transport & mixing of chemical airmasses in idealized baroclinic lifecycles

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background

- synoptic scale eddies important for transport (tracers and water vapor) in the atmosphere

- a lot of work has been done, on lifecycle dynamics…
  - early work of Hoskins & Simmons (70's and 80's)
  - Thorncroft, Hoskins, McIntyre (QJRMS, 1993)
  - Hartmann et al (1998, 2000) & others

- … but little work on transport/mixing in lifecycles (only a couple of papers in the literature!)

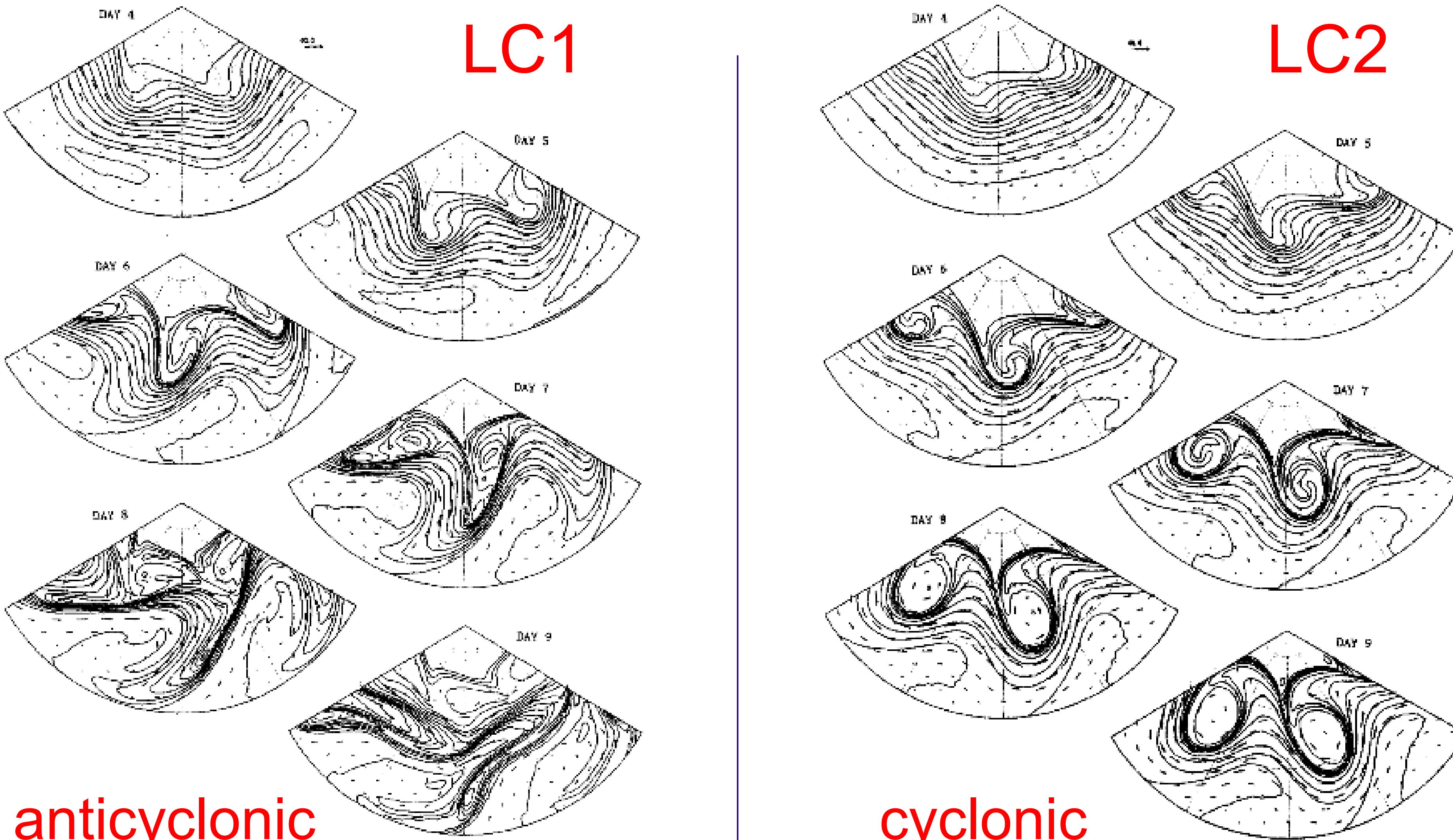
our questions

- transport/mixing from large-scale advection alone?
  - across the tropopause (either way)
  - from boundary layer into the stratosphere

- transport/mixing in LC1 vs LC2 lifecycles?
  - ENSO and NAO change ratio of LC1/LC2's
  - so what happens to the transport/mixing?

- what do the mixing airmasses look like? differences between LC1 and LC2?

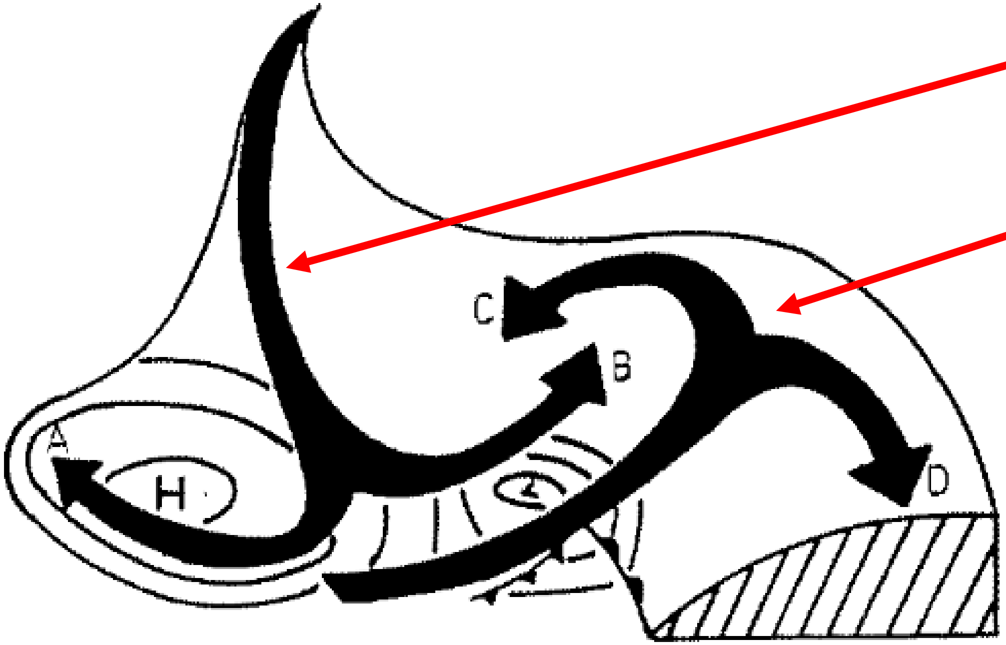
lifecycle "paradigms"



[θ on 2 PVU surface, from Thorncroft, Hoskins & McIntyre, 1993]

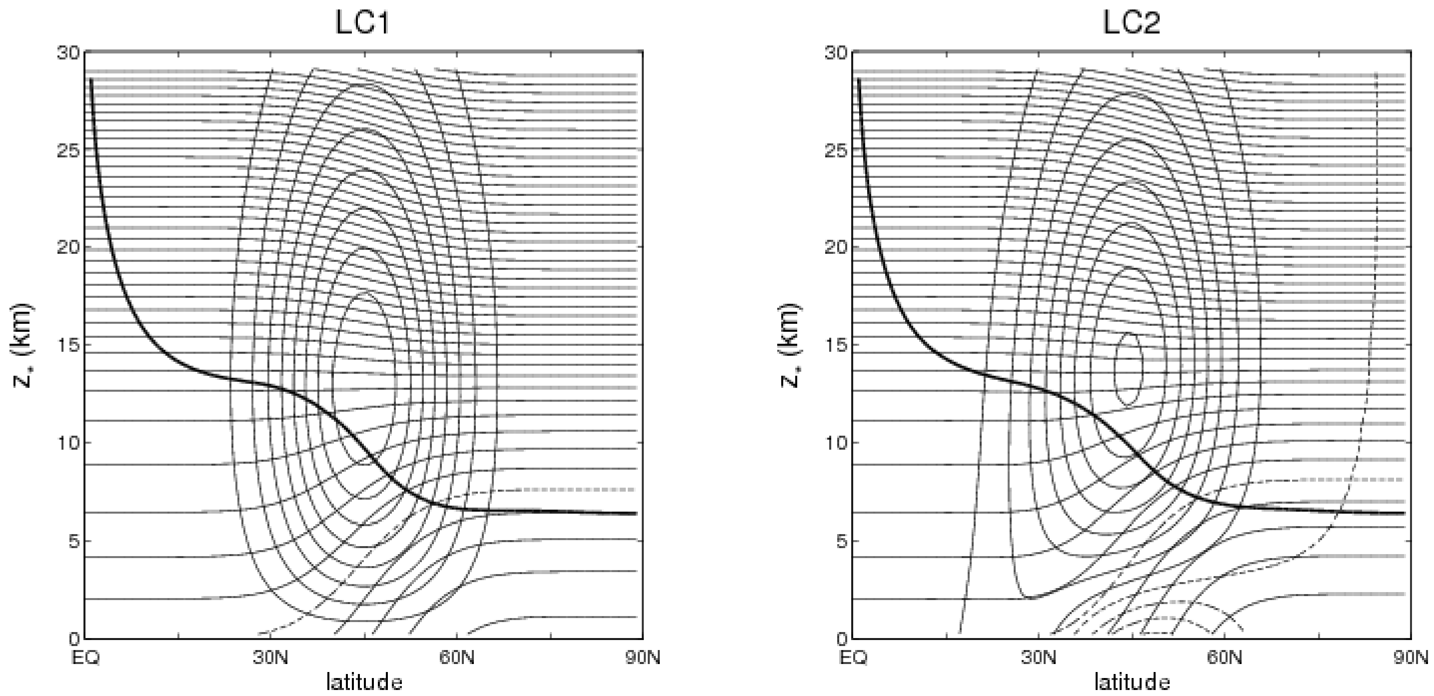
what do the airmasses look like?

Thorncroft, Hoskins & McIntyre (1993)



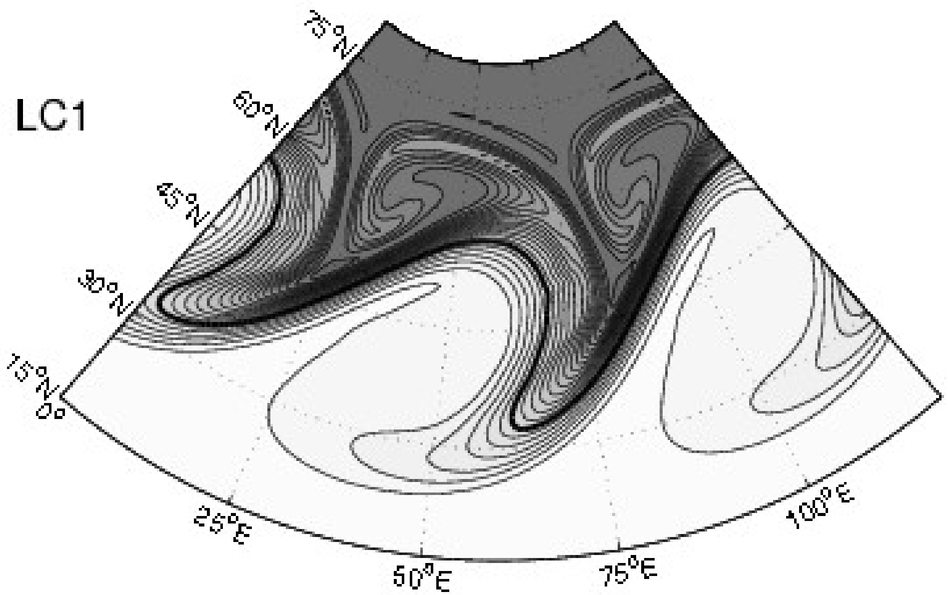
- "dry intrusion"
- "warm conveyor belt"
- this is only a sketch
- can we compute it?

initial u and θ

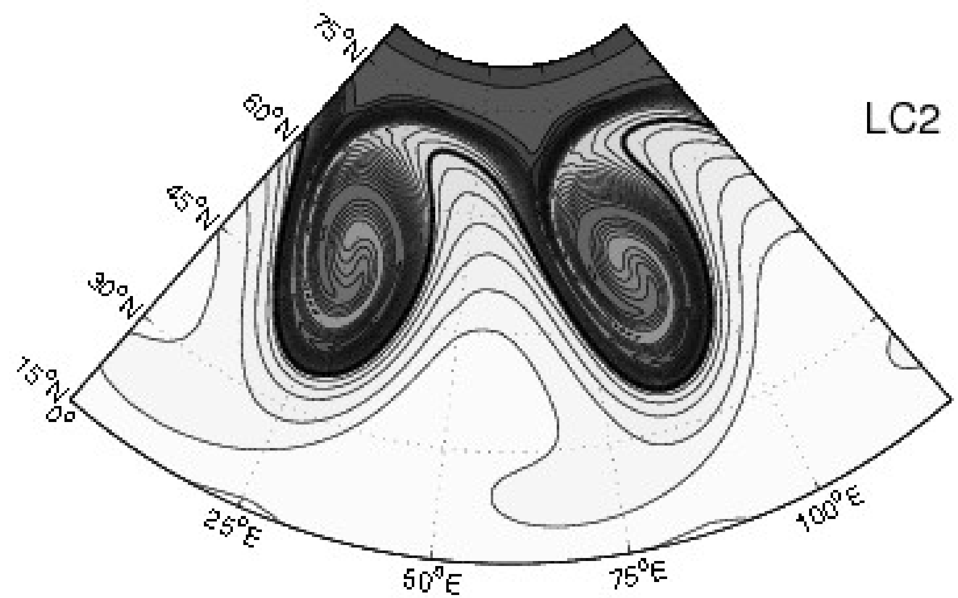


- initial conditions very similar to Thorncroft et al (1993)
- but… analytically specified here (hence reproducible)
- model top @ 30 km (tropopause in middle of domain)
- levels equally spaced in z not σ

PV on θ = 335 K (day 8)



LC1: anticyclonic

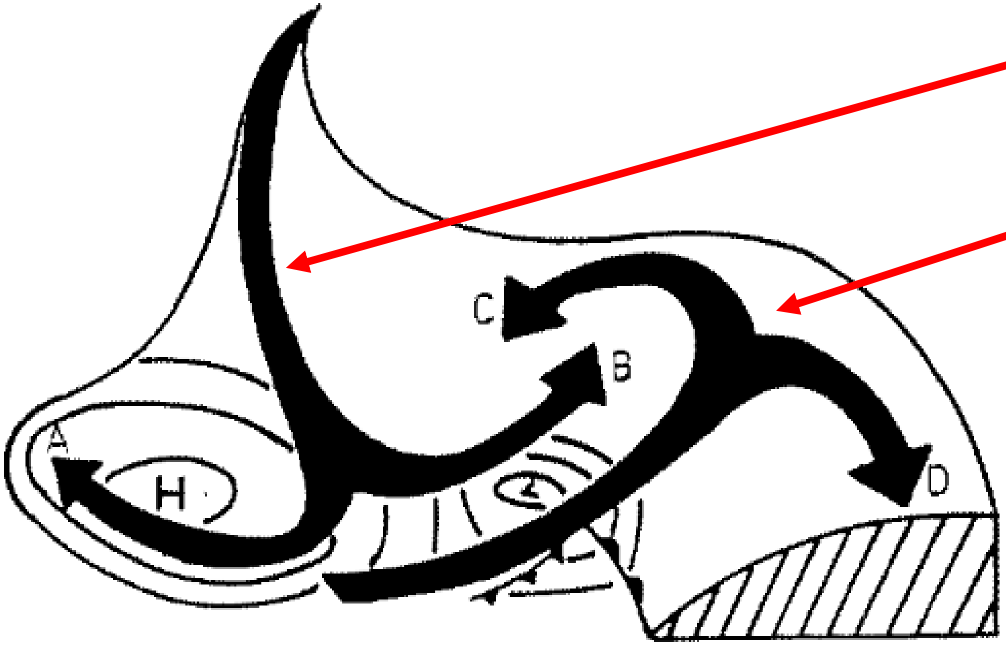


LC2: cyclonic

- we solve dry, adiabatic primitive equations
- in spherical geometry with m = 6 symmetry
- we compute at: T42L30 & T85L60 & T170L120
- T170L120: $dx = dy = 0.7°$ & dz = 250 m

what do the airmasses look like?

Thorncroft, Hoskins & McIntyre (1993)



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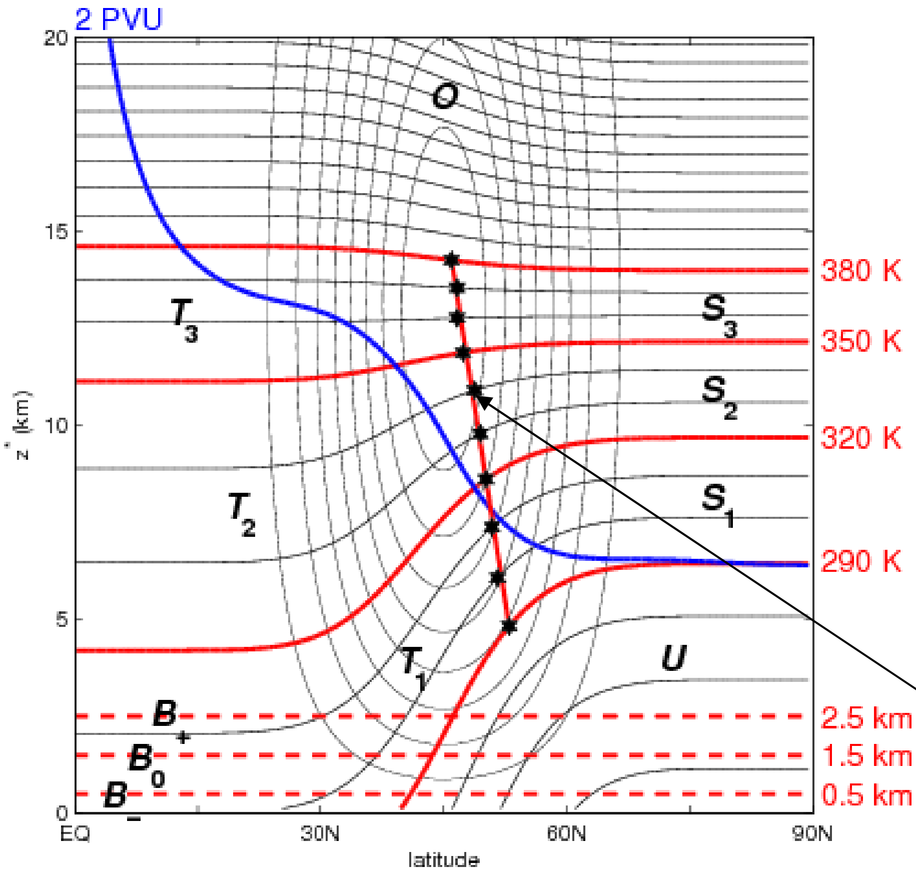
initializing tracers as airmasses



O → overworld

U → underworld

S's &T's → middleworld

T_1, T_2, T_3 → troposphere

S_1, S_2, S_3 → stratosphere

B_-, B_0, B_+ → boundary layer

max PV gradients = tropopause

- *all tracers have values 1 or 0 at initial time*
- *define S = $S_1+S_2+S_3+O$ and T = $T_1+T_2+T_3+U=1-S$*
- *define the tropopause as S = 1-T = 0.5 for all times*

quantifying mixing

- using tracers to define the tropopause allows for simple & natural definitions of transport

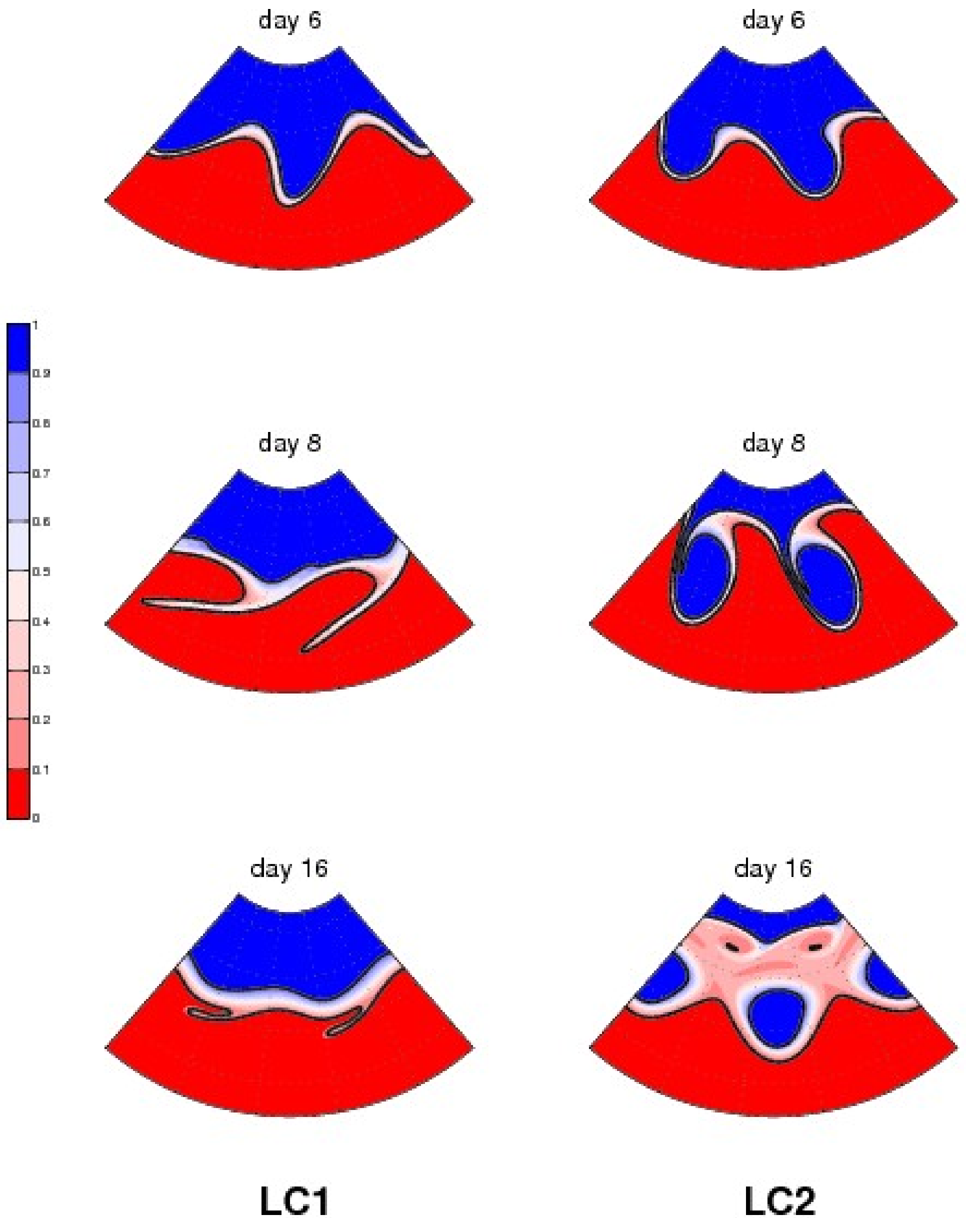
- no need to worry about the shape of tropopause!

- e.g. lower troposphere → stratosphere

$$T_1 \rightarrow \mathcal{S} = \int_{\mathcal{S}} T_1 \, \rho \, dV$$

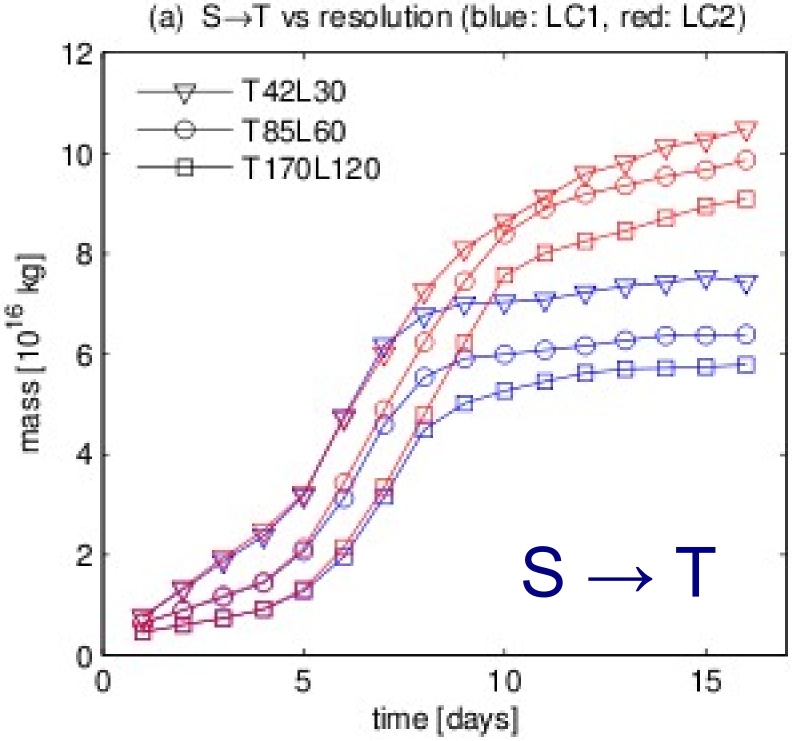
- very easy to compute in practice

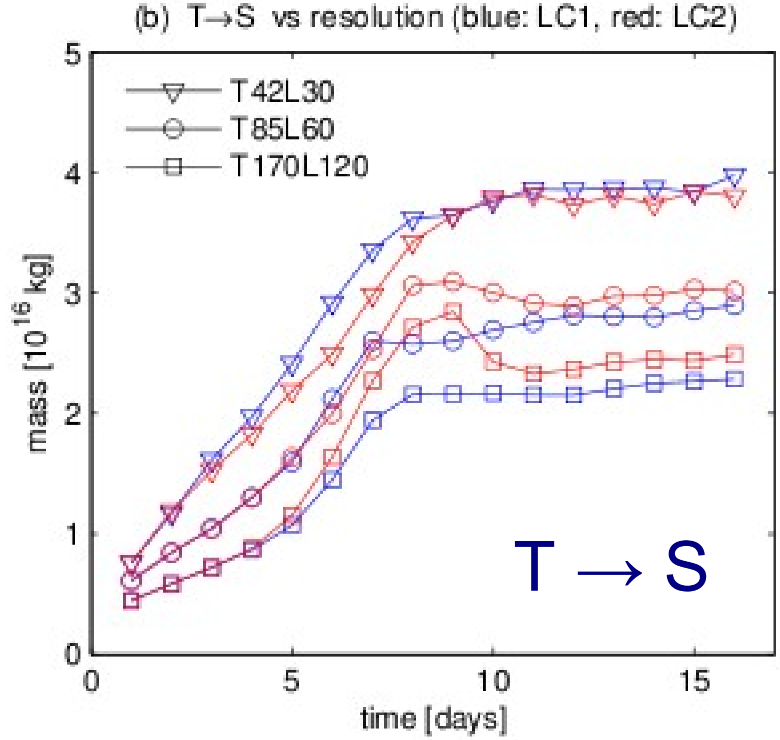
middleworld airmasses θ = 335 K



- blue: stratospheric air (S>0.9)
- red: tropospheric air (S<0.1)
- white'ish: mixed air
- black lines delimit the the mixing zone (SxT > 0.1)
- mixing zone is narrow for LC1 and broad for LC2
- expect more mixing for LC2 than for LC1
- mixed air is red implying bigger S → T

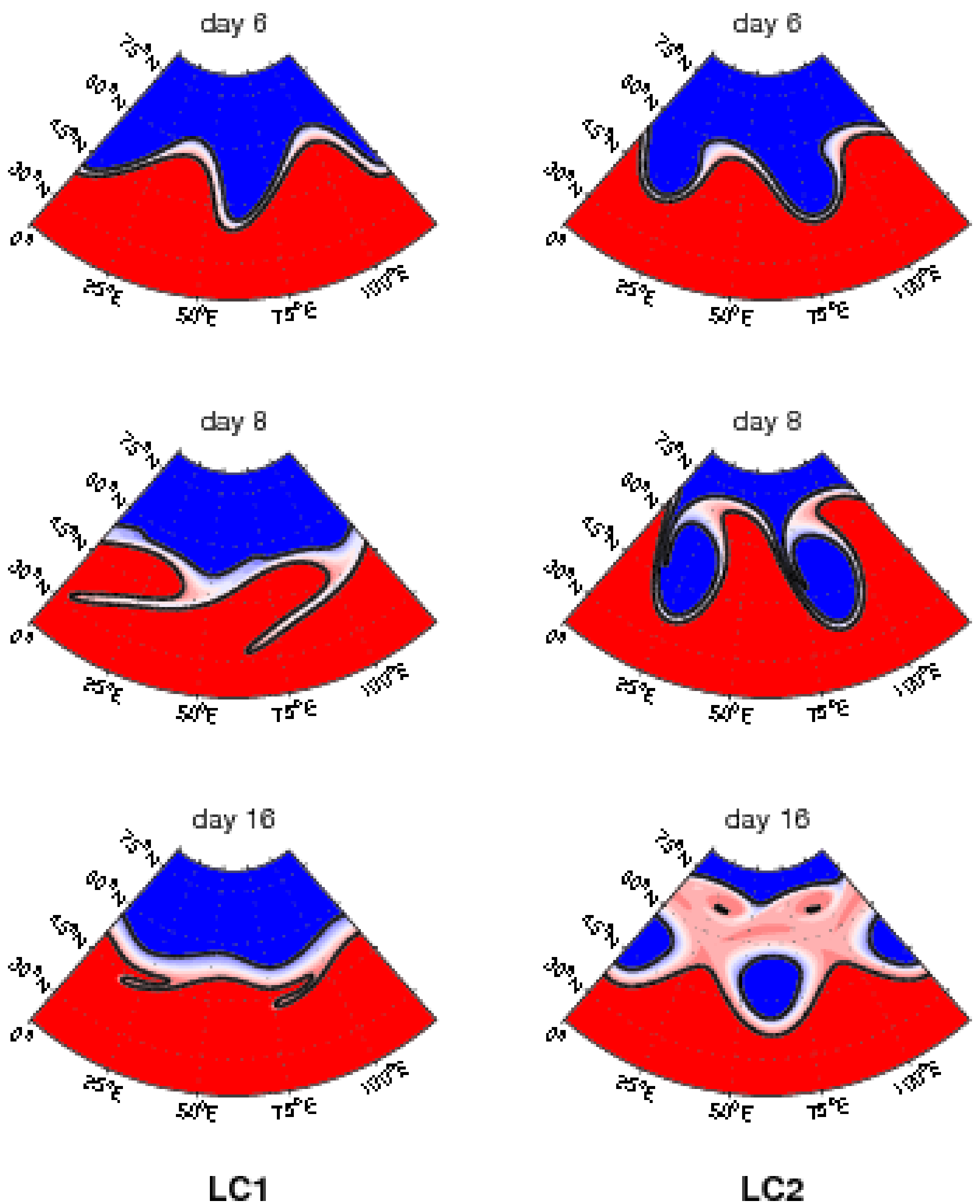
two-way cross-tropopause transport





- S → T greater for LC2 by about 50%
- T → S about same for both
- these results independent of resolution

T170L120

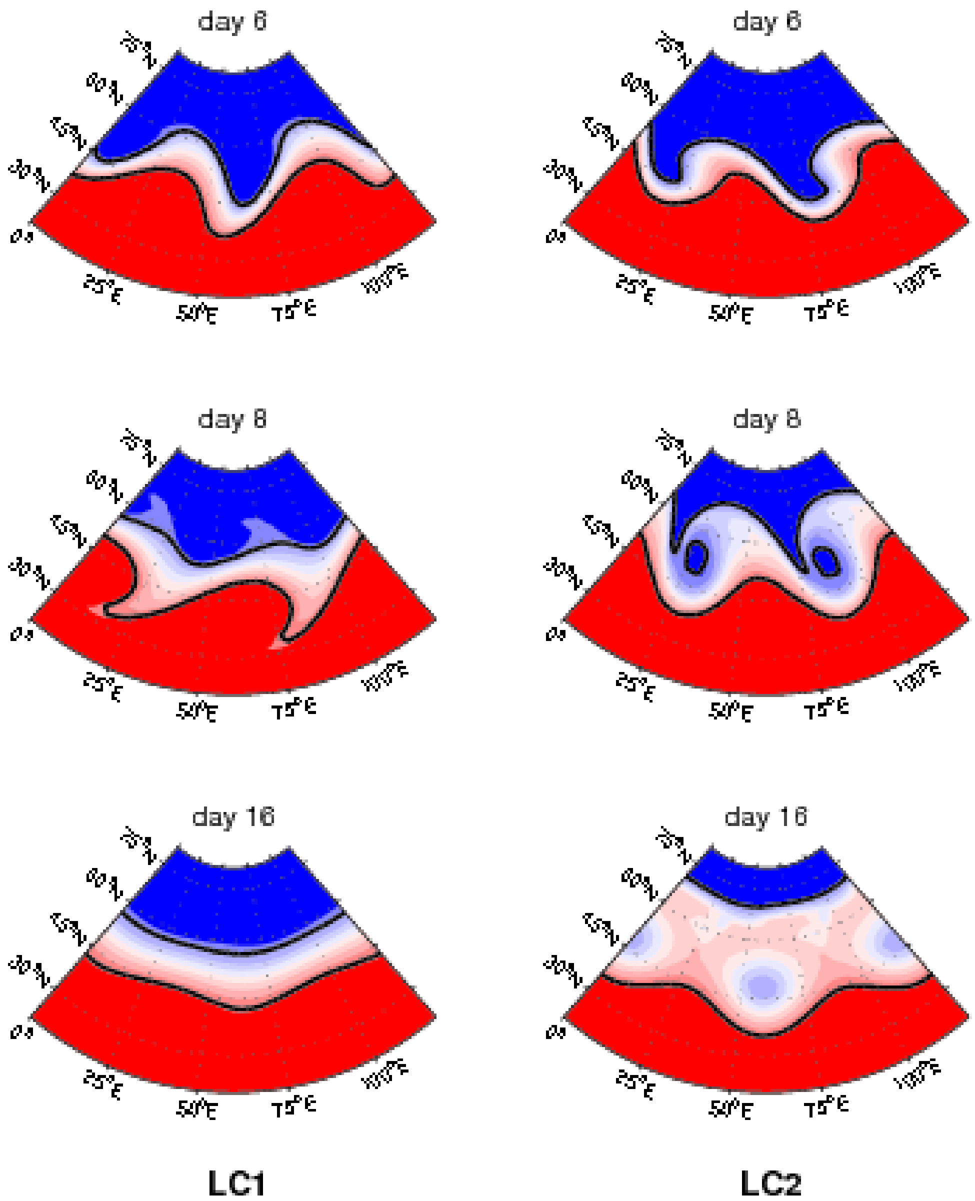


T170L120

dlat, dlon = 0.7°

and dz = 250m

T42L30

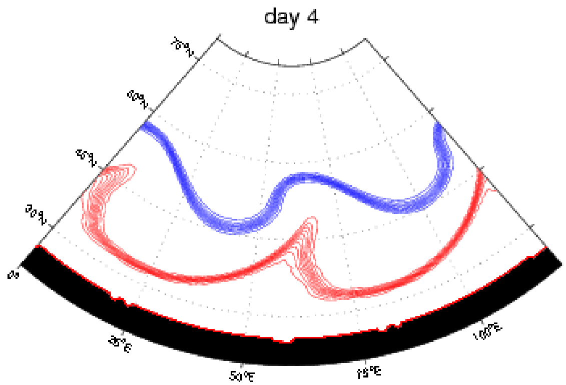


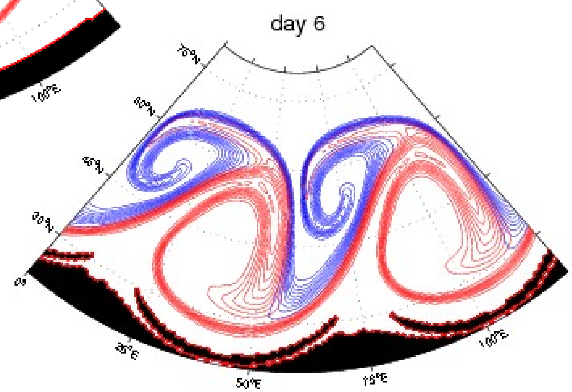
T42L30

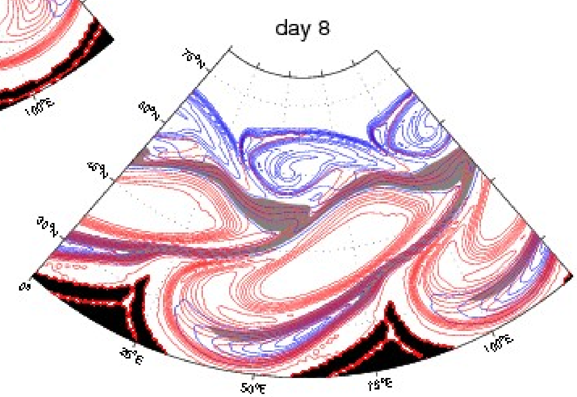
dlat, dlon = 2.8°

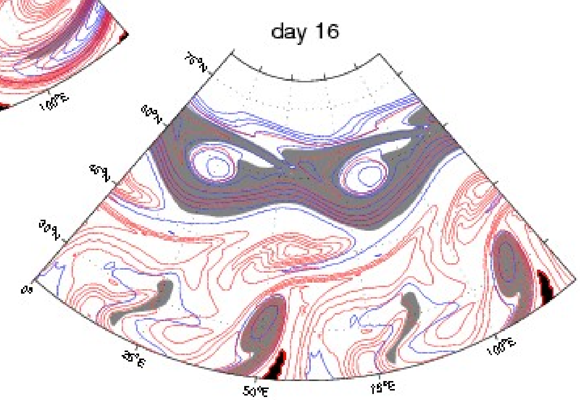
and dz = 1km

BL and stratospheric air on 300K







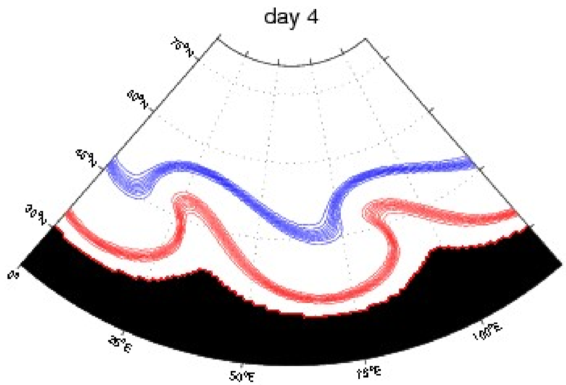


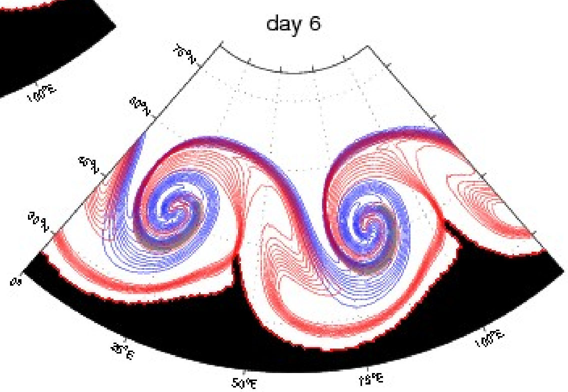
LC1 life cycle

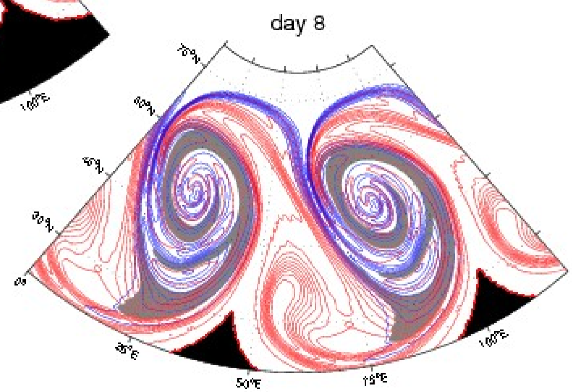
- red: BL air
- blue: stratospheric air
- gray: “mixing region”, i.e. $B_0 x S>0.1$
- largest mixing occurs in the cyclones

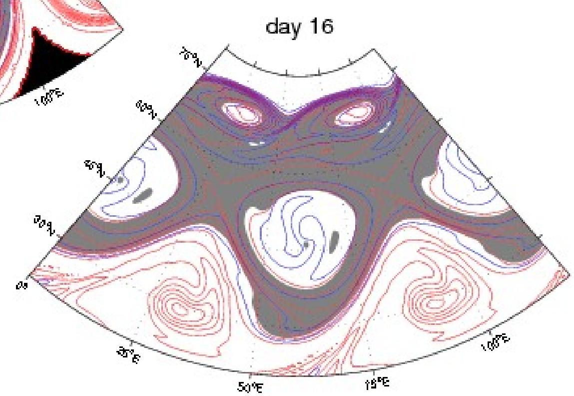
BL and stratospheric air on 300K

LC2 life cycle







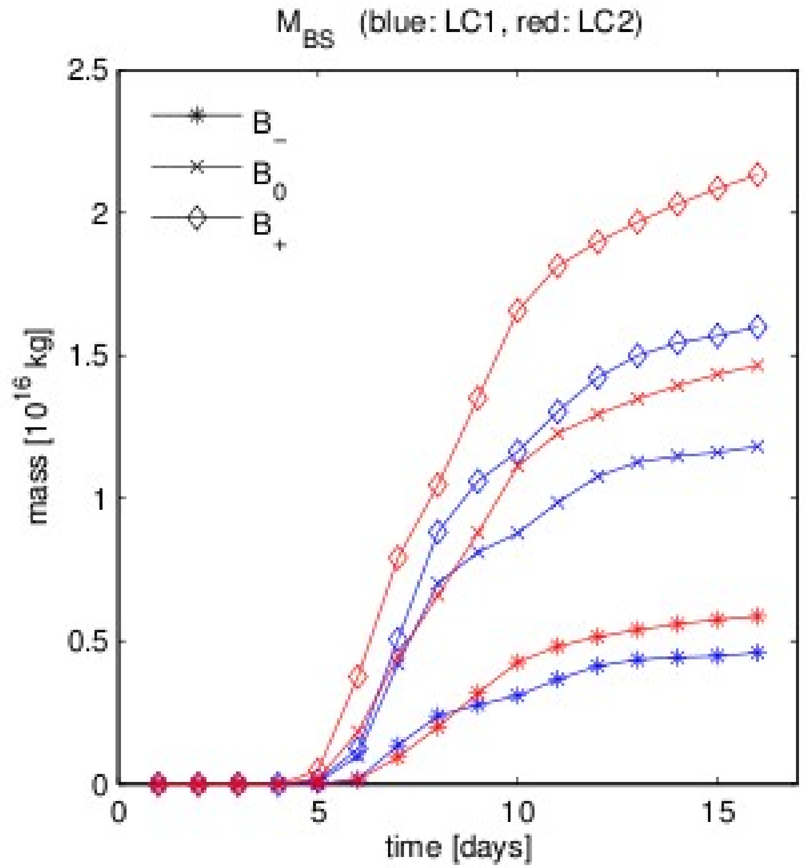


- red: BL air
- blue: stratospheric air
- gray: “mixing” region, i.e. $B_0xS>0.1$
- largest mixing occurs around cyclones

reality check…

- courtesy of NOAA
- SeaWiFS image
- taken 31 August 2000
- over the North Atlantic

mixing of BL and stratospheric air

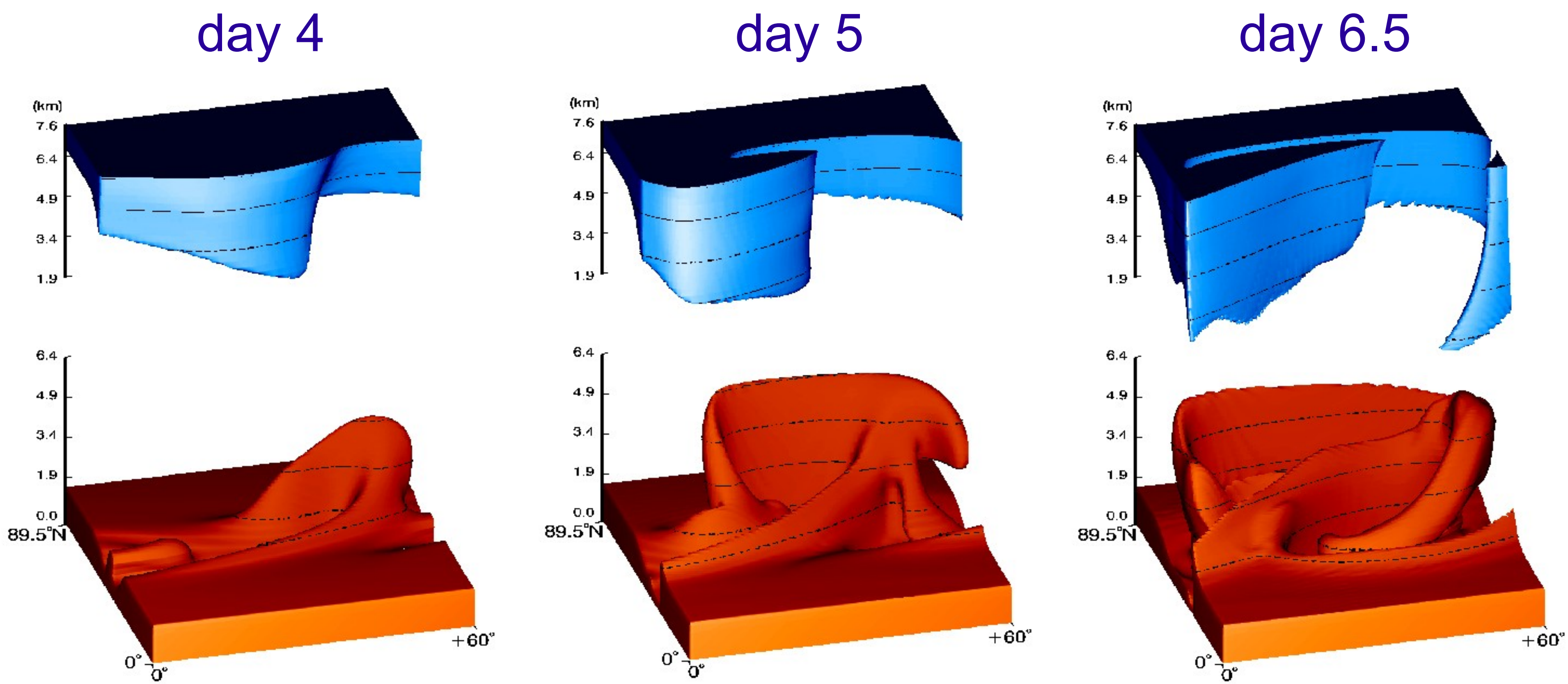


- plot shows

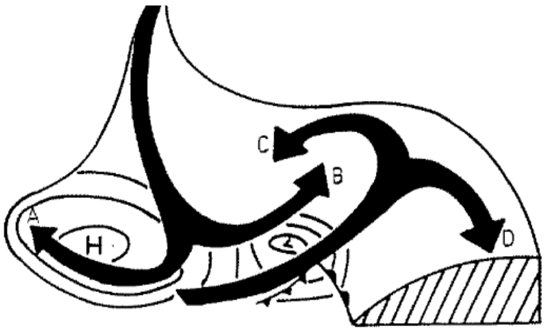
$$M_{BS} = \int_{\mathcal{A}} B_0 S \, \rho \, dV$$

- integral over whole atmos
- larger mixing for LC2 roughly by 30%
- amount of BL air uplifted in the free atmosphere is comparable for LC1 & LC2

LC1 → 3d view of BL and statospheric air



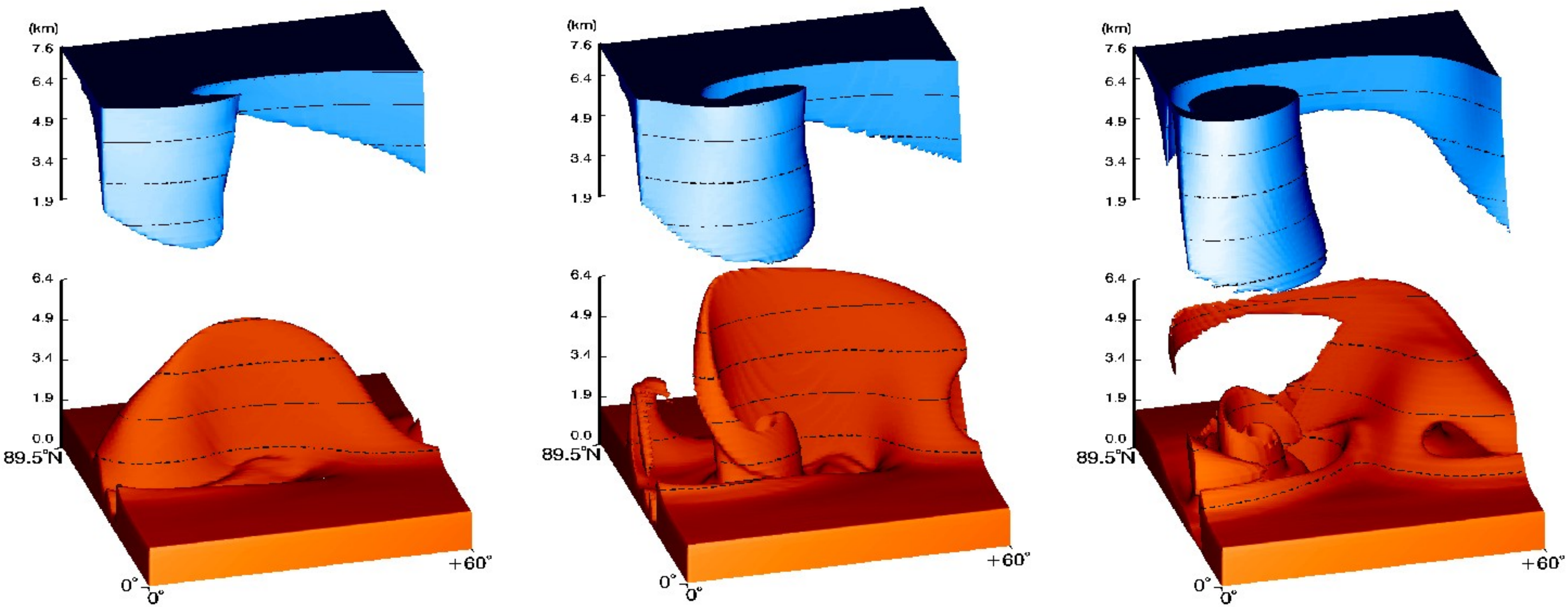
red → BL air & blue → stratospheric air
airmasses are slotted together: separation artificial



→ branches C and B appear first
→ branch C is a sheet, branch D is a tube
→ branch A appears at day 6.5

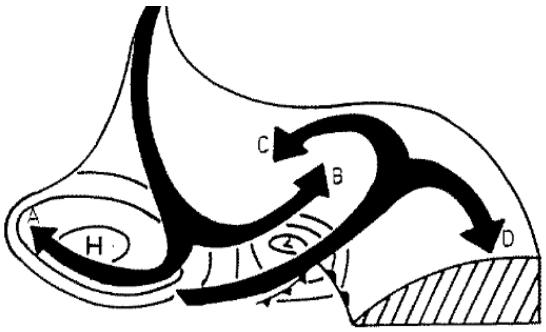
LC2 → *3d view of BL and statospheric air*

day 4.5 day 5.5 day 7



red → BL air & blue → stratospheric air
airmasses are slotted together: separation artificial

→ branches C and B are the DOUBLE spiral
→ branch D turns cyclonic
→ branch A is completely absent



ENSO & strat-trop exchange

- Shapiro et al (2001) have shown that +ve ENSO is associated with increases in LC2/LC1

- Zeng & Pyle (2005) have shown increased O_3 of stratospheric origin in the troposphere for +ve ENSO

- our results provide the missing link
  1. +ve ENSO means more LC2
  2. more LC2s means more S → T transport
  3. and thus more strat O_3 in the troposphere

strat-trop exchange & climate change

- LC2 have deeper mixing regions than LC1
- LC2 / LC1 frequency change in future climate would then affect the thickness of the ExTL
- IPCC/AR4 suggests that SH jet will move poleward
- poleward jet is associated with more LC1s
- possibly thinner tropopause layer
- HIGHLY SPECULATIVE…

take home message

- stronger mixing in LC2 than LC1
- most mixing occurs in cyclones (even for LC1!)
- caveat: highly idealized results…
  (transport/mixing due to large scale advection alone)
- could be used to test numerical schemes of CTMs
- relative importance of diabatic process, convection, small scale turbulence, etc can now be assessed

thank you…

← a North Pacific cyclone
from SeaWiFS

[paper in JGR, 2007]