Lecture 3: Global upper troposphere – lower stratosphere (UTLS)

• Overview: why is the UTLS interesting?

• Structure of the global tropopause and relation to tracers

• Double tropopauses

• The tropopause inversion layer
Global structure of the tropopause:

Strong change in stability across the tropopause:

- Troposphere: vertically well-mixed; via convection and baroclinic instability
- Stratosphere: dynamically stable (mostly); circulation forced by radiation and forcing from troposphere (upward propagating waves)
Ozone

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

Ozone column density, DU/km

Satellite climatology in January
**Ozone**

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

Ozone column density, DU/km

![Satellite climatology in January](image)

- Mean meridional circulation
- Eddy mixing
- Stratosphere-troposphere exchange
Carbon monoxide (CO)

- Emitted from combustion (tropospheric source gas)
- Photochemical lifetime of ~2 months (useful as a dynamical tracer)
- Strong gradients across tropopause

Measurements from ACE-FTS satellite transport from mesosphere

Strong gradients in chemical behavior demonstrates that the tropopause acts as a boundary separating distinct air masses

H₂O exhibits similar behavior

main emissions in NH

Park et al., 2013, J. Geophys. Res.
Atmospheric Chemistry Experiment
Fourier Transform Spectrometer (ACE-FTS)

FTS measurements: $2.2 - 13.3 \, \mu m$
10+ years of data (Feb. 2004 – present)
~ 3,500 occultations /year

Resolution: ~300 km horizontal, 3 km vertical

ACE occultations
measurement pattern: repeats every year

Low latitudes: 4 samples / year
Randel et al., 2012, J. Geophys. Res.
ACE-FTS measurements and retrievals for carbon monoxide (CO)

Simulated CO spectrum

Transmittance

ACE-FTS measurements

microwindows for CO retrieval

Clerbaux et al., ACP, 2008
In ACE-FTS version 3.0 (37 molecules): CO₂, H₂O, O₃, N₂O, CO, CH₄, NO, NO₂, HNO₃, HF, HCl, ClONO₂, N₂O₅, CFC-11, CFC-12, OCS, HCN, CH₃Cl, CF₄, CCl₄, COF₂, C₂H₂, C₂H₆, CH₃OH, SF₆, HCOOH, HCFC-22, N₂, O₂, CFC-113, HCFC-141b, HCFC-142b, HNO₃, H₂O₂, H₂CO, COCl₂, COClF

- New: HFC-23 and acetone (needs work)
- Future?: HFC-134a, C₂H₄, SO₂, NH₃, PAN, propane, BrONO₂, ClO, HOCl, CH₃CN, CH₃CHO...

- also many isotopes

Boone and Bernath, 2009:
The Atmospheric Chemistry Experiment: status and latest results, 5th Atmospheric Limb Conference and Workshop
Other tropospheric hydrocarbons measured by ACE-FTS

**Ethane C$_2$H$_6$**  
lifetime: 2 months  
short-lived species have sharper cross-tropopause gradients

**Acetylene C$_2$H$_2$**  
lifetime: 2 weeks

**Hydrogen cyanide HCN**  
lifetime: years  
min due to ocean loss  
• but loss due to contact with ocean

Park et al., 2013, J. Geophys. Res.
Different hydrocarbons are often correlated, because of common sources (i.e. combustion). ACE-FTS data are ideal to study these relationships.

Park et al., 2013, J. Geophys. Res.

Ratios of tracers with different lifetimes can characterize photochemical age of air.
In the tropical upper troposphere, CO is closely linked with convective outflow.
Seasonal cycle in upper troposphere
deep tropics 15° N-S: semiannual variation of CO at 13 km (level near convective outflow)

Park et al., 2013, J. Geophys. Res.
Note: often useful to analyze observational data in combination with model results

Park et al., 2013, J. Geophys. Res.
Model also captures horizontal structure

147 hPa observations

WACCM simulation

Park et al., 2013, J. Geophys. Res.
Definitions of the tropopause

• Lapse rate tropopause (WMO definition)

• Cold point (most relevant in the tropics)

• Specific value of potential vorticity (PV=2-4)

  advantage: continuously valued, useful for dynamics/transport studies

  disadvantage: requires meteorological analysis; cannot calculate from temp profiles alone
What processes maintain the tropopause?

**tropics:**

- Lapse rate from radiative-convective equilibrium
- Mean upwelling
- Cold point tropopause \( \sim 17 \text{ km} \)
- Main convective outflow \( \sim 12 \text{ km} \)

*e.g. Thuburn and Craig 2000*
What processes maintain the tropopause?

extra-tropics:

Formation and maintenance of the extratropical tropopause by baroclinic eddies

Peter Haynes, 1 John Scinocca, 2 and Michael Greenslade 1

GRL 2001

‘stirring effect of baroclinic eddies acting against a smooth thermal relaxation’

Colors: lapse rate  dashed lines: PV

relaxation state

equilibrium with baroclinic eddies

baroclinic eddies organize flow to give a sharp vertical and horizontal transitions
Cross-section of extratropical UTLS

**Questions:**

• Large-scale transport and mixing (when, where and how?)

• Seasonal and interannual variability (processes and trends)

• Monsoonal circulations (especially Asian summer monsoon)

• Influences of deep convection (continental and tropical)

Gettelman et al 2011
Transport and mixing: when, where and how?

Research aircraft measurements near large tropopause fold

START08 experiment, Pan et al, 2009-2007
Using tracer correlations to understand the chemical transition region

Zahn et al 2000
Hoor et al 2002
Pan et al 2004
Example for individual profile (aircraft measurements):

Pan et al 2004
Where is the mixing layer compared to the tropopause?

result: mixing layer ~2 km think, centered near tropopause

Pan et al., 2004, J. Geophys. Res.
tracer correlations from ACE-FTS satellite data

identifying the mixing layer from $O_3 - H_2O$ correlations

vertical profile of mixing layer

but note vertical resolution of ACE-FTS ~ 2-3 km

Hegglin et al 2009
Using tracer correlations to identify spatial structure of mixing

mixing identified in tracer correlations

thin mixing layer
cyclonic (poleward) side of jet

broad mixing layer on cyclonic (poleward) side of jet

Pan et al, 2007
Transport pathways and signatures of mixing in the extratropical tropopause region derived from Lagrangian model simulations


2011, JGR

**Observations**

**CLaMS simulations**

Simulation of tracer correlations is a sensitive test for model transport calculations.
Transport pathways and mixing deduced from CLaMS
Lagrangian transport model

Vogel et al, 2011, JGR
Key points:

• Tropical tropopause ~ 17 km, convective-radiative balances

• Extratropical tropopause ~ 8-10 km, baroclinic eddies

• Strong chemical gradients demonstrate distinct air masses across tropopause

• Tropical transport to the upper troposphere via deep convection

• Chemical tracers are a powerful tool to diagnose transport and mixing (e.g. spatial structure of mixing layers)

Next: two interesting aspects of the tropopause:

1) double tropopauses

2) tropopause inversion layer
Extratropical temperature profiles often have multiple tropopauses.

**WMO (1957) tropopause definition:**

If above the first tropopause the average lapse rate between any level and all higher levels within 1 km exceeds 3°C/km, then a second tropopause can occur.

Randel et al., 2007, J. Geophys. Res.
**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
statistical distribution of tropopause heights from radiosondes at Charleston 1950-2003
Location of double tropopauses for one day (ERA40 data)

red lines: PV = 1, 2, 3, 4 at 200 hPa (tropopause)

Randel et al., 2007, J. Geophys. Res.
Not a new result: Bjerknes and Palmen (1937); Kochanski (1955); Shapiro (1978), .......

Tropopause structure associated with developing baroclinic wave

Shapiro, 1978 1981

double tropopause
seasonal variation of profiles with multiple tropopauses

maximum during winter

2 trops

3 trops

good agreement between radiosondes and GPS

GPS climatology: percent of winter (DJF) soundings with a double tropopause

maximum in subtropics

Randel, Seidel and Pan, JGR, 2007
Climatological height of tropopauses from GPS data

Randel et al., 2007, J. Geophys. Res.
Cross-section near Charleston

suggestive of transport from tropics

static stability $N^2$

Randel et al., 2007, J. Geophys. Res.
Double tropopauses and tropospheric intrusions

Pan et al, JGR, 2009
Differences in ozone for single vs. double tropopause derived from SAGE II satellite data

Consistent pattern of less ozone for double tropopauses

Randel et al., 2007, J. Geophys. Res.
Aircraft measurements during START08 experiment:

Blue: region of tropospheric intrusion

Double tropopause with low lapse rate and low ozone

Pan et al., 2010, Bull. Amer. Meteor. Soc.
Key points:

- double tropopauses occur frequently in subtropics, especially during winter
- thermal and chemical structure consistent with intrusions from tropics above subtropical jets
Double tropopause formation in idealized baroclinic life cycles: The key role of an initial tropopause inversion layer

S. Wang and L. M. Polvani

JGR 2011

Idealized LC1 life cycle

model generates double tropopause (red), but in air moving from high latitudes

* different from observations

???
The tropopause inversion layer (TIL)

average vertical structure from high-resolution radiosondes near 45° N, calculated using ground-based and tropopause-based coordinates
examples using GPS data in tropopause-based coordinate

Randel et al, JAS, 2007

height relative to tropopause

temp

stability

layer of high stability
Climatology of inversion layer from GPS data

N² in tropopause coordinates

DJF

JJA

summer polar maximum

Randel et al, JAS, 2007
What causes the inversion layer?

- dynamics?
- cyclone / anticyclones asymmetries?
- radiation or other process?

Profiles of $N^2$ for idealized cyclonic and anticyclonic circulations, in tropopause-relative coordinates

Wirth 2003
Balanced dynamical structure (Hoskins et al. 1985)

Cyclonic

- Isentropes
- Winds
- Warm
- Cold
- Low tropopause

Anti-cyclonic

- High tropopause
- Warm

Strong stability (inversion layer)
Study the dependence of tropopause statistics on UTLS circulation

-> segregate GPS soundings according to 200 hPa vorticity

200 hPa relative vorticity Jan 2, 2002

GPS soundings
dependence of tropopause height on vorticity

![Graph showing the distribution of vorticity and its relationship with the number of observations for cyclones and anticyclones.](a)

![Graph showing the height of LRT1 as a function of vorticity for cyclones.](b) lower LRT1 for cyclones
profiles binned according to vorticity (~2500 total)

(to test hypothesis that climatological inversion layer due mainly to anticyclones)

Randel et al., 2007, J. Atmos. Sci.
strength of the inversion vs. circulation

\[ T(Z_{LRT1} + 2\text{km}) - T(Z_{LRT1}) \]

Result: inversion exists for cyclones (weaker) and anti-cyclones (stronger)

systematically stronger for anticyclonic flow

Randel et al, JAS, 2007
How do radiative processes contribute to the inversion layer?

Vertical profiles in tropopause coordinates

What is the radiative effect of transition layer?

temp changes due to observed H₂O and O₃ (compared to hypothetical dashed curves)

water vapor and ozone both influence thermal structure (especially water vapor near tropopause)

calculations using Fixed Dynamical Heating (FDH)
e.g. Forster and Shine 1997

Randel et al., 2007, J. Atmos. Sci.
tropopause inversion layer during polar summer

Radiosonde at Eureka (80° N)

- Persistent feature, observed in almost all profiles during summer in both hemispheres (why?)

Radiosondes and nearby COSMIC soundings

COSMIC allows ~100 times more observations than radiosondes, to study space-time variability of inversion layer

Radiosondes and nearby COSMIC GPS soundings

COSMIC allows ~100 times more observations than radiosondes, to study space-time variability of inversion layer.


summer inversion is ubiquitous
Strength of polar tropopause inversion

$$T(z_{trop} + 2\text{km}) - T(z_{trop})$$

daily data from COSMIC, average over polar cap

*COSMIC 70° - 90° N*

8 K

*Arctic*

*COSMIC 70° - 90° S*

8 K

*Antarctic*

summer maximum in both hemispheres

Latitudinal structure of summer inversion

\[ T(z_{\text{trop}} + 2\text{km}) - T(z_{\text{trop}}) \]

Note the remarkable symmetry between hemispheres.

What causes the strong polar inversion layer?

* Water vapor near the tropopause *

Seasonal cycle at tropopause (9 km)

Seasonal vertical profiles

Polar water vapor measurements from ACE-FTS satellite

Radiative response to UTLS water vapor

Fixed Dynamical Heating calculations (e.g. Forster and Shine 1997)

Enhanced water vapor leads to strong cooling near tropopause

- Explains the seasonal cycle, vertical structure and magnitude of the tropopause inversion

Randel and Wu, JAS, 2010
Similar $\text{H}_2\text{O}$ behavior is seen in the Southern Hemisphere

Why does this occur during polar summer?

(a) H$_2$O DJF

(b) Summer DJF Winter

ACE-FTS data

relative vertical gradient in H$_2$O (%/km)

strongest vertical gradients in H$_2$O across tropopause

Hegglin et al 2009
Key points:

• tropopause inversion layer is a ubiquitous feature in extratropics

• evident for cyclones and anticyclones; much stronger for anticyclones (as expected)

• inversion layer strongest over summer poles; remarkable NH-SH symmetry

• radiative calculations show polar inversion layer is a response to strong H\textsubscript{2}O gradients (and suggests this is a mechanism for other regions)
Reference

- Boone, C. and Bernath, P., 2009: The atmospheric chemistry experiment: Status and latest results, 5th Atmospheric Limb Conference and Workshop (Helsinki, Finland, invited talk).
Reference2


Reference