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:

- what controls tropical upwelling (temps, ozone and stratospheric H$_2$O)?
- 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

Richard J. Reed and Charles L. Vlcek

JAS 1969

- Dynamically forced, but exactly how?
- Extratropical stratosphere, tropical waves, ??

![Diagram](image)

Fig. 1. Amplitude (°C) and phase (time of maximum) of annual temperature variation.
Amplitude of the tropical annual cycle in temperature

What causes the annual cycle? Dynamically-forced upwelling

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

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

There is also a large annual cycle in ozone above the tropical tropopause.
Ozone annual cycle amplitude normalized by background \[ \frac{A_1}{<A>} \].

Upper troposphere seasonal cycle is different among stations.

HALOE satellite

Narrow vertical layer ~ 16-19 km

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 and temperature 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:

\[
\begin{align*}
\frac{\partial \chi}{\partial t} &= -v^* \frac{1}{a} \frac{\partial \chi}{\partial \phi} - w^* \frac{\partial \chi}{\partial z} + \nabla \cdot M + P - L, \\
\frac{\partial T}{\partial t} + v^* \frac{1}{a} \frac{\partial T}{\partial \phi} + w^* S &= \overline{Q},
\end{align*}
\]

Variations in upwelling \( w^* \) result in correlated temperature and tracers

* for tracers with strong vertical gradients

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

% tropical ozone due to in-mixing

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
• Observational analysis of upwelling effect on tracers
• MLS observations of ozone, CO 2004-2011
• ERAinterim meteorology
• 3 estimates of upwelling: $w^*$ (from reanalysis)
  $w^*_Q$ (thermodynamic balance)
  $w^*_m$ (momentum balance)
3 estimates of tropical upwelling \( w^* \) from observations:

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

residual circulation from reanalysis \( w^* \)

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

accurate radiative heating rate

\[
(w_m^*)(z) = \frac{-e^{-z/H}}{\phi_0} \int_{-\phi_0}^{\phi_0} \frac{a \cos \phi d\phi}{\int_{-\phi_0}^{\phi_0} a \cos \phi d\phi} \left\{ \int_{-\phi_0}^{\phi_0} \frac{e^{-z'/H} \cos \phi}{\hat{f}(\phi, z')} \left[ D F(\phi, z') - \bar{u}_t(\phi, z') \right]_m dz' \right\} \phi_0
\]

thermodynamic balance \( w_Q^* \)

momentum balance \( w_m^* \)

EP flux divergence
Latitude structure of upwelling from 3 estimates

Abalos et al., 2012, Atmos. Chem. Phys.
Daily variations in upwelling 18° N-S

Large annual cycles and significant sub-seasonal variability

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

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

Result: upwelling ~ radiative heating

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

Residual = unresolved eddy effects + imbalances from resolved terms

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

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

Annual cycle follows upwelling

Result: 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?

The near-tropopause structure 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 *

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:

\[
\tilde{T}_t = -\tilde{v}^* \tilde{T}_y - \tilde{w}^* S + \tilde{Q} - e^{z/H} \left[ e^{-z/H} \left( \frac{\tilde{T}_y}{S} + \tilde{w} \tilde{T}_i \right) \right]_z.
\]

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:

\[
\frac{\partial \chi}{\partial t} = -u^* \frac{1}{a} \frac{\partial \chi}{\partial \phi} - w^* \frac{\partial \chi}{\partial z} + \nabla \cdot M + P - L
\]

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

\[
\frac{\partial \bar{\chi}}{\partial t} = -\bar{v} \frac{1}{a} \frac{\partial \bar{\chi}}{\partial \phi} - \frac{\bar{w}}{a} \frac{\partial \bar{\chi}}{\partial z} + \nabla \cdot M + P - L
\]

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

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

Ozone column density, DU/km

[Image of Satellite climatology in January showing mean meridional circulation, eddy mixing, and stratosphere-troposphere exchange.]
WACCM eddy flux tendencies $\frac{d}{dy} (v'O_3')$

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

WACCM \ O_3 \ 400K \ JJA
Phase-speed vs. latitude spectra for eddy fluxes ($v' \text{O}_3'$)

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

NH winter eddy ozone transport at 440 K

following Randel and Held 1991

Abalos et al., 2013, Atmos. Chem. Phys.
WACCM CO budget

\[
\frac{\partial \bar{X}}{\partial t} = -\bar{v}^* \frac{1}{a} \frac{\partial \bar{X}}{\partial \phi} - \bar{w}^* \frac{\partial \bar{X}}{\partial z} + \nabla \cdot M + P - L
\]

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')

- 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**
  

- **Equatorial waves**
  

- **Subtropics** (baroclinic eddies from midlatitudes)
  
Evaluating upwelling from subtropical EP fluxes

Seasonal mean EP fluxes

wave forcing extends deeper during DJF

both extratropical and tropical waves contribute to subtropical forcing

Randel, Garcia and Wu, 2008
Ortland and Alexander, 2013:

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

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

\[
(w^*_m)(z) = \frac{-e^{-z/H}}{\int_0^\phi \frac{a \cos \phi d\phi}{\cos \phi}} \left\{ \int_0^\infty e^{-z'/H} \cos \phi \left[ DF(\phi, z') - \bar{u}_m(\phi, z') \right] d\phi \right\}
\]

\[w^*_m \quad \text{and} \quad w^*_Q\]

remove annual cycle

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

ERAi reanalysis 1979-2011

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

Boreal winter
DJFM

Coherent signals in ozone tendencies

Regressions onto $w^*_m$

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

EP flux ‘centers of action’ for forcing transient tropical upwelling:

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

regressions


extreme event composites

Difference
How does remote forcing influence tropical upwelling?

response to high latitude forcing

Subtropical upper troposphere

Correlation reference

Deep barotropic wind response

response to subtropical forcing

response to subtropical forcing

response to subtropical forcing

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

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

dT/dt and circulation

EP fluxes

high latitude stratosphere forcing

subtropical upper troposphere forcing

20 hPa

50 hPa

100 hPa

Lower branch of the BDC is primarily related to subtropical wave forcing.

Residual circulation

EP fluxes

note coherent tropospheric effects

subtropical EP fluxes drive lower branch of BDC

Is stratospheric forcing correlated with subtropical forcing?

Is subtropical forcing related between the two hemispheres?

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

Extra slides
Regressions onto $w^*_m$

SH winter JJAS

Note contribution from (transient) equatorial waves

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


Reference3