})_h$$

Similar to the mass budget equation EXCEPT the addition of the turbulent flux term.

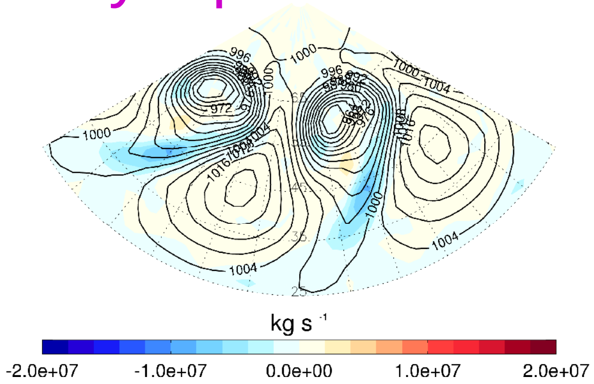
This term is assumed to be small.

Tracer Budget

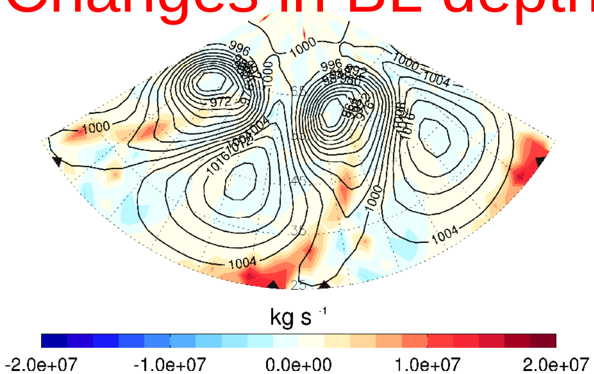
Convergence



Synoptic ascent

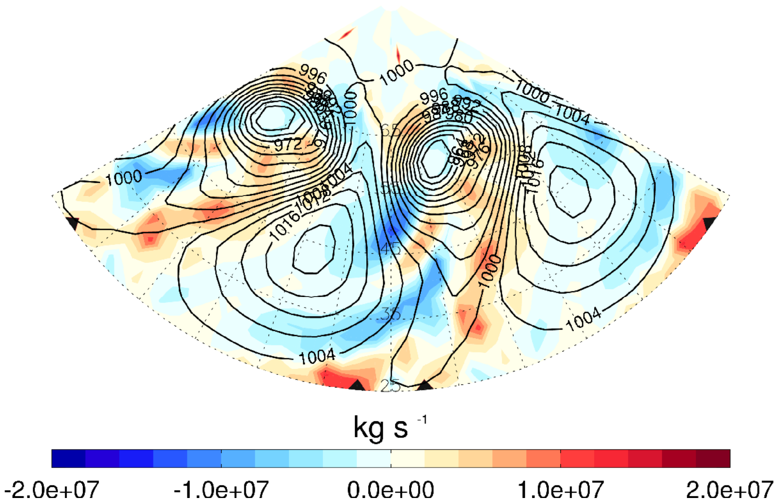


Changes in BL depth

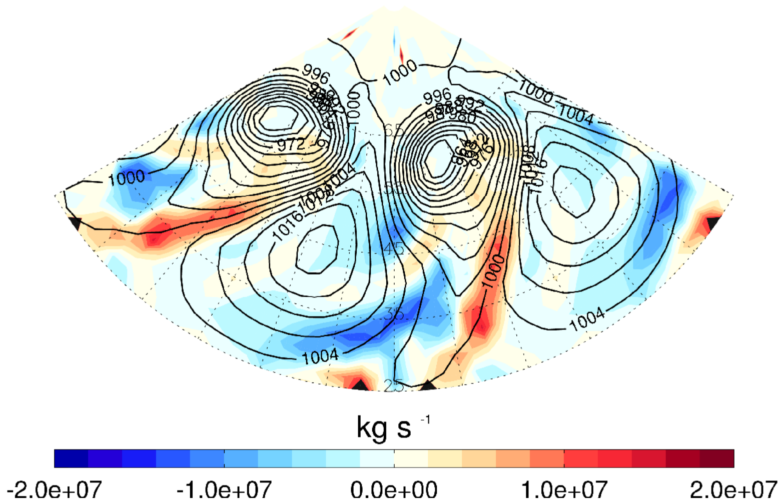


Tracer is not transported from the troposphere into the boundary layer in the same way mass is

Total tracer budgets



Total as calculated

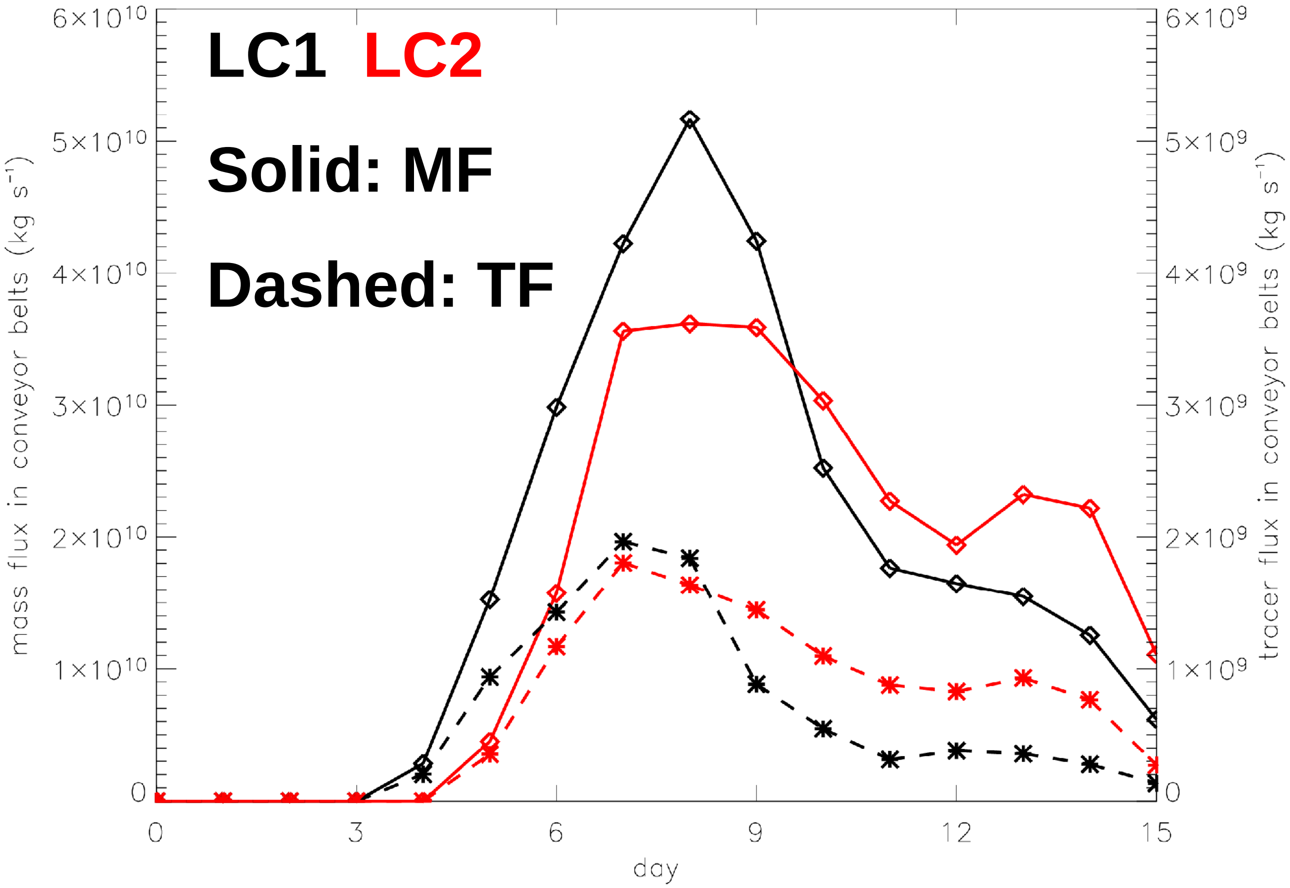


Direct model output

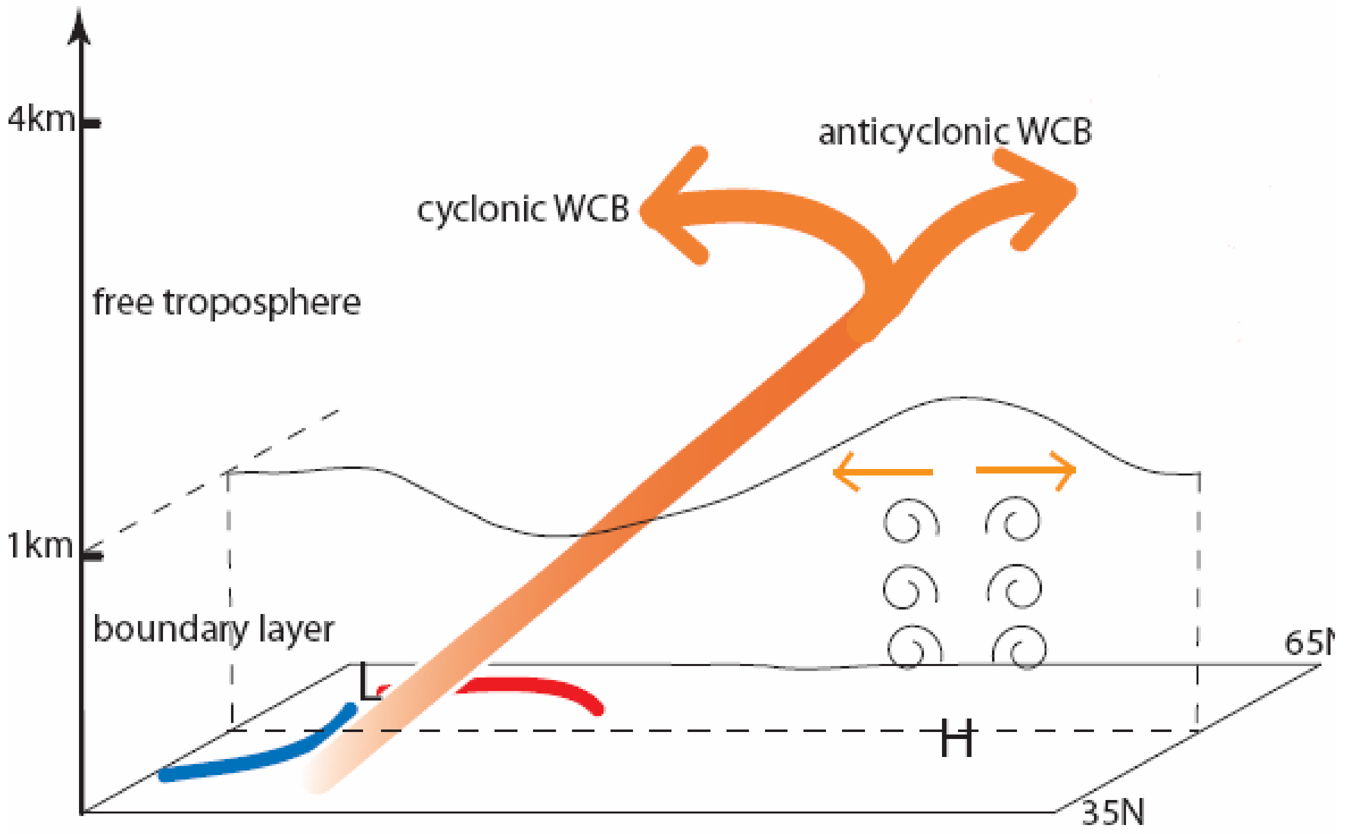
Dominated by convergence and the synoptic term.

Shows where tracer either accumulates or becomes depleted within the boundary layer

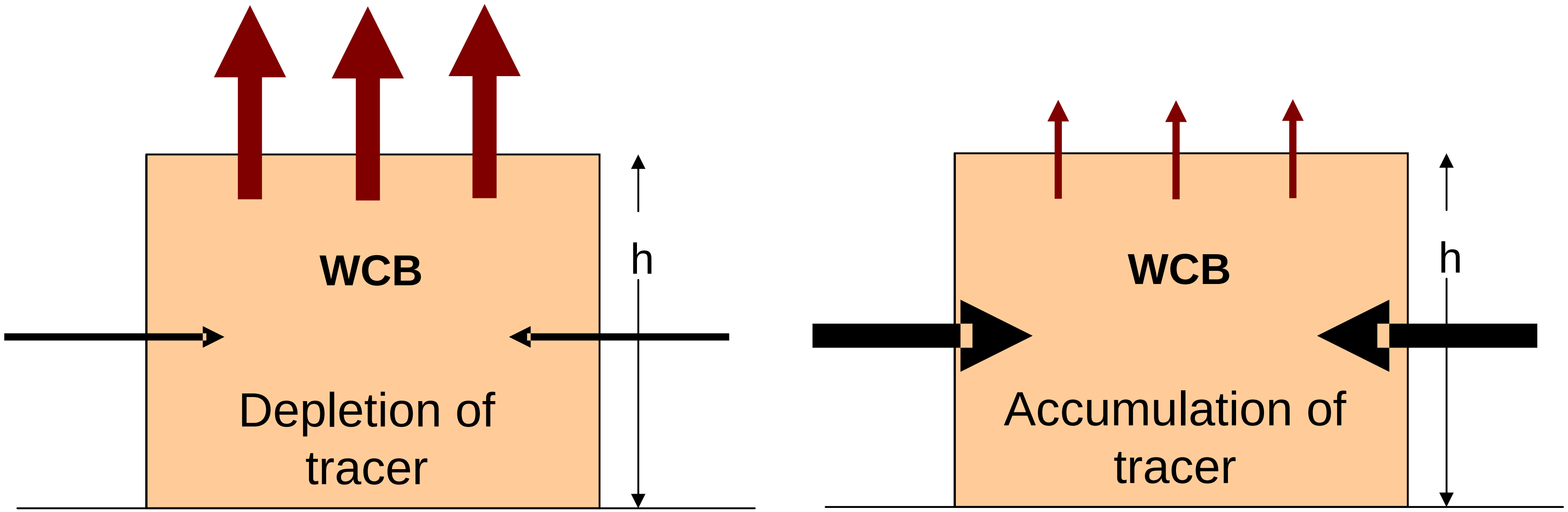
Conveyor belt mass and tracer fluxes



Conceptual model of transport processes



Conceptual model of controls on ventilation



Mass flux in and out of the volume must balance but the tracer flux in does not need to equal the tracer flux out

Hypothesis

- Tracer flux into the source region is controlled by
    1. Ekman convergence
    2. Horizontal gradients in tracer concentration

- Tracer flux out is controlled by
    1. The strength of the warm conveyor belt
    2. The availability of tracer in the source region

- Investigate the parameter space using the new idealised UM

Initial results with Unified Model

- We have simulated LC1 and LC2 type cyclones with a passive tracer in the idealised version of the UM

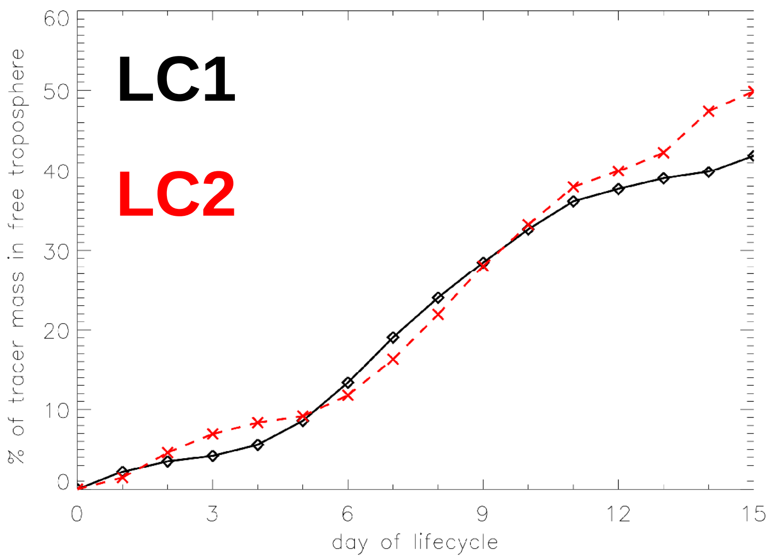
LC1 type cyclone (Unified Model)

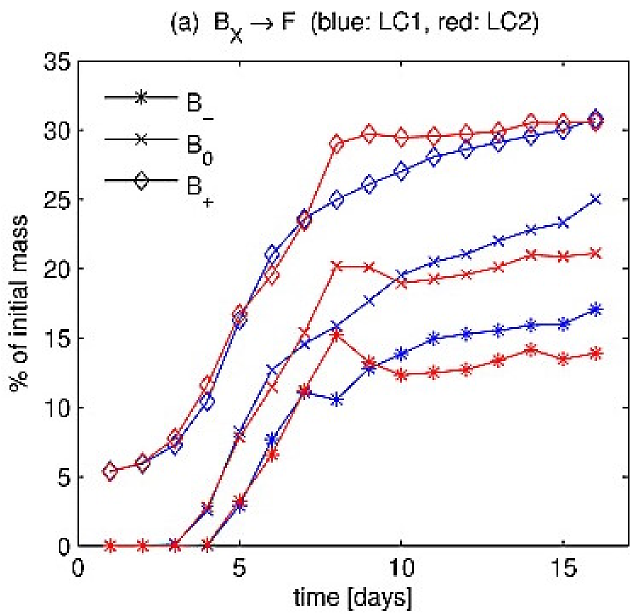
Summary

- Have performed the first idealised tracer experiments with a realistic boundary layer scheme
- Transport in the boundary layer is vital
    1. Turbulent mixing
    2. Ekman divergence and convergence
- Only the conveyor belt footprint regions of the boundary layer can be ventilated
- Availability of tracer in this region determines how efficient ventilation by conveyor belts is
- Transport in the free troposphere is by warm conveyor belts
- Can we derive an analytical formula based on simple dynamical parameters to predict the amount of boundary layer ventilation?


Questions?
www.met.rdg.ac.uk/~swr05vas

Comparison with Polvani & Esler (2007)





No B.L Scheme

Same LC1 and LC1

Including the boundary layer weakens the lifecycles but STILL leads to more boundary layer ventilation