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:

- Tropical upwelling influences temps, ozone and stratospheric H$_2$O
- Two-way mixing from baroclinic eddies and monsoons
- Deep convection impacts from below
- Cirrus and climate impacts

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

Randel and Jensen, 2013, Nat. Geosci.

Plumb (2002); also Birner and Bonish, 2011
Stratospheric $H_2O$ is controlled by tropical cold point temperatures

Interannual changes during 1992-2014

- Near-global mean ($60^\circ$ N-S) water vapor at 82 hPa from combined HALOE-MLS data
- Cold-point tropical tropopause temperatures
- $r=0.78$

black: radiosondes
red: GPS (after 2001)
Interannual variability of tropical tropopause layer clouds

Sean M. Davis, Calvin K. Liang, and Karen H. Rosenlof

GRL, 2013

warm temps, less clouds
What controls variability of the cold-point tropopause?

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

\[ T(z) \]

Main convective outflow \( \sim 12 \text{ km} \)

Radiative balance

Lapse rate from radiative-convective equilibrium

Cold point tropopause \( \sim 17 \text{ km} \)
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)

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

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

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

\[
\frac{\partial \overline{T}}{\partial t} + \overline{w^*} S = -\alpha(\overline{T} - \overline{T_e})
\]
Tropical variability for 10° N-S

Amplitude of the tropical annual cycle in temperature

- very small annual cycle in troposphere
- narrow vertical scale, peak in lower stratosphere
- GPS
- radiosondes
- tropopause
QBO is the large interannual signal in the stratosphere

Regression fits of QBO and ENSO 2001-2013

\[ T = a \times \text{ENSO} + b_1 \times \text{QBO}_1 + b_2 \times \text{QBO}_2 \]

ENSO fits

ENSO GPS temperature

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


ENSO ERAi zonal wind

wind maxima in subtropics,
extending into lower stratosphere
deseasonalized


remove QBO and ENSO ('residual' variability)
Components of zonal mean temperature variance

EOF analysis of residuals

Tropical cooling linked to stratospheric sudden warmings (SSW)

EOF1: deep stratosphere mode

SH warming Sept 2002

NH warming Jan 2009

Tropical cooling linked to stratospheric sudden warmings (SSW)

EOF1: deep stratosphere mode

PC1

spatial structure of temp anomalies

SH warming Sept 2002

NH warming Jan 2009

Large stratospheric sudden warming in January 2009

Harada et al., 2010

Polar stratosphere temperature

High latitude planetary wave forcing

Polar vortex near 30 km

Potential vorticity

Split of polar vortex
Regression of global temperatures and EP flux onto PC1

- **NH winter**
  - Cooling in tropics

- **SH winter**
  - High latitude wave fluxes and polar warming

Near-tropopause signal

EOF2: near-tropopause mode

PC2

temperature regression onto PC2

maximum in tropical lower stratosphere

anti-correlation with tropical troposphere

Near-tropopause signal: correlation maps

regression onto PC2

correlation wrt 12 km

time series of tropical temperature anomalies

strong correlation over narrow layer ~16-19 km

weak anti-correlation with troposphere

Spectrum analysis

Power spectra for zonal mean T

Zonal mean MJO signal: Virts and Wallace, 2014
tropical coh² with respect to 12 km

- Low frequency maximum in lower stratosphere (similar to ENSO)
- Reference at 12 km
- Shaded regions ~99% significant
- Maximum near cold point
- Cold point tropopause
- 30-60 days: MJO

$\text{coh}^2$ with respect to 12 km

$\text{coh}^2$ 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

MJO ERAi zonal winds

Extreme near-tropopause event

3 factors contributing to anomalous tropical temps:

- QBO shear
- tropospheric La Nina
- cold Arctic stratosphere (weak BDC)

Deseasonalized anomalies

\[ r = 0.78 \]

stratospheric water vapor response to warm tropopause
Links to tropical upwelling

\[ \frac{\partial \bar{T}}{\partial t} + \bar{w}^* S = -\alpha (\bar{T} - \bar{T}_e) \]

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:

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

residual circulation from reanalysis $w^*$

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

accurate radiative heating rate

thermodynamic balance $w_Q^*$

$$\langle w^*_m \rangle (z) = \frac{-e^{-z/H}}{\phi_0} \frac{1}{a \cos \phi d\phi} \left\{ \int_{-\phi_0}^{\phi_0} \int e^{-z'/H} \cos \phi \hat{f}(\phi, z') \left[ DF(\phi, z') - \bar{u}_t(\phi, z') \right] \mu_m \text{d}z' \right\}^{\phi_0}_{-\phi_0}$$

momentum balance $w_m^*$

EP flux divergence

zonal wind tendencies
What forces transient tropical upwelling?

Regression of EP flux onto $w^*_m$

Modulation of climatological EP flux

subtropical EP fluxes

Abalos et al, 2014, JAS

Quantifying the relationship between $w^*$ and $T$:

\[ \frac{\partial \bar{T}}{\partial t} + \bar{w}^* S = -\alpha (\bar{T} - \bar{T}_e) \]

harmonic expansion

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

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

temperature response to upwelling:

\[ \sqrt{\frac{T_\sigma^2}{w_\sigma^2}} = \frac{S}{\sqrt{\alpha^2 + \sigma^2}}. \]
Spectrum analysis

Power spectra for $T$ and $w^*_m$

- Enhanced response at low frequencies (longer than 150 days)

- T sensitivity to $w^*_m$

- Note weak response for MJO periods

\[ \sqrt{\frac{T^2}{\sigma}} = \frac{S}{\sqrt{\alpha^2 + \sigma^2}} \]

Radiative damping time scales derived from:

\[
\frac{\sqrt{T^2}}{\sqrt{w^2}} = \frac{S}{\sqrt{\alpha^2 + \sigma^2}}.
\]


- Lower stratosphere temps especially sensitive to low frequency forcing
- Cause of enhanced annual cycle and large T variance in lower stratosphere
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
Deep and shallow branches of Brewer-Dobson circulation

GPS EOF patterns

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

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

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

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

MJO confined to troposphere.

in a global model, stratospheric H$_2$O increases with tropospheric temperature

**Fig. 2.** Time series of annual-average H$_2$O$_{ov-entry}$ 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 $\Delta T$ 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
deseasonalized
also remove QBO, ENSO

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

subtropical upper troposphere forcing

Reference1
