Tropical tropopause dynamics observed from a decade of GPS radio occultation data

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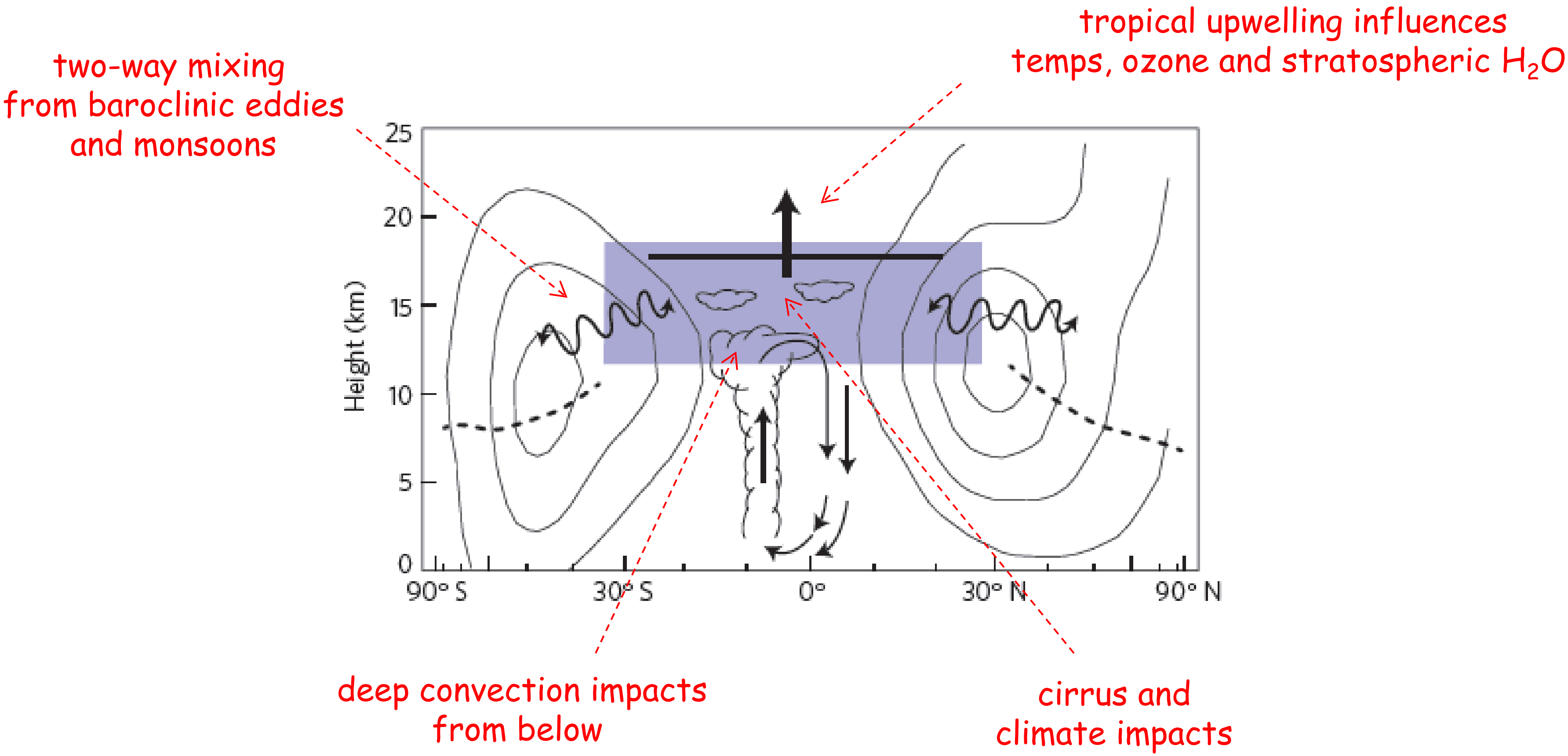
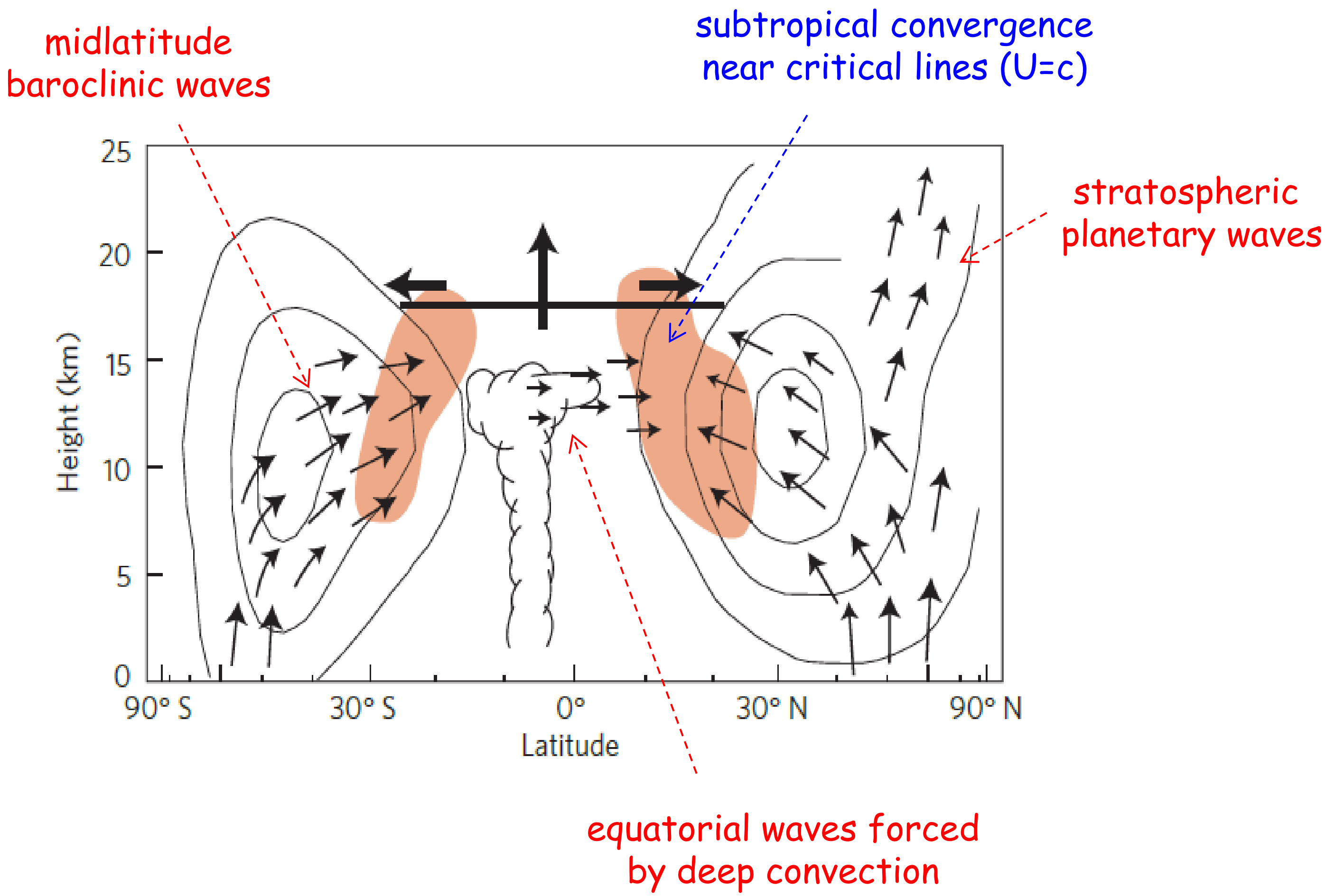
Transport near the tropical tropopause layer (TTL)

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



Randel and Jensen, 2013, Nat. Geosci.

Dynamical forcing of tropical upwelling

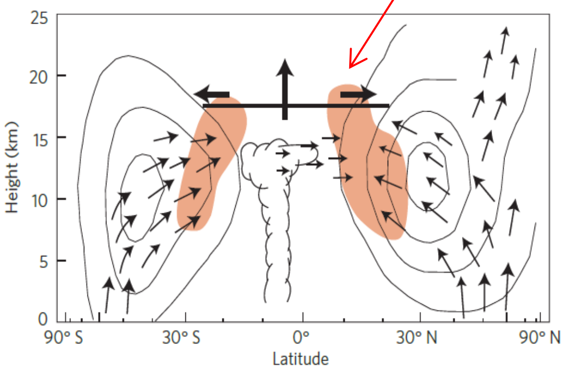


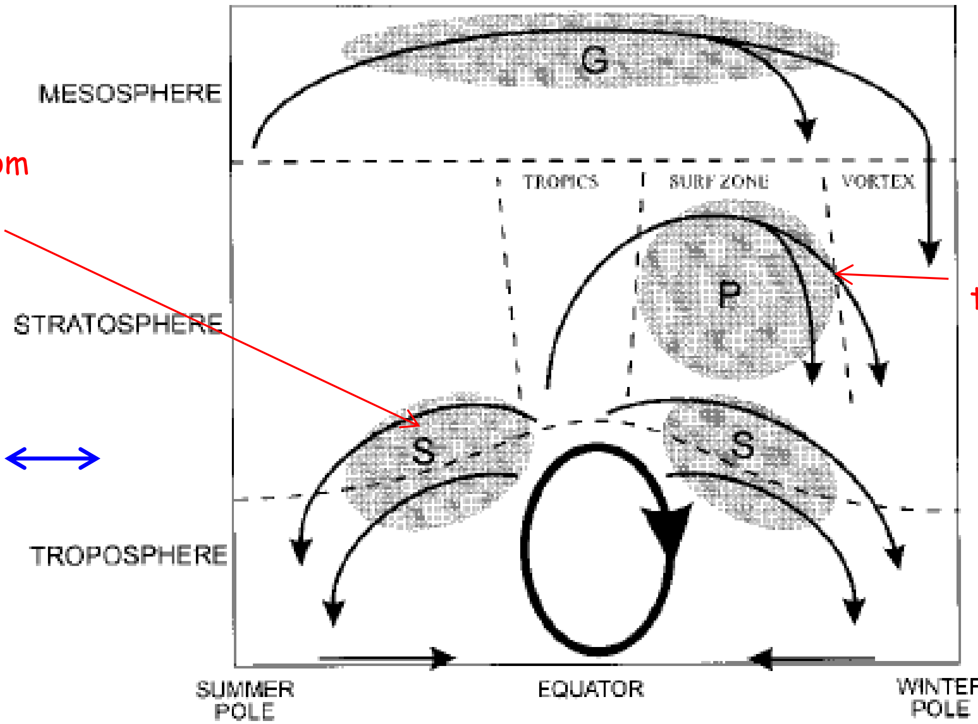
Randel and Jensen, 2013, Nat. Geosci.

Deep and shallow branches of Brewer-Dobson circulation

shallow branch from synoptic waves

deep branch tied to planetary waves





Randel and Jensen, 2013, Nat. Geosci.

Plumb (2002); also Birner and Bonish, 2011

Stratospheric H_2O is controlled by tropical cold point temperatures

Brewer, 1949

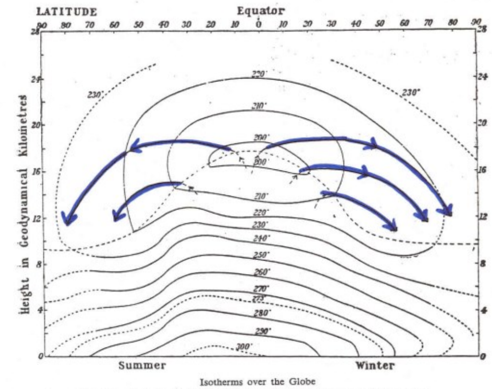
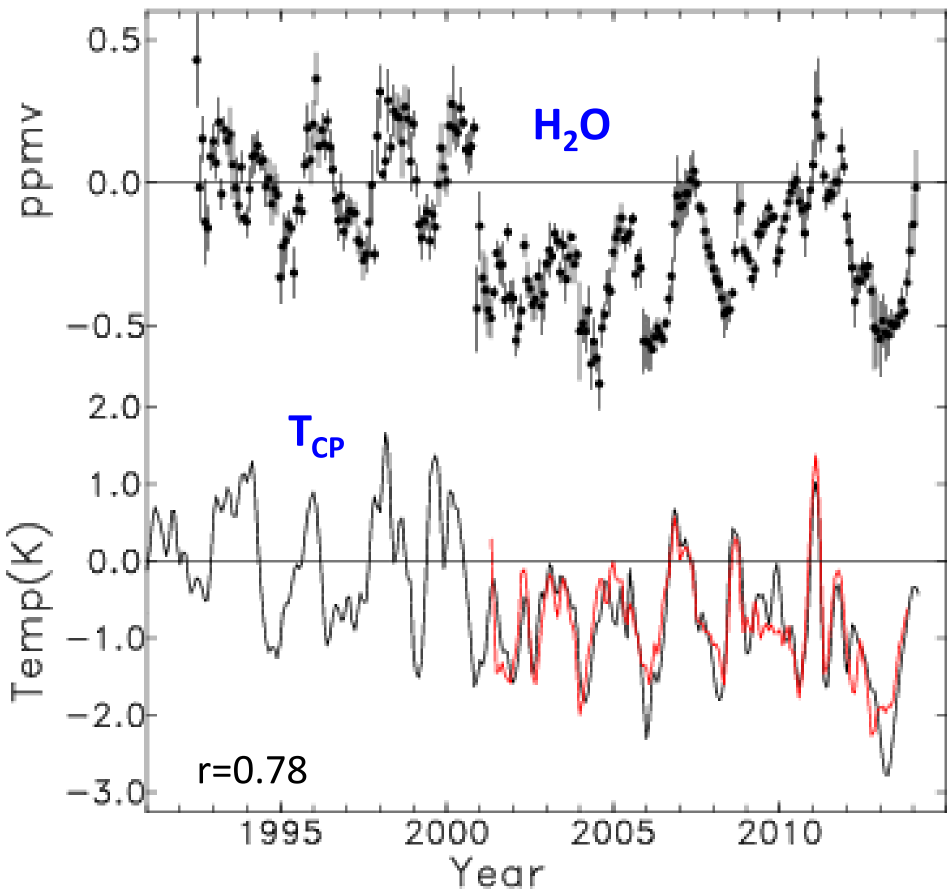


FIG. 5. A supply of dry air is maintained by a slow mean circulation from the equatorial tropopause.

Interannual changes during 1992-2014



near-global mean (60° N-S) water vapor at 82 hPa from combined HALOE-MLS data

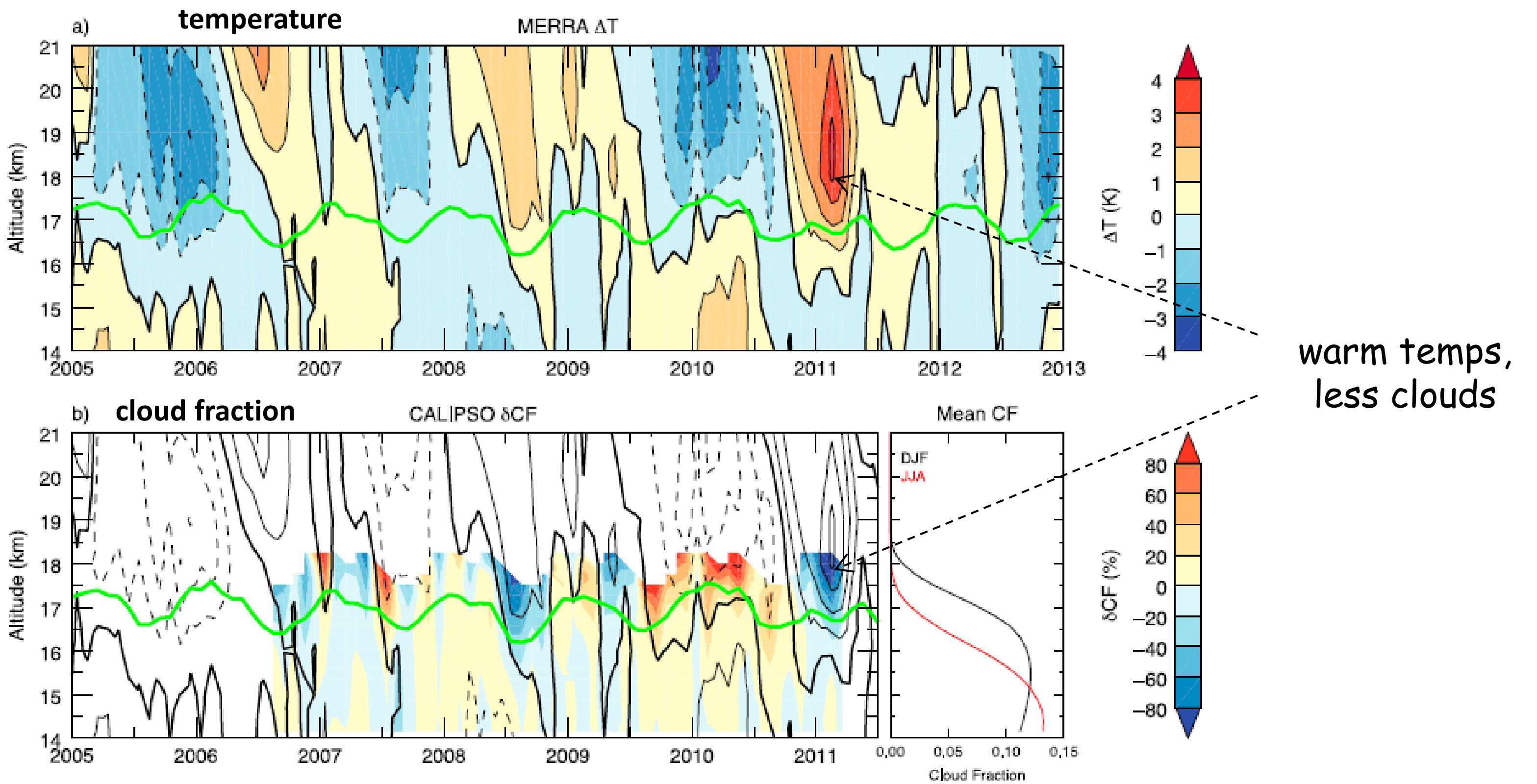
cold-point tropical tropopause temperatures

black: radiosondes
red: GPS (after 2001)

Interannual variability of tropical tropopause layer clouds

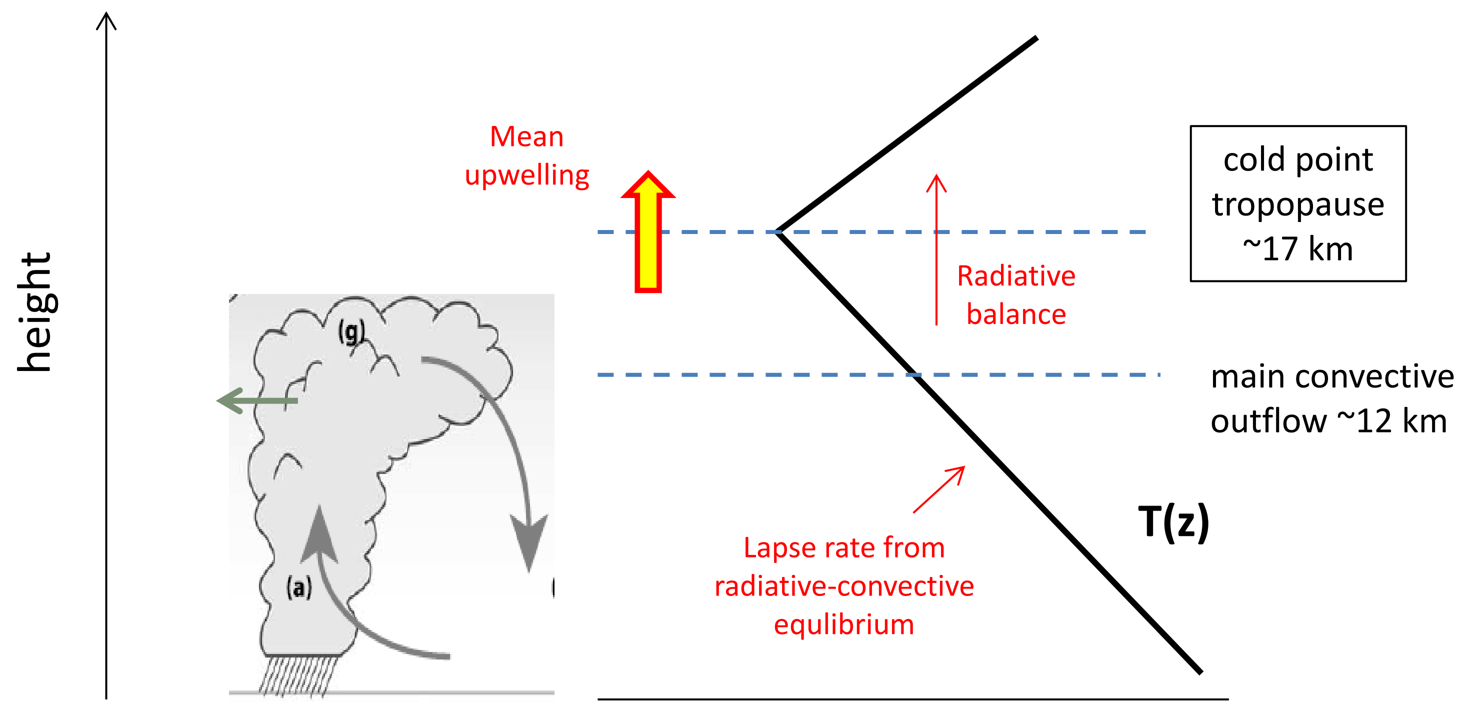
Sean M. Davis,[1,2] Calvin K. Liang,[3] and Karen H. Rosenlof[1]

GRL, 2013



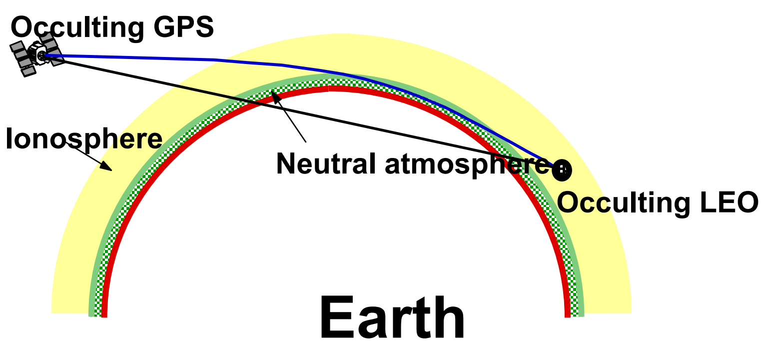
What controls variability of the cold-point tropopause?

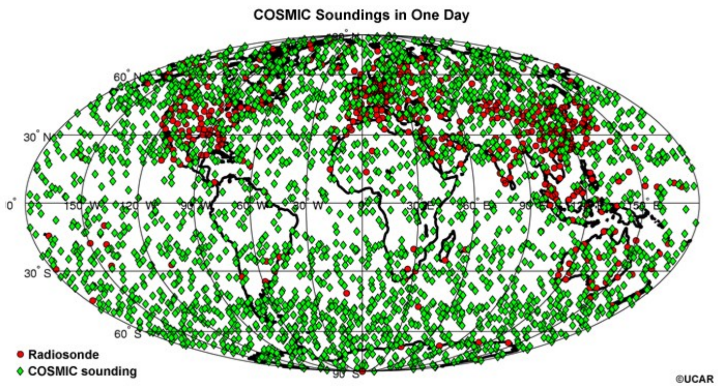
- Convection or tropospheric temperatures?
- Dynamically-forced upwelling?



GPS radio occultation

Basic measurement principle: Deduce atmospheric properties based on precise measurement of phase delay





Utility of GPS Radio Occultation:

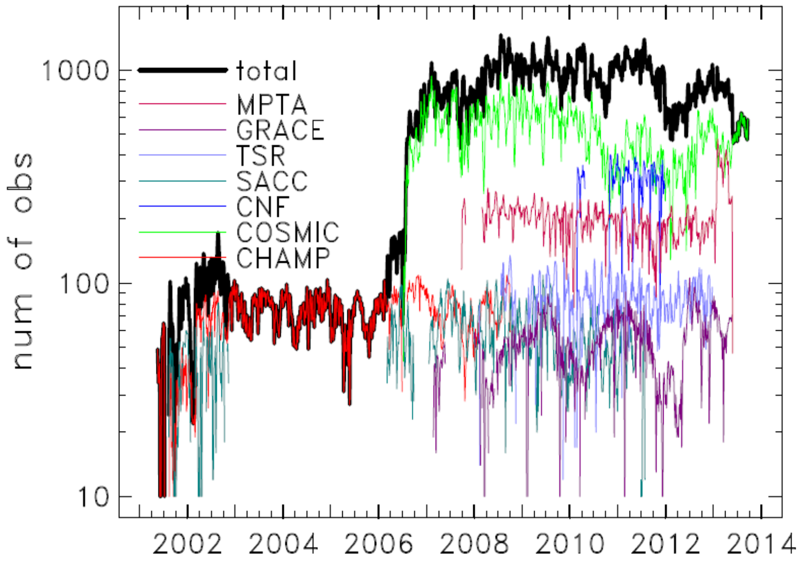
- Long-term stability
- All-weather operation
- High vertical resolution (< 1 km)
- High accuracy: Averaged profiles to < 0.1 K

Using GPS data to understand variability of tropical temperature:

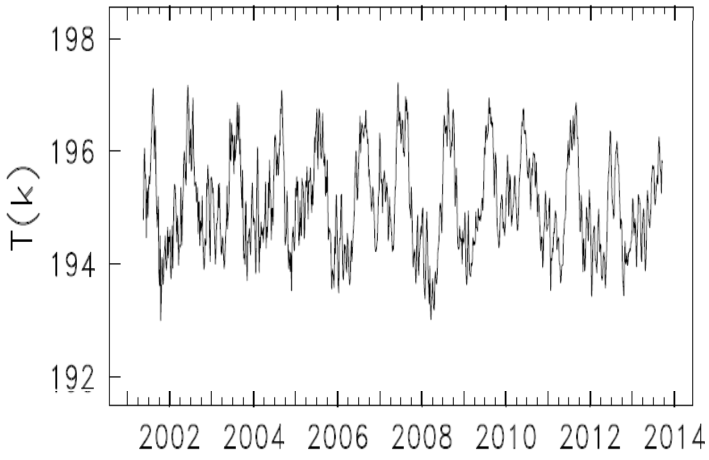
- Construct a global, zonal average data set from GPS observations
- 5-day (pentad) averages for 2001-2013 (over 12 complete years)

total > 6,200,000 occultations

Number of obs / pentad for 10° N-S



Example: 16 km, 10° N-S



Randel and Wu, 2014, J. Atmos. Sci.

Choose to analyze zonal averages because they are governed by a relatively simple equation:

TEM thermodynamic balance

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

↓

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

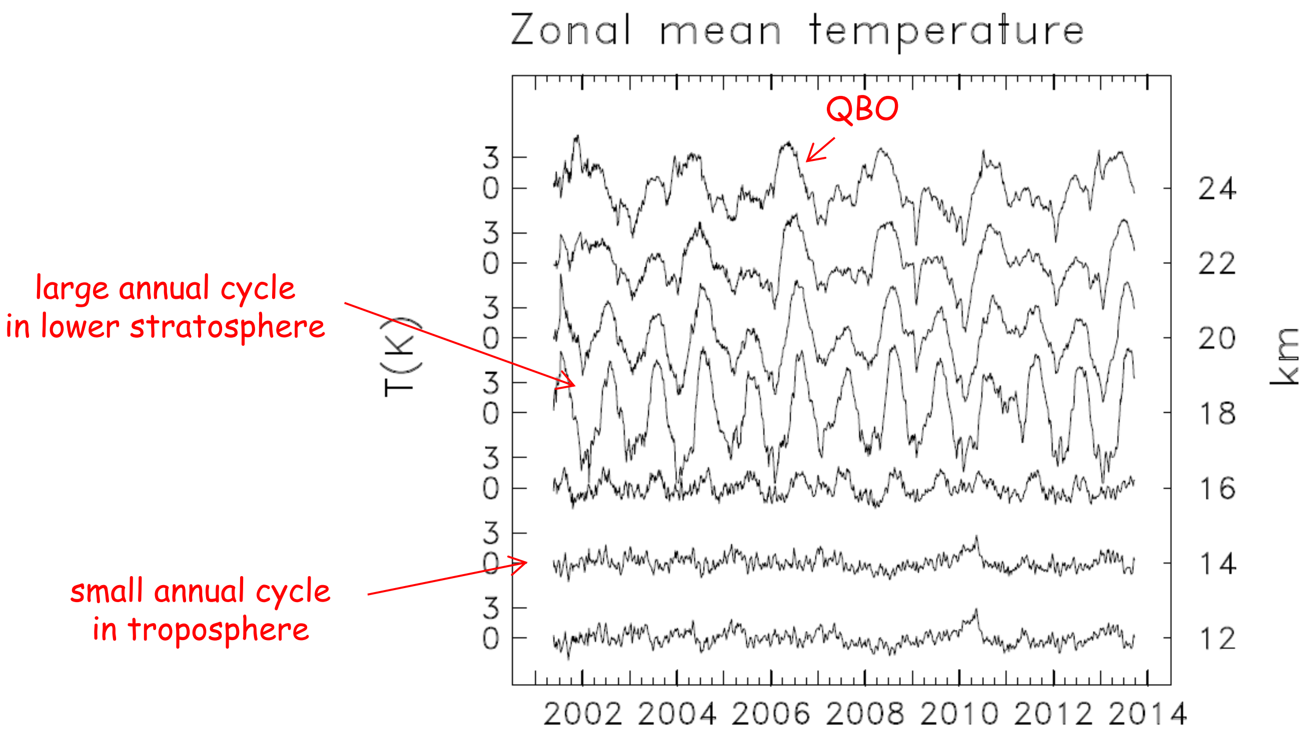
approximate balance in tropics

↓

$$\frac{\partial \overline{T}}{\partial t} + \overline{w}^* S = -\alpha(\overline{T} - \overline{T}_e)$$

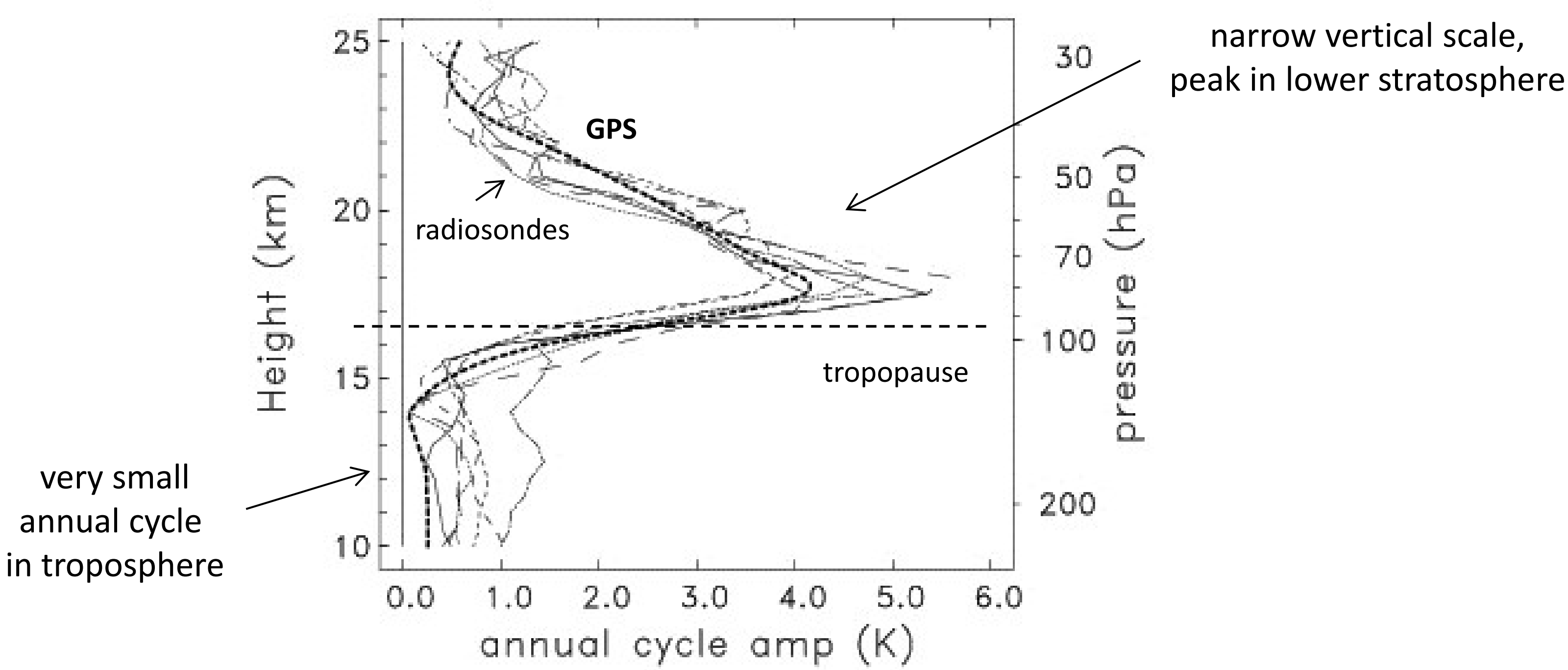
linear damping approximation (in stratosphere)

Tropical variability for 10° N-S



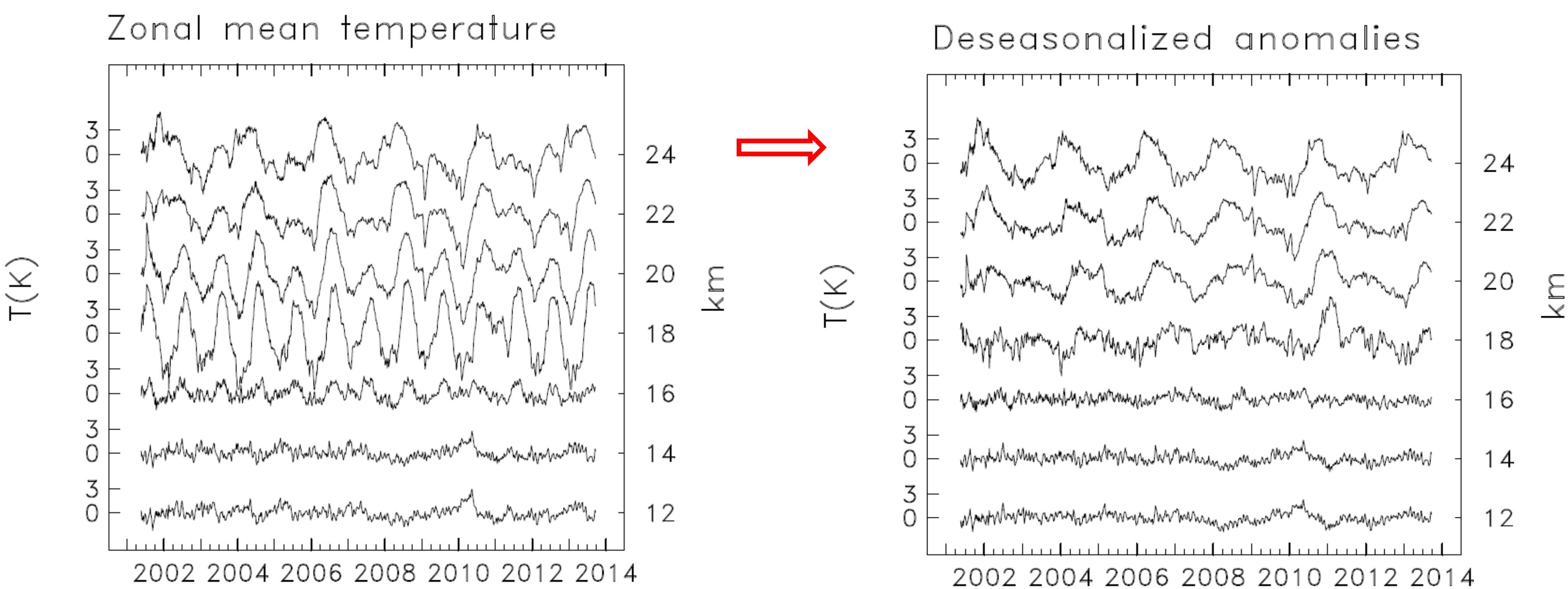
Randel and Wu, 2014, J. Atmos. Sci.

Amplitude of the tropical annual cycle in temperature



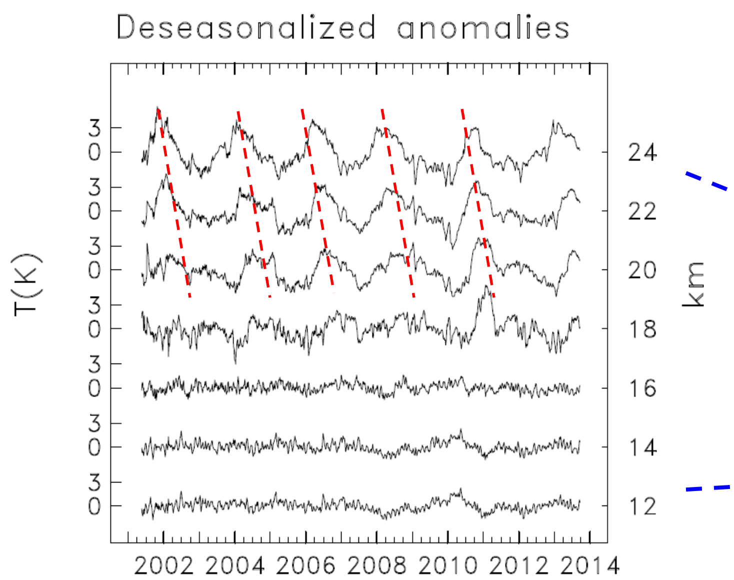
'raw' time series

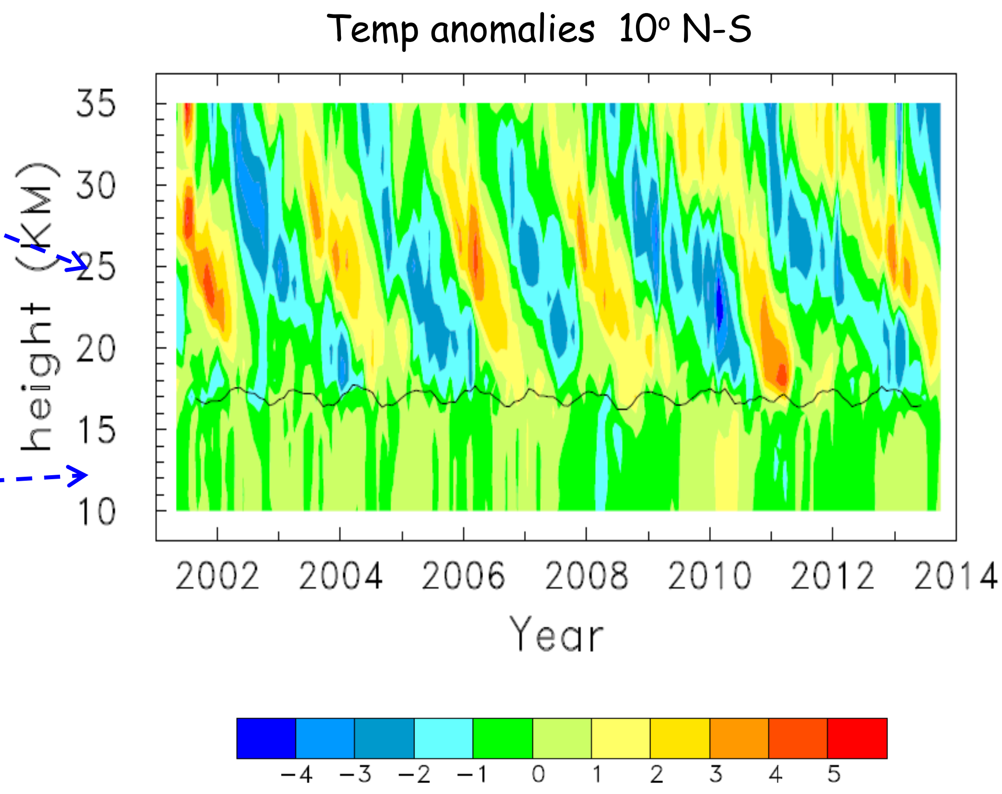
remove seasonal cycle



Randel and Wu, 2014, J. Atmos. Sci.

QBO is the large interannual signal in the stratosphere





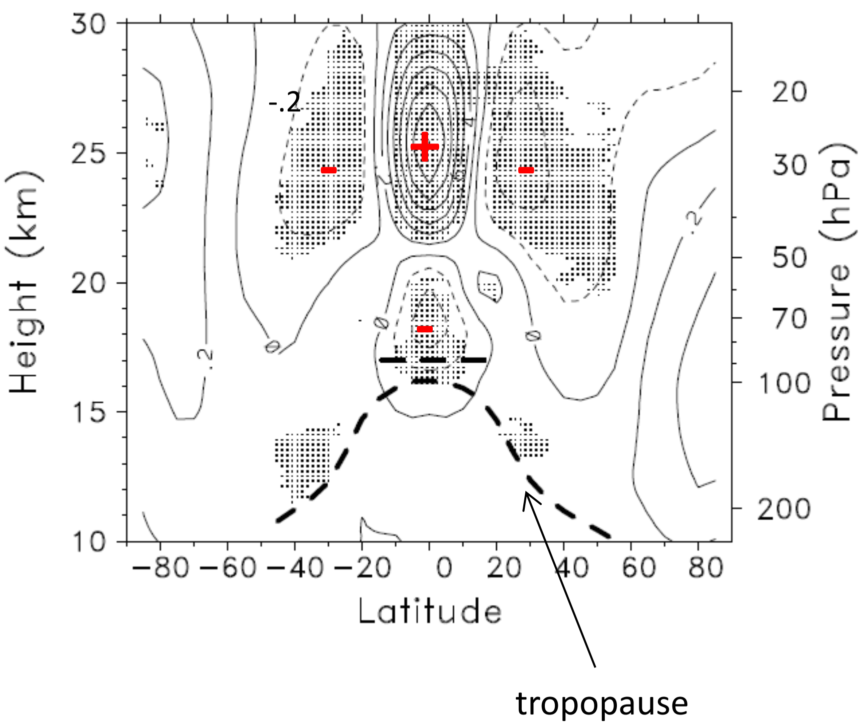
Randel and Wu, 2014, J. Atmos. Sci.

Regression fits of QBO and ENSO 2001-2013

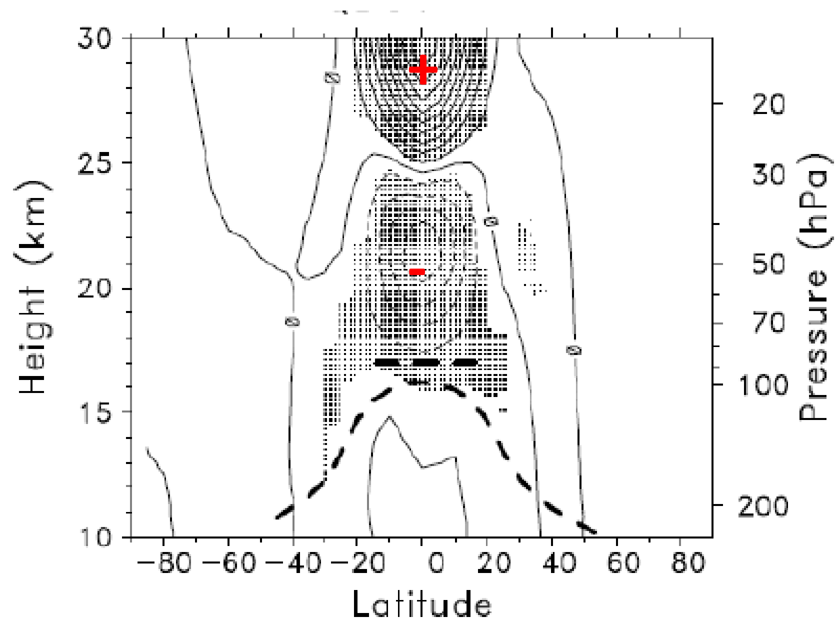
$$T = a * ENSO + b_1 * QBO_1 + b_2 * QBO_2$$

proxy time series

QBO_1 GPS temperature



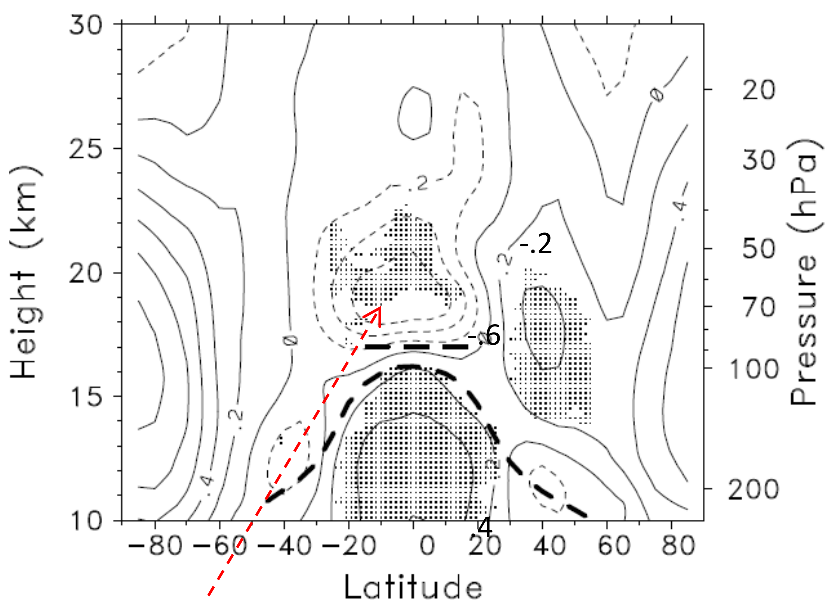
QBO_1 ERAi zonal wind



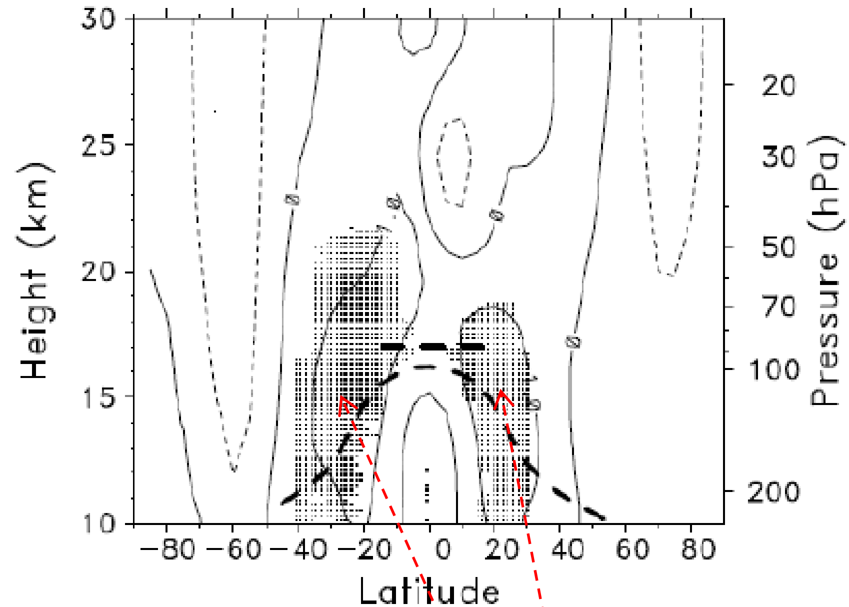
Randel and Wu, 2014, J. Atmos. Sci.

ENSO fits

ENSO GPS temperature



ENSO ERAi zonal wind



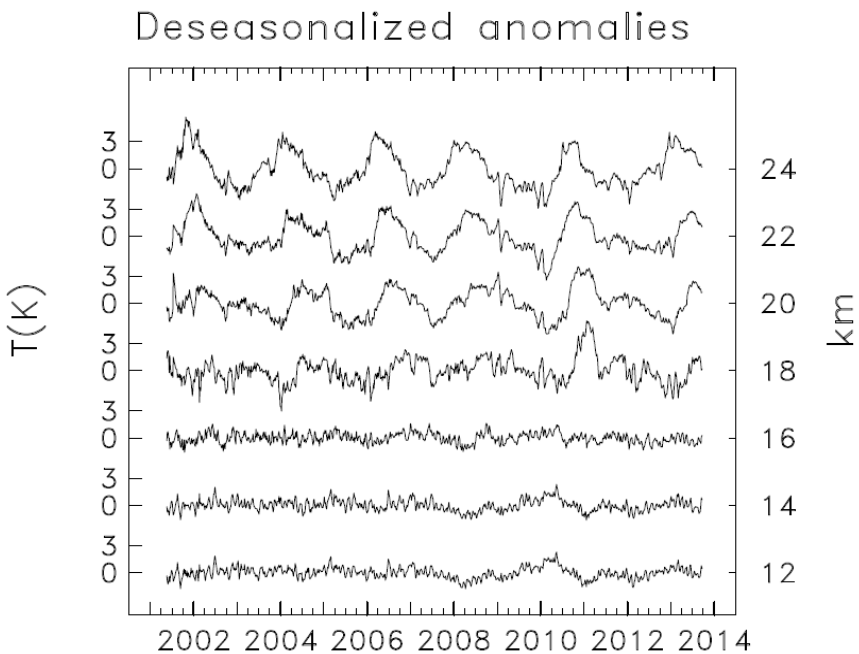
stratosphere cooling
tied to enhanced upwelling
e.g. Calvo et al 2010

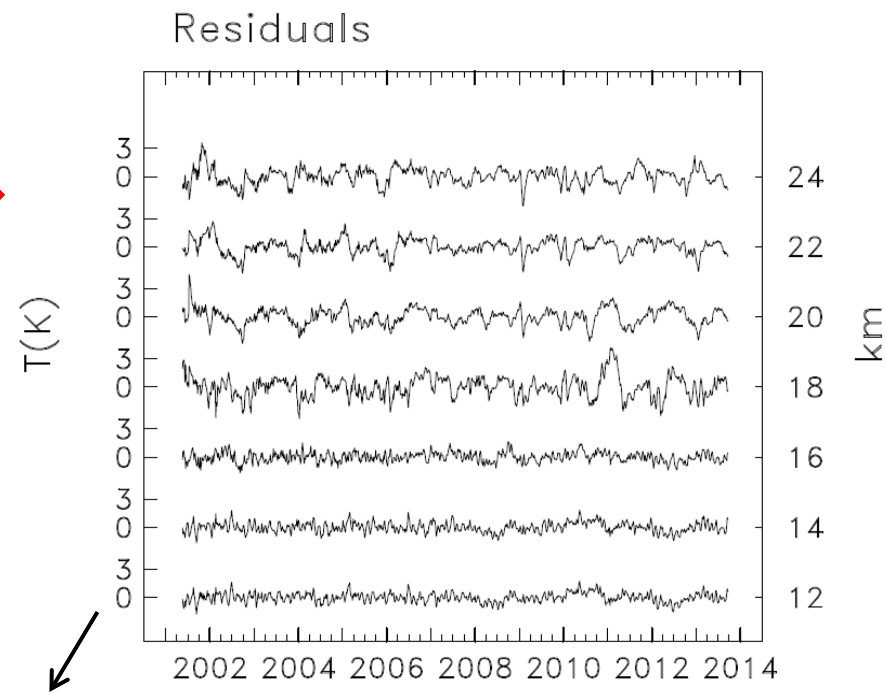
wind maxima in subtropics,
extending into lower stratosphere

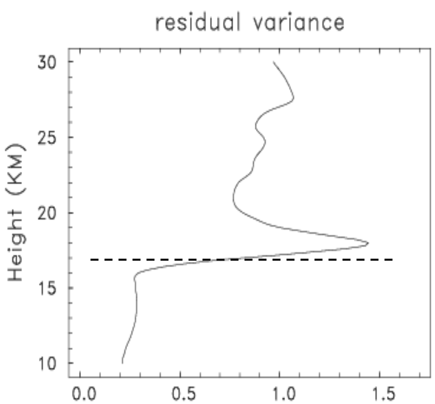
Randel and Wu, 2014, J. Atmos. Sci.

deseasonalized

remove QBO and ENSO ('residual' variability)



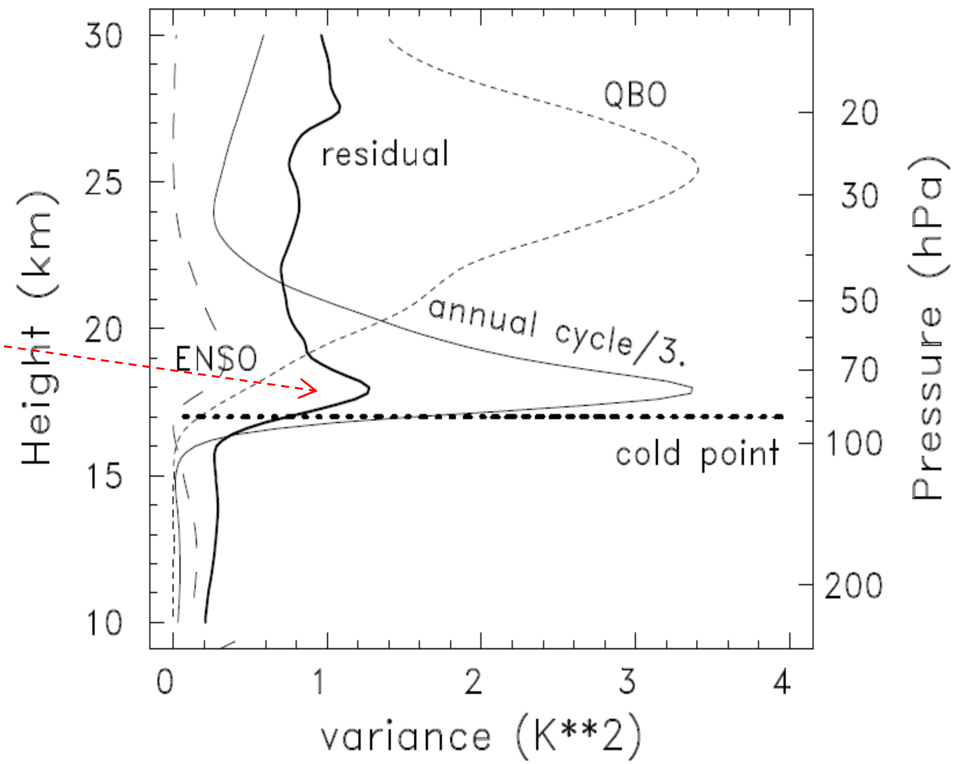




Randel and Wu, 2014, J. Atmos. Sci.

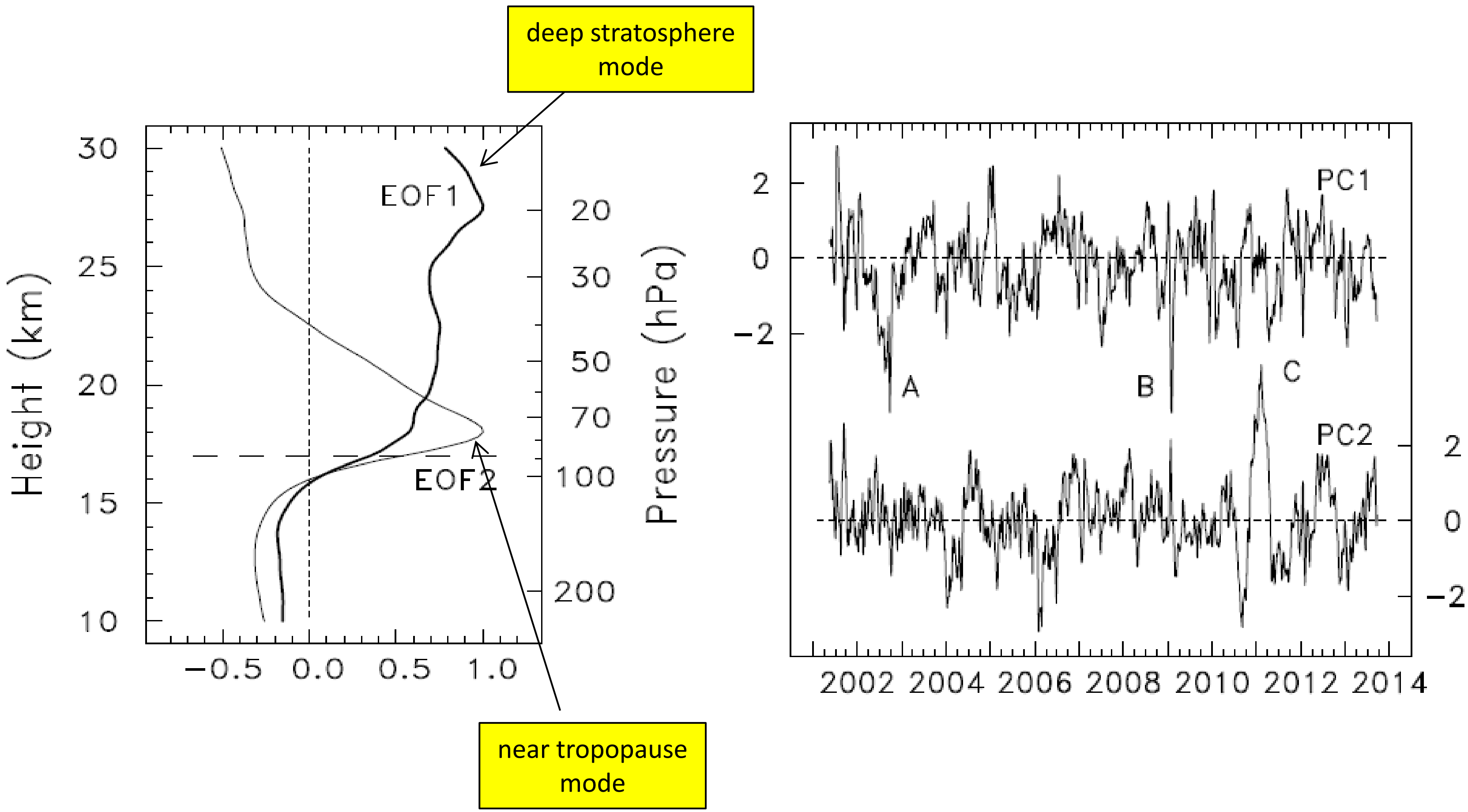
Components of zonal mean temperature variance

residual dominates
deseasonalized
variance
near tropopause



Randel and Wu, 2014, J. Atmos. Sci.

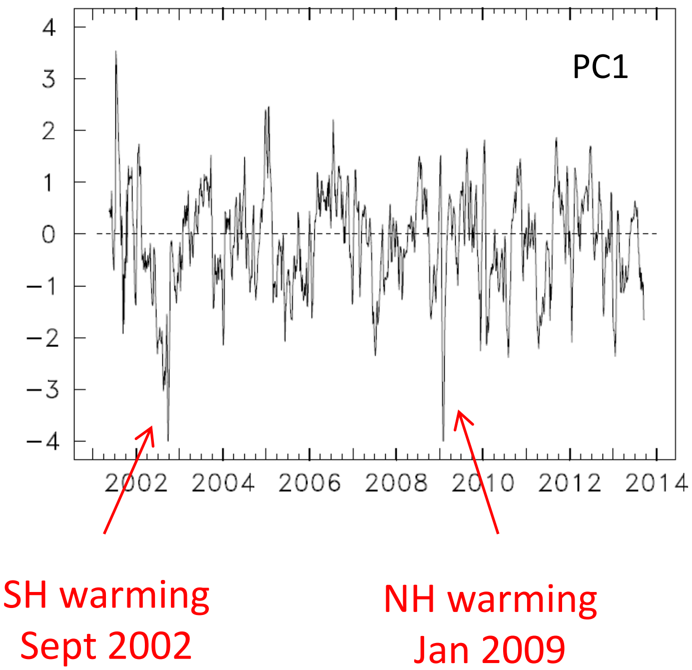
EOF analysis of residuals



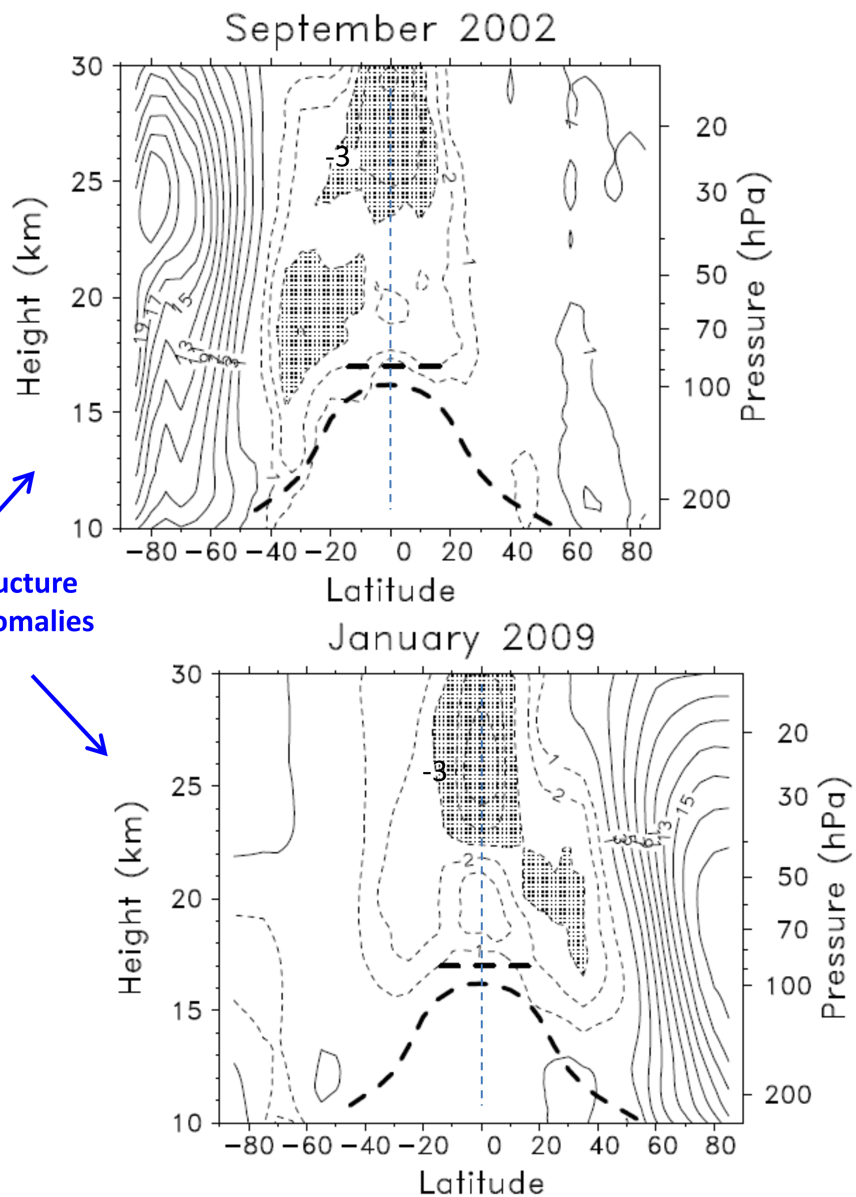
Randel and Wu, 2014, J. Atmos. Sci.

Tropical cooling linked to stratospheric sudden warmings (SSW)

EOF1: deep stratosphere mode



spatial structure of temp anomalies



Randel and Wu, 2014, J. Atmos. Sci.

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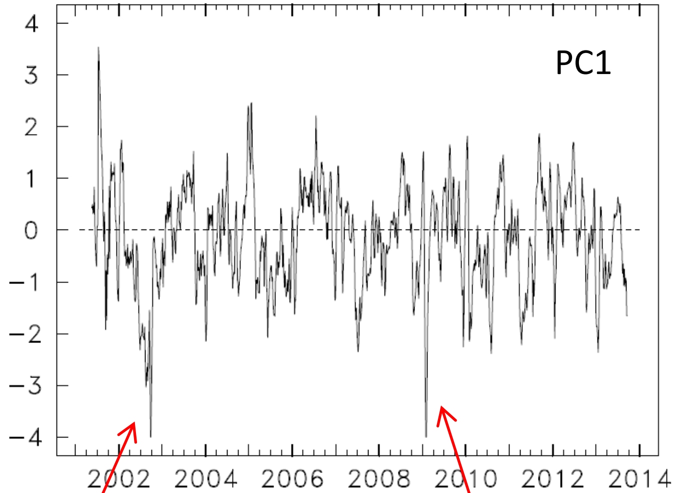
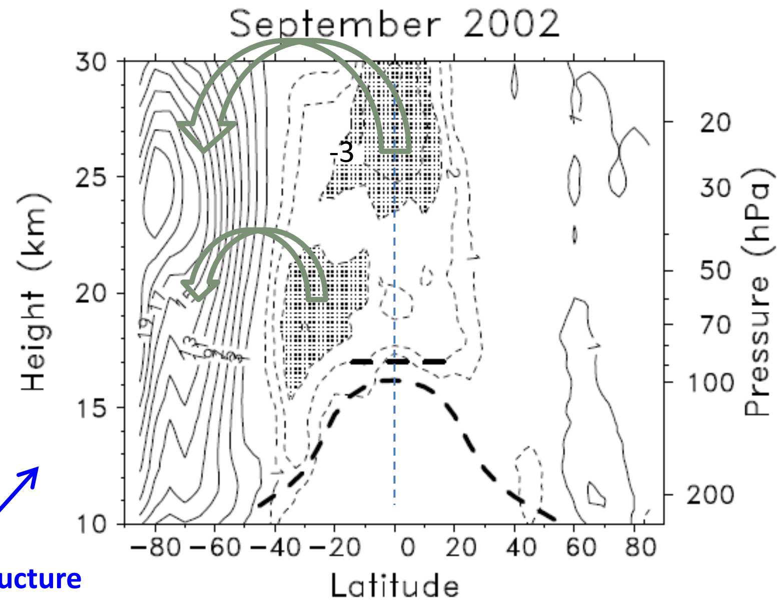
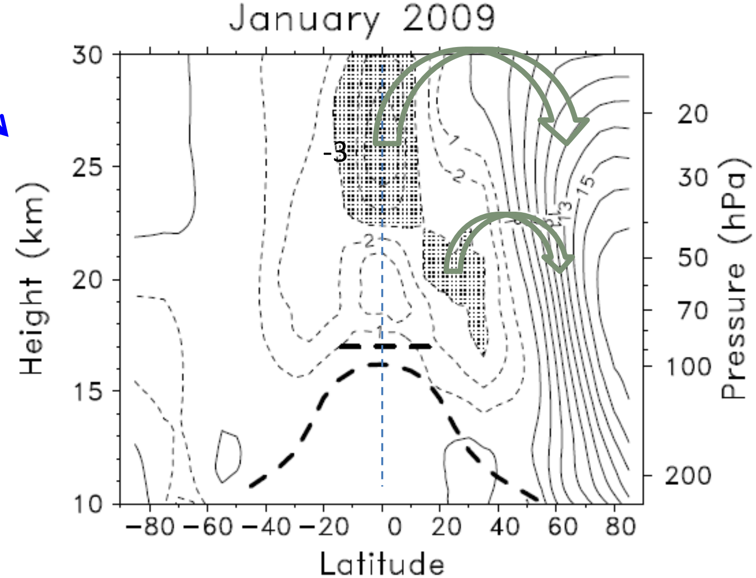


SH warming
Sept 2002

NH warming
Jan 2009

spatial structure of temp anomalies

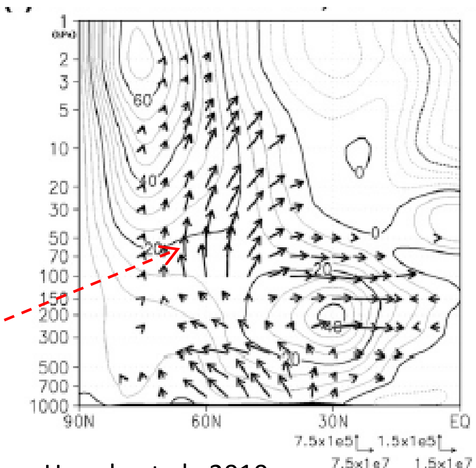




Randel and Wu, 2014, J. Atmos. Sci.

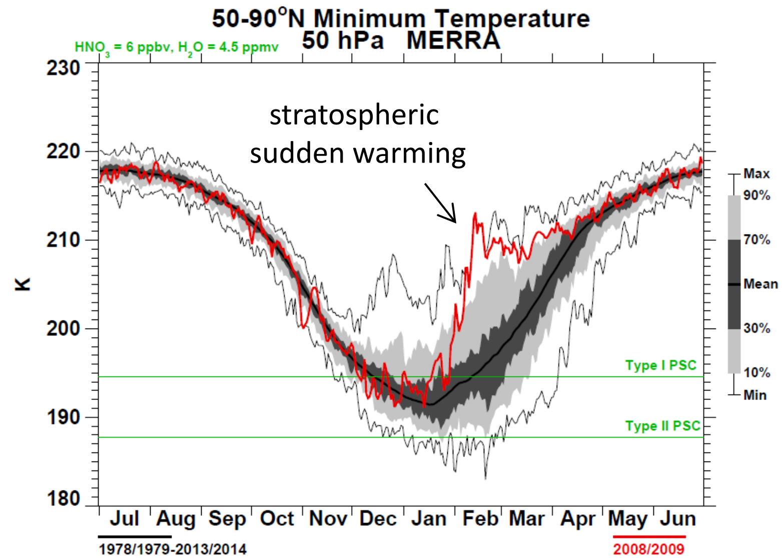
Large stratospheric sudden warming in January 2009

high latitude planetary wave forcing



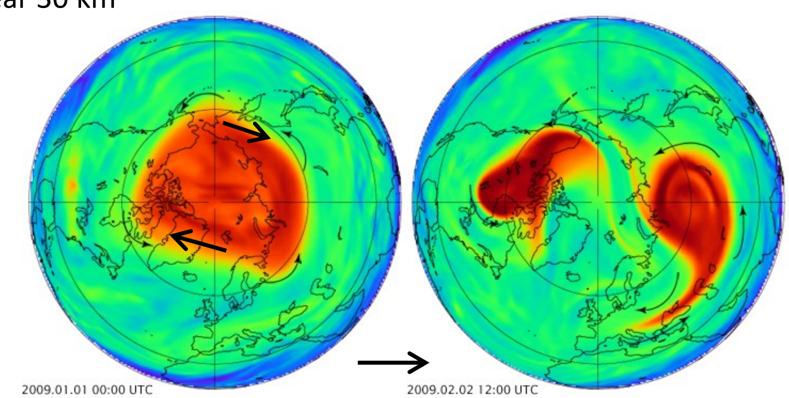
Harada et al , 2010

Polar stratosphere temperature



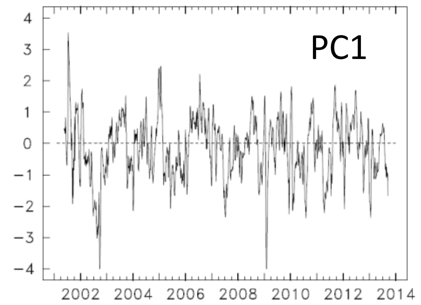
polar vortex near 30 km

potential vorticity



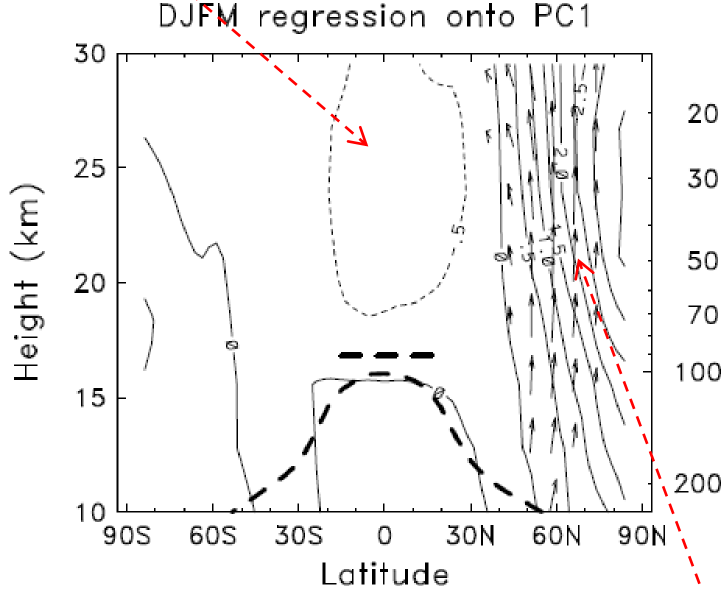
split of polar vortex

Regression of global temperatures and EP flux onto PC1

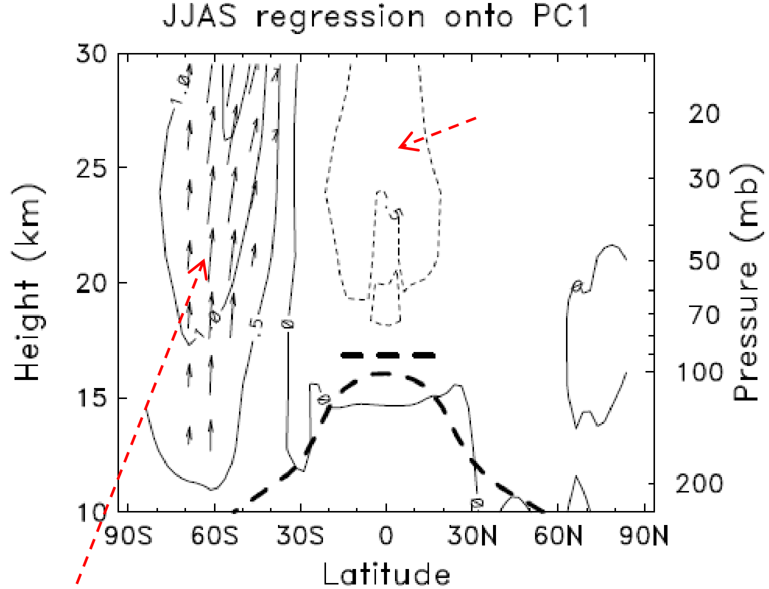


cooling in tropics

NH winter



SH winter

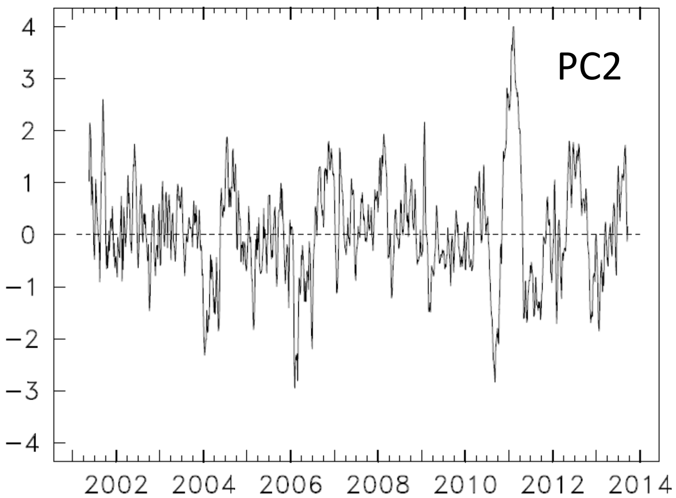


high latitude wave fluxes and polar warming

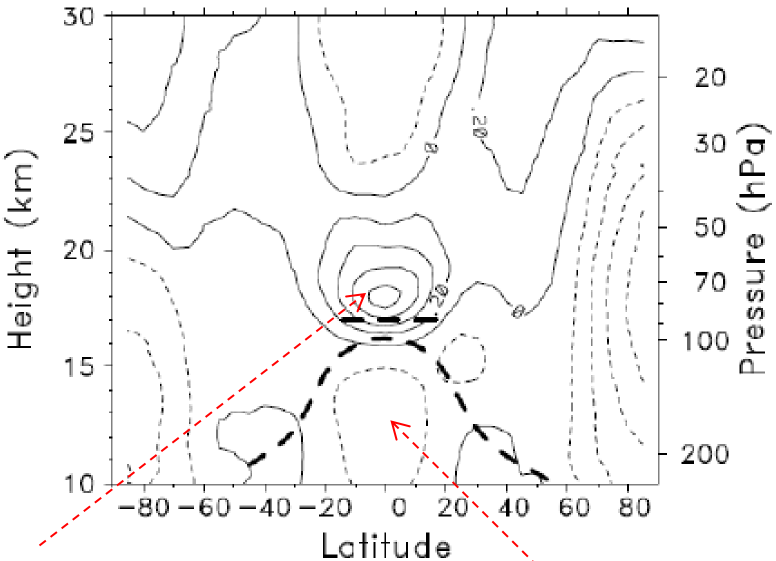
Randel and Wu, 2014, J. Atmos. Sci.

Near-tropopause signal

EOF2: near-tropopause mode



temperature regression onto PC2



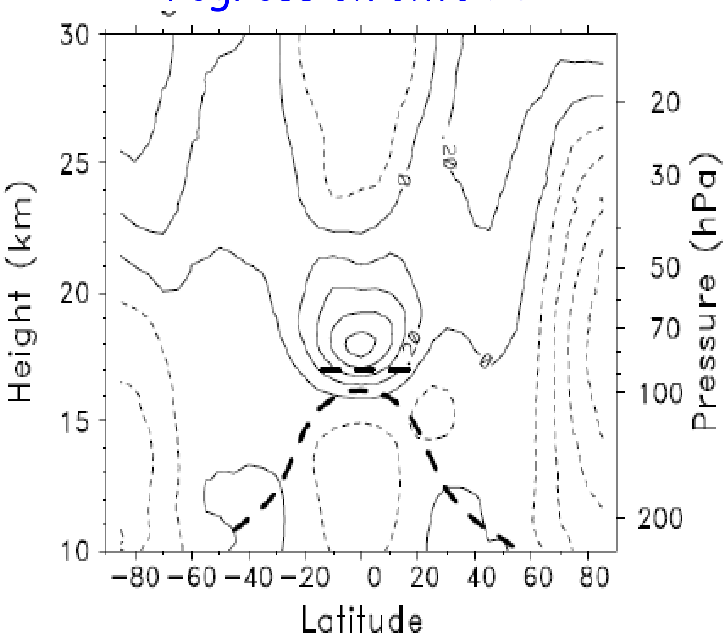
maximum in tropical lower stratosphere

anti-correlation with tropical troposphere

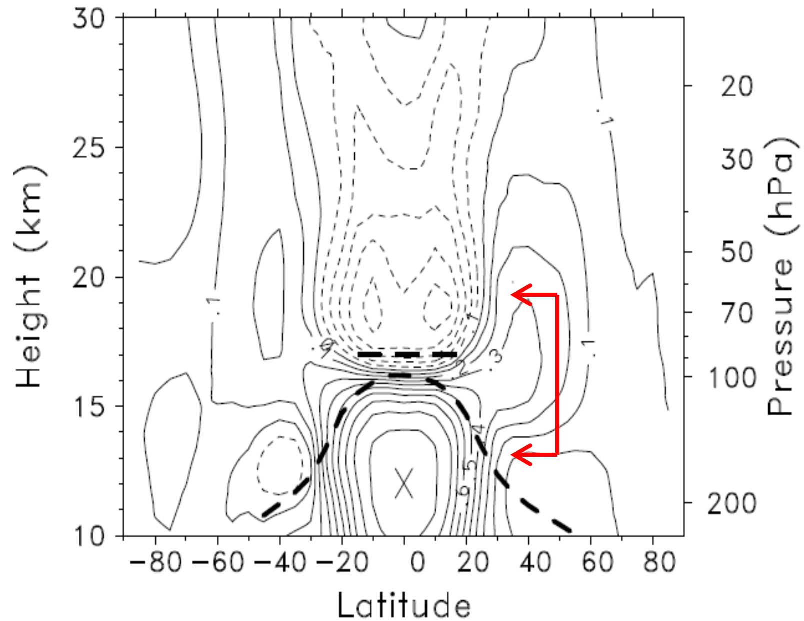
Randel and Wu, 2014, J. Atmos. Sci.

Near-tropopause signal: correlation maps

regression onto PC2

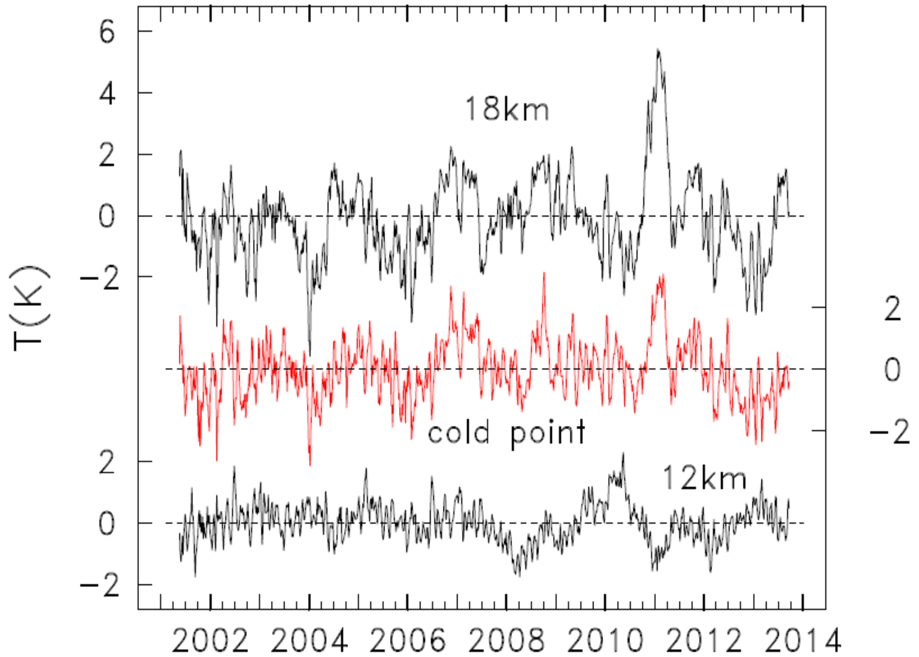


correlation wrt 12 km

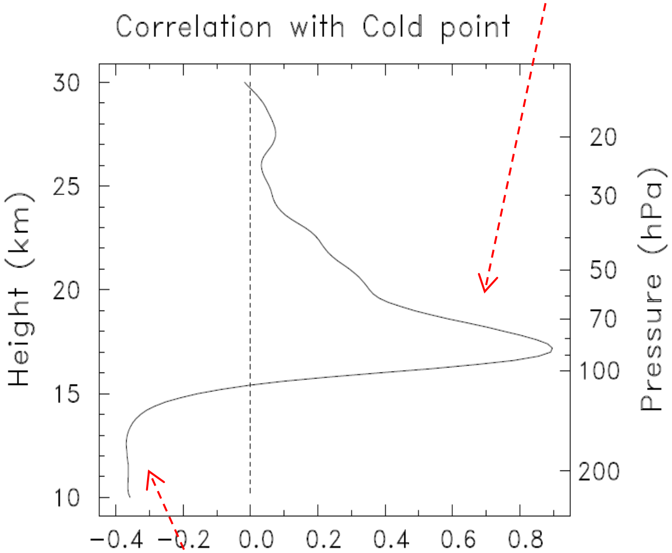


Randel and Wu, 2014, J. Atmos. Sci.

time series of tropical temperature anomalies



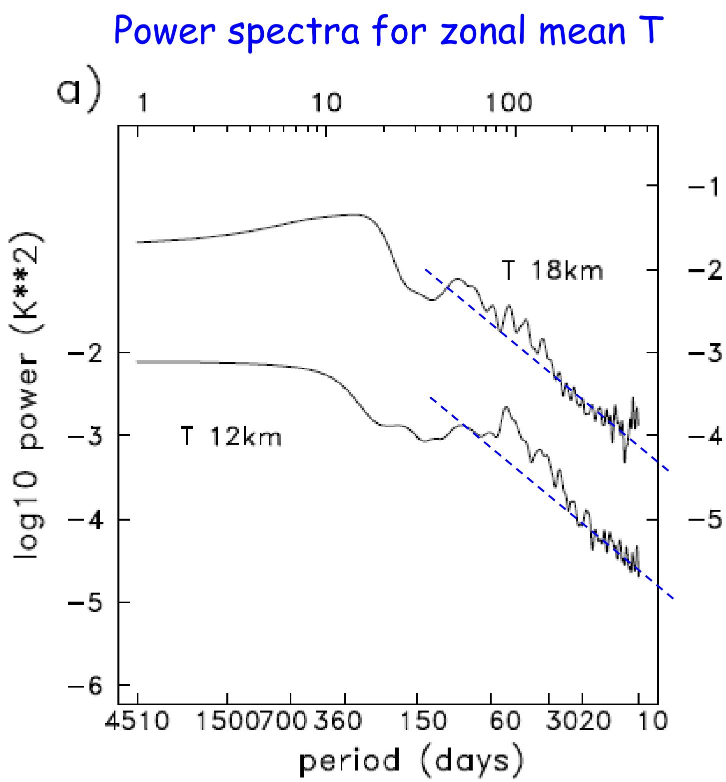
strong correlation over narrow layer ~16-19 km

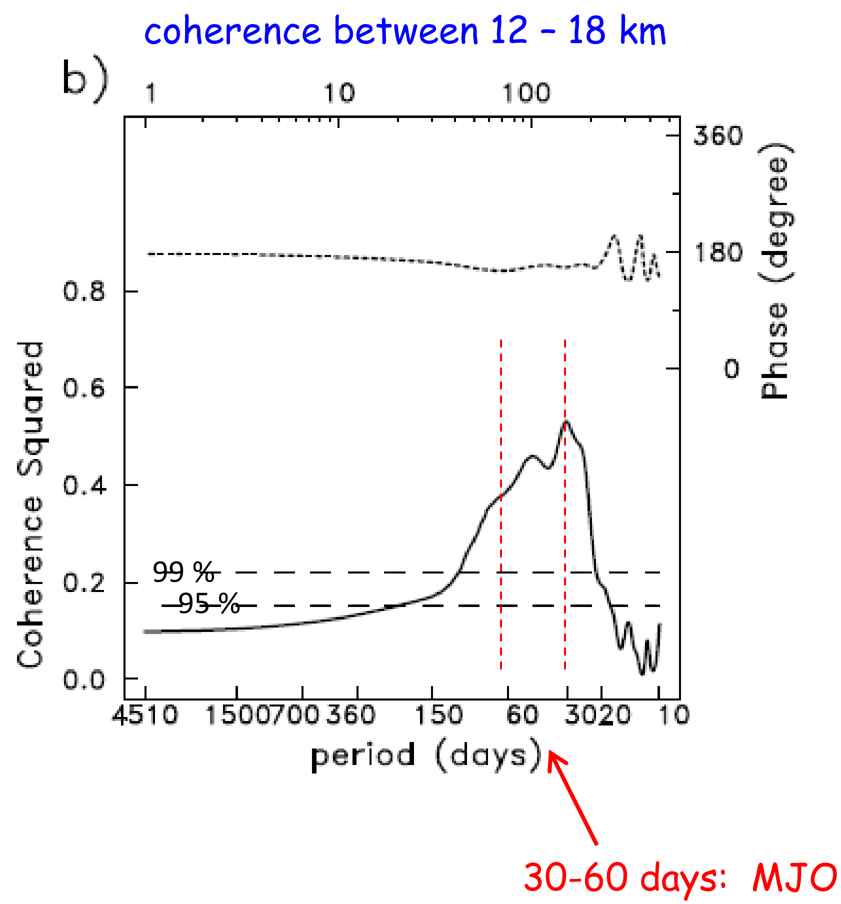


weak anti-correlation with troposphere

Randel and Wu, 2014, J. Atmos. Sci.

Spectrum analysis

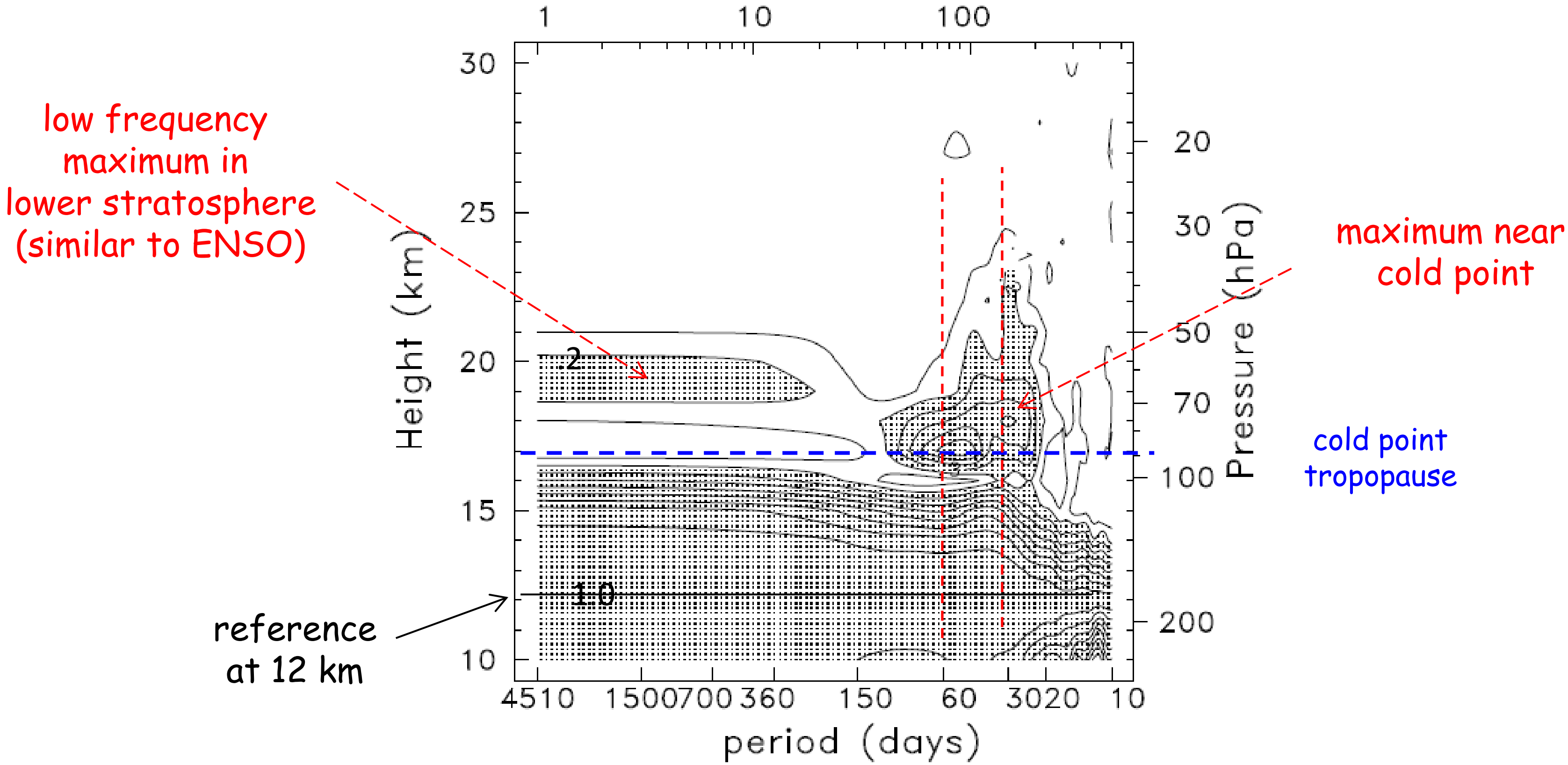




Zonal mean MJO signal: Virts and Wallace, 2014

tropical coh^2 with respect to 12 km

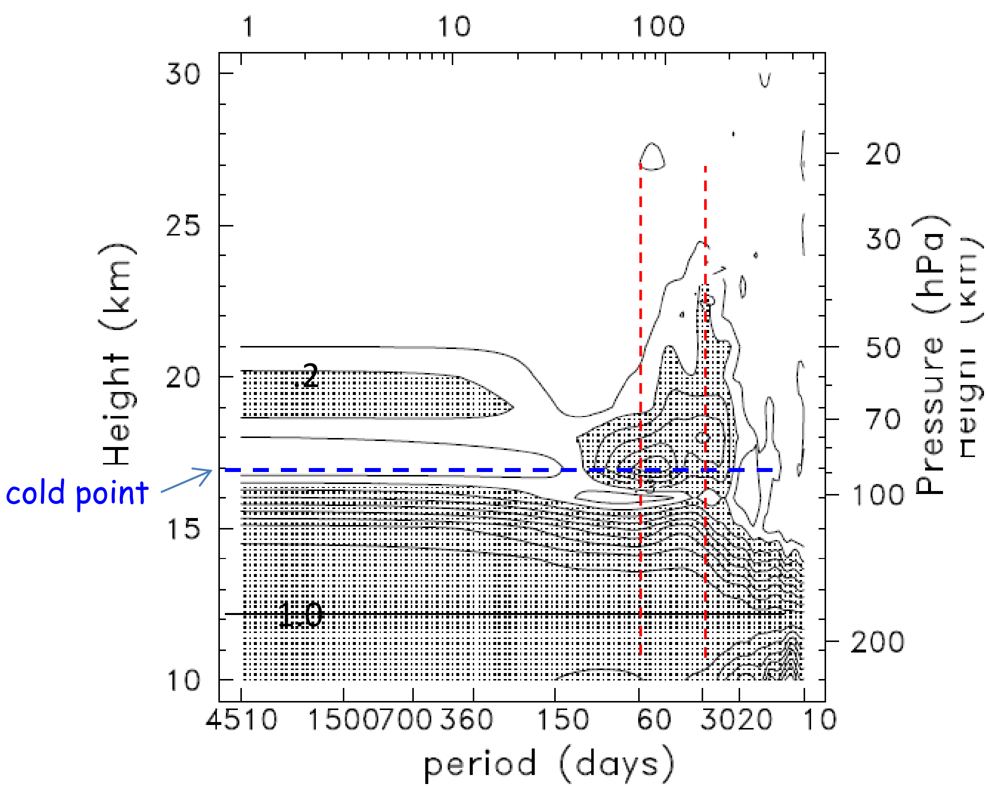
shaded regions
~99% significant



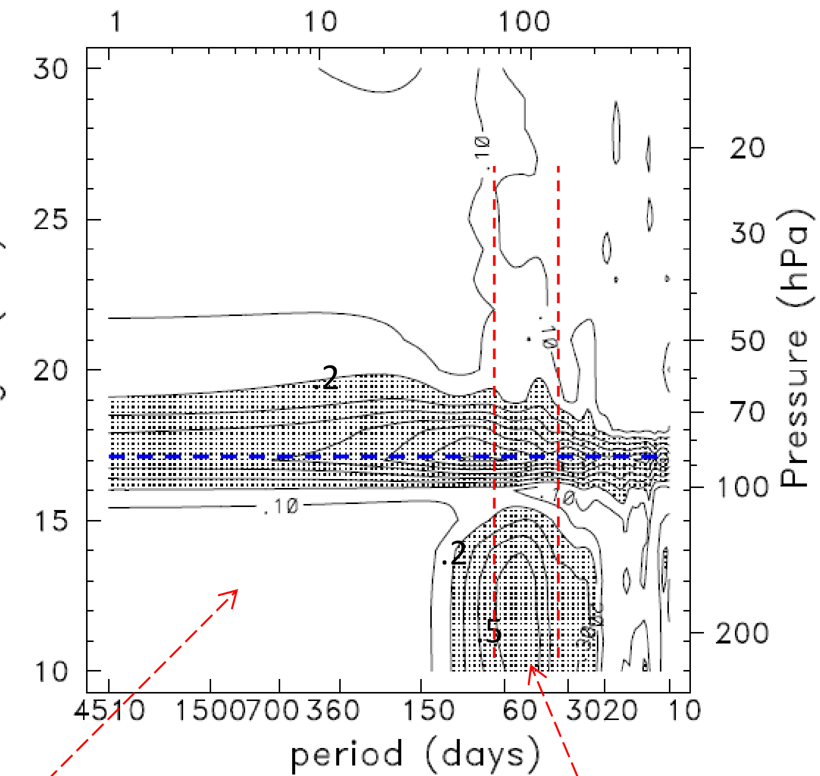
30-60 days: MJO

Randel and Wu, 2014, J. Atmos. Sci.

coh² with respect to 12 km



coh² with respect to the cold point

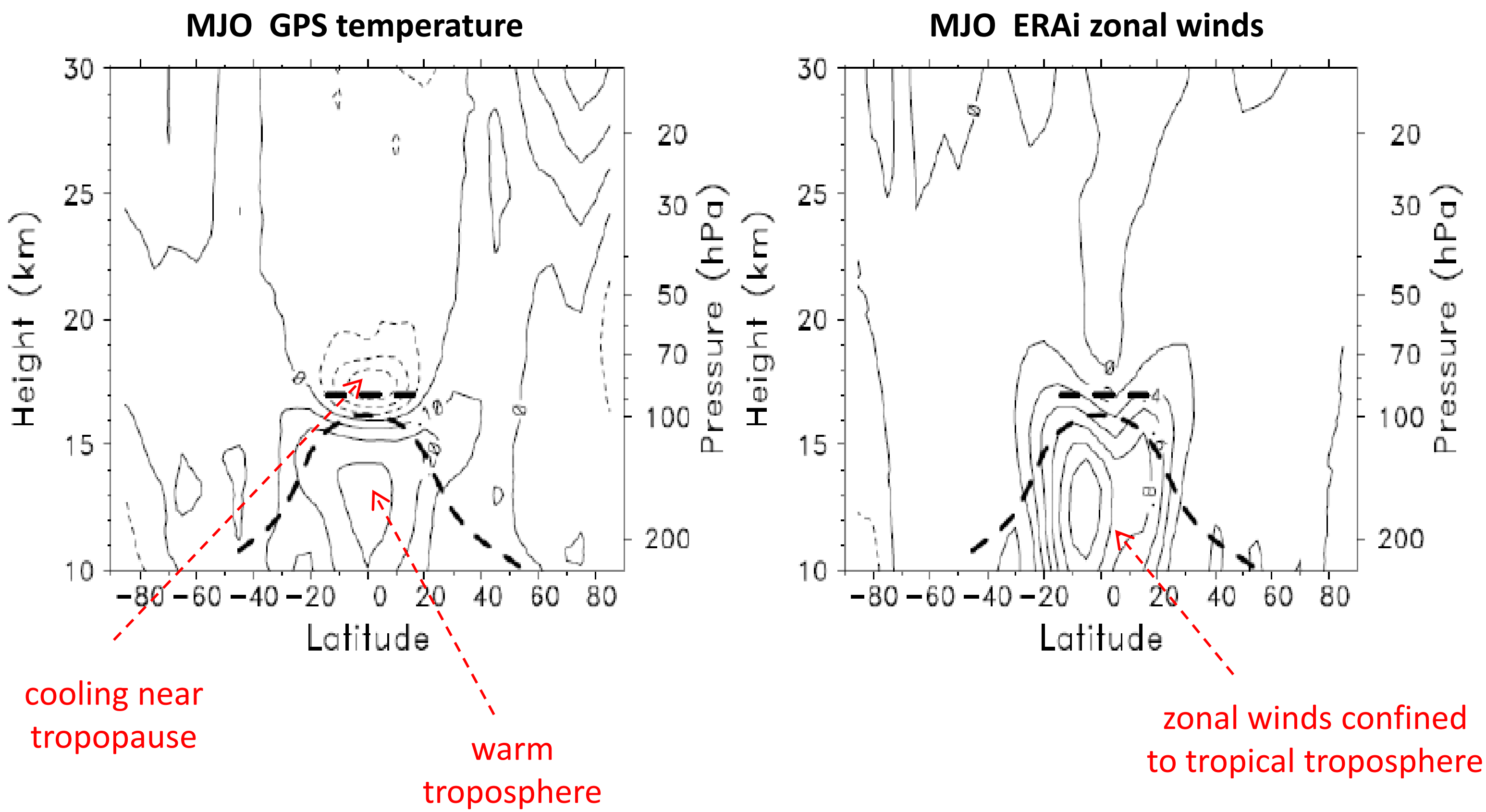


small coherence for seasonal to interannual variations

coherence with troposphere for MJO time scales

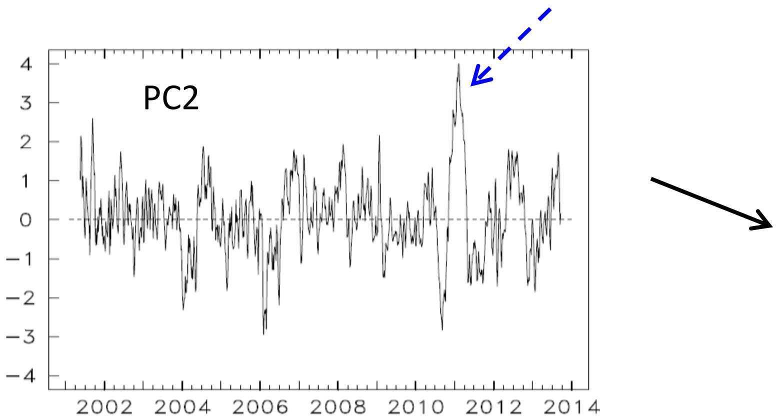
Randel and Wu, 2014, J. Atmos. Sci.

Structure of zonal mean MJO (filtered 25-80 days bandpass)

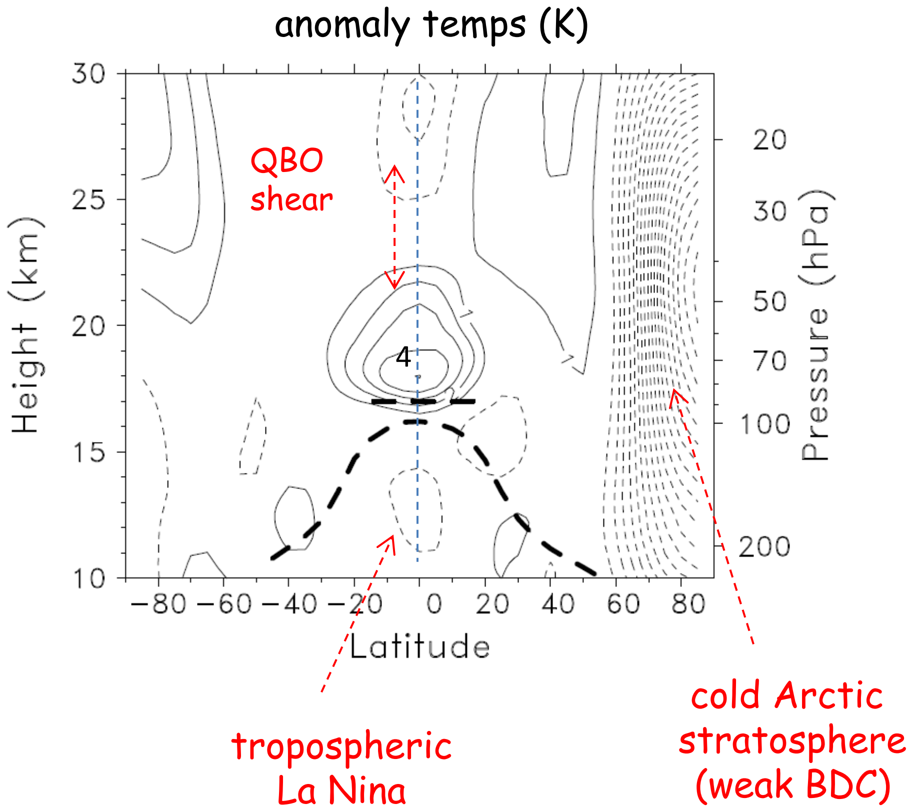


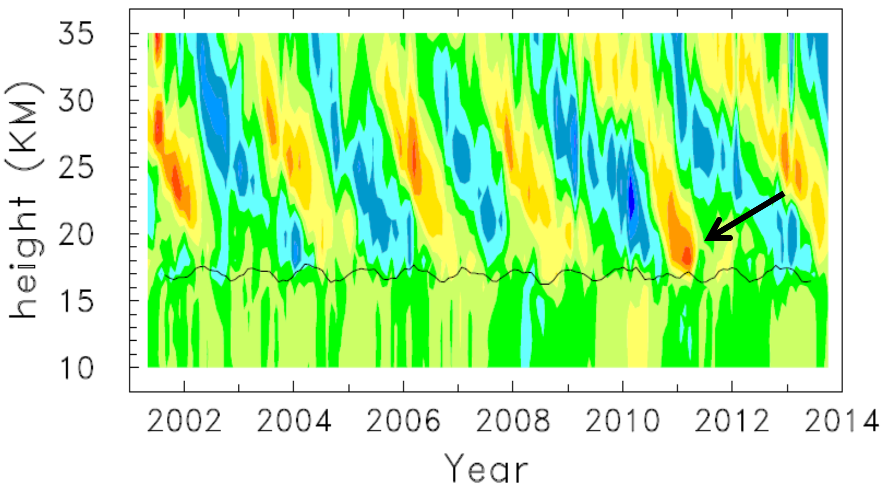
Randel and Wu, 2014, J. Atmos. Sci.

Extreme near-tropopause event

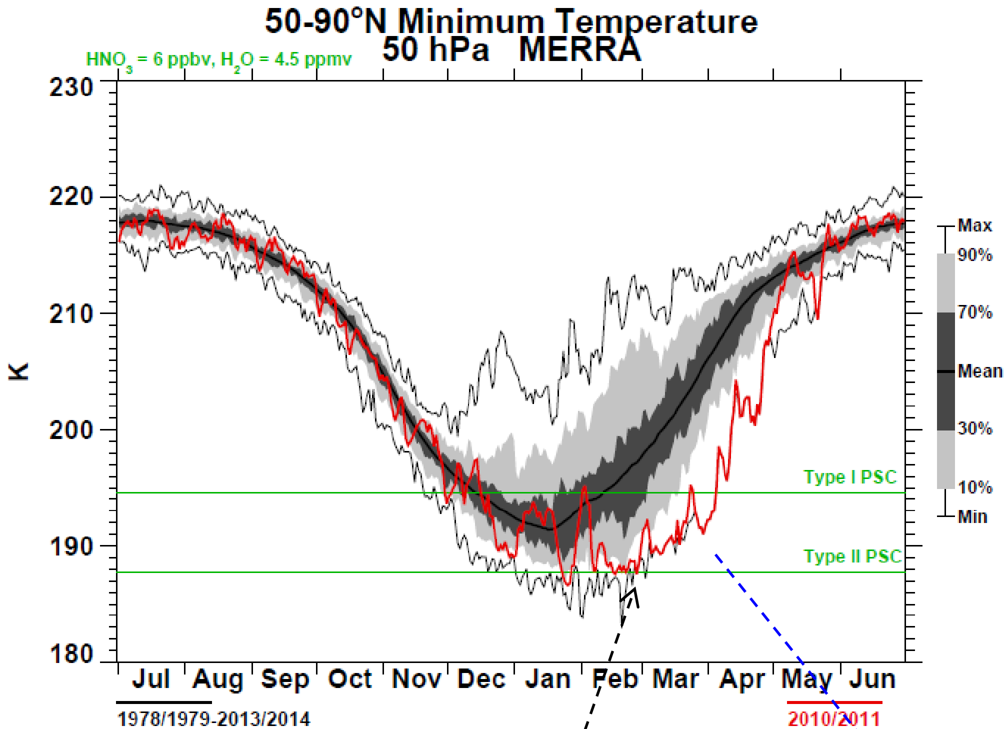


3 factors contributing to anomalous tropical temps:



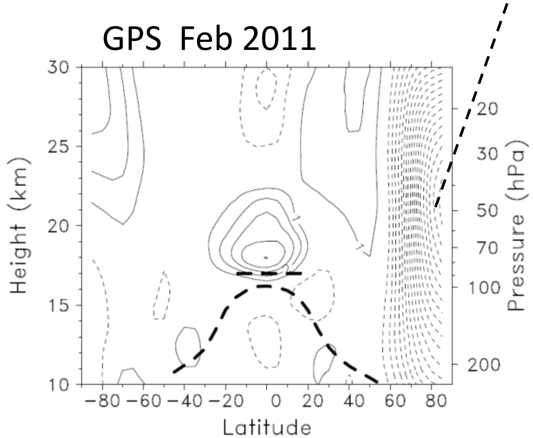


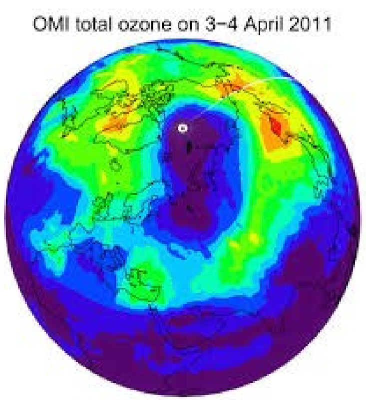
Randel and Wu, 2014, J. Atmos. Sci.



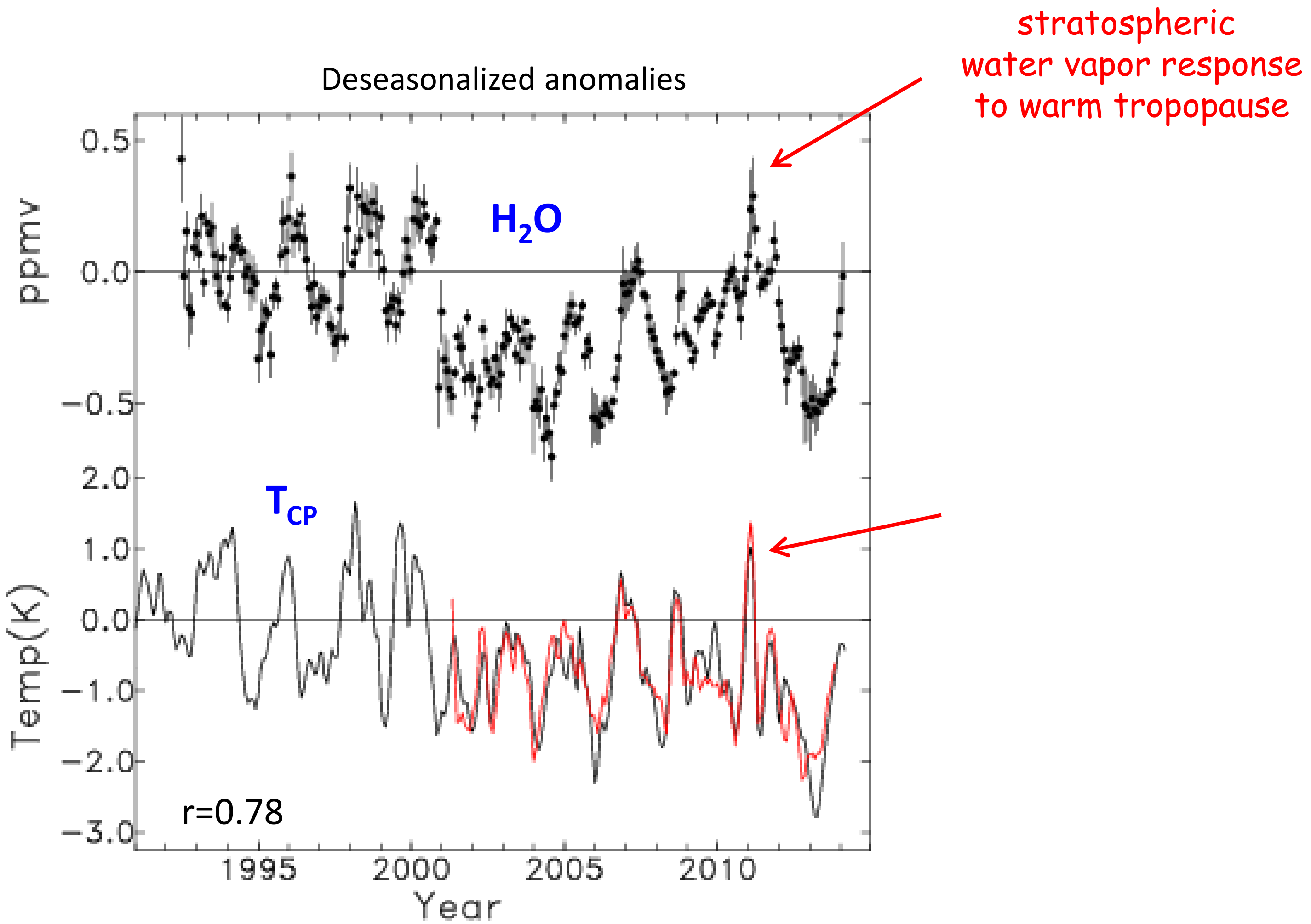
coldest Arctic spring in observational record (1979-2014)

Arctic 'ozone hole' in spring 2011



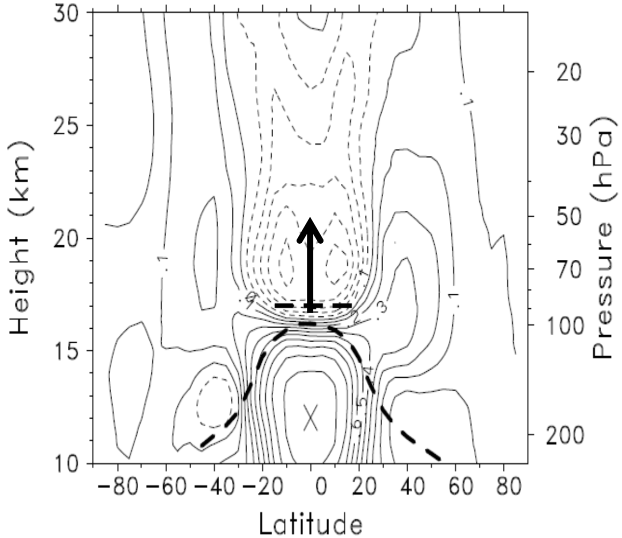


Randel and Wu, 2014, J. Atmos. Sci.


Deseasonalized anomalies
stratospheric
water vapor response
to warm tropopause
H_2O
ppmv
0.5
0.0
−0.5
T_{CP}
2.0
1.0
0.0
−1.0
−2.0
−3.0
Temp(K)
r=0.78
1995
2000
2005
2010
Year

Links to tropical upwelling

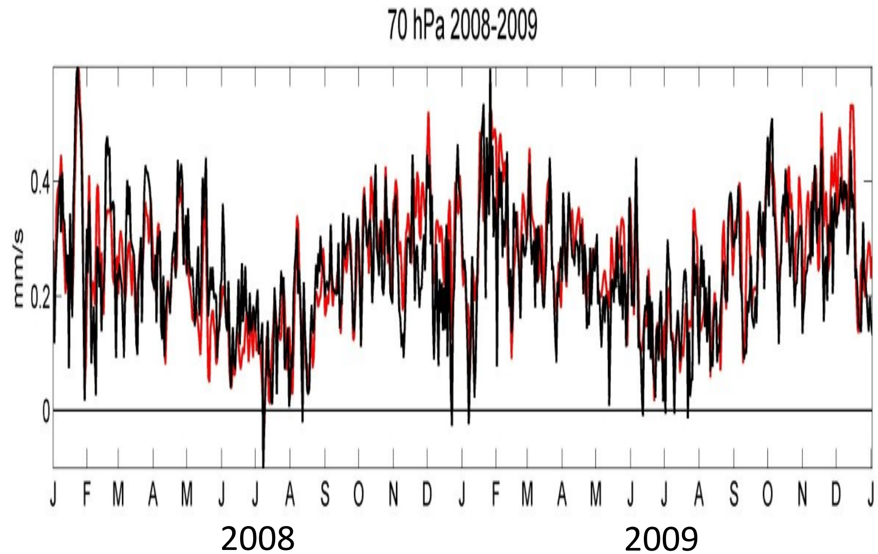
$$\frac{\partial \overline{T}}{\partial t} + \overline{w}^* S = -\alpha(\overline{T} - \overline{T}_e)$$



two estimates of upwelling:

w^*_m momentum balance

w^*_Q thermodynamic balance



Abalos et al, 2014, JAS

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^*

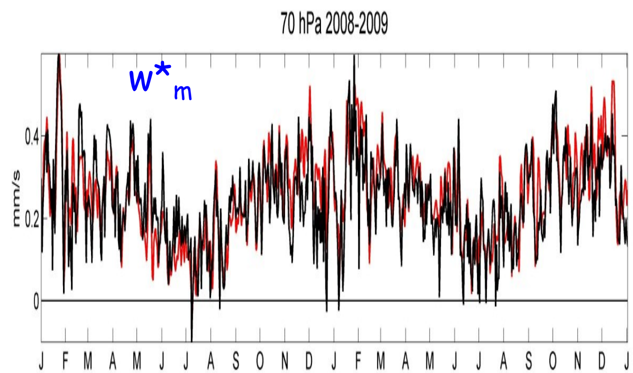
$$\langle\overline{w}_m^*\rangle(z) = \frac{-e^{z/H}}{\int_{-\phi_0}^{\phi_0} a\cos\phi d\phi}\left\{\int_z^\infty \frac{e^{-z'/H}\cos\phi}{\hat{f}(\phi,z')}\left[DF(\phi,z') - \overline{u}_t(\phi,z')\right]_{\overline{m}} dz'\right\}_{-\phi_0}^{\phi_0}$$

momentum balance w_m^*

EP flux divergence

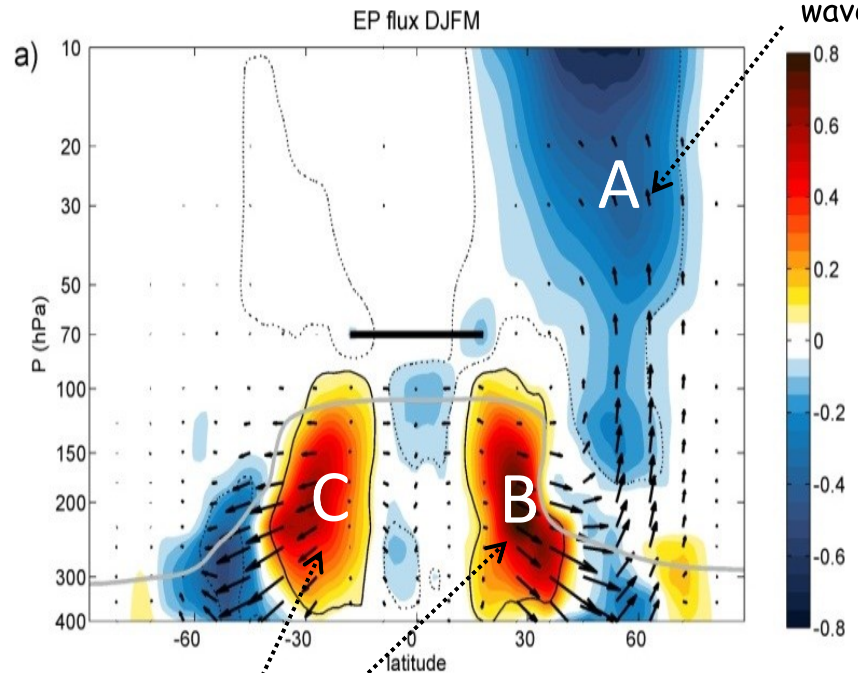
zonal wind tendencies

What forces transient tropical upwelling?



Regression of EP flux onto w*m

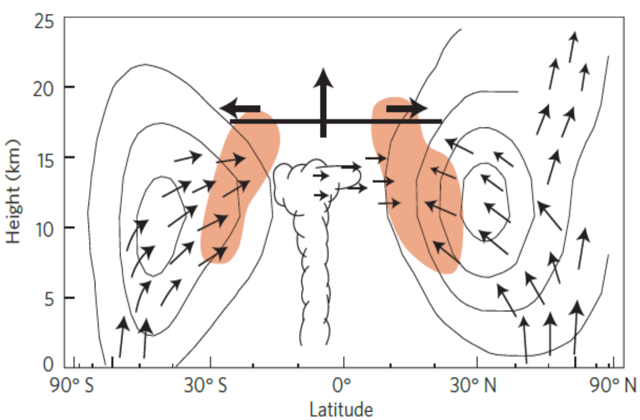
planetary waves



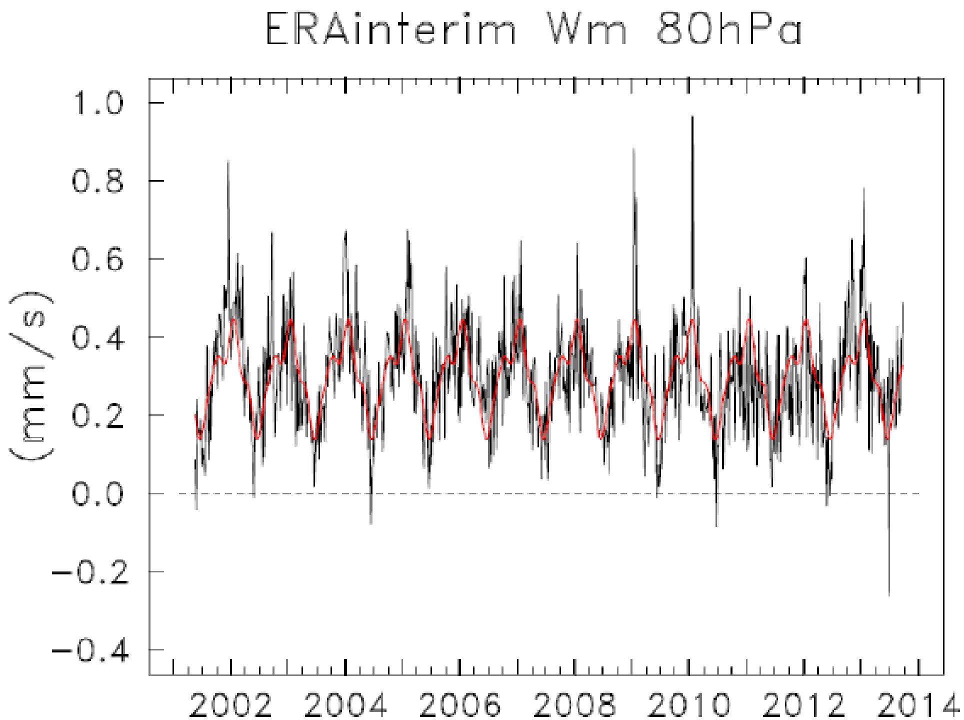
subtropical EP fluxes

Abalos et al, 2014, JAS

Modulation of climatological EP flux



Randel and Wu, 2014, J. Atmos. Sci.



Randel and Wu, 2014, J. Atmos. Sci.

Quantifying the relationship between w* and T:

$$\frac{\partial \overline{T}}{\partial t} + \overline{w}^* S = -\alpha(\overline{T} - \overline{T}_e)$$

harmonic expansion

$$[\overline{T}(t), \overline{w}^*(t)] = \sum [T_\sigma, w_\sigma] \exp(i\sigma t),$$

$$T_\sigma = -w_\sigma S \frac{\alpha - i\sigma}{\alpha^2 + \sigma^2}.$$

temperature response
to upwelling:

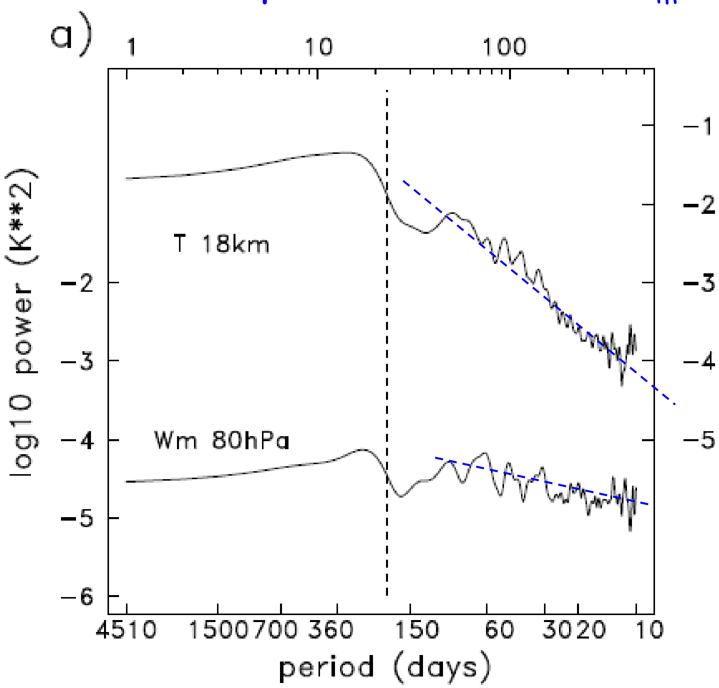
$$\sqrt{\frac{T_\sigma^2}{w_\sigma^2}} = \frac{S}{\sqrt{\alpha^2 + \sigma^2}}.$$

radiative damping
time scale

frequency

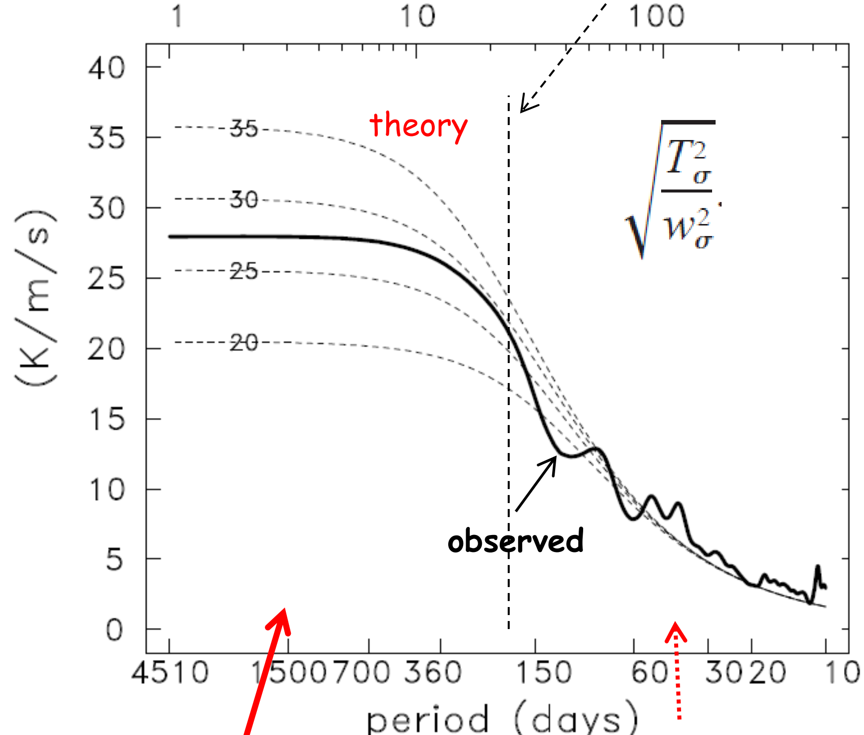
Spectrum analysis

Power spectra for T and w*$_m$



T sensitivity to w*$_m$

frequency where $\sigma \sim \alpha$



$$\sqrt{\frac{T_\sigma^2}{w_\sigma^2}}.$$

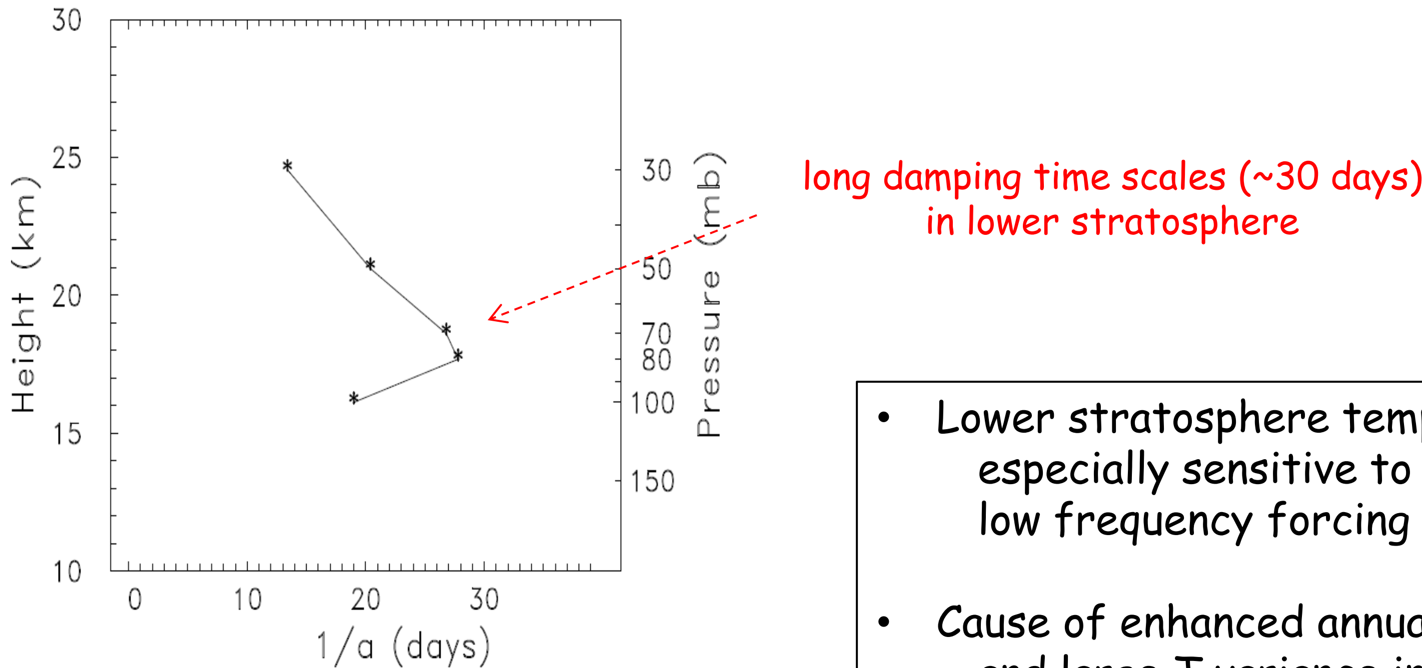
note weak response for MJO periods

enhanced response at low frequencies (longer than 150 days)

$$\sqrt{\frac{T_\sigma^2}{w_\sigma^2}} = \frac{S}{\sqrt{\alpha^2 + \sigma^2}}.$$

Randel and Wu, 2014, J. Atmos. Sci.

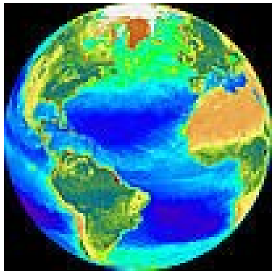
Radiative damping time scales derived from: $\sqrt{\frac{T_\sigma^2}{w_\sigma^2}} = \frac{S}{\sqrt{\alpha^2 + \sigma^2}}.$



- Lower stratosphere temps especially sensitive to low frequency forcing
- Cause of enhanced annual cycle and large T variance in lower stratosphere

Randel and Wu, 2014, J. Atmos. Sci.

Key points:

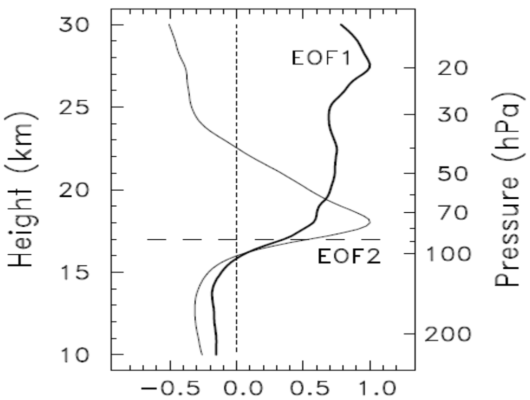


- Novel high vertical resolution temperature record from GPS
- Strong, coherent QBO, ENSO, SSW and MJO signals in GPS data
- 2 modes of stratospheric variability: deep, shallow branches of BDC
- Cold point T variability tied to tropopause-level upwelling

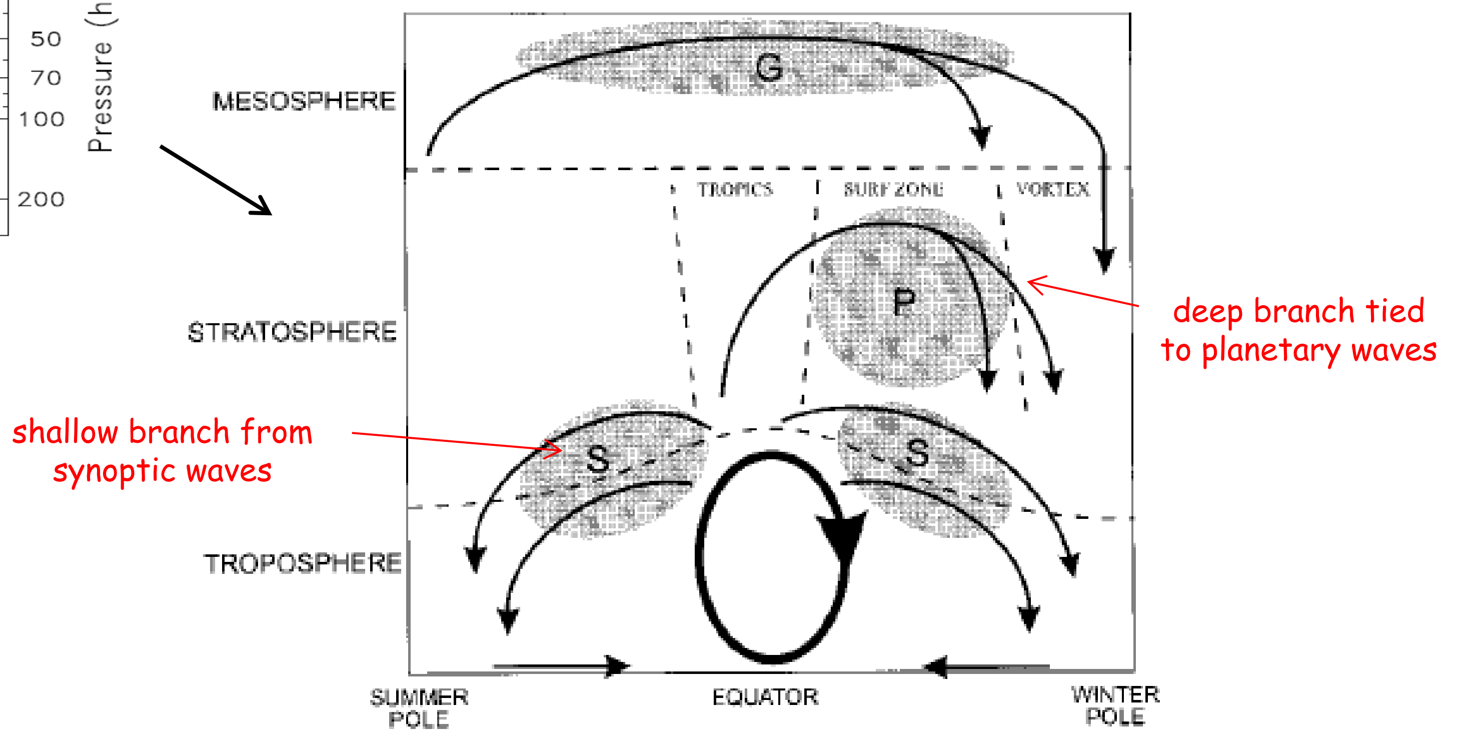
  - anti-correlated with troposphere for MJO variations
  - no correlation with troposphere for seasonal to interannual time scales

- Lower stratosphere T most sensitive to low frequency forcing

GPS EOF patterns



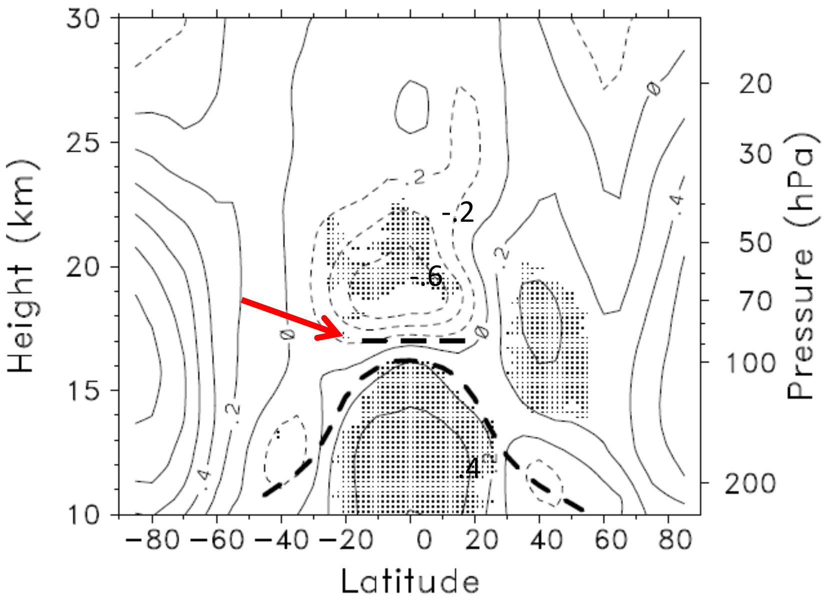
Deep and shallow branches of Brewer-Dobson circulation



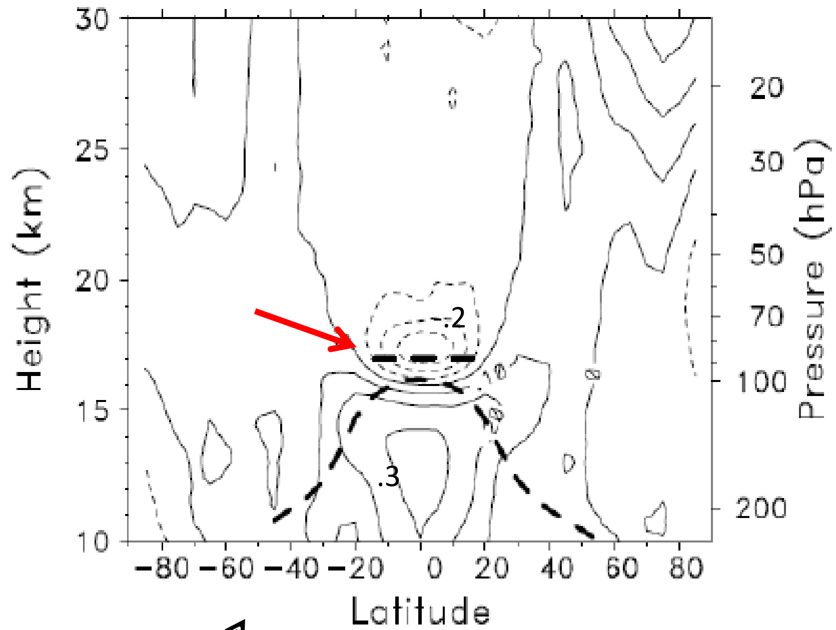
Plumb (2002); also Birner and Bonish, 2011

ENSO and MJO temperature signals from GPS

ENSO



MJO



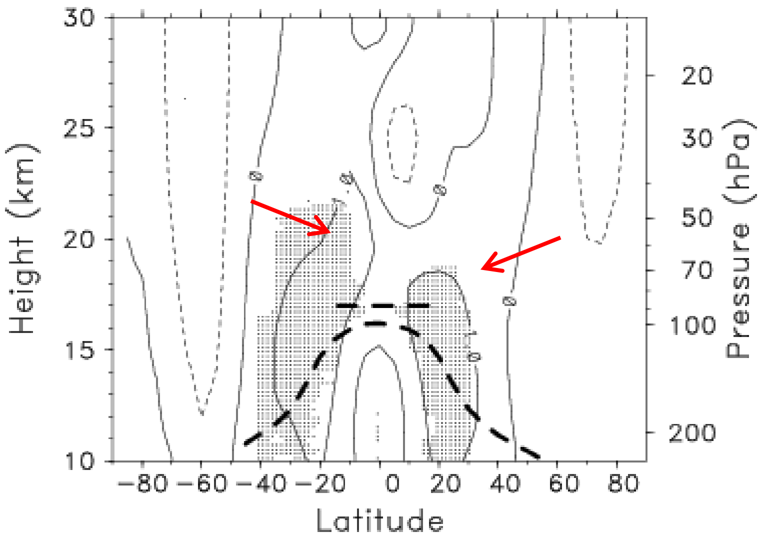
Similar spatial structure, but different vertical structure near tropopause. Why?

Randel and Wu, 2014, J. Atmos. Sci.

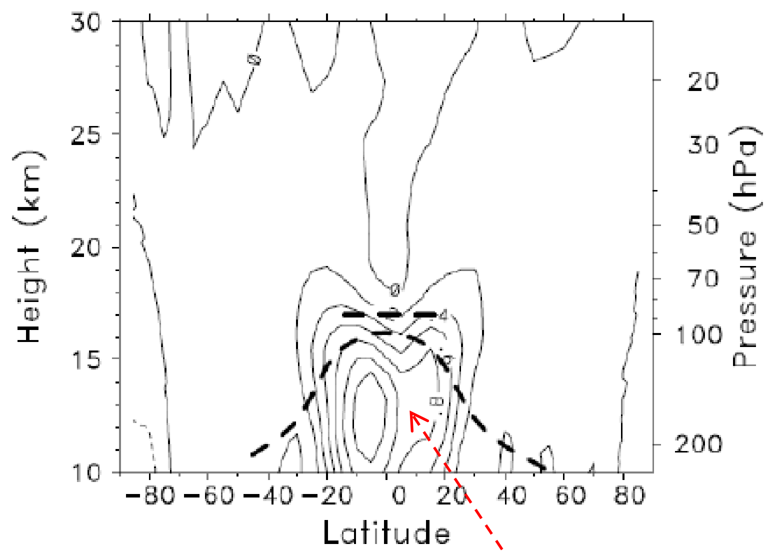
Why is the stratospheric upwelling signature of ENSO ‘deeper’ than the MJO?

Zonal wind anomalies linked
to ENSO and MJO

ENSO



MJO



For ENSO, zonal winds (and influence on wave driving)
extends into lower stratosphere
well above cold point tropopause

MJO confined
to troposphere

Randel and Wu, 2014, J. Atmos. Sci.

Stratospheric water vapor feedback

A. E. Dessler[a,1], M. R. Schoeberl[b], T. Wang[a], S. M. Davis[c,d], and K. H. Rosenlof[c]

PNAS 2013

in a global model, stratospheric H_2O increases with tropospheric temperature

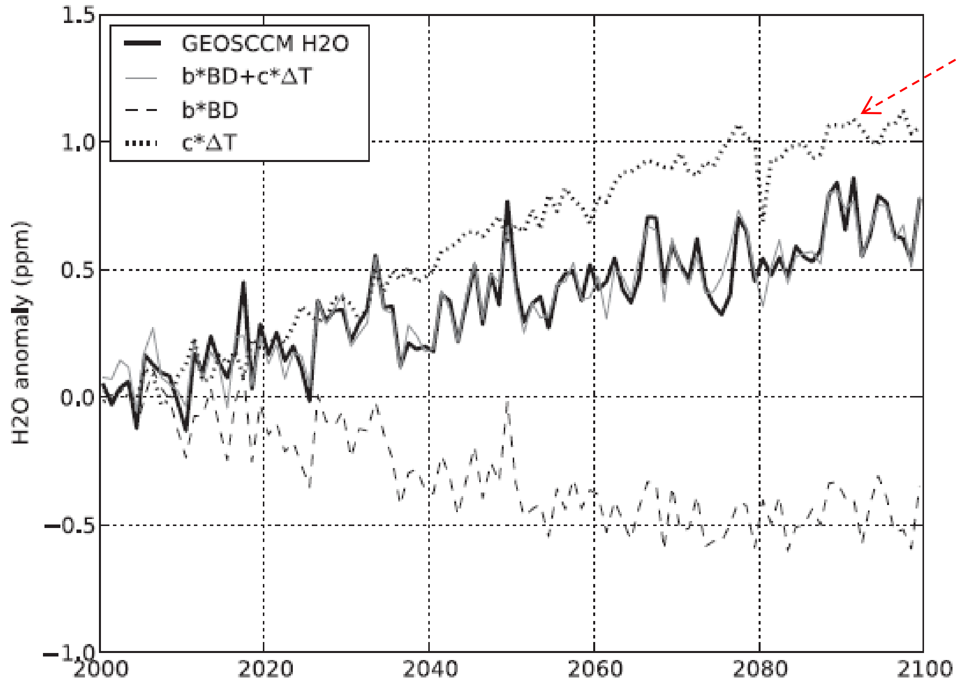
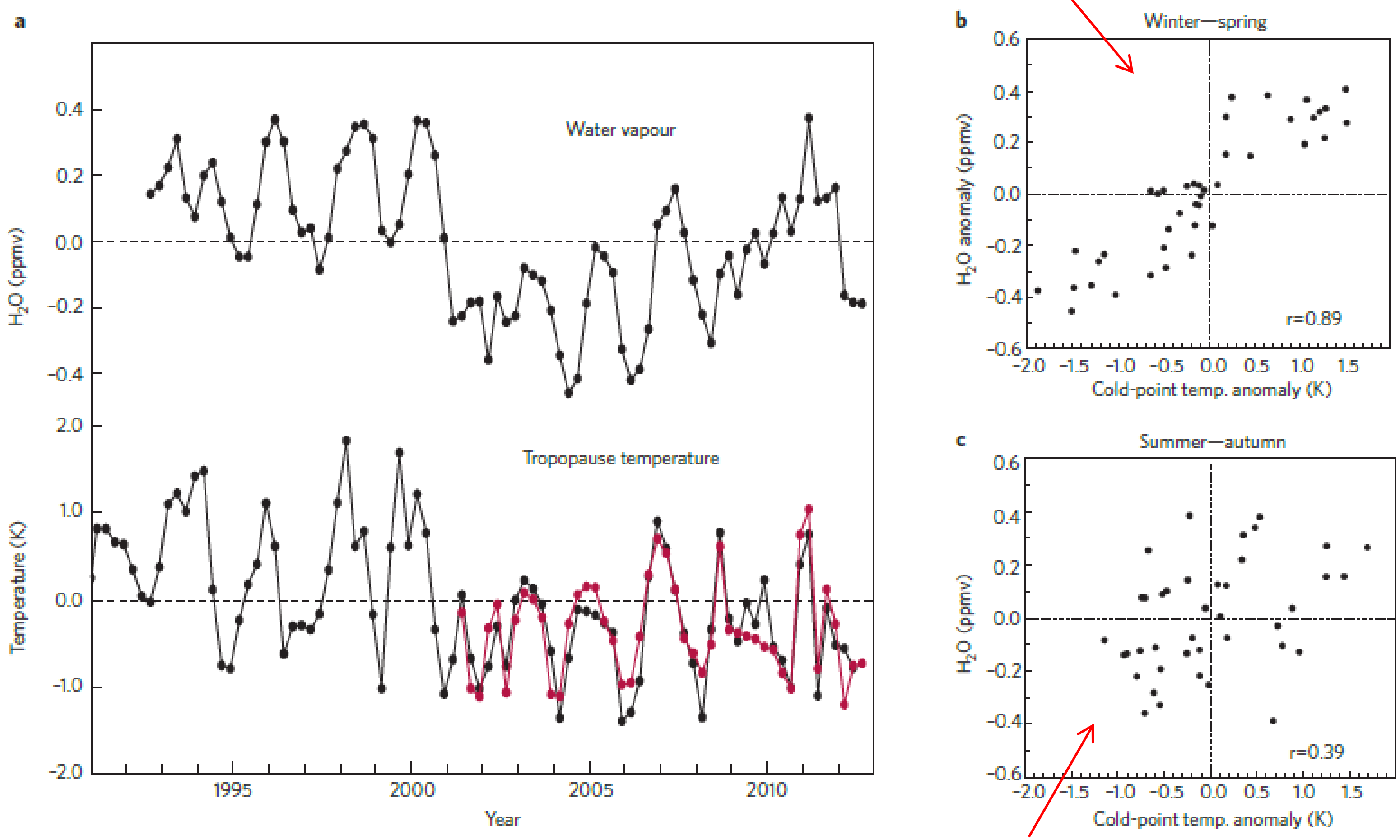


Fig. 2. Time series of annual-average $H_2O_{ov\text{-}entry}$ anomalies from the GEOSCCM (black) and the reconstruction from a multivariate least-squares regression (gray) over the 21st century. The dashed and dotted lines are the BD and ΔT terms of the regression, respectively.


Thank you


Thank you for inviting me to FDEPS!

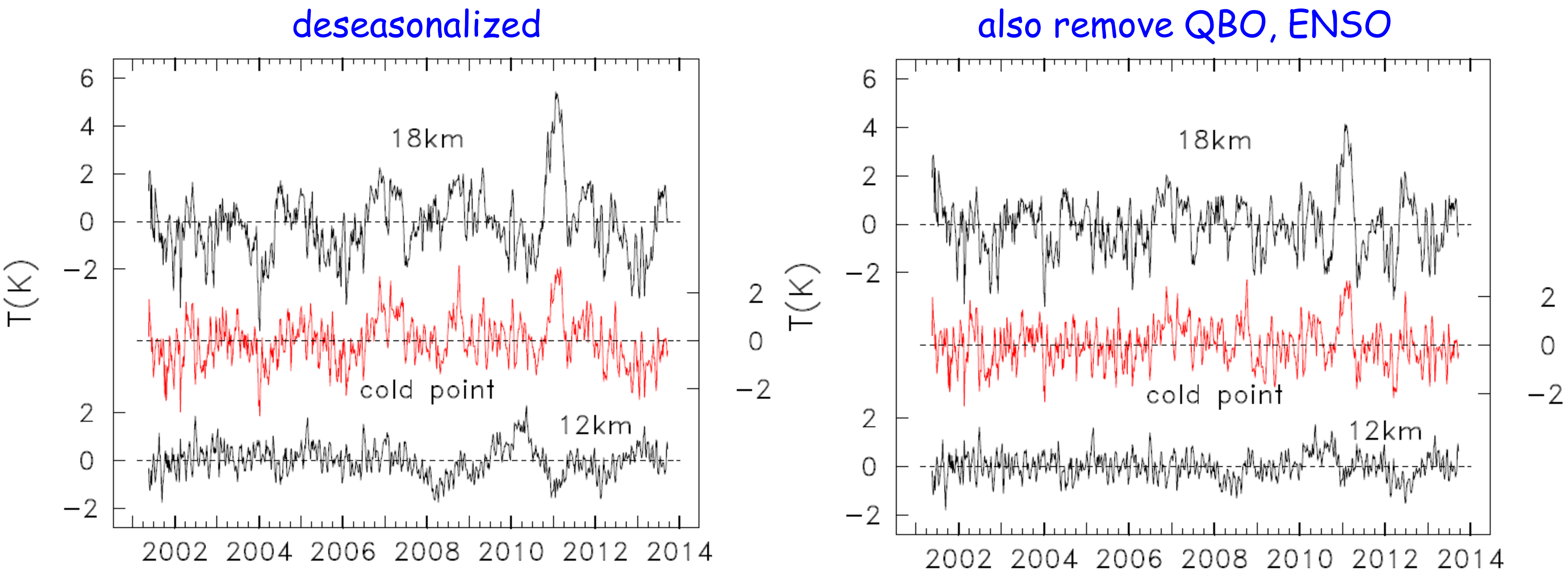
extremely high correlations
during NH winter-spring



weaker correlations
during NH summer-fall

Randel and Jensen, 2013

Time series of tropical temperature residuals



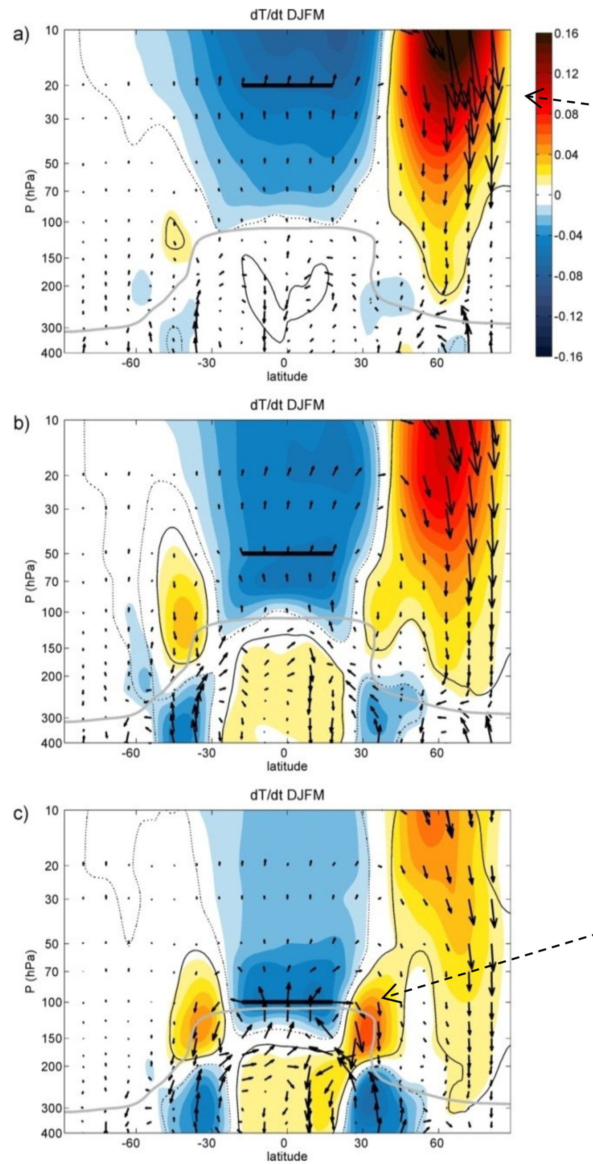
Randel and Wu, 2014, J. Atmos. Sci.

Dependence on the reference altitude for w^*_m

20 hPa

50 hPa

100 hPa



upper branch of Brewer-Dobson circulation

lower branch of BDC

Abalos et al, 2014, JAS

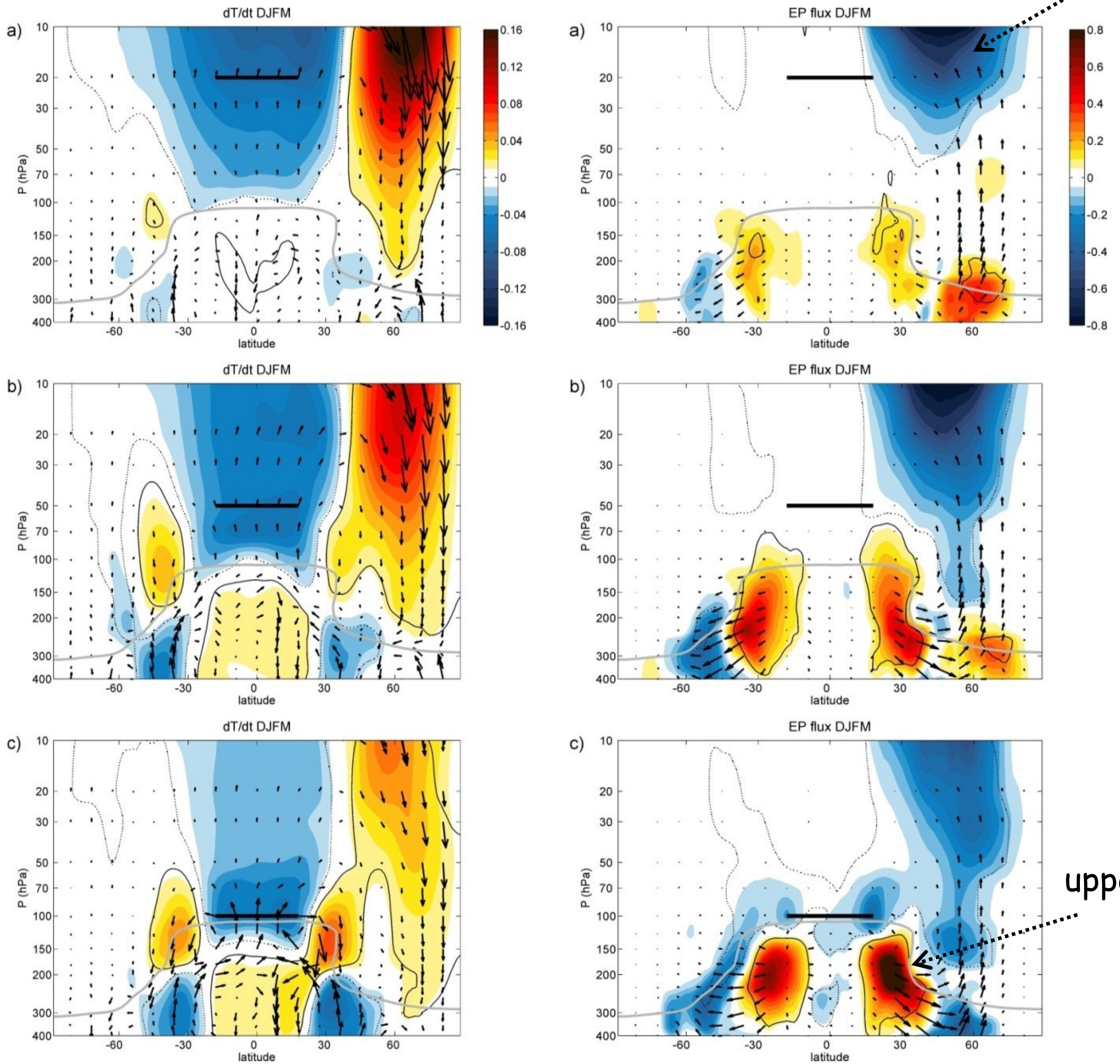
dT/dt and circulation EP fluxes

high latitude stratosphere forcing

20 hPa

50 hPa

100 hPa



subtropical upper troposphere forcing

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

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