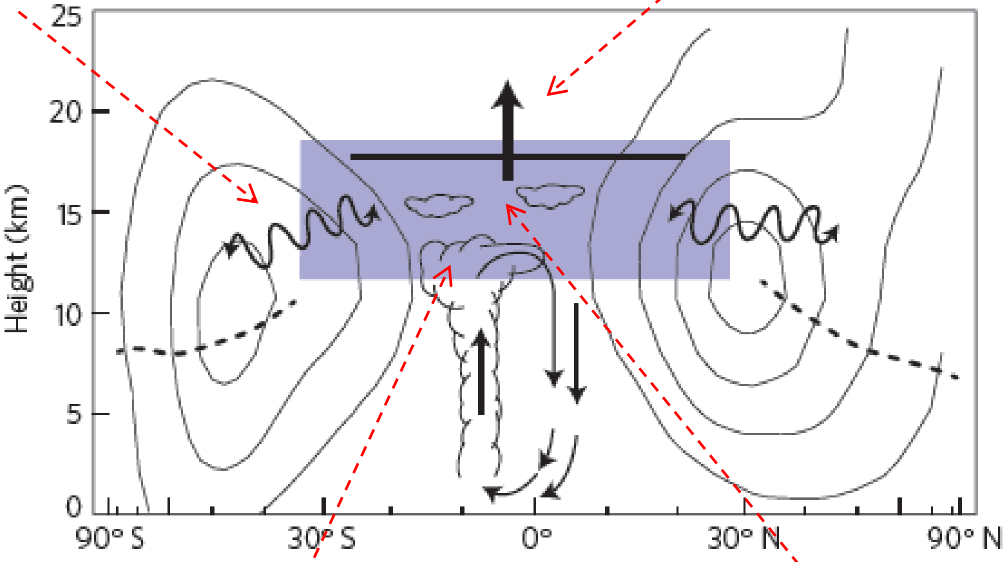
Tropical tropopause dynamics observed from a decade of GPS radio occultation data

- Temperatures from GPS radio occultation
- Observed tropical variability: seasonal cycle, QBO, ENSO,

  Brewer-Dobson circulation and MJO
- What controls the cold point tropopause?

Transport near the tropical tropopause layer (TTL)

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



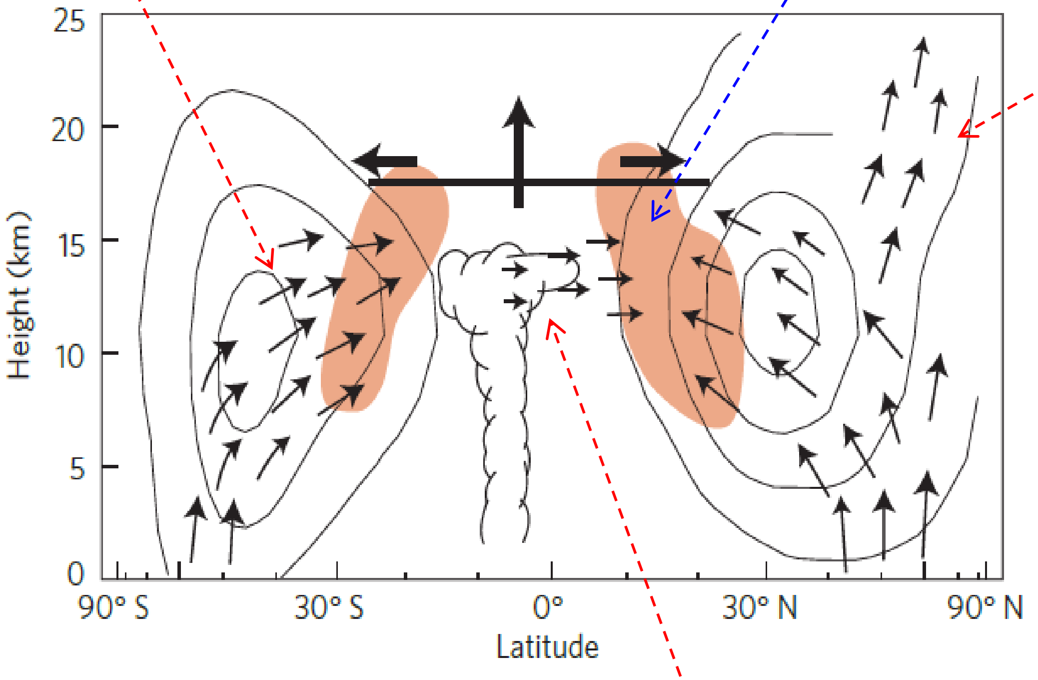
two-way mixing
from baroclinic eddies
and monsoons

tropical upwelling influences
temps, ozone and stratospheric H_2O

deep convection impacts
from below

cirrus and
climate impacts

Dynamical forcing of tropical upwelling



midlatitude
baroclinic waves

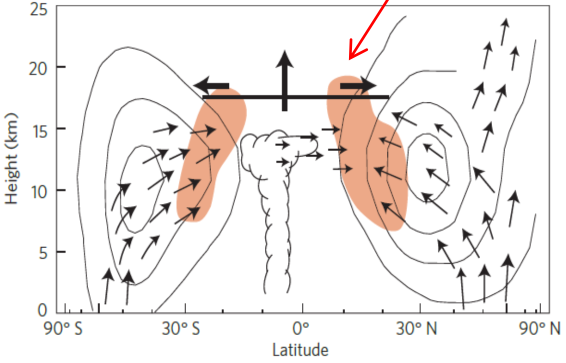
subtropical convergence
near critical lines (U=c)

stratospheric
planetary waves

equatorial waves forced
by deep convection

Deep and shallow branches of Brewer-Dobson circulation

shallow branch from synoptic waves



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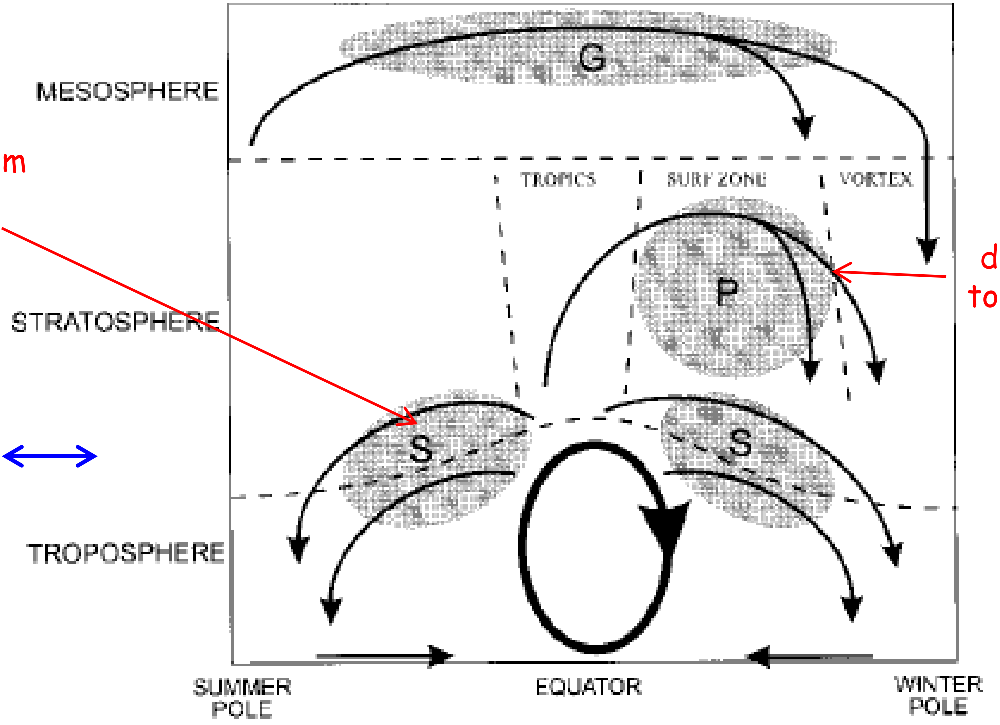


deep branch tied to planetary waves

Plumb (2002); also Birner and Bonish, 2011

Stratospheric H_2O is controlled by tropical cold point temperatures

Brewer, 1949

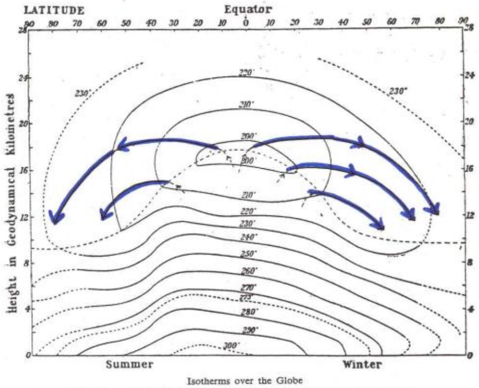
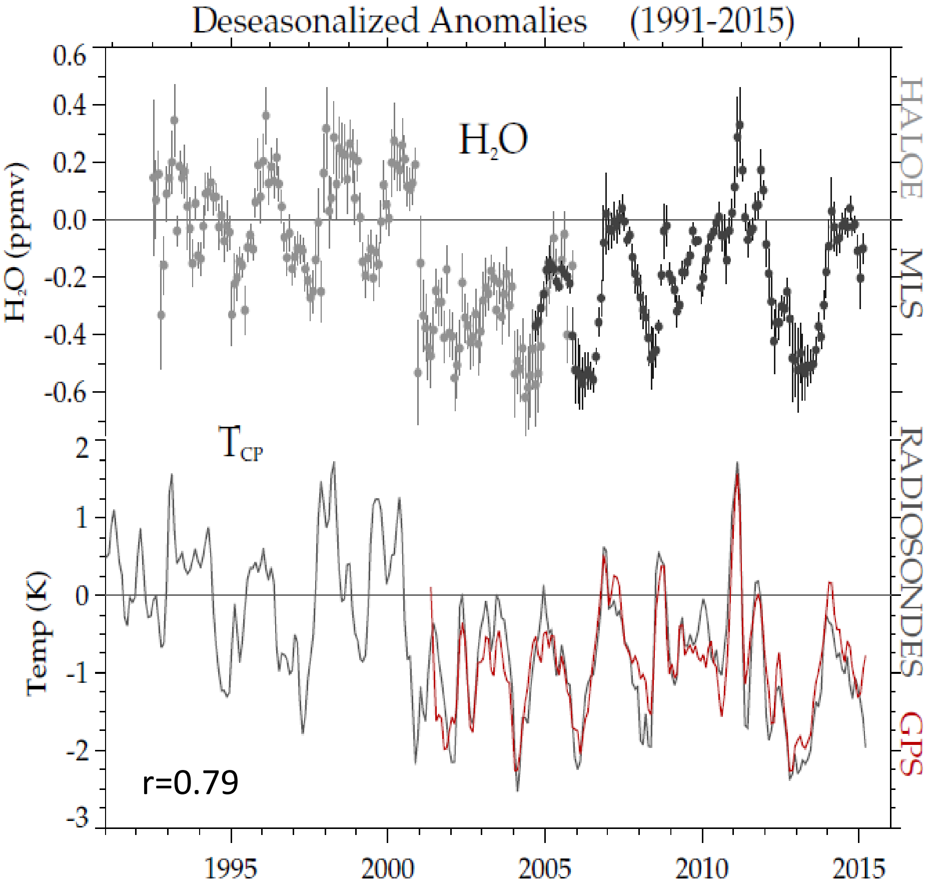


Fig. 5. A supply of dry air is maintained by a slow mean circulation from the equatorial tropopause.



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

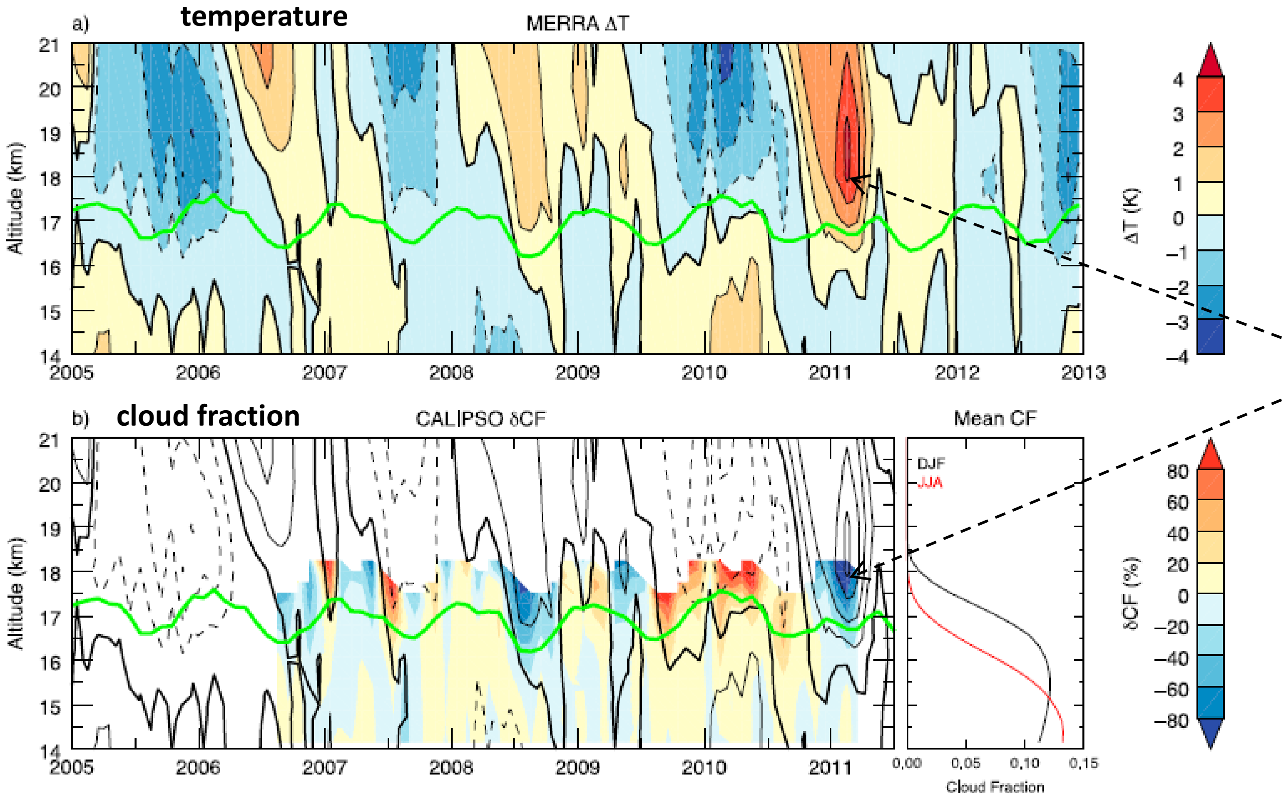
cold-point tropical
tropopause temperatures

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



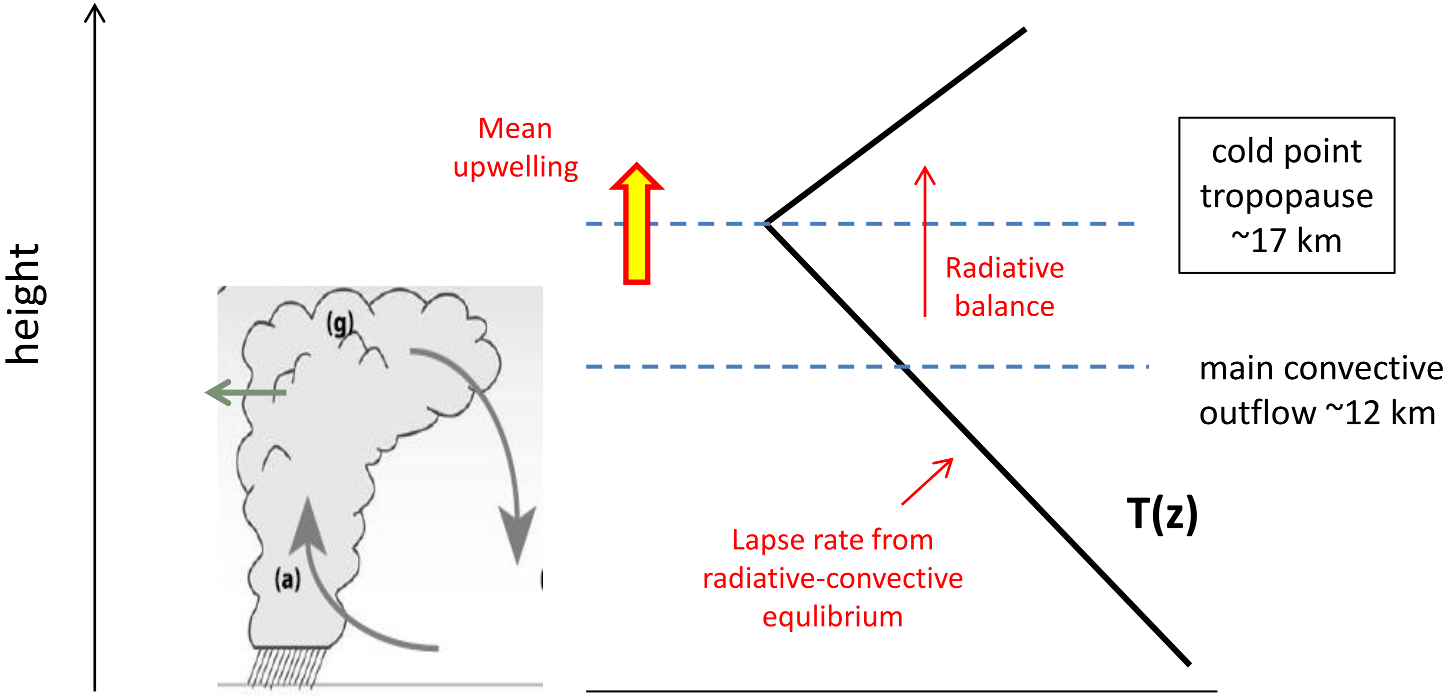
temperature

cloud fraction

warm temps,
less clouds

What controls variability of the cold-point tropopause?

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



height

Mean upwelling

cold point tropopause ~17 km

Radiative balance

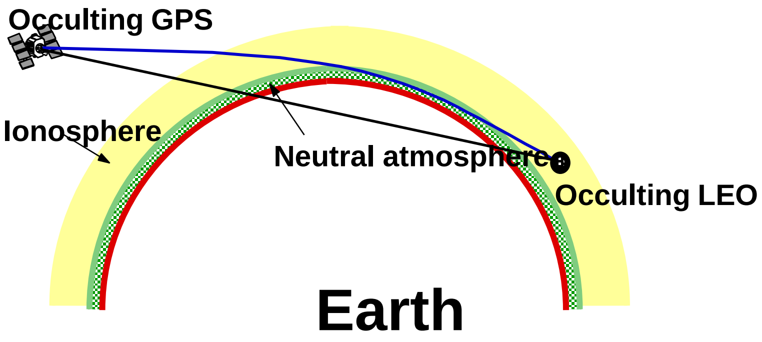
main convective outflow ~12 km

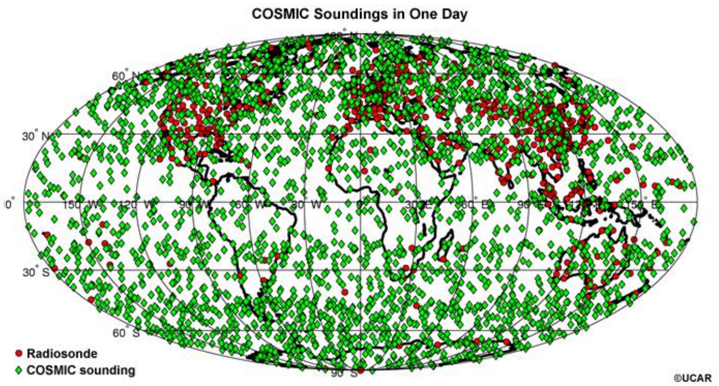
T(z)

Lapse rate from radiative-convective equlibrium

GPS radio occultation

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



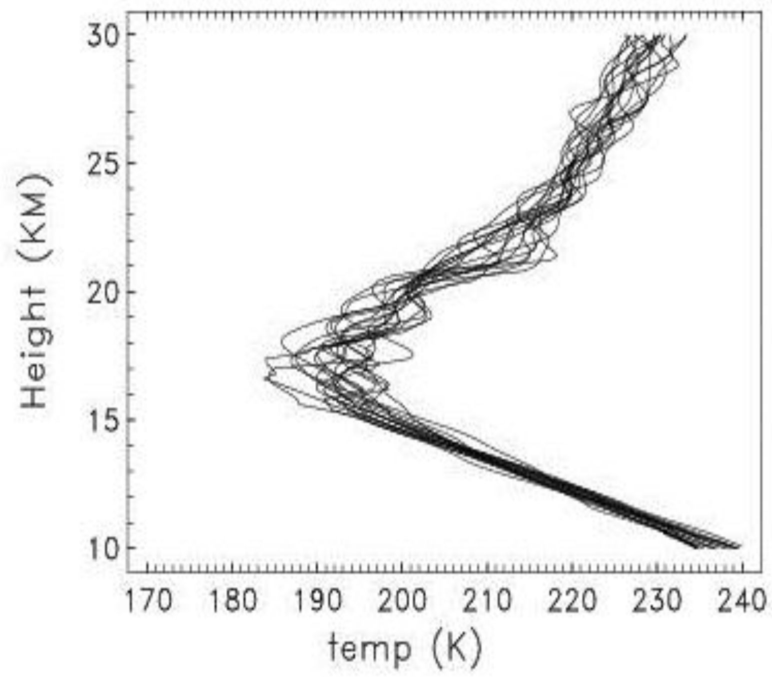


Utility of GPS Radio Occultation:

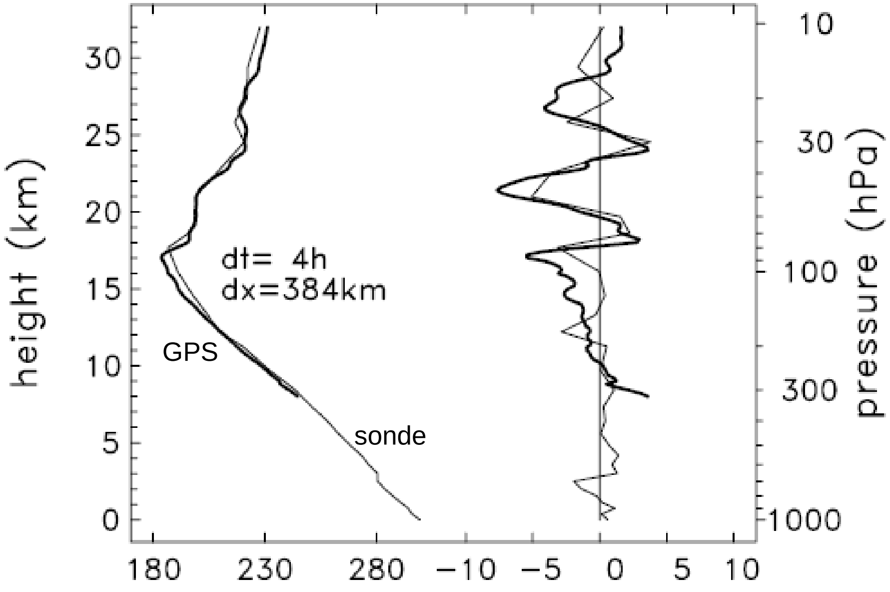
- Long-term stability
- All-weather operation
- High vertical resolution (< 1 km)
- High accuracy: Averaged profiles to < 0.1 K

accurate, high vertical resolution temperatures from GPS

sample of tropical profiles from GPS

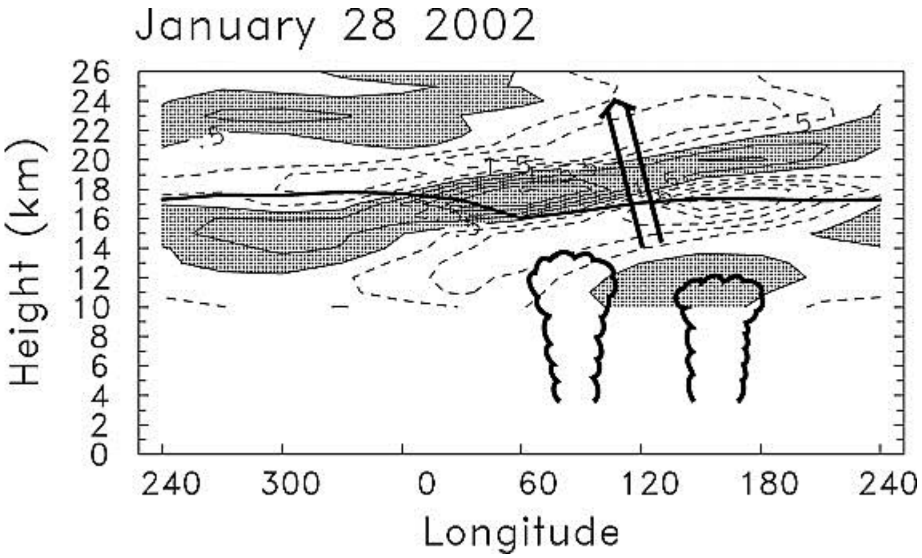


sonde-GPS comparison

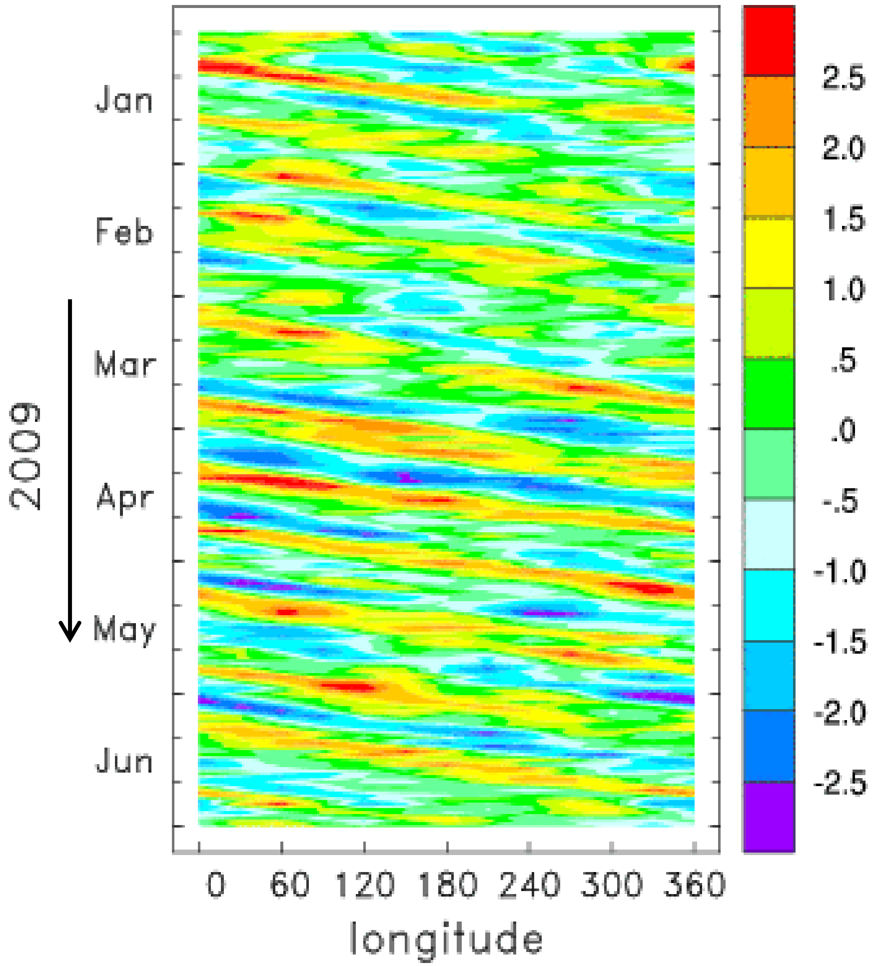


Global-scale Kelvin waves observed by GPS

Kelvin waves: narrow vertical scales and eastward phase tilt with height



temp anomalies at 19 km



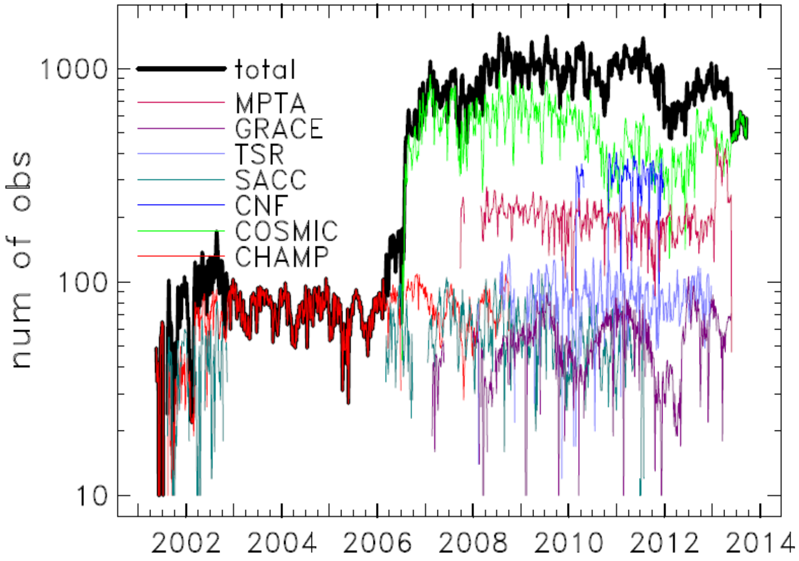
<u>GPS studies of tropical waves:</u>
Tsuda et al 2000; Randel and Wu 2005;
Alexander et al 2008; Kim and Son, 2012;
+ others.

Using GPS data to understand variability of tropical temperature:

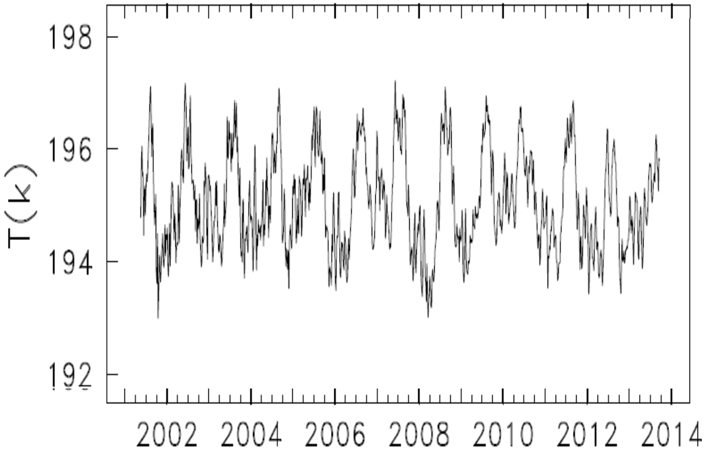
- Construct a global, zonal average data set from GPS observations
- 5-day (pentad) averages for 2001-2013 (over 12 complete years)

total > 6,200,000 occultations

Number of obs / pentad for 10° N-S



Example: 16 km, 10° N-S



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

TEM
thermodynamic
balance

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

$$\downarrow$$

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

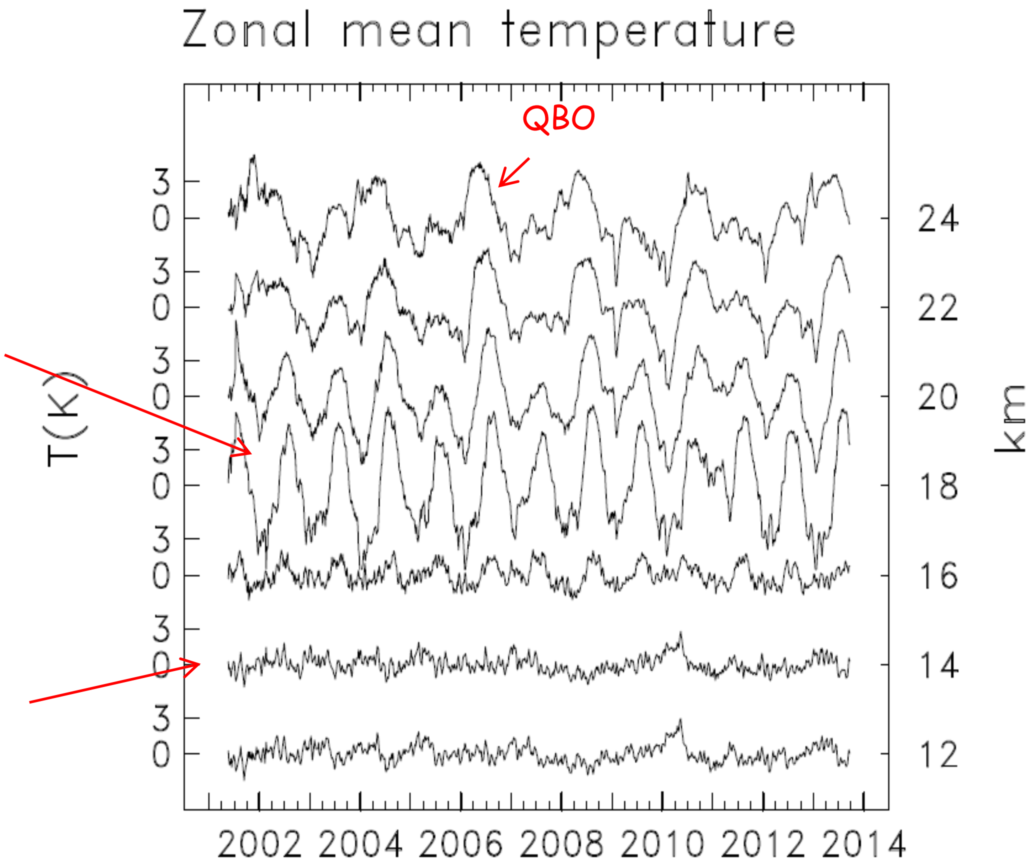
approximate
balance in tropics

$$\downarrow$$

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

linear damping
approximation
(in stratosphere)

tropical variability for 10° N-S

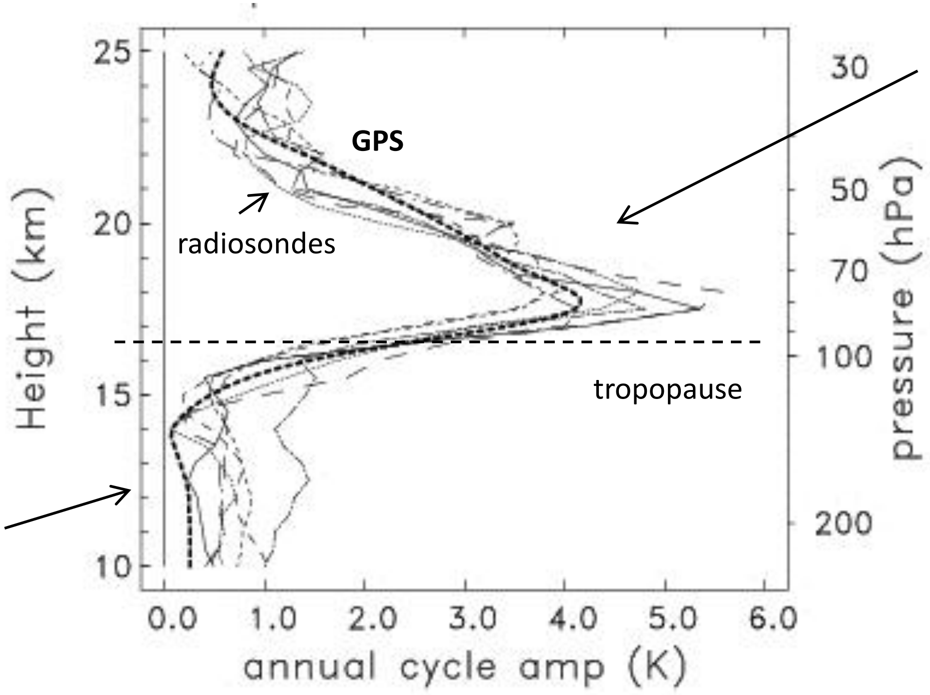


QBO

large annual cycle
in lower stratosphere

small annual cycle
in troposphere

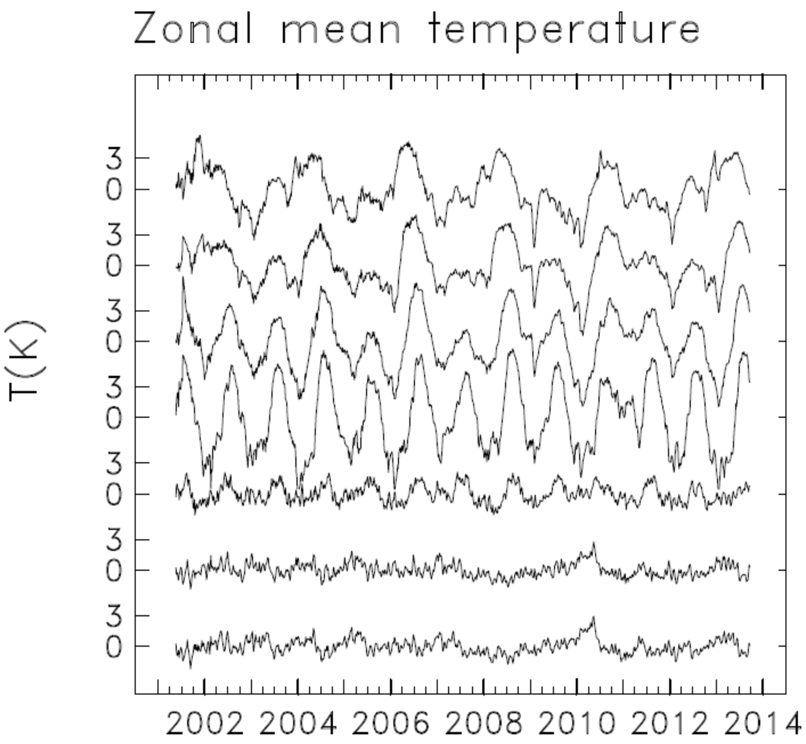
Amplitude of the tropical annual cycle in temperature



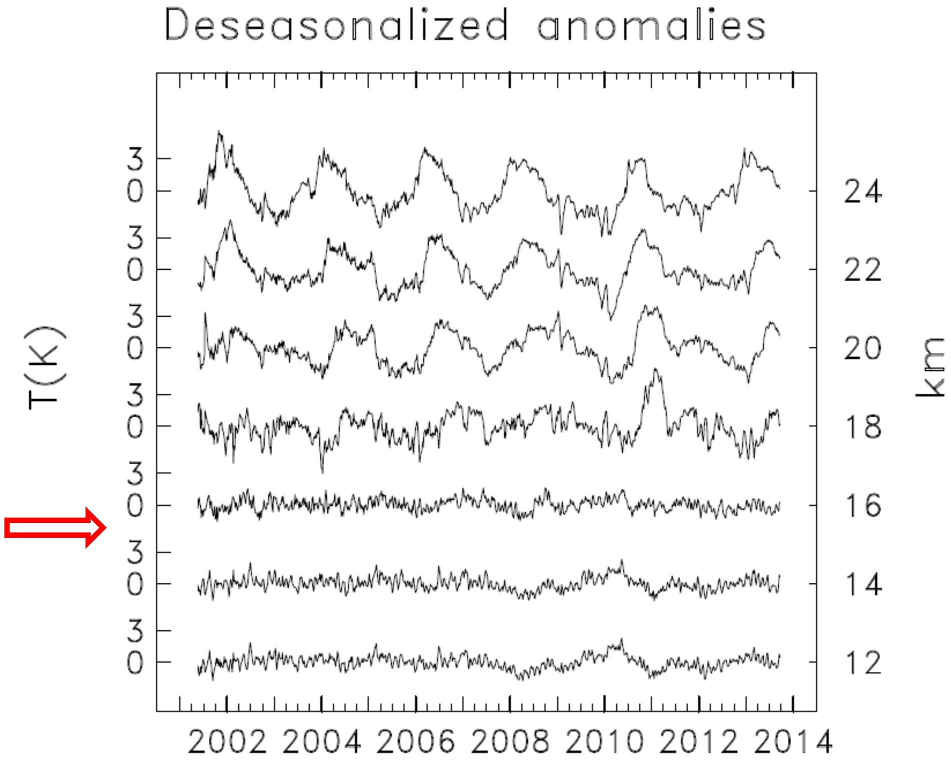
narrow vertical scale,
peak in lower stratosphere

very small
annual cycle
in troposphere

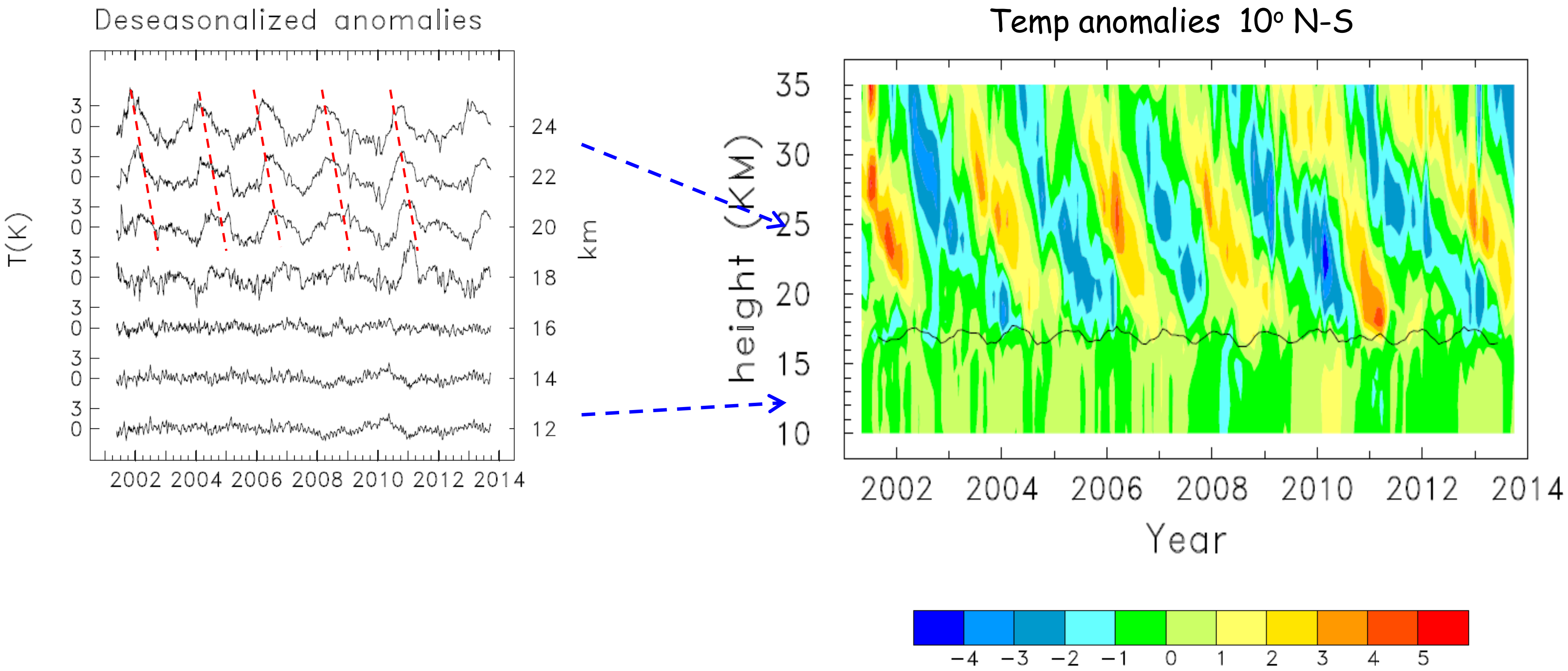
‘raw’ time series



remove seasonal cycle



QBO is the large interannual signal in the stratosphere



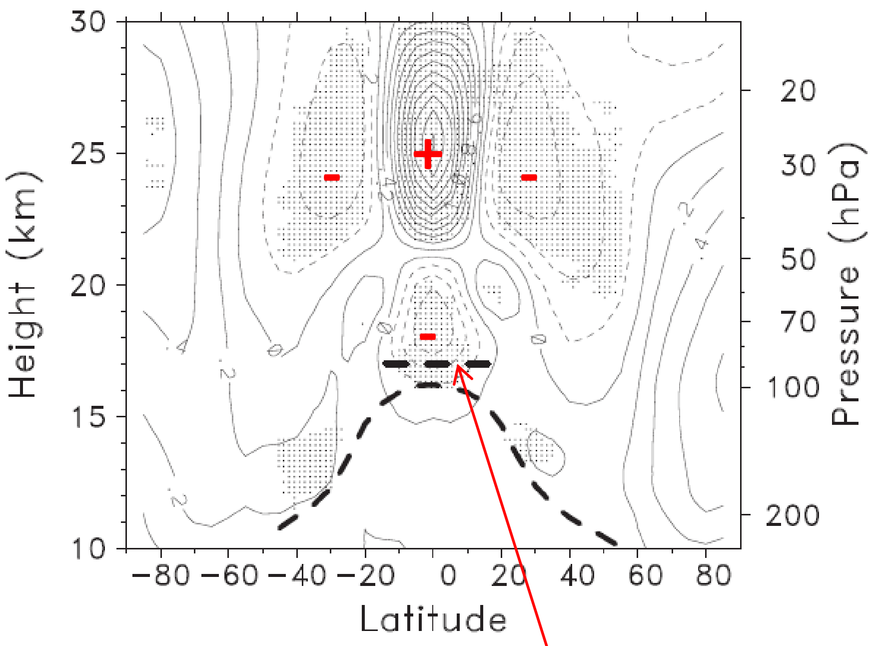
Temp anomalies 10° N-S

Regression fits of QBO and ENSO 2001-2013

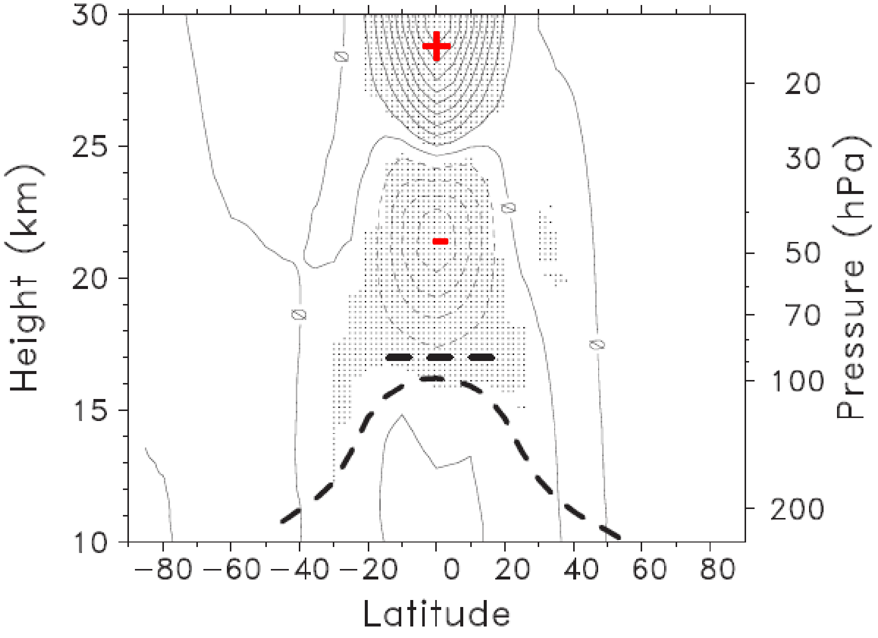
$$T = a * \mathrm{ENSO} + b_1 * \mathrm{QBO}_1 + b_2 * \mathrm{QBO}_2$$

proxy
time
series

QBO_1 GPS temperature



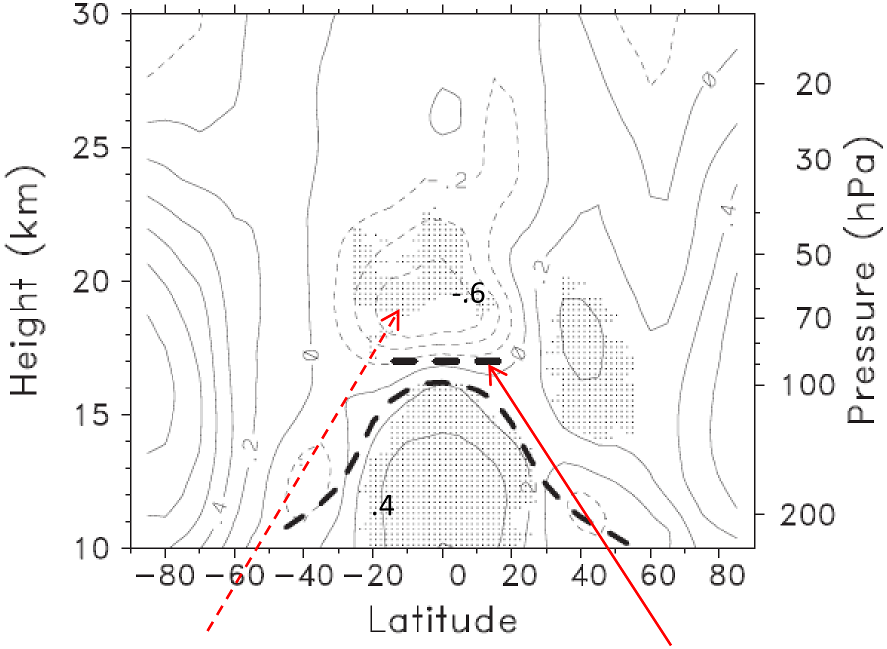
QBO_1 ERAi zonal wind



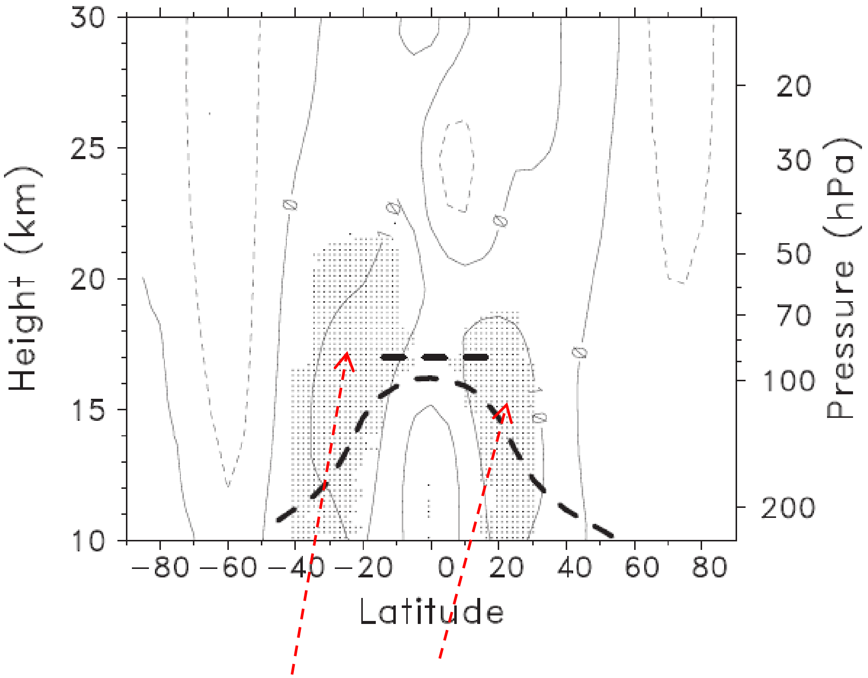
influence on cold point ~ 0.5 K

ENSO fits

ENSO GPS temperature



ENSO ERAi zonal wind

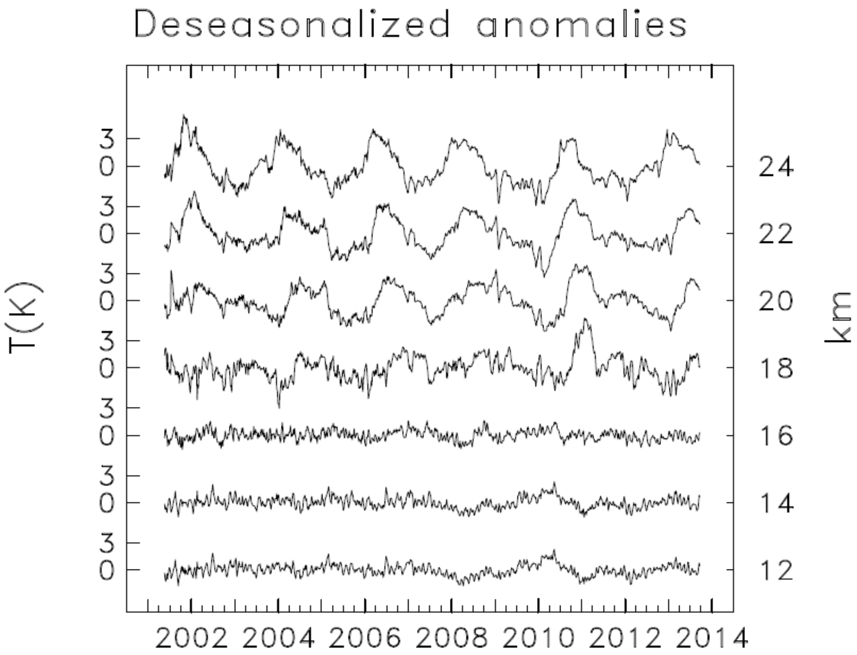


stratosphere cooling
tied to enhanced upwelling
e.g. Calvo et al 2010

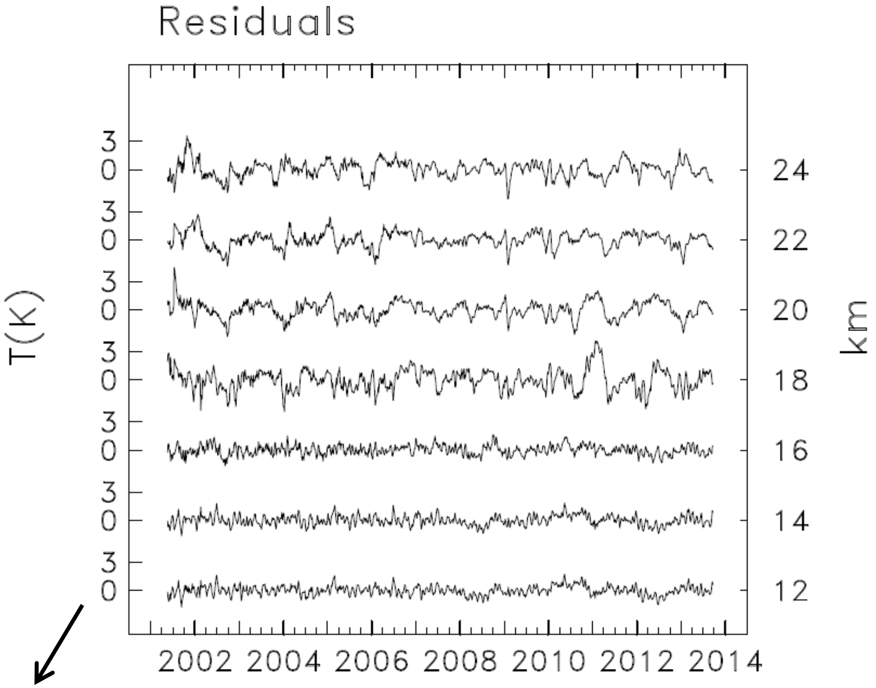
small influence on
cold point

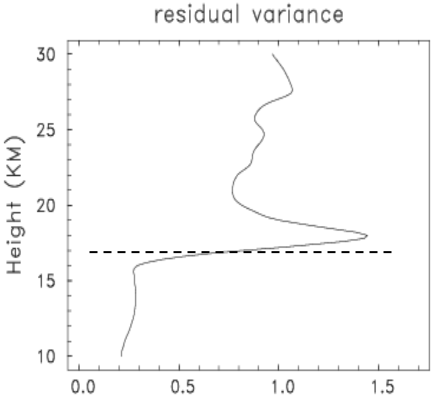
wind maxima in subtropics,
extending into lower stratosphere

deseasonalized

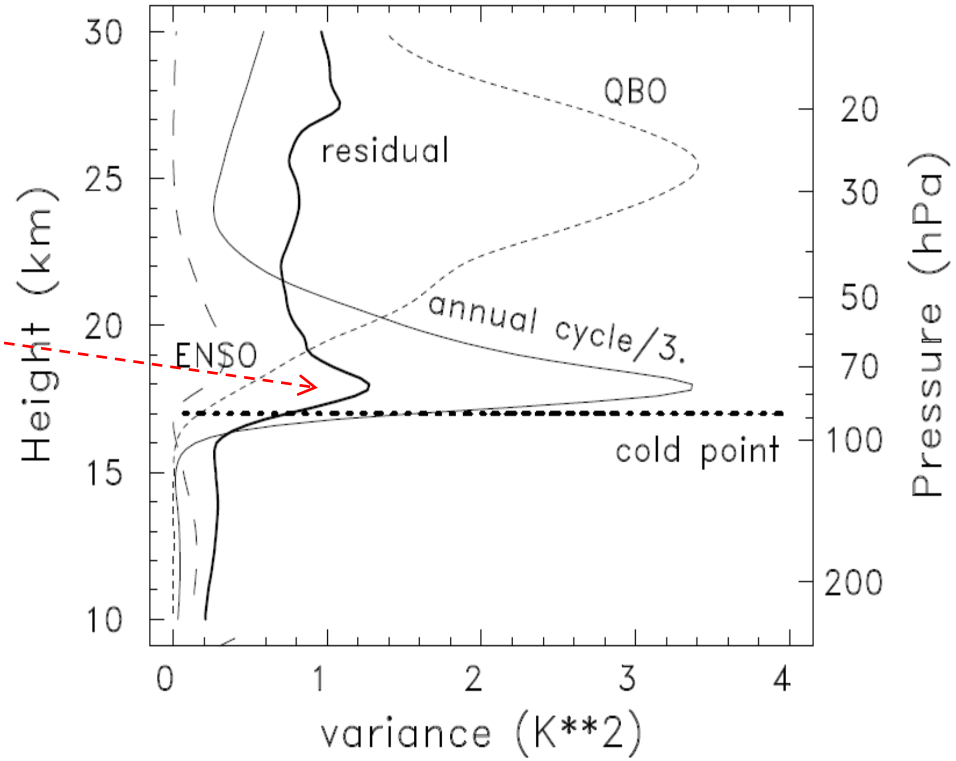


remove QBO and ENSO
('residual' variability)





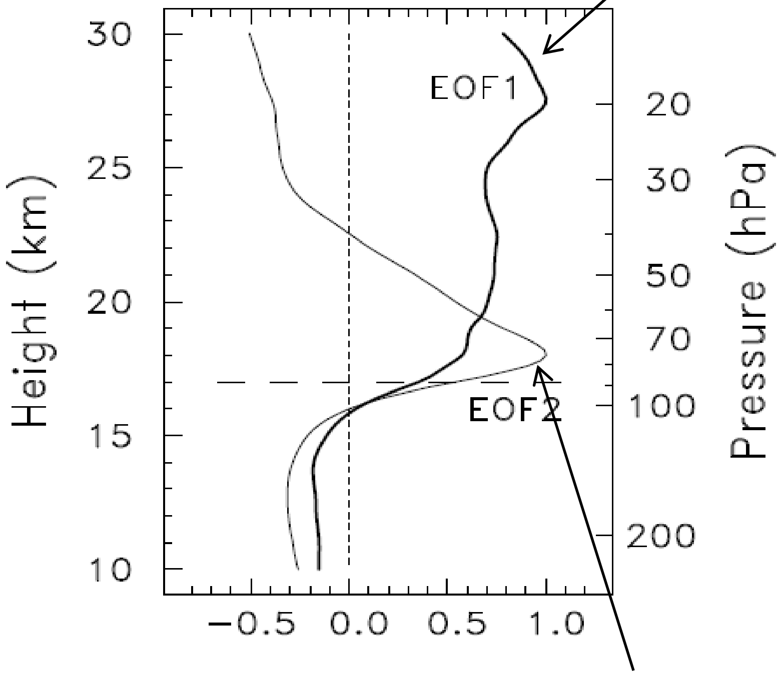
components of zonal mean temperature variance



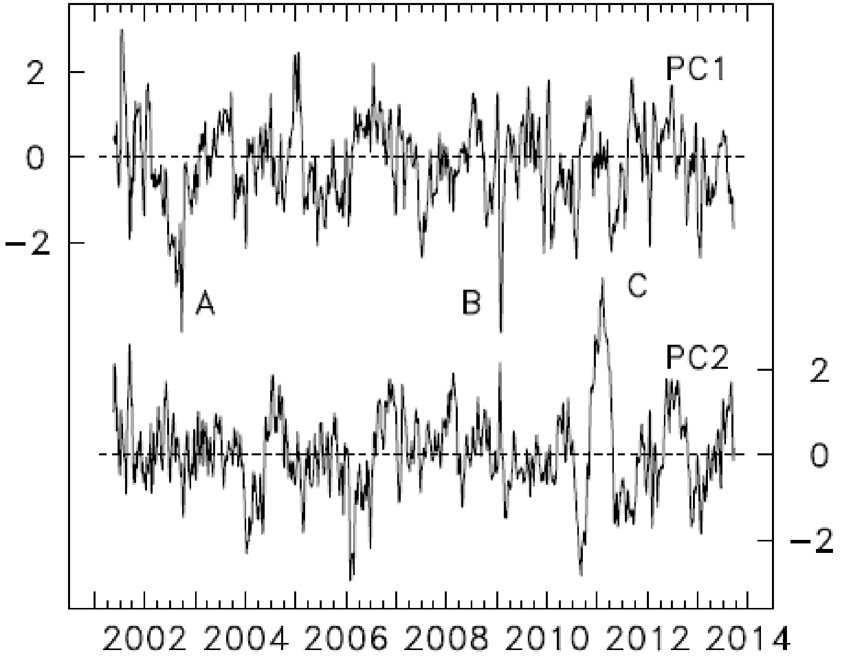
residual dominates
deseasonalized
variance
near tropopause

EOF analysis of residuals

deep stratosphere mode

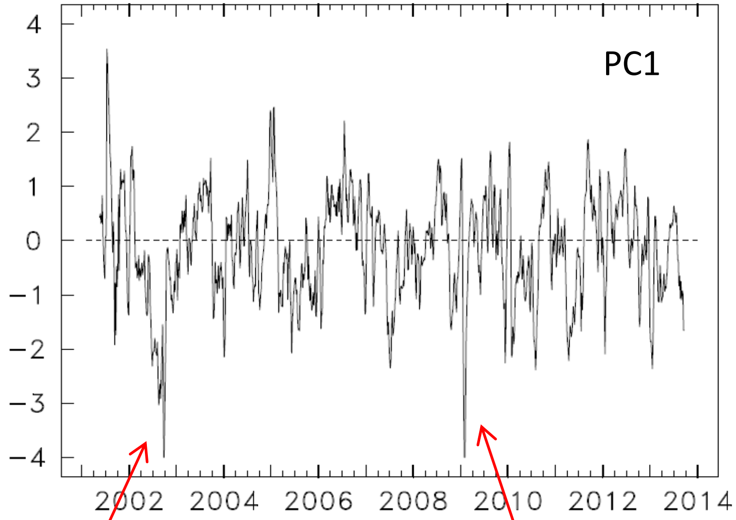


near tropopause mode



Tropical cooling linked to stratospheric sudden warmings (SSW)

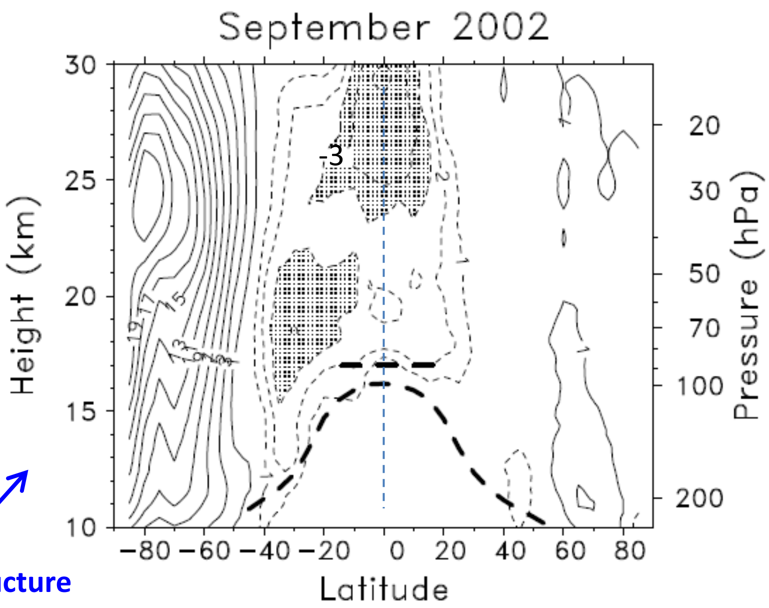
EOF1: deep stratosphere mode

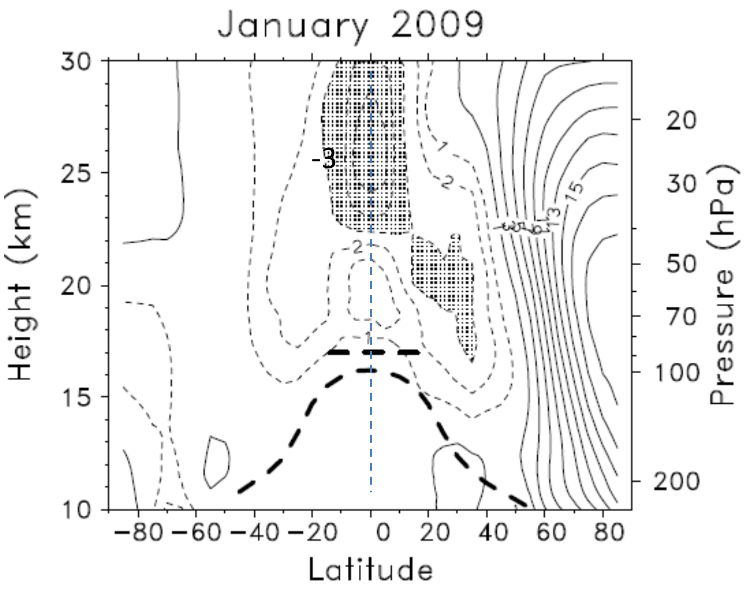


SH warming
Sept 2002

NH warming
Jan 2009

spatial structure
of temp anomalies





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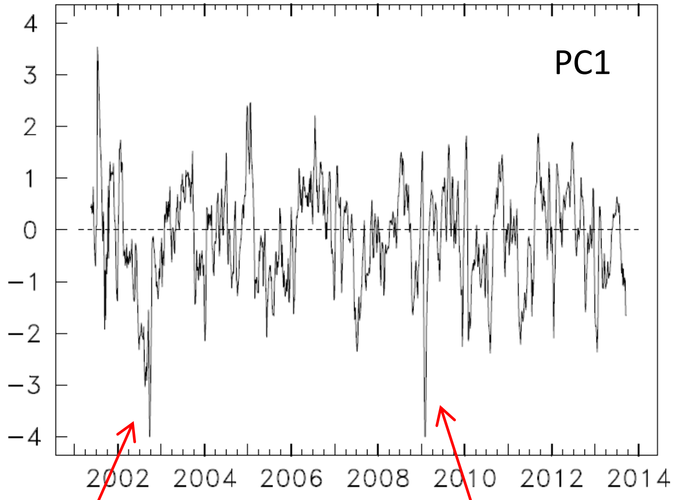

SH warming
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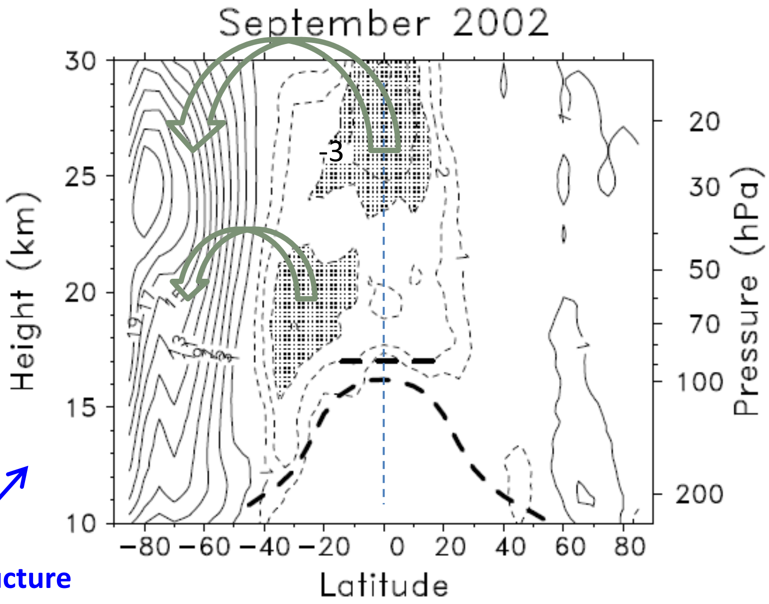
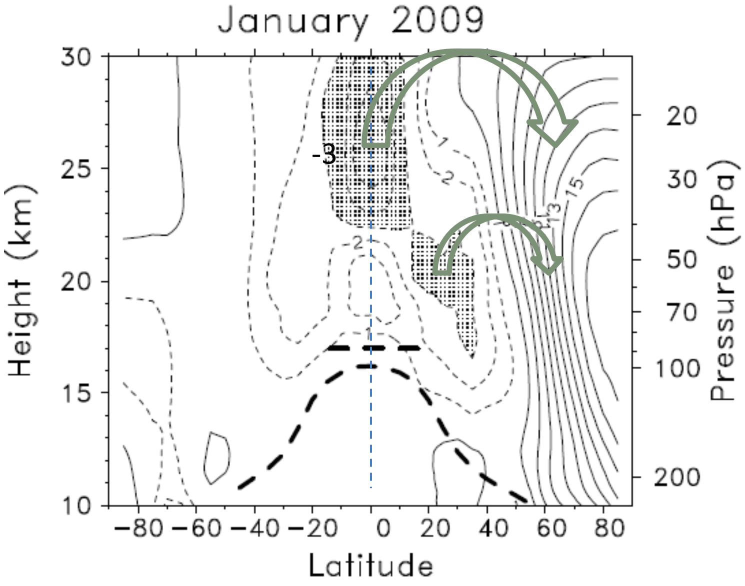
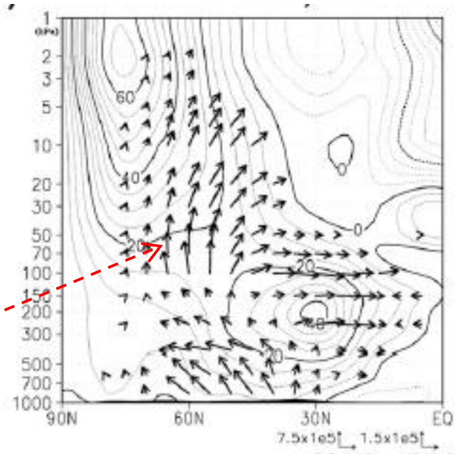




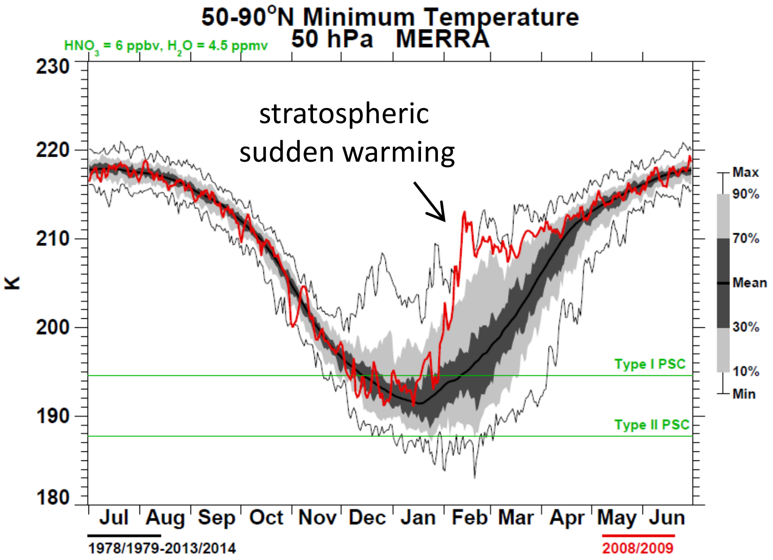
Large stratospheric sudden warming in January 2009



high latitude planetary wave forcing

Harada et al , 2010

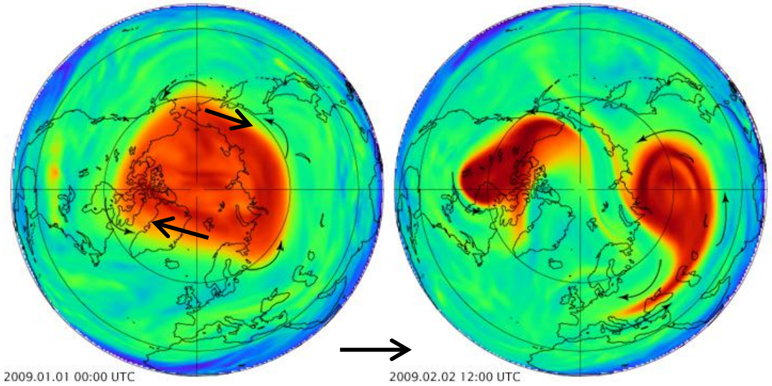
Polar stratosphere temperature



stratospheric sudden warming

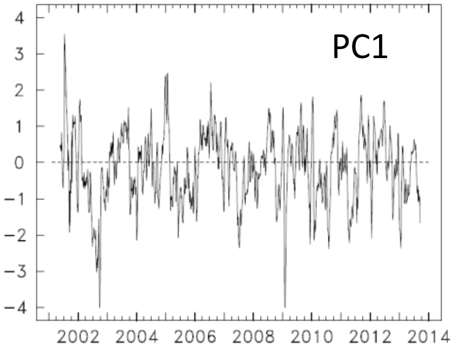
polar vortex near 30 km

potential vorticity



split of polar vortex

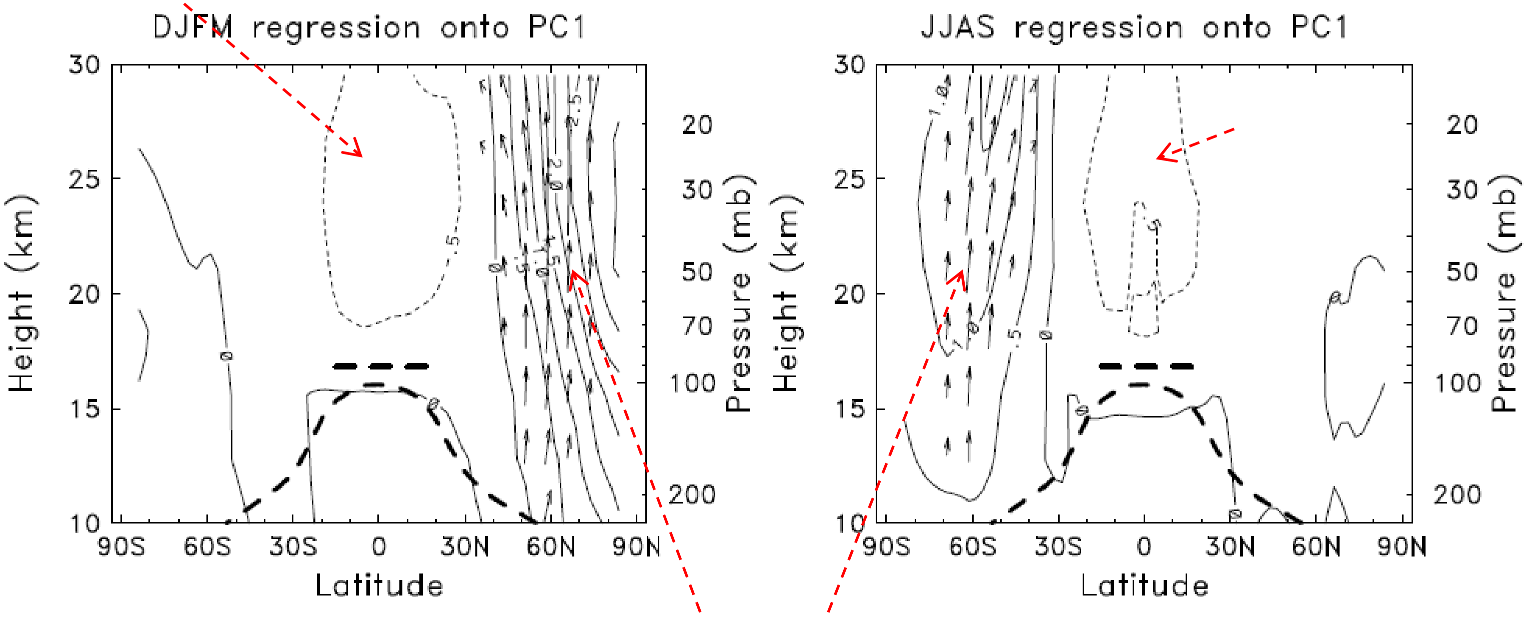
Regression of global temperatures and EP flux onto PC1



cooling in tropics

NH winter

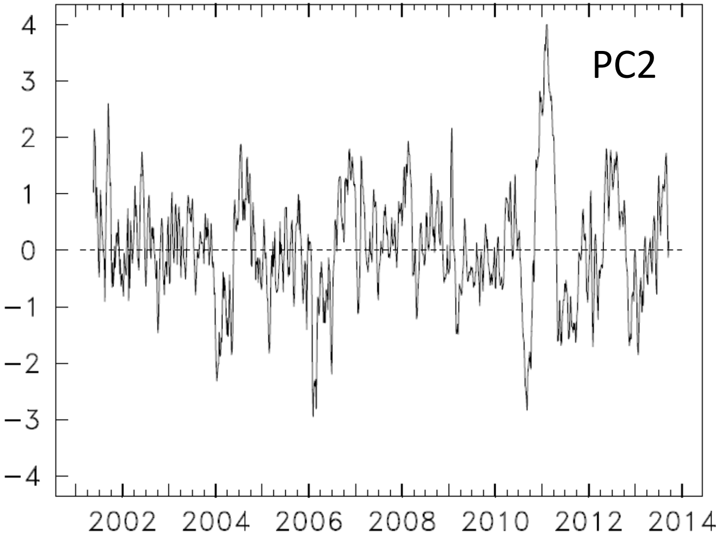
SH winter



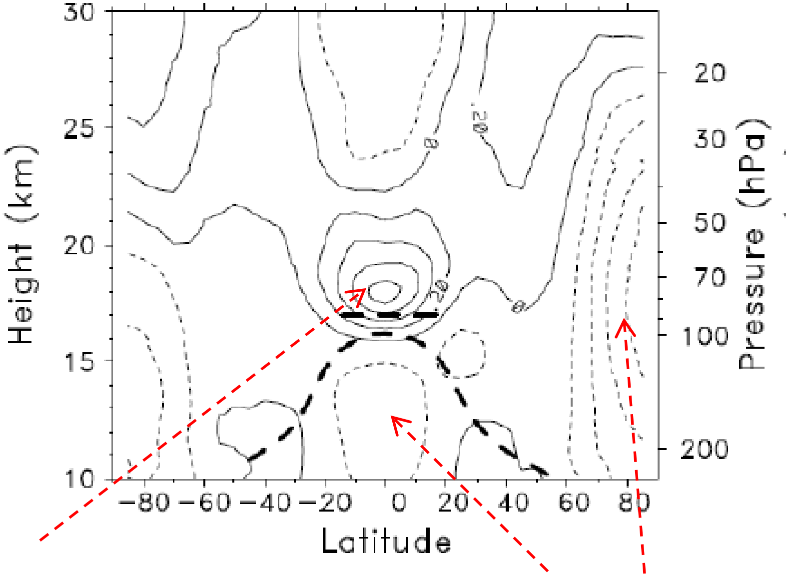
high latitude EP fluxes and polar warming

near-tropopause signal

EOF2: near-tropopause mode



temperature regression onto PC2

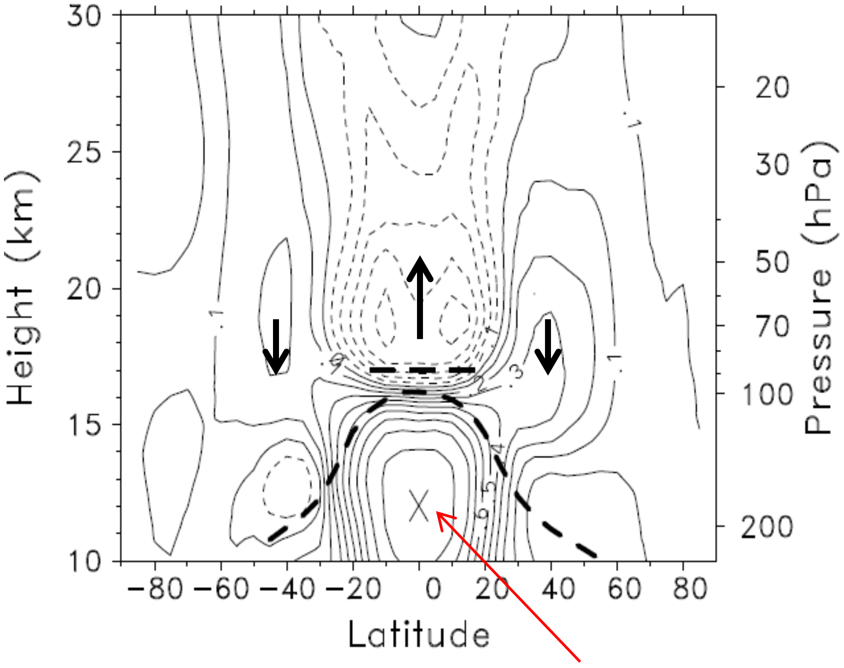


maximum in tropical lower stratosphere

anti-correlation with tropical troposphere and polar stratosphere

near-tropopause signal: correlation maps

correlation wrt 12 km

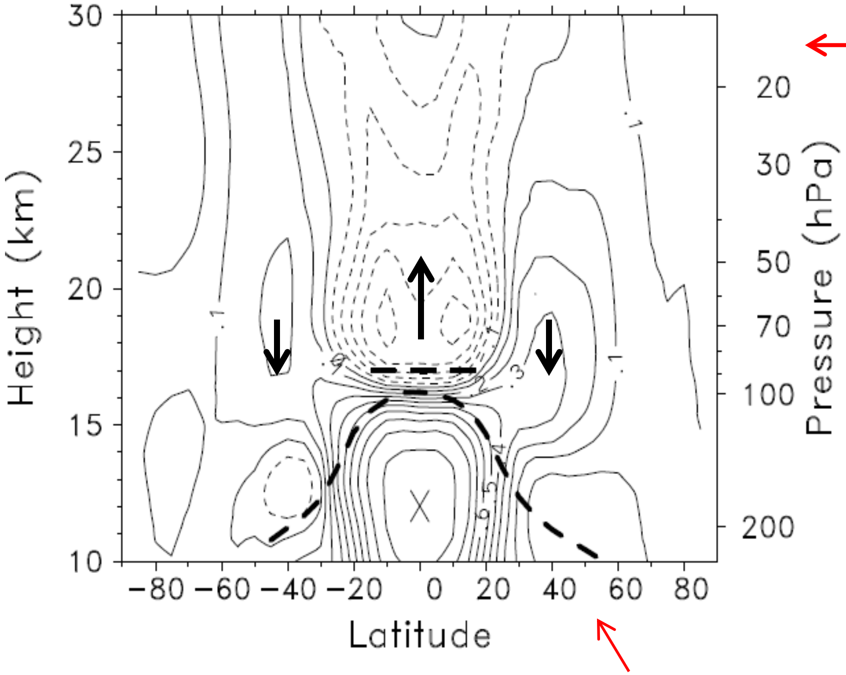


reference

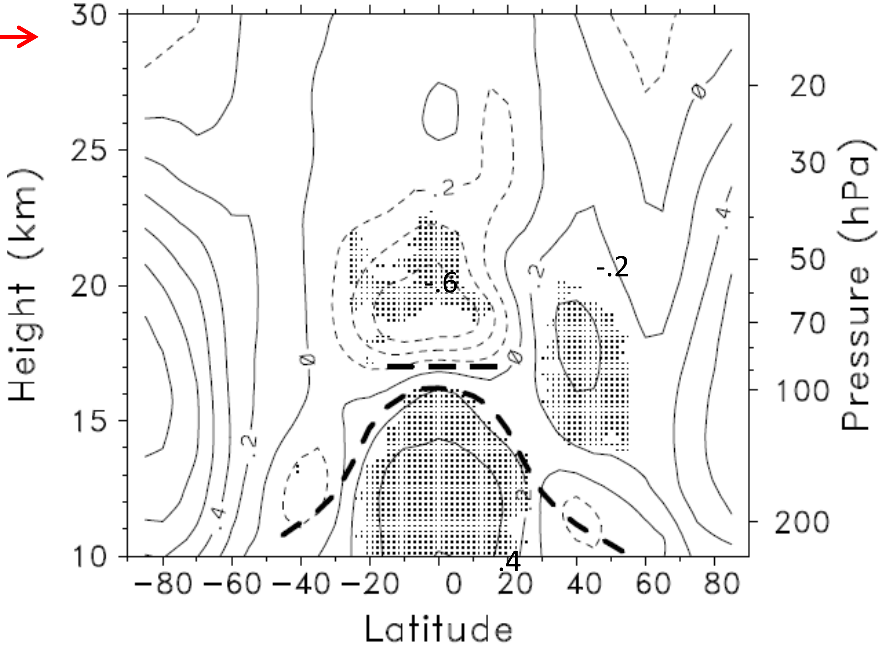
tropical tropospheric warming
linked with lower branch
of BDC

Similar to ENSO signal

correlation wrt 12 km

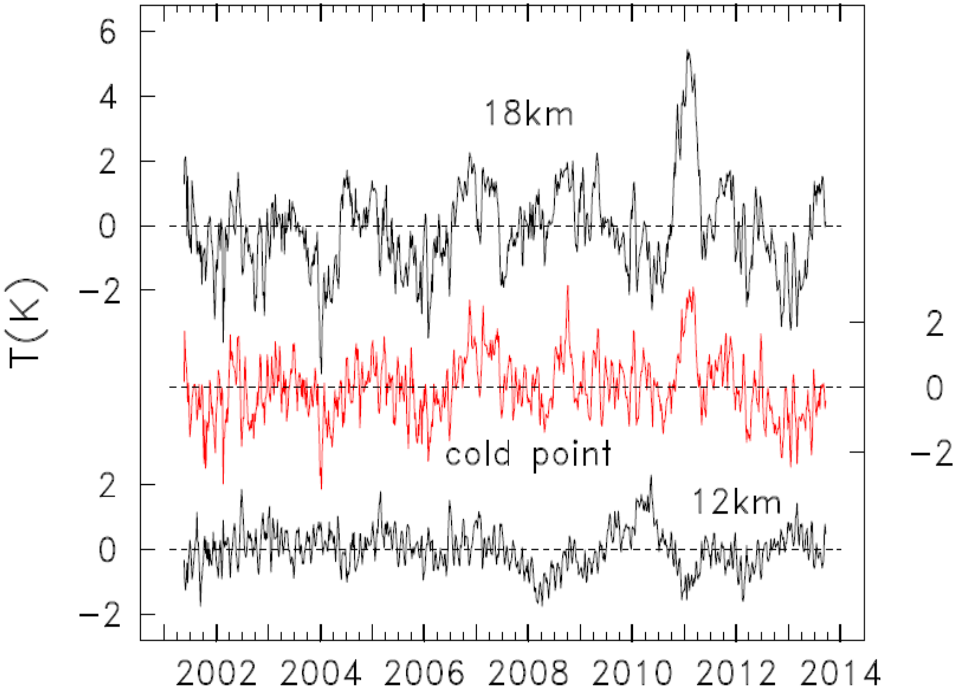


ENSO signal

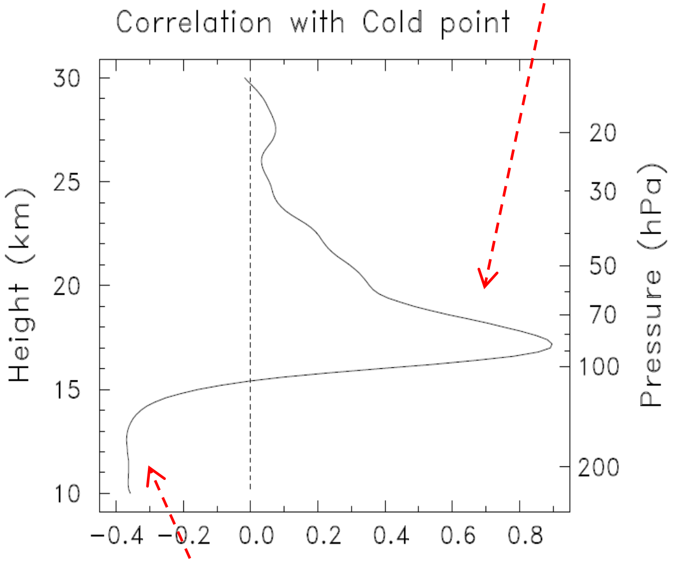


but recall ENSO ‘removed’
before this calculation

detailed variability near the cold point tropopause



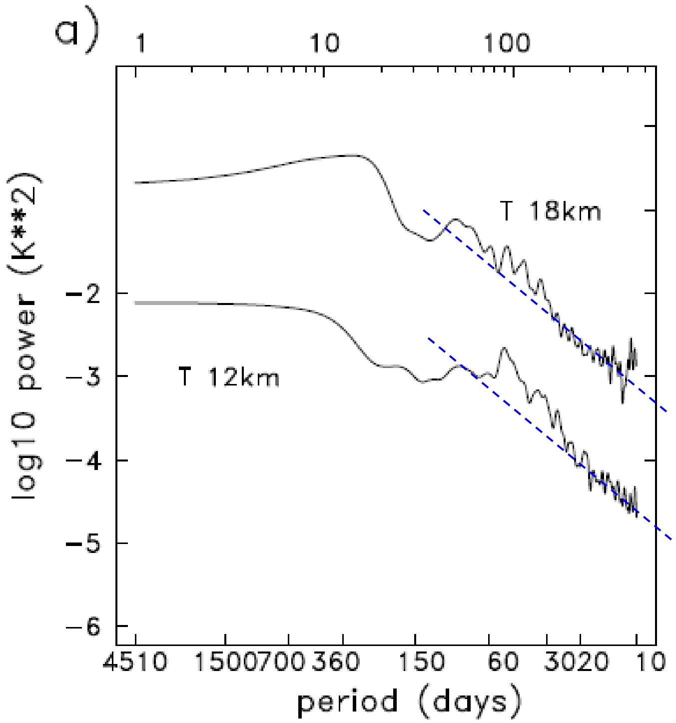
strong correlation
over narrow layer
~16-19 km



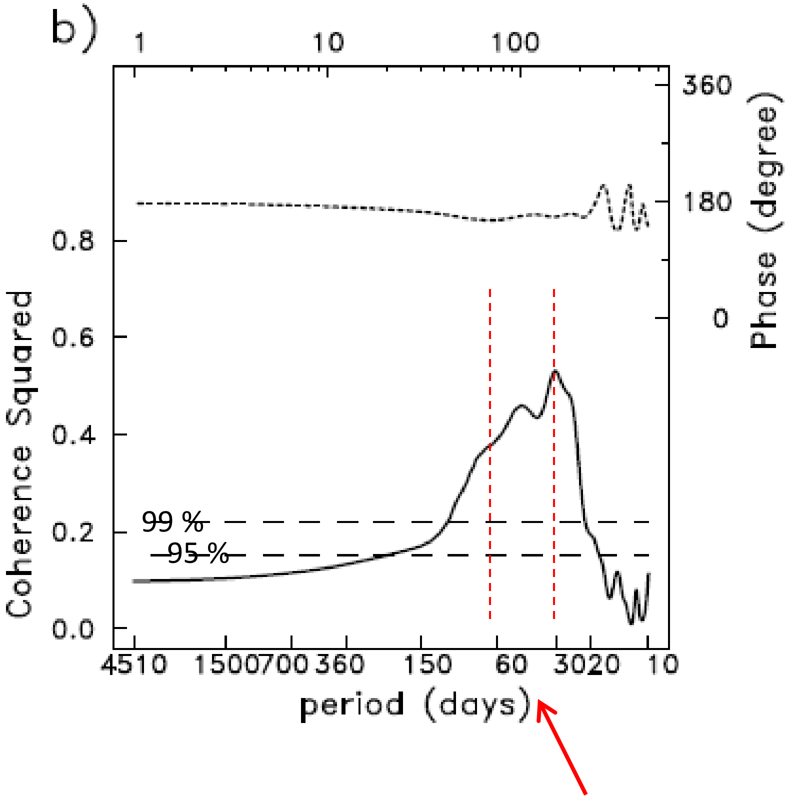
weak anti-correlation
with troposphere

spectrum analysis

Power spectra for zonal mean T



coherence between 12 - 18 km

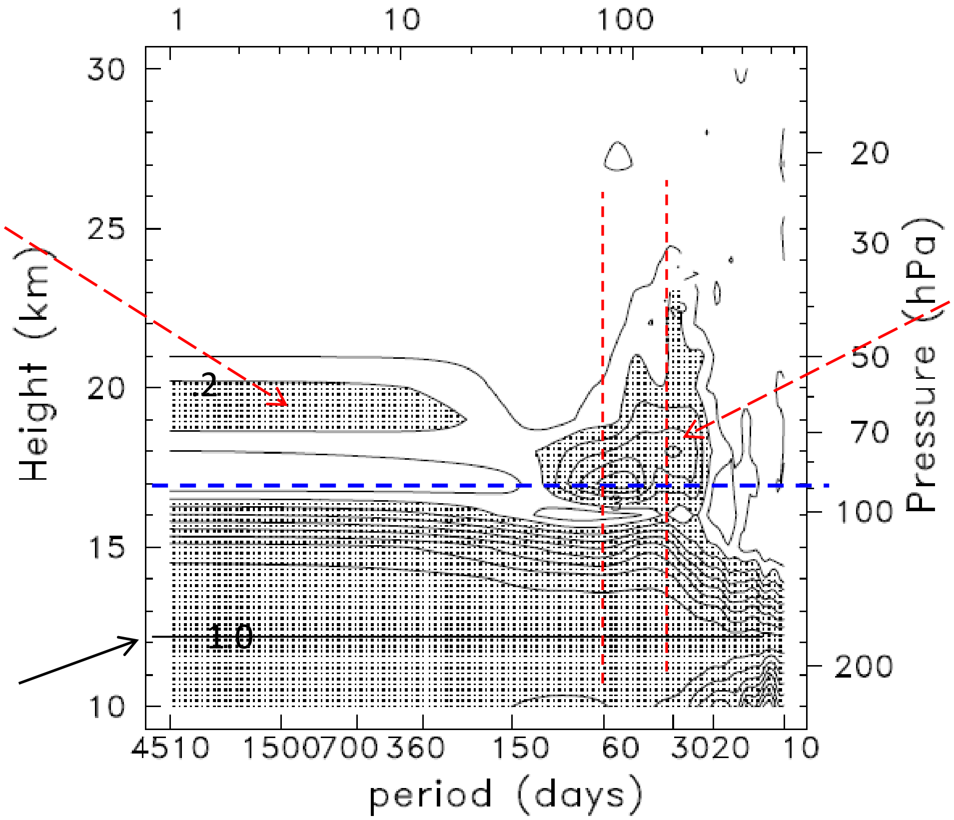


30-60 days: MJO

Zonal mean MJO signal: Virts and Wallace, 2014

tropical coh^2 with respect to 12 km

shaded regions
~99% significant



low frequency
maximum in
lower stratosphere
(similar to ENSO)

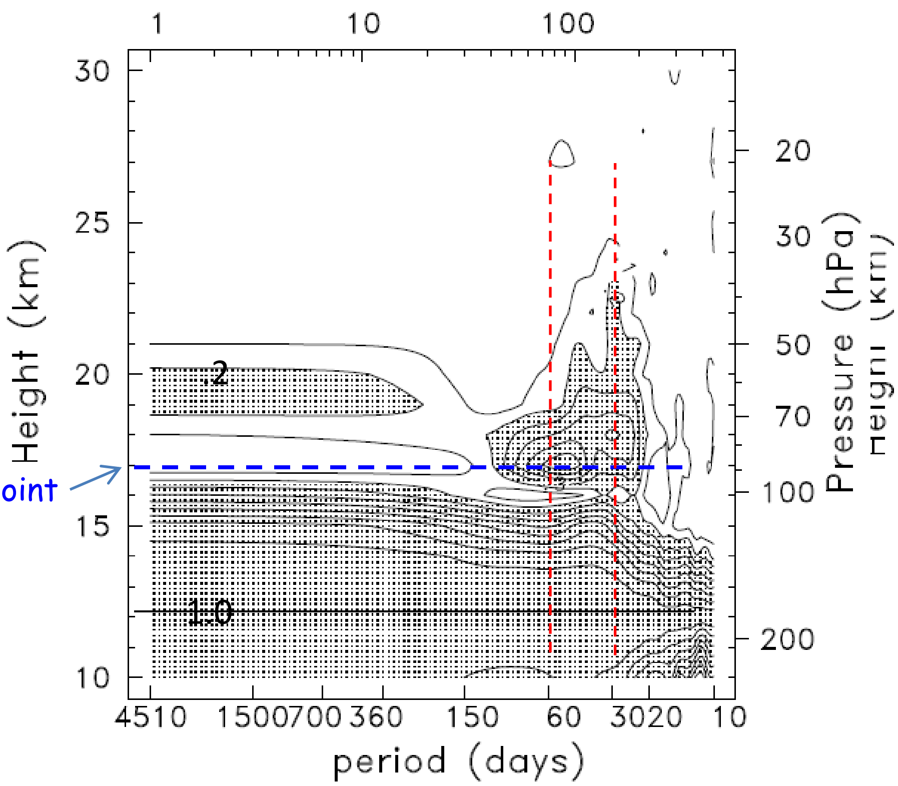
maximum near
cold point

cold point
tropopause

reference
at 12 km

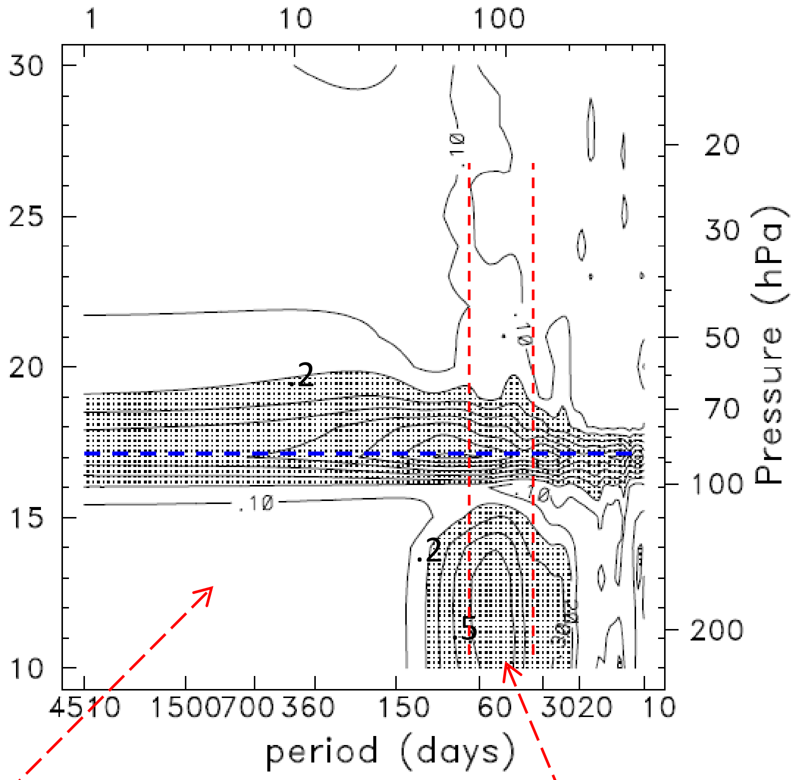
30-60 days: MJO

coh^2 with respect to 12 km



cold point

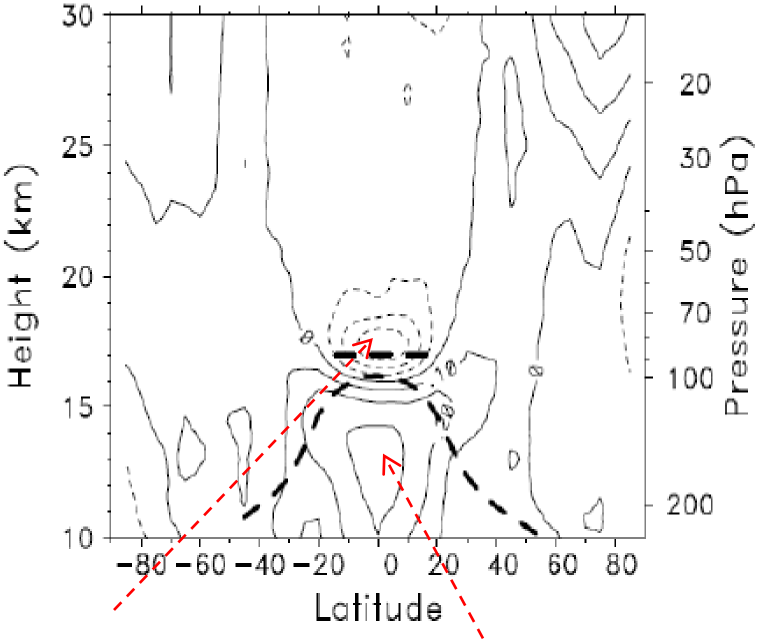
coh^2 with respect to the cold point



small coherence for seasonal to interannual variations

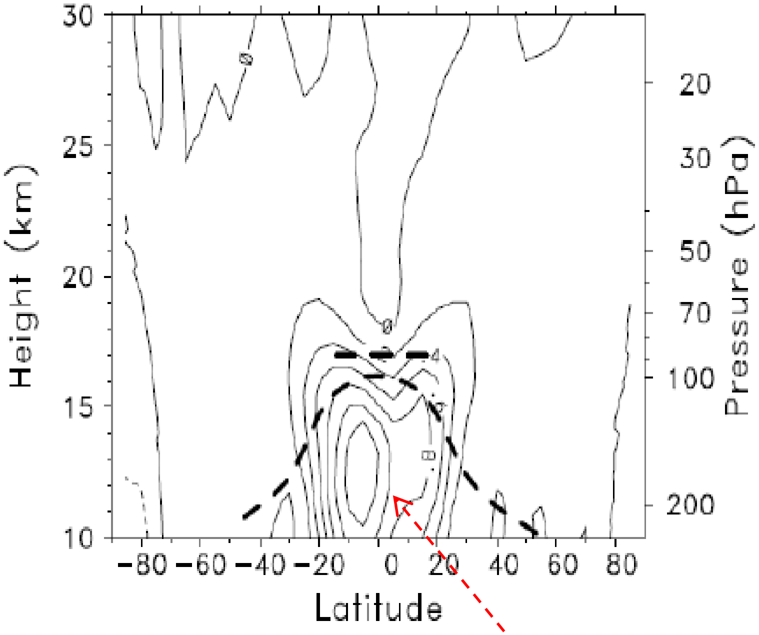
coherence with troposphere for MJO time scales

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


MJO GPS temperature

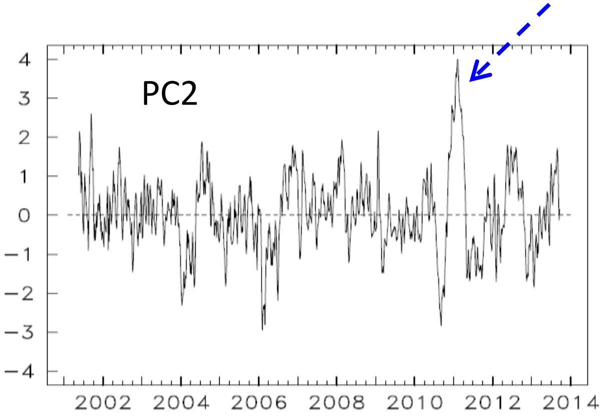
cooling near tropopause

warm troposphere

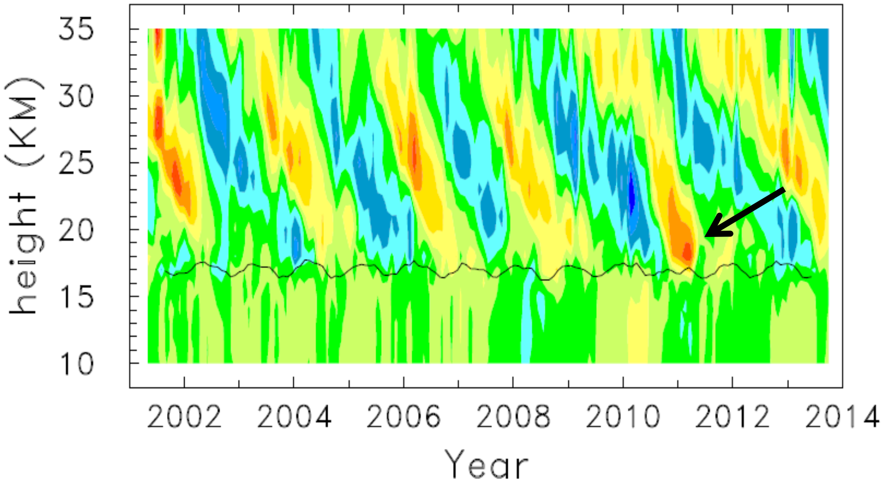

MJO ERAi zonal winds

zonal winds confined to tropical troposphere

extreme near-tropopause event

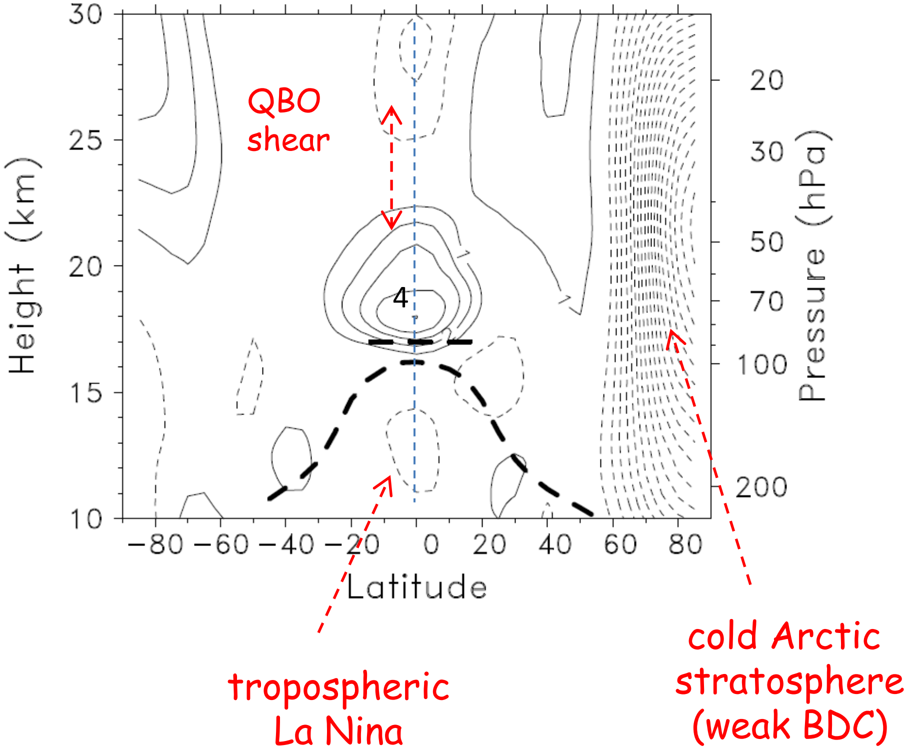


deseasonalized anomalies over equator



3 factors contributing to anomalous tropical temps:

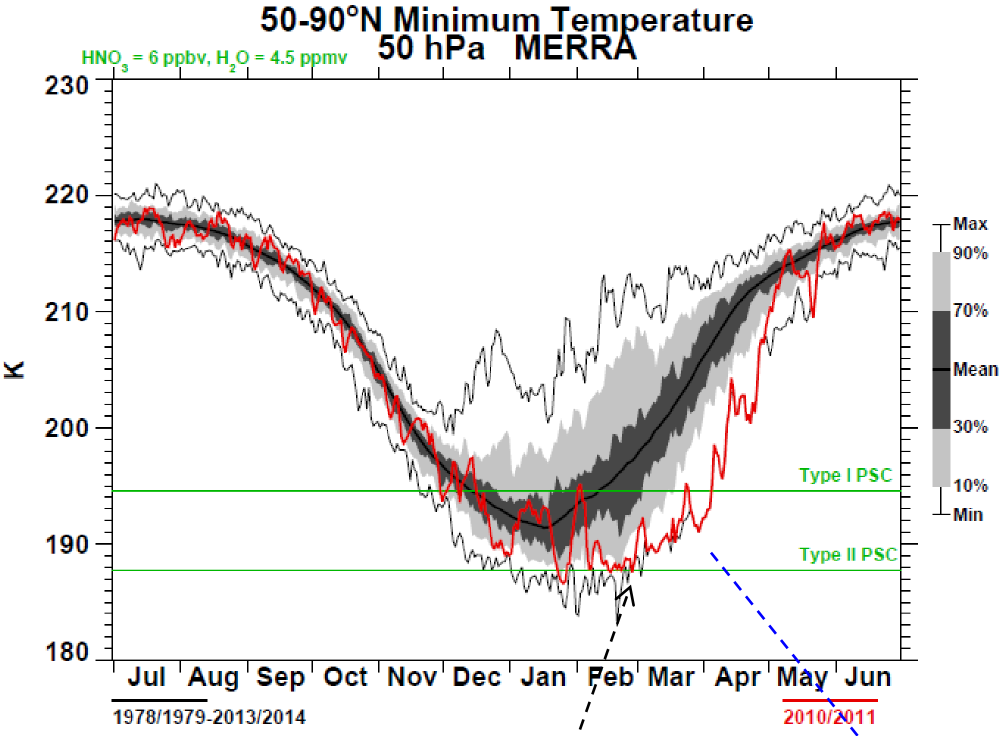
anomaly temps (K)



QBO shear

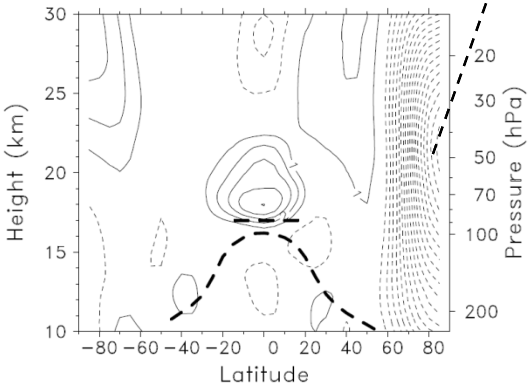
tropospheric La Nina

cold Arctic stratosphere (weak BDC)



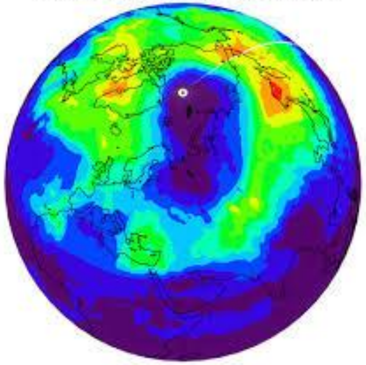
coldest Arctic spring in observational record (1979-2014)

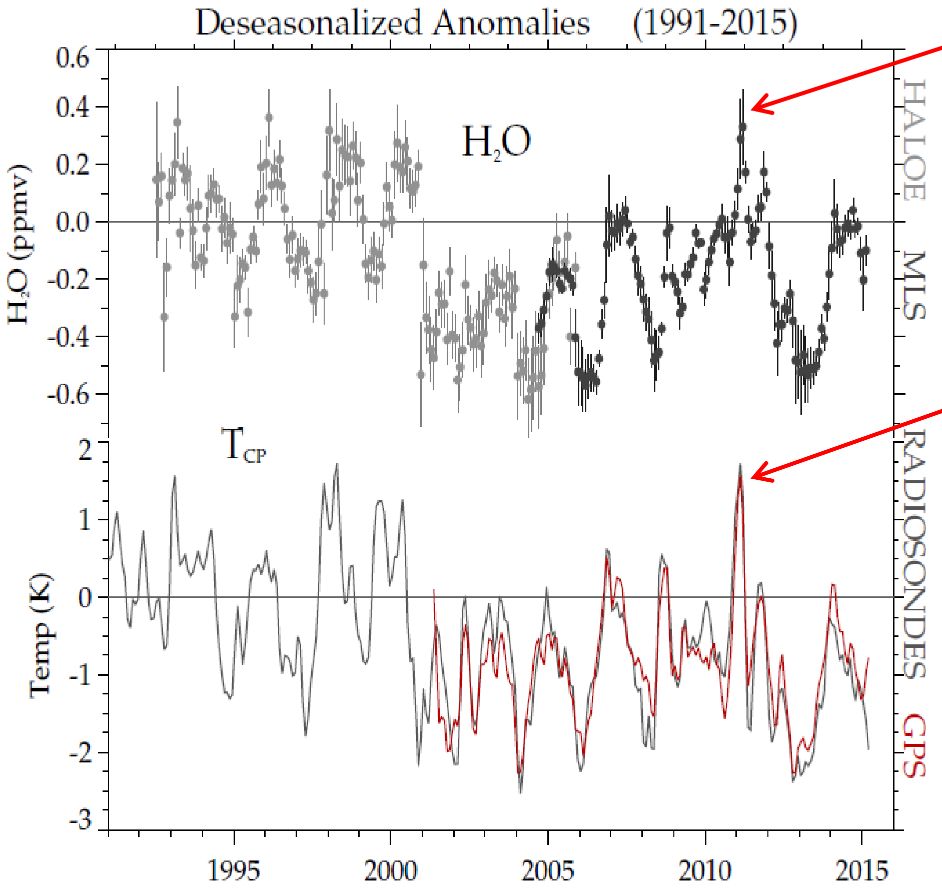
GPS Feb 2011



Arctic 'ozone hole' in spring 2011

OMI total ozone on 3–4 April 2011

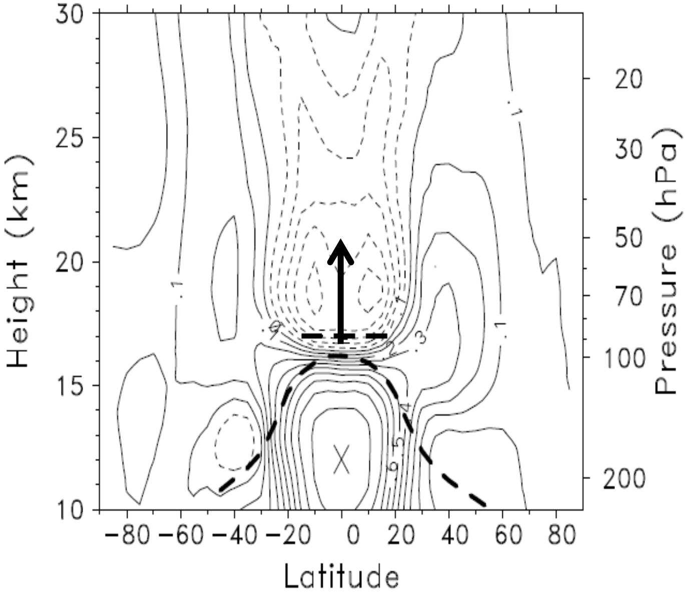




stratospheric
water vapor response
to warm tropopause

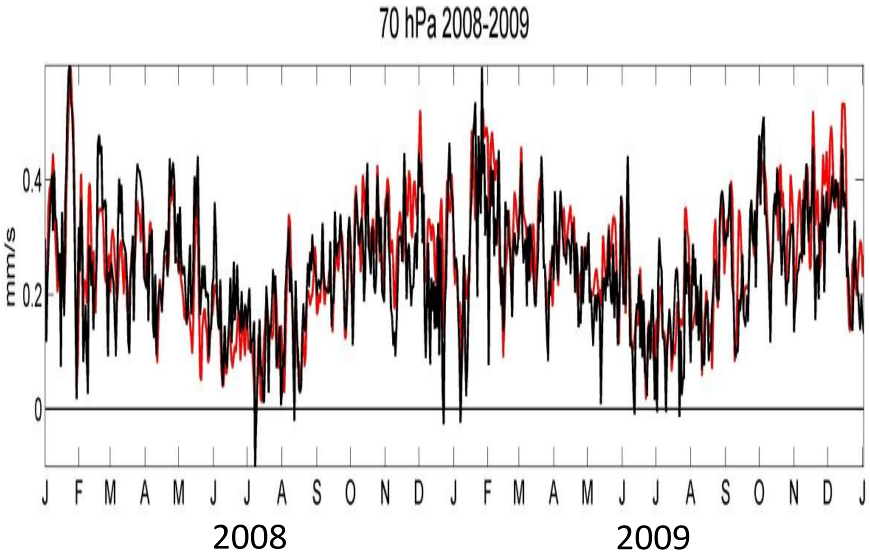
links to tropical upwelling

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



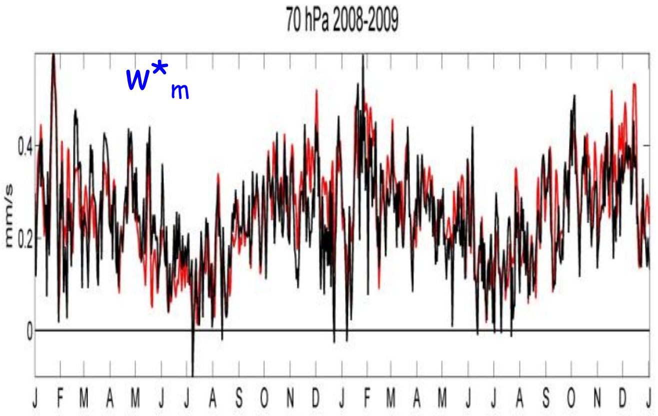
two estimates
of upwelling:

w^*_m momentum balance
w^*_Q thermodynamic balance

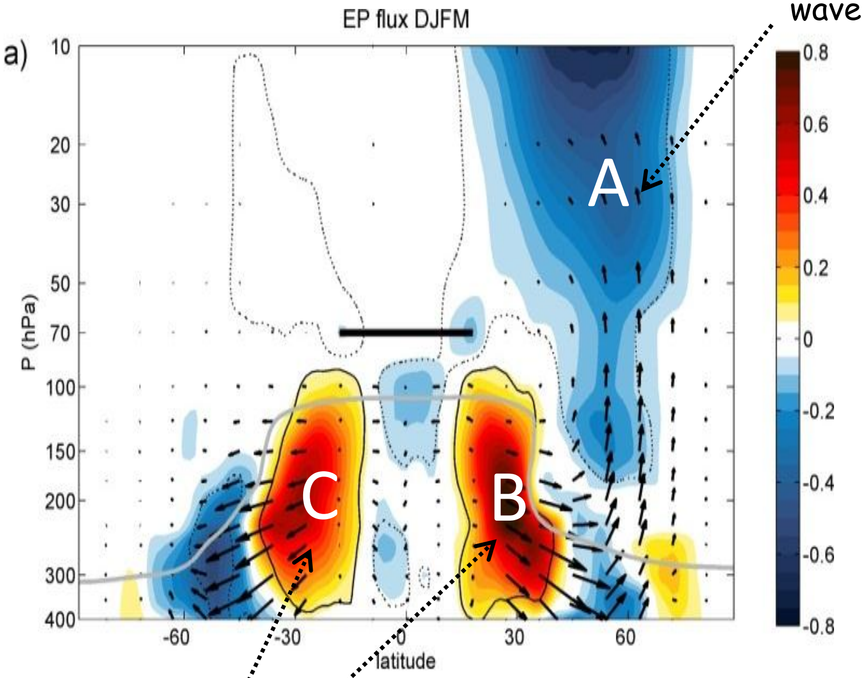


Abalos et al, 2014, JAS

Dynamically forced transient tropical upwelling



regression of EP flux onto w^*_m

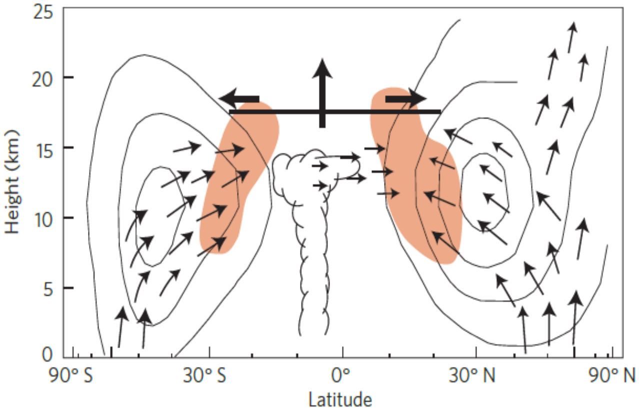


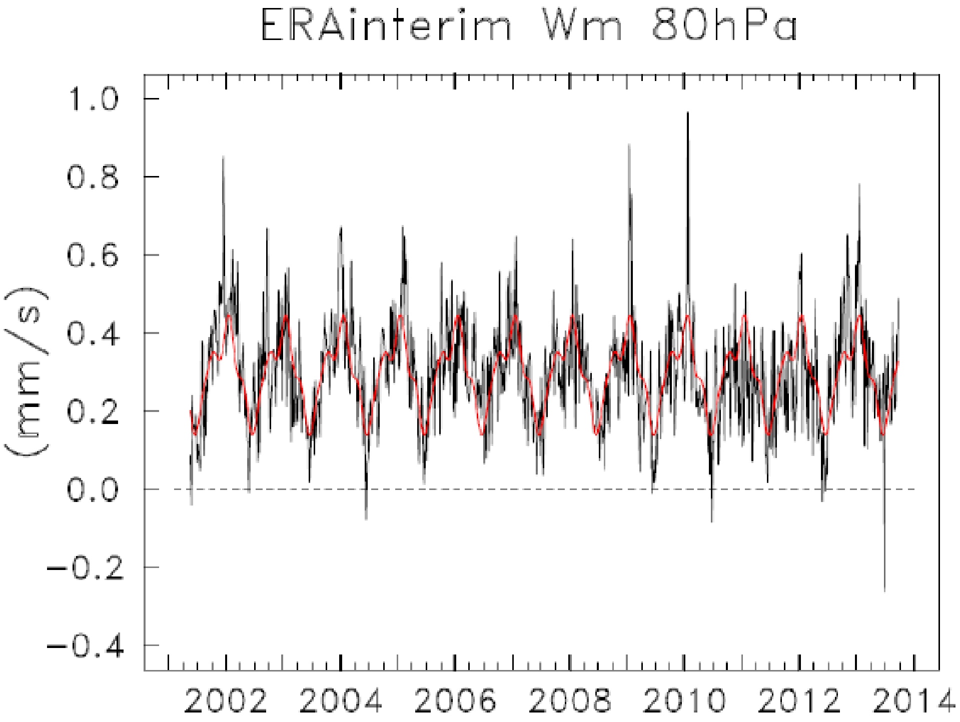
planetary waves

subtropical EP fluxes

Abalos et al, 2014, JAS

Modulation of climatological EP flux




ERAinterim Wm 80hPa
(mm/s)
1.0
0.8
0.6
0.4
0.2
0.0
−0.2
−0.4
2002
2004
2006
2008
2010
2012
2014

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:

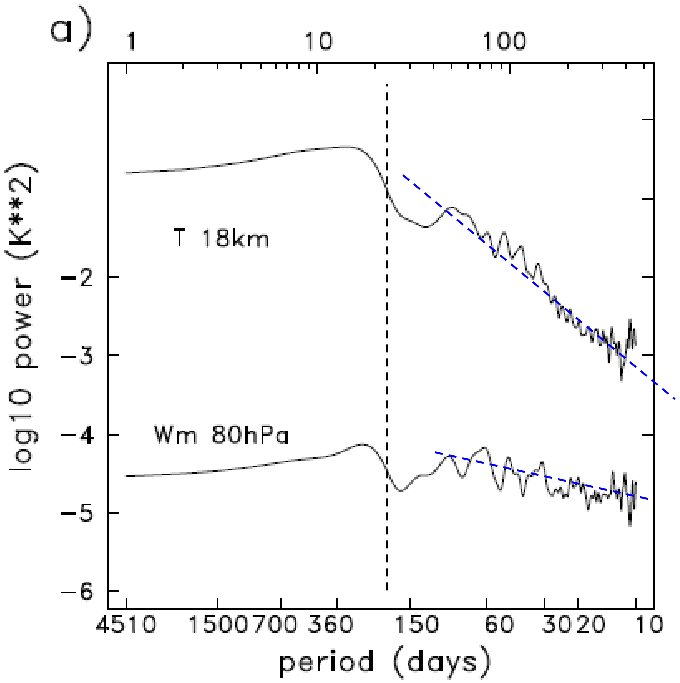
$$\boxed{\sqrt{\frac{T_\sigma^2}{w_\sigma^2}}. = \frac{S}{\sqrt{\alpha^2 + \sigma^2}}.}$$

radiative damping time scale

frequency

Spectrum analysis

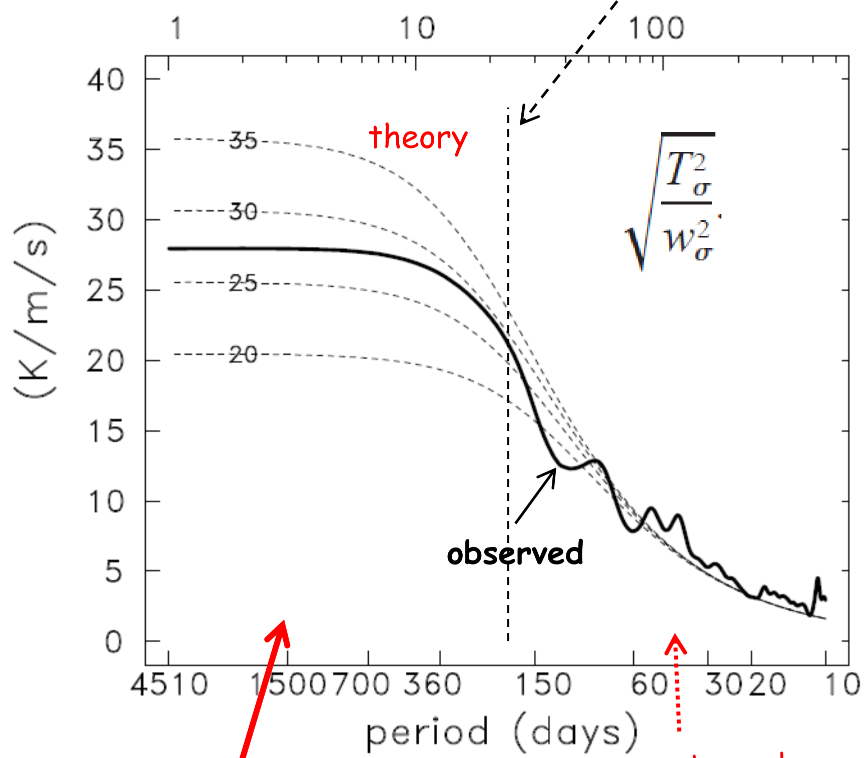
Power spectra for T and w^*_m



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

T sensitivity to w^*_m

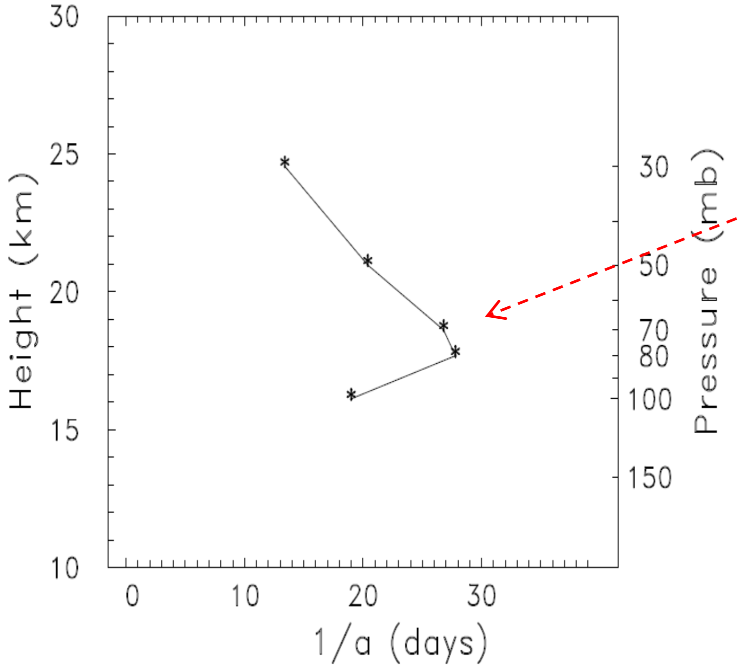
frequency where
σ ~ α



enhanced response
at low frequencies
(longer than 150 days)

note weak response
for MJO periods

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



long damping time scales (~30 days)
in lower stratosphere

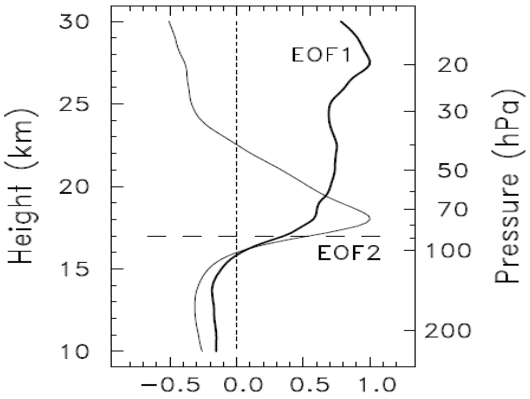
- Lower stratosphere temps are especially sensitive to low frequency forcing
- Cause of enhanced annual cycle and large T variance in lower stratosphere

Key points:

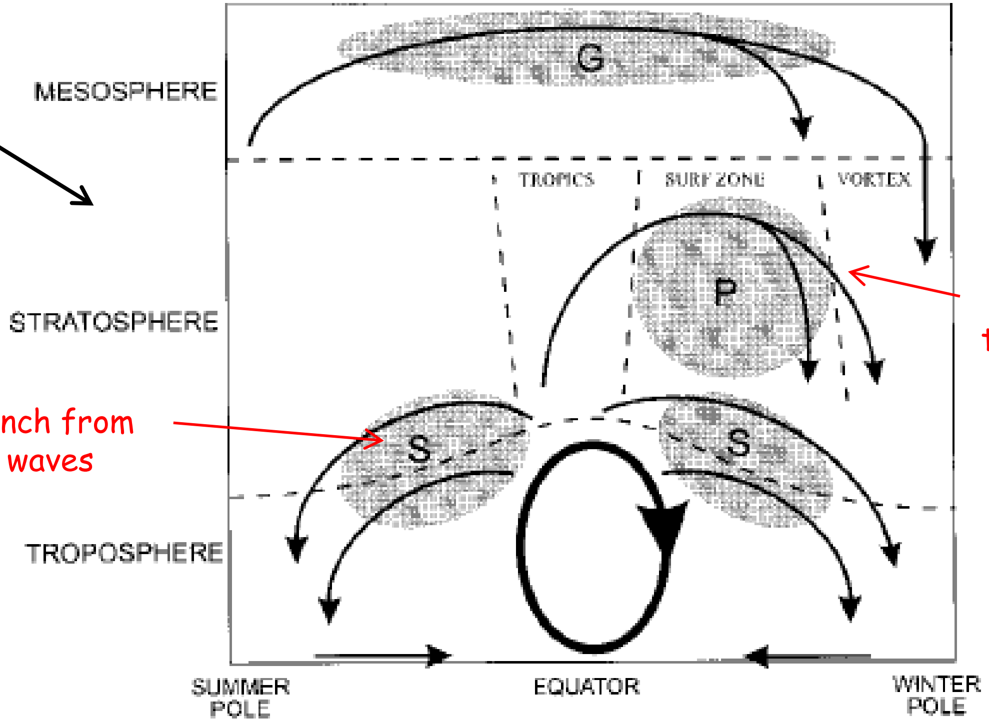
- Novel high vertical resolution temperature record from GPS
- Strong, coherent QBO, ENSO, SSW and MJO signals in GPS data
- 2 modes of stratospheric variability: deep, shallow branches of BDC
- Cold point T variability tied to tropopause-level upwelling
  - anti-correlated with troposphere for MJO variations
  - no correlation with troposphere for seasonal to interannual time scales (ENSO)
- Lower stratosphere T most sensitive to low frequency forcing
  - factor of ~10 increase for periods > 180 days

Randel and Wu, JAS, 2015

GPS EOF patterns



Deep and shallow branches of Brewer-Dobson circulation



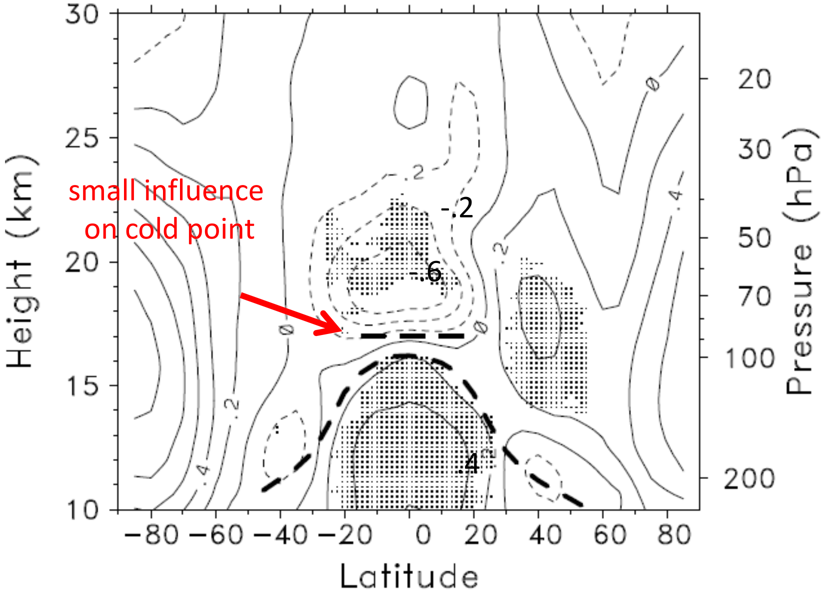
deep branch tied to planetary waves

shallow branch from synoptic waves

Plumb (2002); also Birner and Bonish, 2011

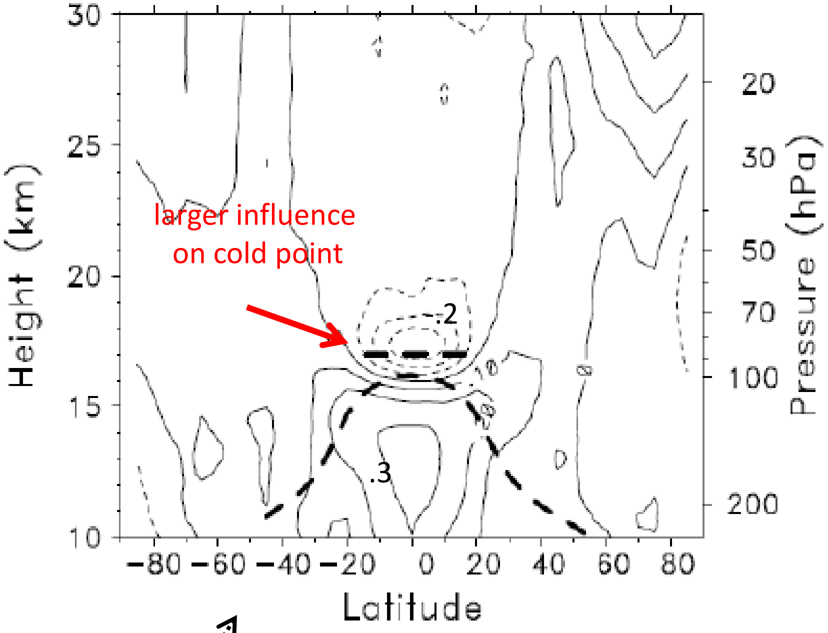
ENSO and MJO temperature signals from GPS

ENSO



small influence
on cold point

MJO



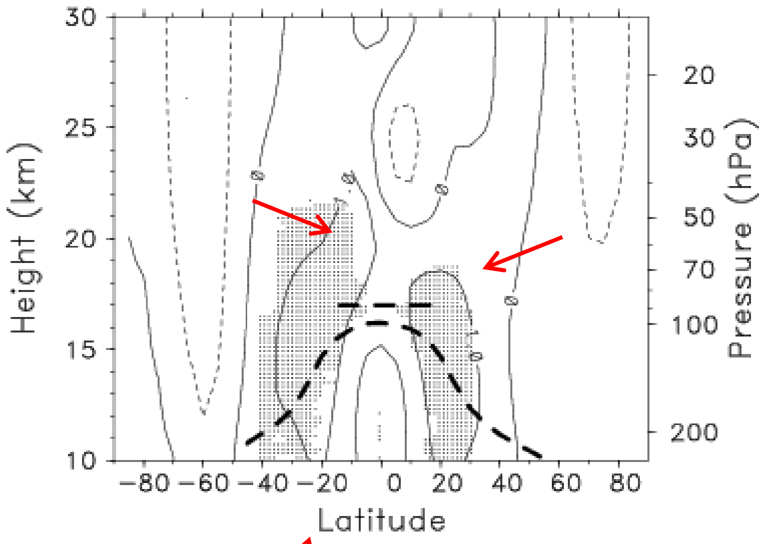
larger influence
on cold point

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

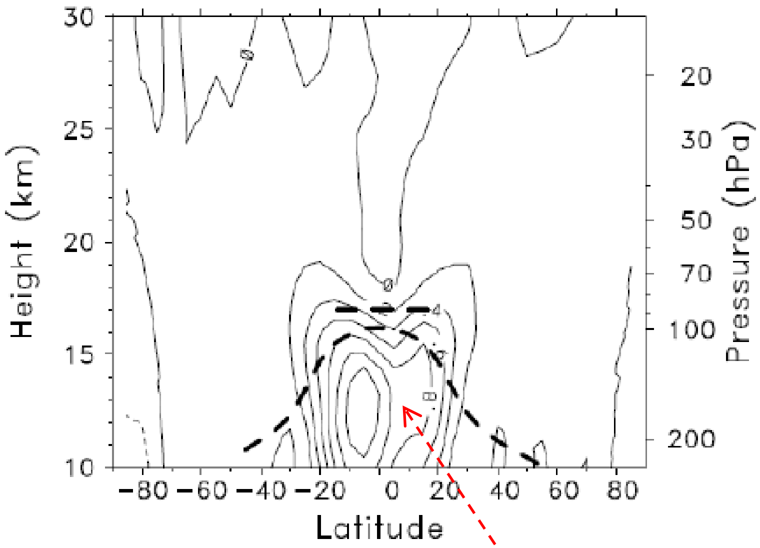
Why is the stratospheric upwelling signature of ENSO 'deeper' than the MJO?

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

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

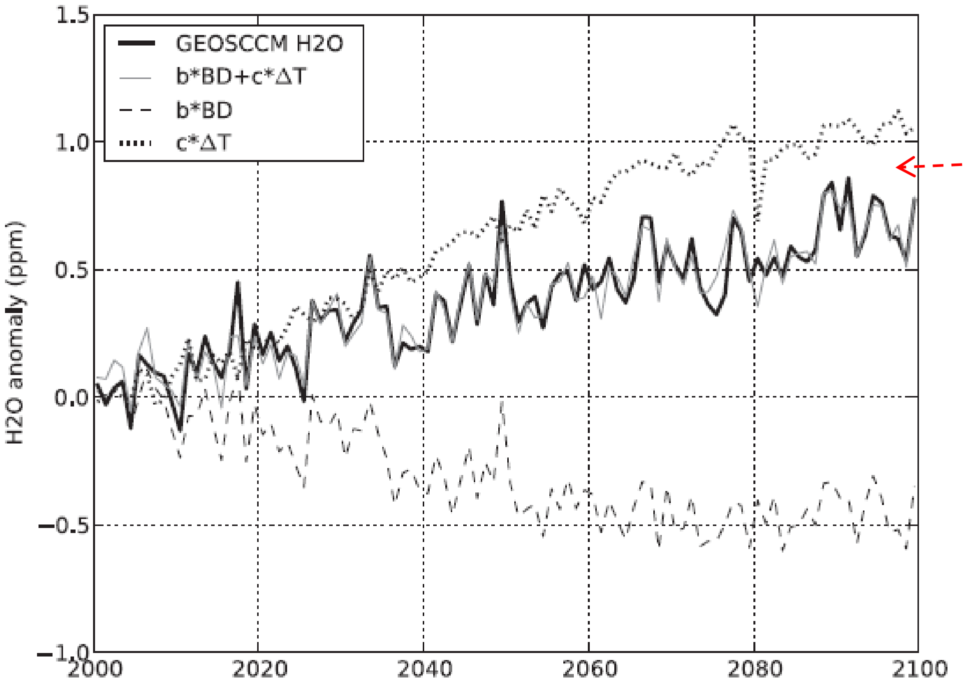


Fig. 2. Time series of annual-average $H_2O_{ov\text{-}entry}$ anomalies from the GEOSCCM (black) and the reconstruction from a multivariate least-squares regression (gray) over the 21st century. The dashed and dotted lines are the BD and ΔT terms of the regression, respectively.

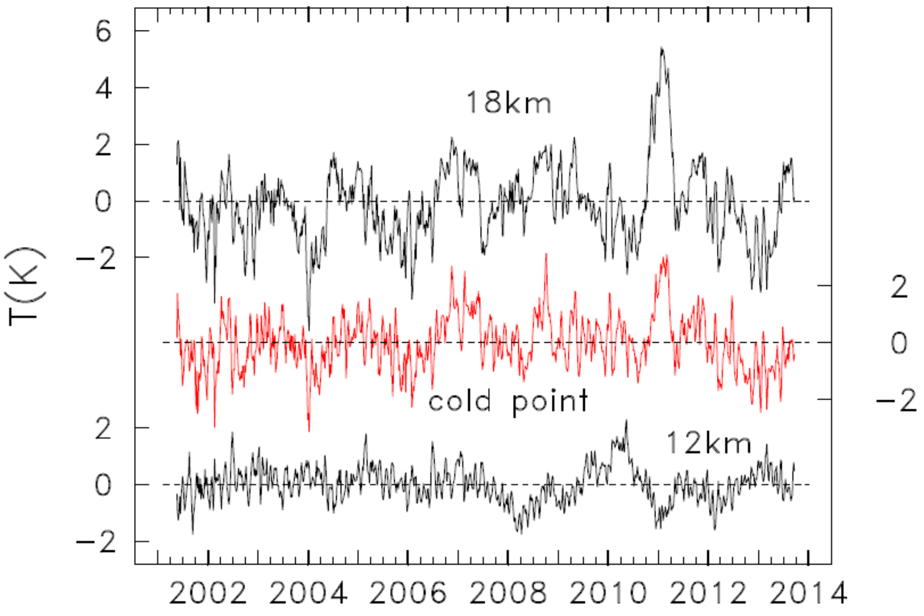
in a global model,
stratospheric H_2O increases
with tropospheric temperature

but GPS data do not show
coupling with the tropical cold point
for low frequency variations

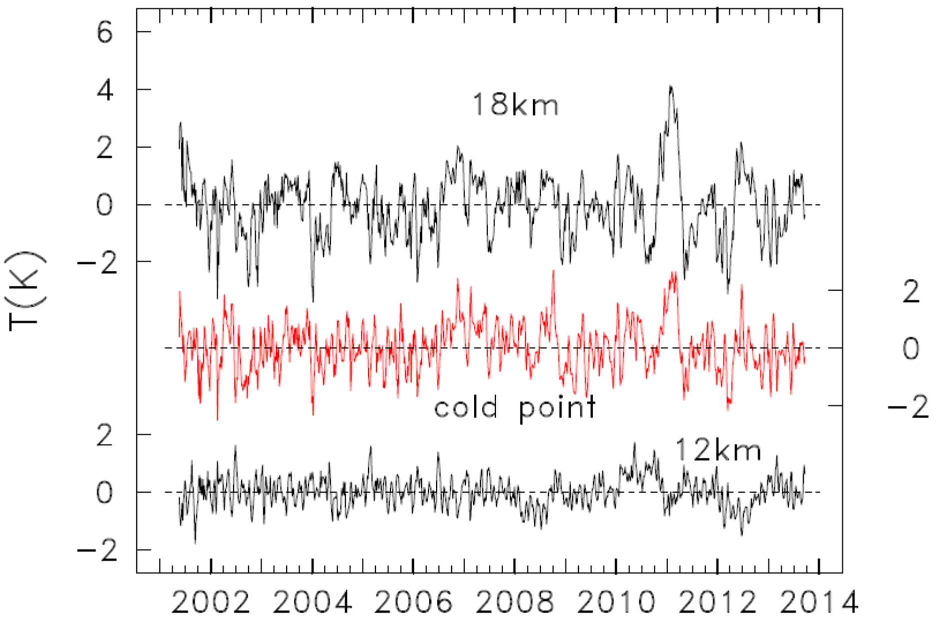
EAPS
Earth, Atmospheric and Planetary Sciences

Thank you for inviting
me to MIT

Time series of tropical temperature residuals



deseasonalized



also remove QBO, ENSO