Circulation and transport in the TTL and tropical lower stratosphere

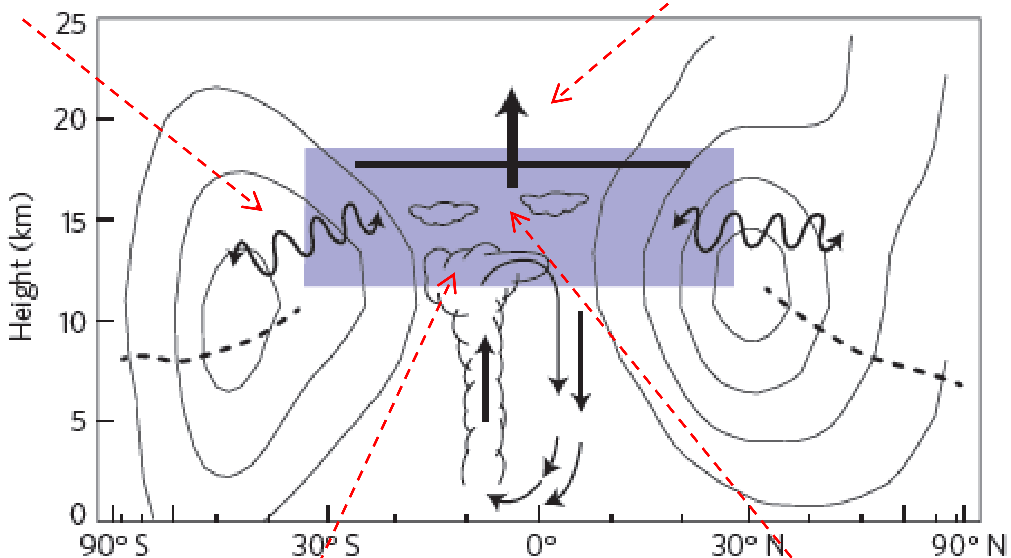
- the large annual cycle in the TTL: temperature and ozone
- observations: temperatures, circulation, trace species
- thermodynamic and constituent budgets in the TTL
- dynamical forcing of tropical upwelling

Transport near the tropical tropopause layer (TTL)

TTL sets 'boundary condition' for global stratosphere
Region with complex balances:

two-way transport by baroclinic eddies and monsoons

tropical upwelling influences temps, ozone and stratospheric H_2O



how does deep convection impact composition?

cirrus and climate impacts

Well-known: large annual cycle in temperature in tropical lower stratosphere

The Annual Temperature Variation in the Lower Tropical Stratosphere[1]

Richard J. Reed[2] and Charles L. Vlcek[3]

JAS 1969

dynamically forced,
but exactly how?

extratropical stratosphere,
tropical waves, ??

narrow
maximum

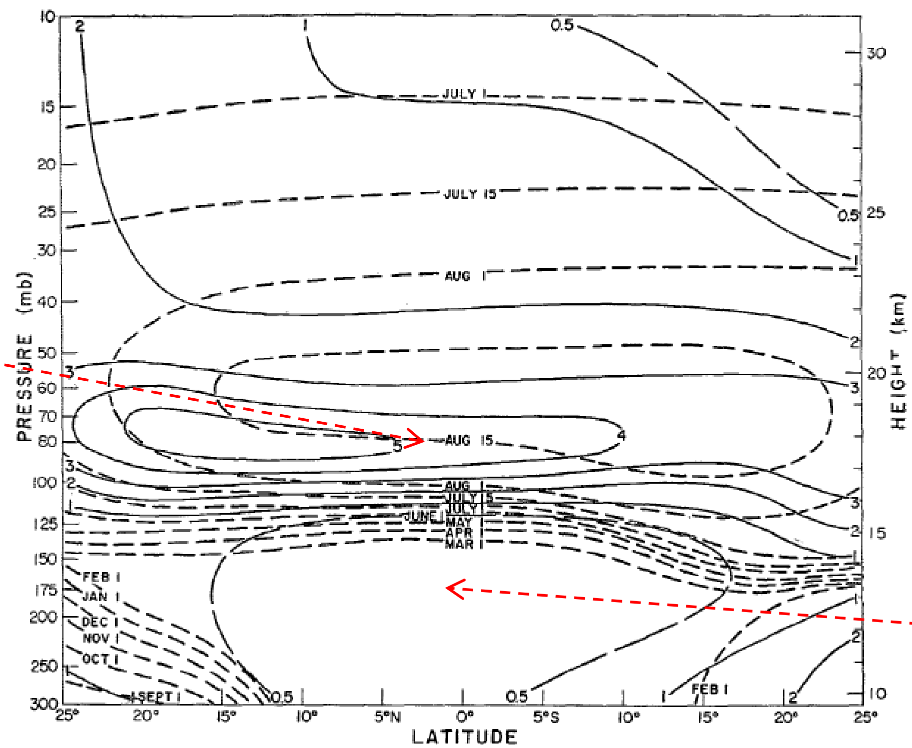
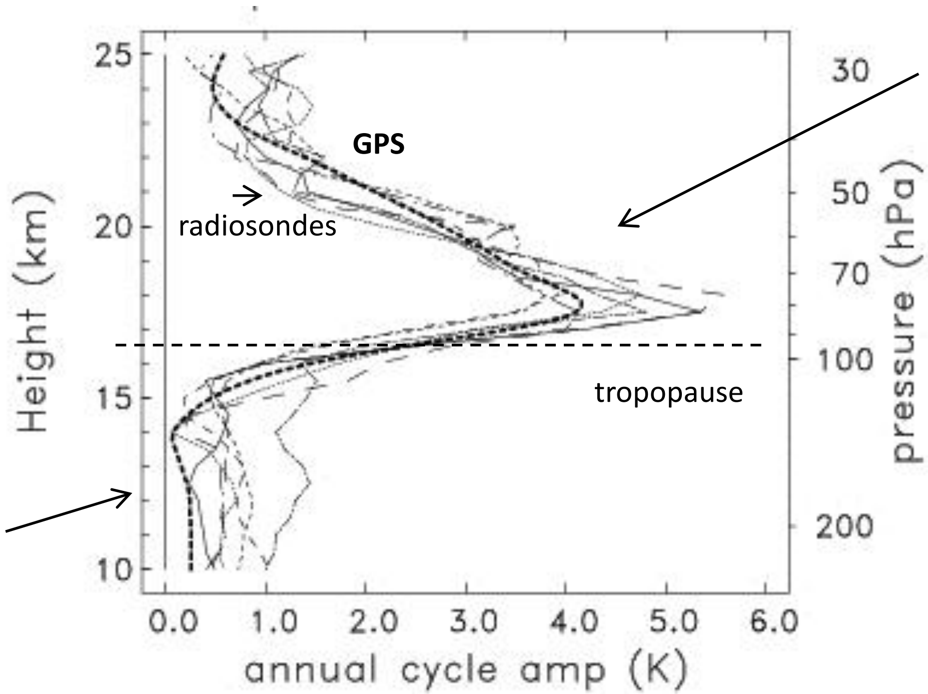


Fig. 1. Amplitude (°C) and phase (time of maximum) of annual temperature variation.

almost zero annual cycle
in tropical troposphere

Amplitude of the tropical annual cycle in temperature



narrow vertical scale, peak in lower stratosphere

very small annual cycle in troposphere

What causes the annual cycle? Dynamically-forced upwelling

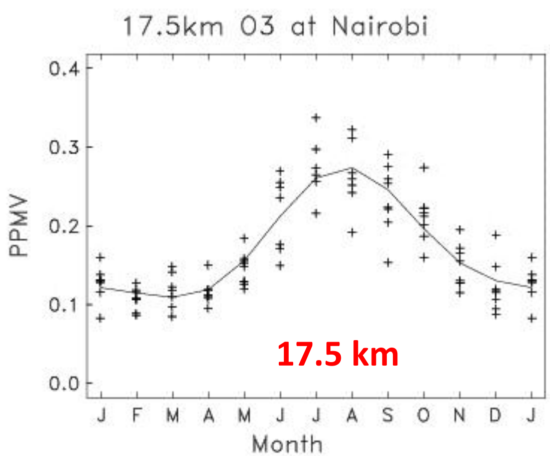
$$\frac{\partial \overline{T}}{\partial t} + \overline{v}^* \frac{1}{a} \frac{\partial \overline{T}}{\partial \phi} + \overline{w}^* S = \overline{Q}.$$

small

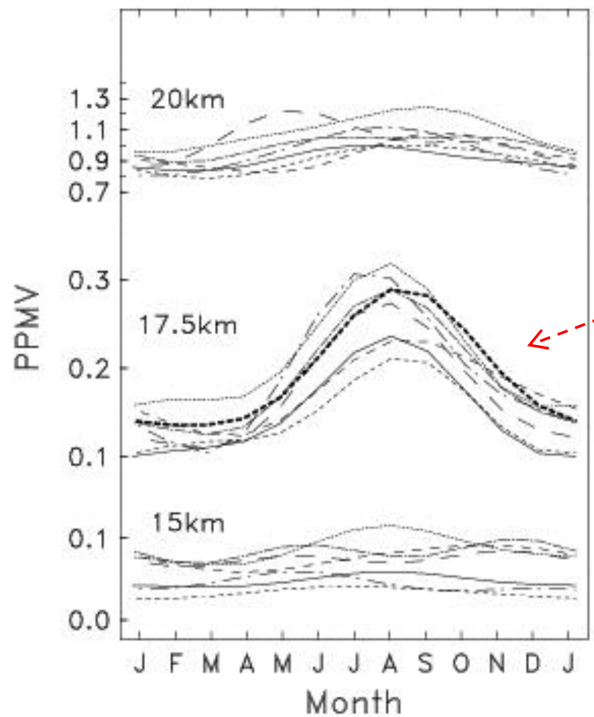
in this region, radiation acts as a damping term, not forcing

There is also a large annual cycle in ozone above the tropical tropopause

Seasonal cycle at Nairobi

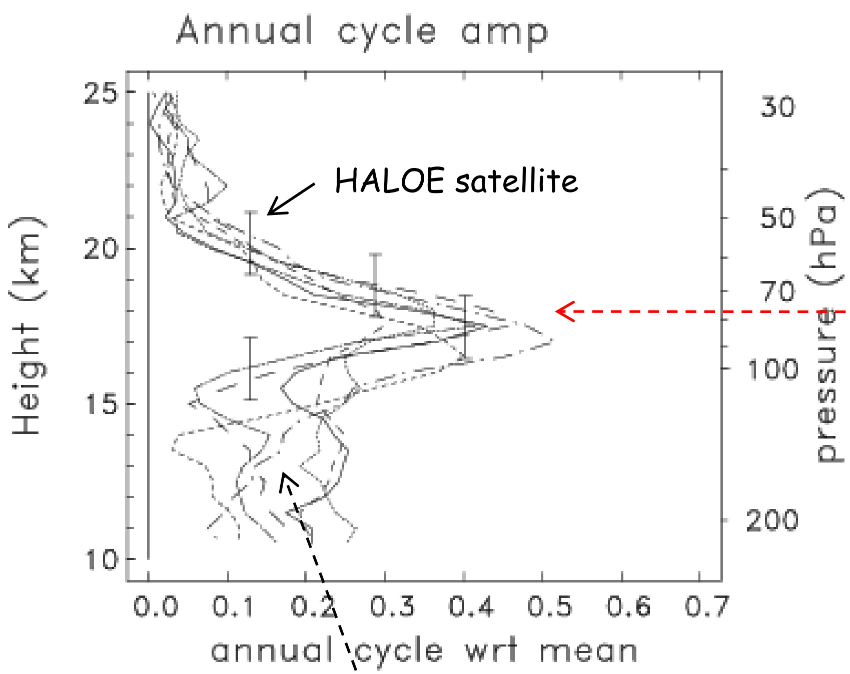


seasonal cycle at 7 SHADOZ ozonesonde stations 10° N-S



Randel and Wu, JAS 2007

Ozone annual cycle amplitude normalized by background $\frac{A_1}{\langle A \rangle}$

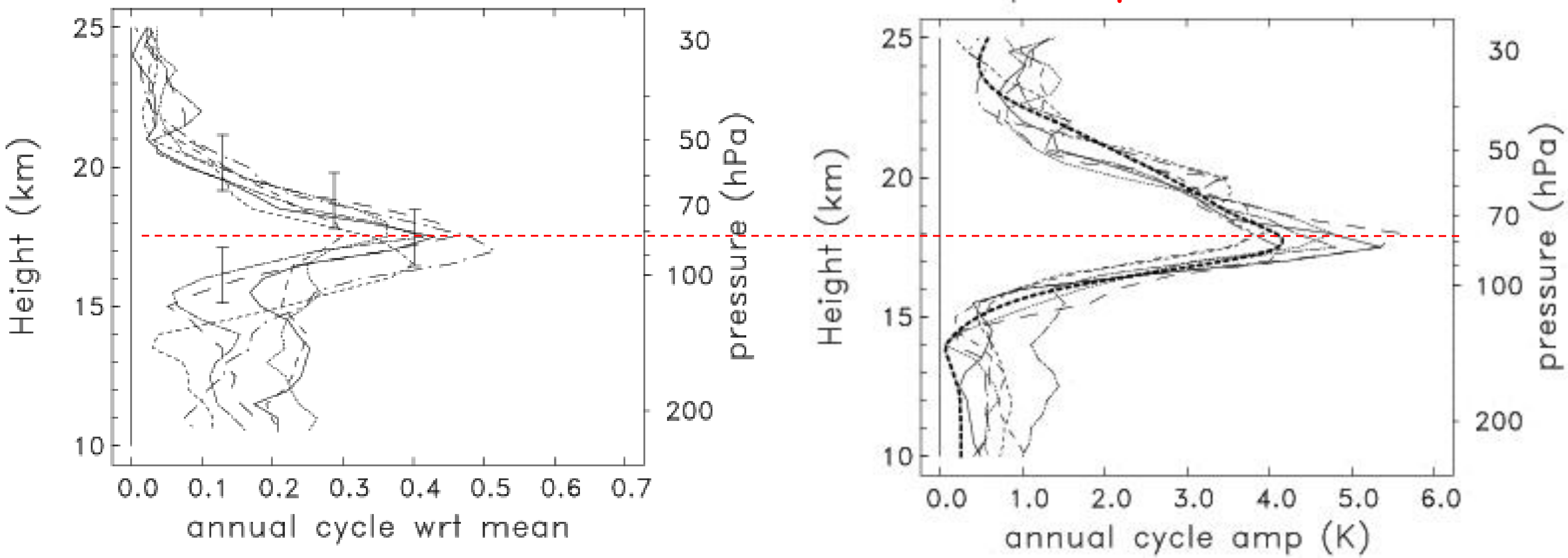


narrow vertical layer
~ 16-19 km

upper troposphere seasonal
cycle is different among stations

Ozone seasonal cycle has similar vertical structure to temperature

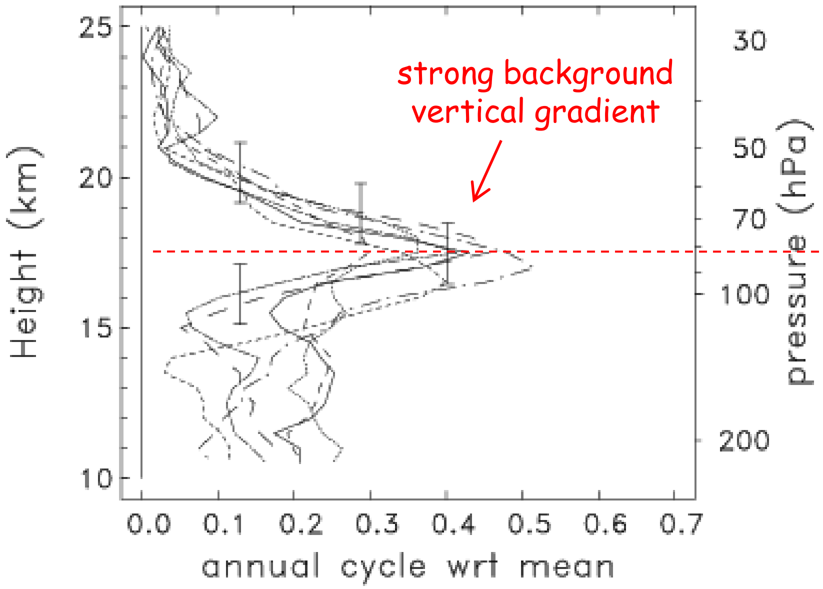
ozone temperature



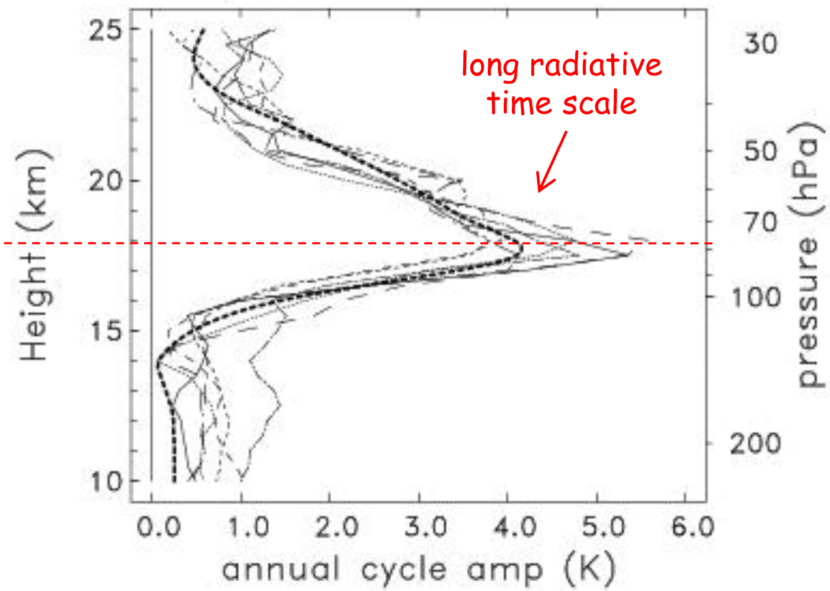
temps from SHADOZ stations
and zonal mean GPS data

Ozone seasonal cycle has similar vertical structure to temperature

ozone

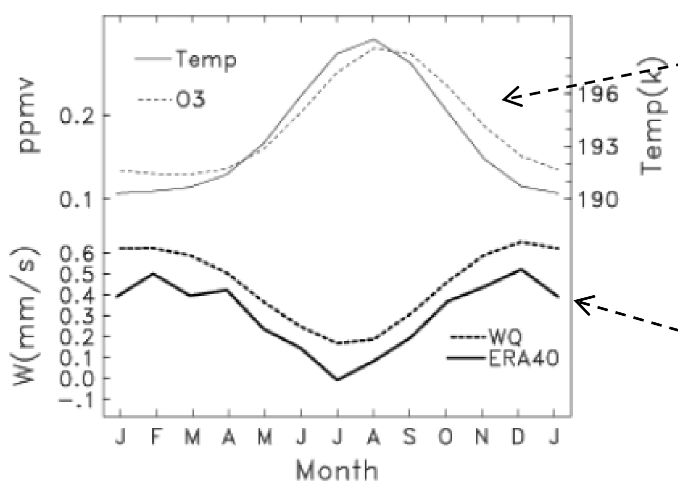


temperature



ozone and temp respond to annual cycle in tropical upwelling

Climatological seasonal cycle



ozone and temp ~ in phase

vertical velocity (2 estimates)

Tracer transport equation similar to thermodynamic equation:

tracer

$$\frac{\partial \overline{\chi}}{\partial t} = -\overline{v}^* \frac{1}{a}\frac{\partial \overline{\chi}}{\partial \phi} - \overline{w}^* \frac{\partial \overline{\chi}}{\partial z} + \nabla \cdot M + P - L$$

temperature

$$\frac{\partial \overline{T}}{\partial t} + \overline{v}^* \frac{1}{a}\frac{\partial \overline{T}}{\partial \phi} + \overline{w}^* S = \overline{Q},$$

↓

idealized situation in tropical lower stratosphere

$$\frac{\partial \overline{\chi}}{\partial t} = -\overline{w}^* \frac{\partial \overline{\chi}}{\partial z}$$

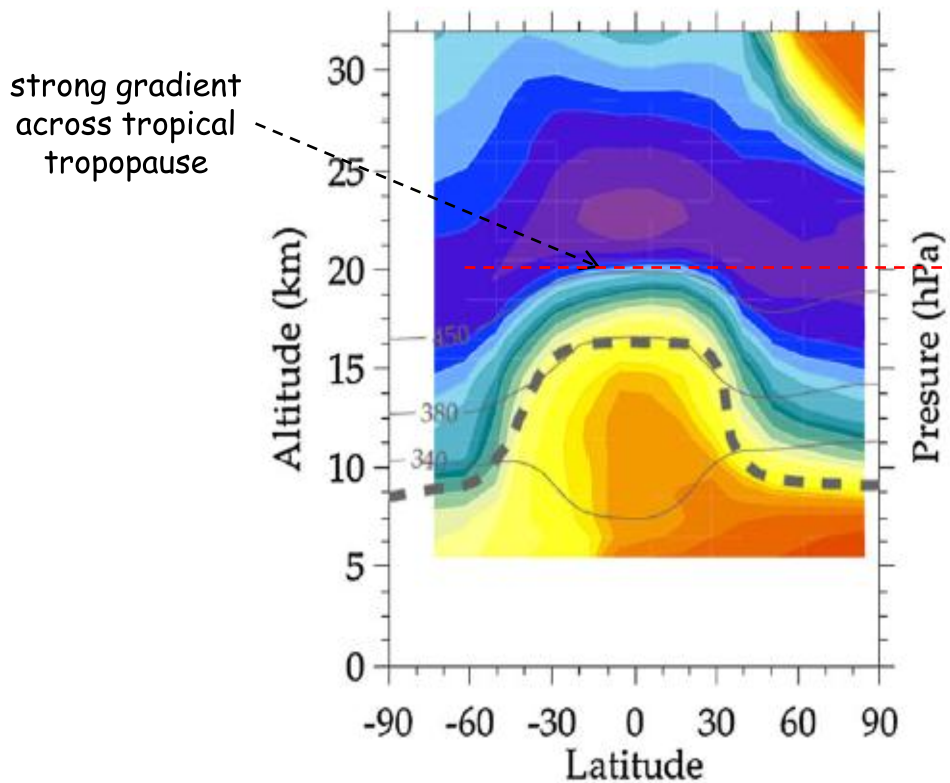
$$\frac{\partial \overline{T}}{\partial t} = -\overline{w}^* S$$

variations in upwelling $\overline{w}^*$ result in correlated temperature and tracers

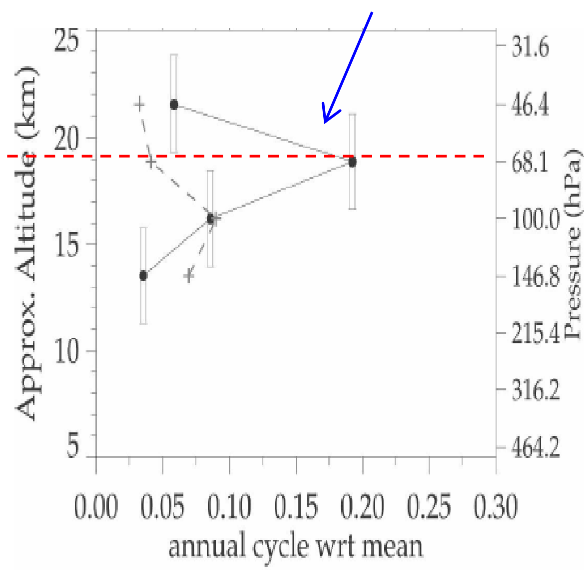
* for tracers with strong vertical gradients

There is a corresponding annual cycle in CO above the tropical tropopause (out of phase with temperature and ozone)

Climatological CO structure

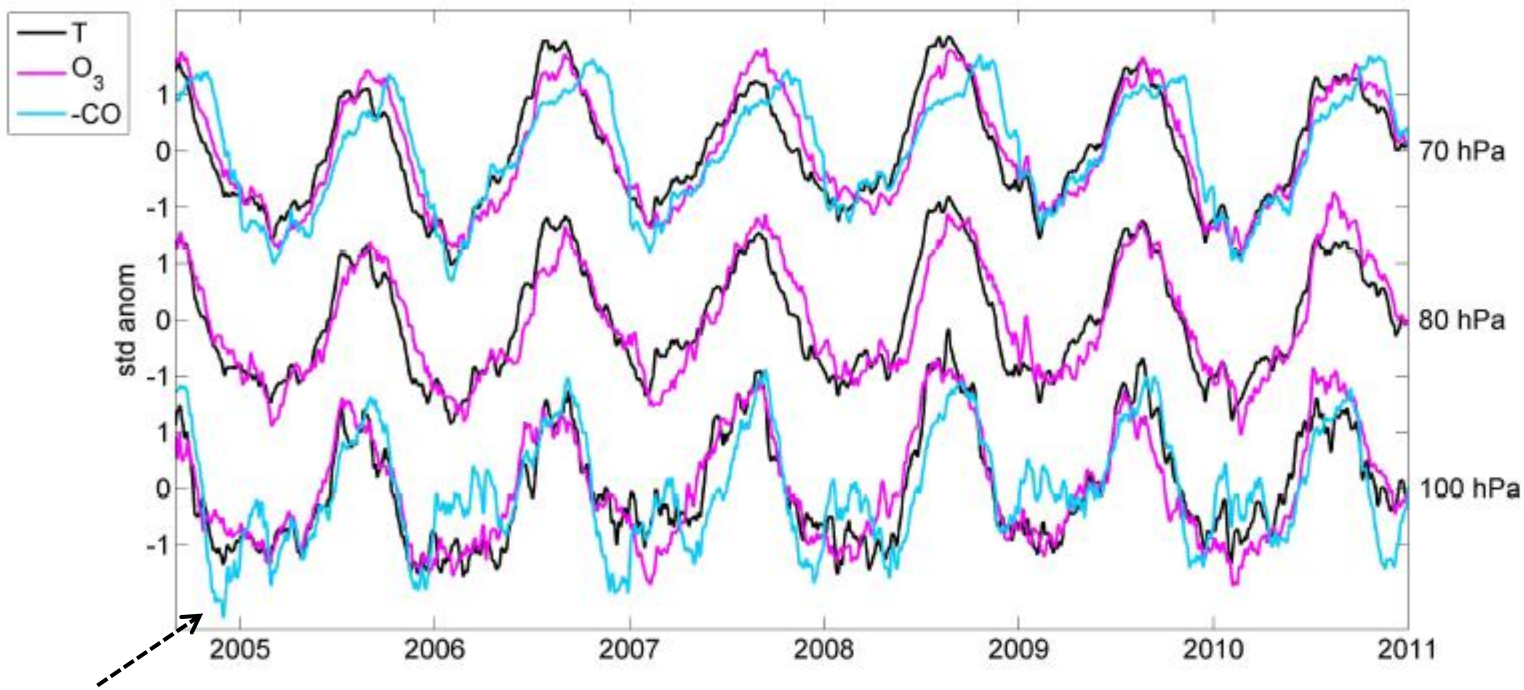


Annual cycle amplitude



Zonal mean temperature, ozone and CO averaged 18° N-S

Temps from ERAinterim, ozone and CO from MLS observations

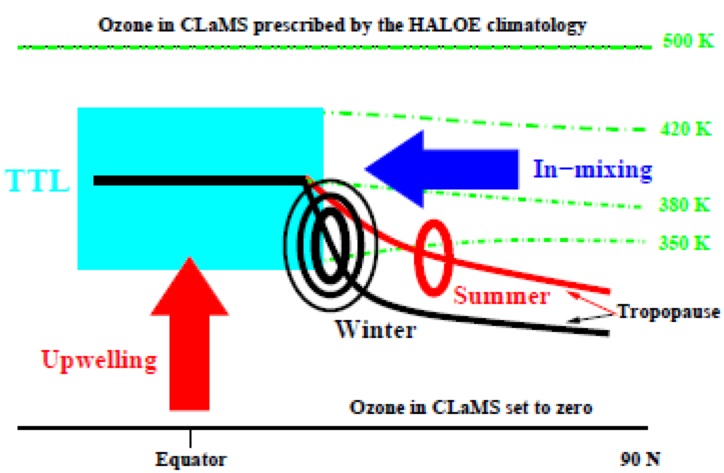


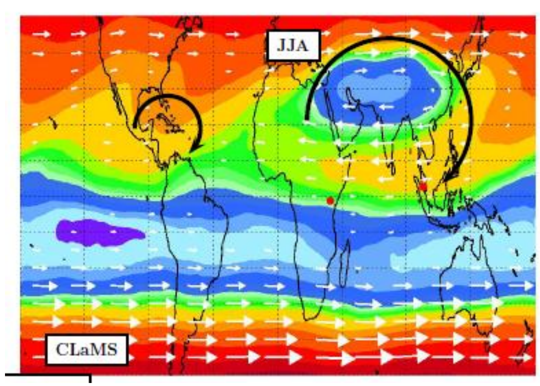
CO inverted scale

Complementary viewpoint: ozone annual cycle due to in-mixing

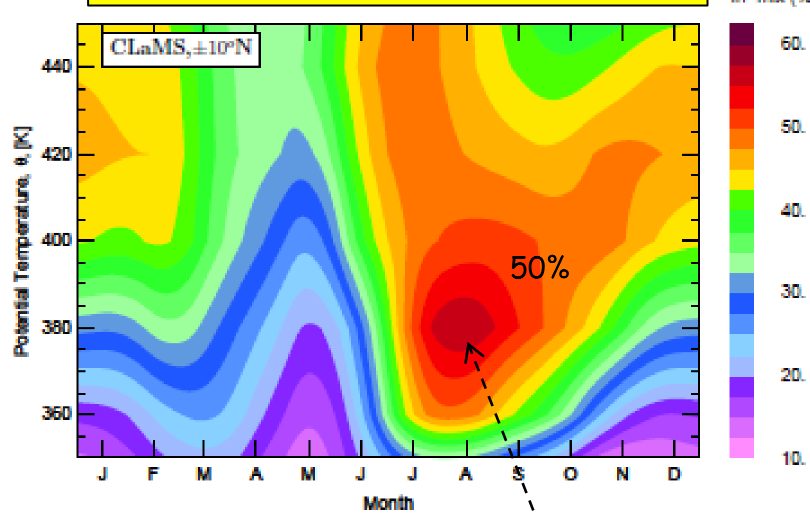
Isentropic calculations using CLaMS Lagrangian model

Konopka et al JGR 2009
Konopka et al ACP 2010
Ploeger et al JGR 2012





% tropical ozone due to in-mixing



summer ozone maximum
due to Asian monsoon transport

Key points:

- Large annual cycle in temperature and ozone in tropical lower stratosphere
- Also for other trace species with strong vertical gradients
- Forcing by upwelling is a simple explanation
- Possible importance of in-mixing linked to monsoon circulations

Variability in upwelling across the tropical tropopause and correlations with tracers in the lower stratosphere

M. Abalos[1], W. J. Randel[2], and E. Serrano[1]

ACP 2012

[1]Depto. de Geofísica y Meteorología, Universidad Complutense de Madrid, Madrid, Spain
[2]National Center for Atmospheric Research, Boulder, Colorado, USA

- Observational analysis of upwelling effect on tracers
- MLS observations of ozone, CO   2004-2011
- ERAinterim meteorology
- 3 estimates of upwelling: w^* (from reanalysis)
  w^*_Q (thermodynamic balance)
  w^*_m (momentum balance)

3 estimates of tropical upwelling w* from observations:

$$\overline{w}^* \equiv \overline{w} + \frac{1}{a\cos\phi}\frac{\partial}{\partial\phi}\left(\cos\phi\frac{\overline{v'T'}}{S}\right)$$

residual circulation from reanalysis w*

accurate radiative heating rate

$$\frac{\partial\overline{T}}{\partial t} = -\overline{v}^*\frac{1}{a}\frac{\partial\overline{T}}{\partial\phi} - \overline{w}^*S + \overline{Q} - \frac{1}{e^{-z/H}}\frac{\partial}{\partial z}\left[e^{-z/H}\left(\overline{v'T'}\frac{\partial\overline{T}/\partial\phi}{a\cdot S} + \overline{w'T'}\right)\right]$$

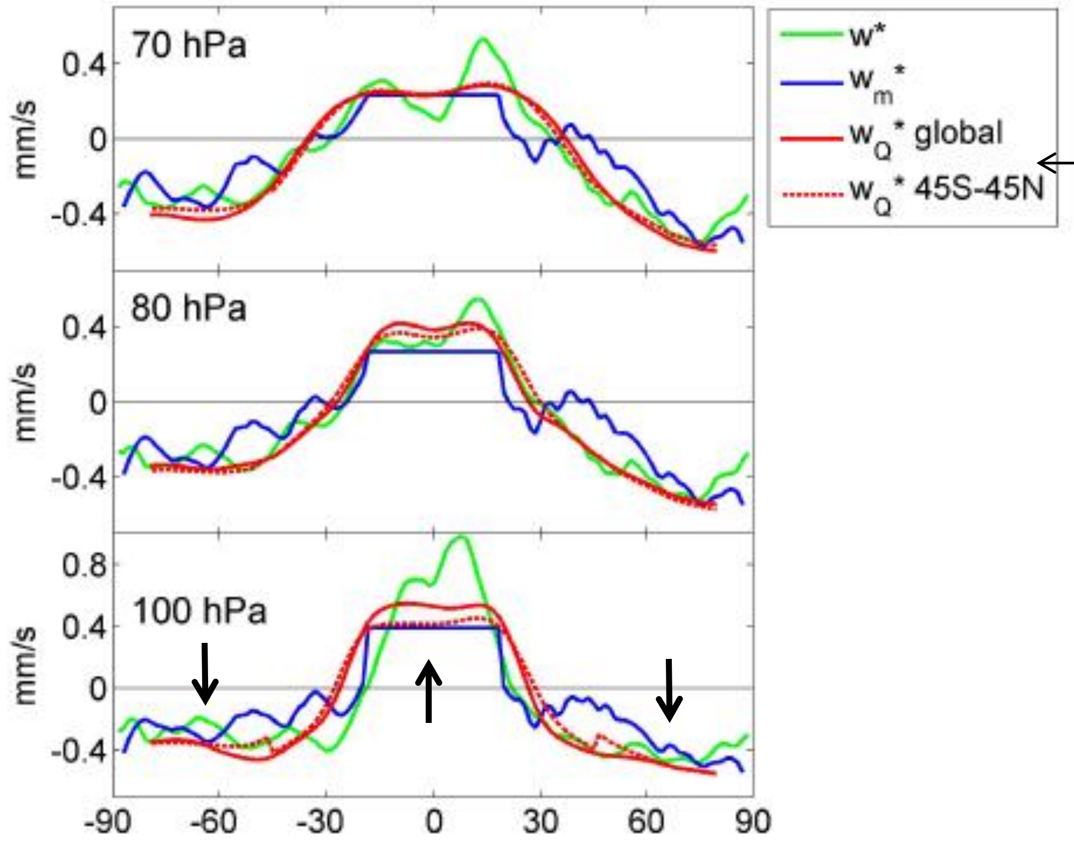
thermodynamic balance w_Q^*

$$\langle\overline{w}_m^*\rangle(z) = \frac{-e^{z/H}}{\int_{-\phi_0}^{\phi_0} a\cos\phi\, d\phi}\left\{\int_z^\infty \frac{e^{-z'/H}\cos\phi}{\hat{f}(\phi,z')}\left[DF(\phi,z') - \overline{u}_t(\phi,z')\right]_{\overline{m}} dz'\right\}_{-\phi_0}^{\phi_0}$$

momentum balance w_m^*

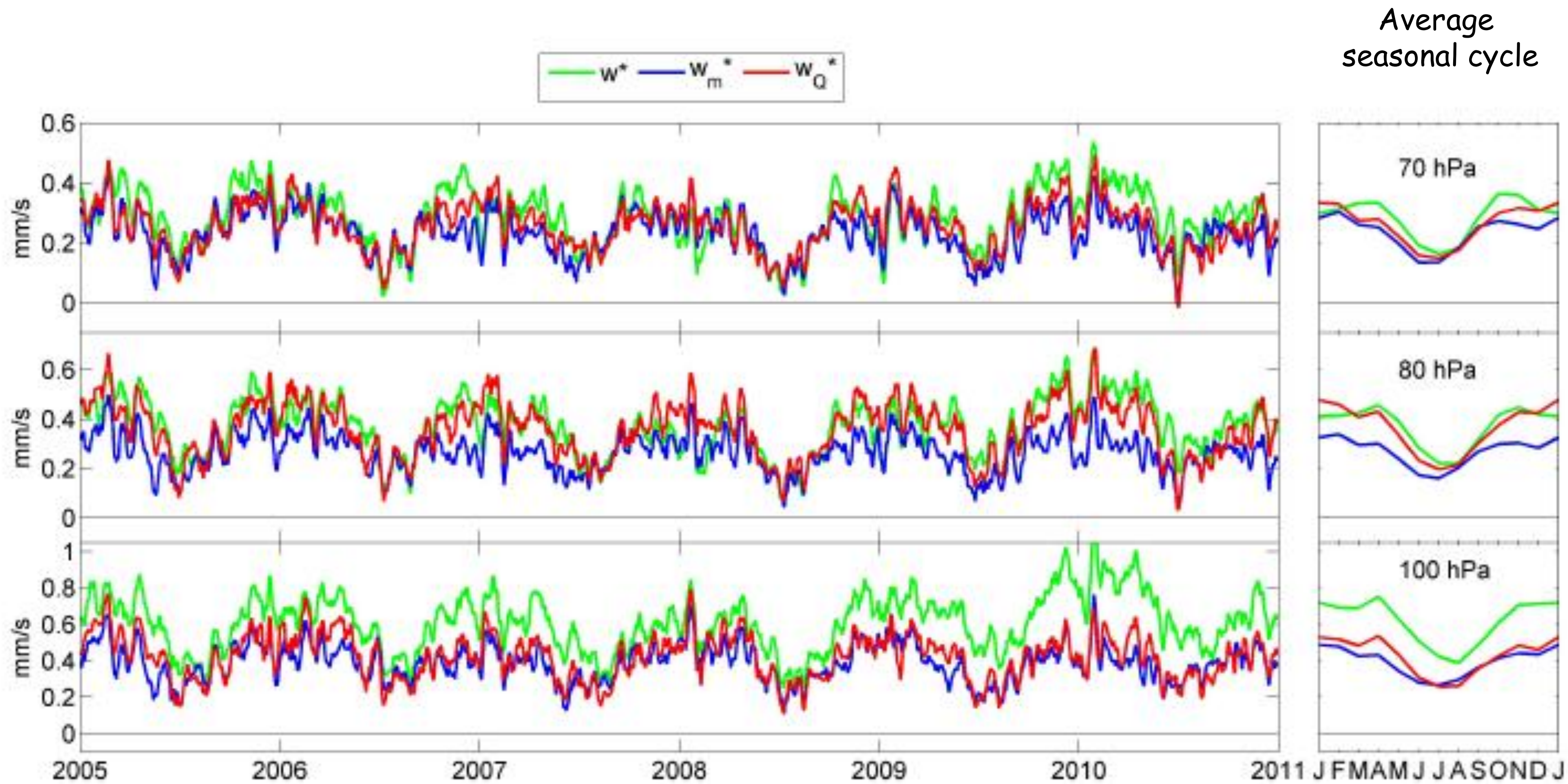
EP flux divergence

Latitude structure of upwelling from 3 estimates



different methods of adjustment

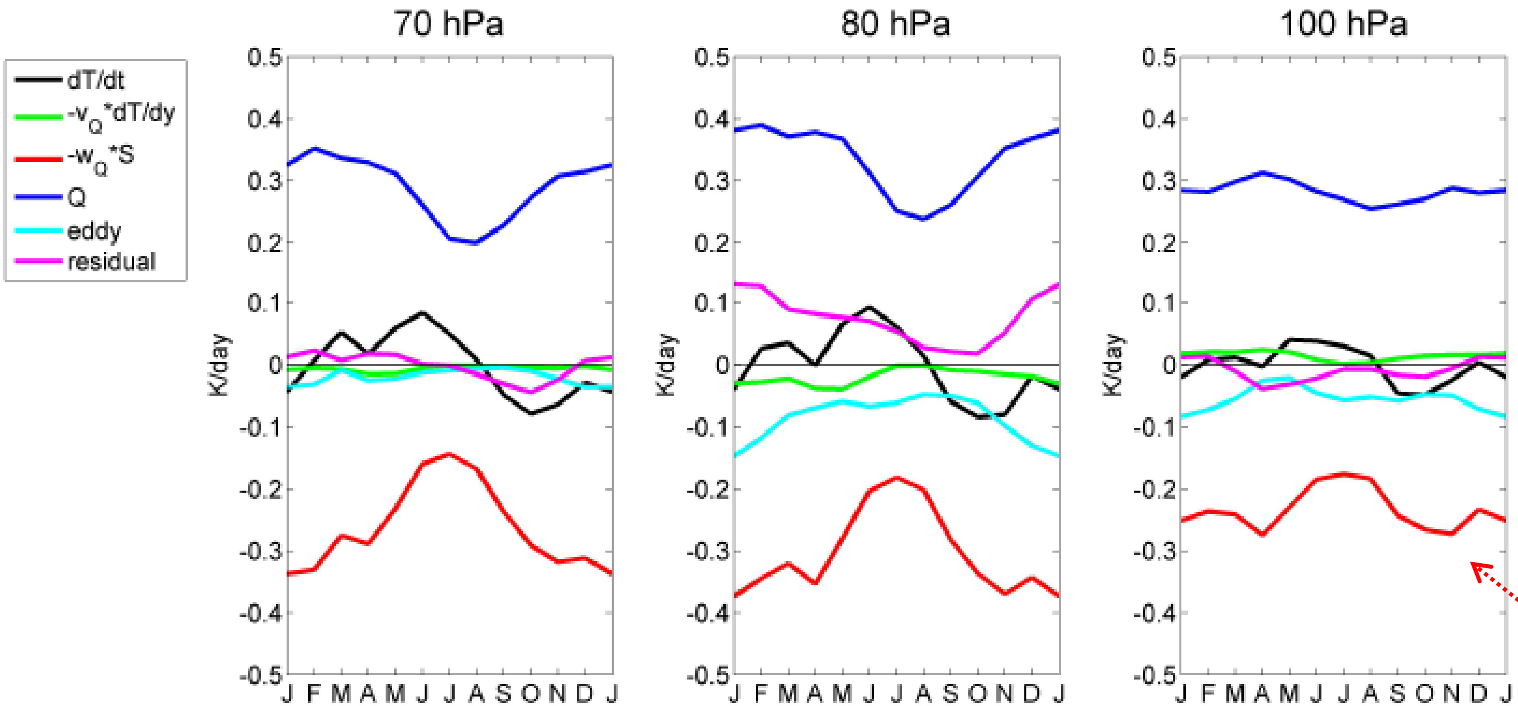
Daily variations in upwelling 18° N-S



Large annual cycles and significant sub-seasonal variability

Thermodynamic balance →

$$\frac{\partial \overline{T}}{\partial t} = -\overline{v}^* \frac{1}{a} \frac{\partial \overline{T}}{\partial \phi} - \overline{w}^* S + \overline{Q} \text{ + eddy term}$$



radiative heating

upwelling w_Q^*

annual cycle follows upwelling

Result: upwelling ~ radiative heating

Ozone budget

$$\frac{\partial \overline{\chi}}{\partial t} = -\overline{v}^* \frac{1}{a}\frac{\partial \overline{\chi}}{\partial \phi} - \overline{w}^* \frac{\partial \overline{\chi}}{\partial z} + \nabla \cdot M + P - L$$

eddy transport

mean advection

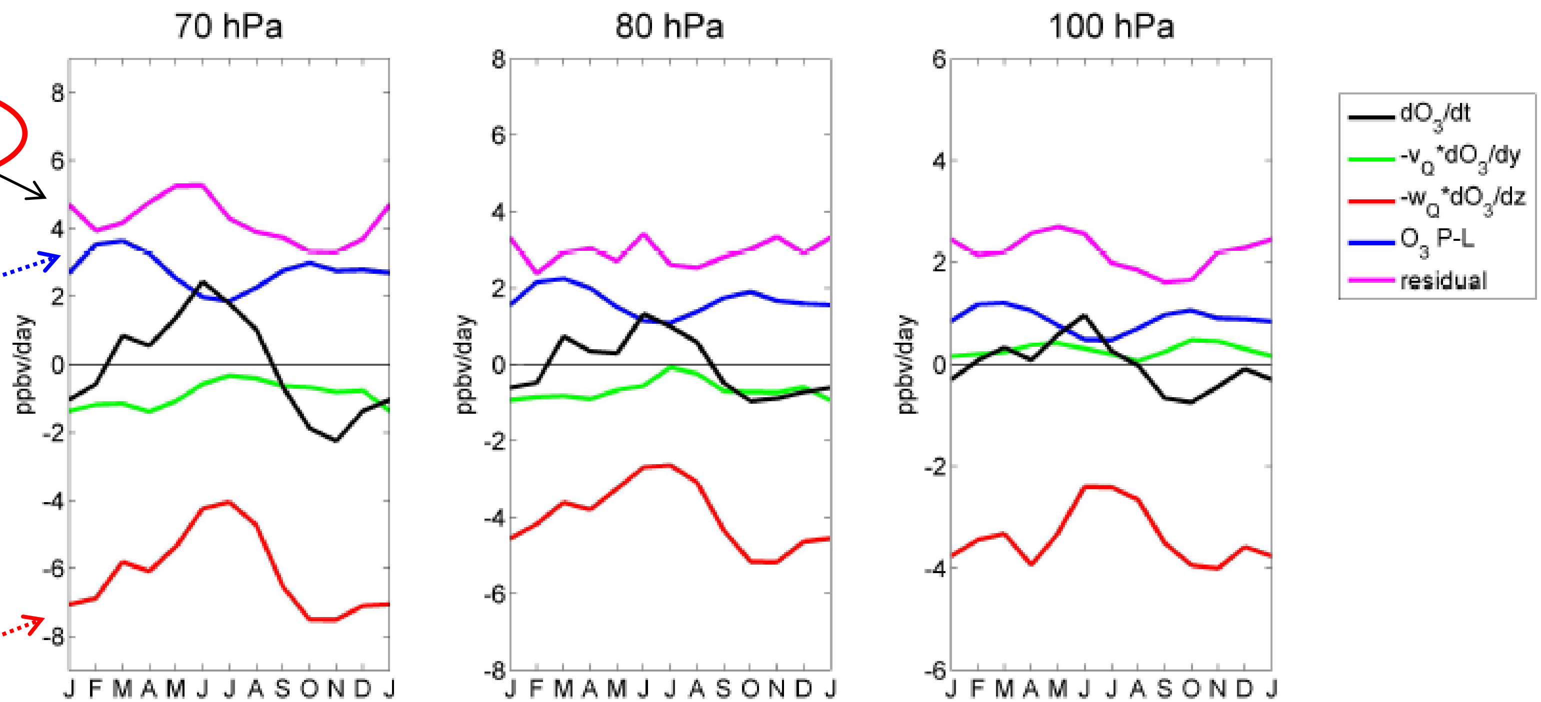
chemistry

Residual = unresolved eddy effects + imbalances from resolved terms

residual

P-L

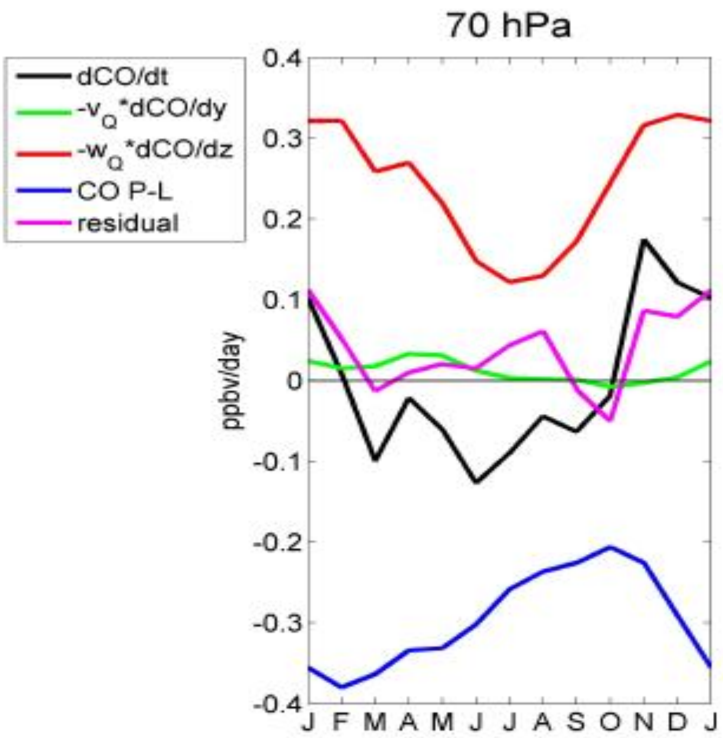
upwelling



annual cycle follows upwelling

Result: upwelling ~ photochemical production + residual (eddy effects?)

CO budget



upwelling

Annual cycle
follows upwelling

P-L

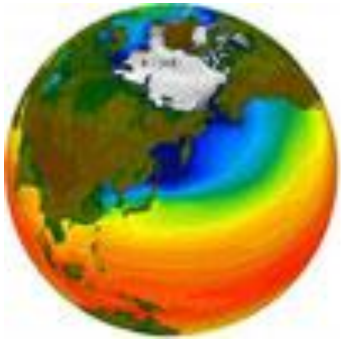
Result: upwelling ~ photochemical loss

Summary from budgets calculated from observations:

- Upwelling is the dominant forcing for temp, ozone and CO
- Relatively large residual for ozone budget; are these due to unresolved eddy effects?

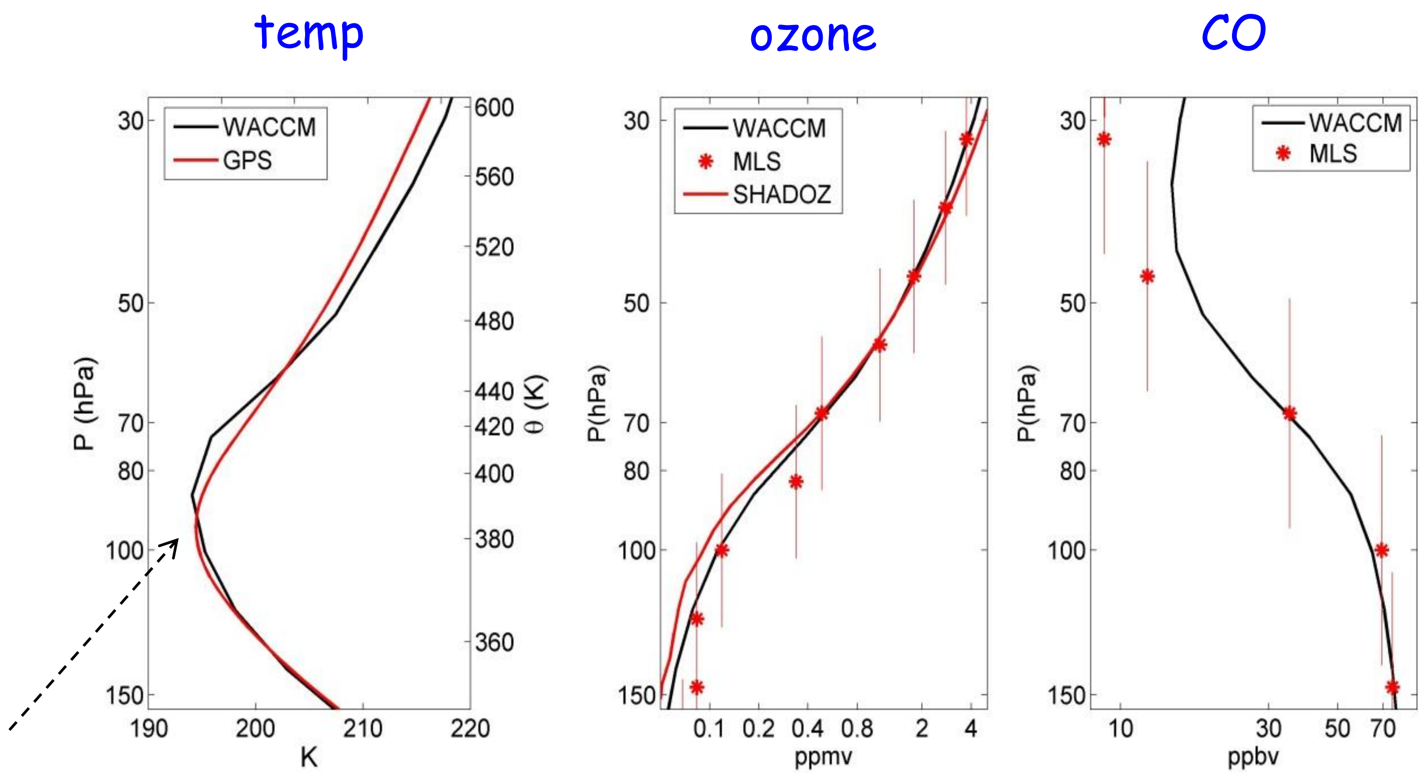
What are the detailed balances in a free-running climate model (WACCM) ?

- Archive and analyze daily output of a standard WACCM simulation



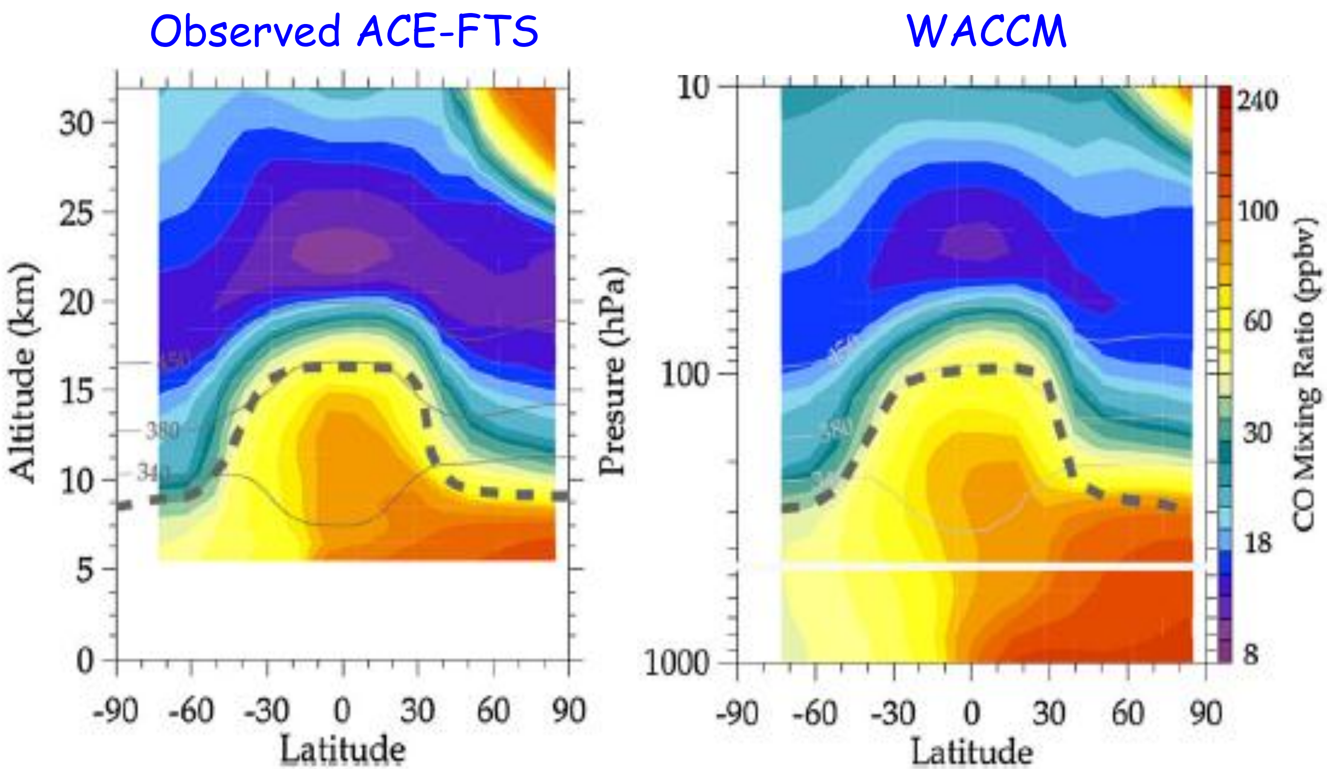
Abalos et al, 2013, ACP

How realistic is the near-tropopause structure in WACCM?



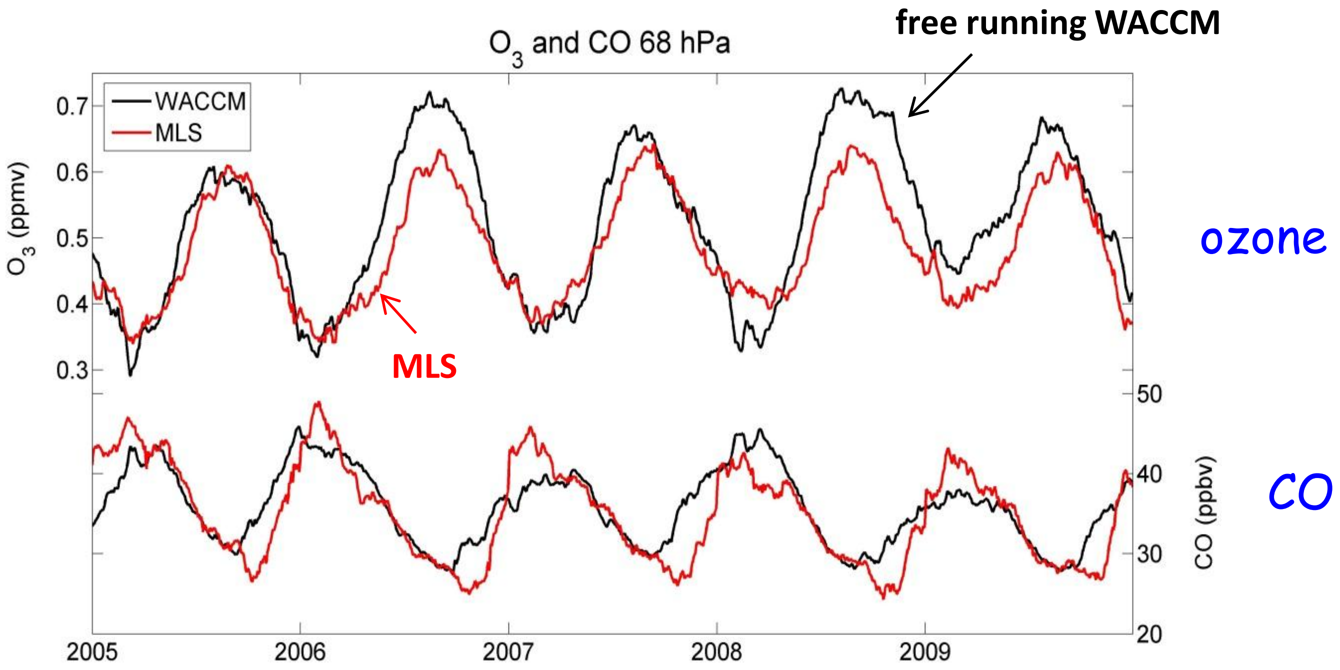
tropopause is slightly higher in WACCM

Accurate simulation of CO in WACCM



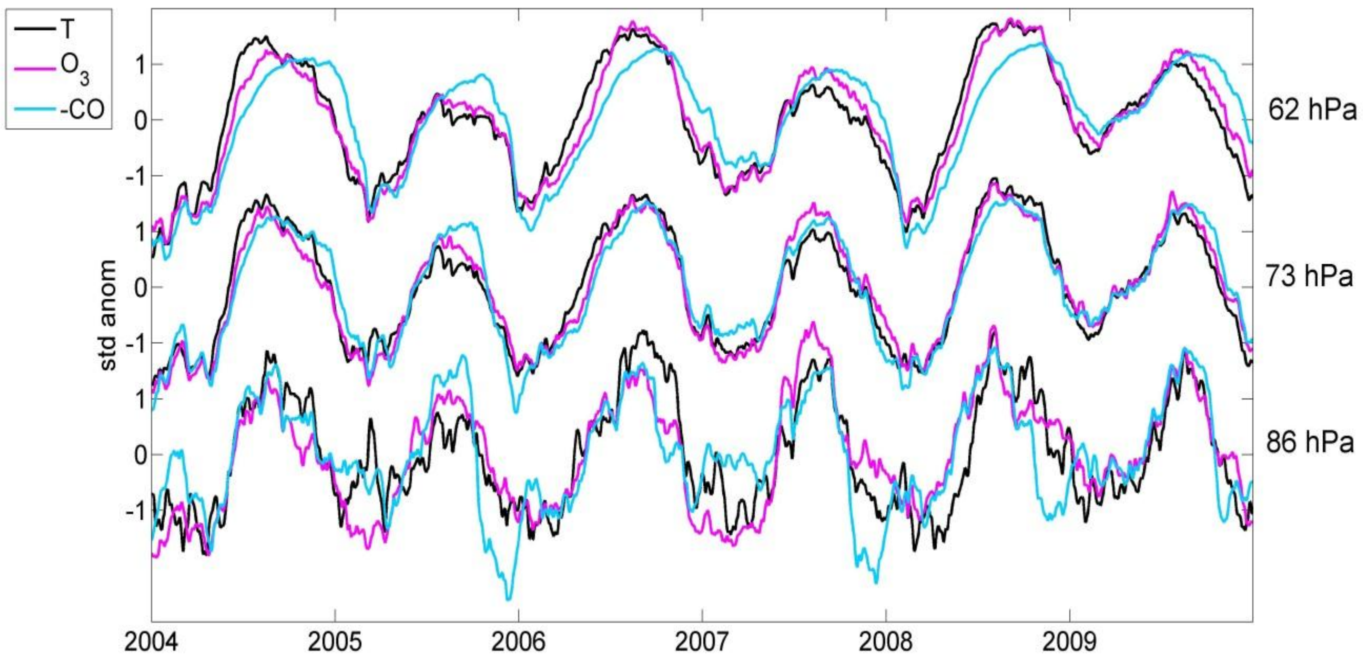
Park et al, JGR 2013

Tropical seasonal variations at 68 hPa (19 km)



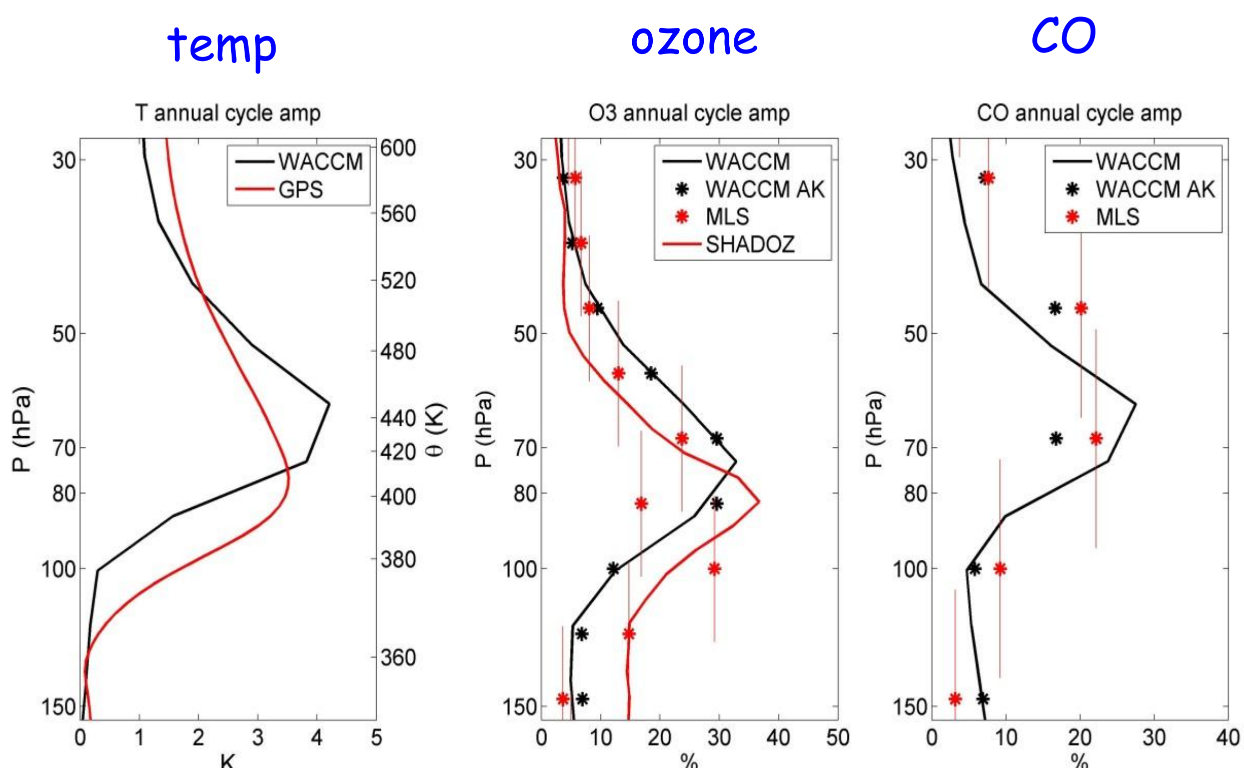
Coherent WACCM variations of T, ozone and CO

* similar to observations *



CO inverted scale

Amplitude of annual cycle

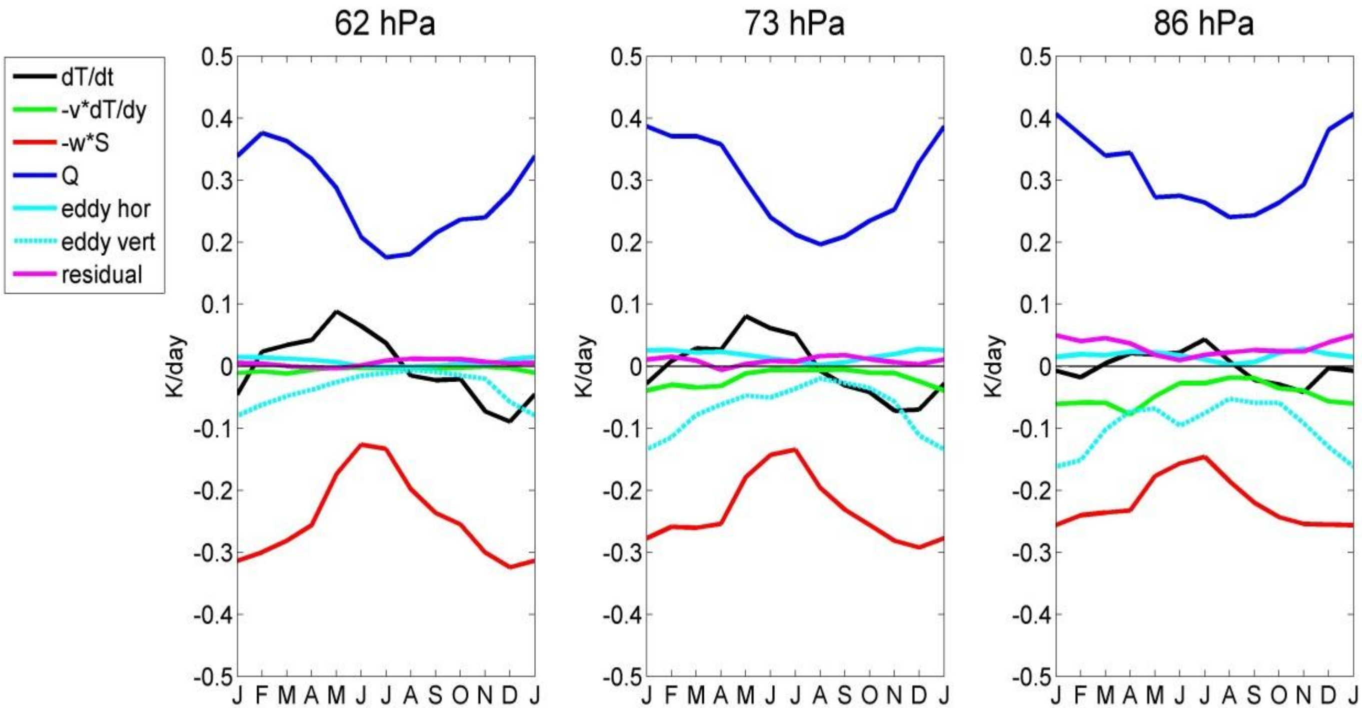


Realistic amplitudes,
but slightly higher
altitude in WACCM

WACCM thermodynamic balance:

$$\bar{T}_t = -\bar{v}^*\bar{T}_y - \bar{w}^* S + \bar{Q} \;- e^{z/H}\left[e^{-z/H}\left(\overline{v'T'}\frac{\bar{T}_y}{S} + \overline{w'T'}\right)\right]_z .$$

eddy fluxes are typically small



radiative heating

eddy term w'T'

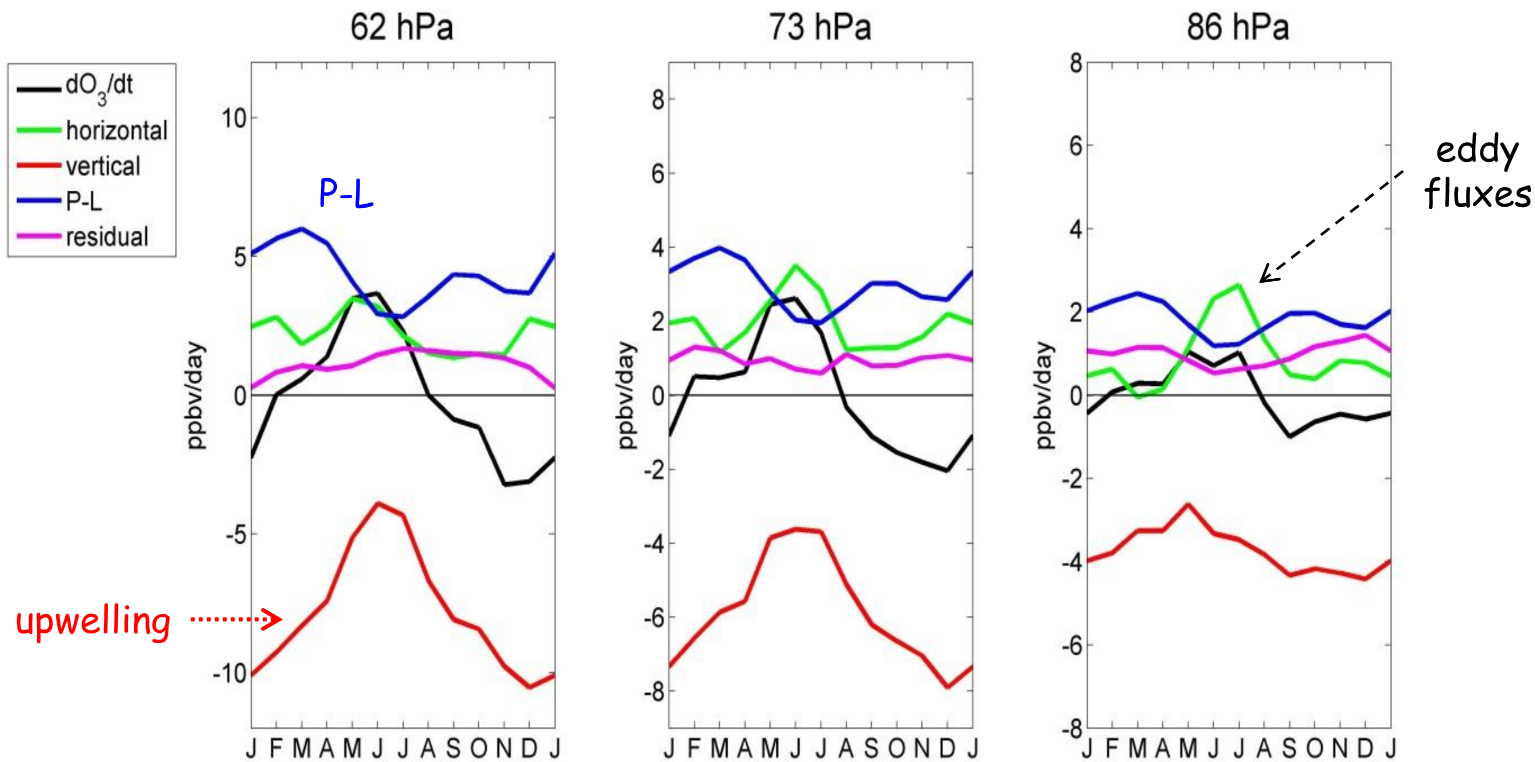
upwelling

Note very small residuals (not always easy with model results)

WACCM ozone budget:

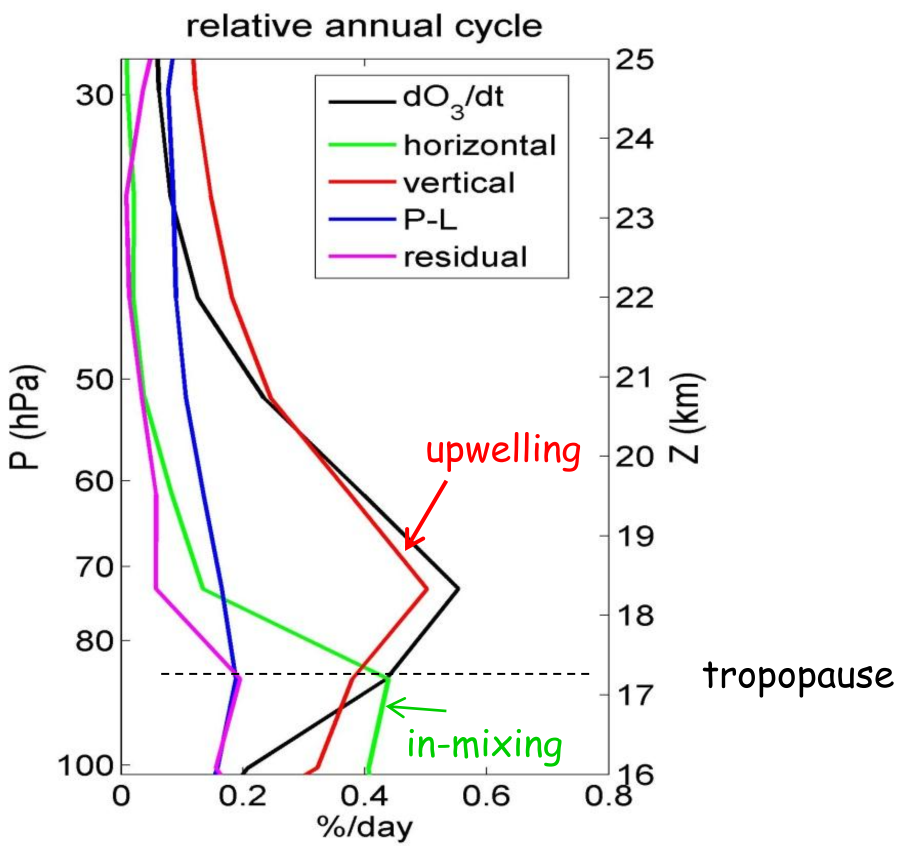
$$\frac{\partial \overline{\chi}}{\partial t} = -\overline{v}^* \frac{1}{a} \frac{\partial \overline{\chi}}{\partial \phi} - \overline{w}^* \frac{\partial \overline{\chi}}{\partial z} + \nabla \cdot M + P - L$$

eddy fluxes



Note: explicitly resolved eddy fluxes are similar to observational 'residuals'

Contribution of terms to forcing ozone annual cycle



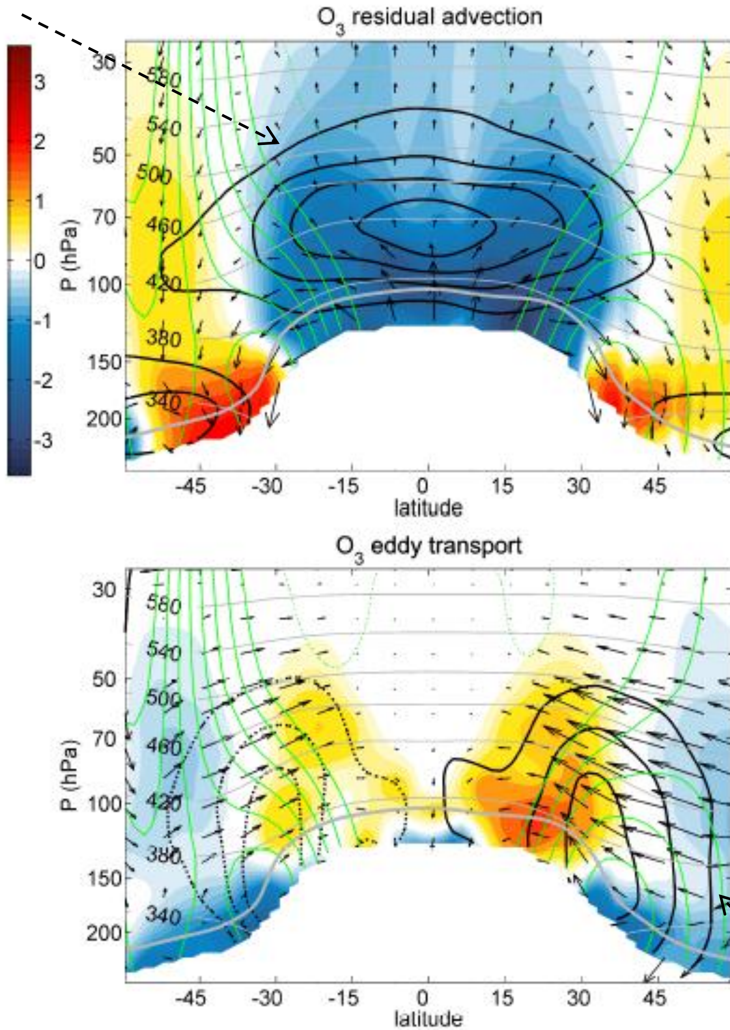
- upwelling is dominant in lower stratosphere
- in-mixing is relatively large near and below tropopause

WACCM ozone budget

$$\frac{\partial \overline{\chi}}{\partial t} = -\overline{v}^* \frac{1}{a}\frac{\partial \overline{\chi}}{\partial \phi} - \overline{w}^* \frac{\partial \overline{\chi}}{\partial z} + \nabla \cdot M + P - L$$

vertical ozone gradient

ozone tendency in % per day



mean advection

$$M_y = -e^{-z/H}\left(\overline{v'\chi'} - \frac{\overline{v'T'}}{S}\bar{\chi}_z\right)$$
$$M_z = -e^{-z/H}\left(\overline{w'\chi'} + \frac{\overline{v'T'}}{S}\bar{\chi}_y\right)$$

eddy transport

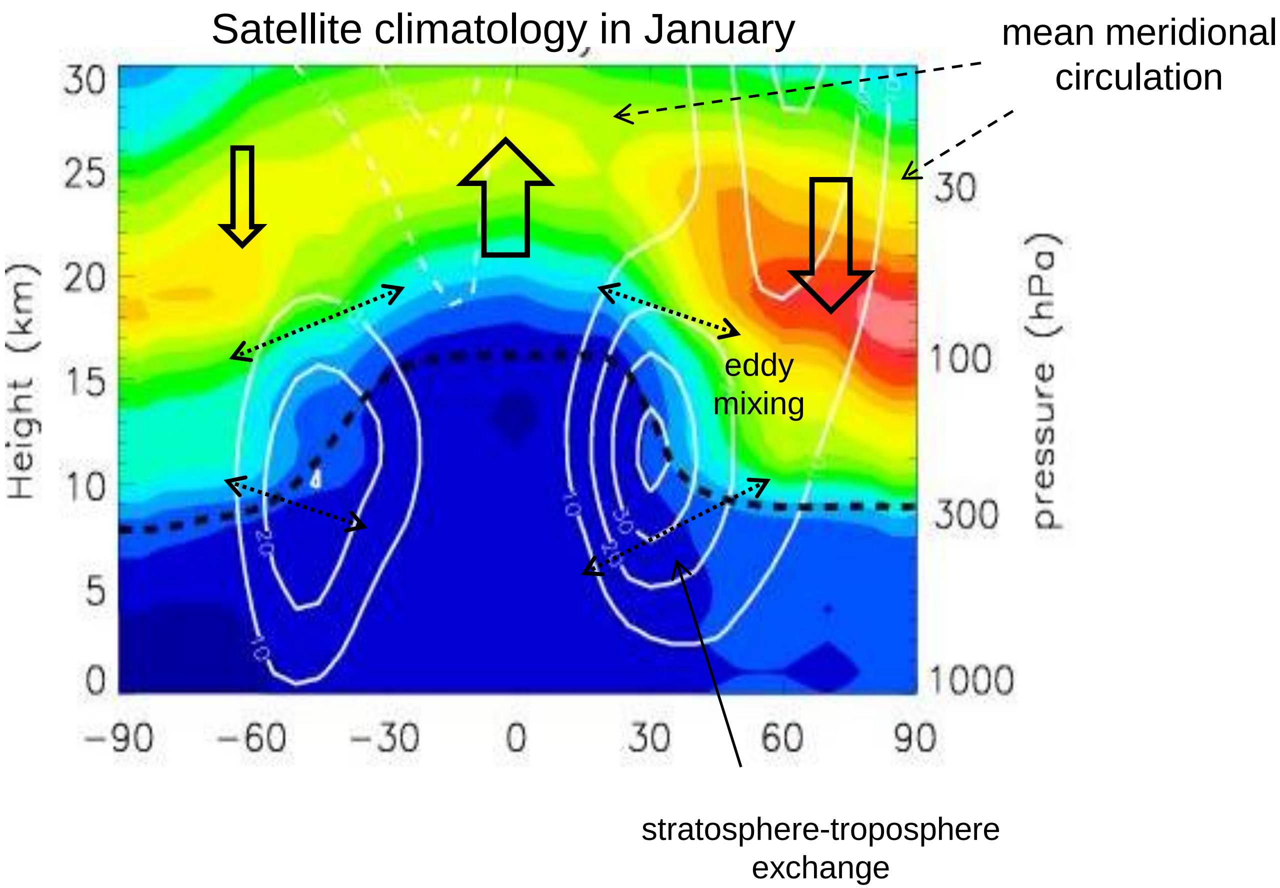
eddy ozone transport from midlatitudes into tropics (downgradient)

latitudinal ozone gradient

Ozone

- Formed in stratosphere (stratospheric source gas)
- Strong gradients across tropopause

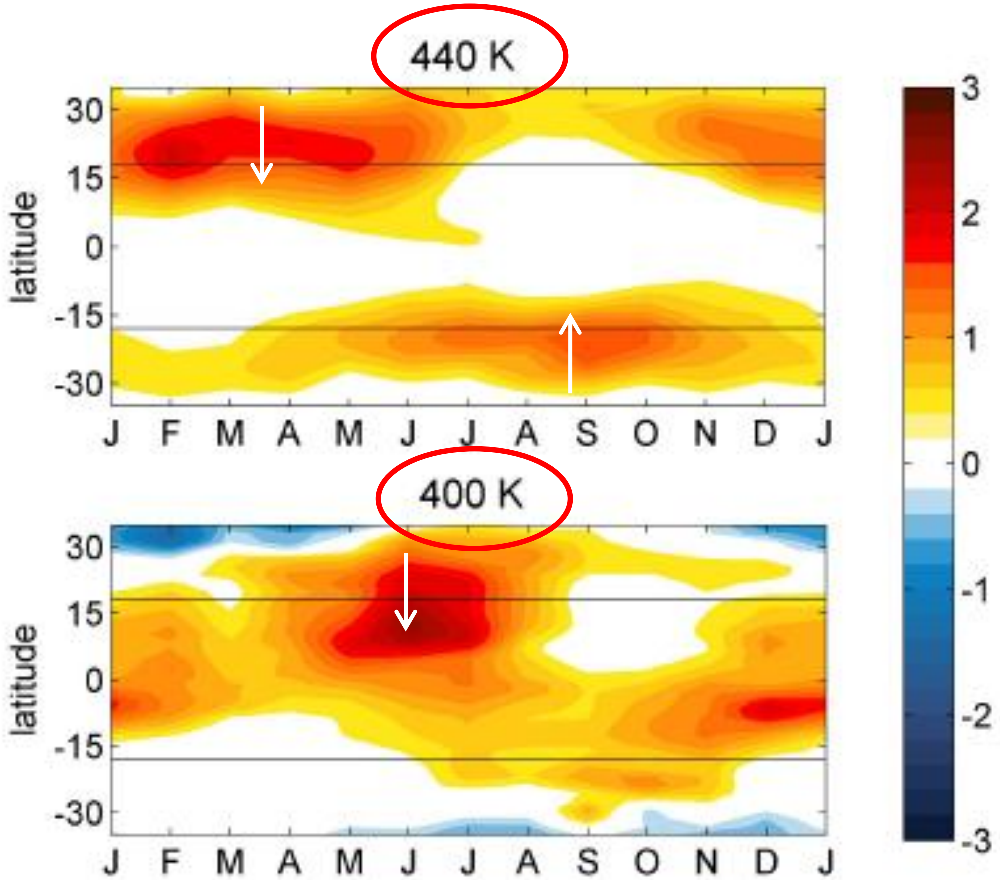
Ozone column density, DU/km



WACCM eddy flux tendencies d/dy ($v'O_3'$)

Winter-spring maximum in both hemispheres

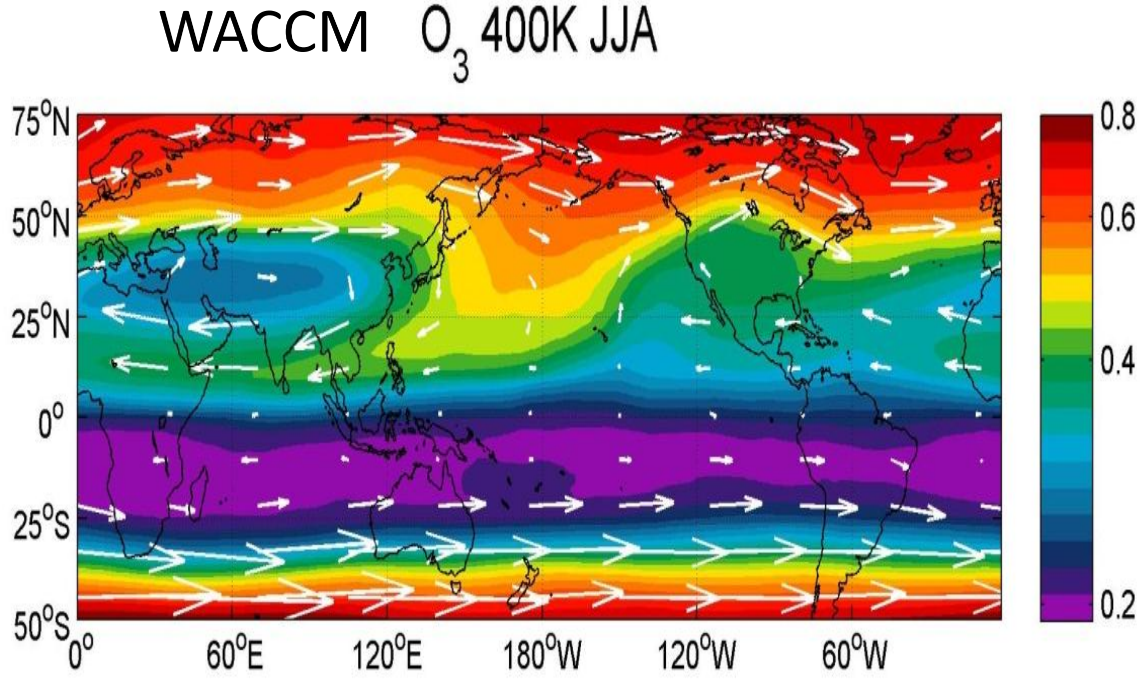
summer maximum



lower stratosphere

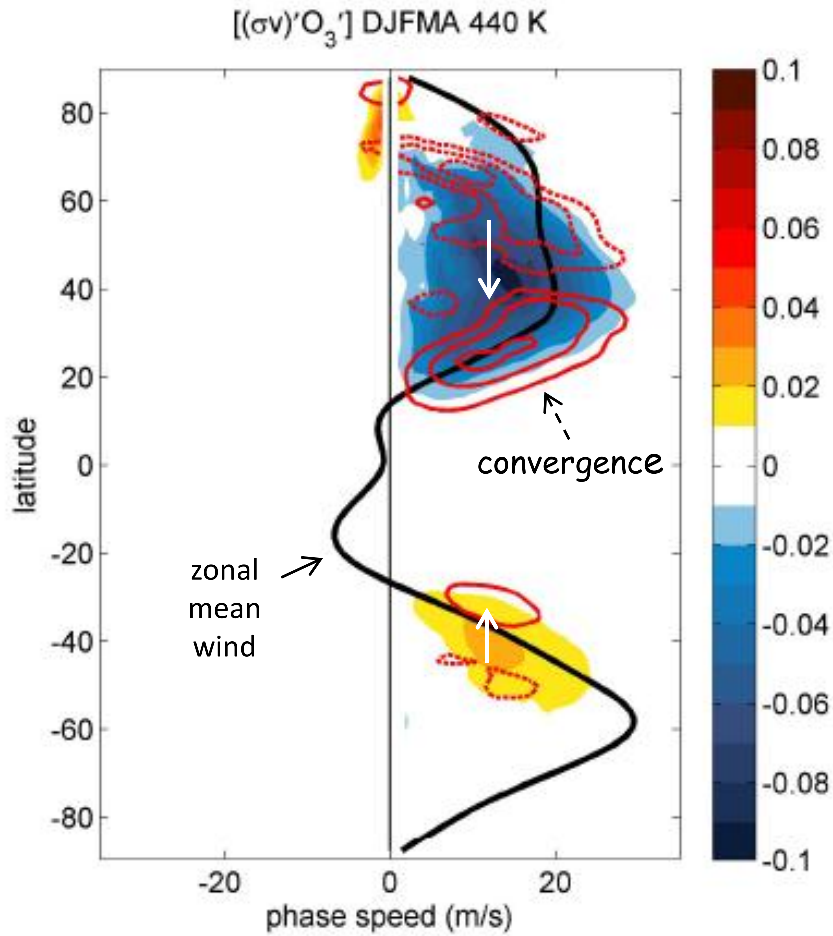
near tropopause

NH summer eddy transport from Asian monsoon anticyclone



Phase-speed vs. latitude spectra for eddy fluxes ($v'O_3'$)

NH winter
eddy ozone
transport
at 440 K



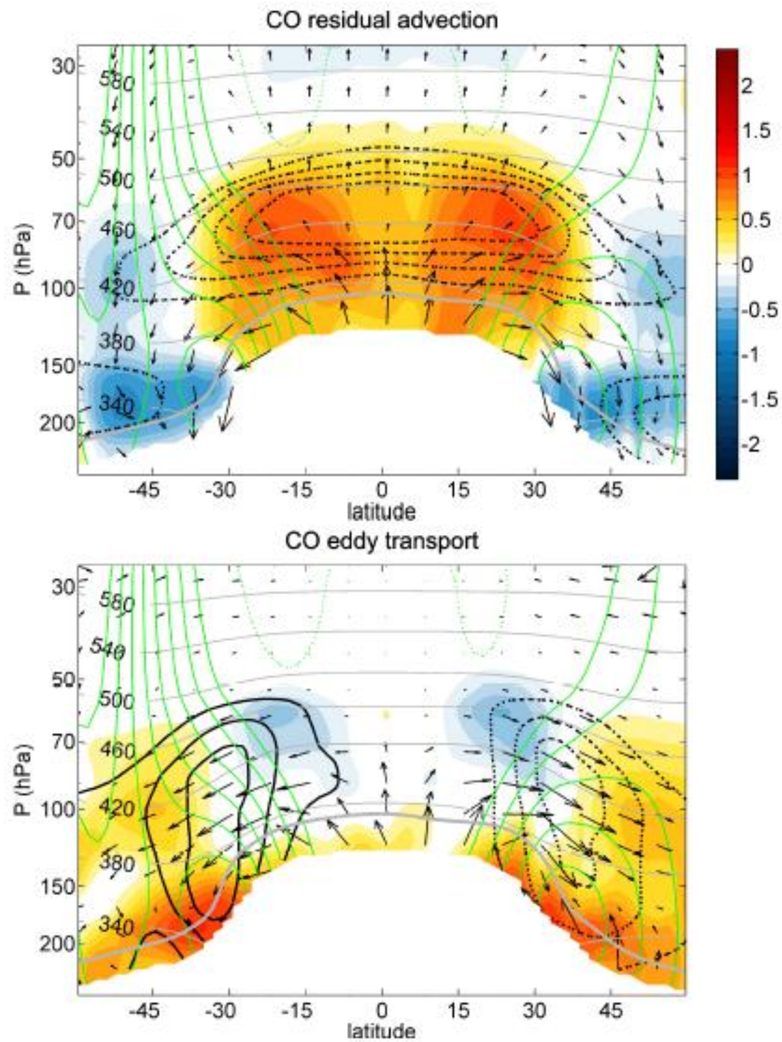
following
Randel and Held 1991

- eddy fluxes into the tropics due to transient Rossby waves
- Eddy fluxes 'see' critical lines ! (u=c)

WACCM CO budget

$$\frac{\partial \overline{\chi}}{\partial t} = -\overline{v}^* \frac{1}{a}\frac{\partial \overline{\chi}}{\partial \phi} - \overline{w}^* \frac{\partial \overline{\chi}}{\partial z} + \nabla \cdot M + P - L$$

CO tendency in % per day



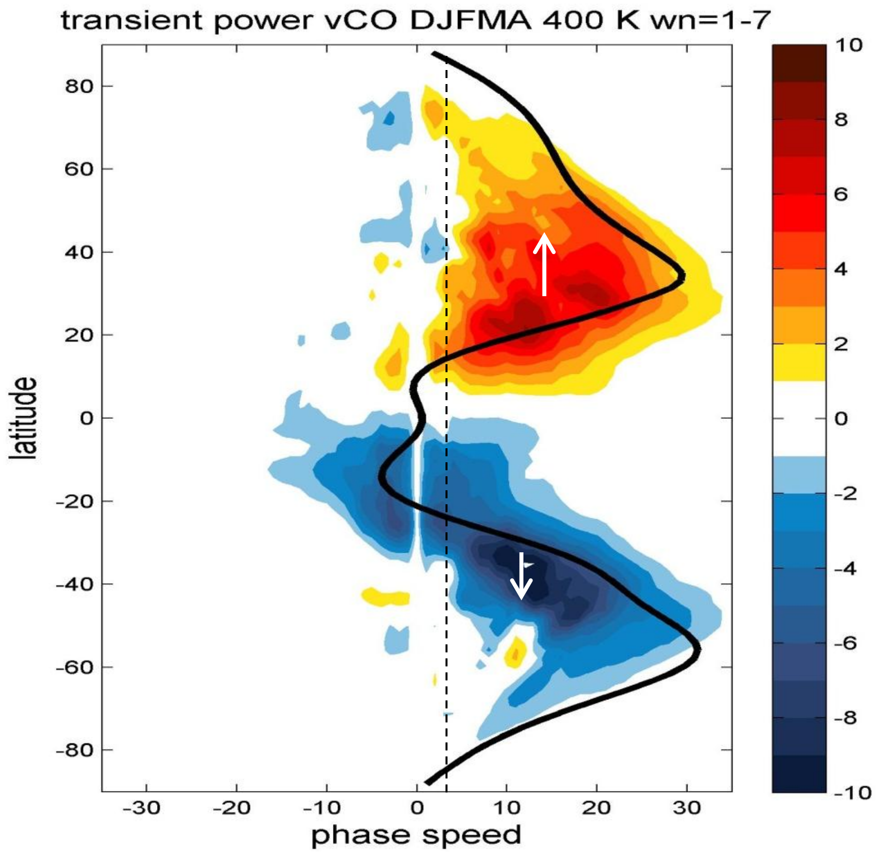
mean advection

eddy transport

relatively small contribution in the tropics for CO

CO eddy fluxes at 400 K   (v'CO')

NH winter
eddy CO
transport
at 400 K



- eddy fluxes out of the tropics
- Eddy fluxes 'see' critical lines !
  (u=c)

Key points:

- WACCM results for temp, ozone and CO are very similar to observations
- Upwelling is a dominant term in all balances, and primarily responsible for the coupled seasonal variations in T, ozone and CO in the tropical lower stratosphere
- Eddy transport into the tropics is important for ozone

  * summertime maximum near tropopause (Asian monsoon)
  * transient Rossby waves in winter lower stratosphere
  * evidence for critical-layer behavior in phase-speed spectra

What drives the annual cycle in tropical upwelling?

- Extratropical stratospheric planetary waves

  Yulaeva et al, 1994, Ueyama and Wallace 2010, Ueyama et al 2013

- Equatorial waves

  Kerr-Munslow and Norton, 2006, Ortland and Alexander, 2013

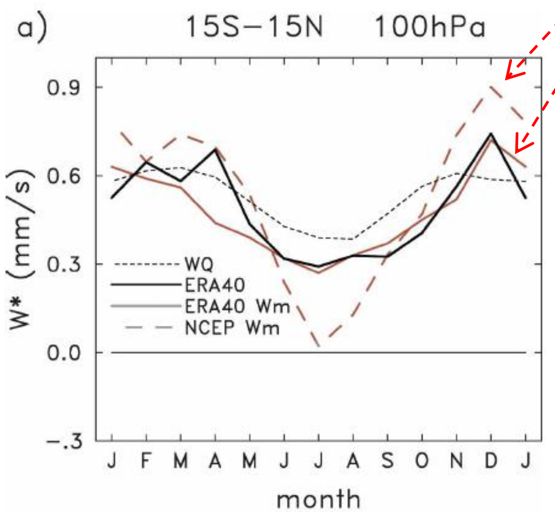
- Subtropics (baroclinic eddies from midlatitudes)

  Randel et al 2008, Taguchi 2009, Chen and Sun 2011,
  Jucker et al 2013, others

Evaluating upwelling from subtropical EP fluxes

upwelling

w^*_m evaluated from subtropical EP fluxes

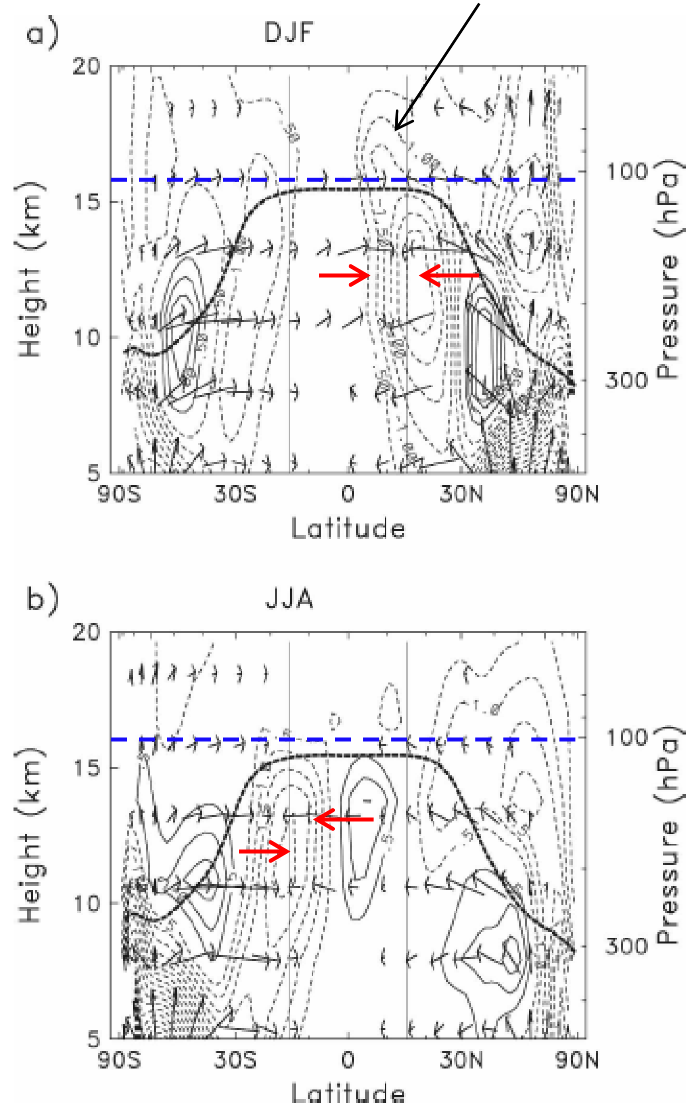


Randel, Garcia and Wu, 2008

both extratropical and tropical waves contribute to subtropical forcing

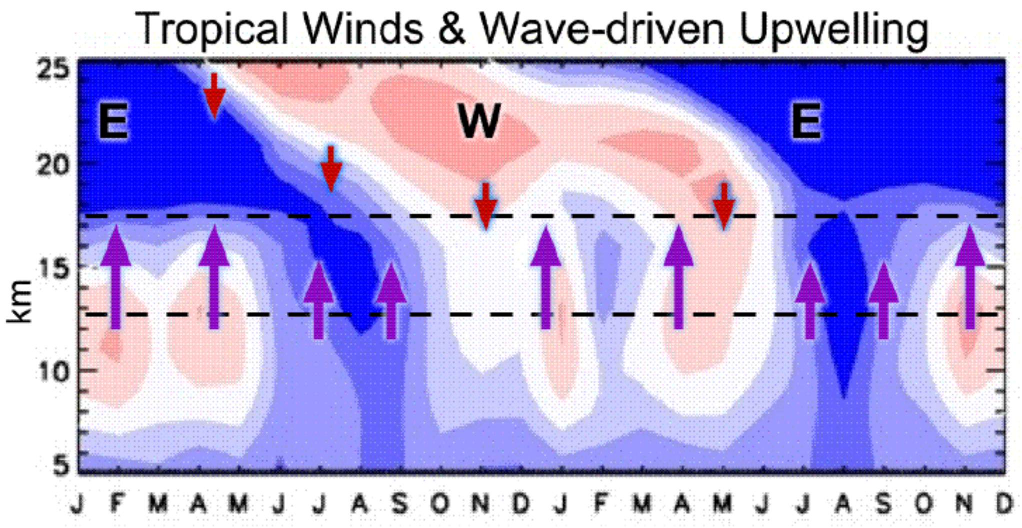
Seasonal mean EP fluxes

wave forcing extends deeper during DJF



Ortland and Alexander, JAS 2014:

Equatorial waves respond to variations in background tropical zonal winds, driving stronger tropical upwelling for westerlies (boreal winter)

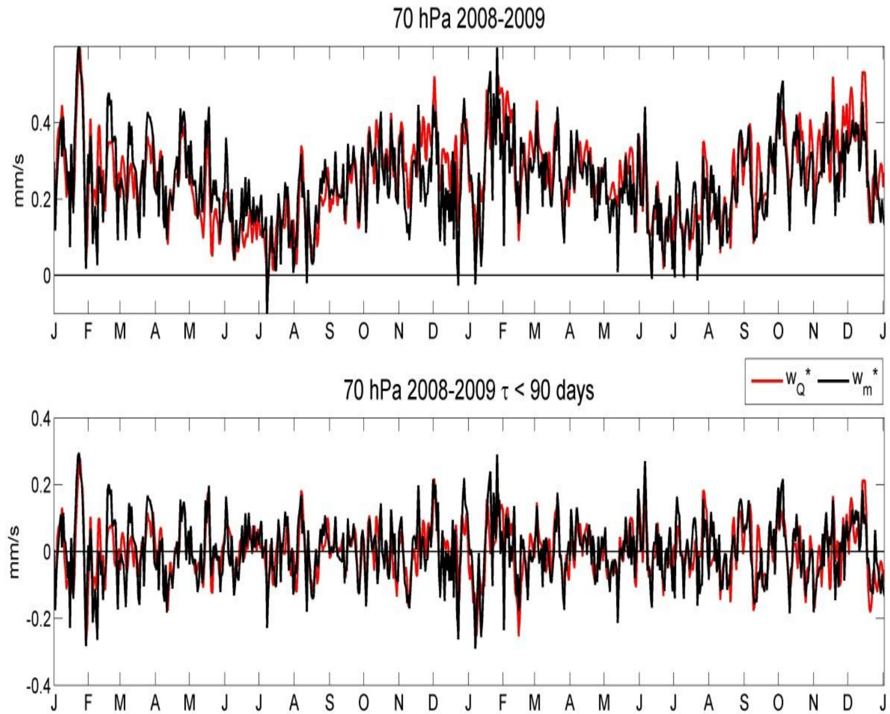


alternative: tropics driven completely by extratropics (e.g. Jucker et al, 2013)

This is still an active topic of research

Dynamics of sub-seasonal variability

$$\langle \overline{w}_m^* \rangle(z) = \frac{-e^{z/H}}{\int_{-\phi_0}^{\phi_0} a\cos\phi\, d\phi} \left\{ \int_z^{\infty} \frac{e^{-z'/H}\cos\phi}{\hat{f}(\phi,z')} \left[DF(\phi,z') - \overline{u}_t(\phi,z') \right]_{\overline{m}} dz' \right\}_{-\phi_0}^{\phi_0}$$



w^*_m and w^*_Q

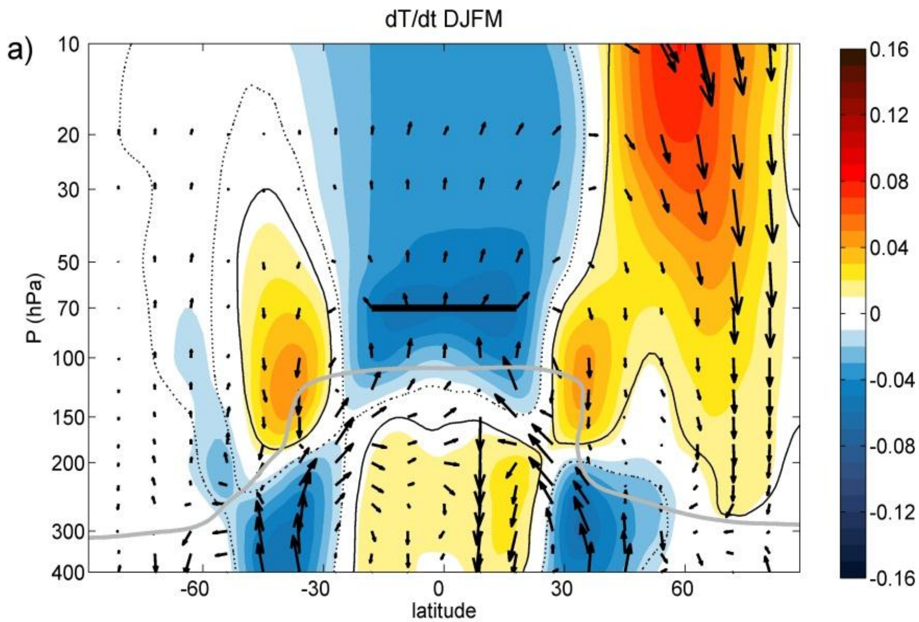
remove annual cycle

use regressions onto w^*_m to identify circulation and dynamical forcing of transient upwelling

ERAi reanalysis 1979-2011

Regressions onto w^*_m : residual circulation and dT/dt

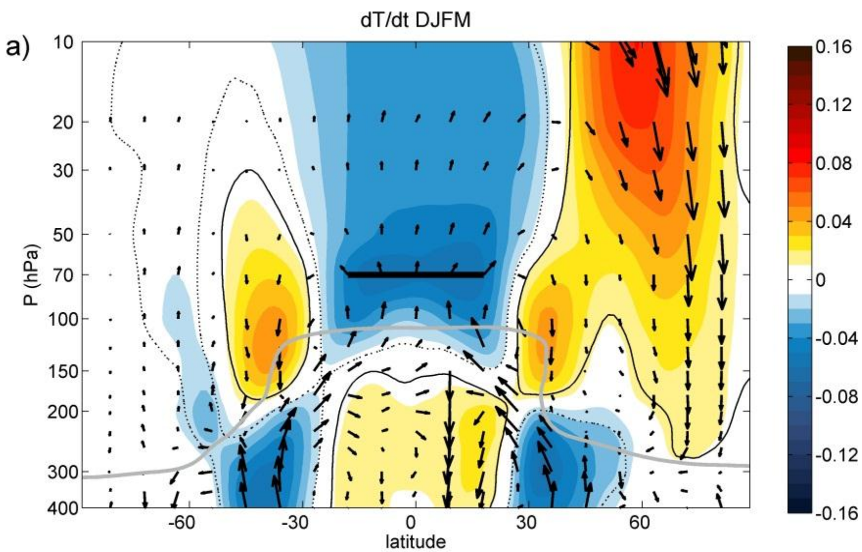
Boreal winter
DJFM



K/day

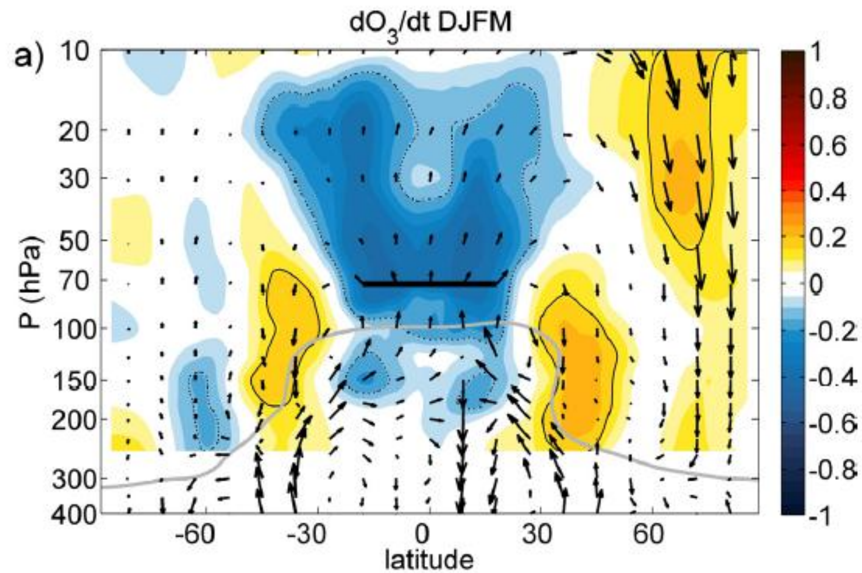
Coherent signals in ozone tendencies

dT/dt



K/day

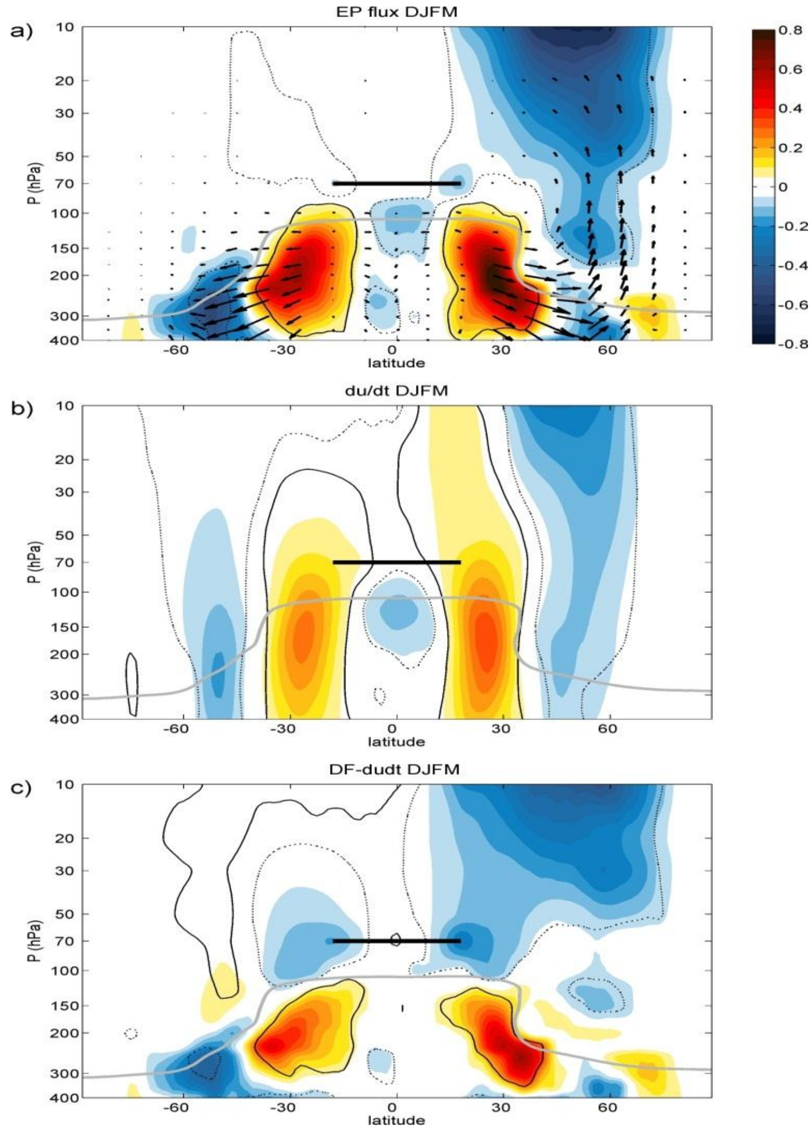
MLS ozone dO_3/dt



ppbv/day

Regressions onto w^*_m

$$\langle \overline{w^*_m}\rangle(z) = \frac{-e^{z/H}}{\int_{-\phi_0}^{\phi_0} a\cos\phi\, d\phi}\left\{\int_z^\infty \frac{e^{-z'/H}\cos\phi}{\hat{f}(\phi,z')}\left[DF(\phi,z') - \overline{u}_t(\phi,z')\right]_{\overline{m}}\,dz'\right\}_{-\phi_0}^{\phi_0}$$



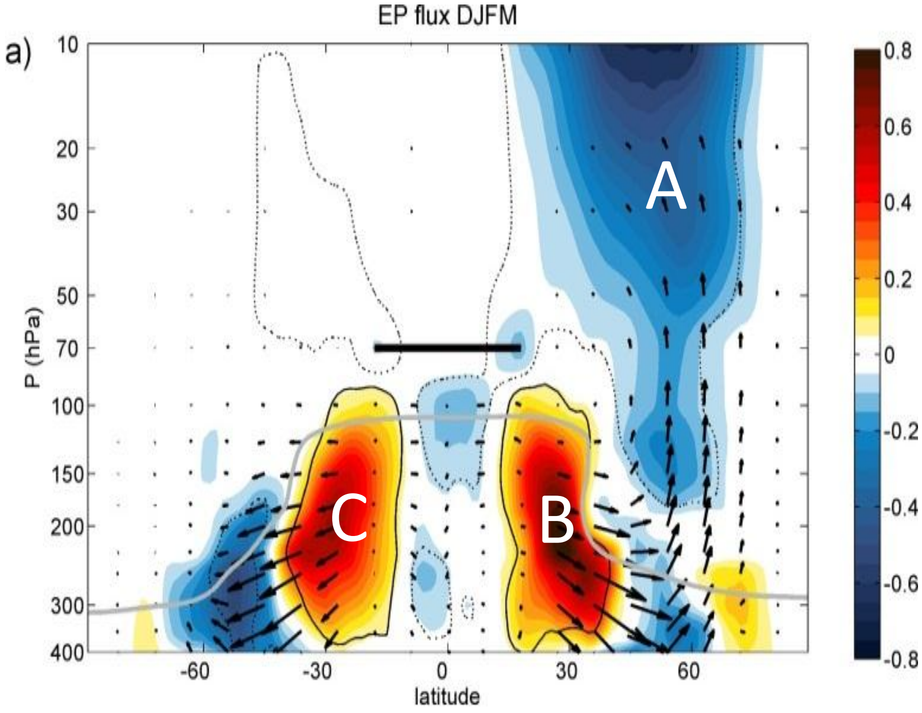
DF

both terms are important

du/dt

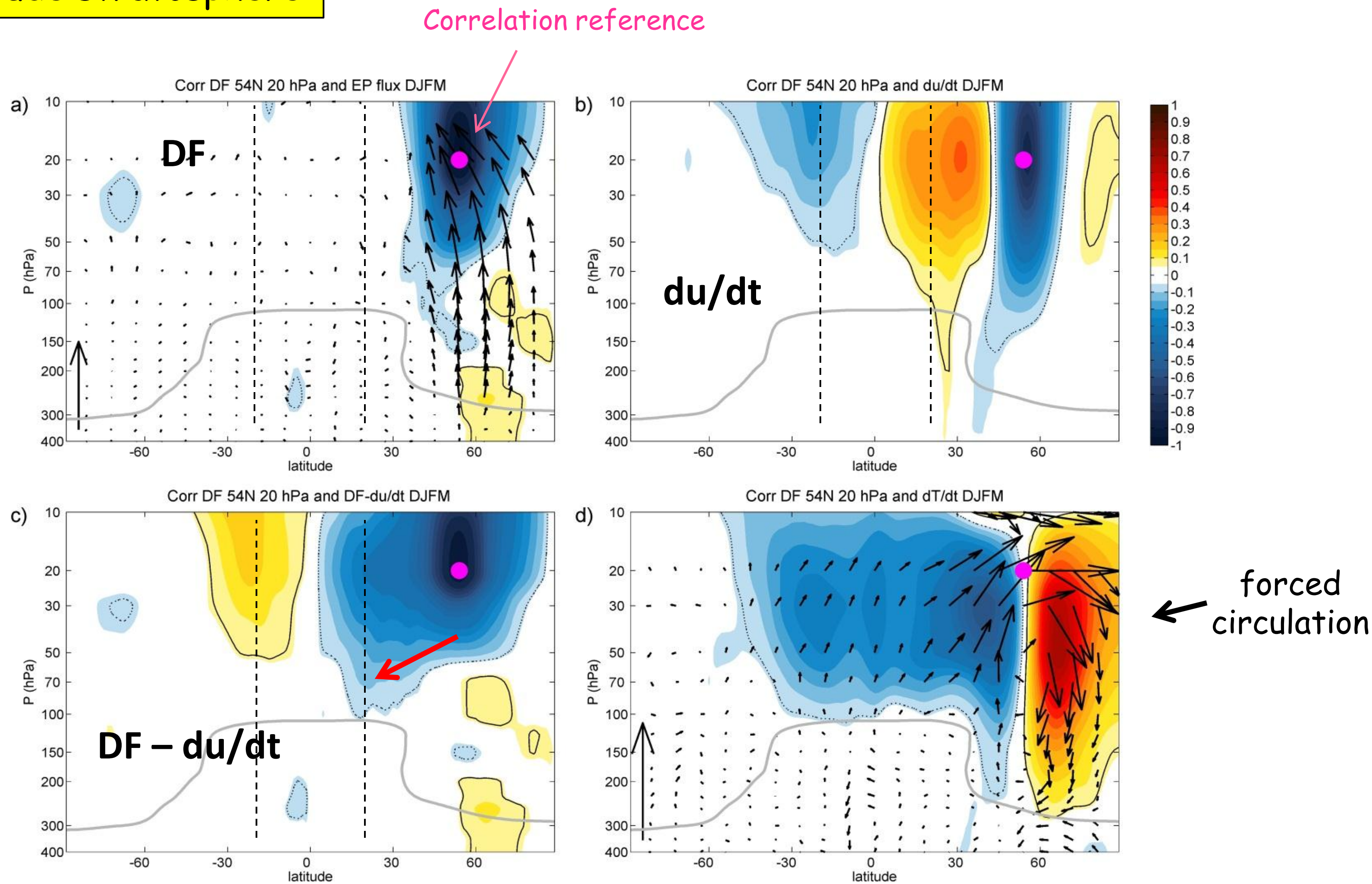
DF – du/dt

EP flux 'centers of action' for forcing transient tropical upwelling:



How does remote forcing influence tropical upwelling?

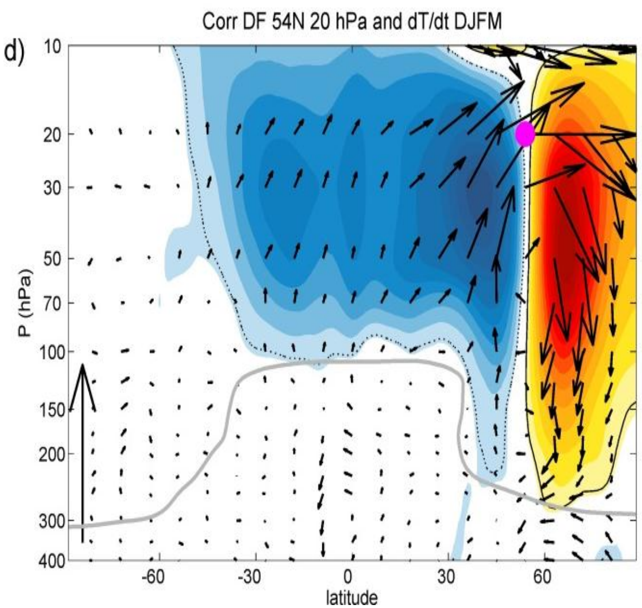
High latitude stratosphere

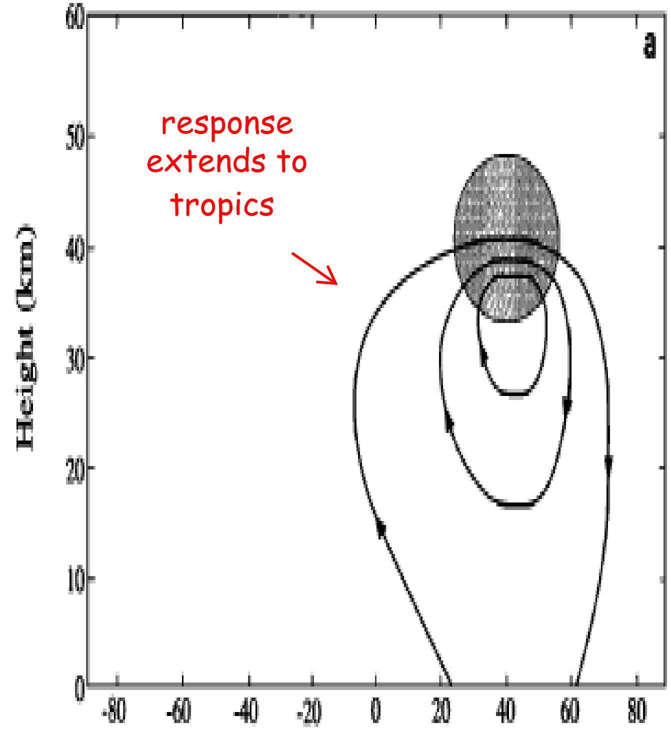


theory (Holton et al, 1995)

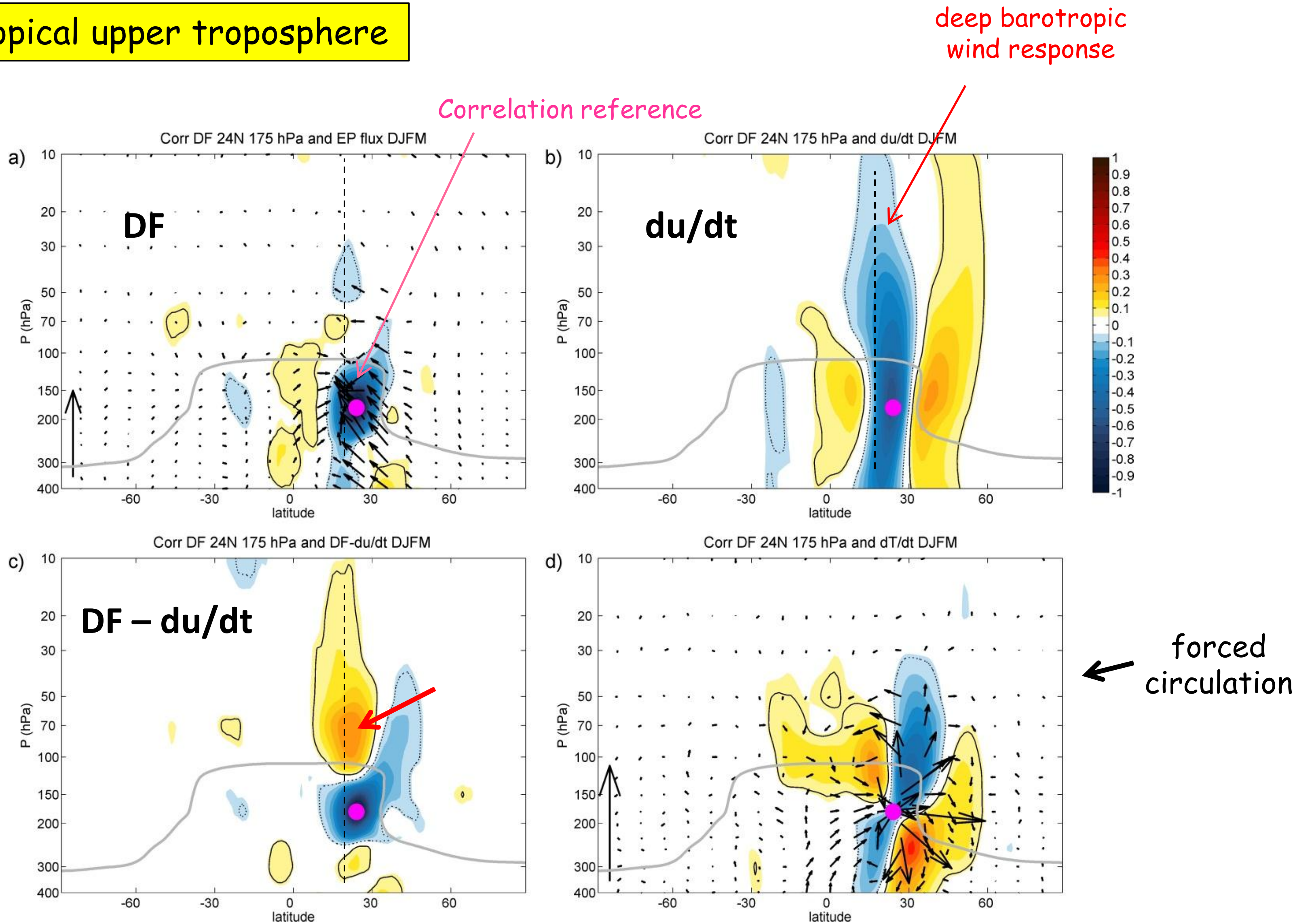
(response to extratropical EP flux divergence)

response to high latitude forcing

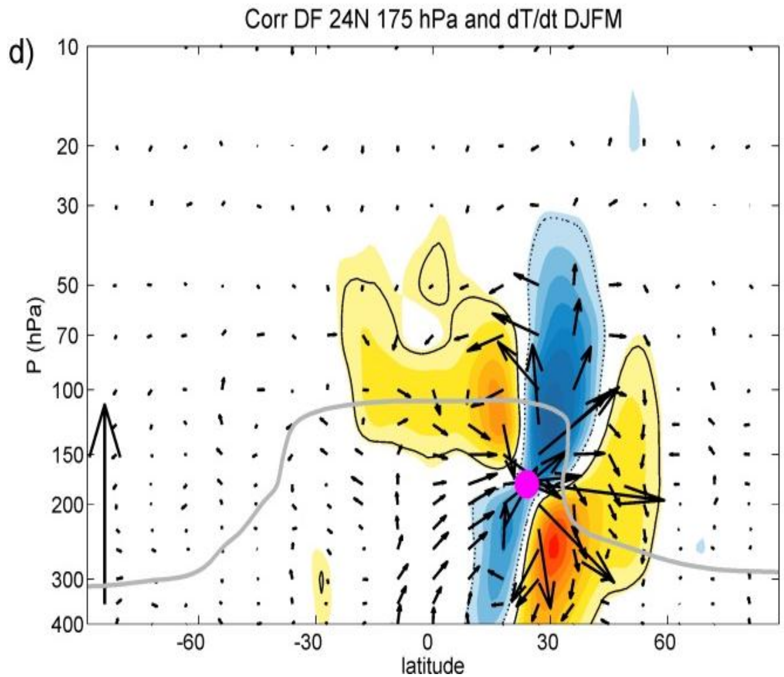




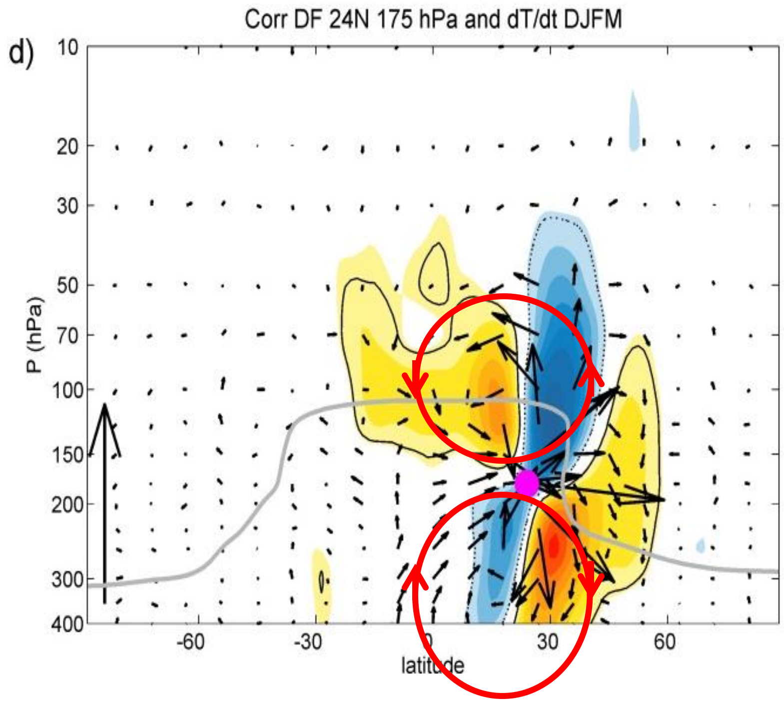
Subtropical upper troposphere



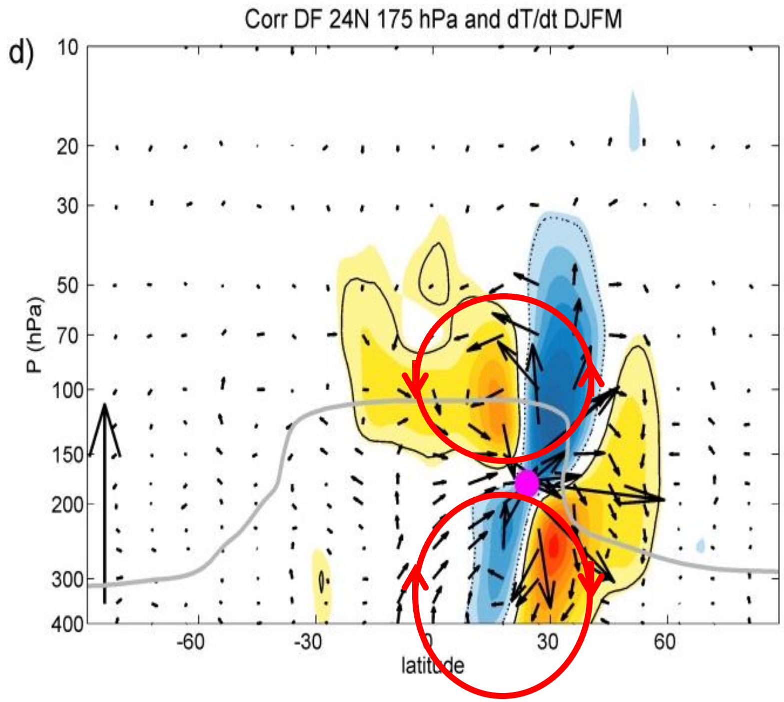
response to subtropical forcing



response to subtropical forcing

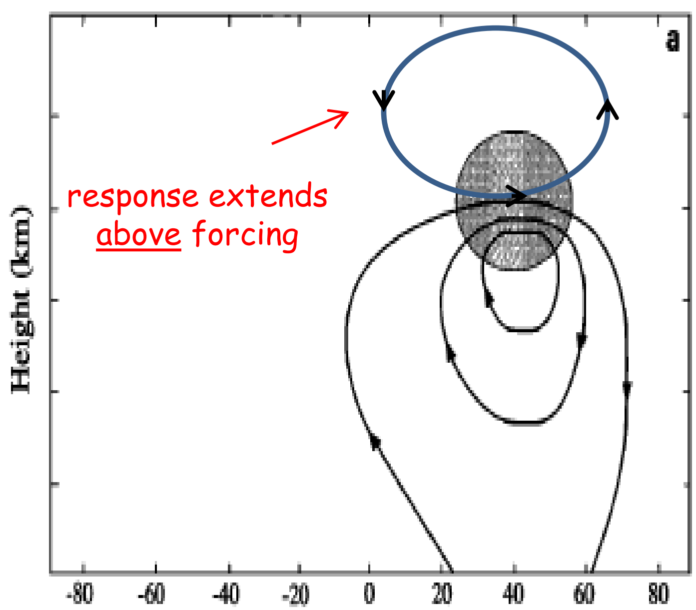


response to subtropical forcing



Net result: subtropical EP flux effective at forcing transient upwelling across tropopause

Theory (Haynes, Holton)

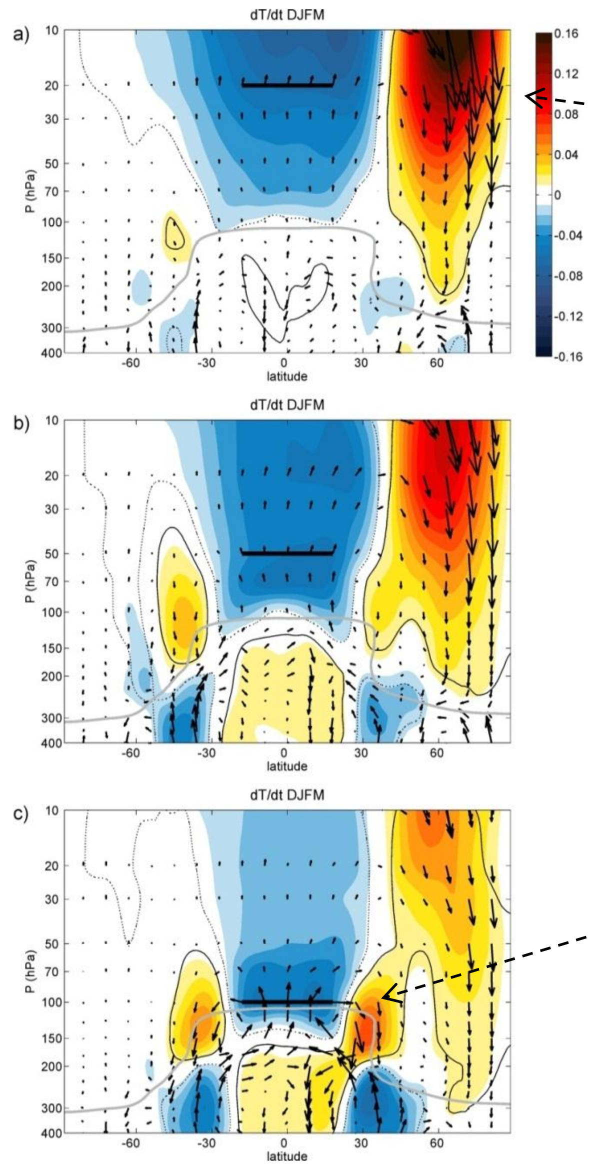


Dependence on the reference altitude for w^*_m

20 hPa

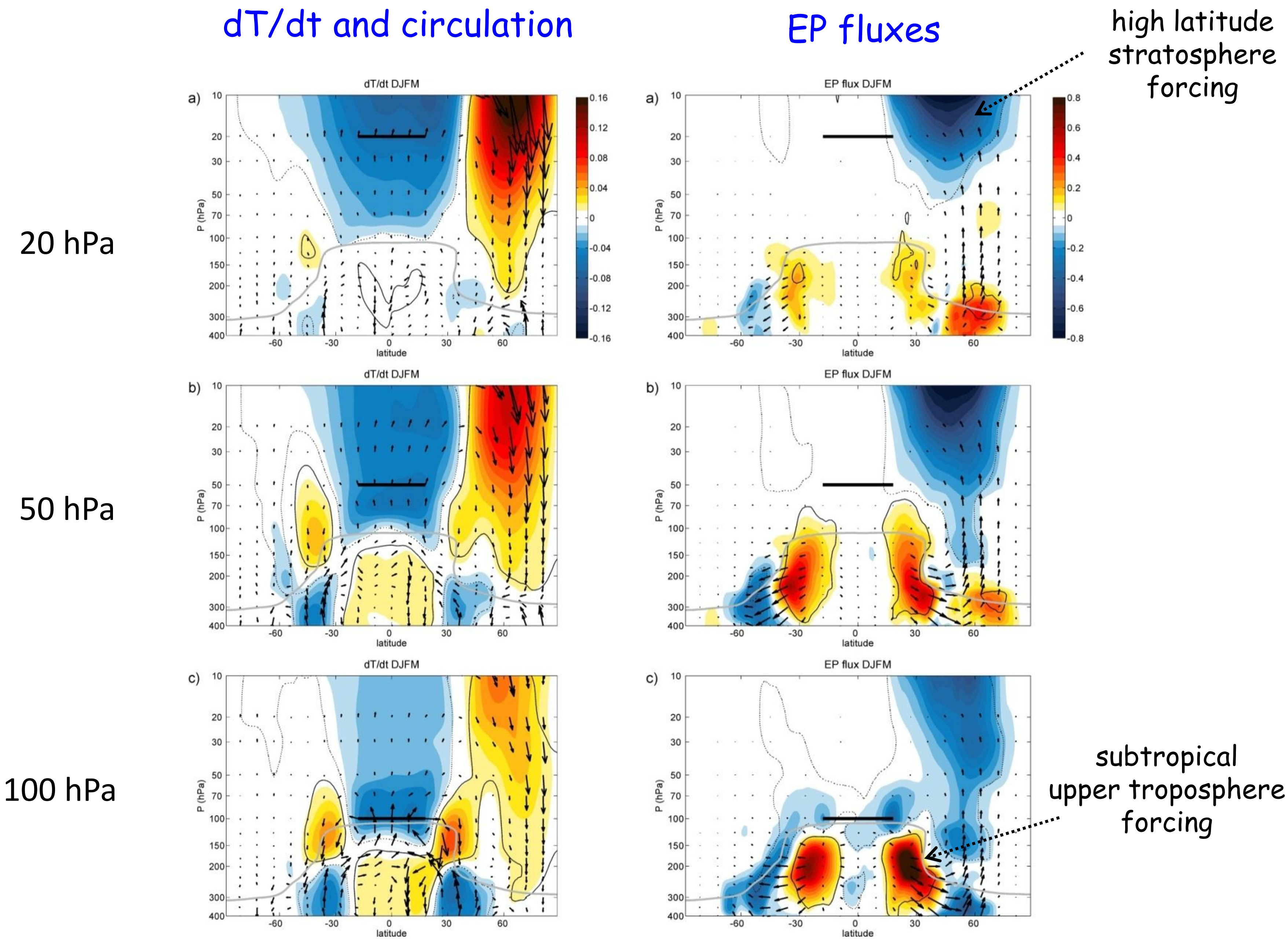
50 hPa

100 hPa



upper branch of Brewer-Dobson circulation

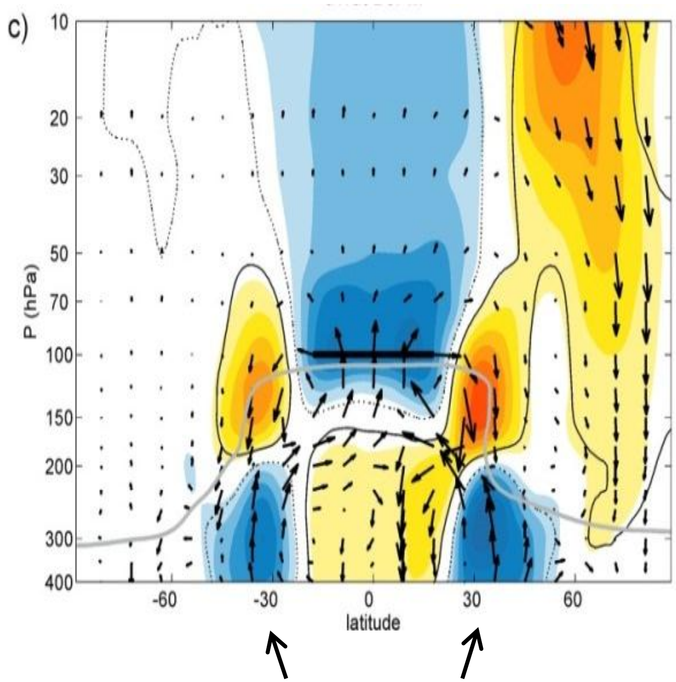
lower branch of BDC



dT/dt and circulation
EP fluxes
high latitude stratosphere forcing
20 hPa
50 hPa
100 hPa
subtropical upper troposphere forcing
a) dT/dt DJFM
b) dT/dt DJFM
c) dT/dt DJFM
a) EP flux DJFM
b) EP flux DJFM
c) EP flux DJFM
P (hPa)
latitude

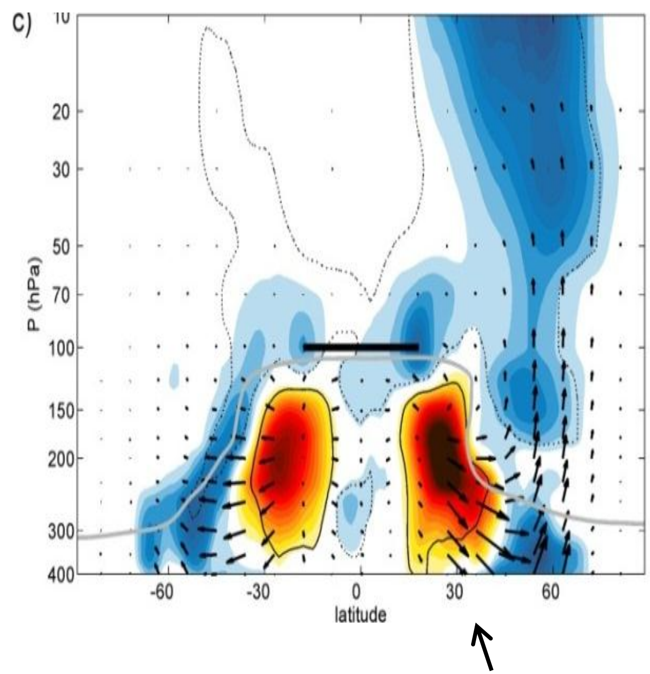
Lower branch of the BDC is primarily related to subtropical wave forcing

Residual circulation



note coherent tropospheric effects

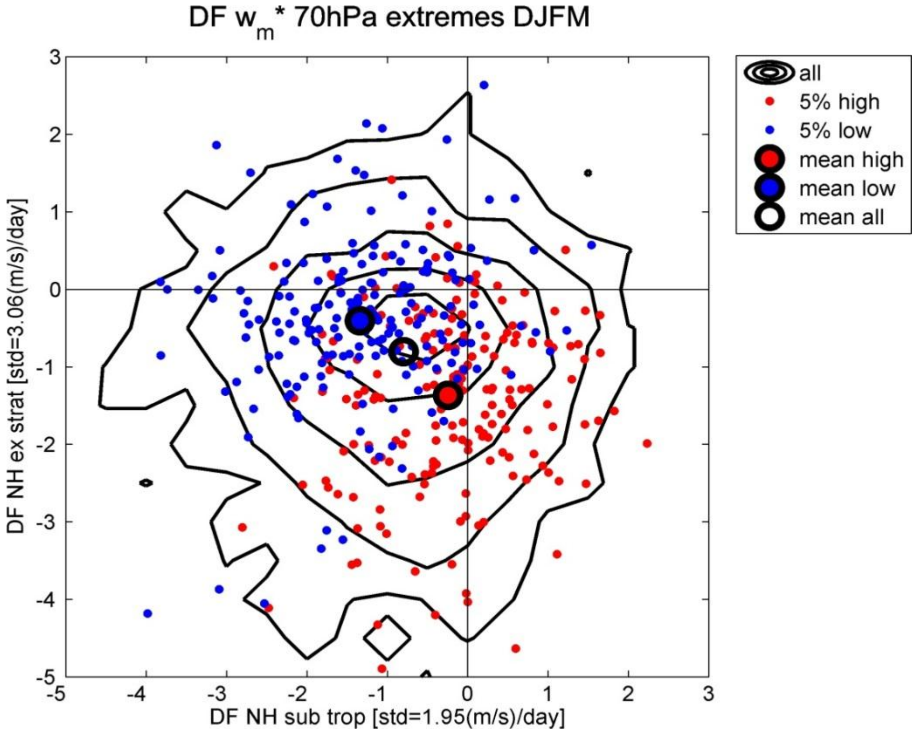
EP fluxes



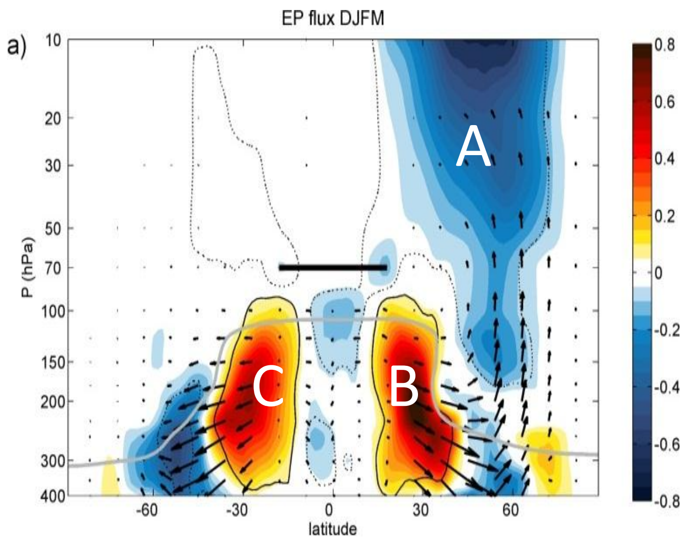
subtropical EP fluxes
drive lower branch of BDC

Is stratospheric forcing correlated with subtropical forcing?

A

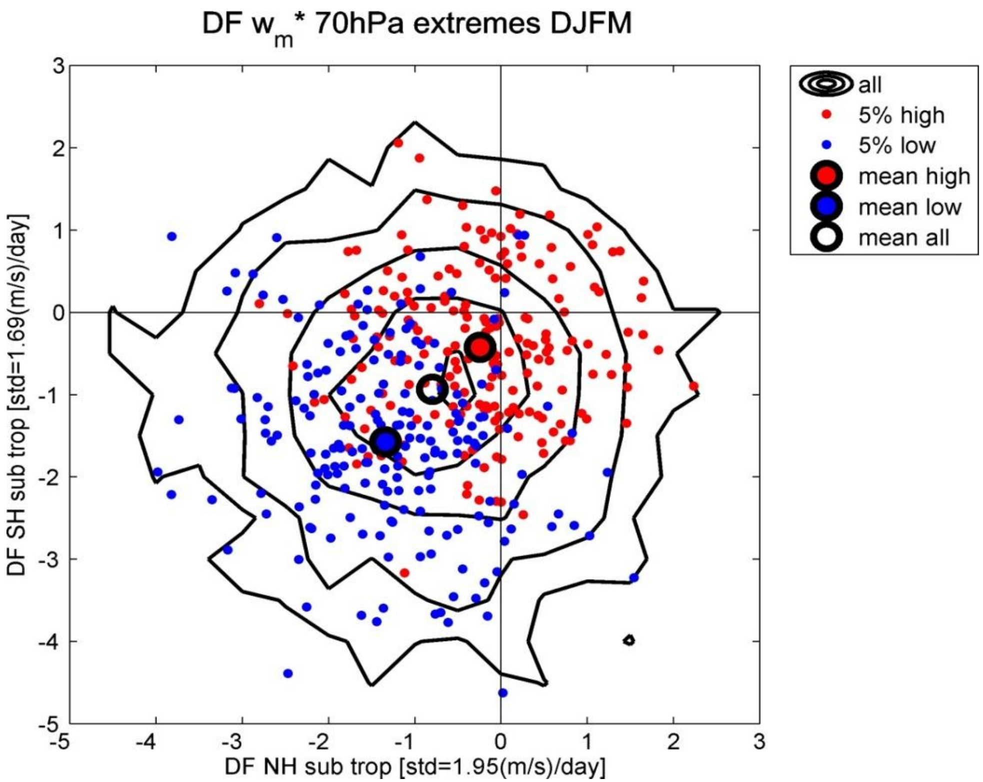


B

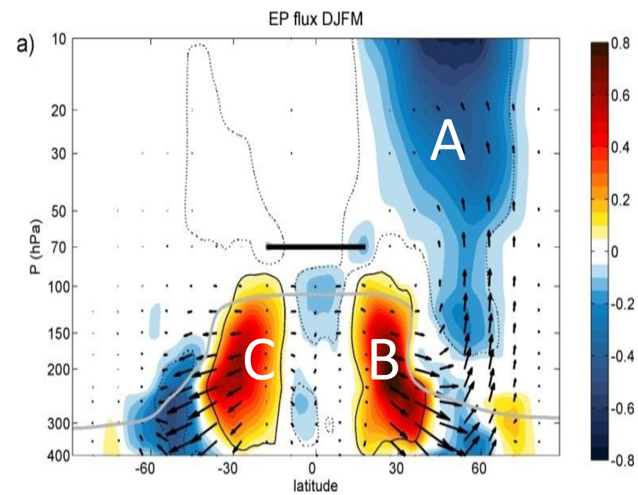


Is subtropical forcing related between the two hemispheres?

C



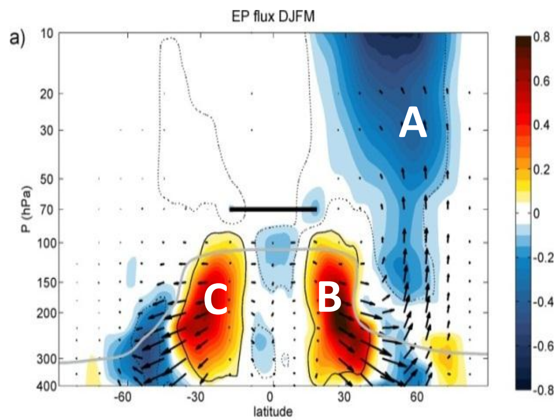
B



Key points:

- Transience in tropical Brewer-Dobson circulation linked to remote wave forcing
    - ➢ high latitude winter stratosphere, subtropics of both hemispheres
- Zonal wind changes are an important component of the remote response
- Clear identification of upper/lower branches of BDC:
    - ➢ Deep branch tied to high latitude stratosphere forcing
    - ➢ Shallow branch linked to subtropical wave dissipation

Plumb 2002



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