Improved understanding of the global tropopause from GPS observations

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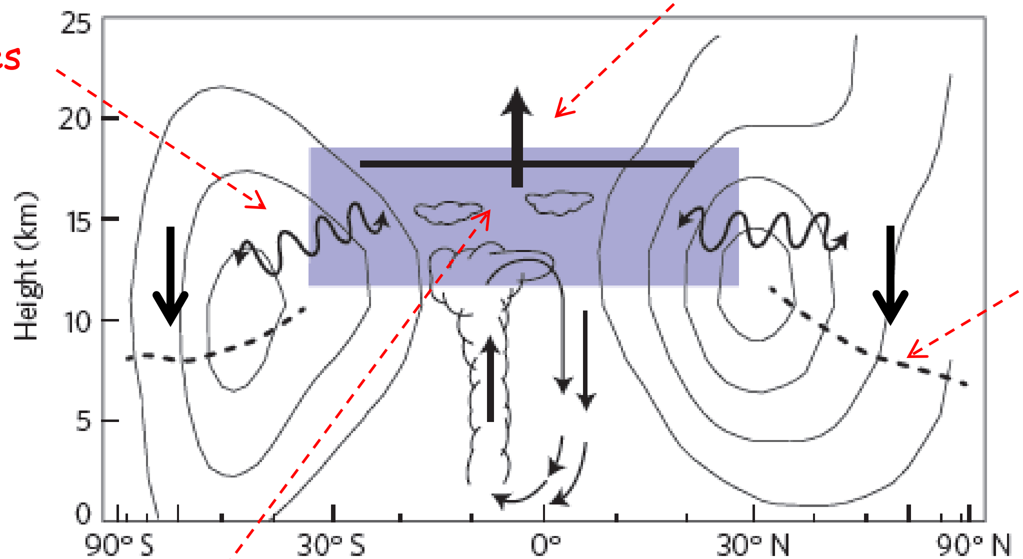
Climate-relevant processes linked to the global tropopause

transport to the stratosphere;
water vapor control by tropopause temperature

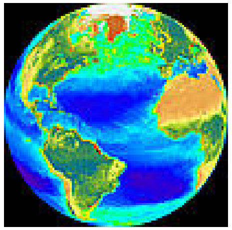
two-way mixing
by baroclinic eddies
and monsoons



inversion layers;
STE

convective influences
and tropopause-level cirrus

* tropopause height and temp. trends



Global tropopause and GPS data:

- GPS measurements provide an optimum tropopause sensor
  - * accuracy, high vertical resolution and global coverage

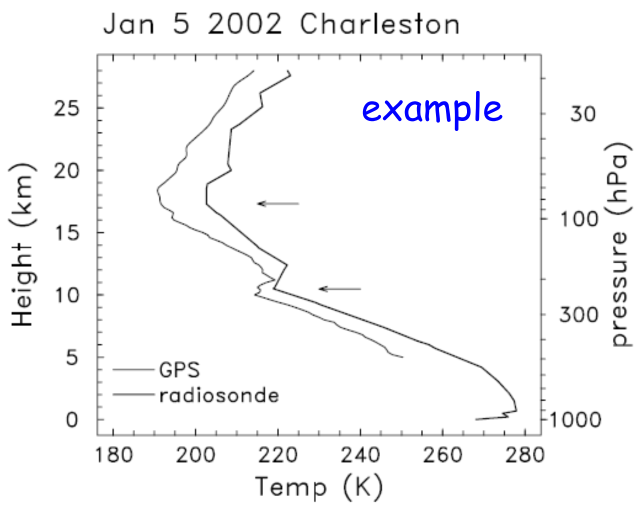
- New insights into tropopause structure and variability:

  - tropopause inversion layer (linked to dynamics/radiative effects of UT water vapor)
  - double tropopauses in subtropics (intrusions into lower strat.)
  - tropical tropopause (variability, and links to clouds and water vapor)

- Additional topics:

  - tropopause height trends (Schmidt et al, 2009)
  - widening of the tropics (Seidel et al, 2008; Davis and Birner, 2013)
  - ExTL mixing layer (e.g. Hegglin et al, 2009)
  - chemicals, isotopes, effects of deep convection, …

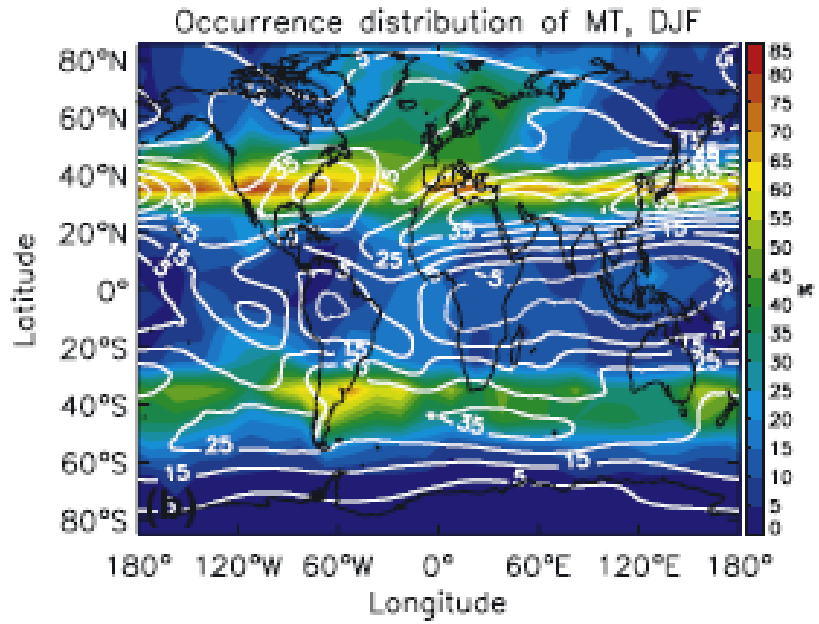
Double tropopauses



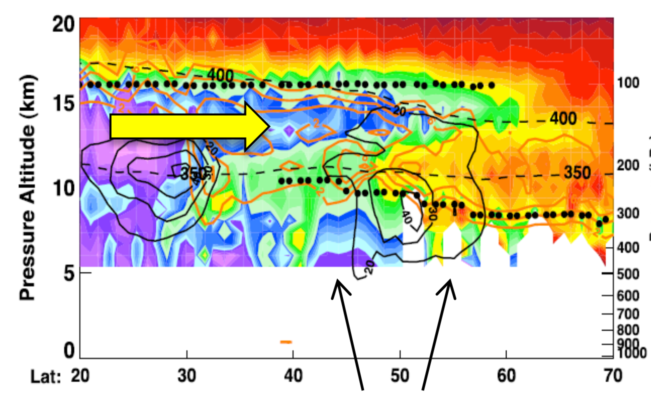
Not exactly new: Bjerknes and Palmen (1937), …

Many studies with GPS data:
Schmidt et al, 2006, Randel et al 2007, Pan et al 2009, Castanheira et al 2010, Son et al, 2011, Peevy et al , 2012, …

Climatology from GPS Schmidt et al 2006



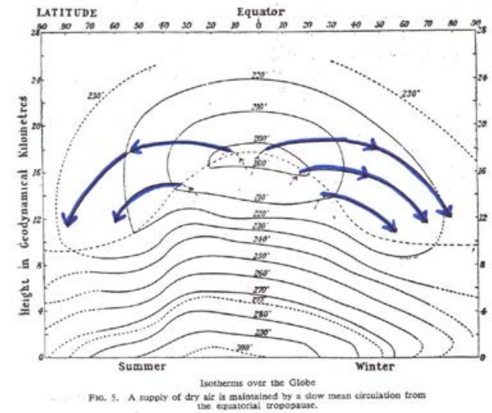
Satellite ozone measurements from HIRDLS



double tropopause linked to intrusion above subtropical jet

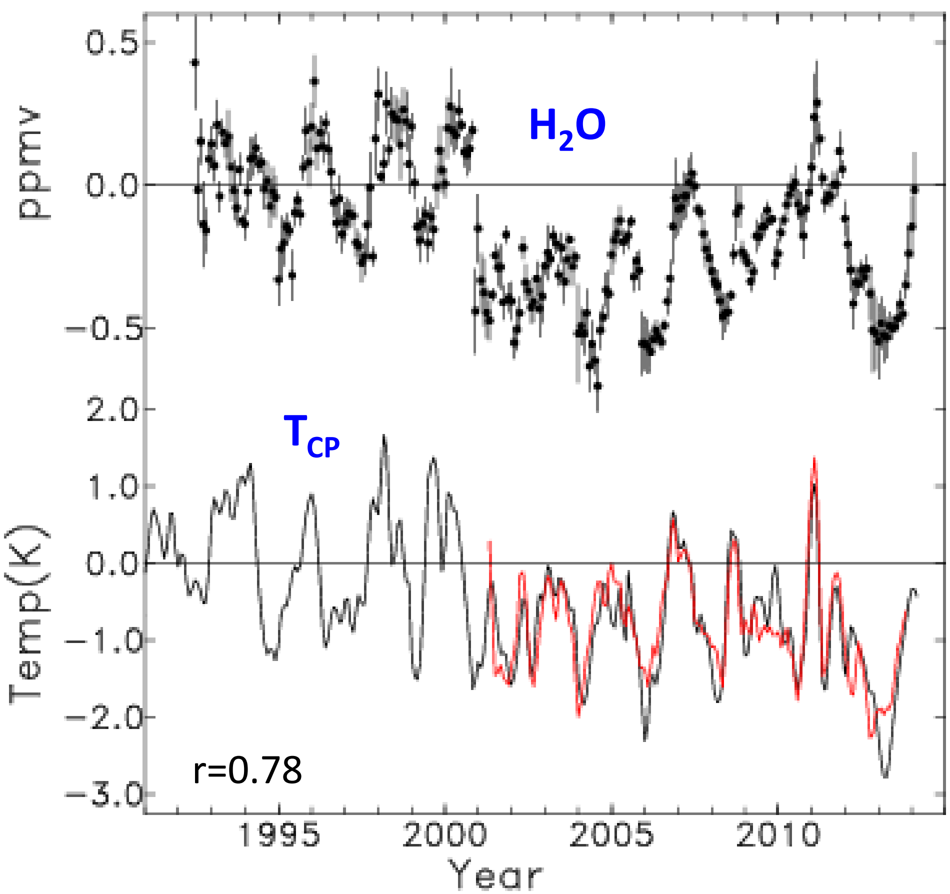
Pan et al, 2009

Brewer, 1949



Stratospheric H_2O is controlled by tropical cold point temperatures

Deseasonalized anomalies



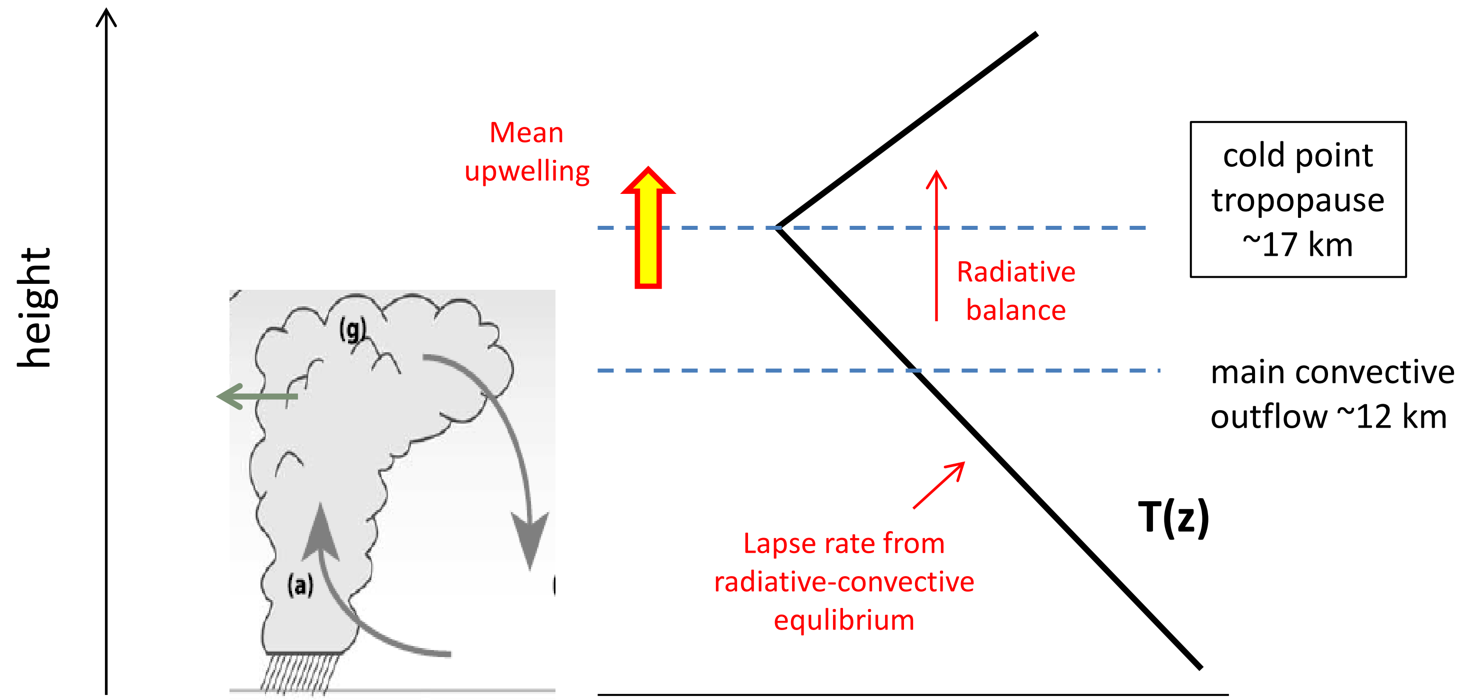
near-global mean (60° N-S) water vapor at 82 hPa from combined HALOE-MLS data

cold-point tropical tropopause temperatures

black: radiosondes
red: GPS (after 2001)

What controls variability of the cold-point tropopause?

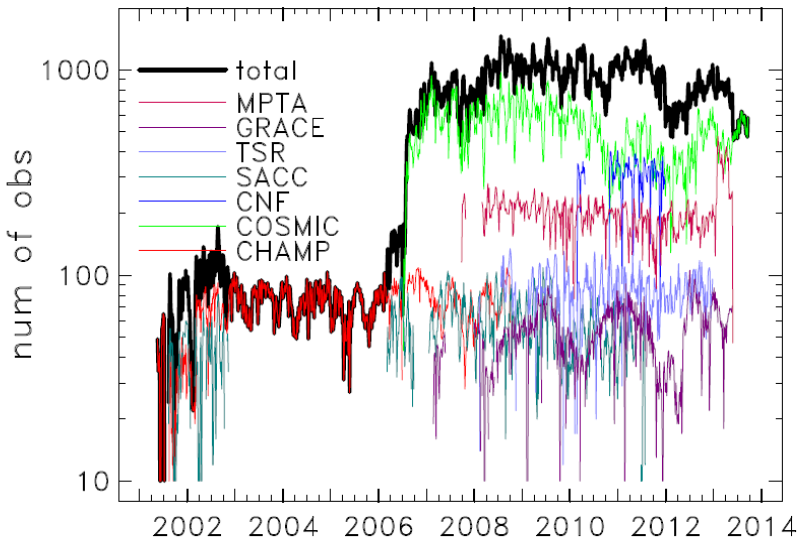
- Convection?
- Dynamically-forced upwelling?



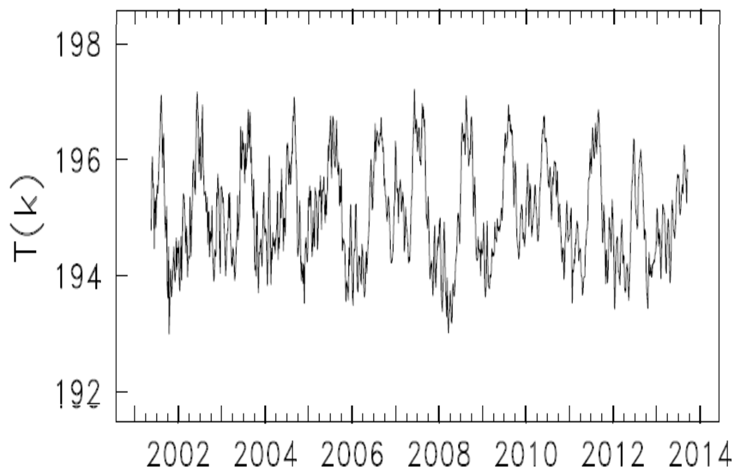
Using GPS data to understand variability of tropical temperature:

- Construct a global, <u>zonal average</u> data set from all GPS observations (CHAMP, COSMIC, METOPA, others; > 6,200,000 occultations)
- 5-day (pentad) averages for 2001-2013 (over 12 complete years)

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

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

$$\downarrow$$

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

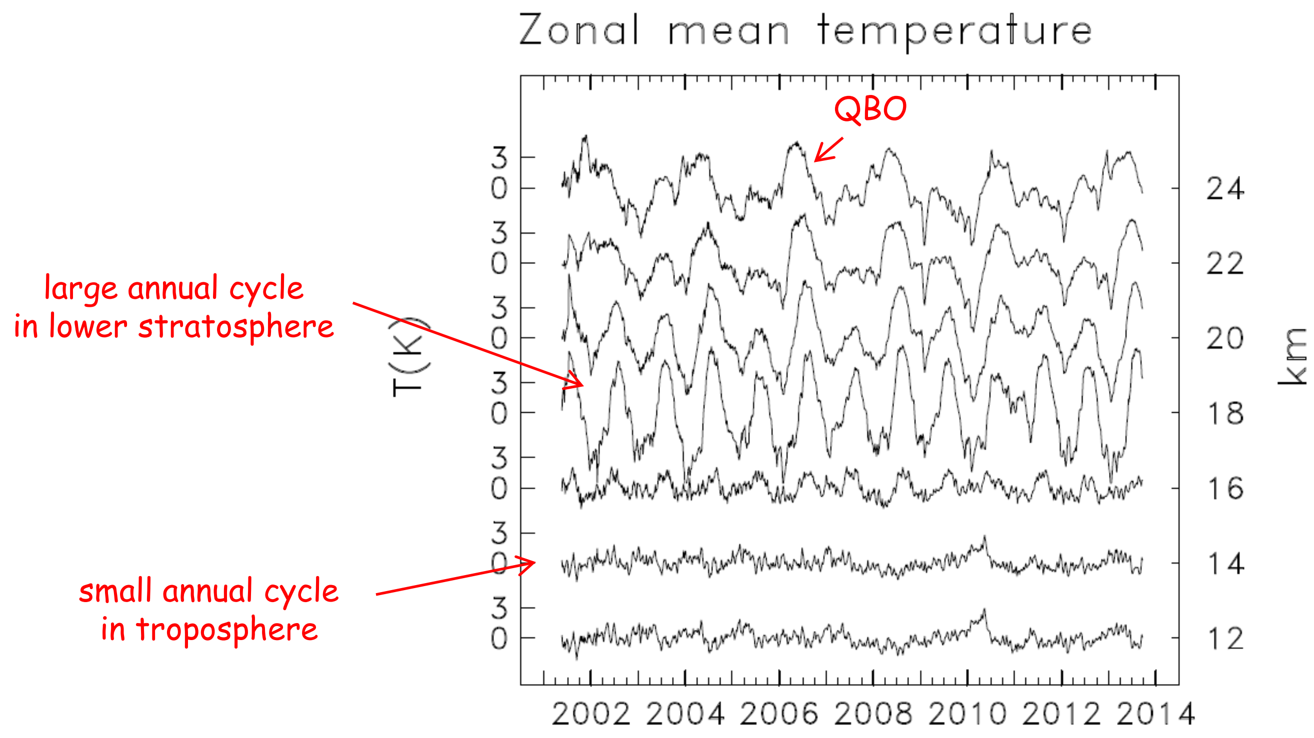
approximate balance in tropics

$$\downarrow$$

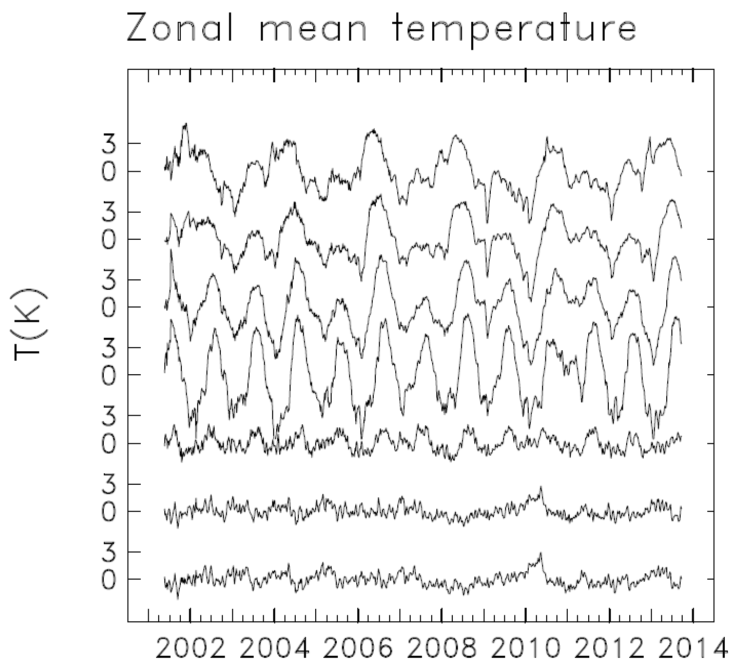
$$\boxed{\frac{\partial \overline{T}}{\partial t} + \overline{w}^* S = -\alpha(\overline{T} - \overline{T}_e)}$$

linear damping approximation (in stratosphere)

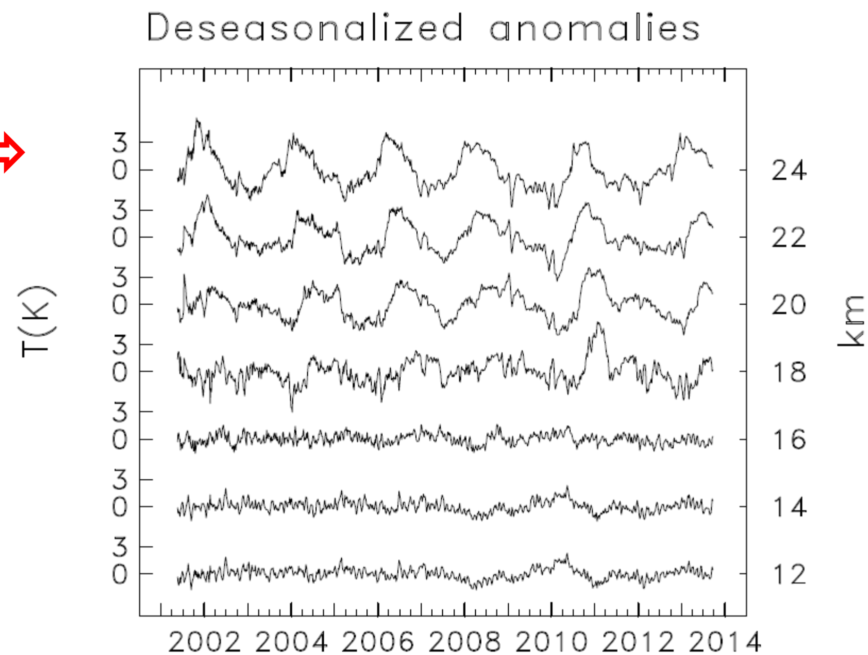
Tropical variability for 10° N-S



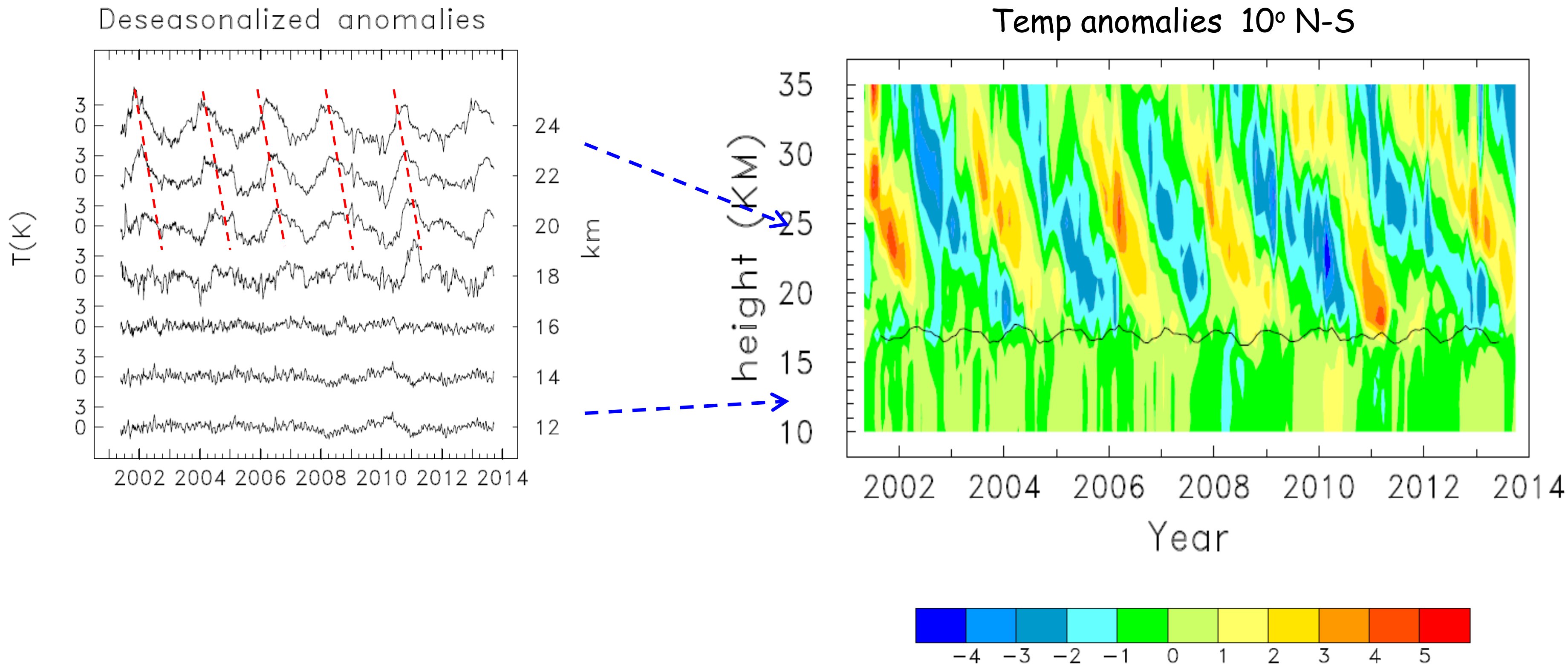
'raw' time series



remove seasonal cycle



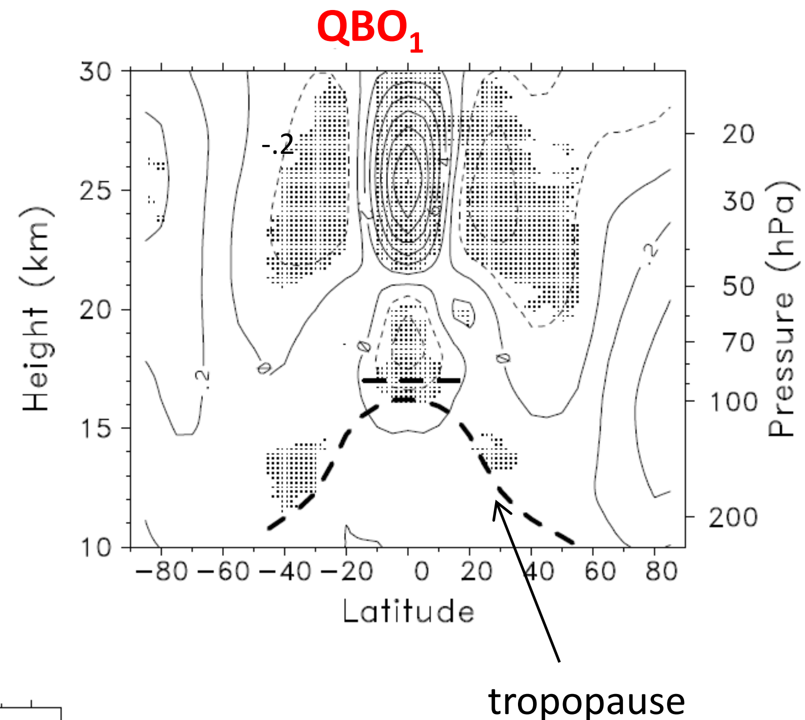
QBO is the large interannual signal in the stratosphere

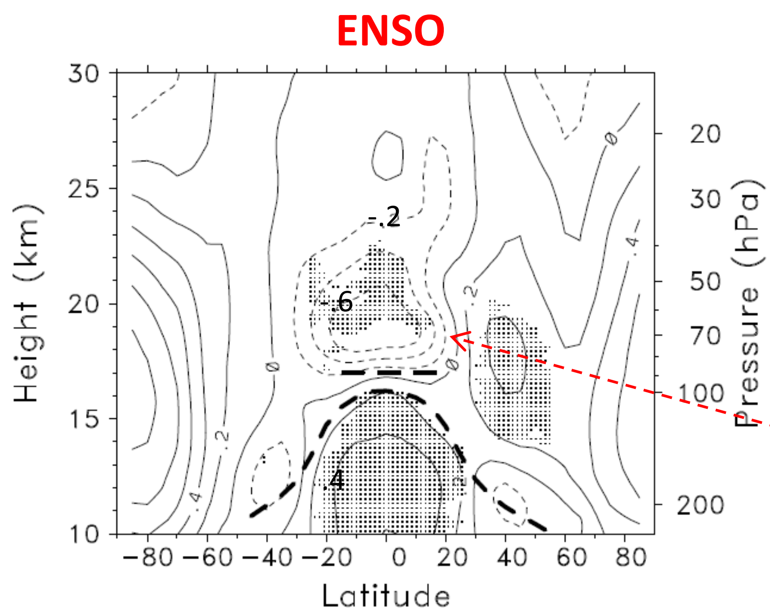


Regression fits of QBO and ENSO 2001-2013

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

proxy time series

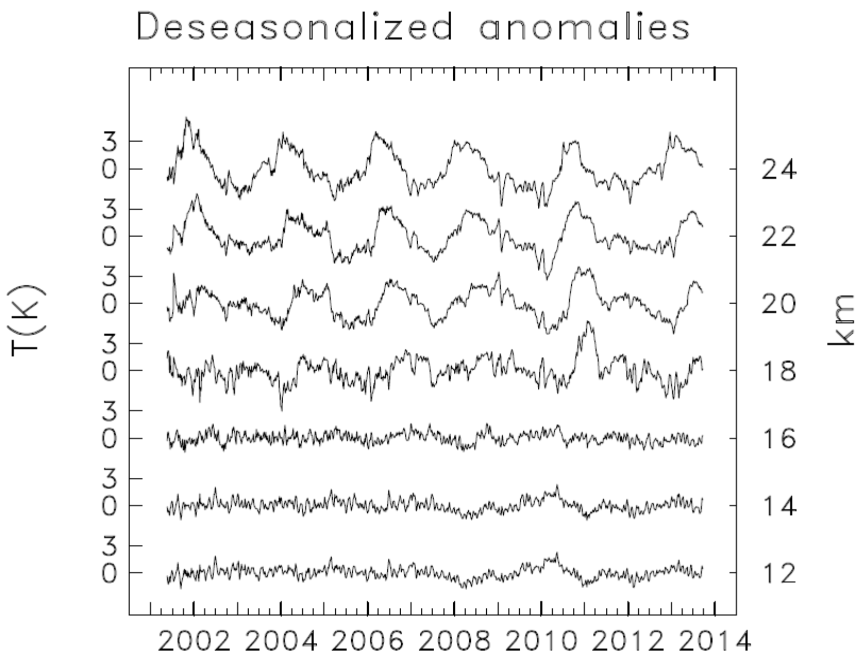


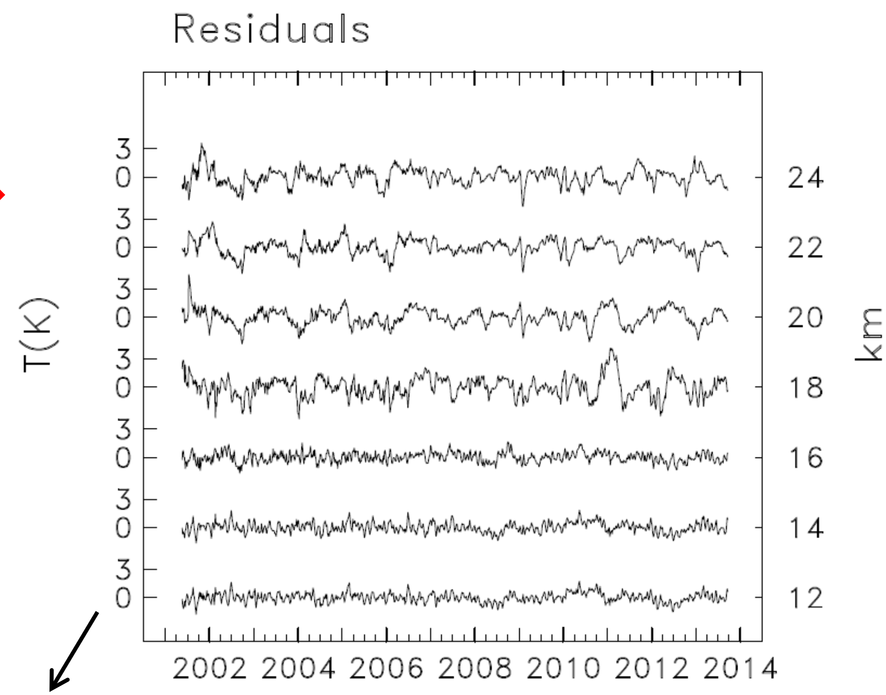


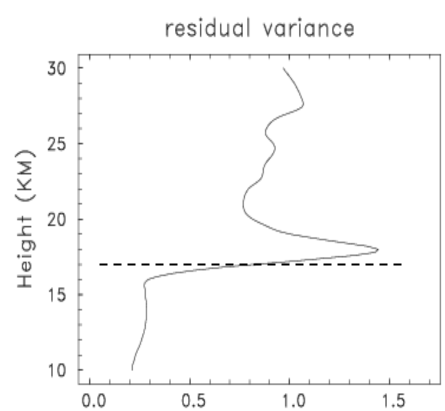
stratosphere cooling
tied to enhanced upwelling
e.g. Calvo et al 2010

deseasonalized

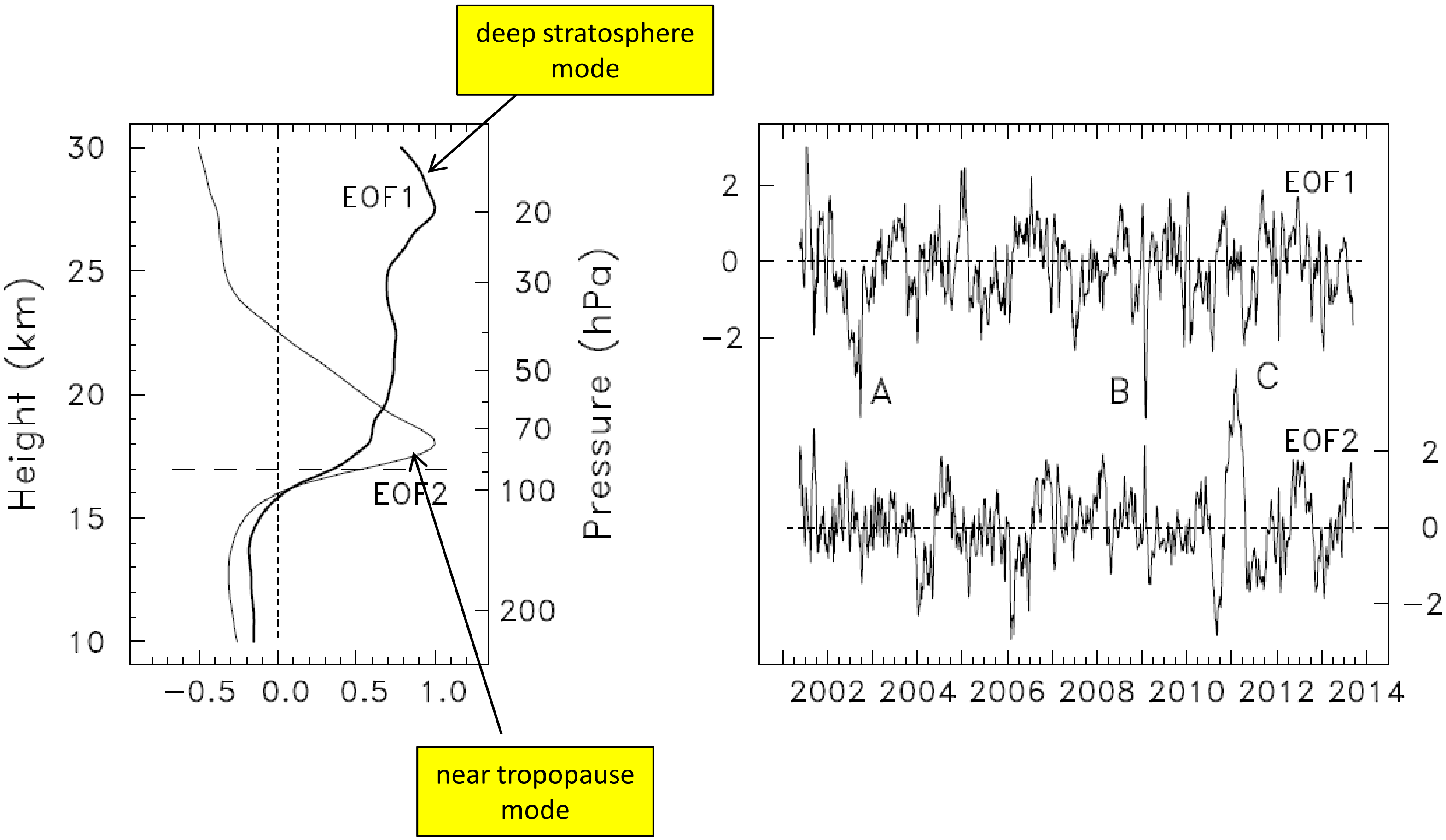
remove QBO and ENSO
('residual' variability)





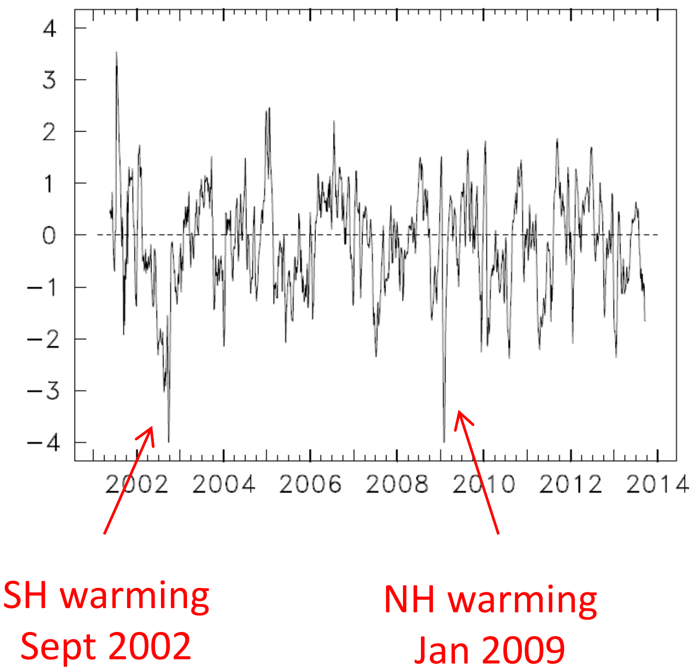


EOF analysis of residuals

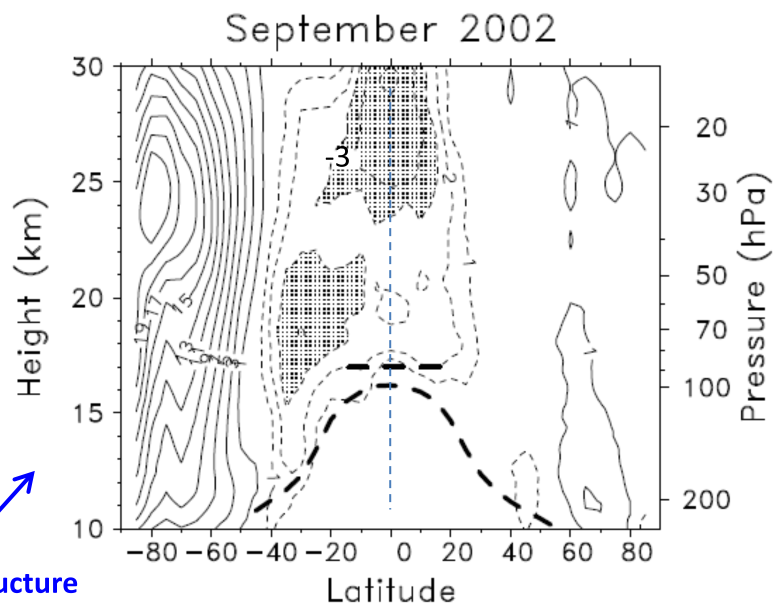


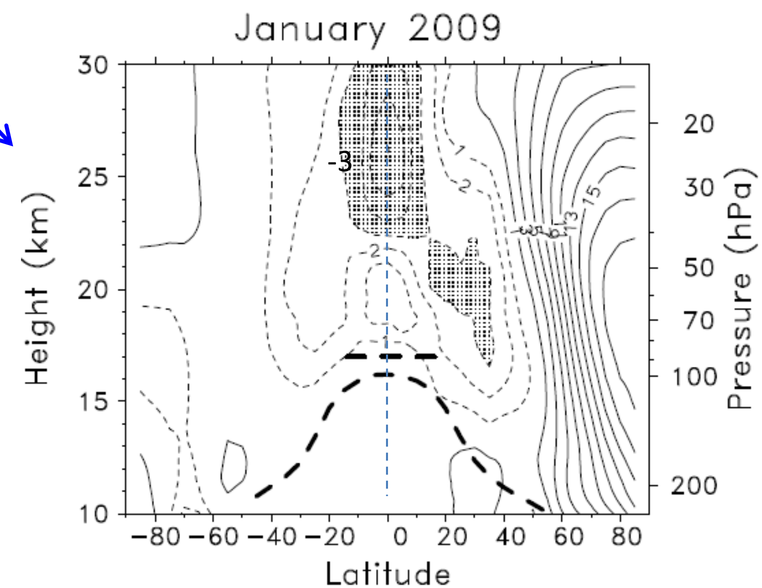
Tropical cooling linked to major stratospheric sudden warmings (SSW)

EOF1: deep stratosphere mode



spatial structure of temp anomalies





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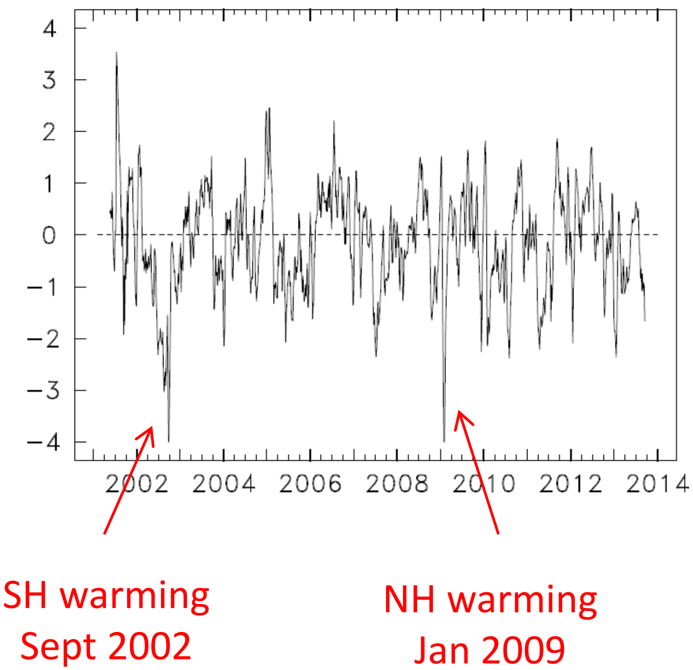
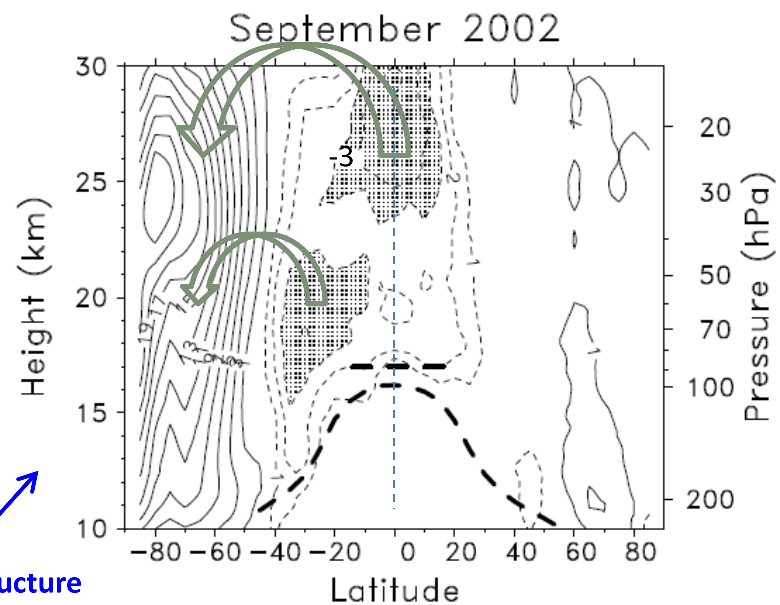
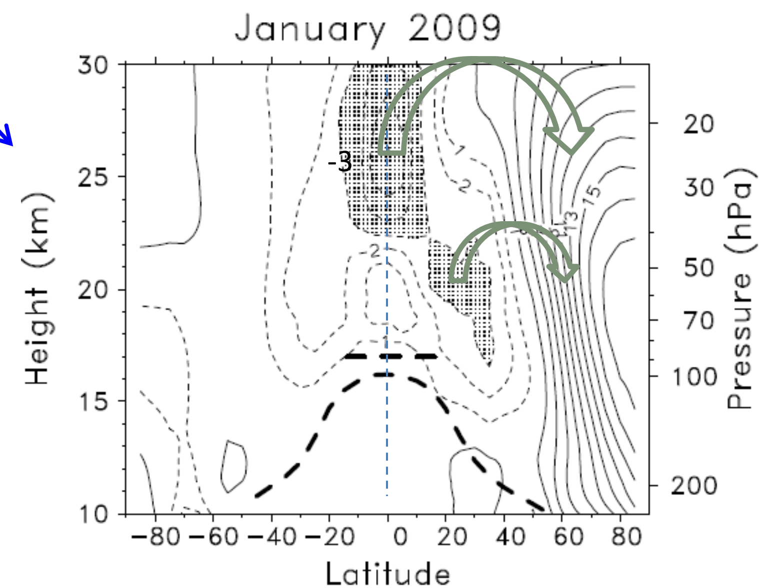
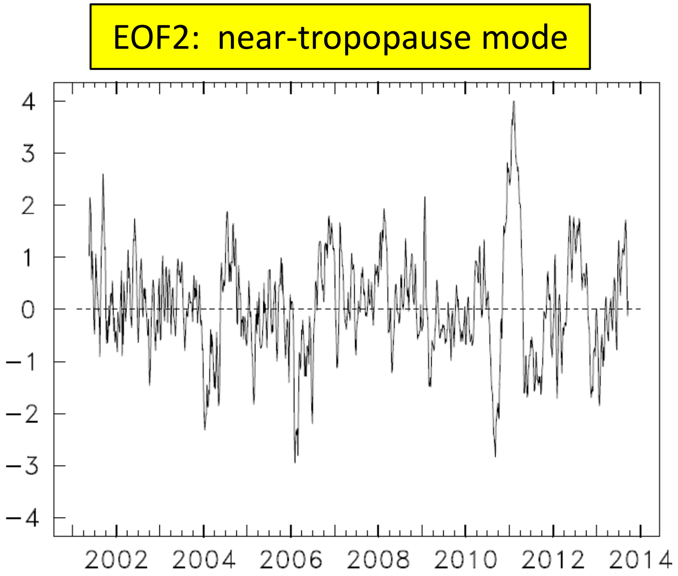


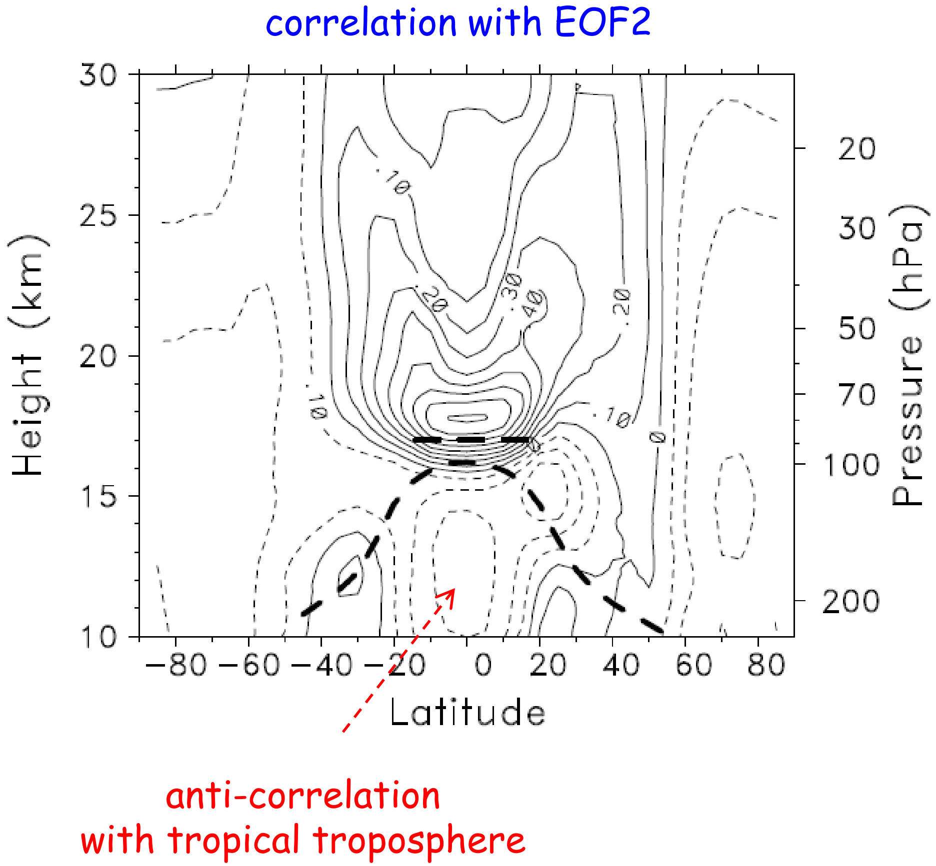
spatial structure of temp anomalies





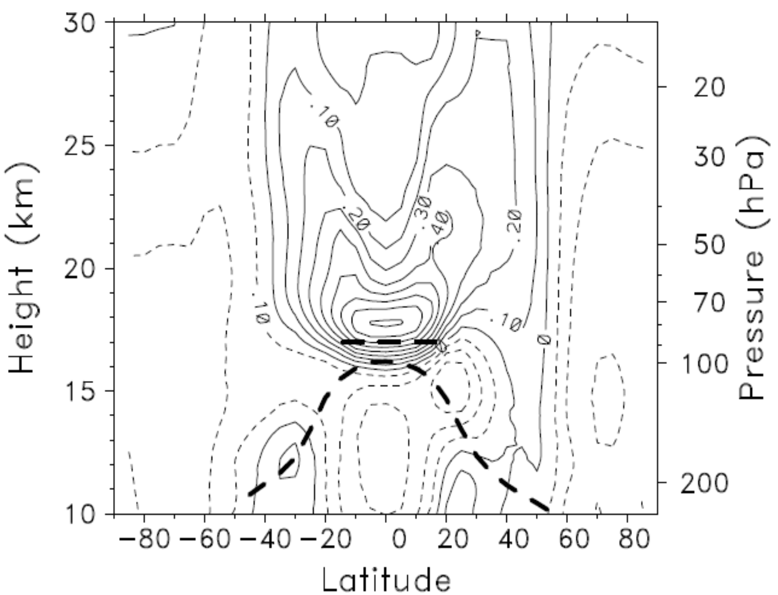
Near-tropopause signal



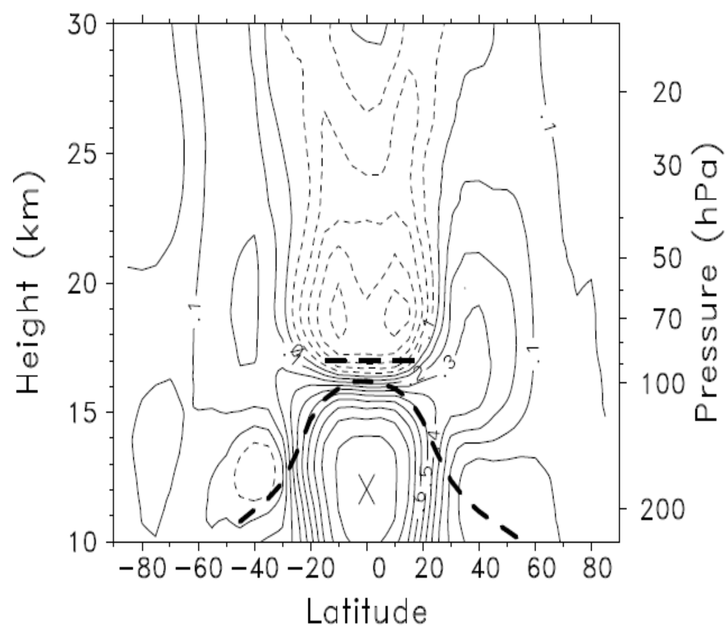


Near-tropopause signal: correlation maps

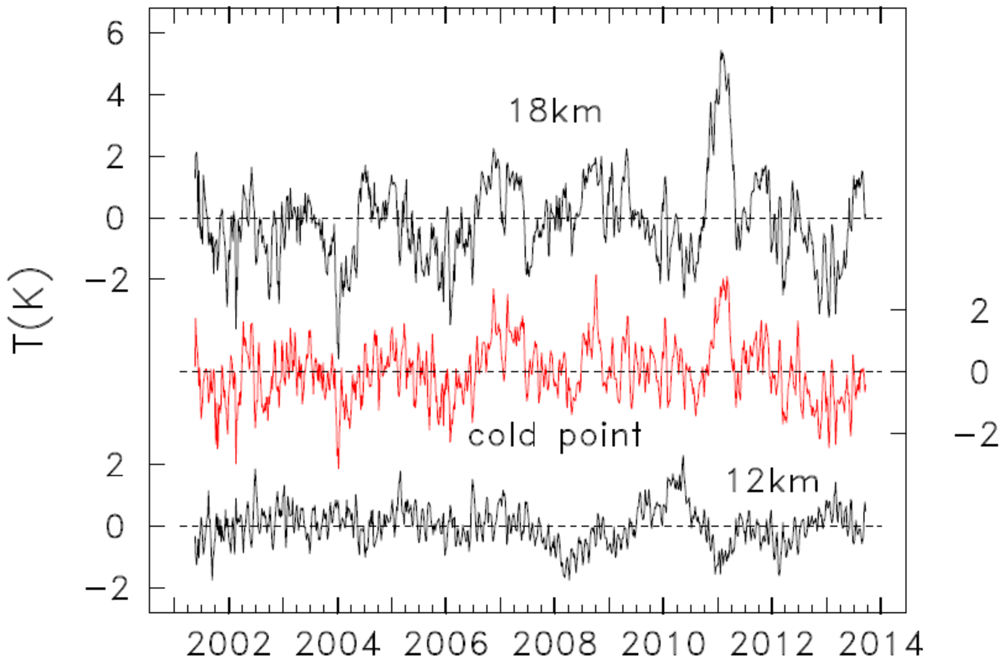
correlation with EOF2

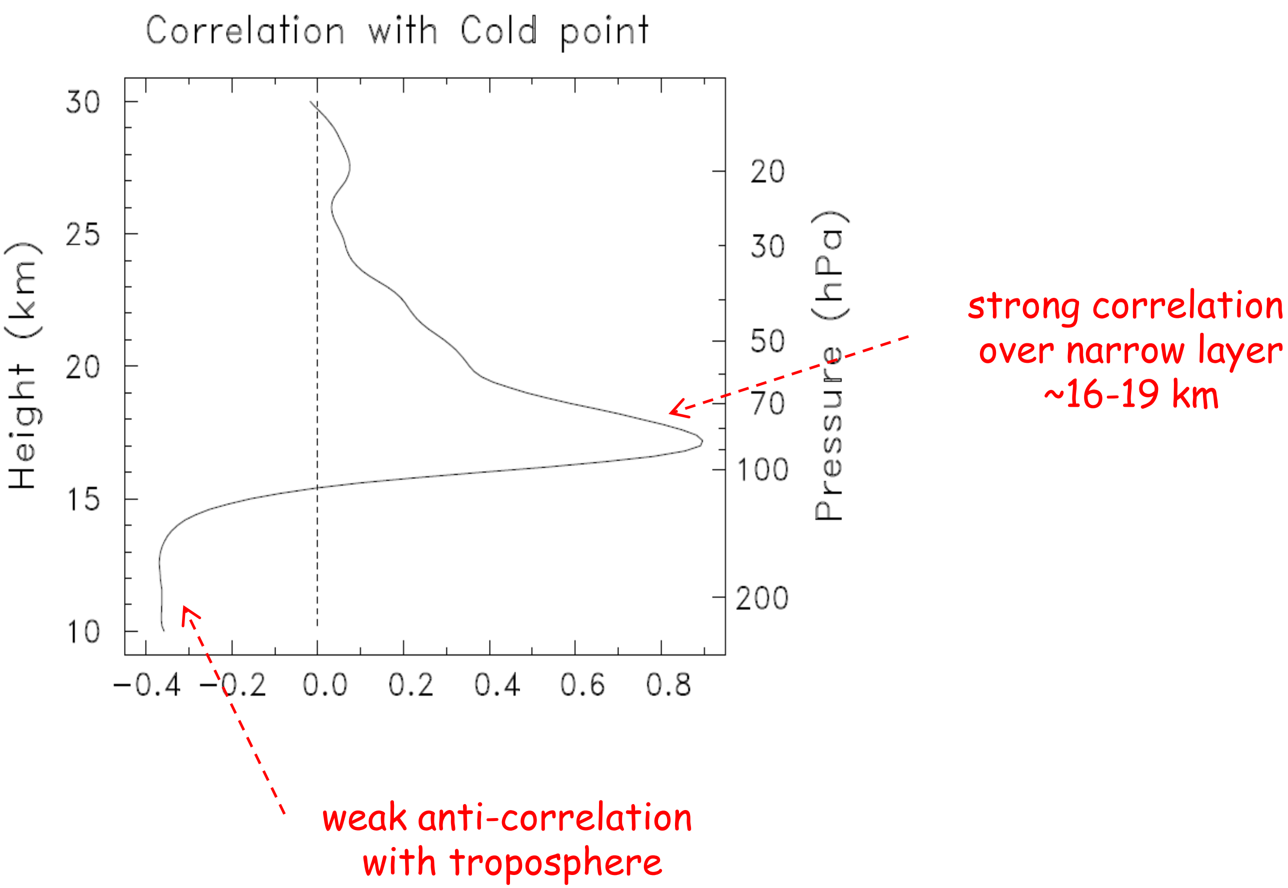


correlation wrt 12 km

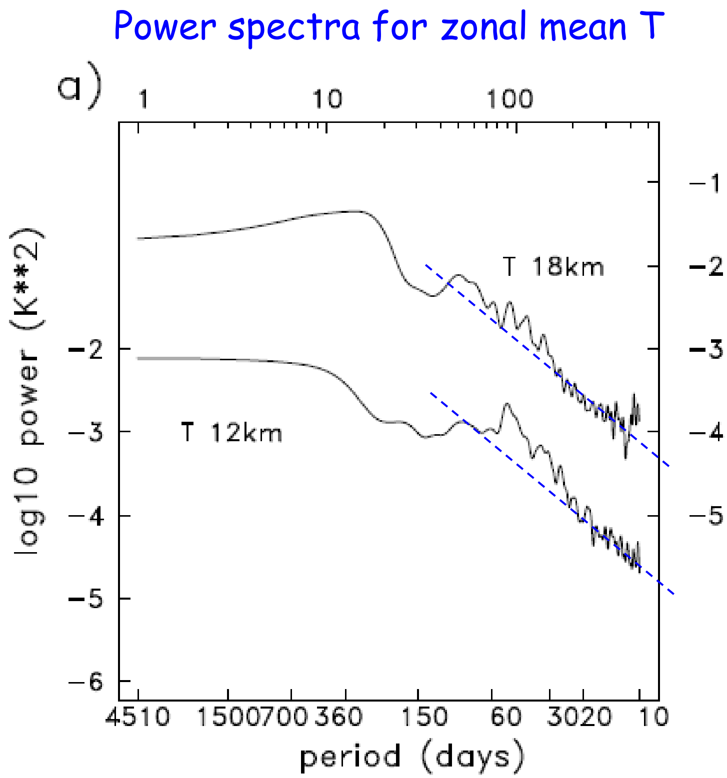


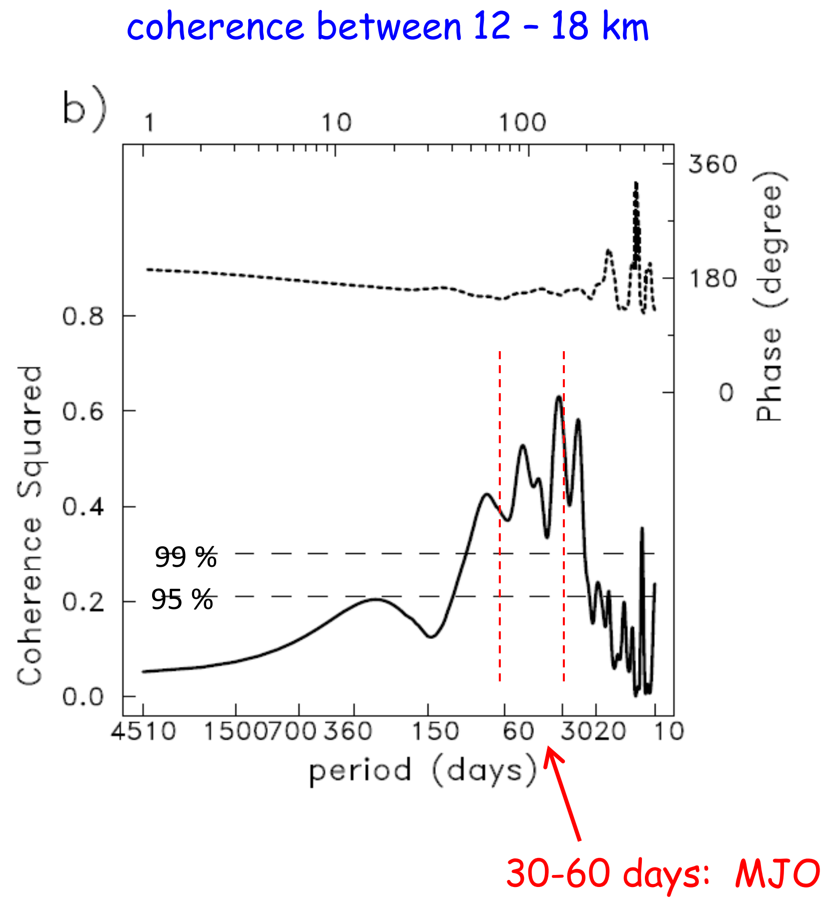
Time series of tropical temperature anomalies




Correlation with Cold point
Height (km)
Pressure (hPa)
30
25
20
15
10
20
30
50
70
100
200
−0.4
−0.2
0.0
0.2
0.4
0.6
0.8
strong correlation
over narrow layer
~16-19 km
weak anti-correlation
with troposphere

Spectrum analysis

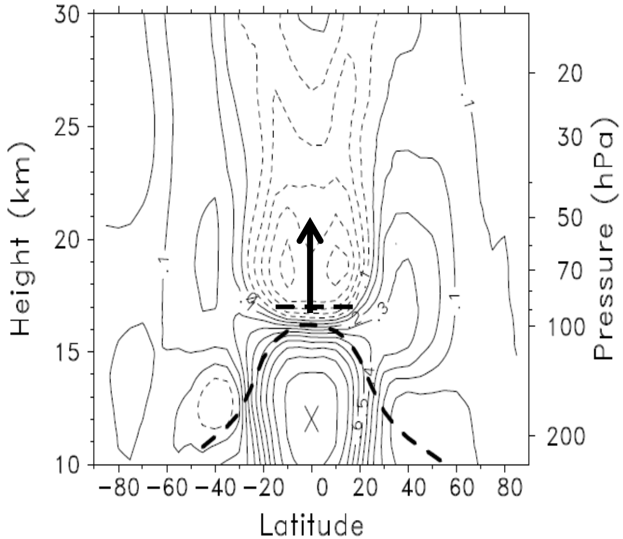




See Virts and Wallace, 2014

Links to tropical upwelling

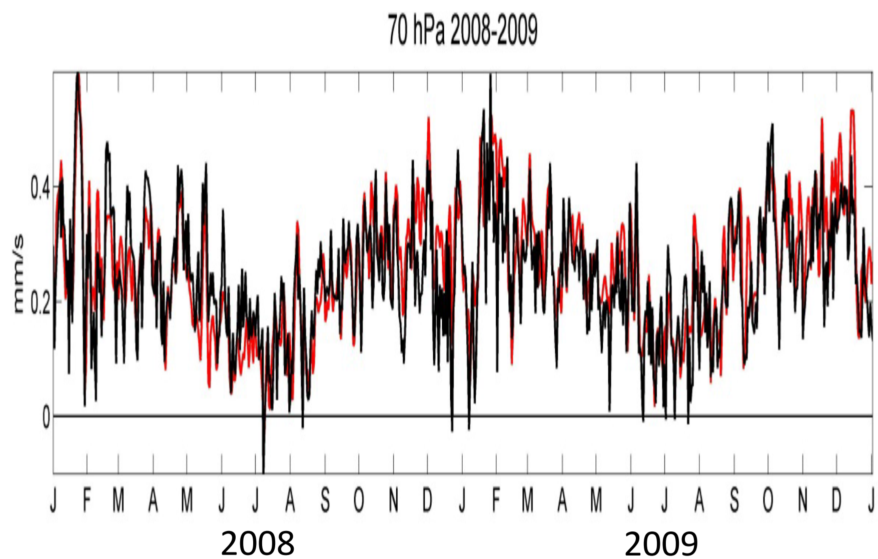
$$\frac{\partial \overline{T}}{\partial t} + \overline{w}^* S = -\alpha(\overline{T} - \overline{T}_e)$$



two estimates of upwelling:

w^*_m momentum balance

w^*_Q thermodynamic balance



Abalos et al, 2014, JAS

Simplified thermodynamic balance:

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

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:

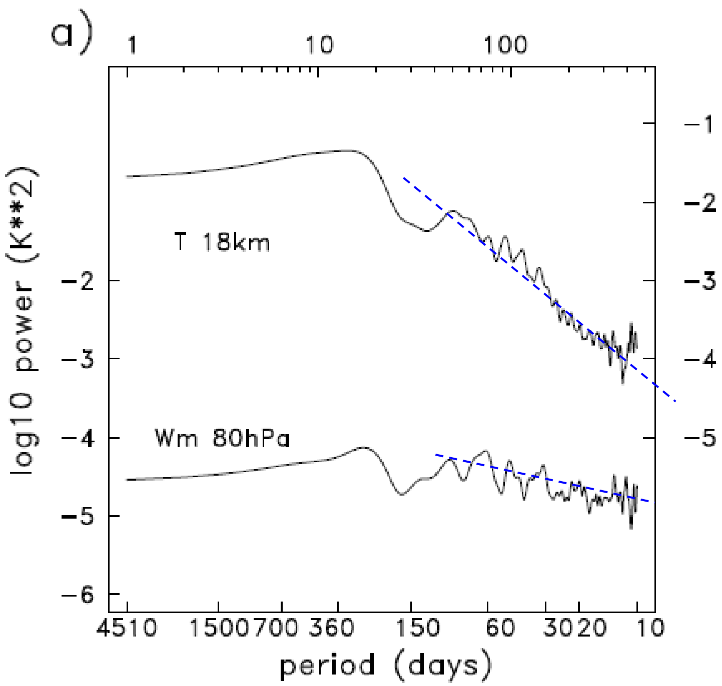
$$\boxed{\sqrt{\frac{\overline{T_\sigma^2}}{w_\sigma^2}} = \frac{S}{\sqrt{\alpha^2 + \sigma^2}}.}$$

radiative damping
time scale

frequency

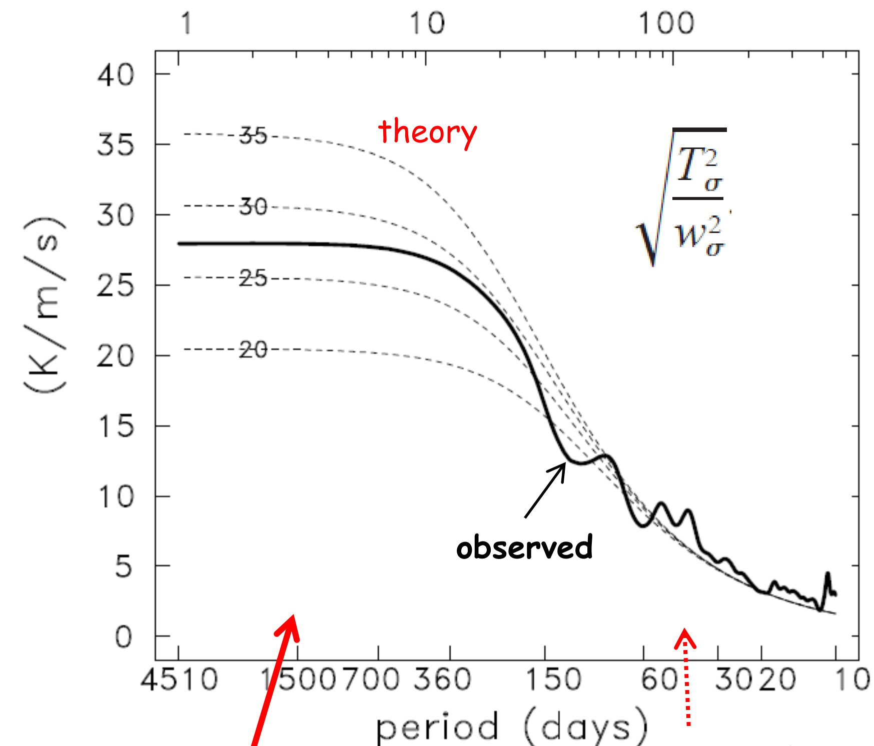
Spectrum analysis

Power spectra for T and w^*_m



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

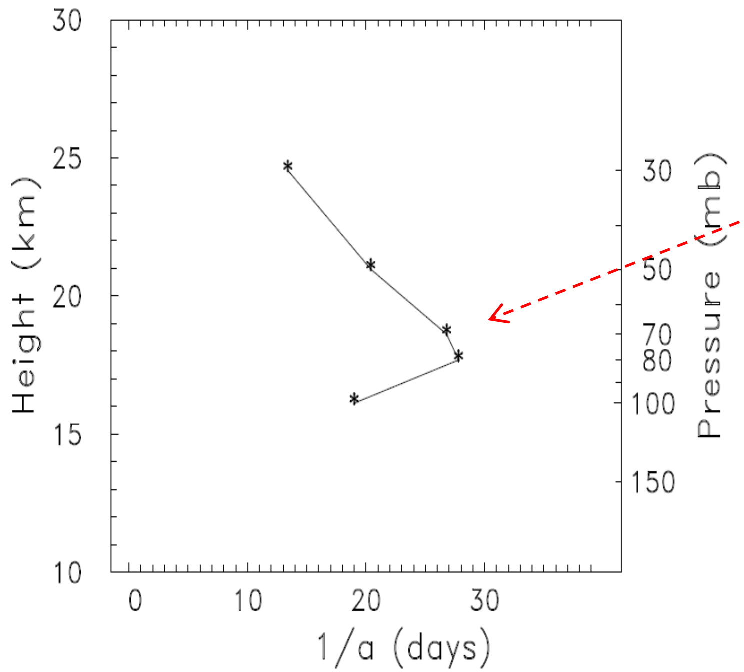
T sensitivity to w^*_m



enhanced response at low frequencies (longer than 150 days)

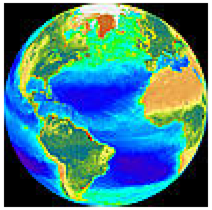
note weak response for MJO periods

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

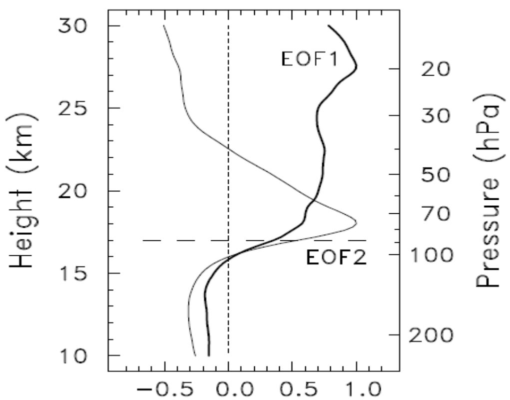
- Lower stratosphere temps especially sensitive to low frequency forcing
- Cause of enhanced annual cycle and large T variance in lower stratosphere



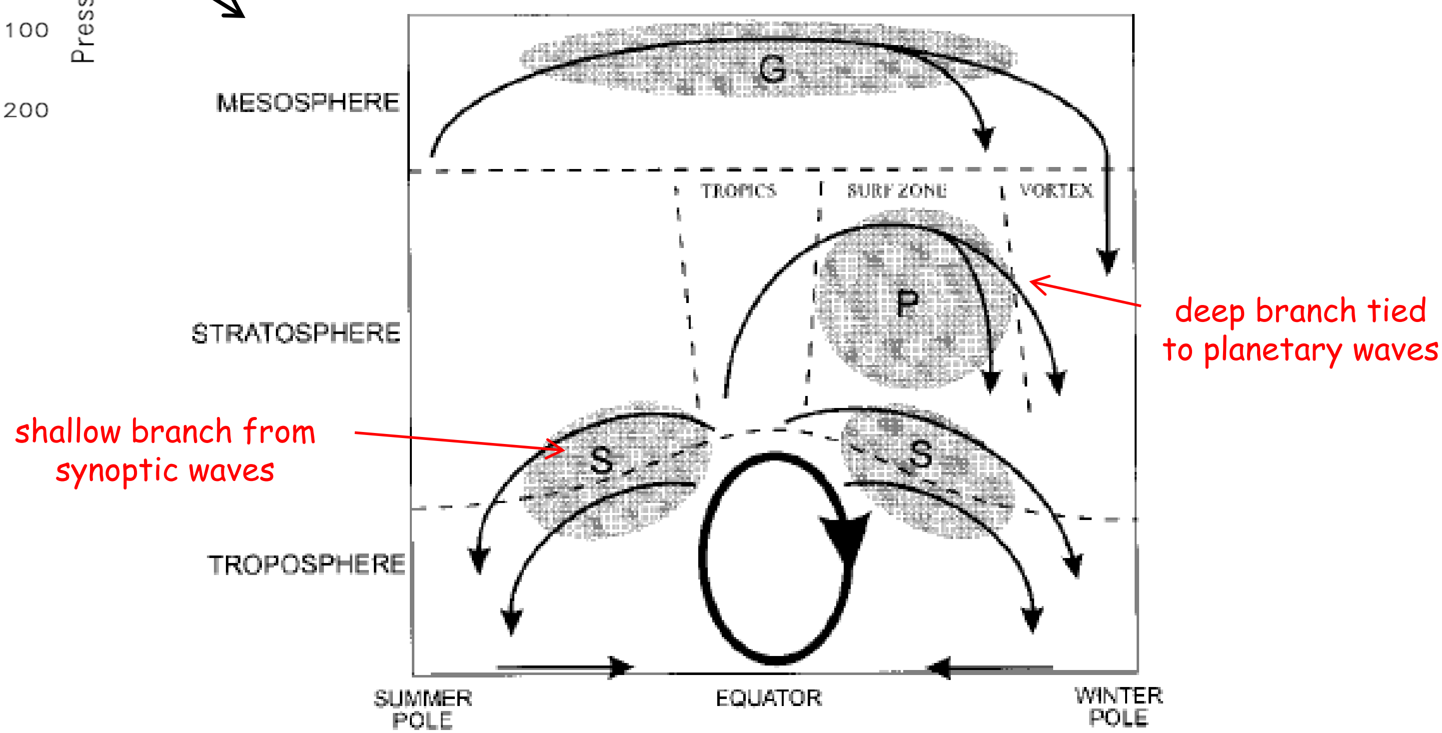
Key points:

- 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 upper troposphere T
- Lower stratosphere T most sensitive to low frequency forcing

GPS EOF patterns



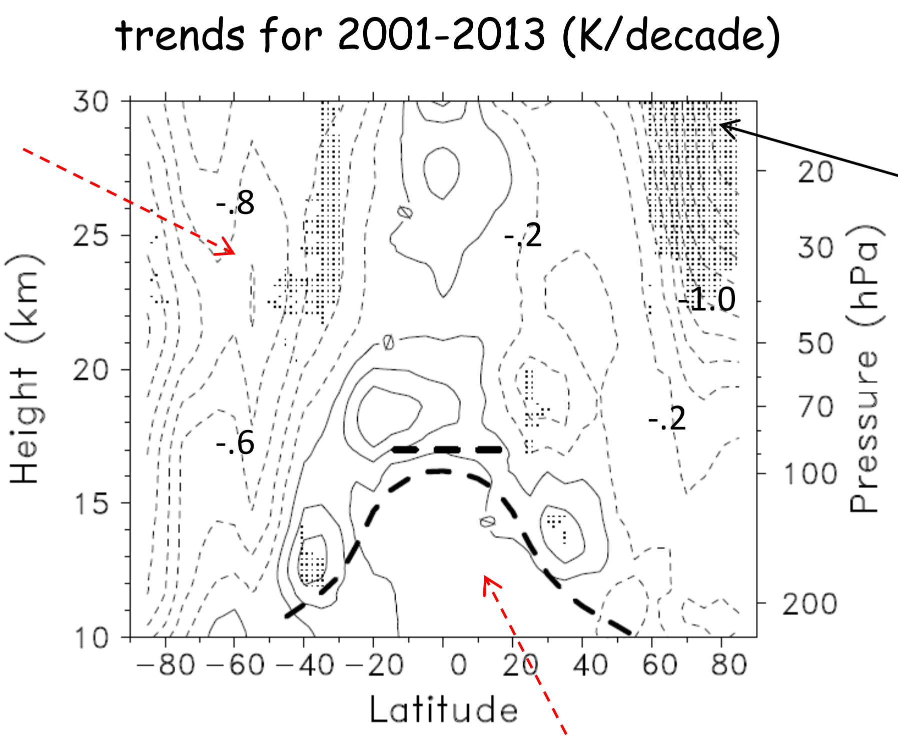
Deep and shallow branches of Brewer-Dobson circulation



Plumb (2002); also Birner and Bonish, 2011

Linear trends from combined GPS record 2001-2013

cooling trends in high latitude stratosphere (not significant)



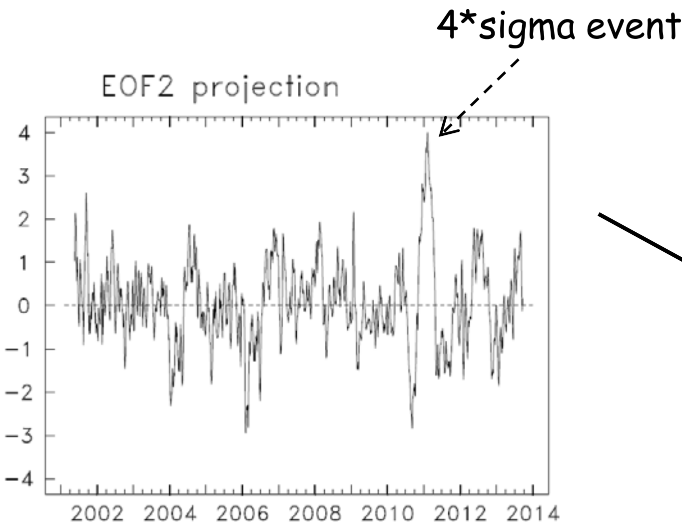
shading = 95% significance

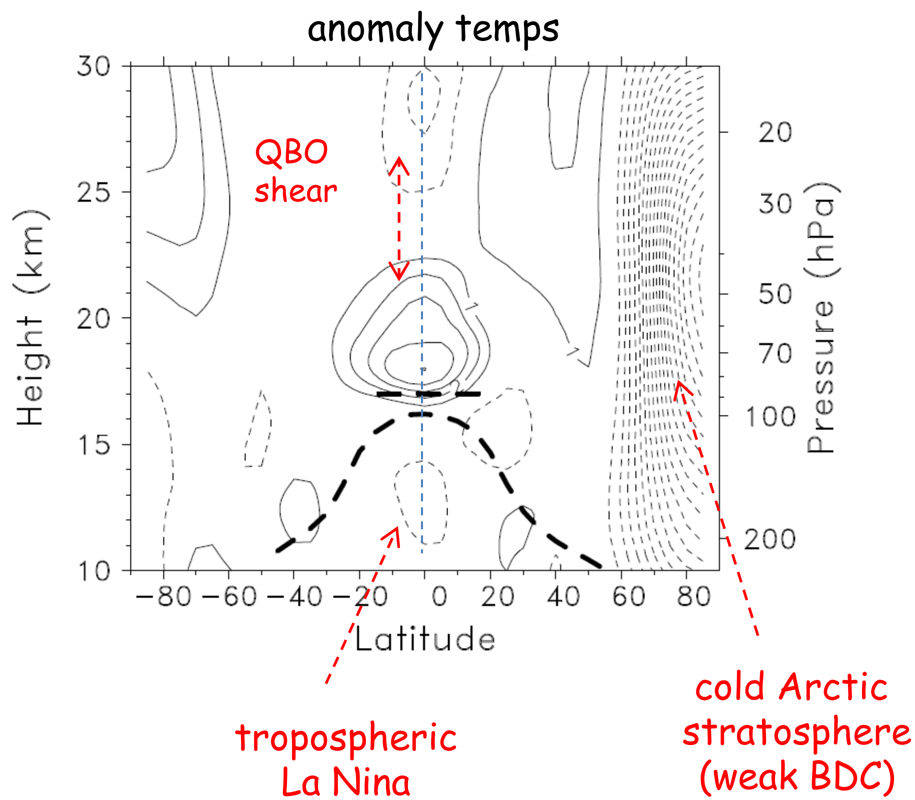
near zero trends
in tropical troposphere

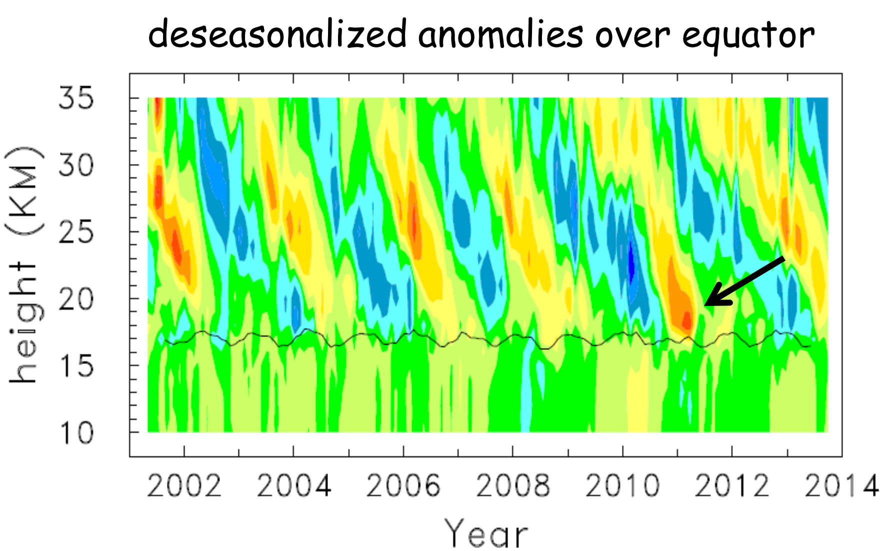

Thank you

Extra slides

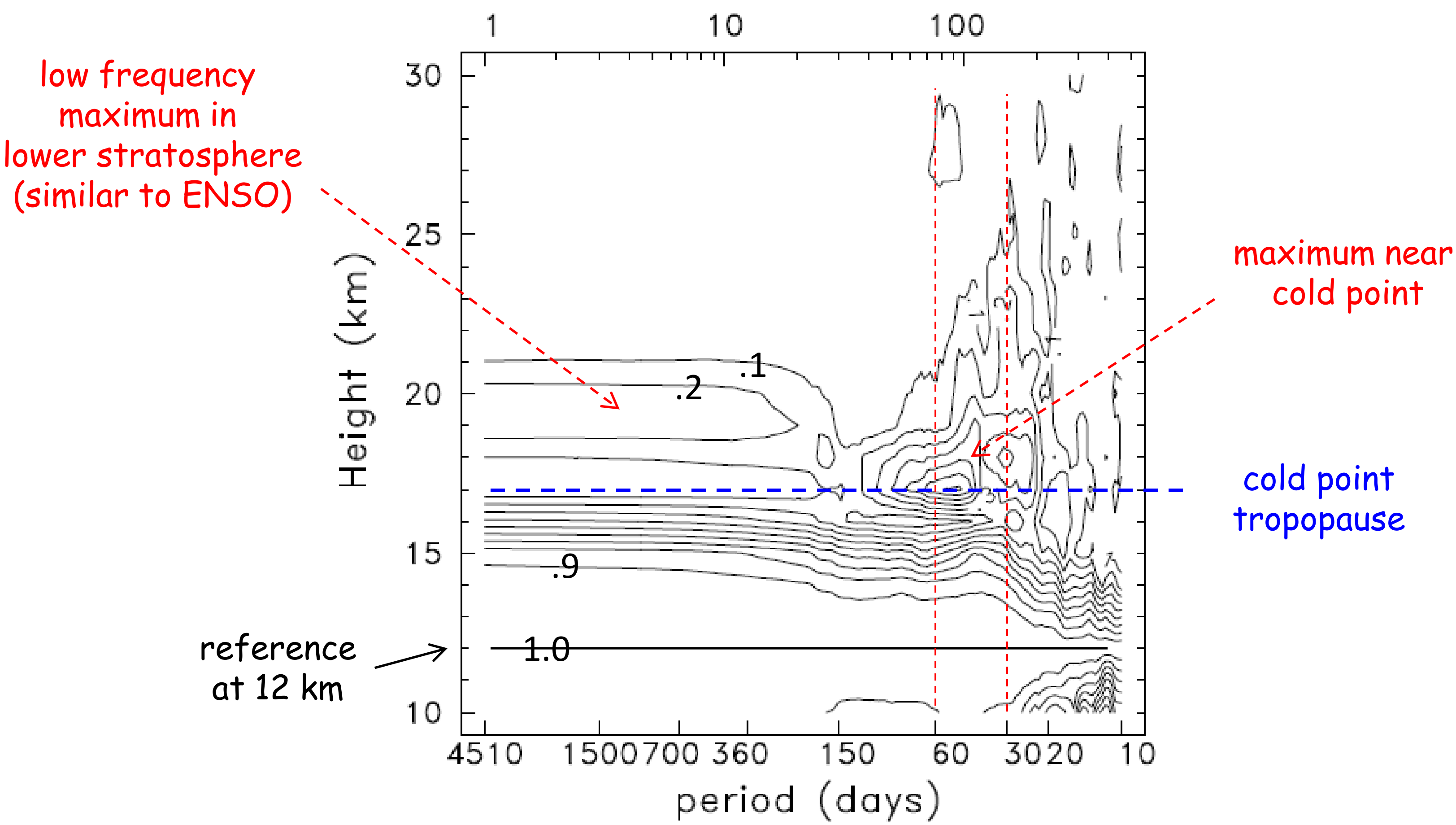
3 factors contributing to anomalous tropical temps:





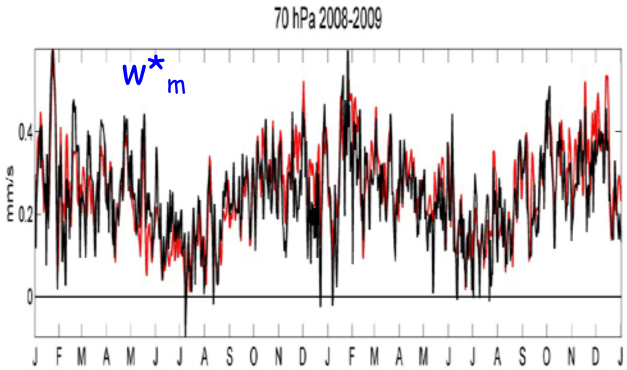


tropical coh^2 with respect to 12 km

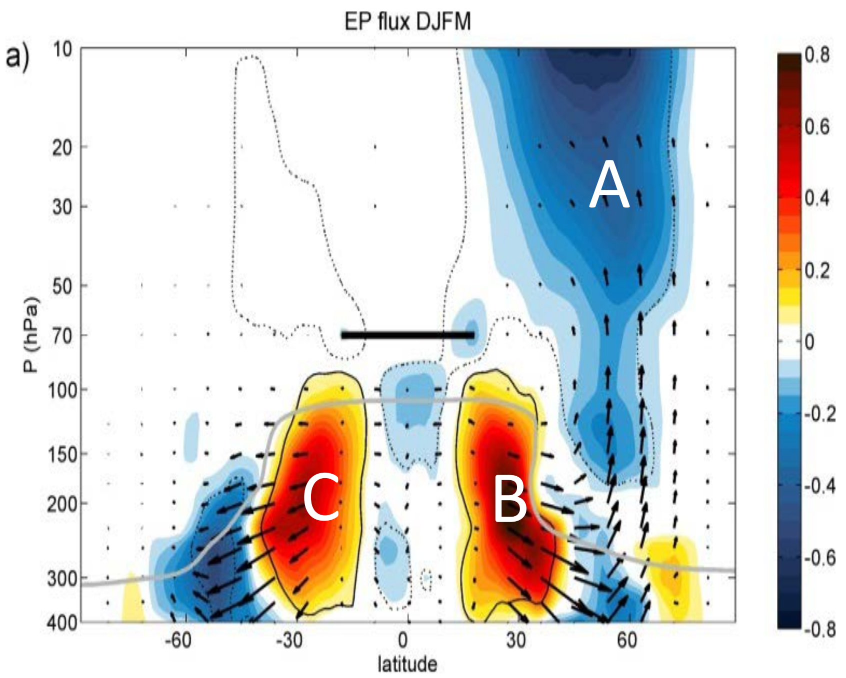


30-60 days: MJO

EP flux divergence forcing of transient upwelling:



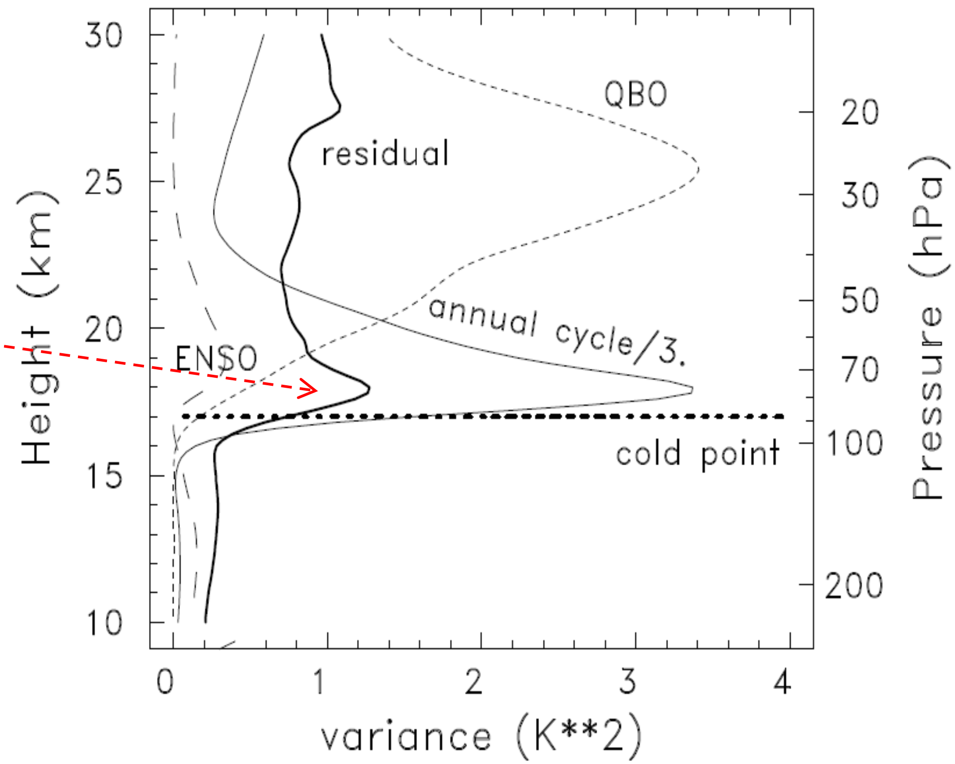
Regression of EP flux onto w^*_m



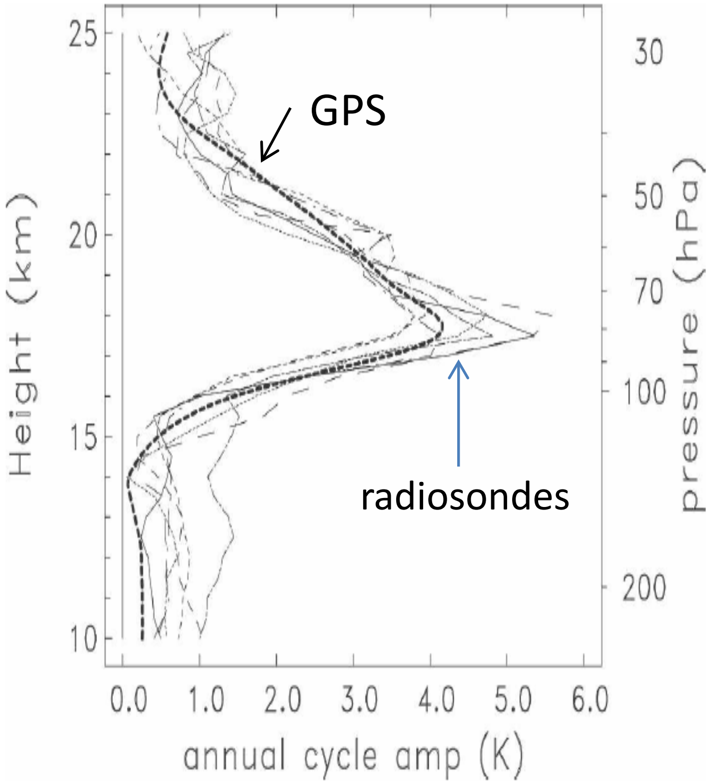
Abalos et al, 2014, JAS

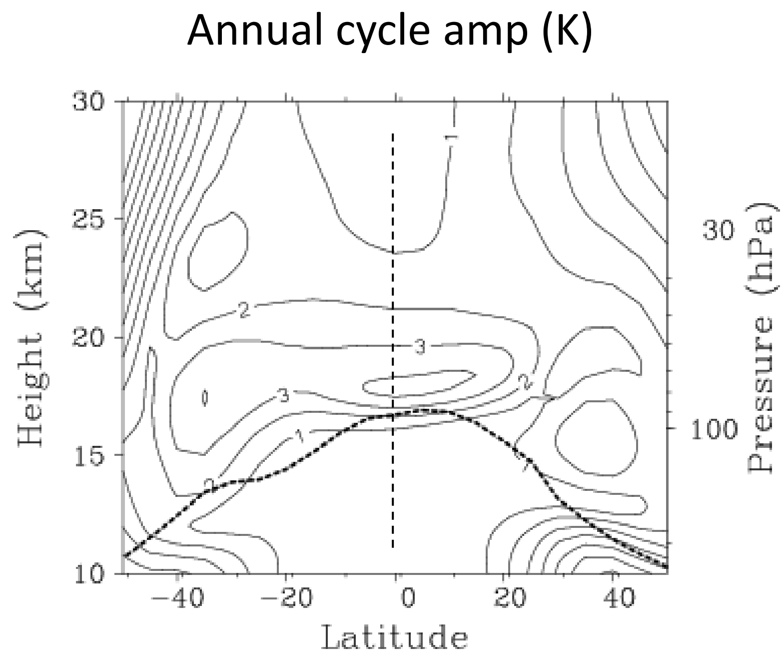
Components of zonal mean temperature variance

residual dominates
deseasonalized
variance
near tropopause

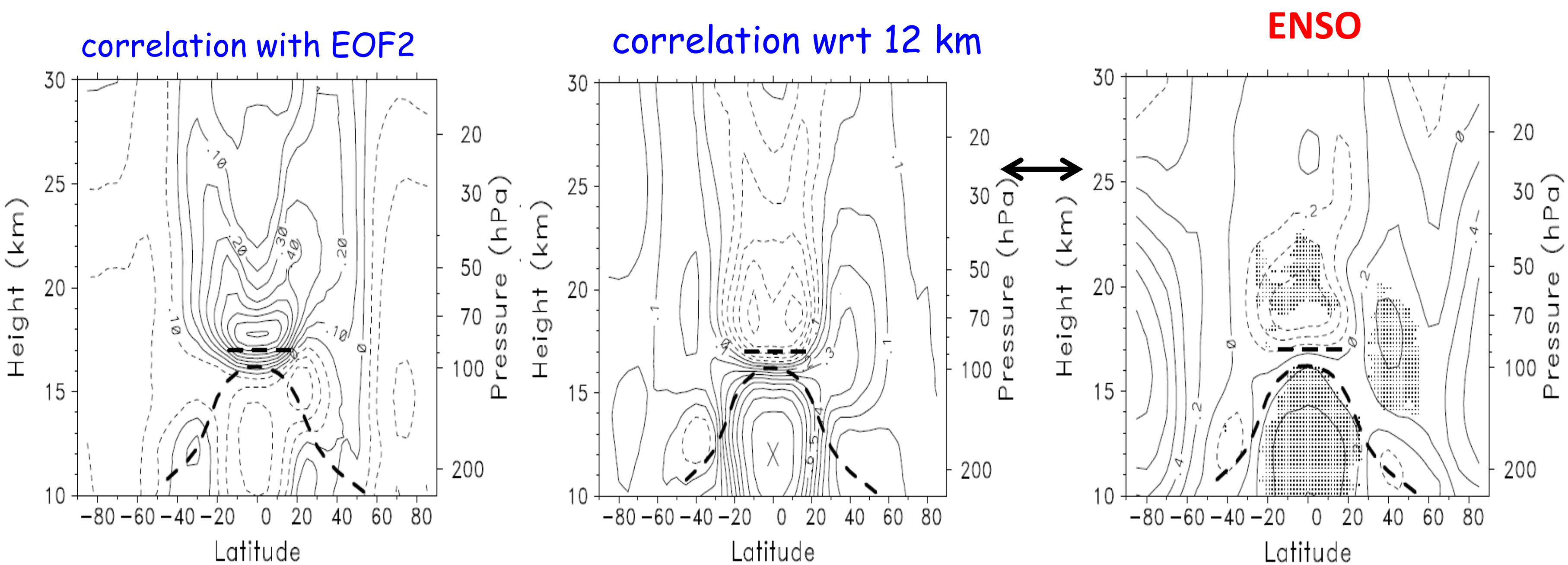


Annual cycle in temperature



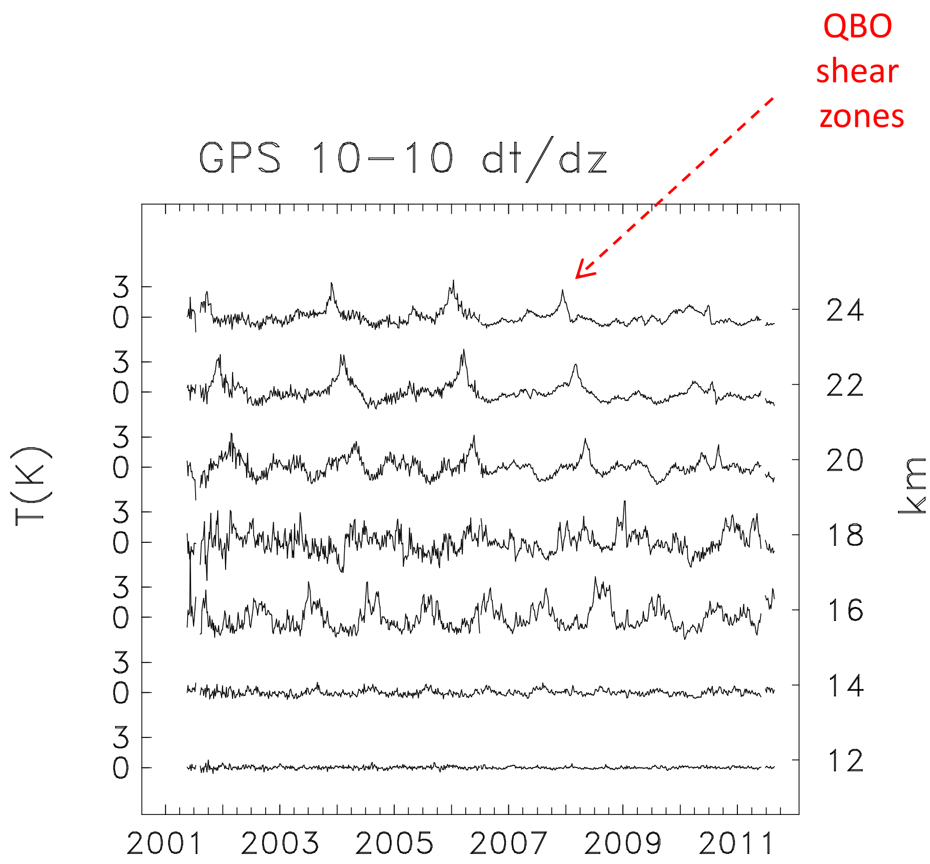


Spatial structure similar to ENSO

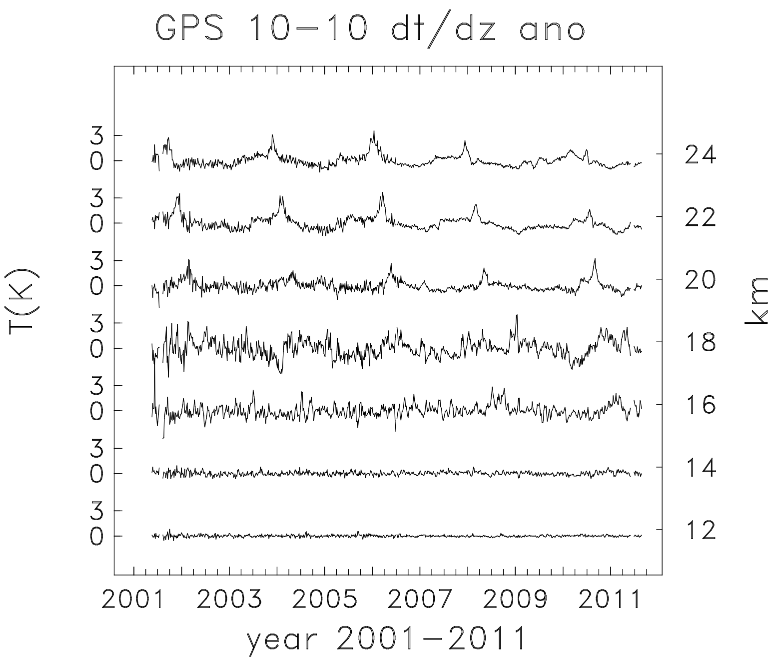


Analysis of lapse rate dT/dz

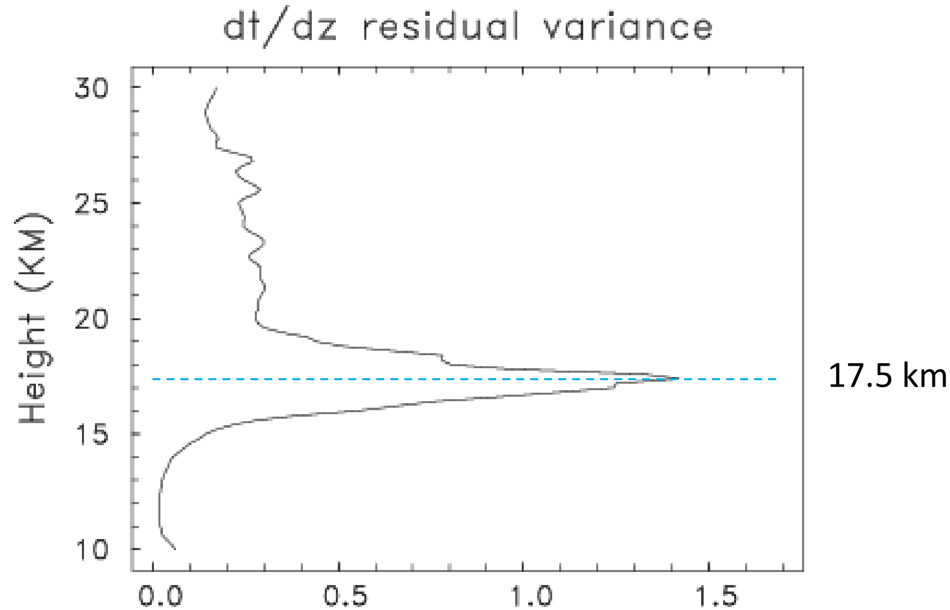
What is more fundamental: T or dT/dz ?



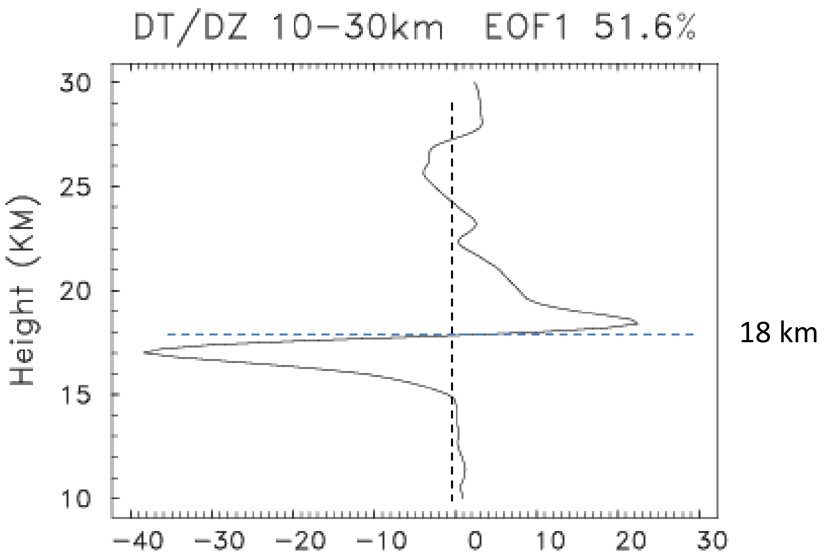
deseasonalized residuals

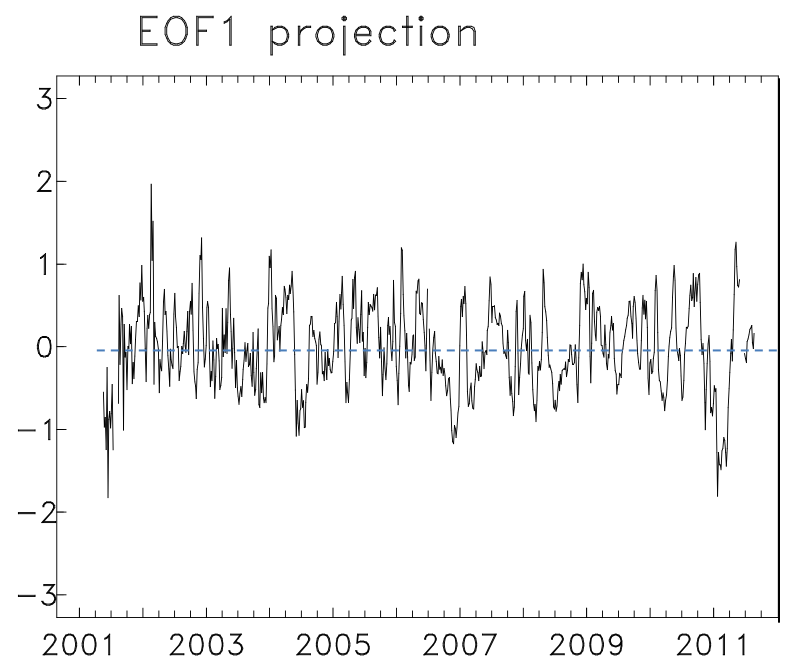


dT/dz variance

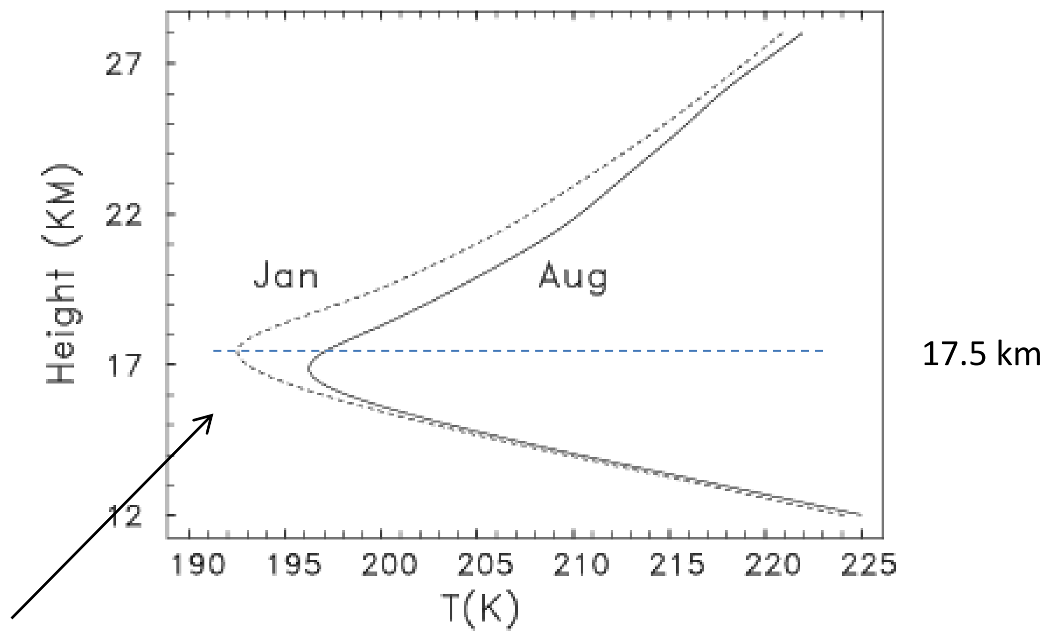


EOF analysis of residuals for dT/dz





Tropical temperature seasonal cycle (the big signal)

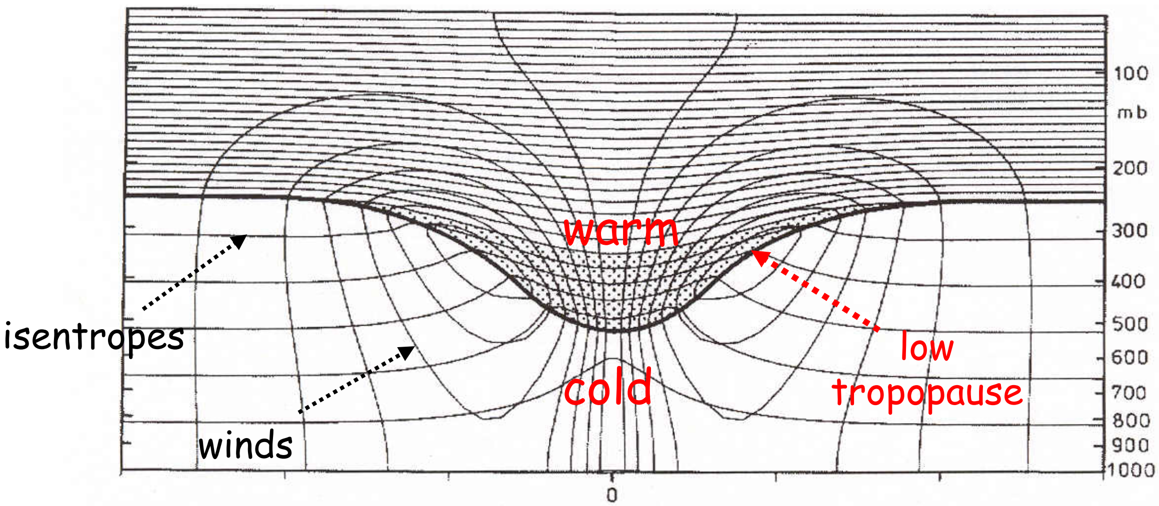


- Large seasonal cycle, but difficult to isolate mechanism(s): both convection and upwelling (and EP fluxes) have seasonal cycles

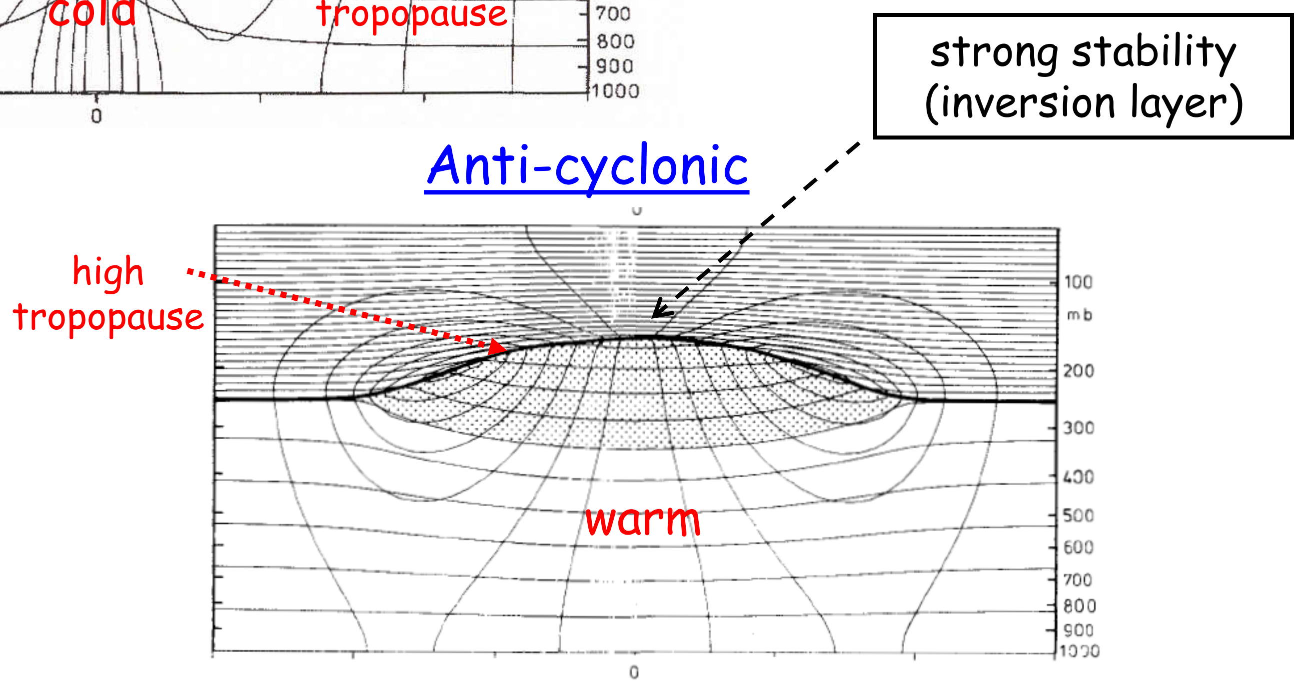
- Examine deseasonalized variability

Balanced dynamical structure (Hoskins et al. 1985)

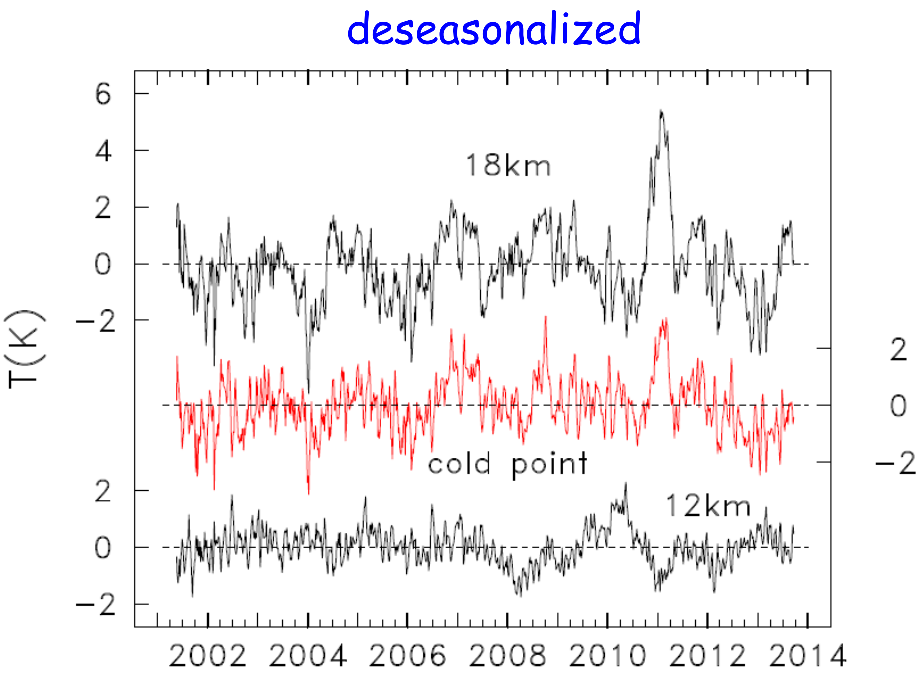
Cyclonic

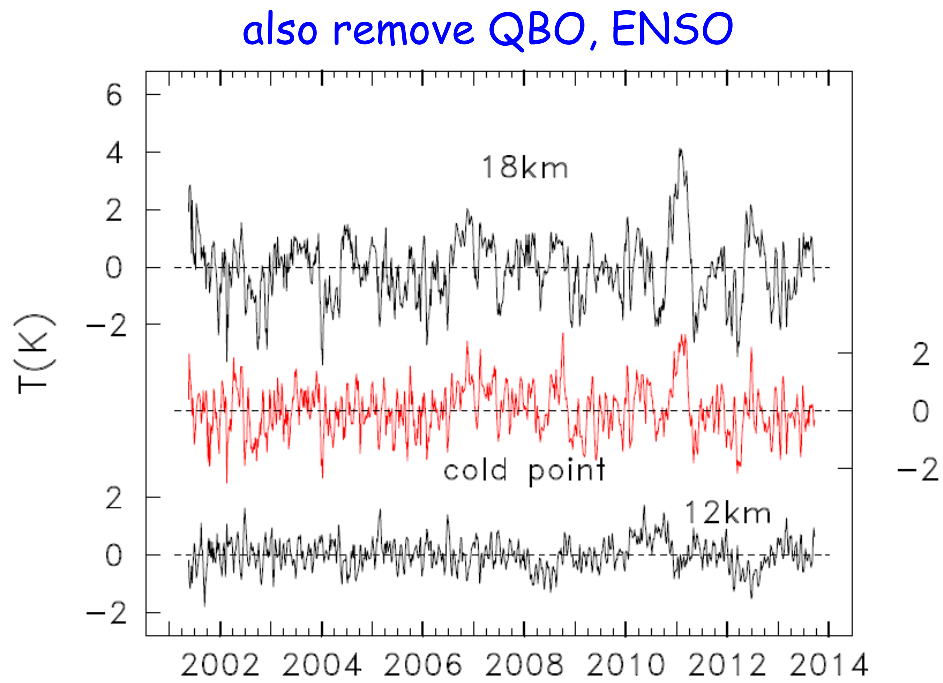


Anti-cyclonic



Time series of tropical temperature residuals





Dynamical forcing of tropical upwelling