Lecture 4: circulation and transport in the TTL and tropical lower stratosphere

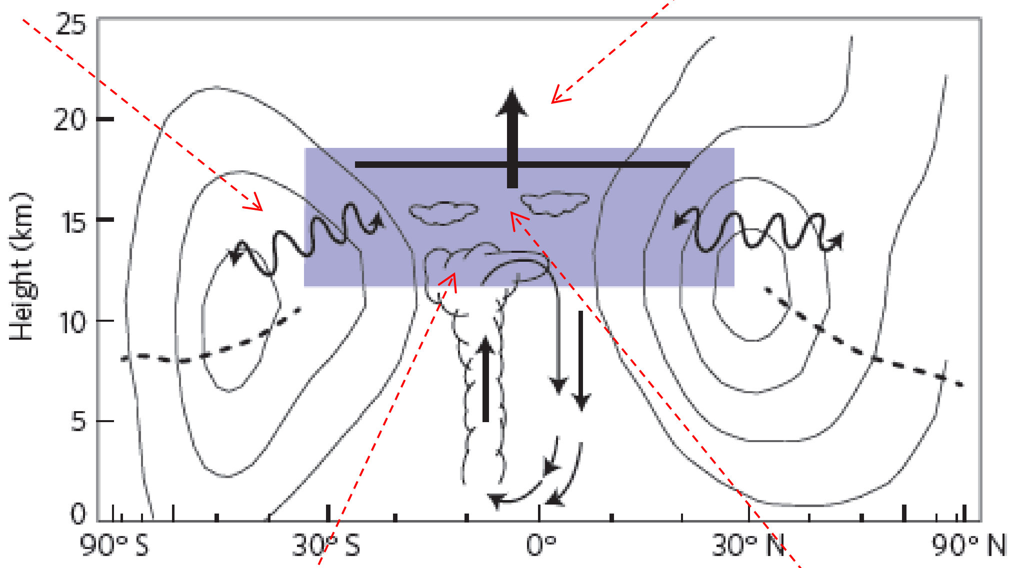
- the large annual cycle in the TTL: temperature and ozone
- observations: temperatures, circulation, trace species
- thermodynamic and constituent budgets in the TTL
- dynamical forcing of tropical upwelling

# Transport near the tropical tropopause layer (TTL)

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

two-way transport by baroclinic eddies

what controls tropical upwelling (temps, ozone and stratospheric $H_2O$)?




how does deep convection impact composition?

cirrus and climate impacts

Randel and Jensen, 2013, Nat. Geosci.

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

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

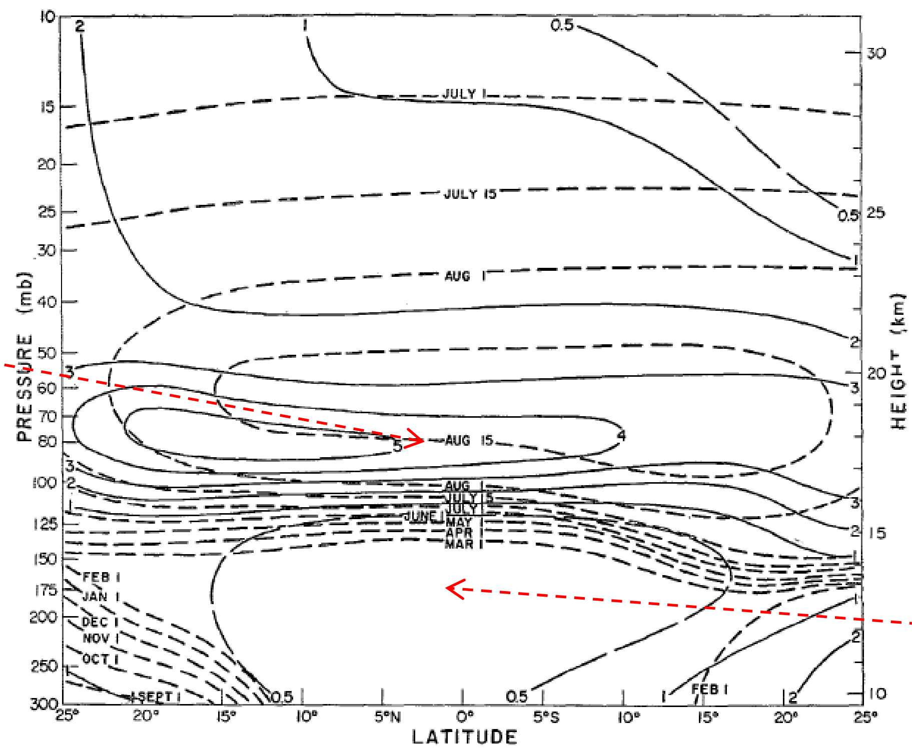
RICHARD J. REED[2] AND CHARLES L. VLCEK[3]

JAS 1969

dynamically forced,
but exactly how?

extratropical stratosphere,
tropical waves, ??

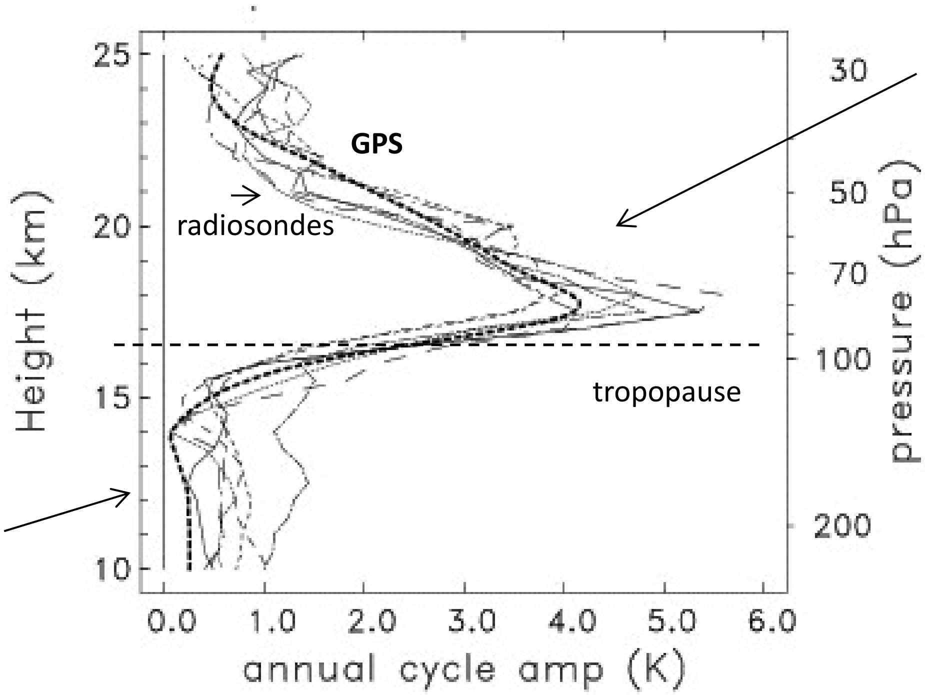
narrow
maximum




almost zero annual cycle
in tropical troposphere

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

## 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

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

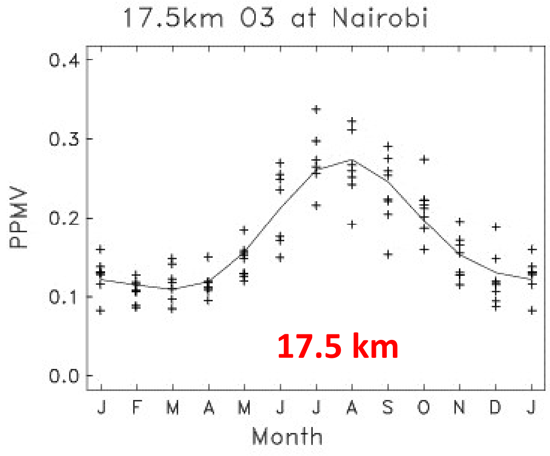
small

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

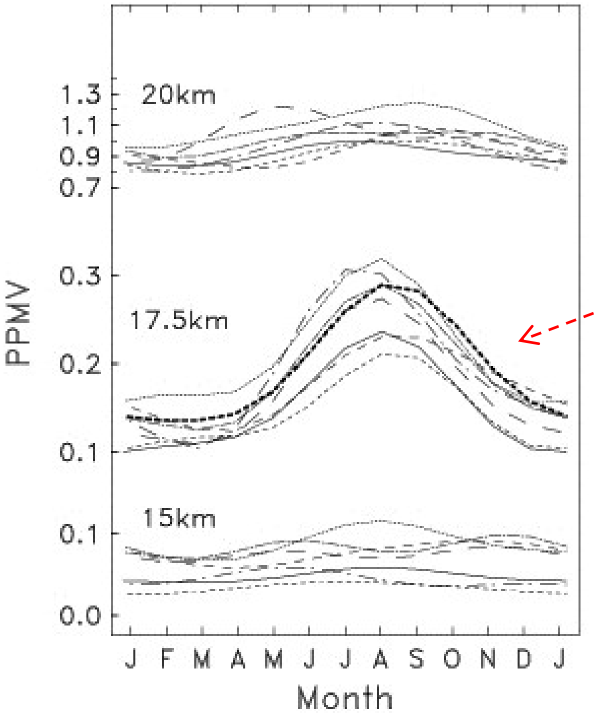
Reed and Vicek, 1969, J. Atmos. Sci.

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

Seasonal cycle
at Nairobi



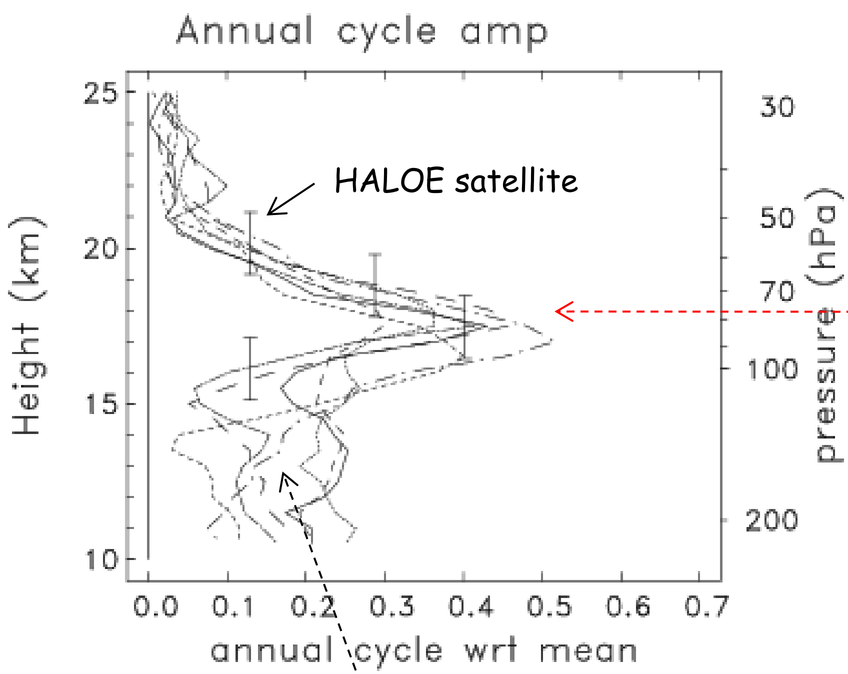

seasonal cycle at
7 SHADOZ ozonesonde
stations 10° N-S




large annual cycle
at all stations, over
narrow vertical layer

Randel et al., 2007, J. Atmos. Sci.

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

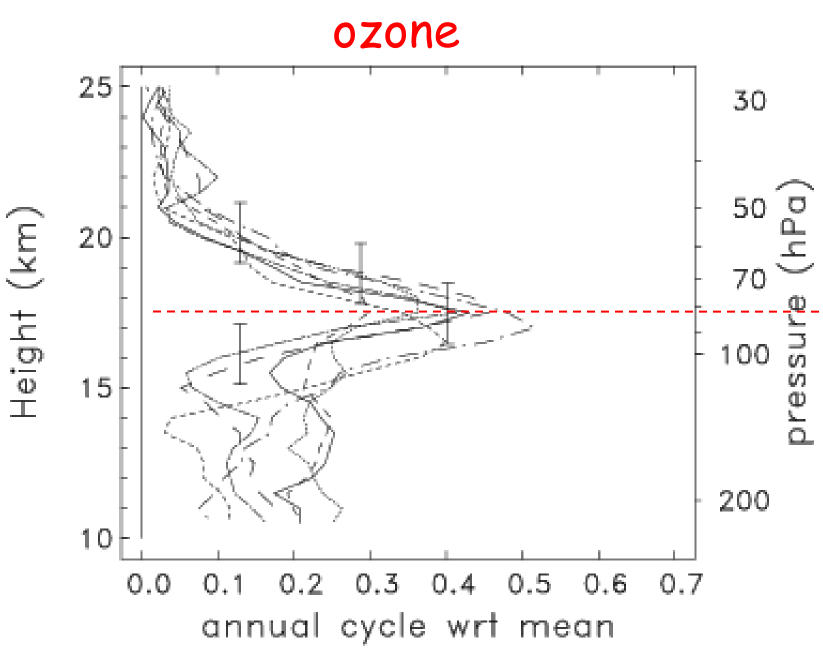


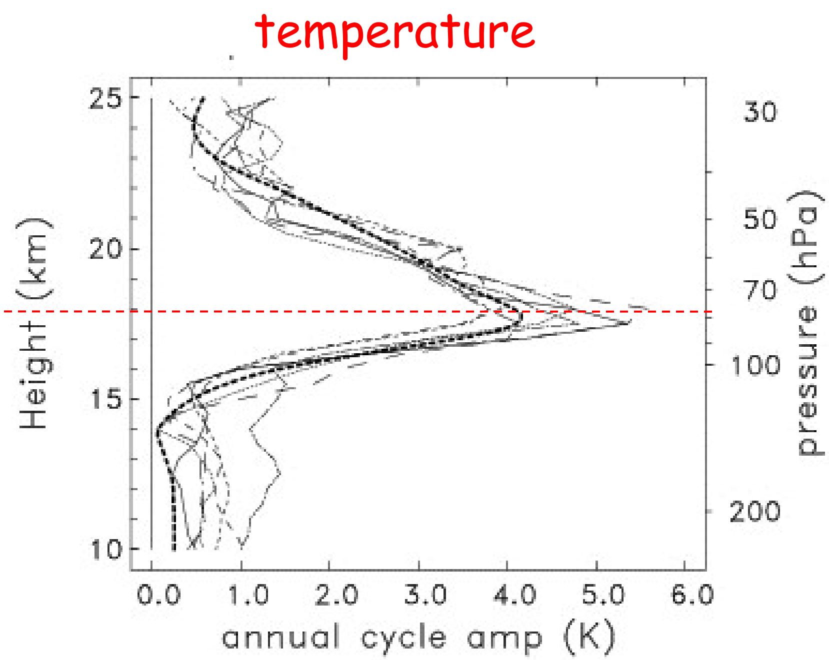

narrow vertical layer
~ 16-19 km

upper troposphere seasonal
cycle is different among stations

Randel et al., 2007, J. Atmos. Sci.

# Ozone seasonal cycle has similar vertical structure to temperature



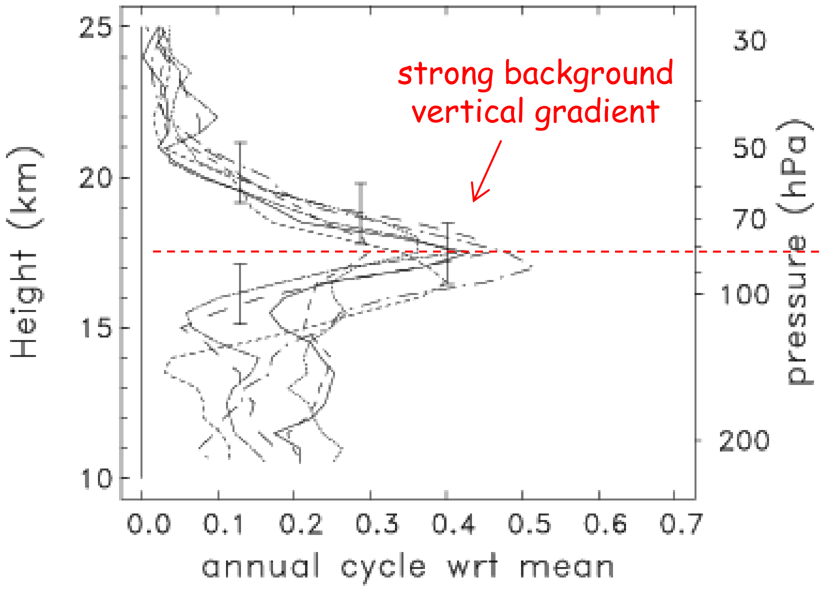




temps from SHADOZ stations
and zonal mean GPS data

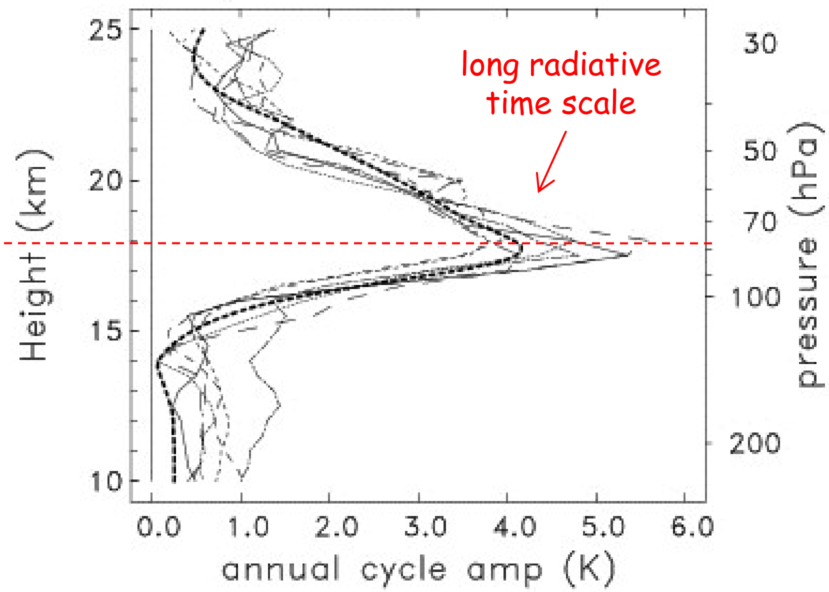
Randel et al., 2007, J. Atmos. Sci.

# Ozone seasonal cycle has similar vertical structure to temperature

ozone

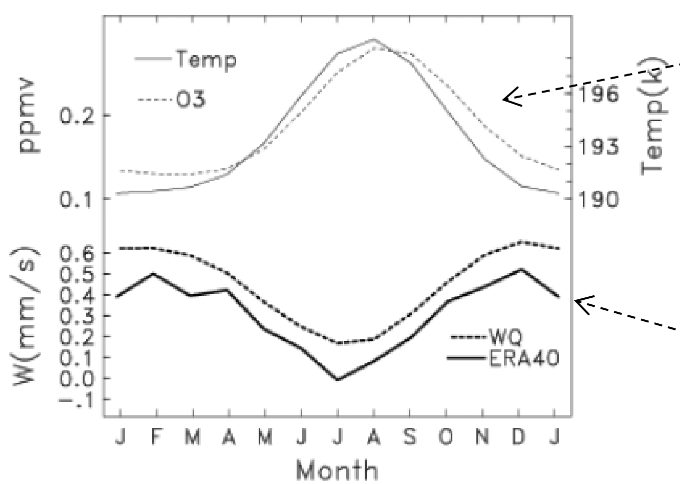



temperature




ozone and temp respond to annual cycle in tropical upwelling

Climatological seasonal cycle




ozone and temp ~ in phase

vertical velocity (2 estimates)

Randel et al., 2007, J. Atmos. Sci.

## 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

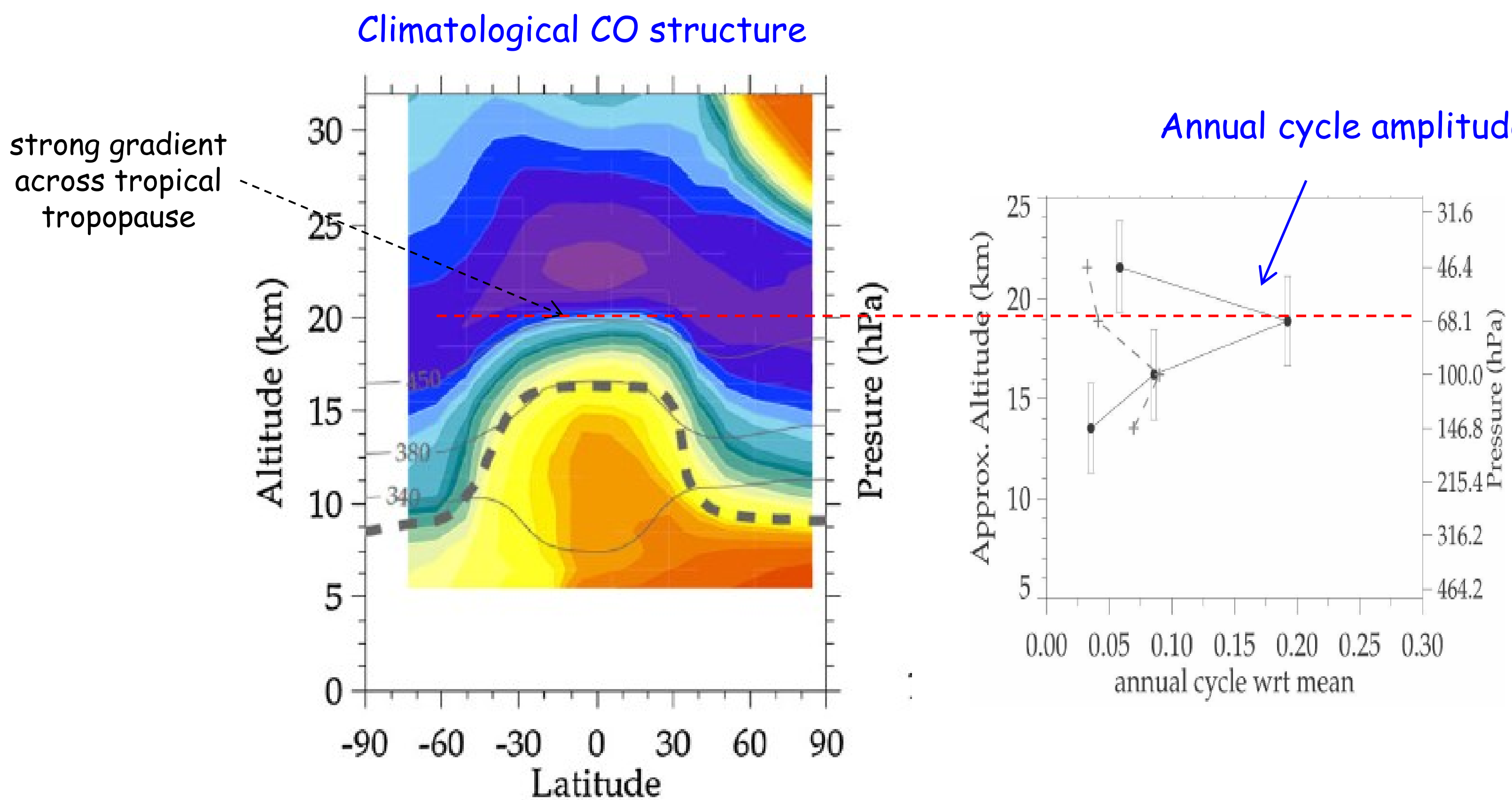
$$\frac{\partial \overline{\chi}}{\partial t} = -\overline{w}^* \frac{\partial \overline{\chi}}{\partial z}$$

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

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

* for tracers with strong vertical gradients

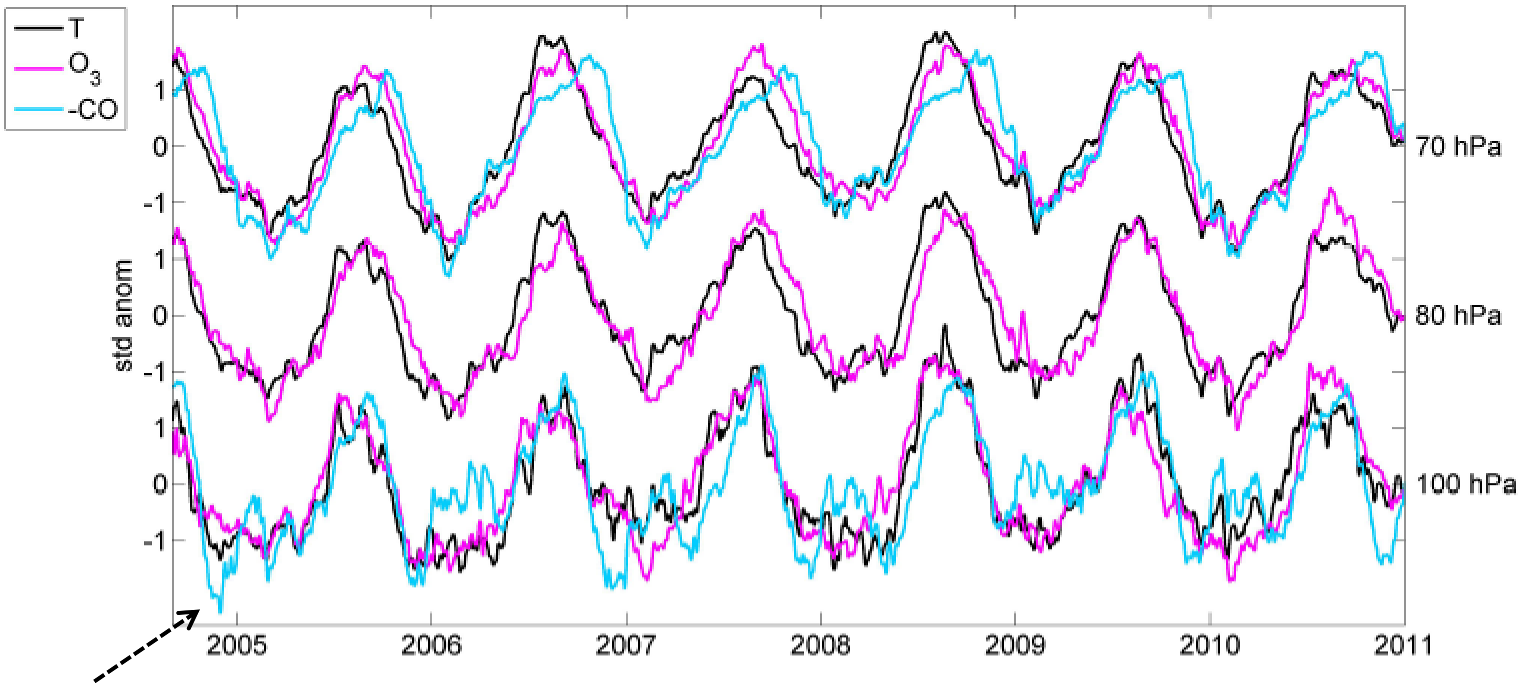
There is a corresponding annual cycle in CO above the tropical tropopause (out of phase with temperature and ozone)




Park et al., 2013, J. Geophys. Res. Atmos.

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

Temps from ERAinterim, ozone and CO from MLS observations



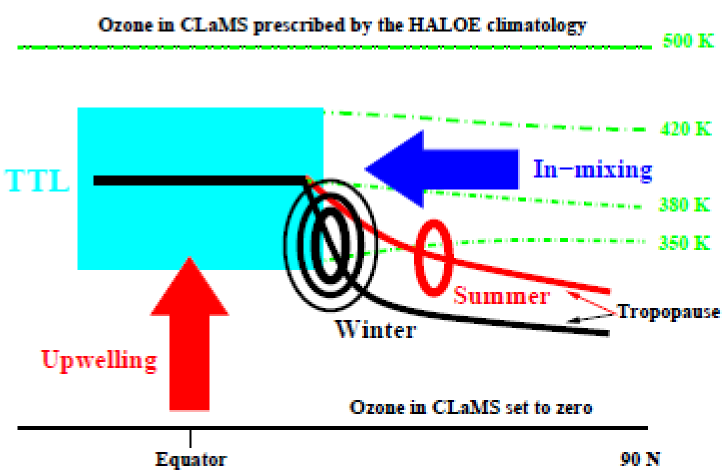

CO inverted scale

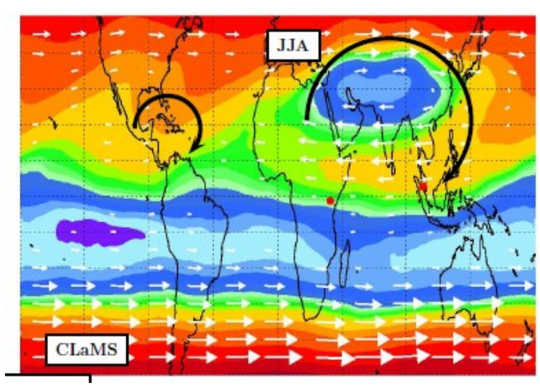
Abalos et al., 2012, Atmos. Chem. Phys.

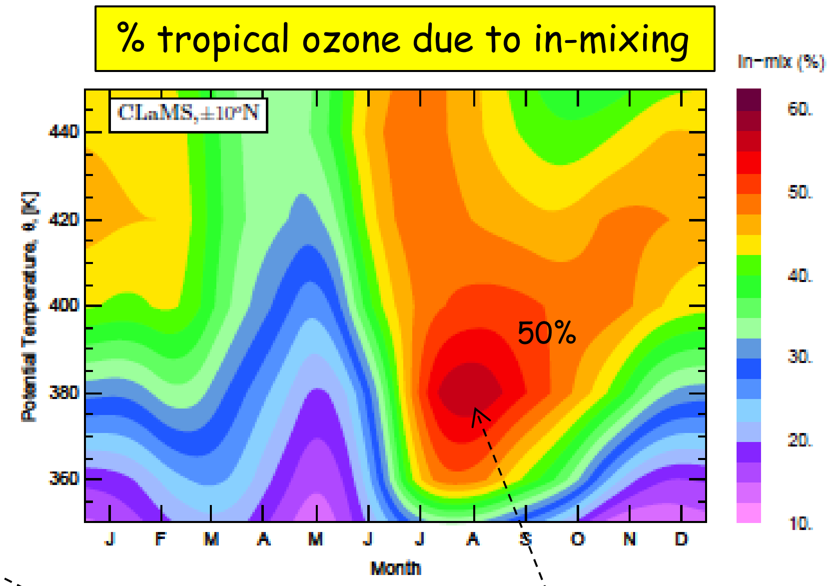
# Complementary viewpoint: ozone annual cycle due to in-mixing

Isentropic calculations using CLaMS Lagrangian model

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



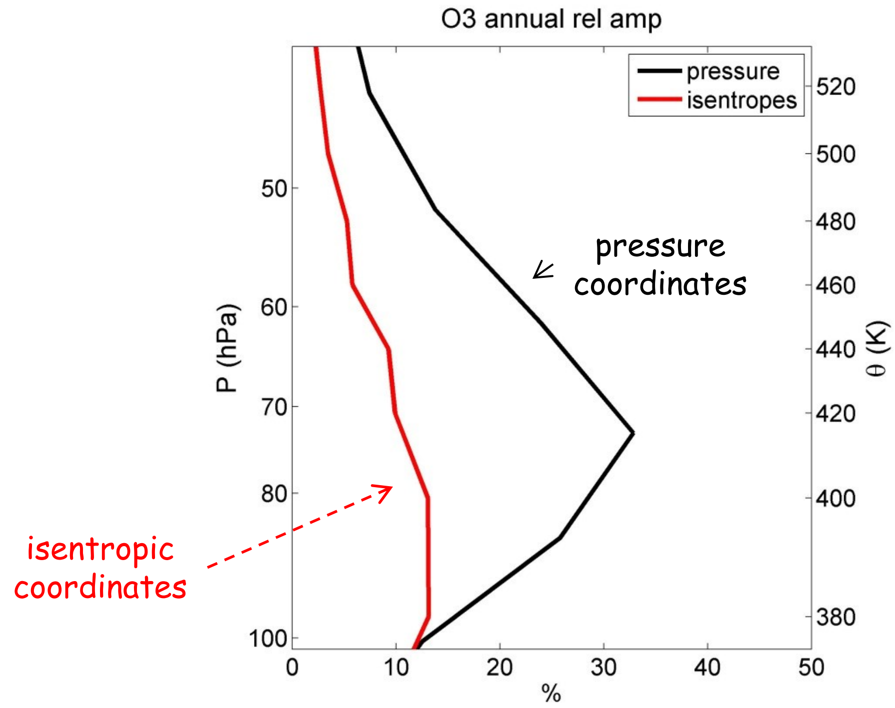




summer ozone maximum
due to Asian monsoon transport

Ozone annual cycle amplitude is reduced in isentropic coordinates because of strong ozone-temperature correlation (forced by upwelling)

Konopka et al JGR 2009



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]

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

ACP 2012

- Observational analysis of upwelling effect on tracers
- MLS observations of ozone, CO   2004-2011
- ERAinterim meteorology
- <u>3 estimates of upwelling</u>:   $w^*$ (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

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

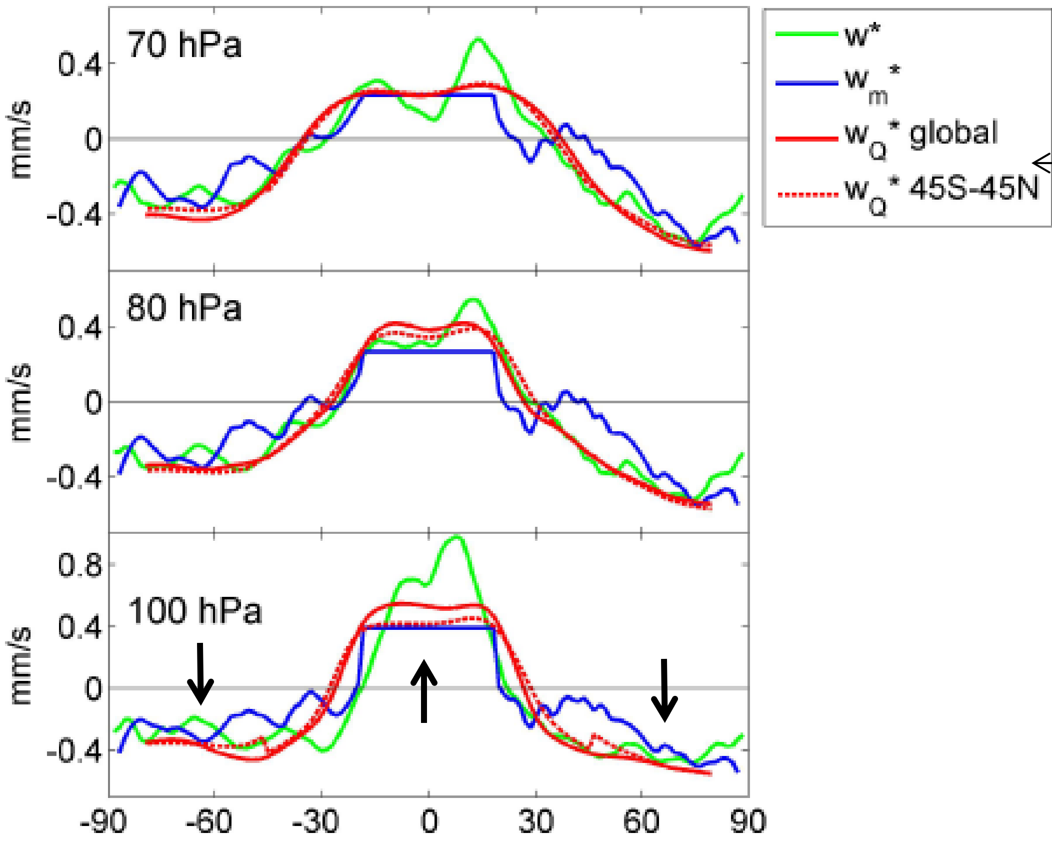
thermodynamic balance $w_Q{}^*$

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

EP flux divergence

momentum balance $w_m{}^*$

# Latitude structure of upwelling from 3 estimates

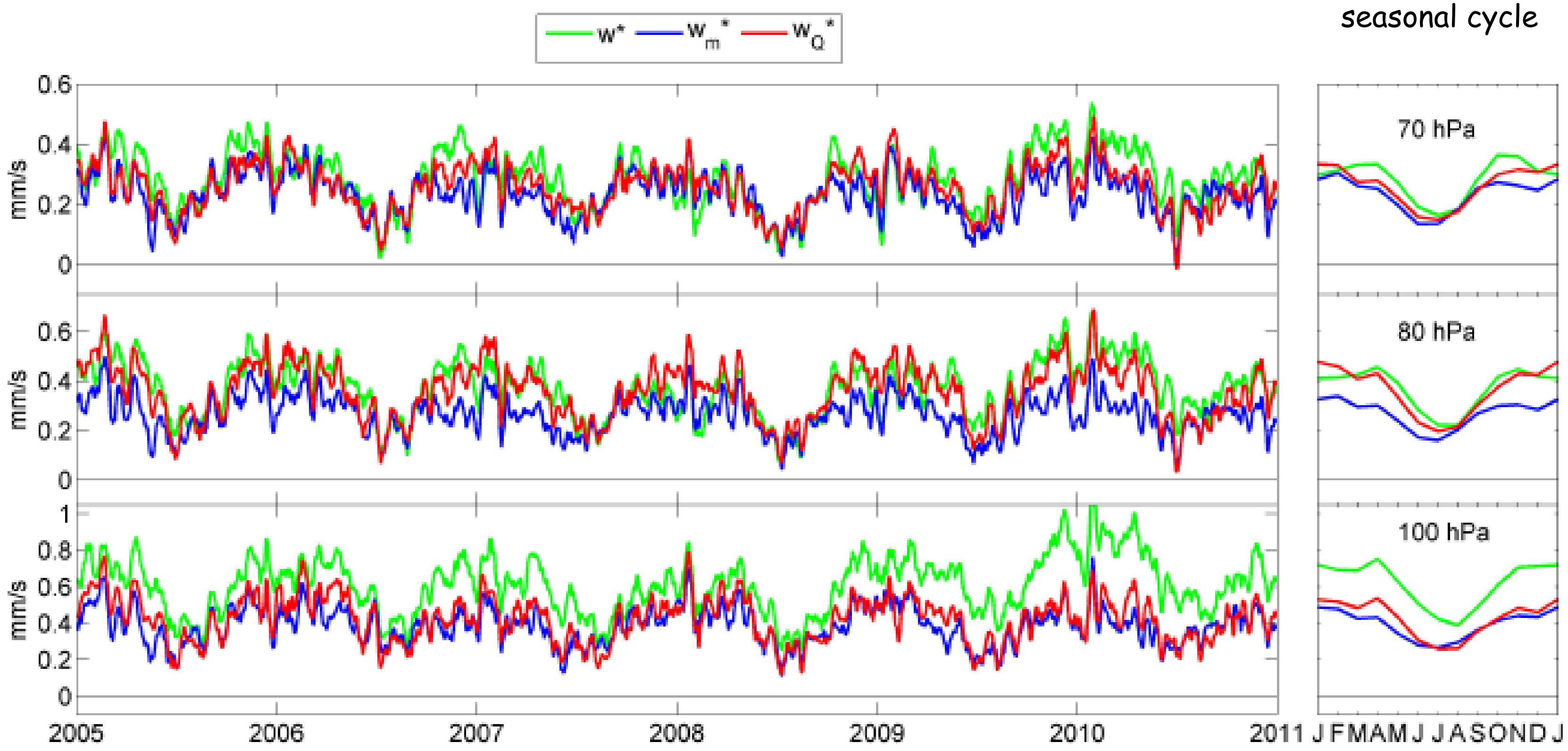



different methods of adjustment

Abalos et al., 2012, Atmos. Chem. Phys.

# Daily variations in upwelling 18° N-S

Average seasonal cycle

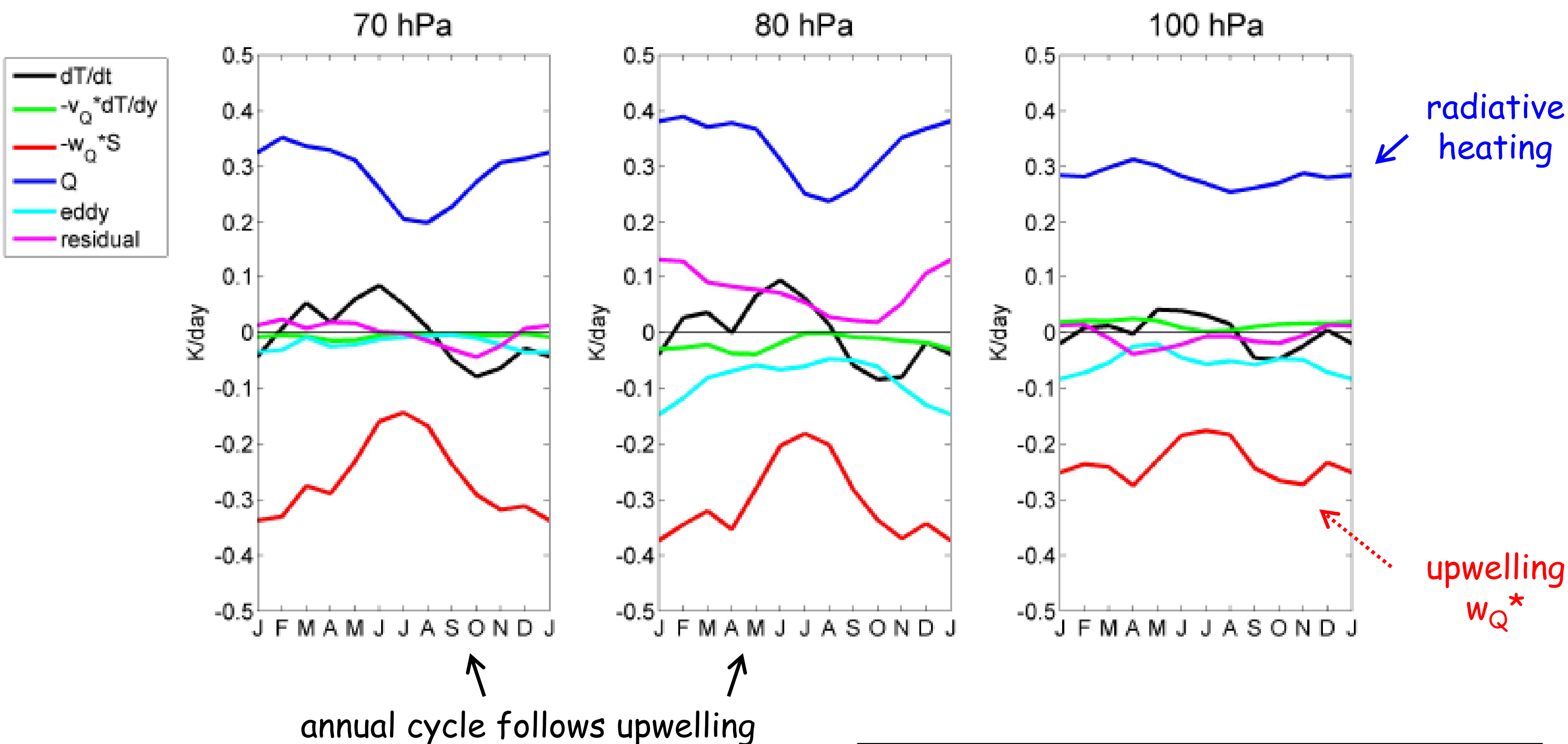



Large annual cycles and significant sub-seasonal variability

Abalos et al., 2012, Atmos. Chem. Phys.

Thermodynamic balance

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




Result: upwelling ~ radiative heating

Abalos et al., 2012, Atmos. Chem. Phys.

# Ozone budget

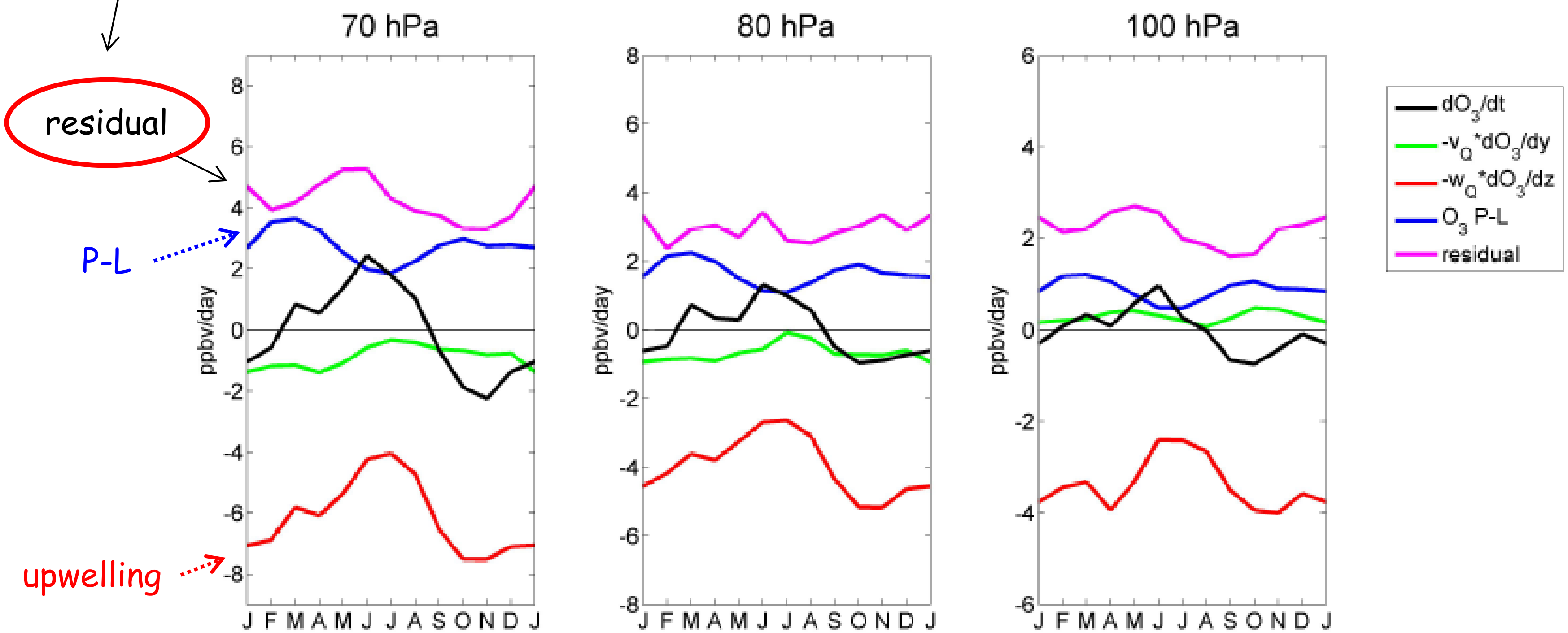
$$\frac{\partial \overline{\chi}}{\partial t} = -\overline{v}^* \frac{1}{a}\frac{\partial \overline{\chi}}{\partial \phi} - \overline{w}^* \frac{\partial \overline{\chi}}{\partial z} + \nabla \cdot M + P - L$$

eddy transport

mean advection

chemistry

Residual = unresolved eddy effects + imbalances from resolved terms

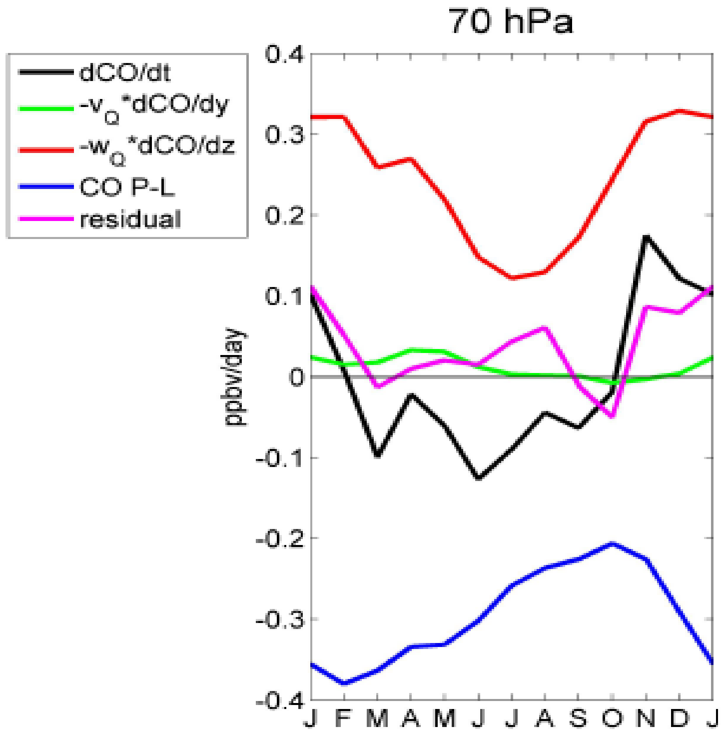



annual cycle follows upwelling

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

Abalos et al., 2012, Atmos. Chem. Phys.

# <u>CO budget</u>




upwelling

Annual cycle
follows upwelling

P-L

**<u>Result:</u> upwelling ~ photochemical loss**

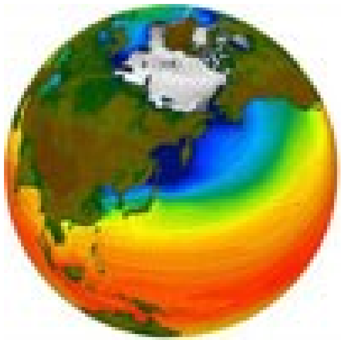
Abalos et al., 2012, Atmos. Chem. Phys.

## 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?

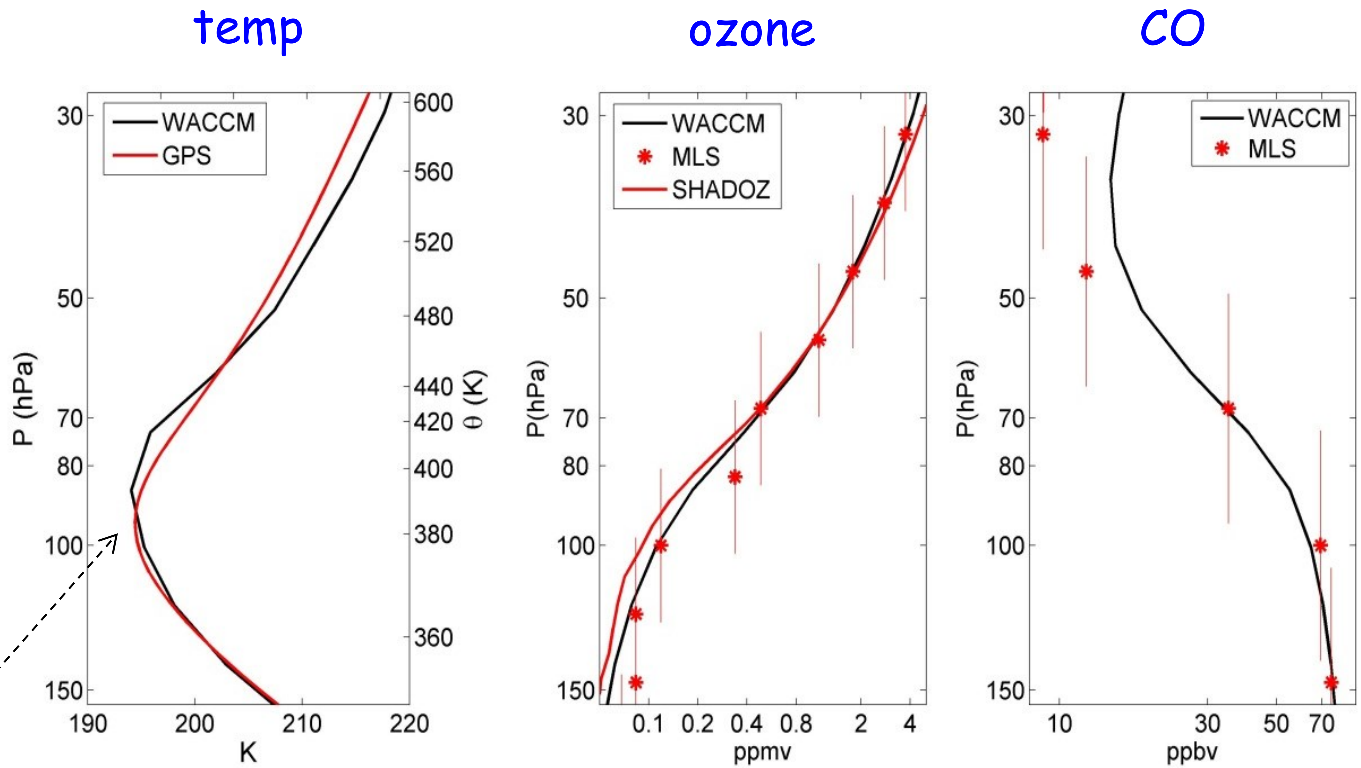
What are the detailed balances in a free-running climate model (WACCM) ?

- Archive and analyze daily output of a standard WACCM simulation



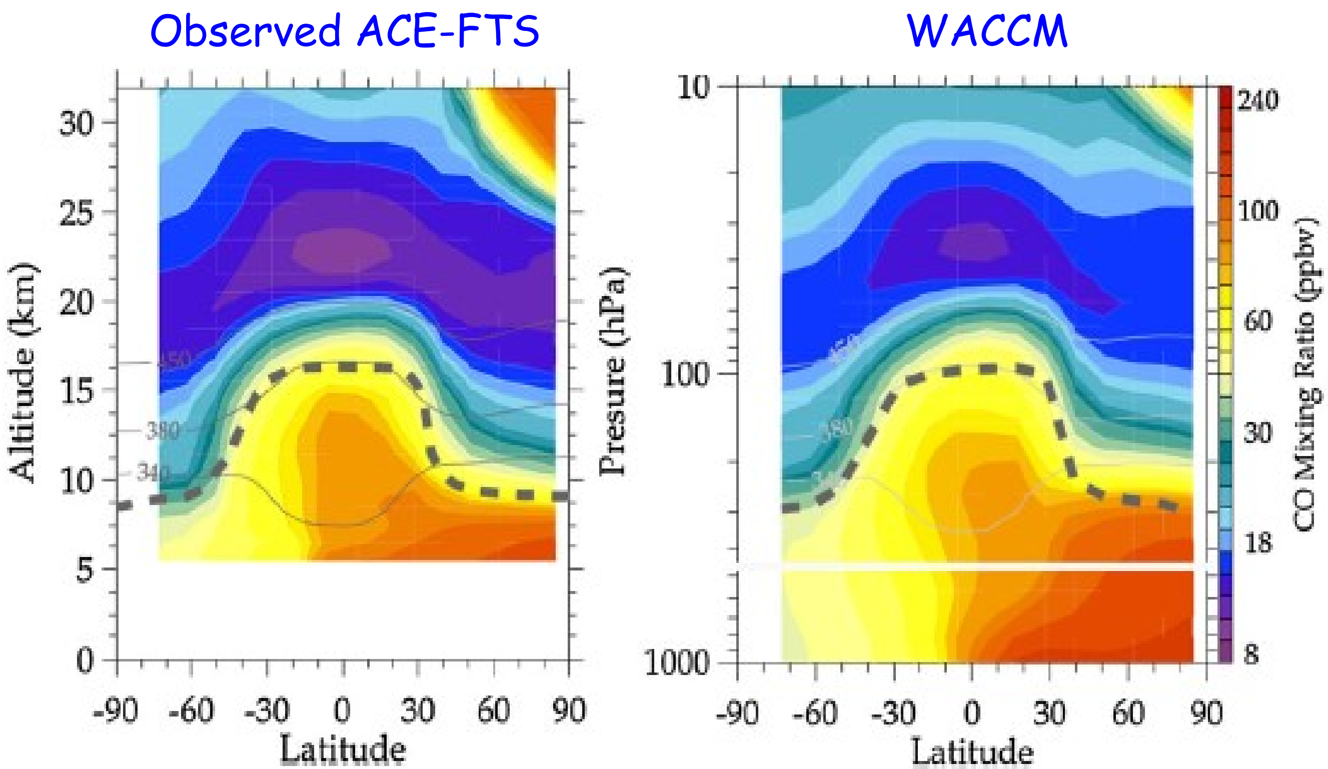
Abalos et al, 2013, ACP

# How realistic is the near-tropopause structure in WACCM?



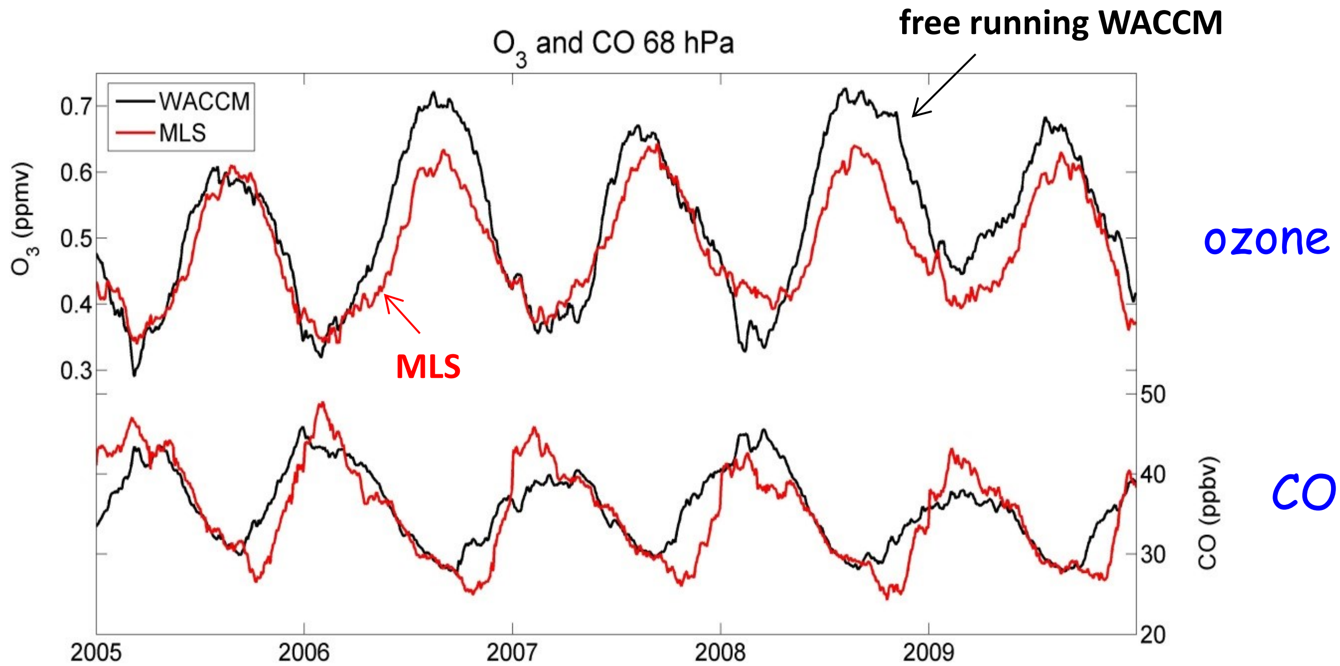

tropopause is slightly higher in WACCM

# Accurate simulation of CO in WACCM




Park et al, JGR 2013

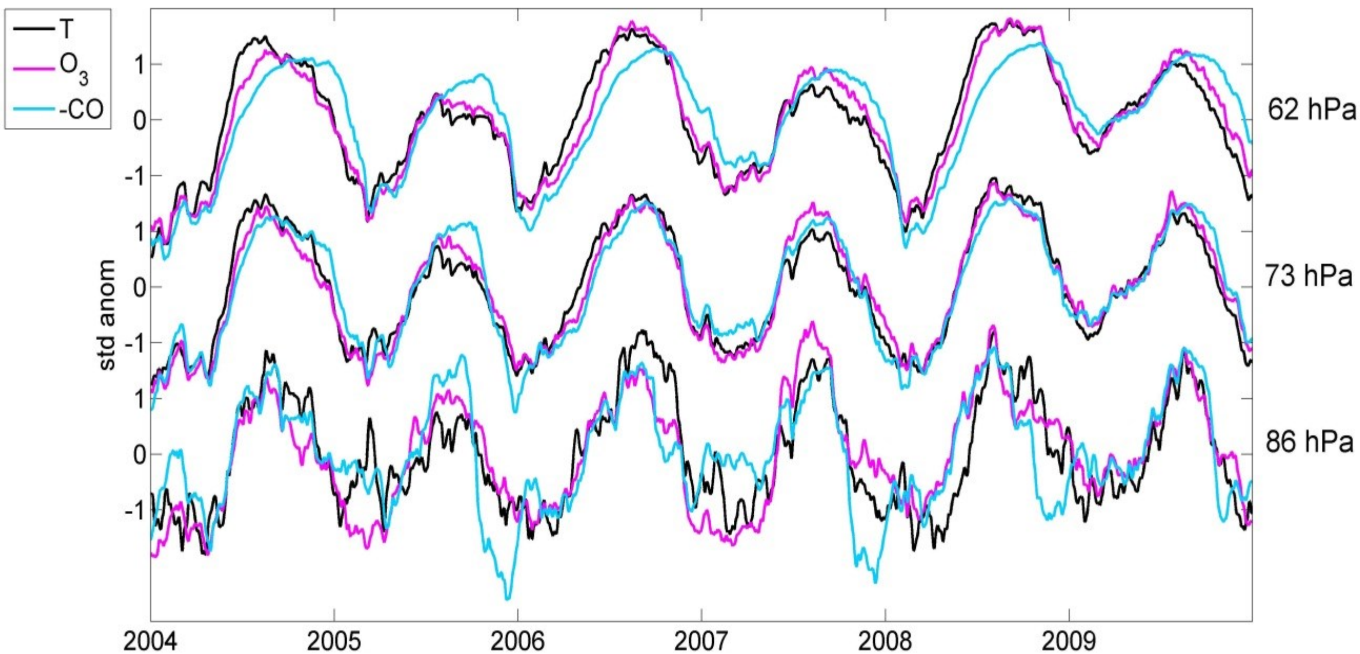
# Tropical seasonal variations at 68 hPa (19 km)




Abalos et al., 2013, Atmos. Chem. Phys.

# Coherent WACCM variations of T, ozone and CO

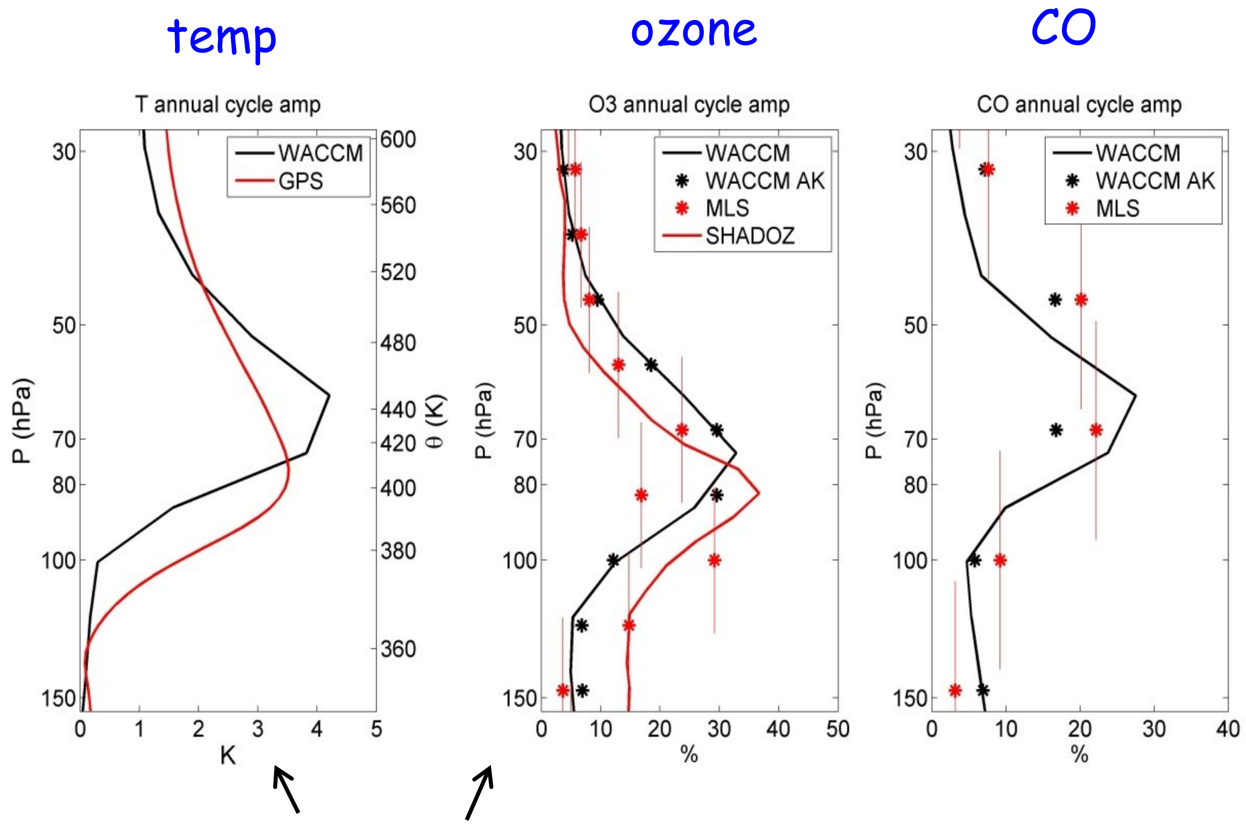
* similar to observations *




CO inverted scale

Abalos et al., 2013, Atmos. Chem. Phys.

# Amplitude of annual cycle



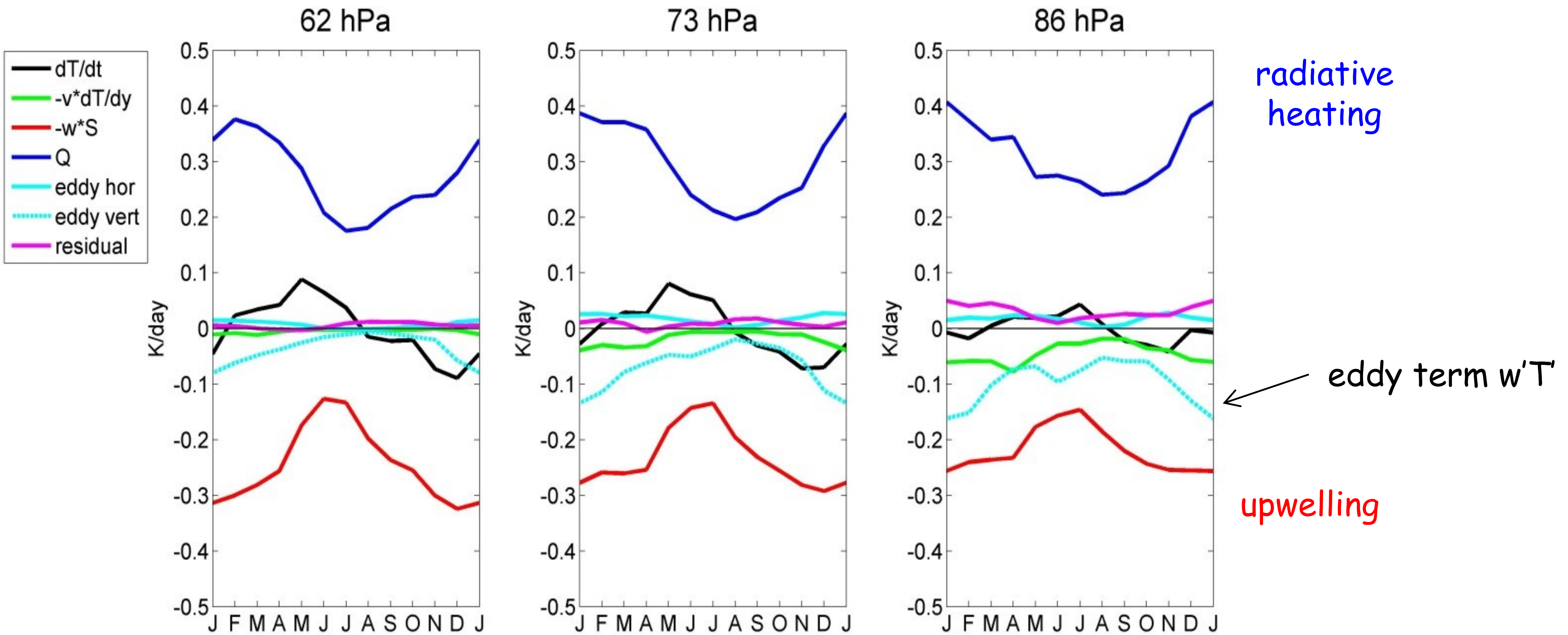

Realistic amplitudes,
but slightly higher
altitude in WACCM

Abalos et al., 2013, Atmos. Chem. Phys.

## 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



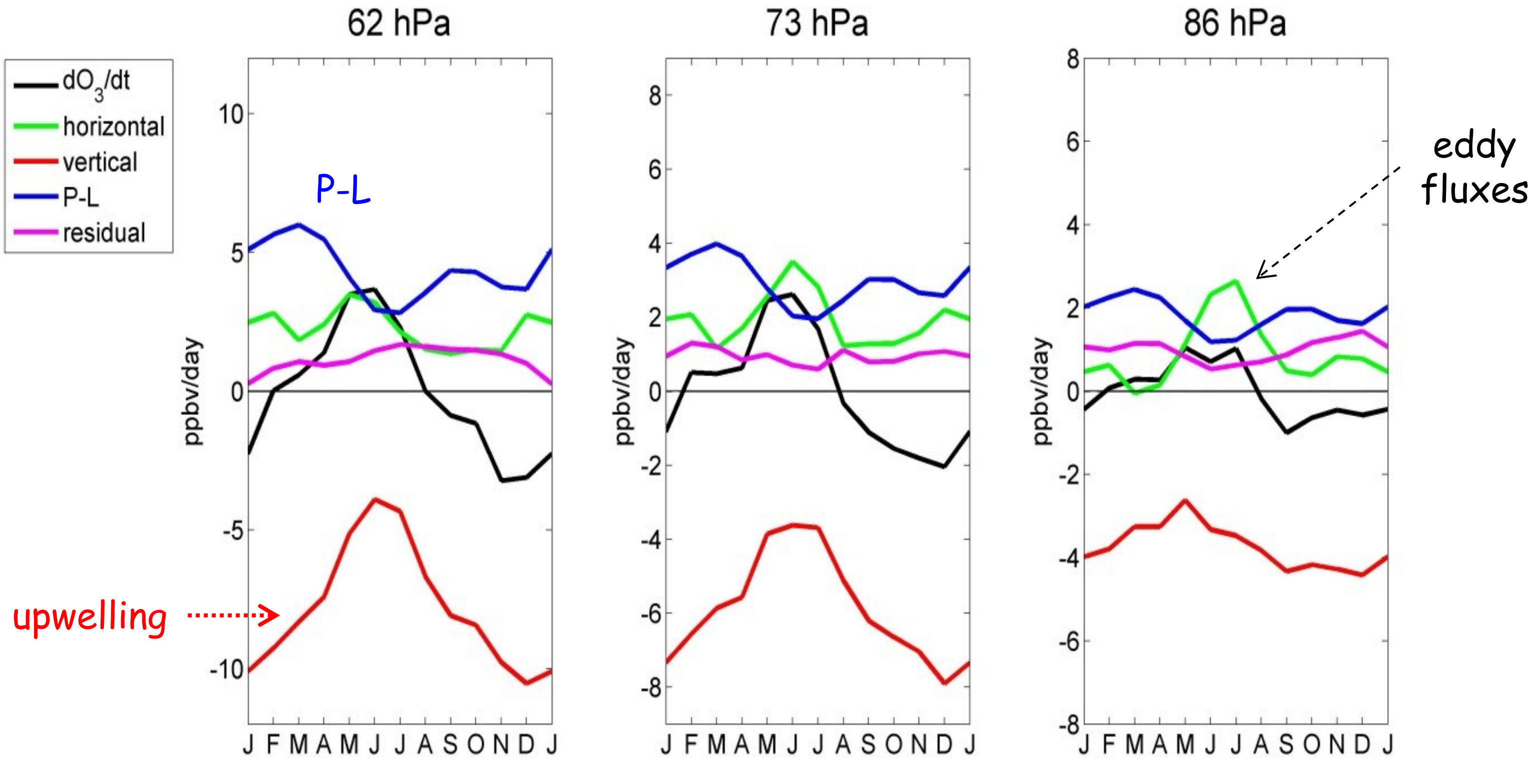

Note very small residuals (not always easy with model results)

Abalos et al., 2013, Atmos. Chem. Phys.

## WACCM ozone budget:

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

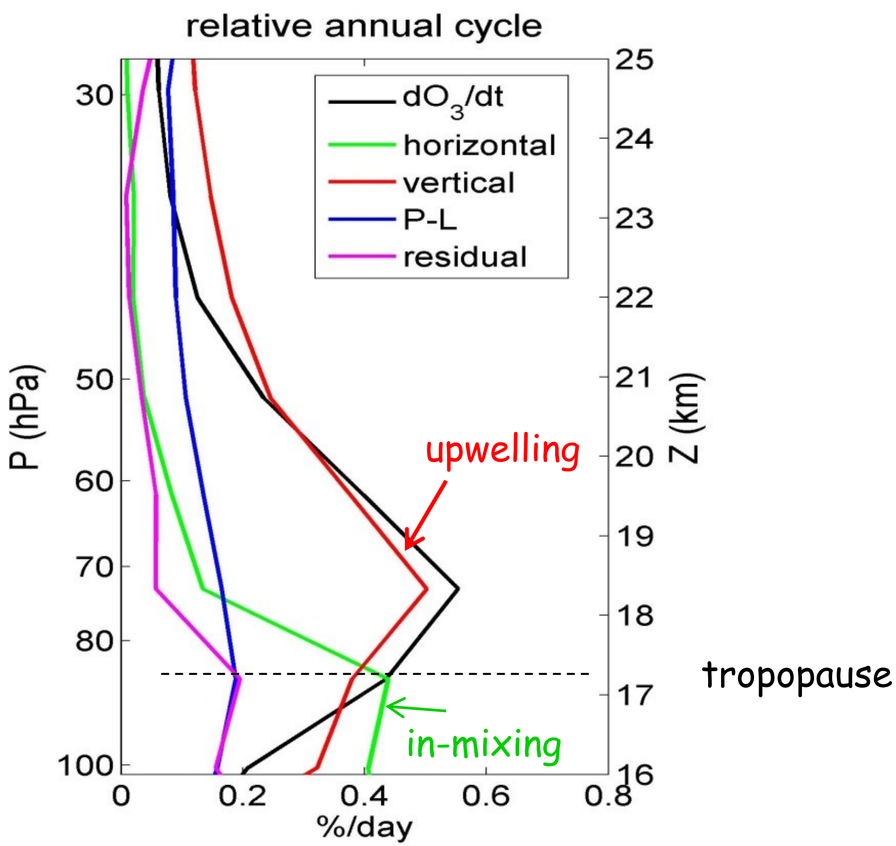
eddy fluxes




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

Abalos et al., 2013, Atmos. Chem. Phys.

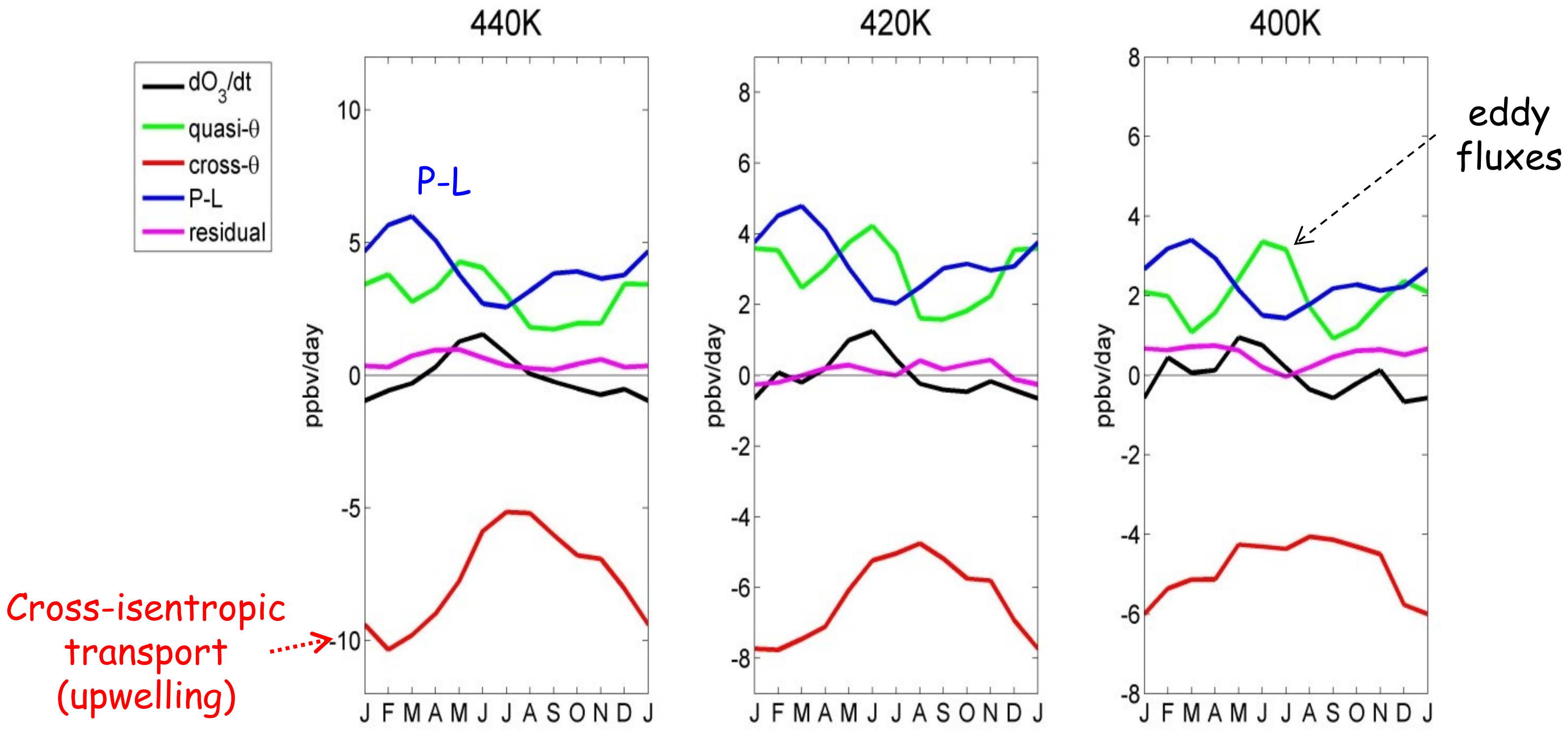
# Contribution of terms to forcing ozone annual cycle




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

Abalos et al., 2013, Atmos. Chem. Phys.

# Ozone budget in isentropic coordinates




Balances are similar to pressure coordinates, but reduced ozone amplitude

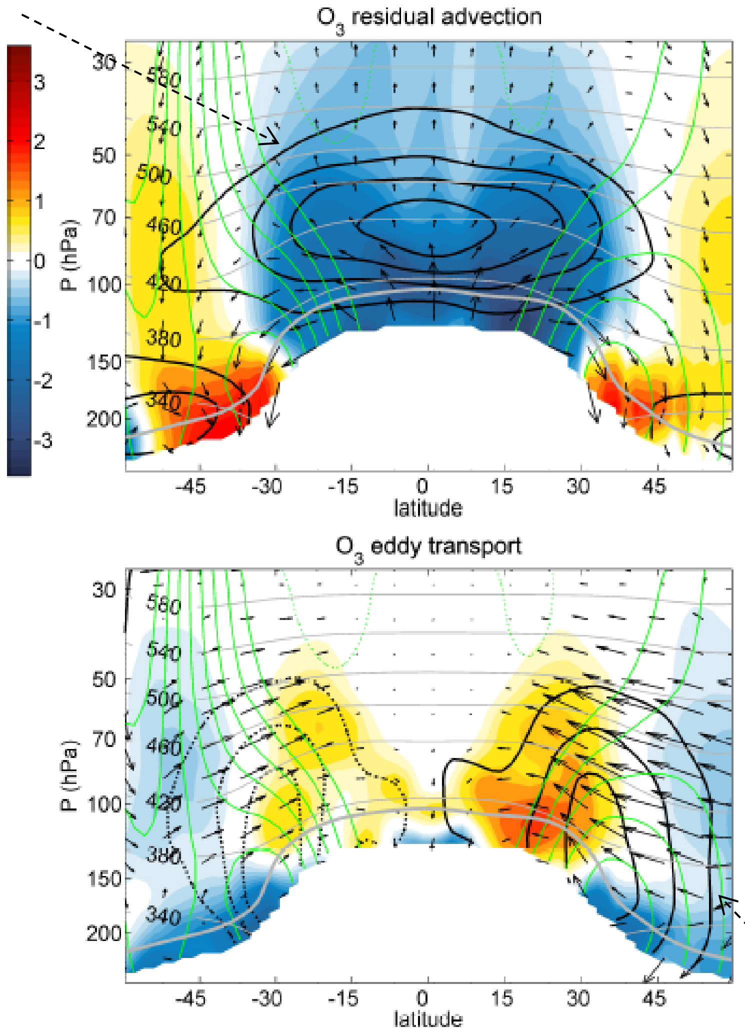
Abalos et al., 2013, Atmos. Chem. Phys.

# 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)

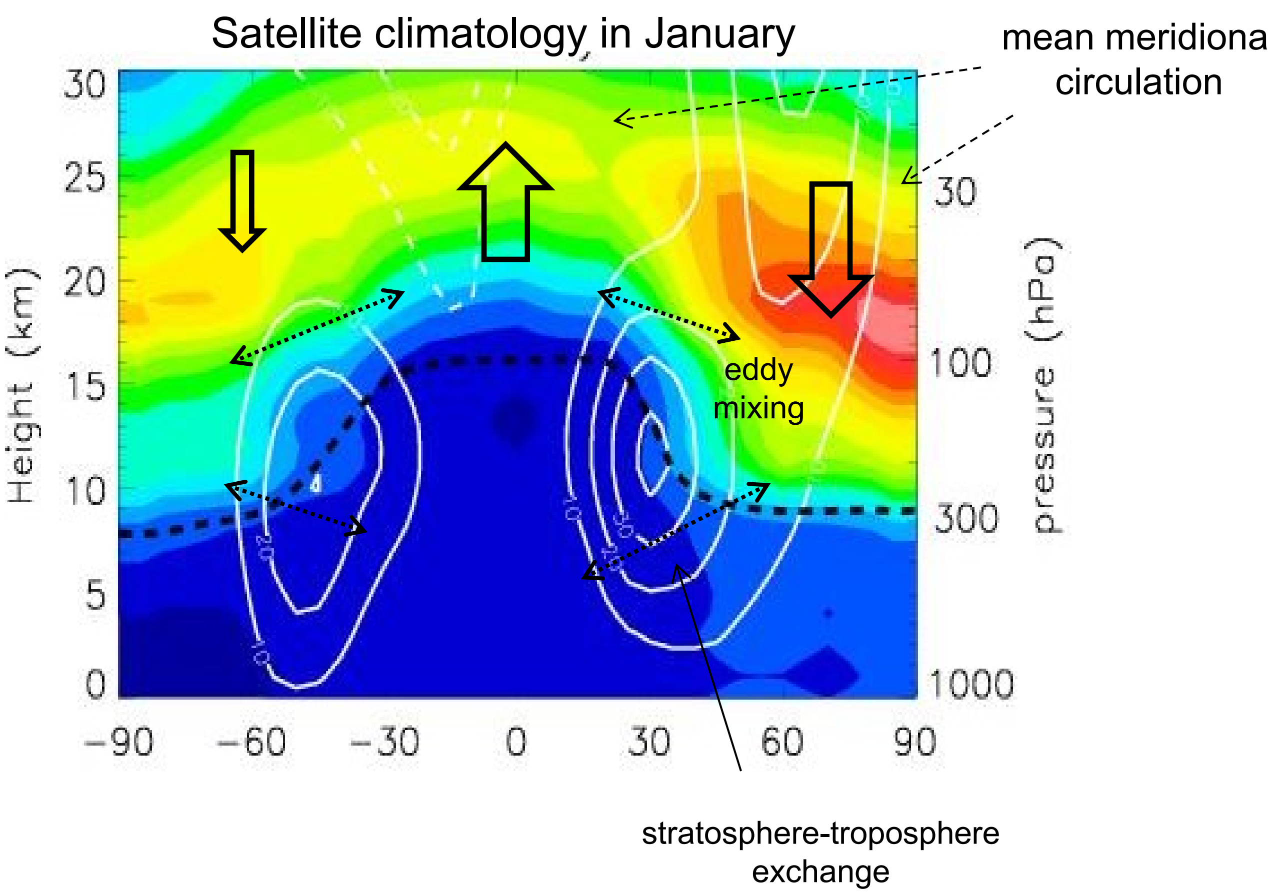
latitudinal ozone gradient

Abalos et al., 2013, Atmos. Chem. Phys.

# Ozone

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

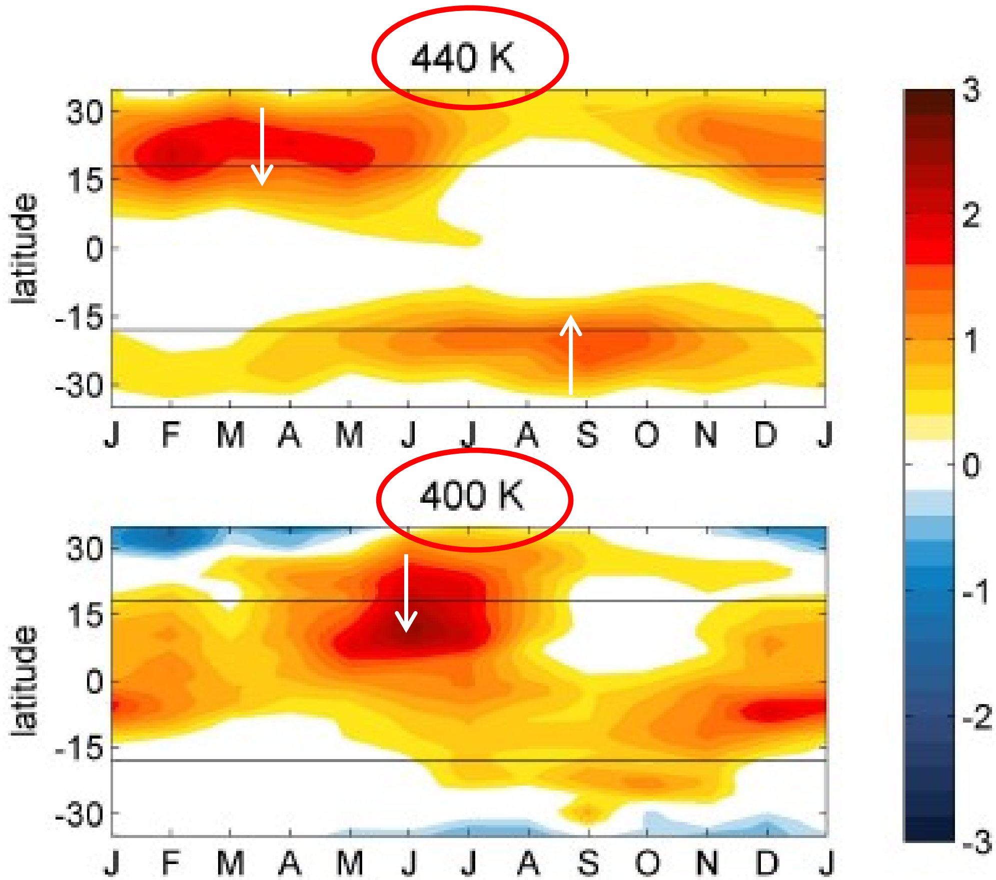
Ozone column density, DU/km



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

Winter-spring maximum in both hemispheres

summer maximum

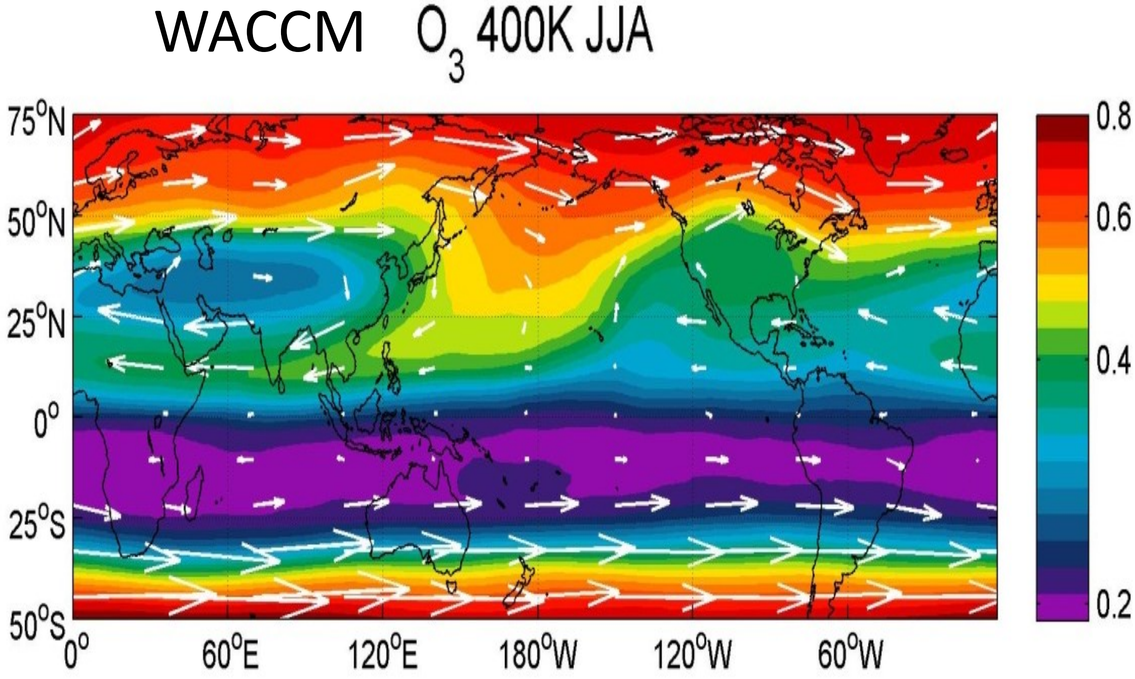



lower stratosphere

near tropopause

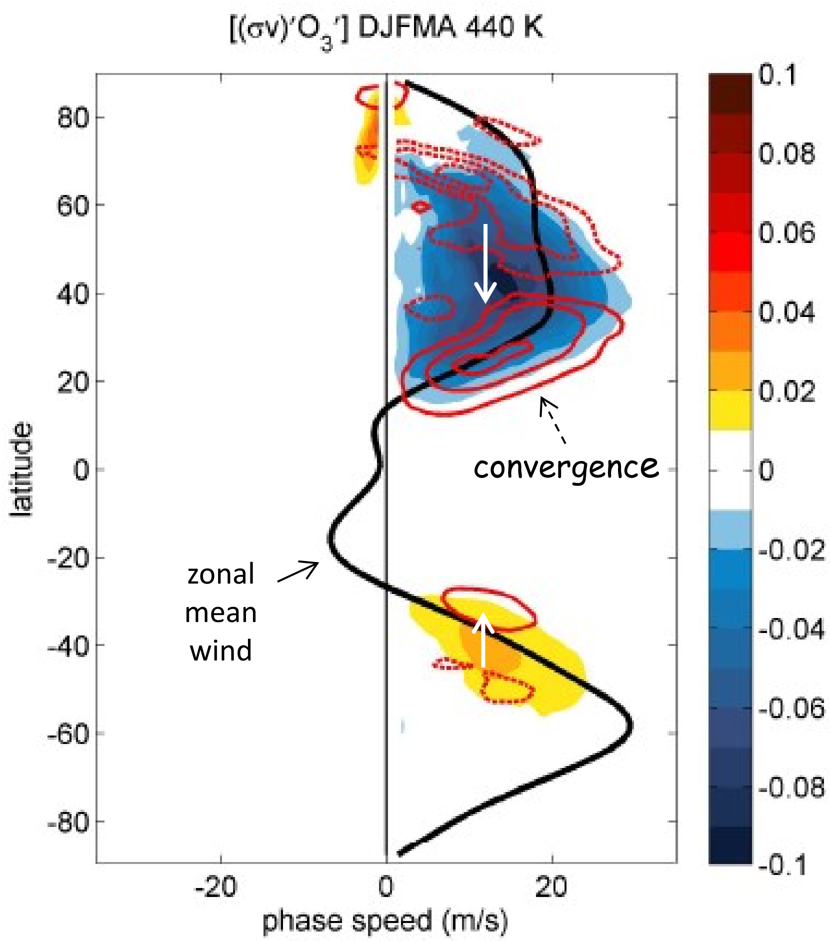
Abalos et al., 2013, Atmos. Chem. Phys.

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

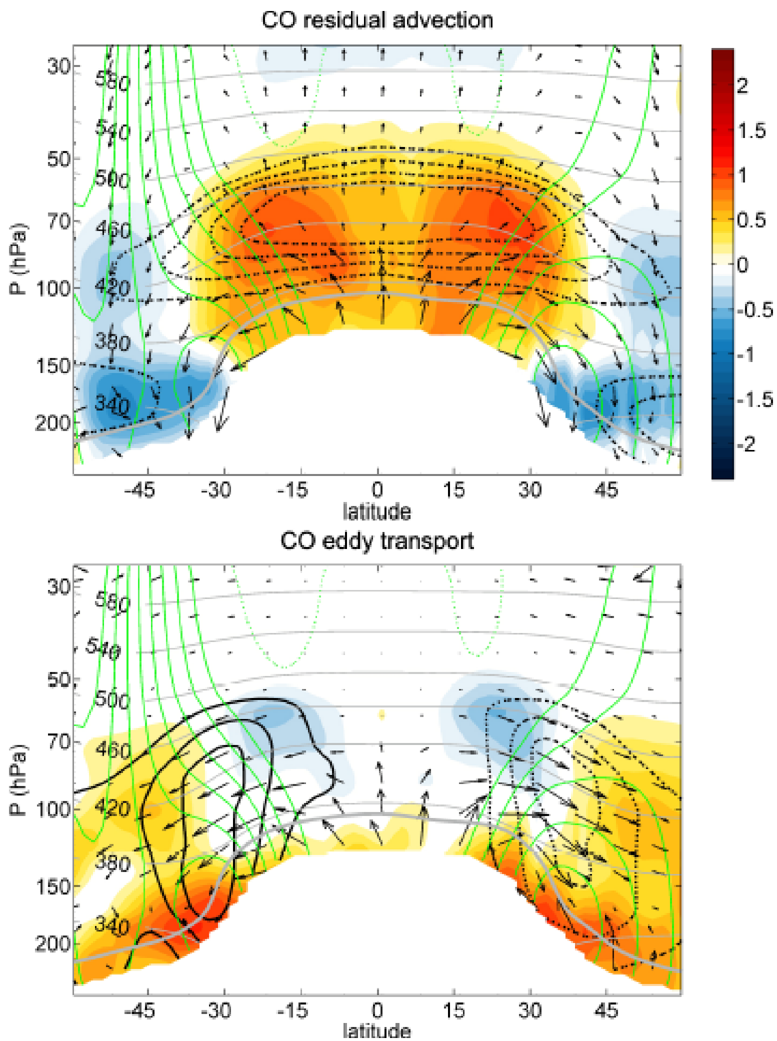
- eddy fluxes into the tropics due to transient Rossby waves
- Eddy fluxes 'see' critical lines ! (u=c)

Abalos et al., 2013, Atmos. Chem. Phys.

# 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

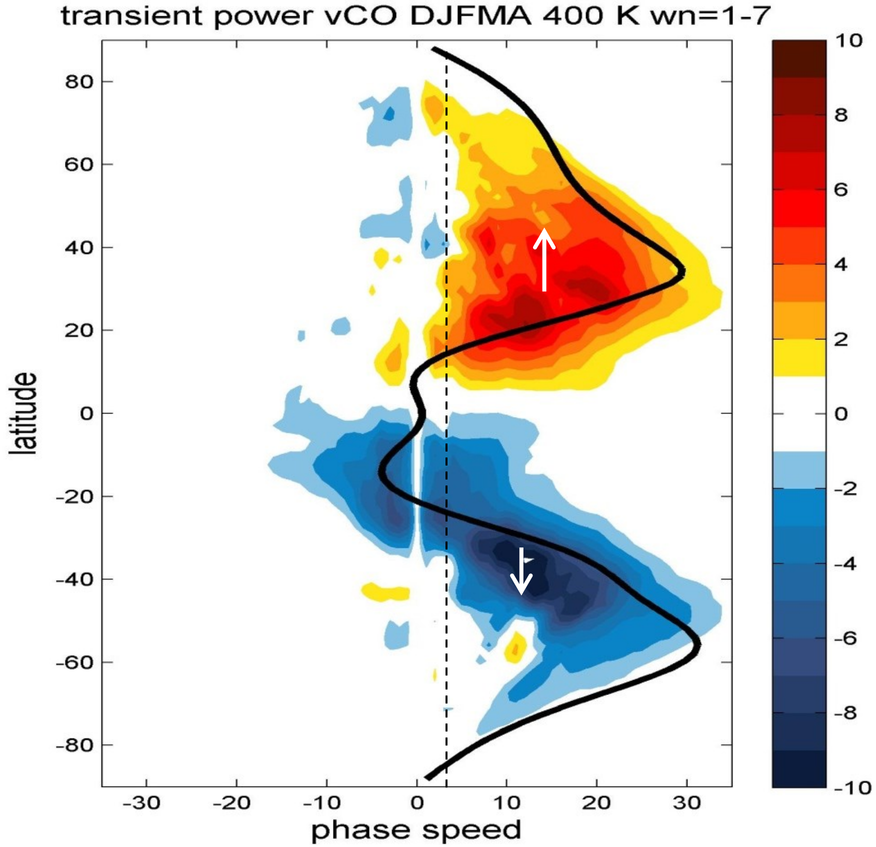
relatively small
contribution in
the tropics for CO

eddy
transport

Abalos et al., 2013, Atmos. Chem. Phys.

# 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

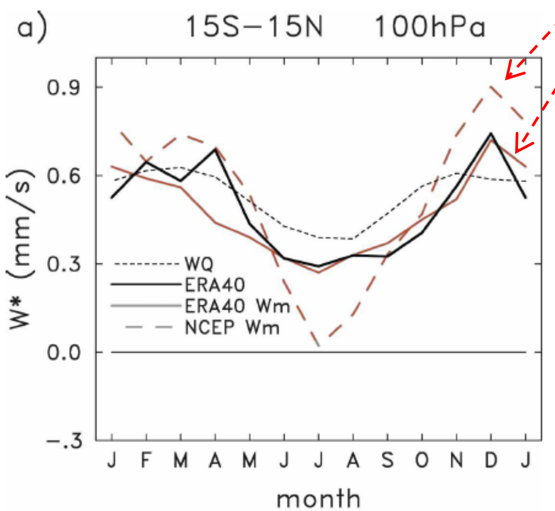
- Subtropics (baroclinic eddies from midlatitudes)

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

# Evaluating upwelling from subtropical EP fluxes

upwelling

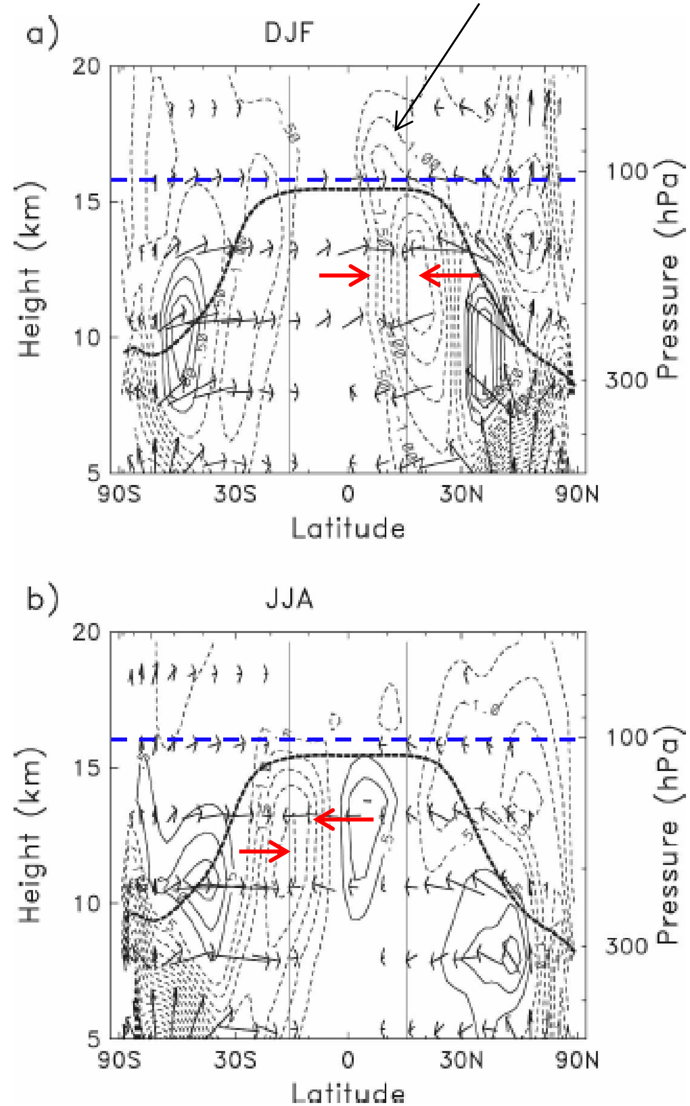
$w^*_m$ evaluated from subtropical EP fluxes




both extratropical and tropical waves contribute to subtropical forcing

Seasonal mean EP fluxes

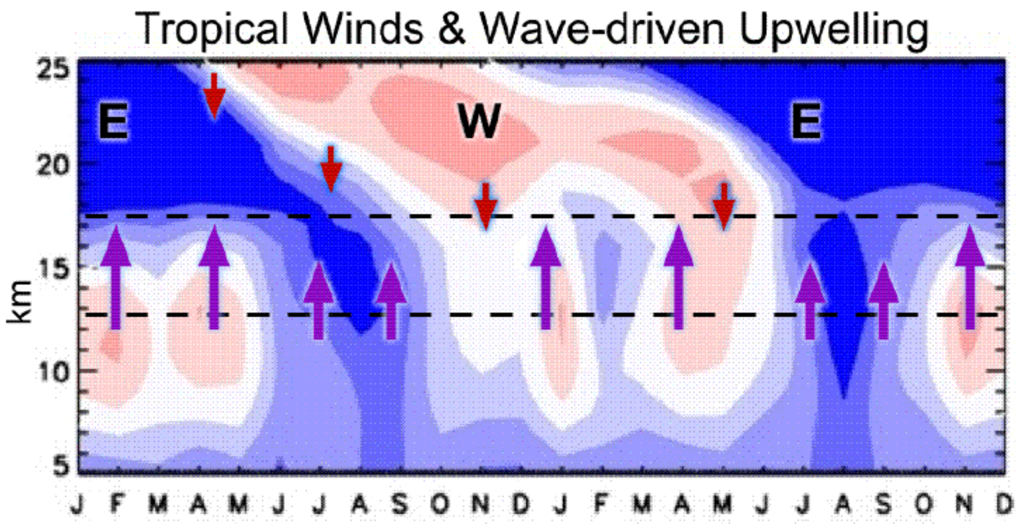
wave forcing extends deeper during DJF




Randel, Garcia and Wu, 2008

Ortland and Alexander, 2013:

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

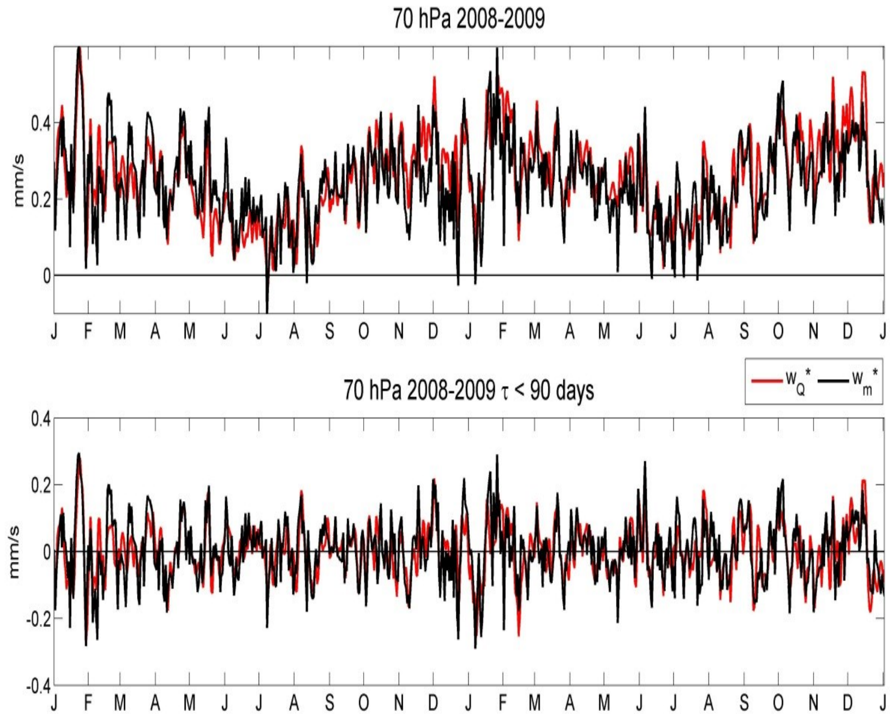



alternative: tropics driven completely by extratropics (e.g. Jucker et al, 2013)

*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

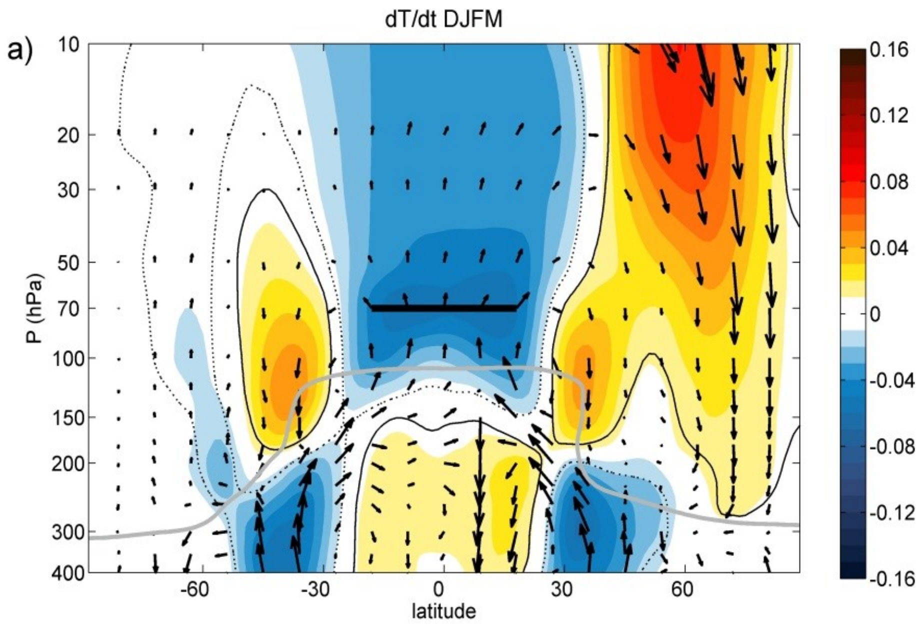
use regressions onto $w^*_m$ to identify circulation and dynamical forcing of transient upwelling

ERAi reanalysis 1979-2011

Abalos et al., 2014, J. Atmos. Sci.

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

Boreal winter
DJFM

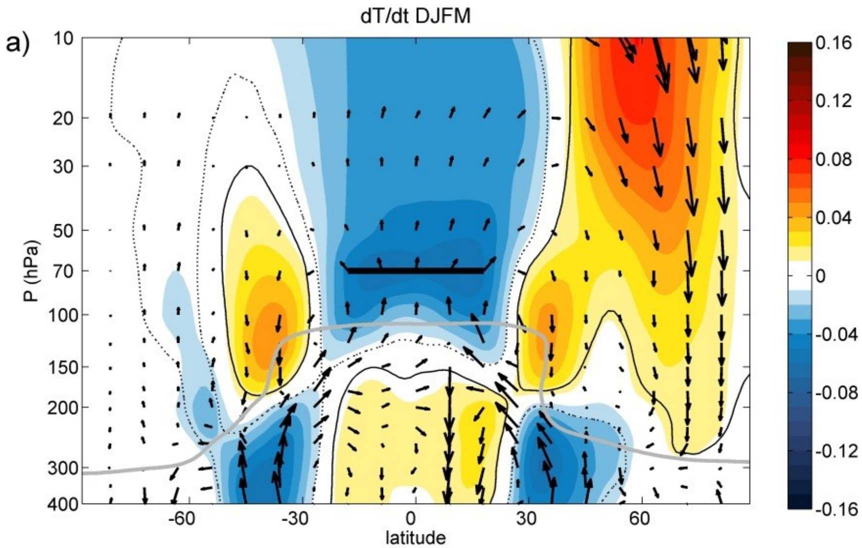



K/day

Abalos et al., 2014, J. Atmos. Sci.

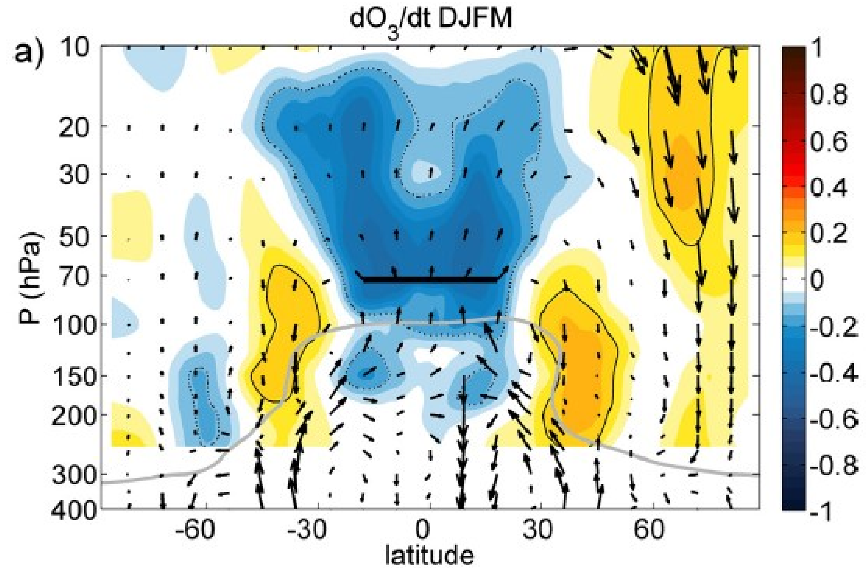
# Coherent signals in ozone tendencies

dT/dt




K/day

MLS ozone $dO_3/dt$

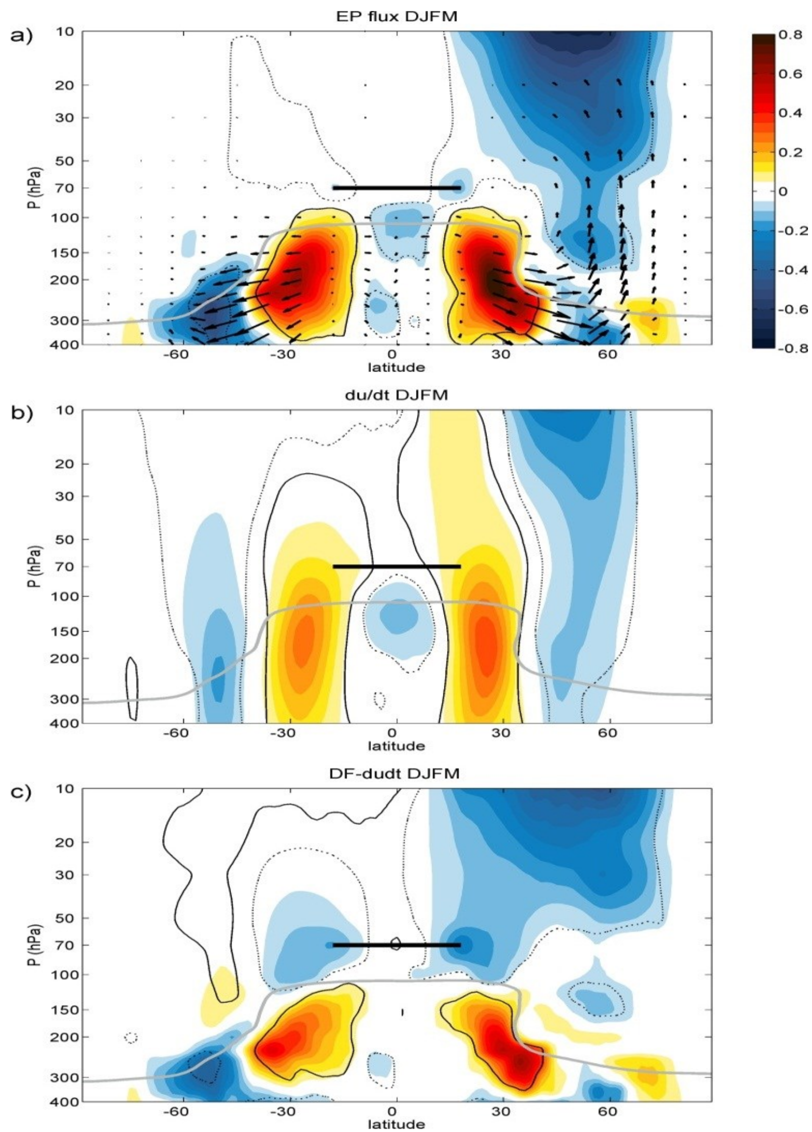



ppbv/day

Abalos et al., 2014, J. Atmos. Sci.

# Regressions onto w*$_m$

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




DF

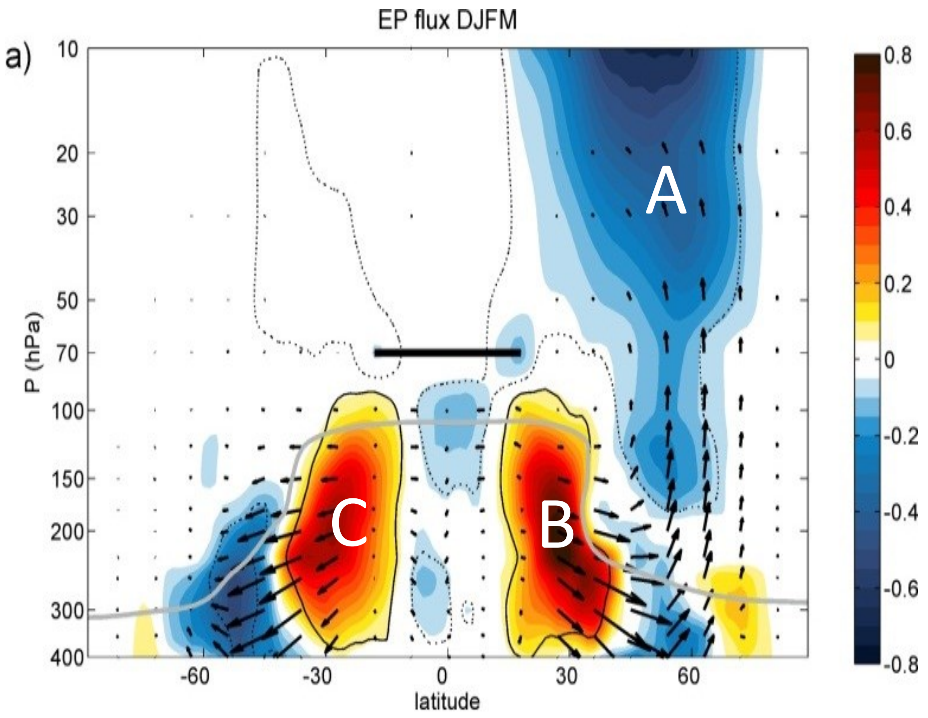
both terms are important

du/dt

DF – du/dt

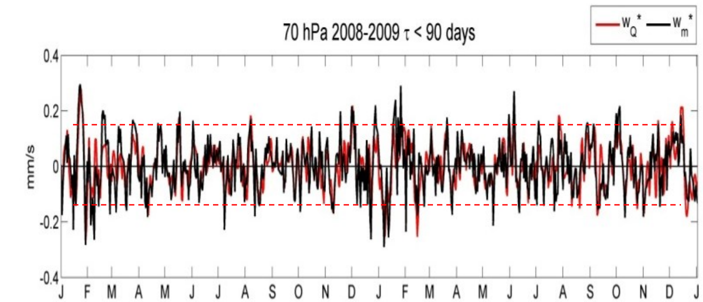
Abalos et al., 2014, J. Atmos. Sci.

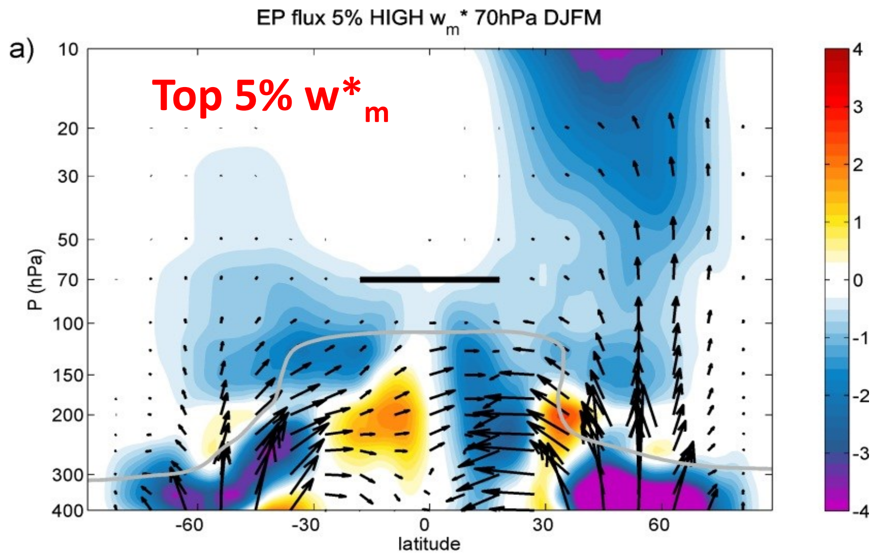
# EP flux 'centers of action' for forcing transient tropical upwelling:

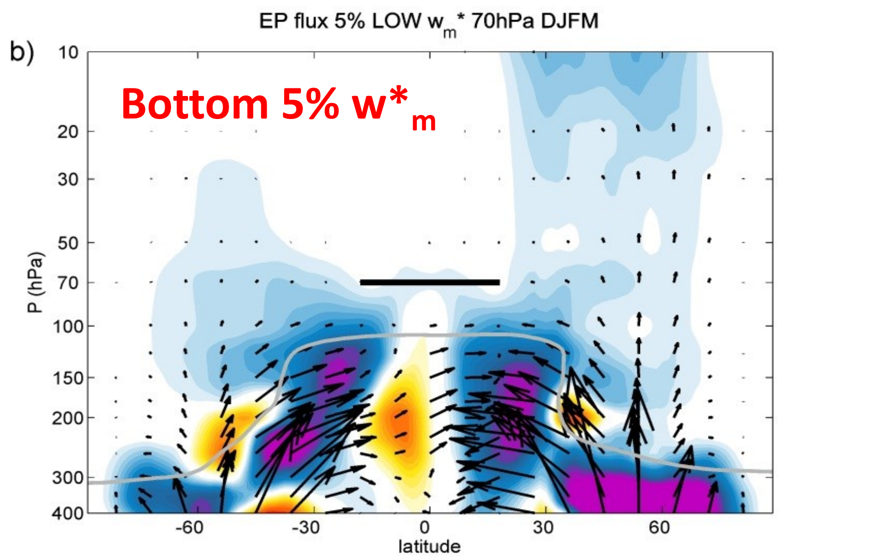


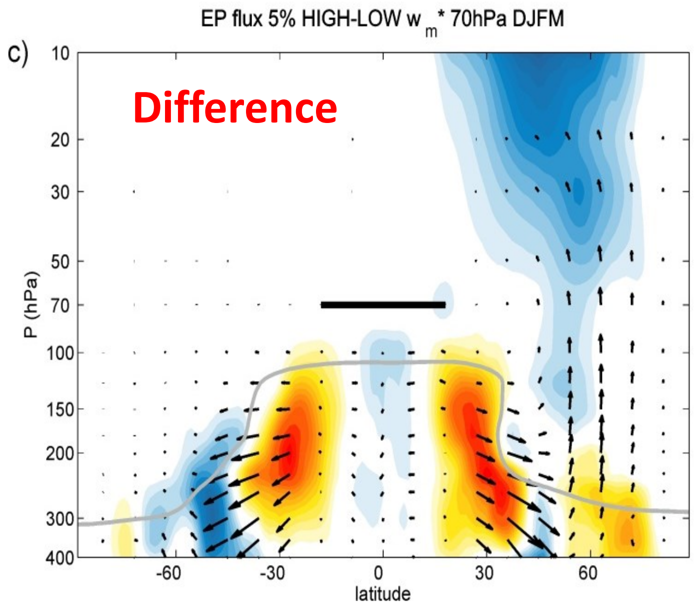

Abalos et al., 2014, J. Atmos. Sci.

# Composites of extreme 5% $w^*_m$ events



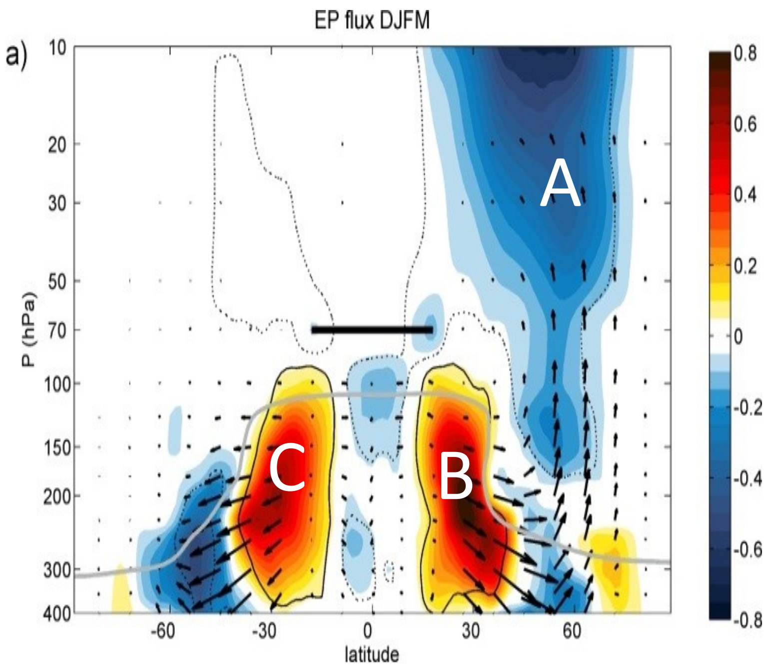



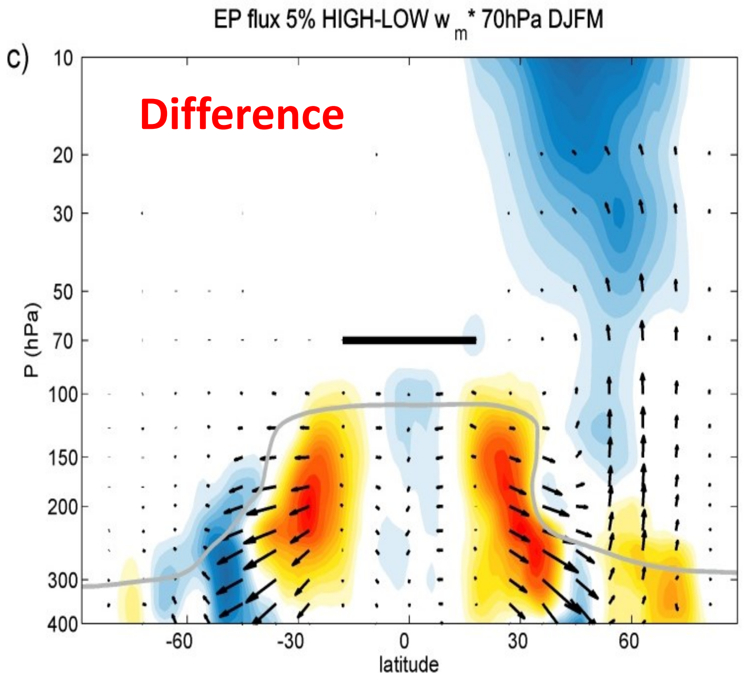




Abalos et al., 2014, J. Atmos. Sci.

## regressions



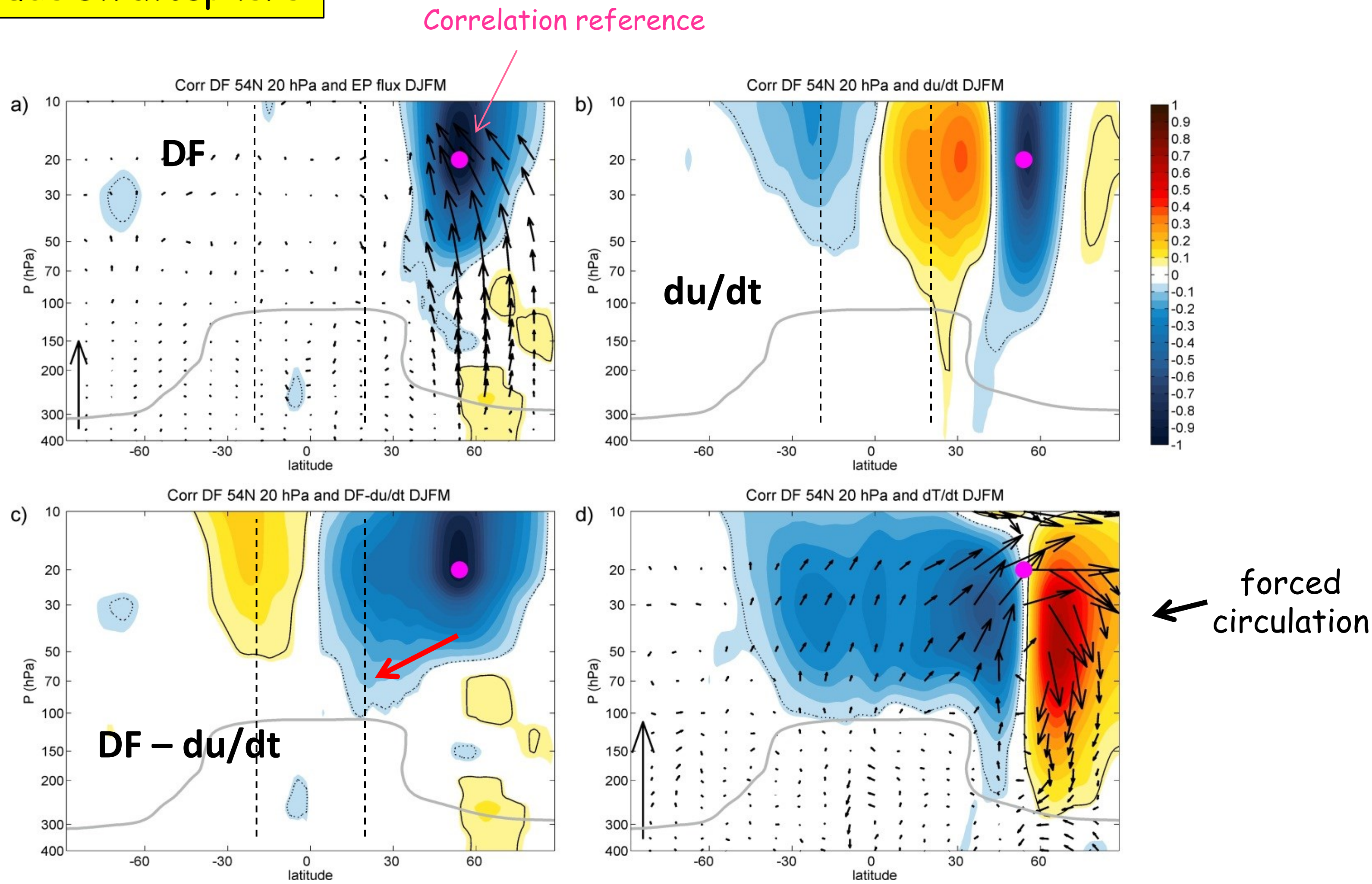

## extreme event composites




Abalos et al., 2014, J. Atmos. Sci.

# How does remote forcing influence tropical upwelling?

High latitude stratosphere

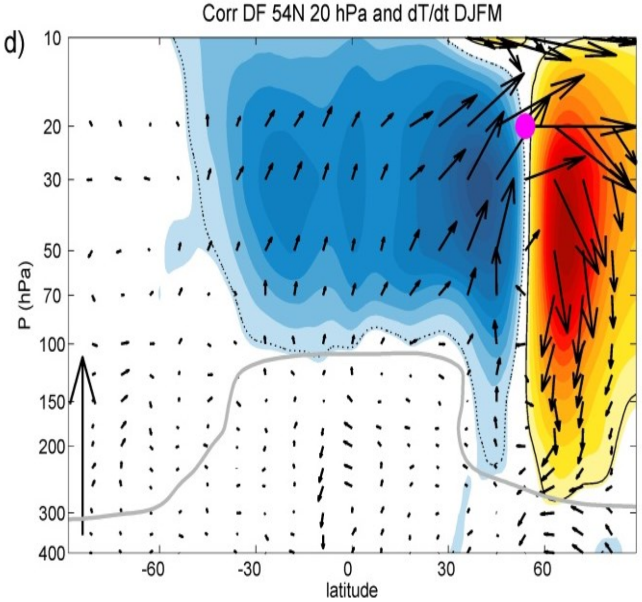


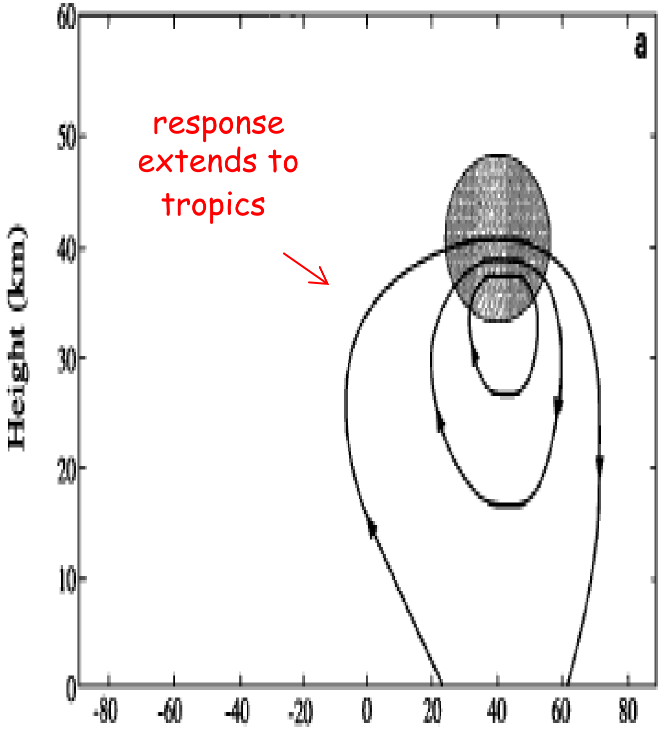

Abalos et al., 2014, J. Atmos. Sci.

theory (Holton et al, 1995)

(response to extratropical EP flux divergence)

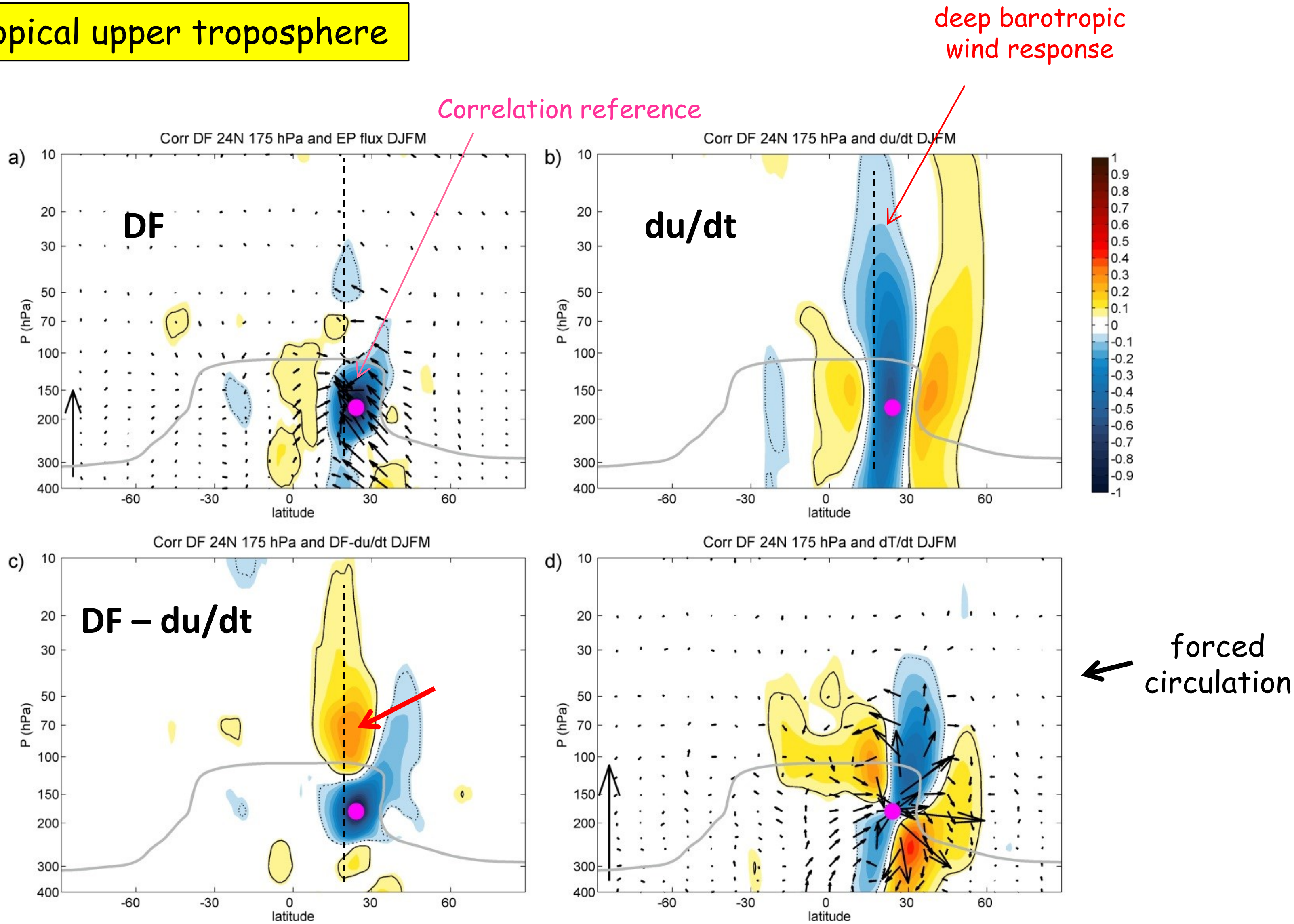
response to high latitude forcing



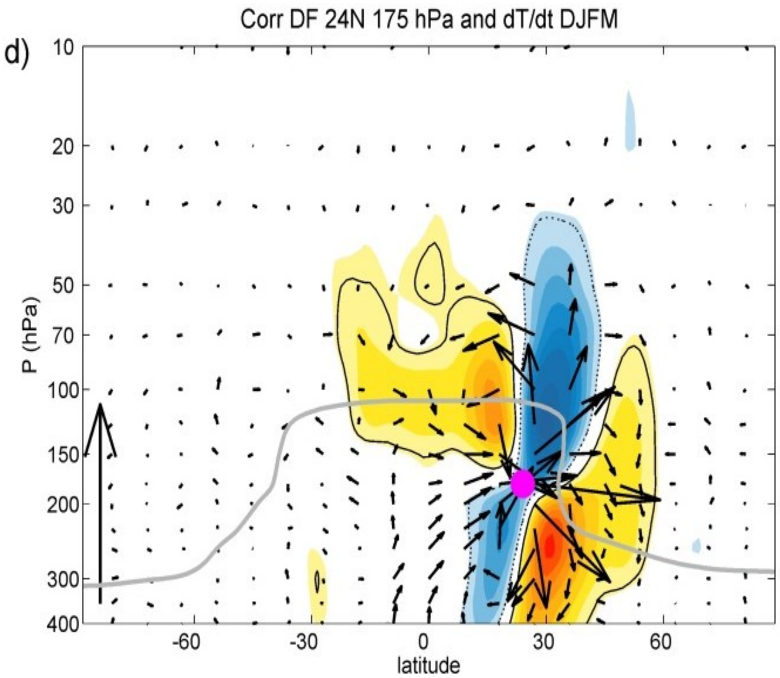

Abalos et al., 2014, J. Atmos. Sci.

# Subtropical upper troposphere



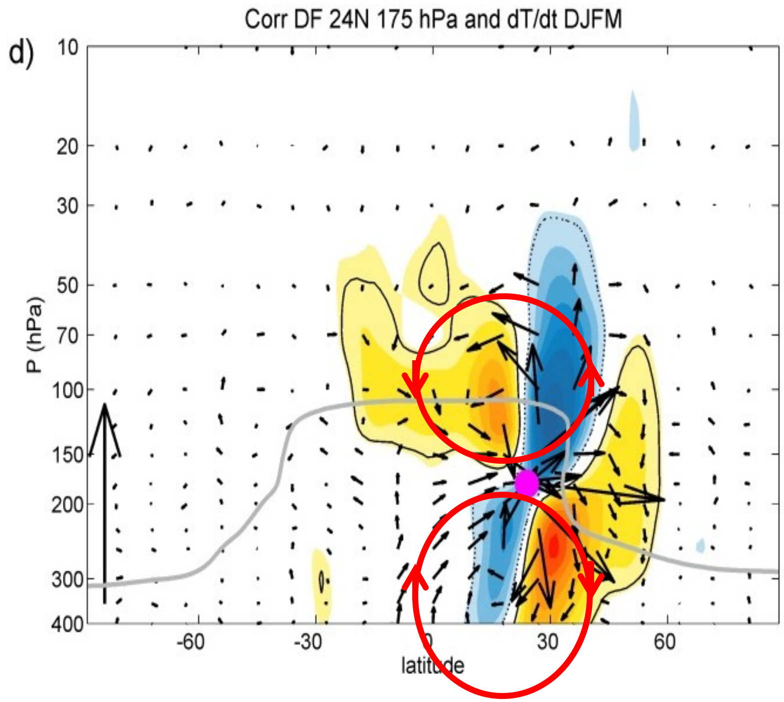

Abalos et al., 2014, J. Atmos. Sci.

# response to subtropical forcing



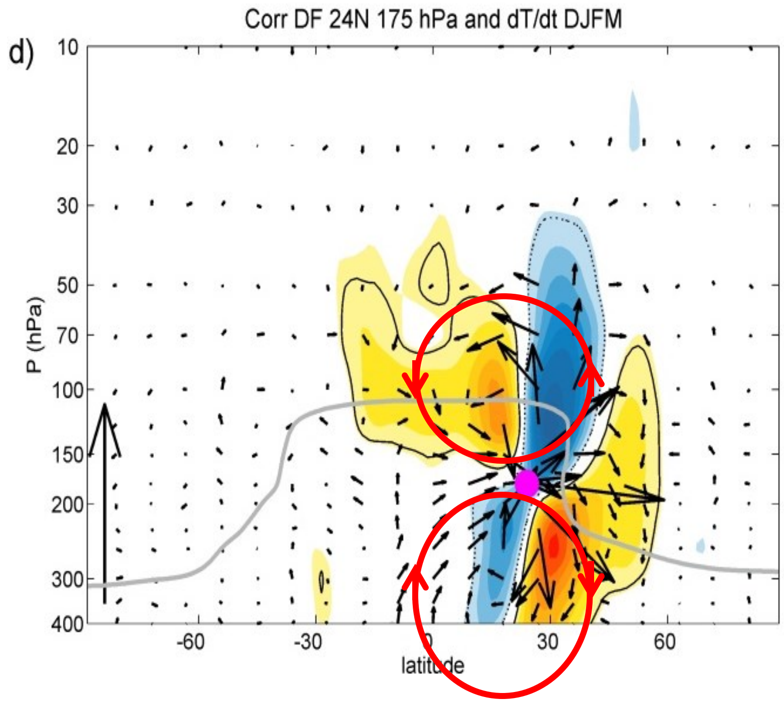

Abalos et al., 2014, J. Atmos. Sci.

# response to subtropical forcing



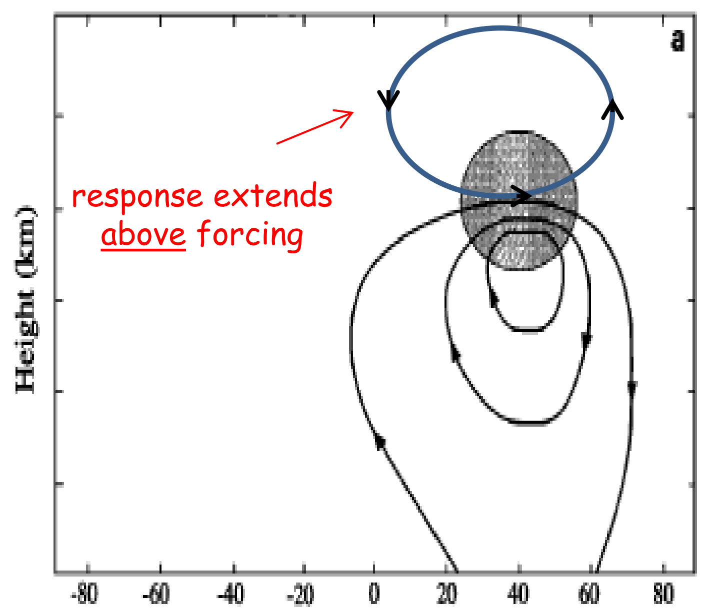

Abalos et al., 2014, J. Atmos. Sci.

response to subtropical forcing




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

Theory (Haynes, Holton)



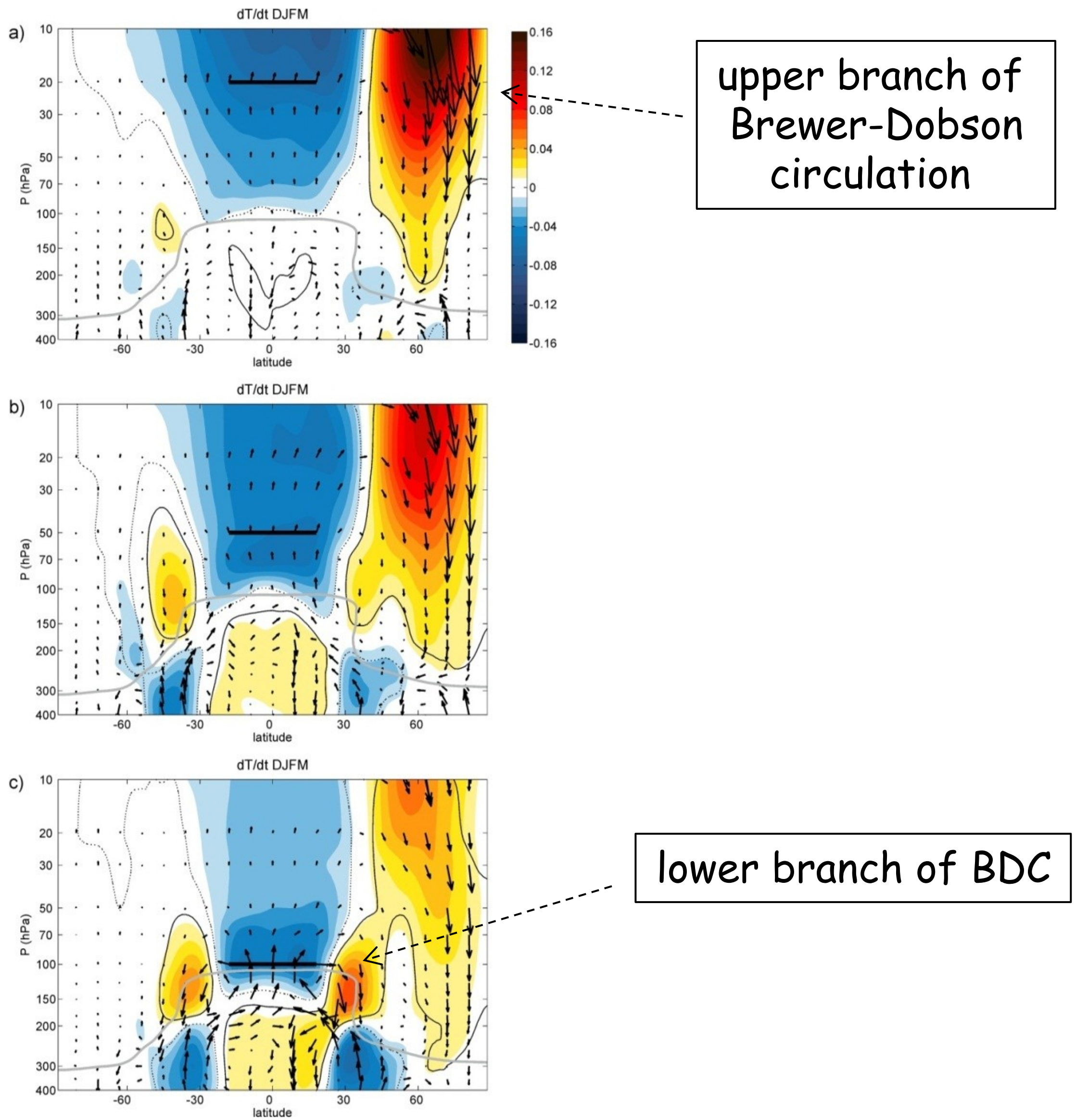

Abalos et al., 2014, J. Atmos. Sci.

# Dependence on the reference altitude for $w^*_m$

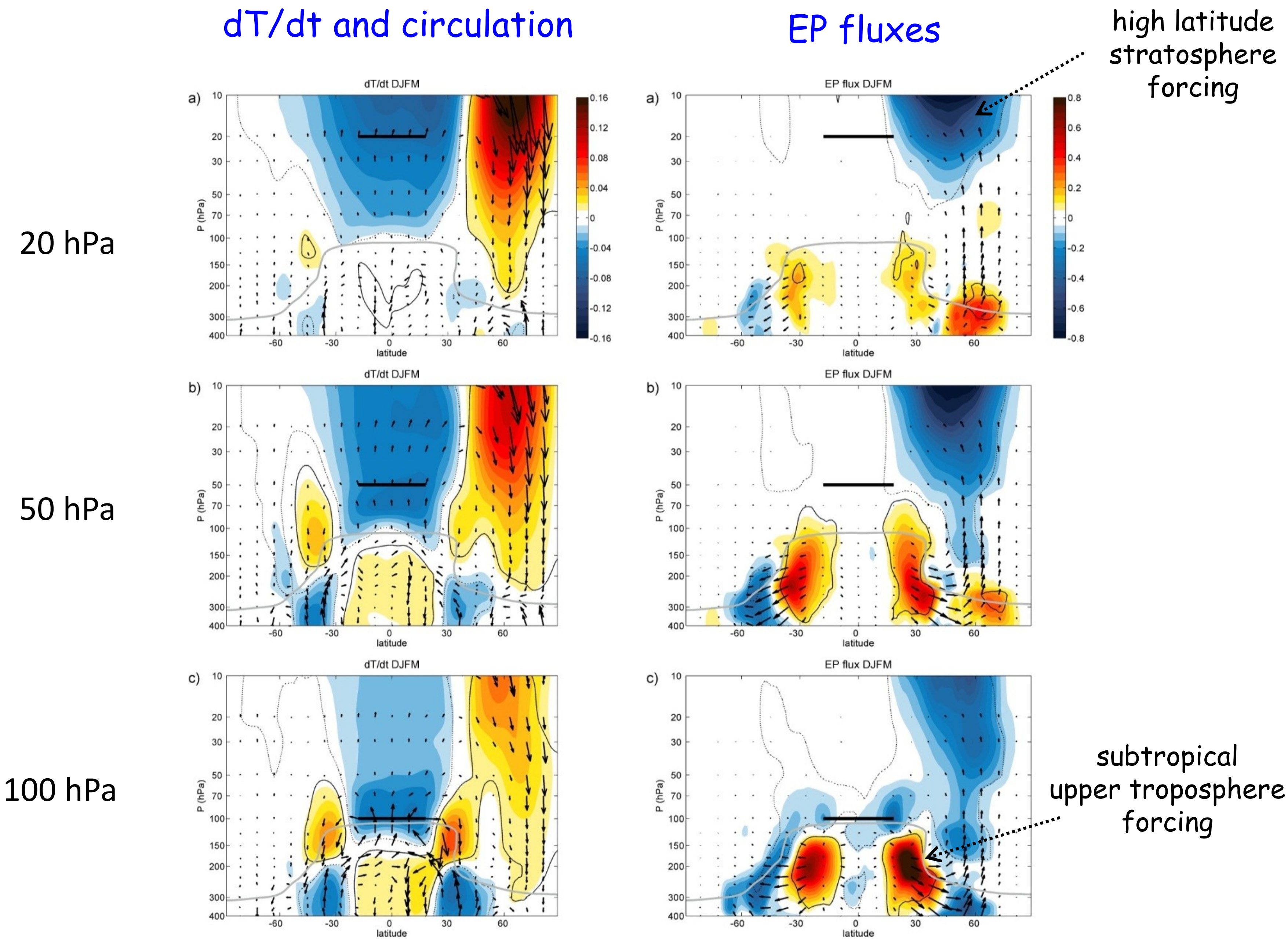
**20 hPa**

**50 hPa**

**100 hPa**



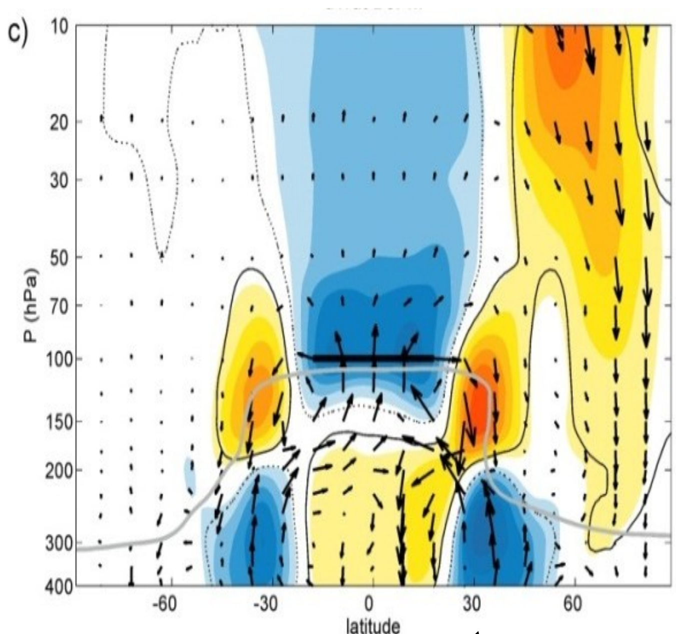

Abalos et al., 2014, J. Atmos. Sci.




Abalos et al., 2014, J. Atmos. Sci.

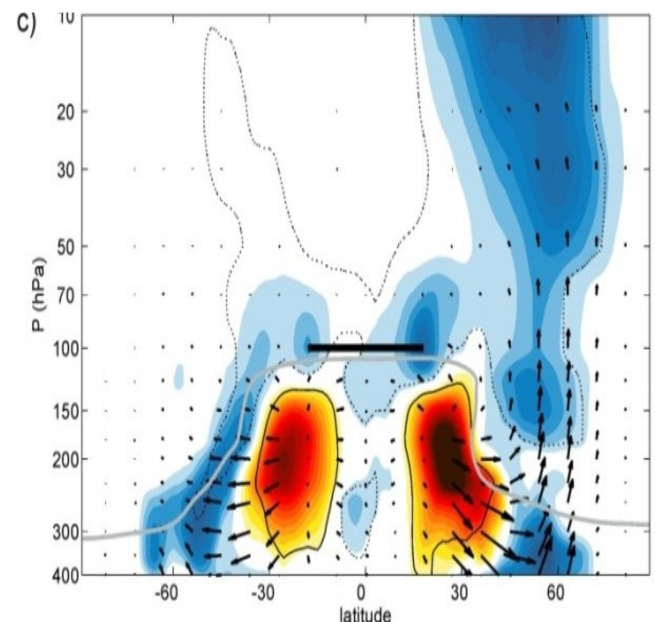
Lower branch of the BDC is primarily related to <u>subtropical wave forcing</u>

Residual circulation




note coherent tropospheric effects

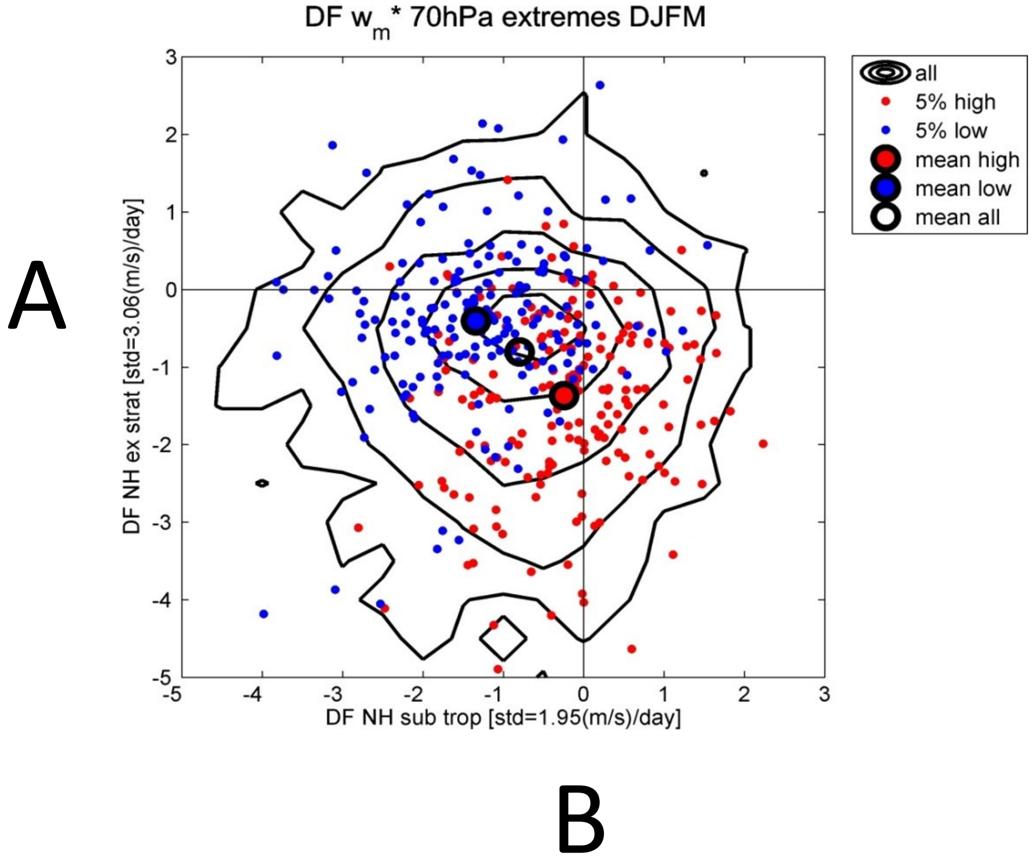
EP fluxes

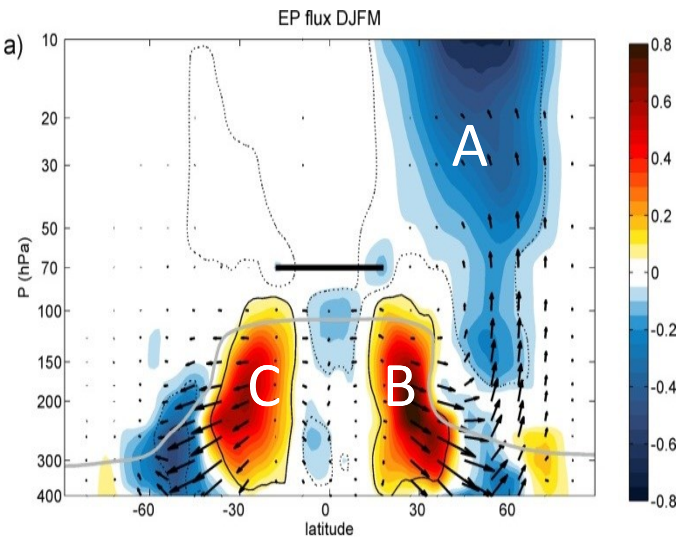



subtropical EP fluxes
drive lower branch of BDC

Abalos et al., 2014, J. Atmos. Sci.

# Is stratospheric forcing correlated with subtropical forcing?

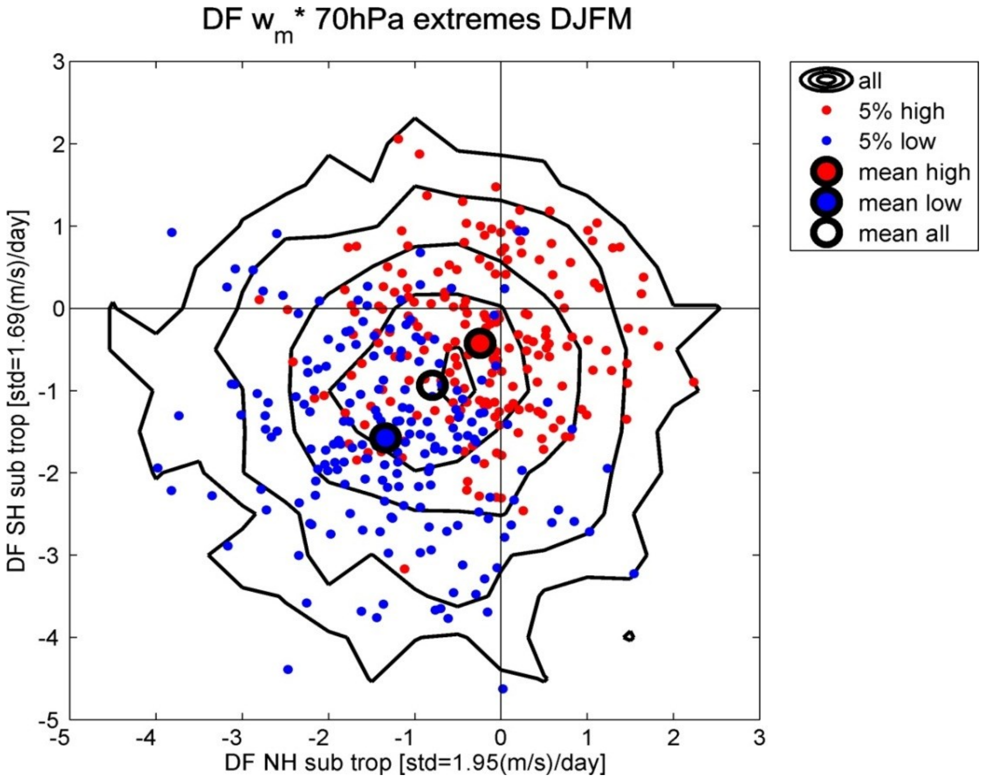


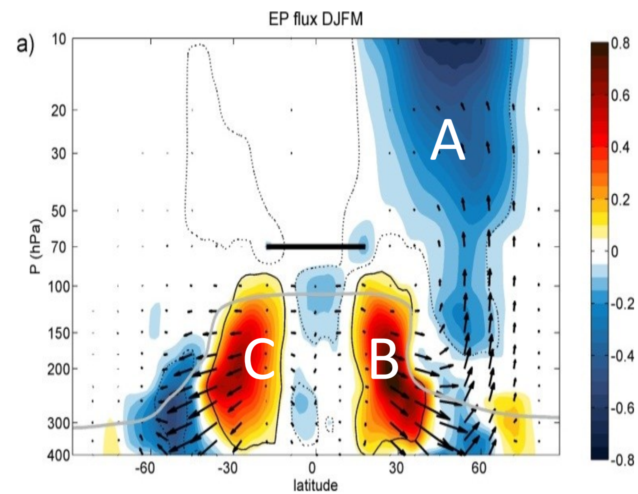

Abalos et al., 2014, J. Atmos. Sci.

# Is subtropical forcing related between the two hemispheres?

C




B

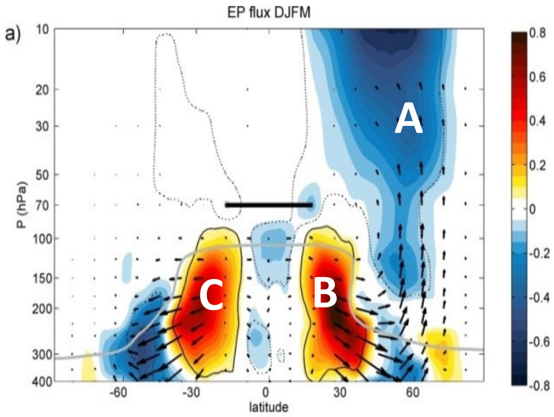



Abalos et al., 2014, J. Atmos. Sci.

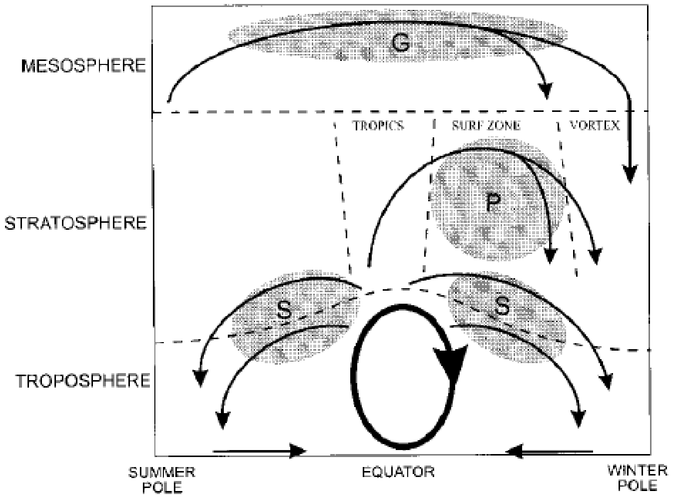
# Key points:

- 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

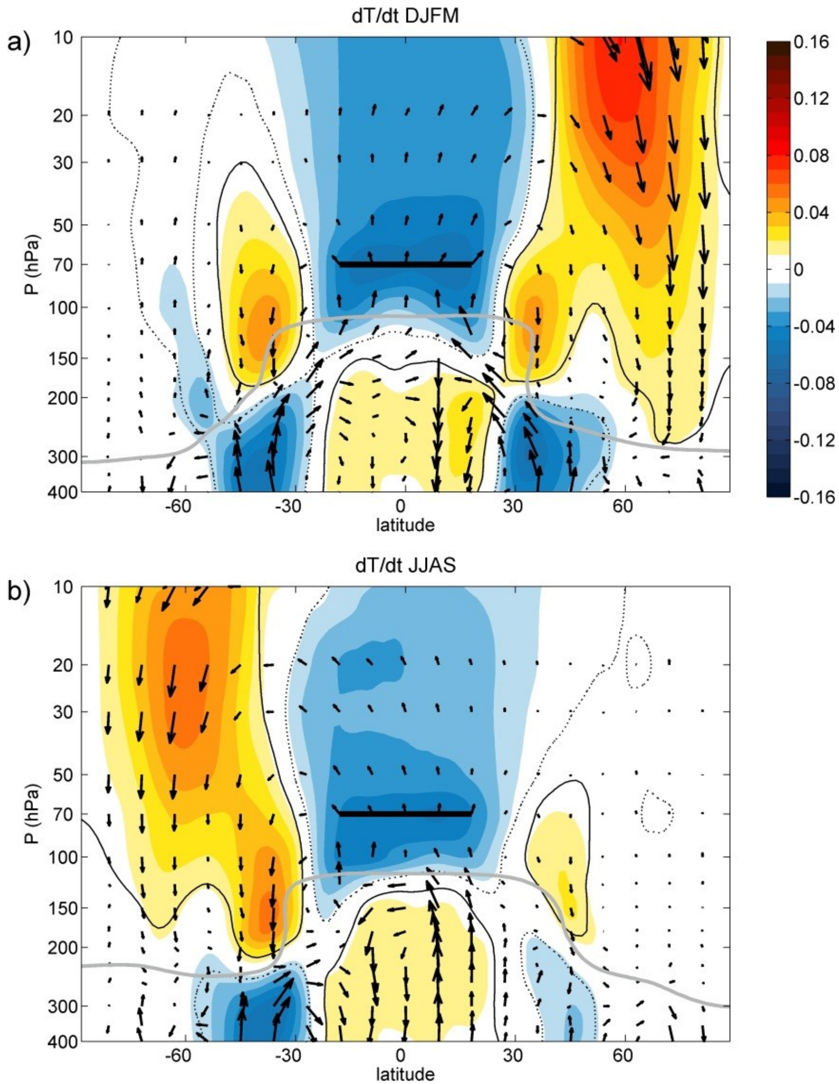



⟷




Abalos et al., 2014, J. Atmos. Sci.

# Extra slides



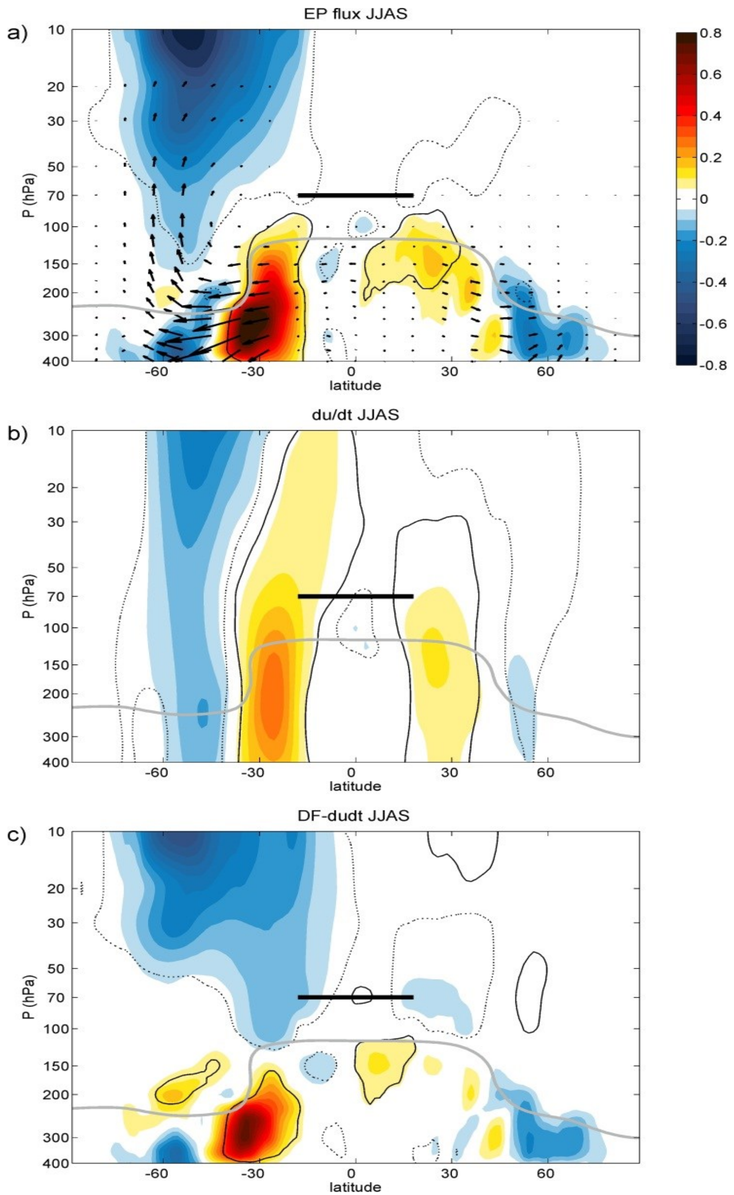

boreal winter
DJFM

boreal summer
JJAS

Abalos et al., 2014, J. Atmos. Sci.

Regressions onto $w^*_m$

SH winter JJAS

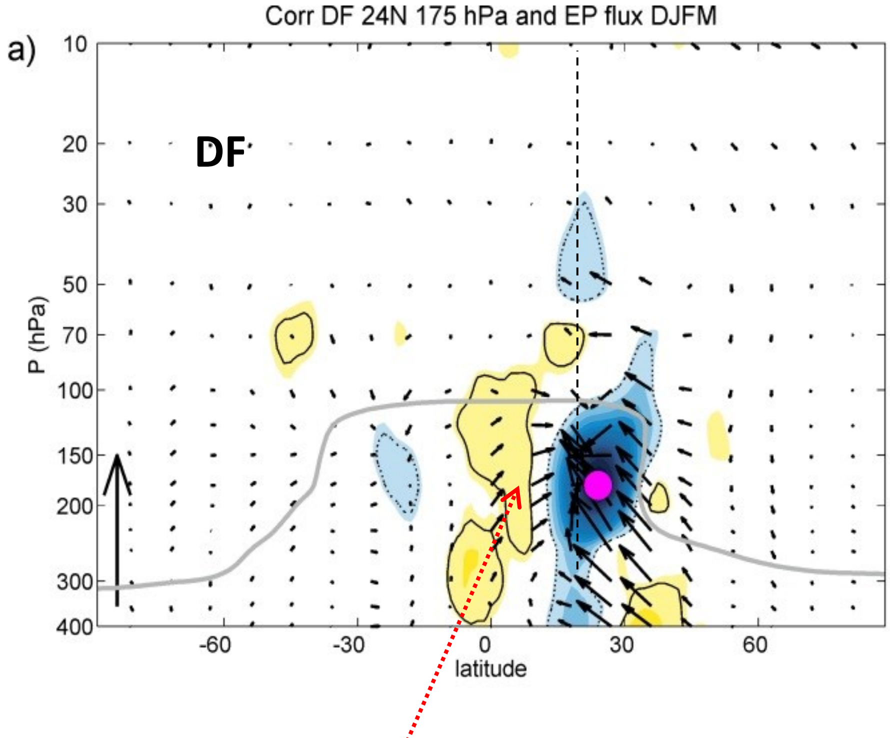



DF

du/dt

DF – du/dt

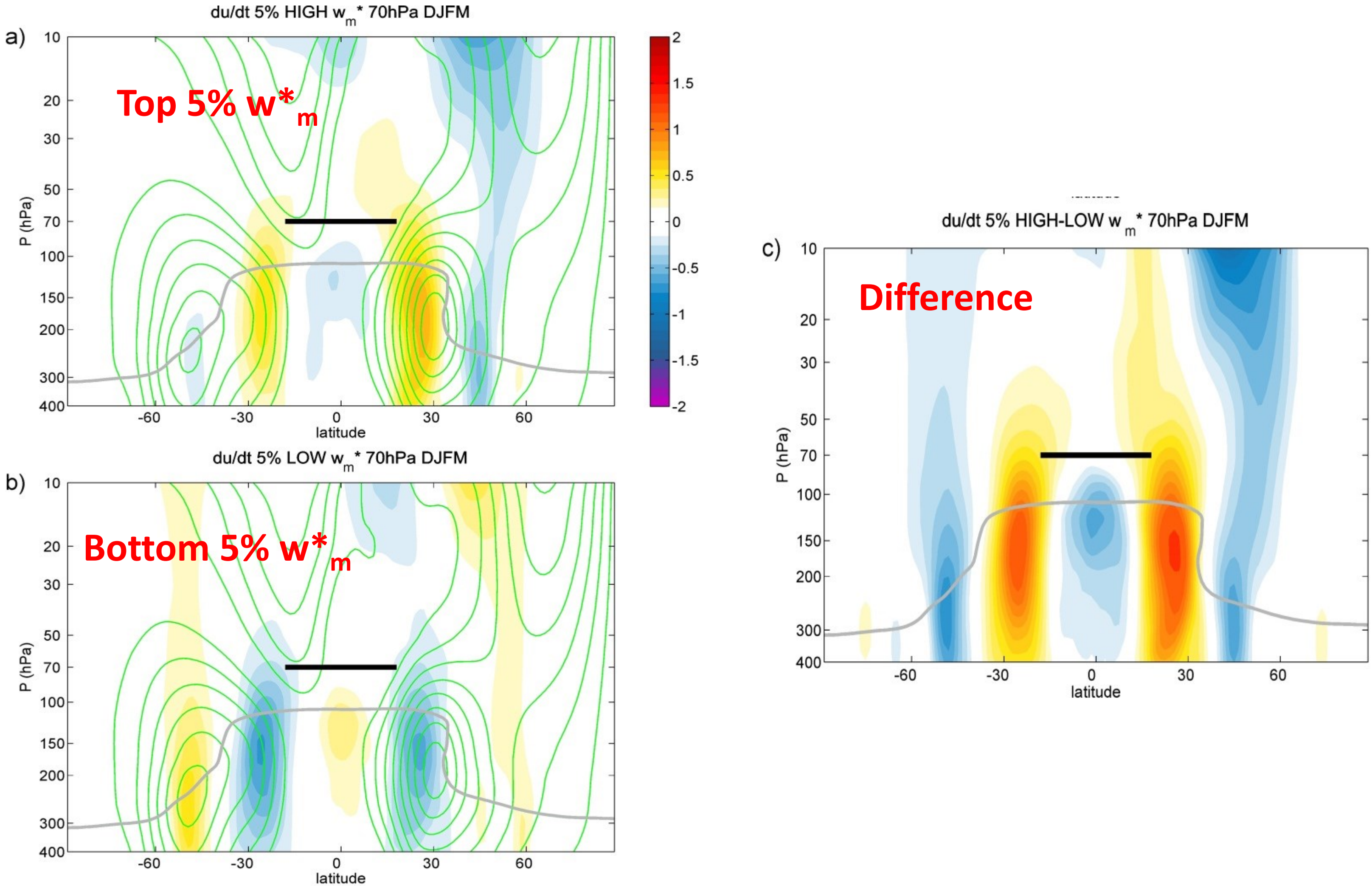
Abalos et al., 2014, J. Atmos. Sci.




Note contribution from (transient) equatorial waves

Abalos et al., 2014, J. Atmos. Sci.

# Composites of extreme 5% $w^*_m$ events: du/dt




Abalos et al., 2014, J. Atmos. Sci.

# Reference1


- Abalos, M., Randel, W.J. and Serrano, E., 2012: Variability in upwelling across the tropical tropopause and correlations with tracers in the lower stratosphere, Atmos. Chem. Phys., 12, 11505-11517.
- Abalos, M., Randel, W.J. and Serrano, E., 2014: Dynamical forcing of sub-seasonal variability in the tropical Brewer-Dobson circulation, J. Atmos. Sci., 71, 3439-3453.
- Abalos, M., Randel, W.J., Kinnison, D.E. and Serrano, E., 2013: Quantifying tracer transport in the tropical lower stratosphere using WACCM, Atmos. Chem. Phys., 13, 10591-10607.
- Chen, G. and Sun, L., 2011: Mechanisms of the tropical upwelling branch of the Brewer-Dobson circulation: The role of extratropical waves, J. Atmos. Sci., 68, 2878-2892.
- Holton, J.R., Haynes, P.H., McIntyre, M.H., Douglass, A.R., Rood, R.B. and Pfister, L., 1995: Stratosphere-troposphere exchange, Rev. Geophys., 33, 403-439.
- Jucker, M., Fueglistaler, S. and Vallis, G.K., 2013: Maintenance of the stratospheric structure in an idealized general circulation model, J. Atmos. Sci., 70, 3341-3358.
- Kerr-Munslow, A.M. and Norton, W.A., 2006: Tropical wave driving of the annual cycle in tropical tropopause temperatures. Part I: ECMWF Analyses, J. Atmos. Sci., 63, 1410-1419.
- Konopka, P., Grooß, J.-U., Gunther, G., Plöeger, F., Pommrich, R., Müller, R. and Livesey, N., 2010: Annual cycle of ozone at and above the tropical tropopause: observations versus simulations with the Chemical Lagrangian Model of the Stratosphere (CLaMS), Atmos. Chem. Phys., 10, 121-132.

# Reference2


- Konopka, P., Grooß, J.-U., Plöger, F. and Müllller, R., 2009: Annual cycle of horizontal in-mixing into the lower tropical stratosphere, J. Geophys. Res., 114, D19111.
- Ortland, D.A. and Alexander, M.J., 2014: The Residual-Mean circulation in the tropical tropopause layer driven by tropical waves, J. Atmos. Sci., 71, 1305-1322.
- Park, M., Randel, W.J., Kinnison, D.E., Emmons, L.K., Bernath, P.F., Walker, K.A., Boone, C.D. and Livesey, N.J., 2013: Hydrocarbons in the upper troposphere and lower stratosphere observed from ACE-FTS and comparisons with WACCM, J. Geophys. Res. Atmos., 118, 1964–1980.
- Ploeger, F., Konopka, P., Müller, R., Fueglistaler, S., Schmidt, T., Manners, J.C., Grooß, J.-U., Günther, G., Forster, P.M. and Riese, M., 2012: Horizontal transport affecting trace gas seasonality in the Tropical Tropopause Layer (TTL), J. Geophys. Res., 117, D09303.
- Plumb, R.A, 2002: Stratospheric transport, J. Meteorol. Soc. Japan, 80, 793-801.
- Randel, W.J. and Held, I.M., 1991: Phase speed spectra of transient eddy fluxes and critical layer absorption, J. Atmos. Sci., 48, 688-697.
- Randel, W.J., Garcia, R.R. and Wu, F., 2008: Dynamical balances and tropical stratospheric upwelling, J. Atmos. Sci., 65, 3584-3595.
- Randel, W.J., Wu, F. and Forster, P., 2007: The extratropical tropopause inversion layer: global observations with GPS data, and a radiative forcing mechanism, J. Atmos. Sci., 64, 4489-4496.

# Reference3


- Randel, W.J. and Jensen, E.J., 2013: Physical processes in the tropical tropopause layer and their role in a changing climate, Nature Geoscience, 6, 169-176.
- Reed, R.J. and Vicek, C.L., 1969: The annual temperature variation in the lower tropical stratosphere, J. Atmos. Sci., 26, 163-167.
- Taguchi, M., 2009: Wave driving in the tropical lower stratosphere as simulated by WACCM. Part I: Annual cycle, J. Atmos. Sci., 66, 2029-2043.
- Ueyama, R., Gerber, E.P., Wallace, J.M. and Frierson, D.M.W., 2013: The role of high-latitude waves in the intraseasonal to seasonal variability of tropical upwelling in the Brewer-Dobson circulation, J. Atmos. Sci., 70, 1631-1648.
- Ueyama, R. and Wallace, J.M., 2010: To what extent does high-latitude wave forcing drive tropical upwelling in the Brewer-Dobson circulation?, J. Atmos. Sci., 67, 1232-1246.
- Yulaeva, E., Holton, J.R. and Wallace, J.M., 1994: On the cause of the annual cycle in tropical lower-stratospheric temperatures, J. Atmos. Sci., 51, 169-174.