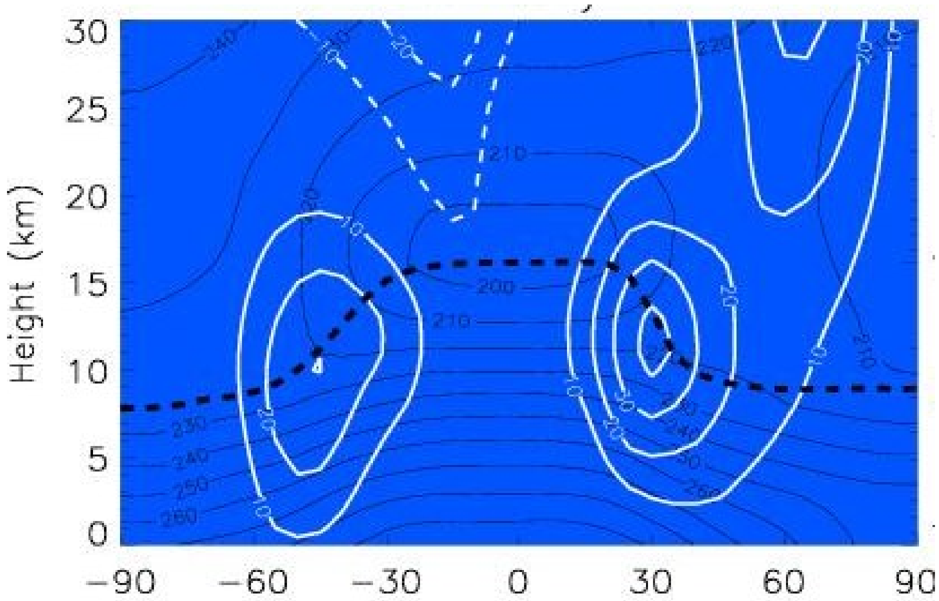
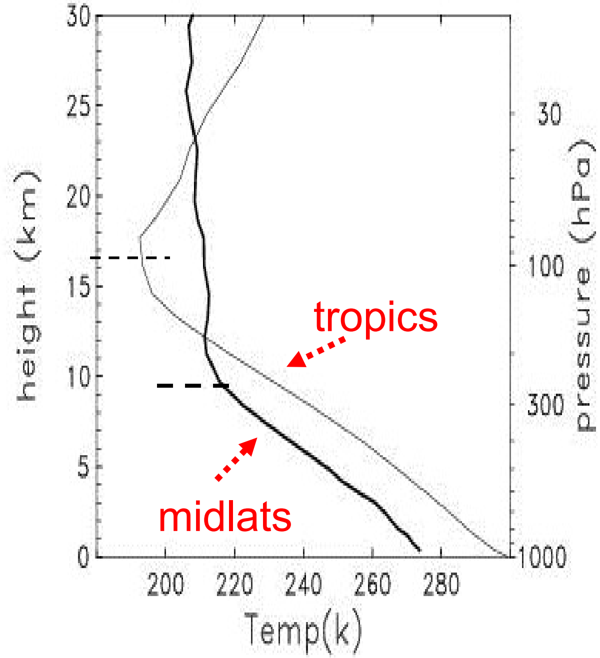
Lecture 3: Global upper troposphere – lower stratosphere (UTLS)

- 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:

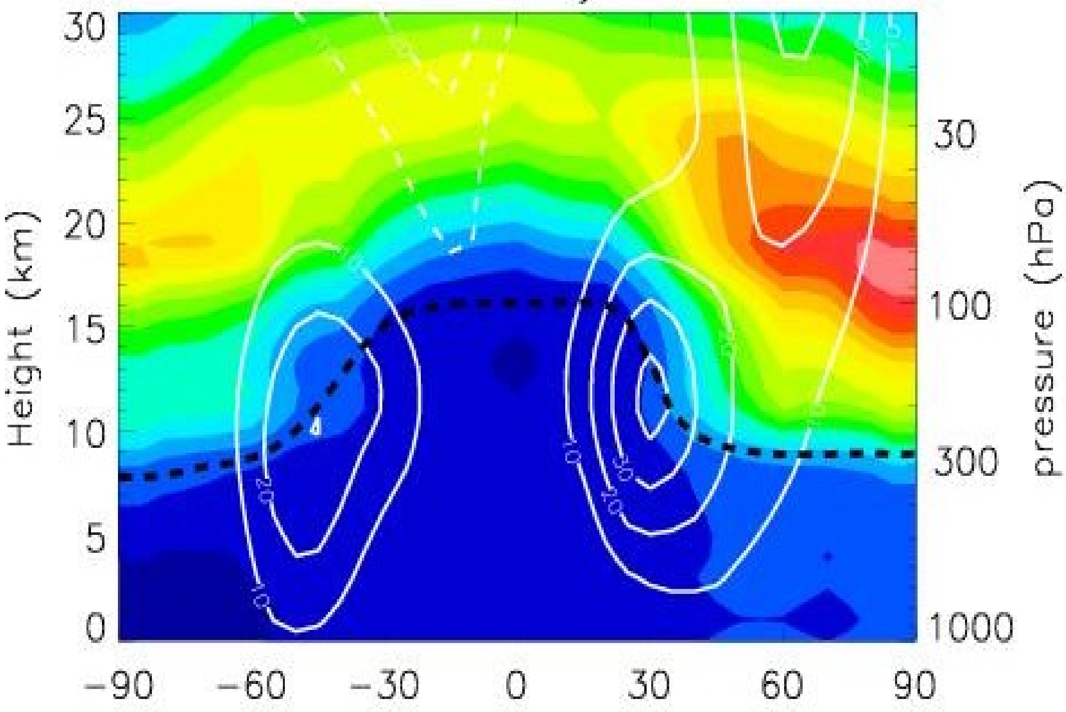
- •Troposphere: vertically well-mixed; via convection and baroclinic instability
- •Stratosphere: dynamically stable (mostly); circulation forced by radiation and forcing from troposphere (upward propagating waves)

Ozone

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

Ozone column density, DU/km

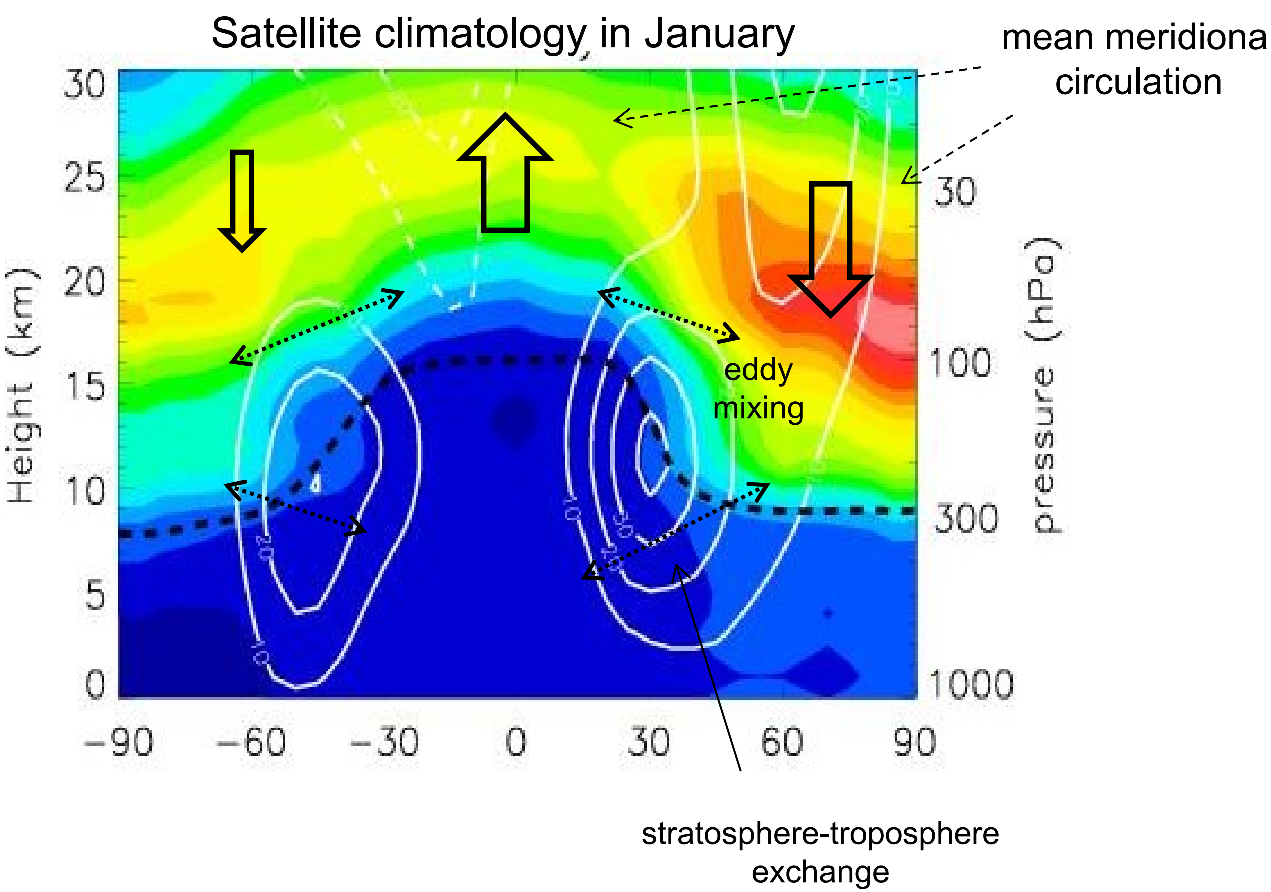
Satellite climatology in January



Ozone

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

Ozone column density, DU/km

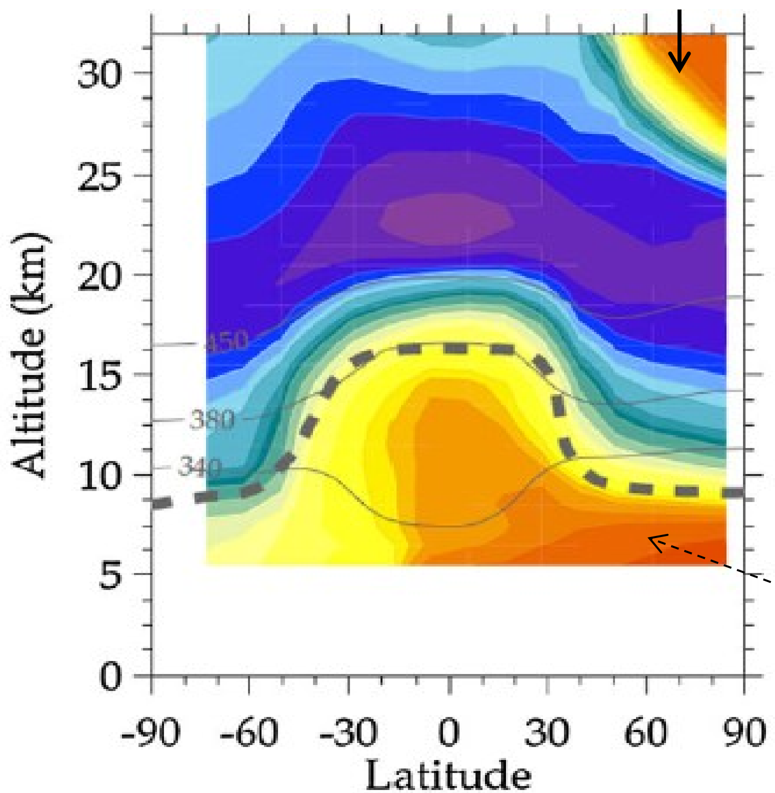


Carbon monoxide (CO)

- 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



main emissions in NH

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

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

H_2O exhibits similar behavior

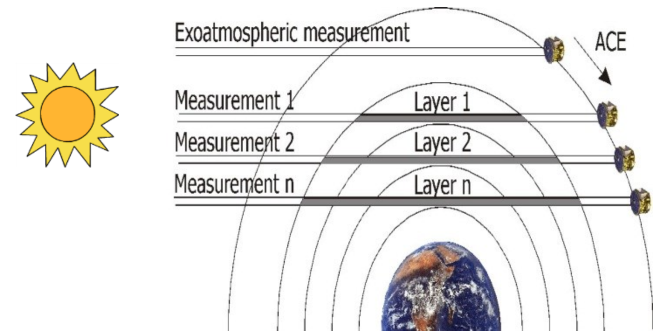
Atmospheric Chemistry Experiment
Fourier Transform Spectrometer (ACE-FTS)

FTS measurements: *2.2 – 13.3 μm*

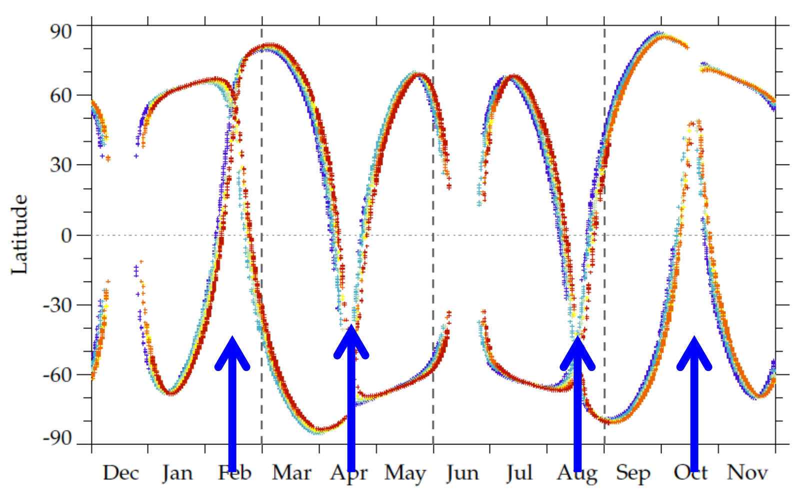
10+ years of data (Feb. 2004 – present)

~ 3,500 occultations /year

Resolution: ~300 km horizontal, 3 km vertical



ACE occultations

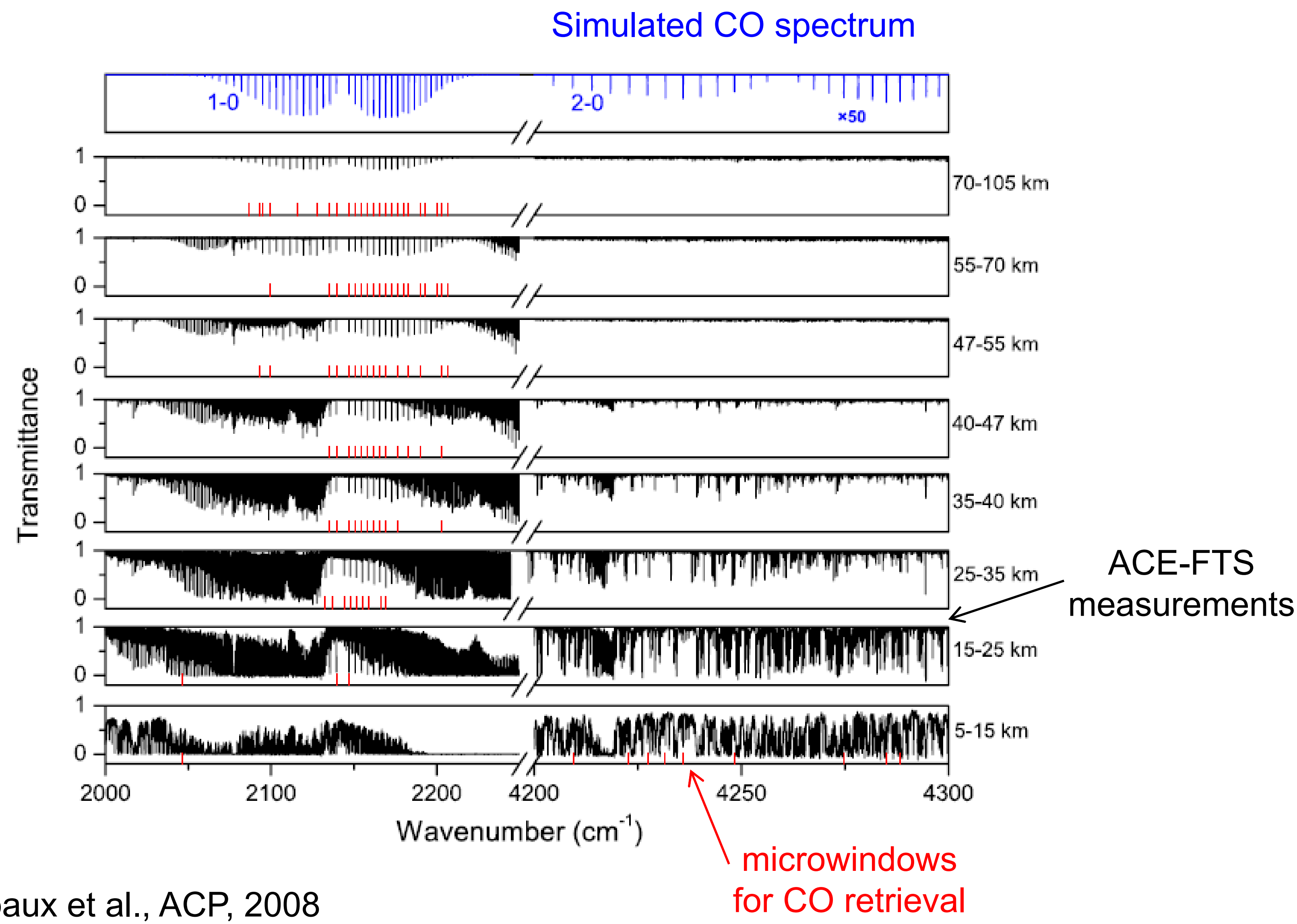


measurement pattern: repeats every year

Low latitudes: 4 samples / year

Randel et al., 2012, J. Geophys. Res.

ACE-FTS measurements and retrievals for carbon monoxide (CO)



Clerbaux et al., ACP, 2008

ACE

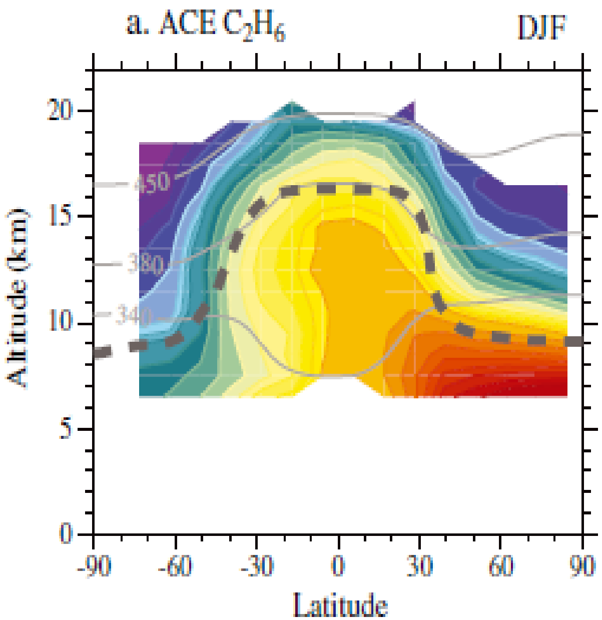
Molecules

- In ACE-FTS version 3.0 (37 molecules): CO_2, H_2O, O_3, N_2O, CO, CH_4, NO, NO_2, HNO_3, HF, HCl, $ClONO_2$, N_2O_5, CFC-11, CFC-12, OCS, HCN, CH_3Cl, CF_4, CCl_4, COF_2, C_2H_2, C_2H_6, CH_3OH, SF_6, HCOOH, HCFC-22, N_2, O_2, CFC-113, HCFC-141b, HCFC-142b, HNO_4, H_2O_2, H_2CO, $COCl_2$, COClF
- New: HFC-23 and acetone (needs work)
- Future?: HFC-134a, C_2H_4, SO_2, NH_3, PAN, propane, $BrONO_2$, ClO, HOCl, CH_3CN, CH_3CHO....
  - also many isotopes

Boone and Bernath, 2009:
The Atmospheric Chemistry Experiment : status and latest results,
5th Atmospheric Limb Conference and Workshop

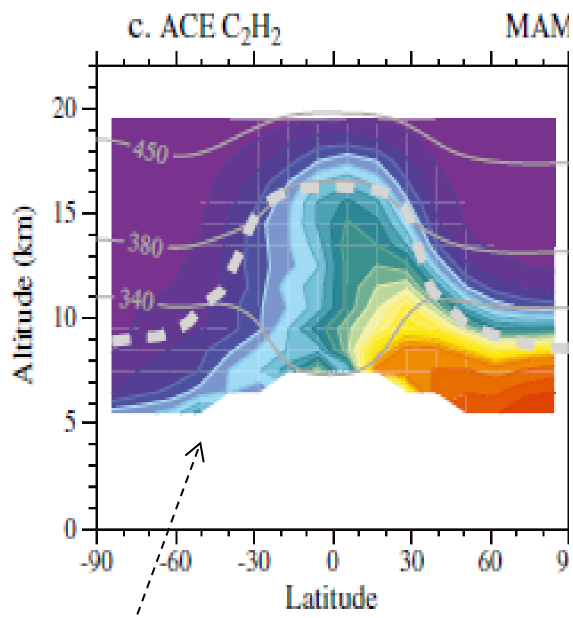
Other tropospheric hydrocarbons measured by ACE-FTS

Ethane C_2H_6



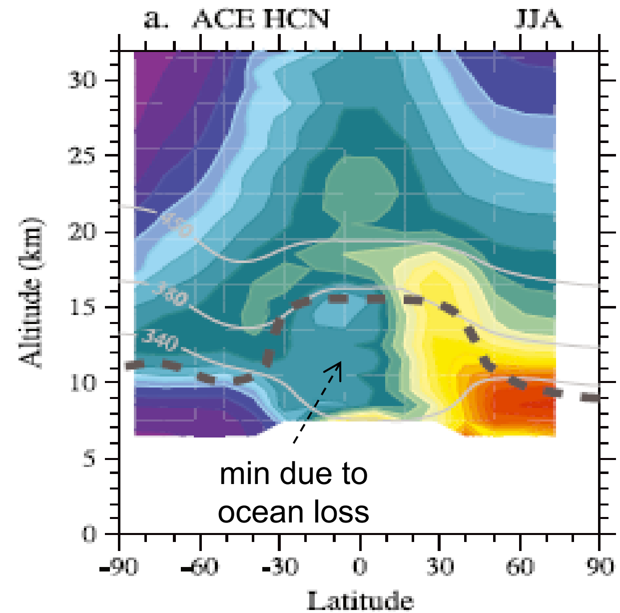
lifetime: 2 months

Acetelyne C_2H_2



lifetime: 2 weeks

Hydrogen cyanide HCN



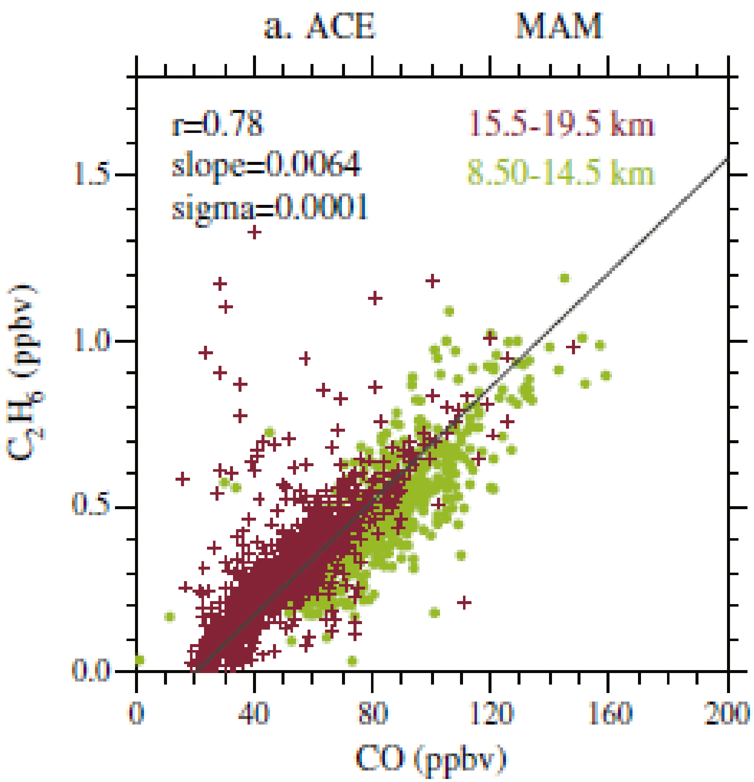
lifetime: years

short-lived species have sharper cross-tropopause gradients

- but loss due to contact with ocean

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

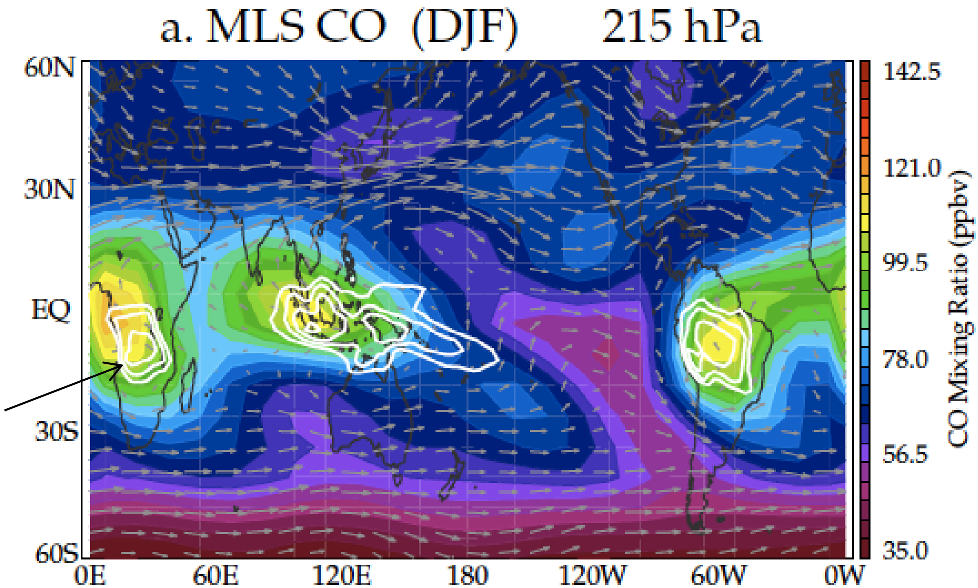
Different hydrocarbons are often correlated, because of common sources (i.e. combustion). ACE-FTS data are ideal to study these relationships.



ratios of tracers with different lifetimes can characterize photochemical age of air

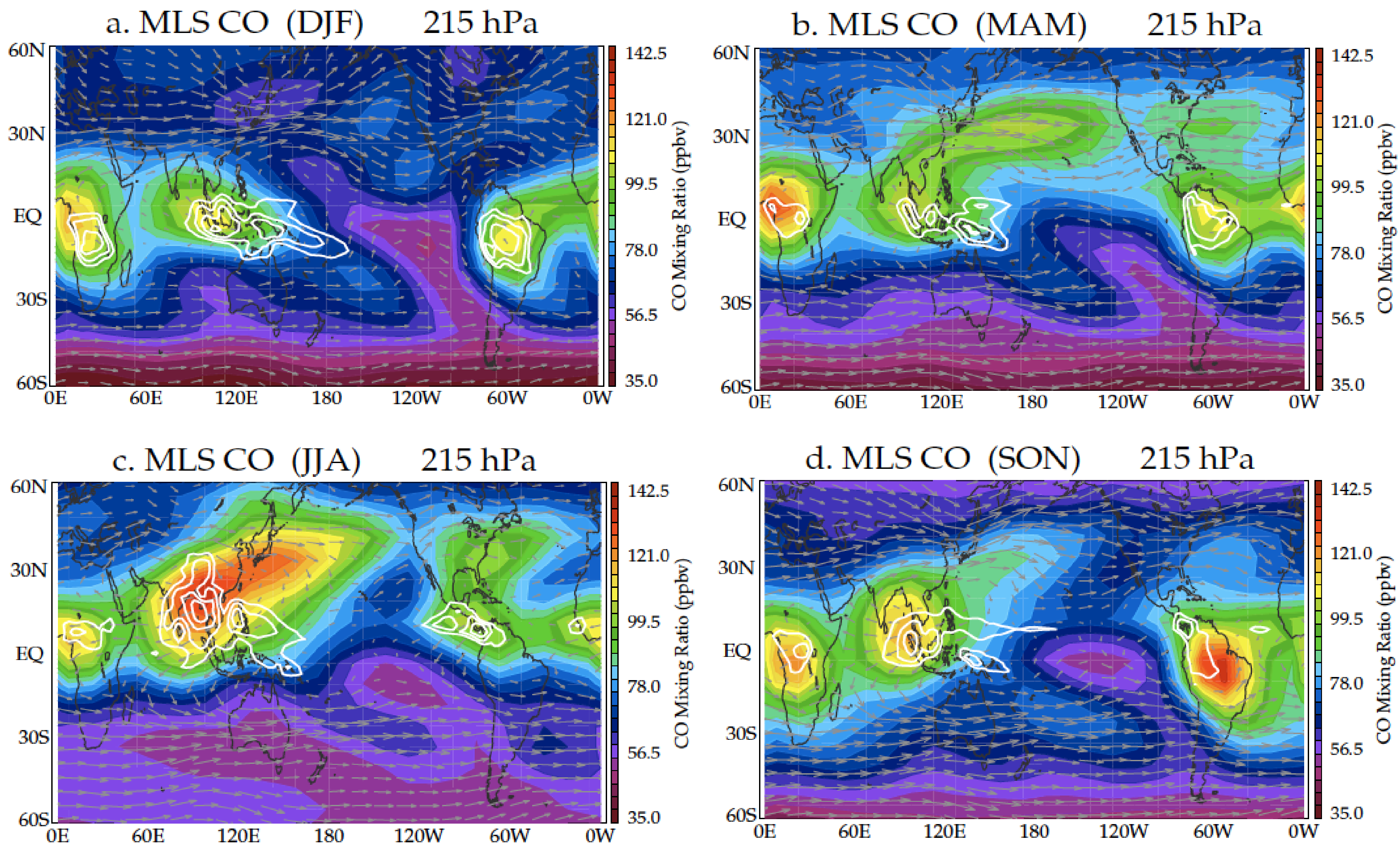
Park et al., 2013, J. Geophys. Res.

In the tropical upper troposphere, CO is closely linked with convective outflow



white lines: climatological deep convection

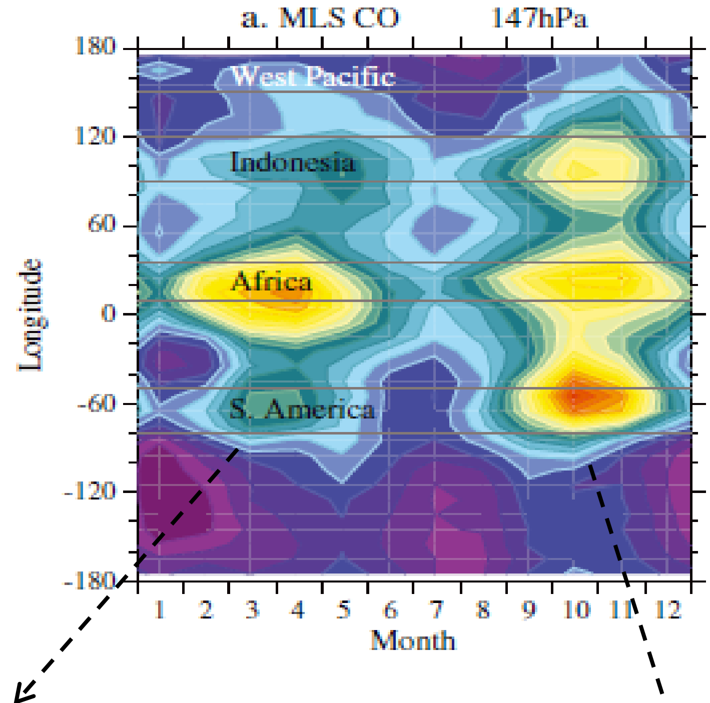
Seasonal cycle in upper troposphere

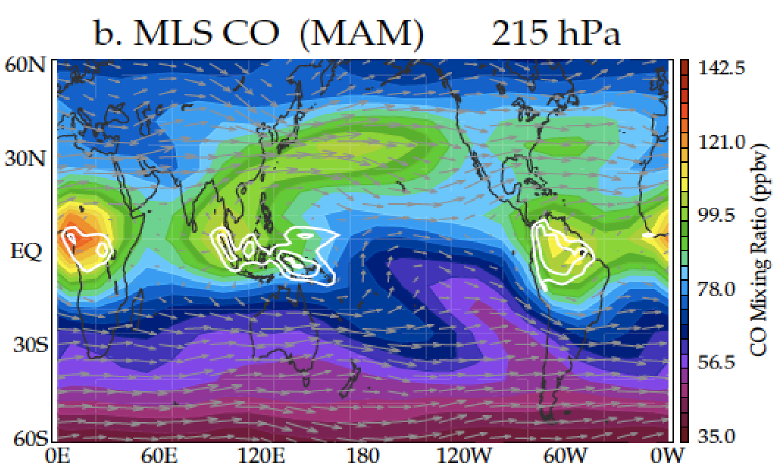


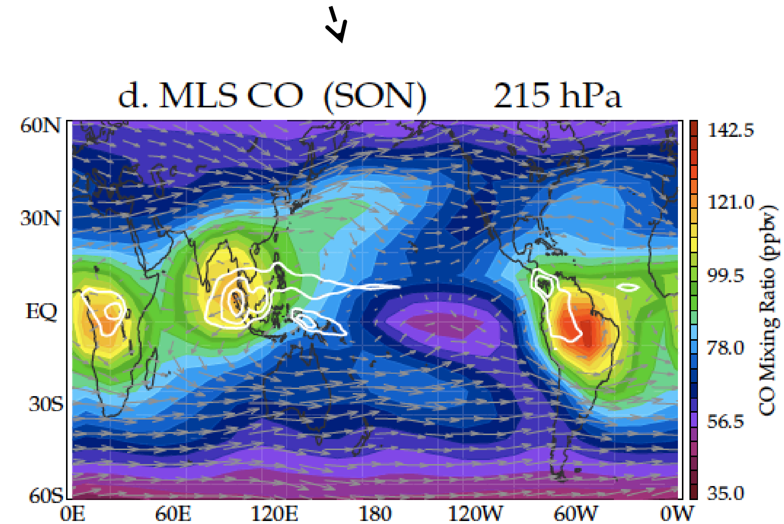
deep tropics 15^{o} N-S:
semiannual variation
of CO at 13 km

(level near
convective outflow)

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

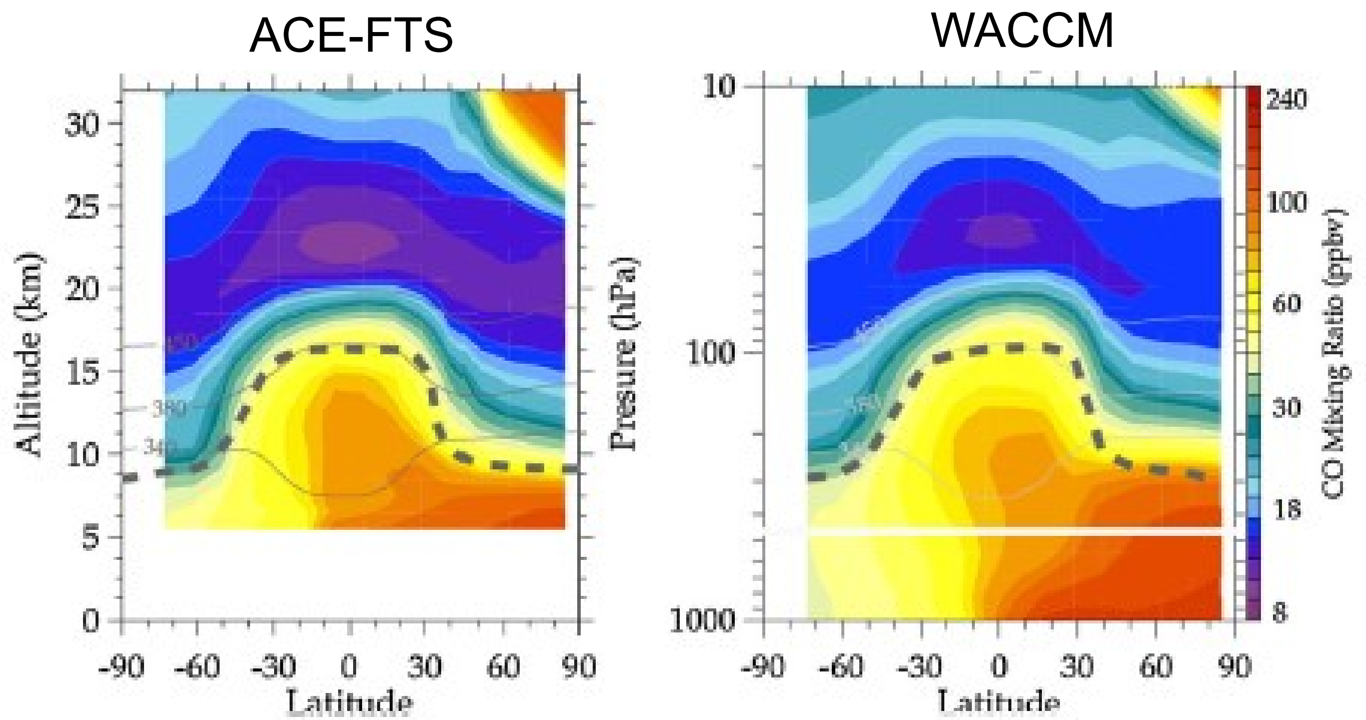






<u>WACCM simulation of CO</u>

model includes observed emissions
and full tropospheric chemistry

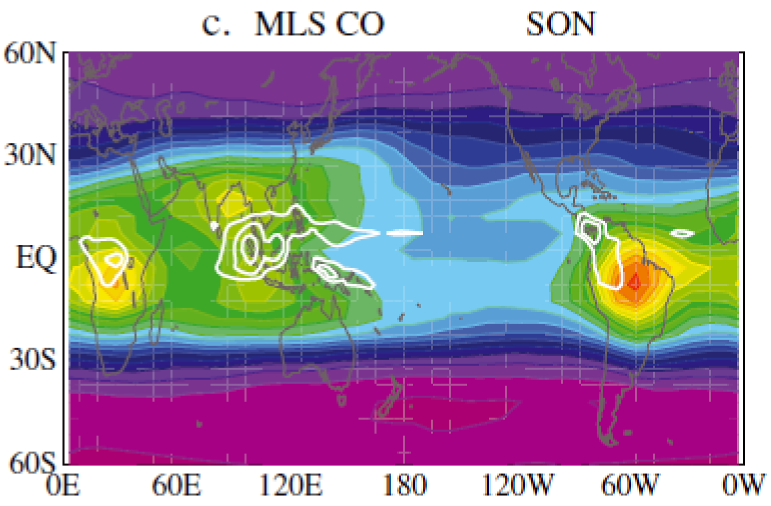


Note: often useful to analyze observational data in combination with model results

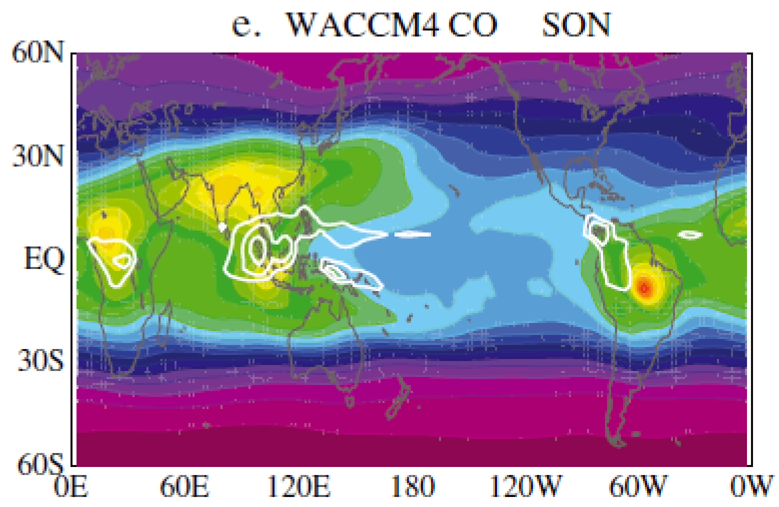
Park et al., 2013, J. Geophys. Res.

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)

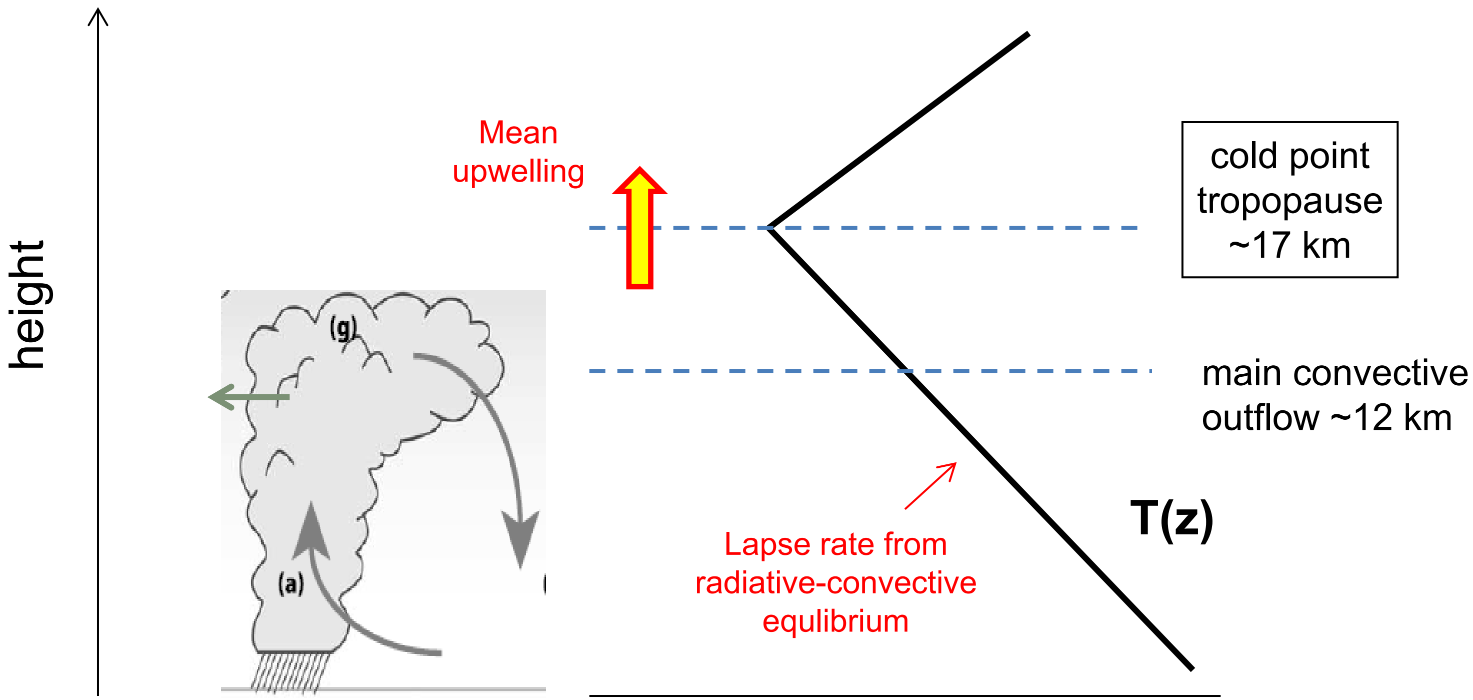
•Specific value of potential vorticity (PV=2-4)

advantage: continuously valued, useful for dynamics/transport studies

disadvantage: requires meteorological analysis; cannot calculate from temp profiles alone

What processes maintain the tropopause?

tropics:



e.g. Thuburn and Craig 2000

What processes maintain the tropopause?

Formation and maintenance of the extratropical tropopause by baroclinic eddies

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

GRL 2001

extra-tropics:

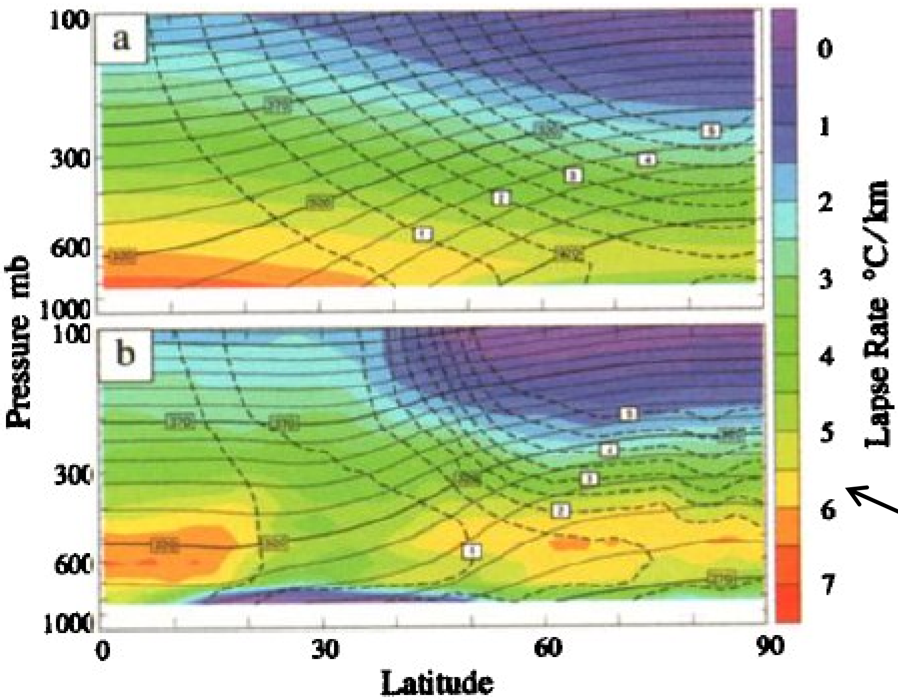
↓

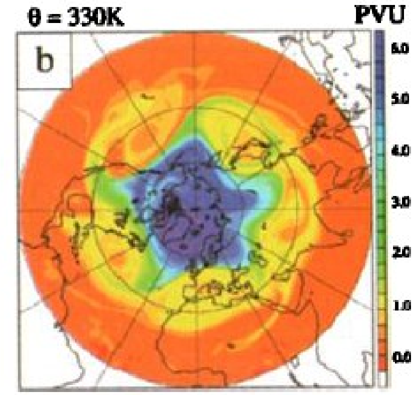
'stirring effect of baroclinic eddies acting against a smooth thermal relaxation'

Colors: lapse rate dashed lines: PV

relaxation state

equilibrium with baroclinic eddies

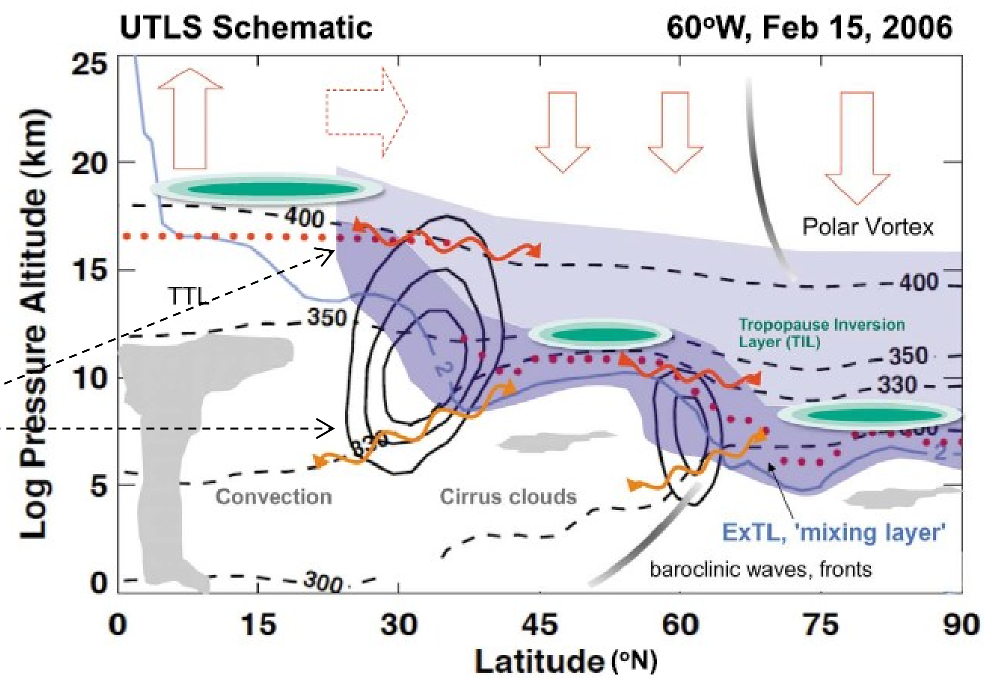




baroclinic eddies organize flow to give a sharp vertical and horizontal transitions

Cross-section of extratropical UTLS

mixing above and below jet, but not across jet core



Gettelman et al 2011

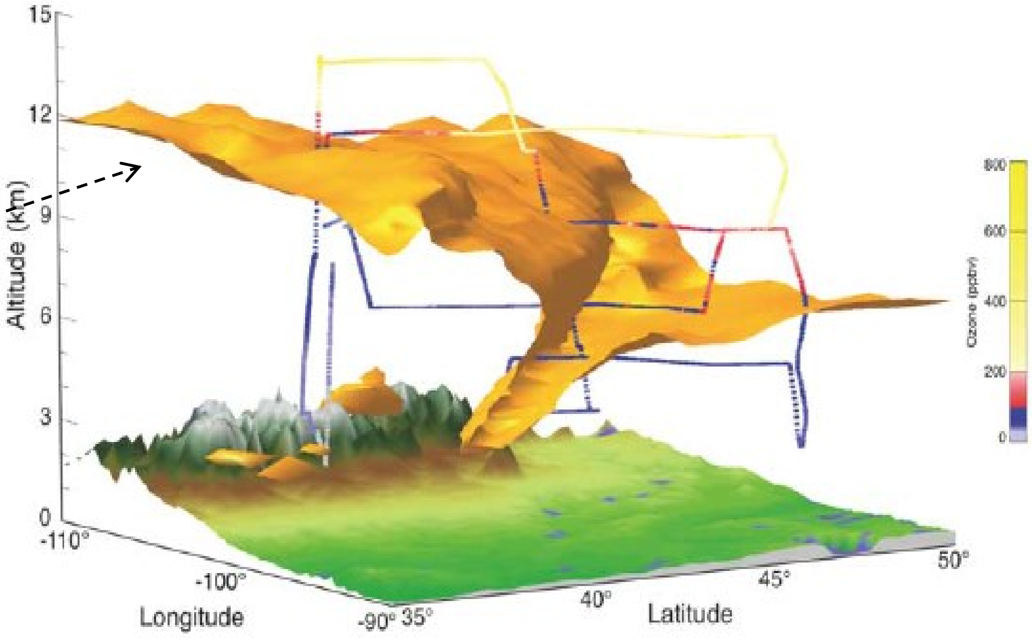
Questions:

- Large-scale transport and mixing (when, where and how?)
- Seasonal and interannual variablity (processes and trends)
- Monsoonal circulations (especially Asian summer monsoon)
- Influences of deep convection (continental and tropical)

Transport and mixing: when, where and how?

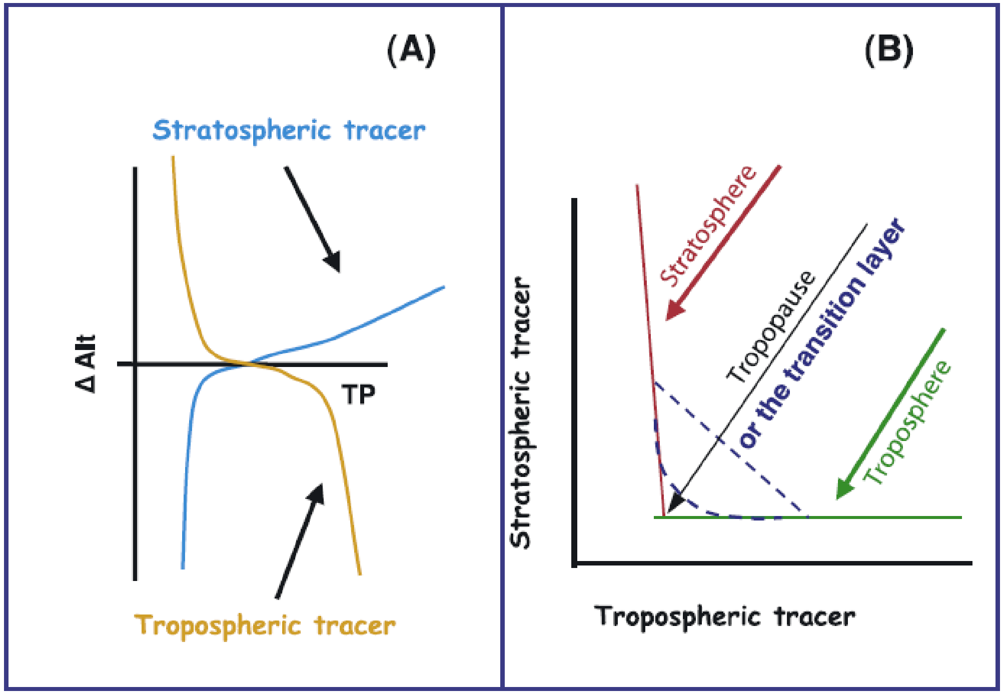
Research aircraft measurements near large tropopause fold

PV=2
isosurface



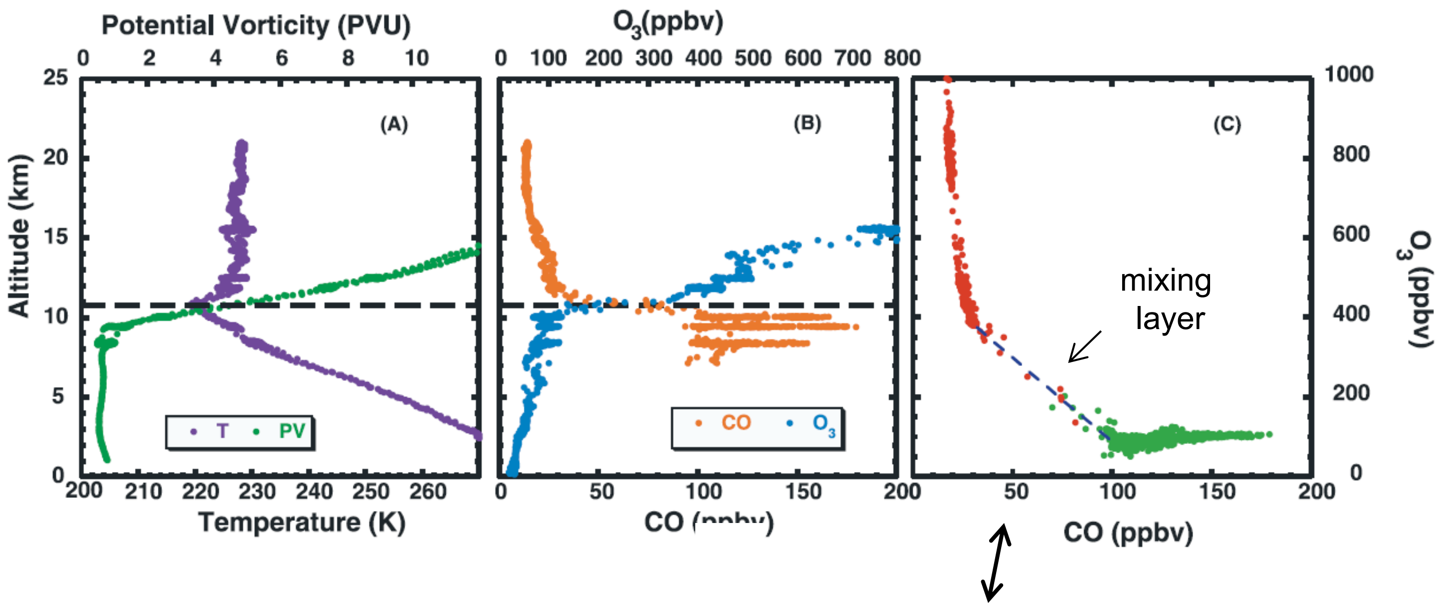
START08 experiment, Pan et al, ~~2009~~ 2007

Using <u>tracer correlations</u> to understand the chemical transition region

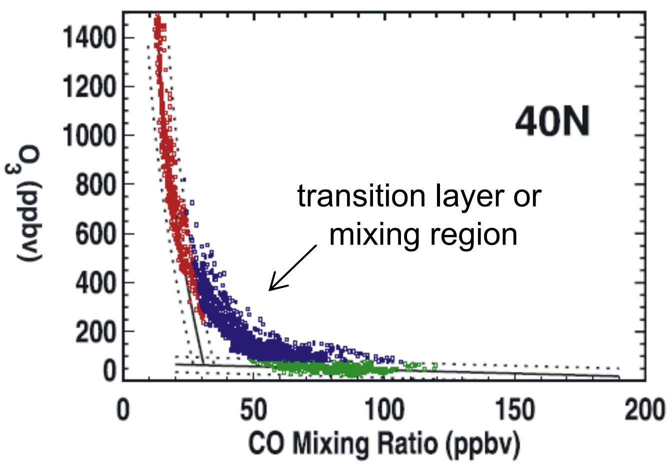


Zahn et al 2000
Hoor et al 2002
Pan et al 2004

Example for individual profile (aircraft measurements):



statistics from many profiles:

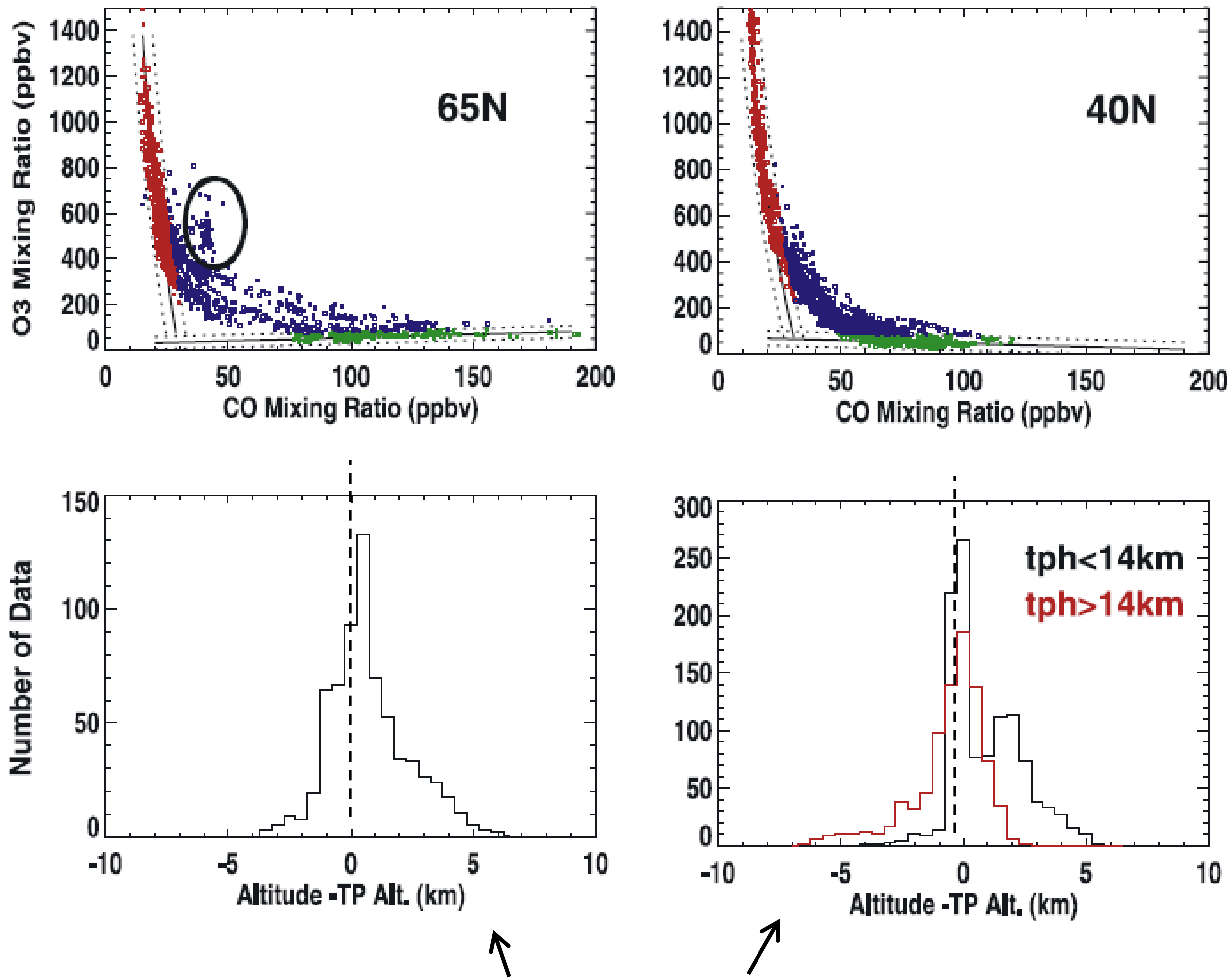


Pan et al 2004

Where is the mixing layer compared to the tropopause?

identify mixing layer

distribution of mixing layer wrt tropopause

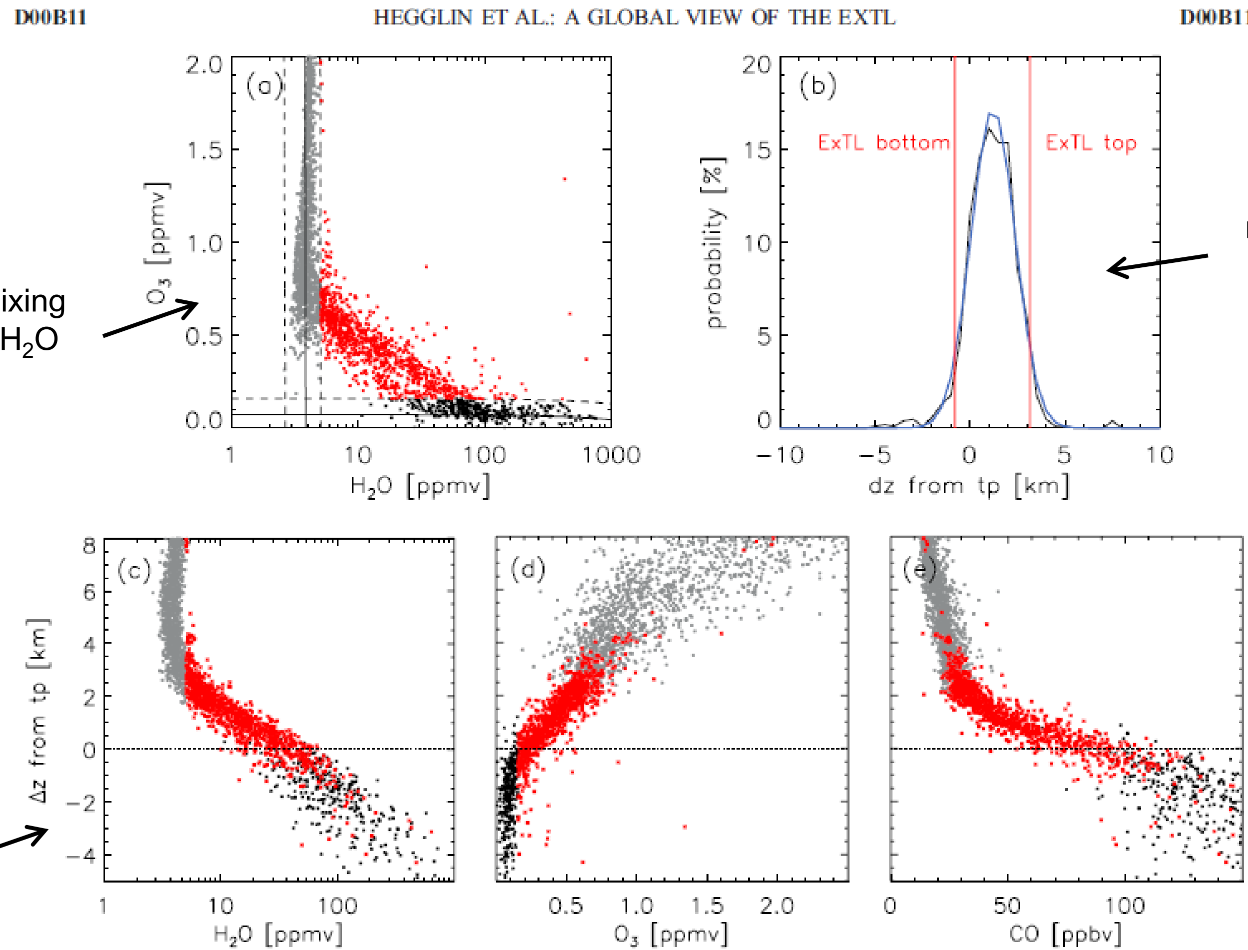


result: mixing layer ~2 km think, centered near tropopause

Pan et al., 2004, J. Geophys. Res.

tracer correlations from ACE-FTS satellite data

identifying the mixing layer from O_3 – H_2O correlations



location of mixing layer wrt tropopause

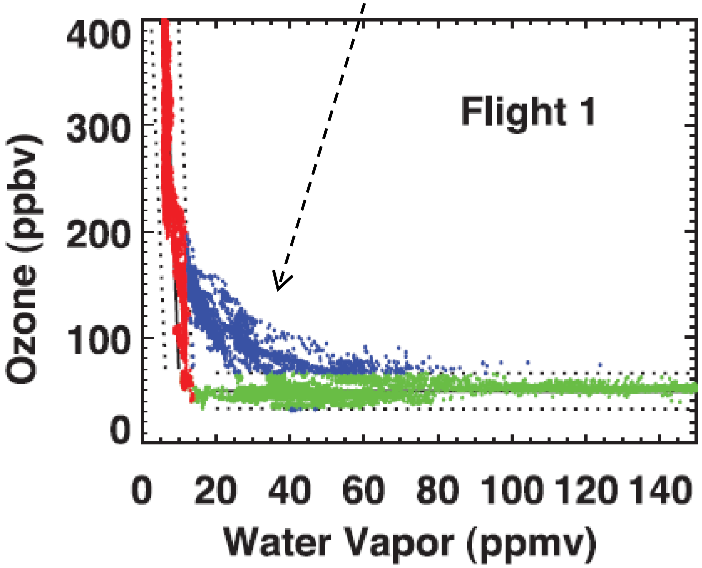
vertical profile of mixing layer

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

Hegglin et al 2009

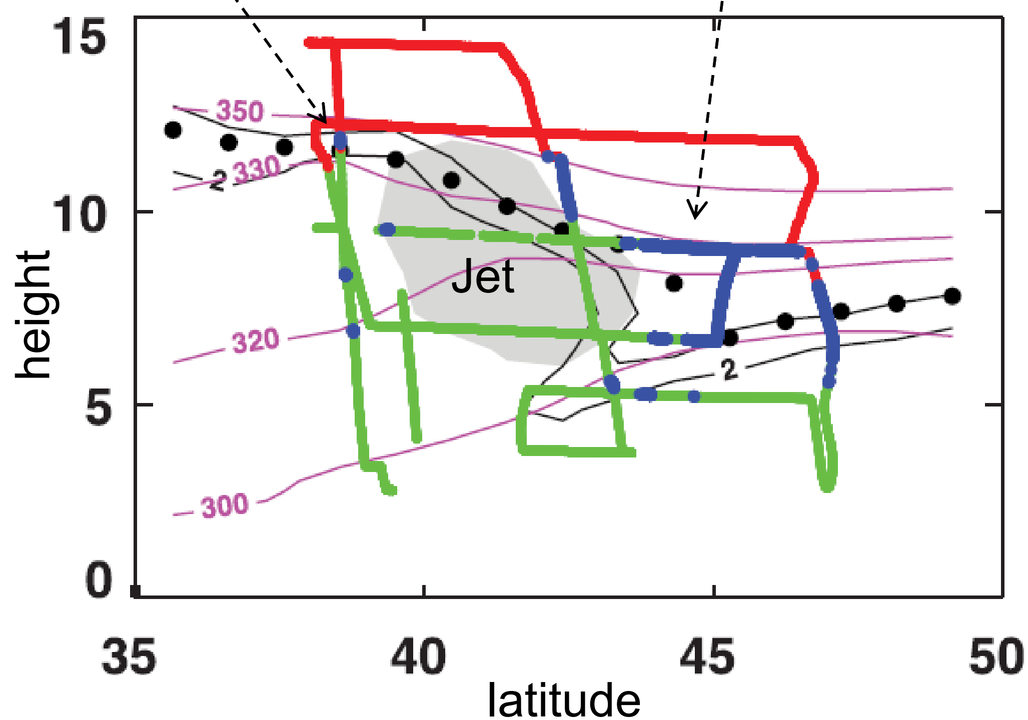
Using tracer correlations to identify spatial structure of mixing

mixing identified in tracer correlations



thin mixing layer

broad mixing layer on cyclonic (poleward) side of jet



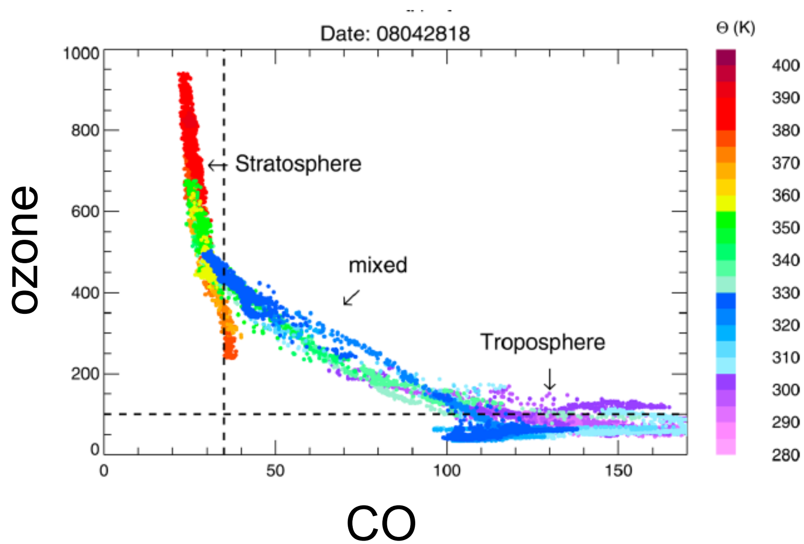
Pan et al, 2007

Transport pathways and signatures of mixing in the extratropical tropopause region derived from Lagrangian model simulations

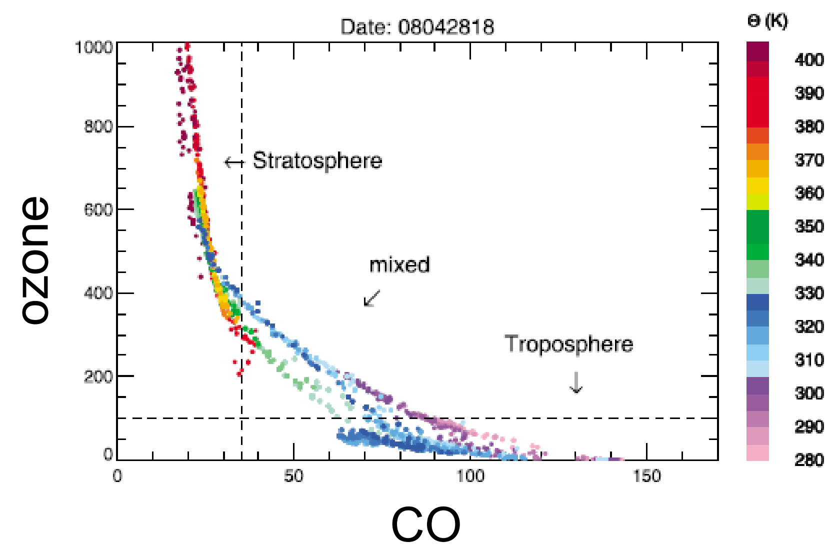
B. Vogel,[1] L. L. Pan,[2] P. Konopka,[1] G. Günther,[1] R. Müller,[1] W. Hall,[2] T. Campos,[2] I. Pollack,[2,3] A. Weinheimer,[2] J. Wei,[4,5] E. L. Atlas,[6] and K. P. Bowman[7]

2011, JGR

observations



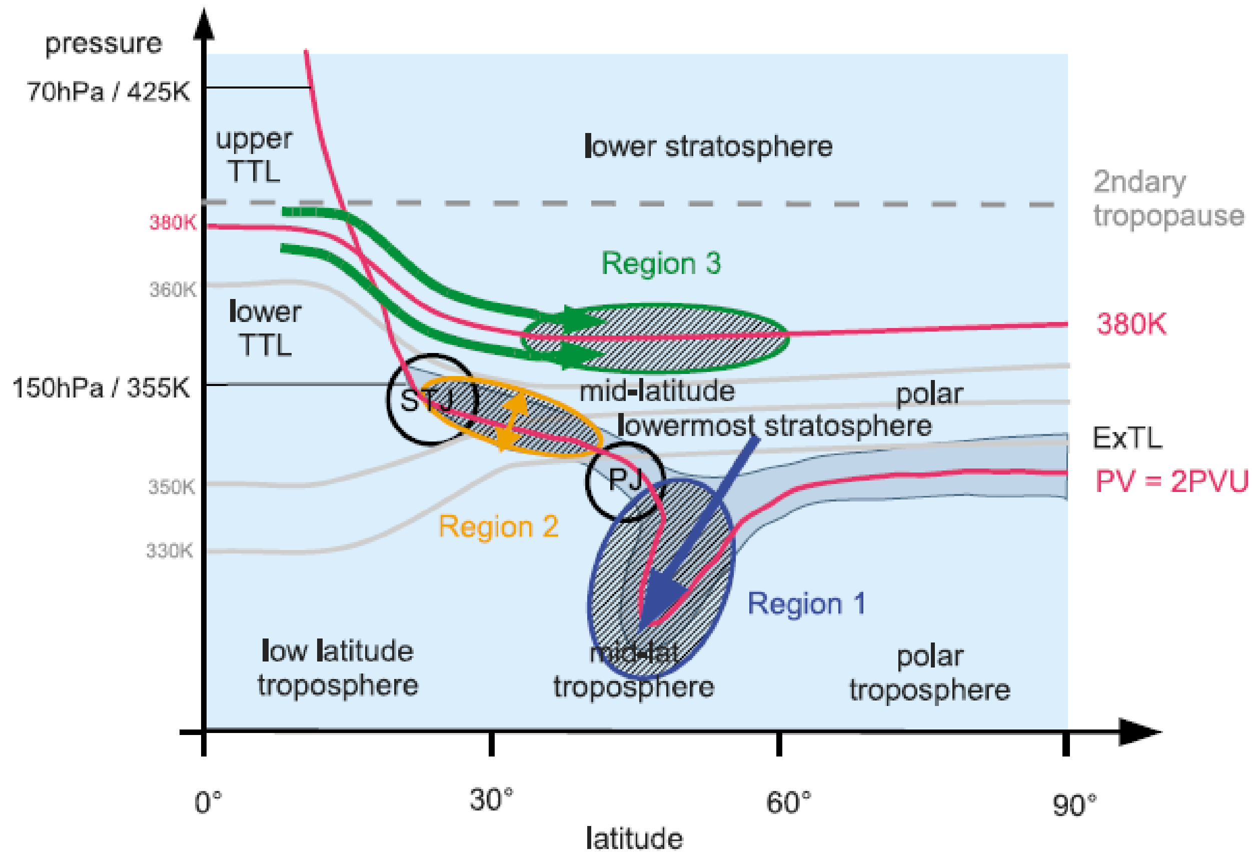
CLaMS simulations



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

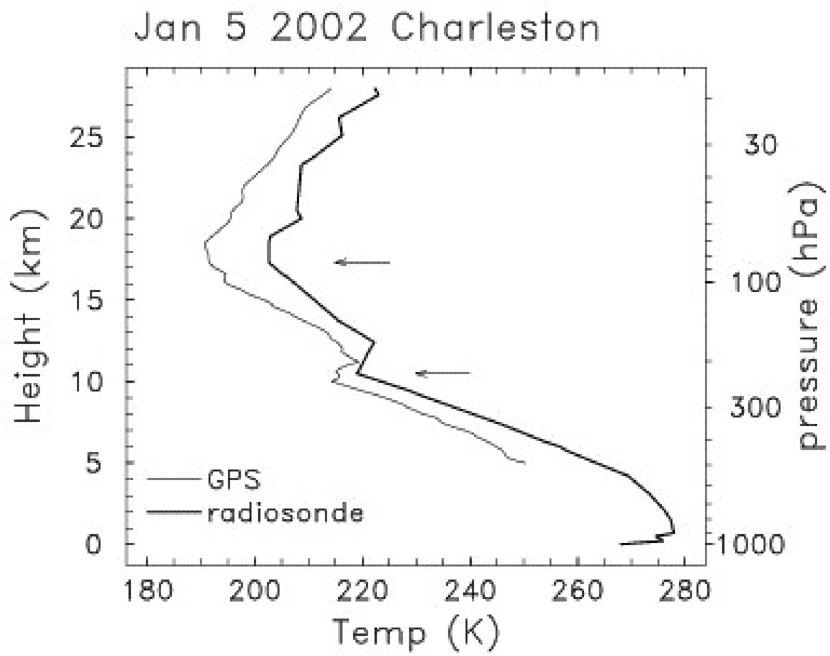
•Chemical tracers are a powerful tool to diagnose transport and mixing
(e.g. spatial structure of mixing layers)

Next: two interesting aspects of the tropopause:

1)double tropopauses

2)tropopause inversion layer

Extratropical temperature profiles often have multiple tropopauses



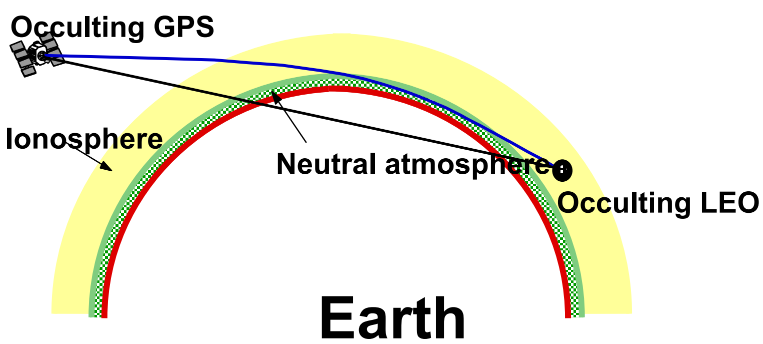
Randel et al., 2007, J. Geophys. Res.

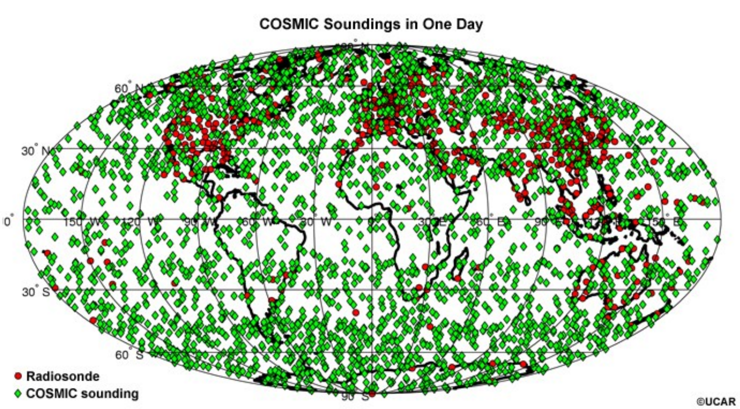
WMO (1957) tropopause definition:

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.

<u>GPS radio occultation</u>

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

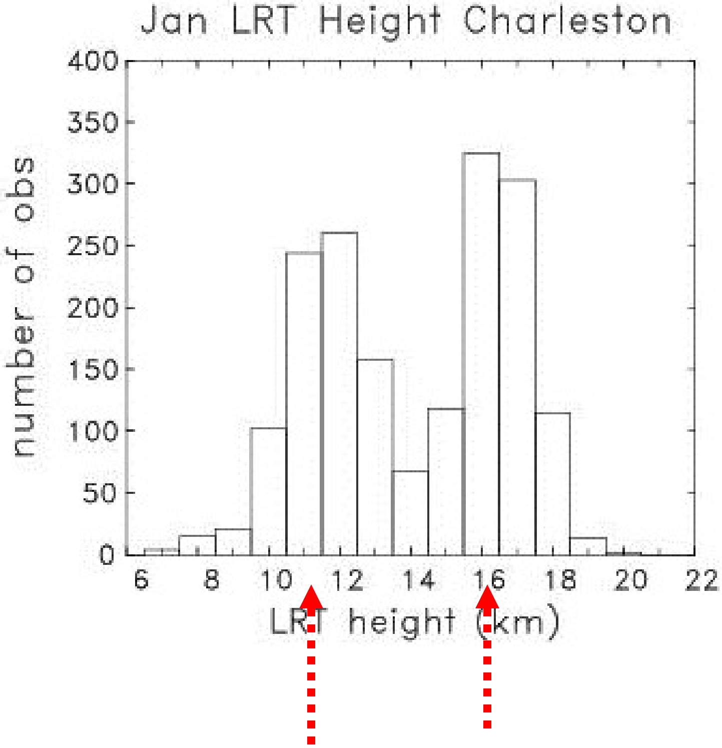




Utility of GPS Radio Occultation:

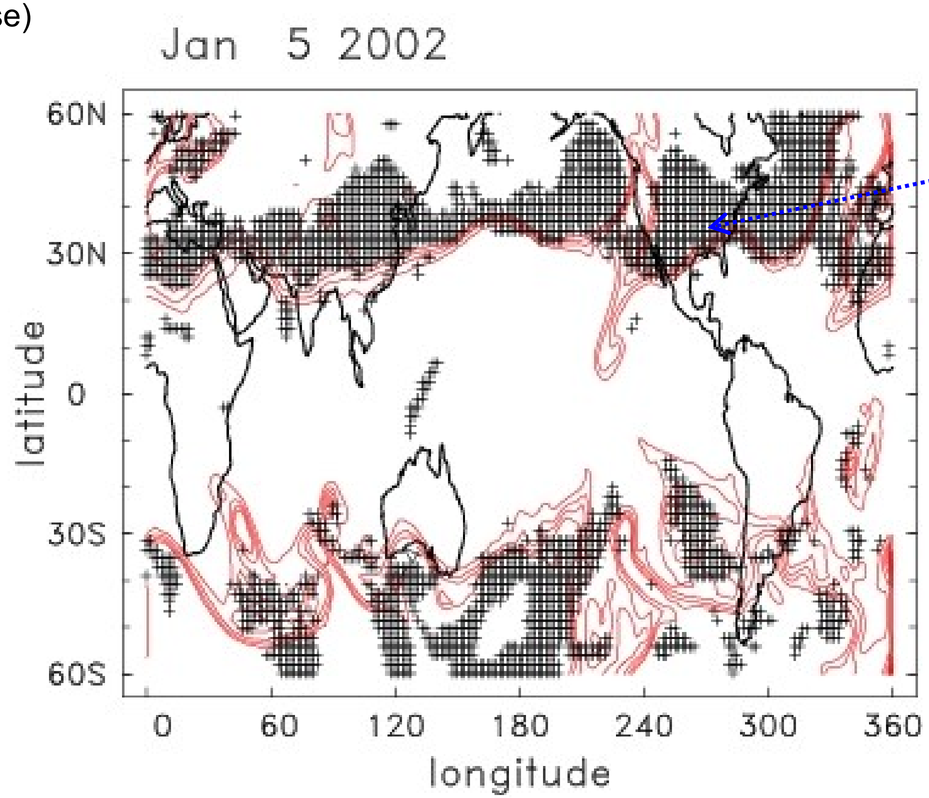
- Long-term stability
- All-weather operation
- High vertical resolution (< 1 km)
- High accuracy: Averaged profiles to < 0.1 K

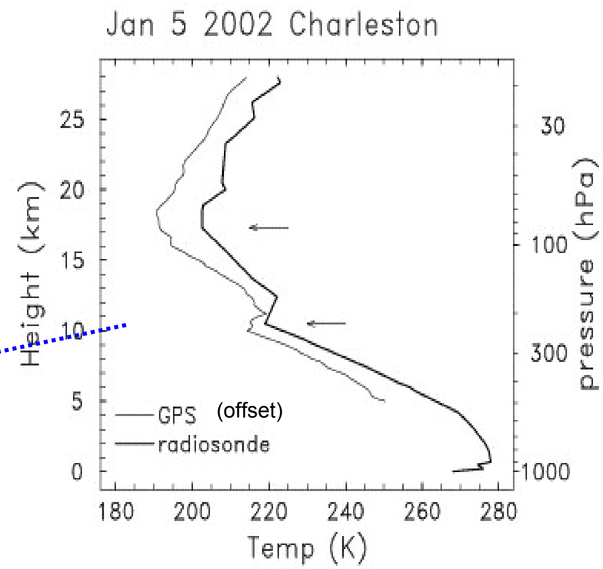
statistical distribution of tropopause heights from radiosondes at Charleston 1950-2003



Location of double tropopauses for one day (ERA40 data)

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



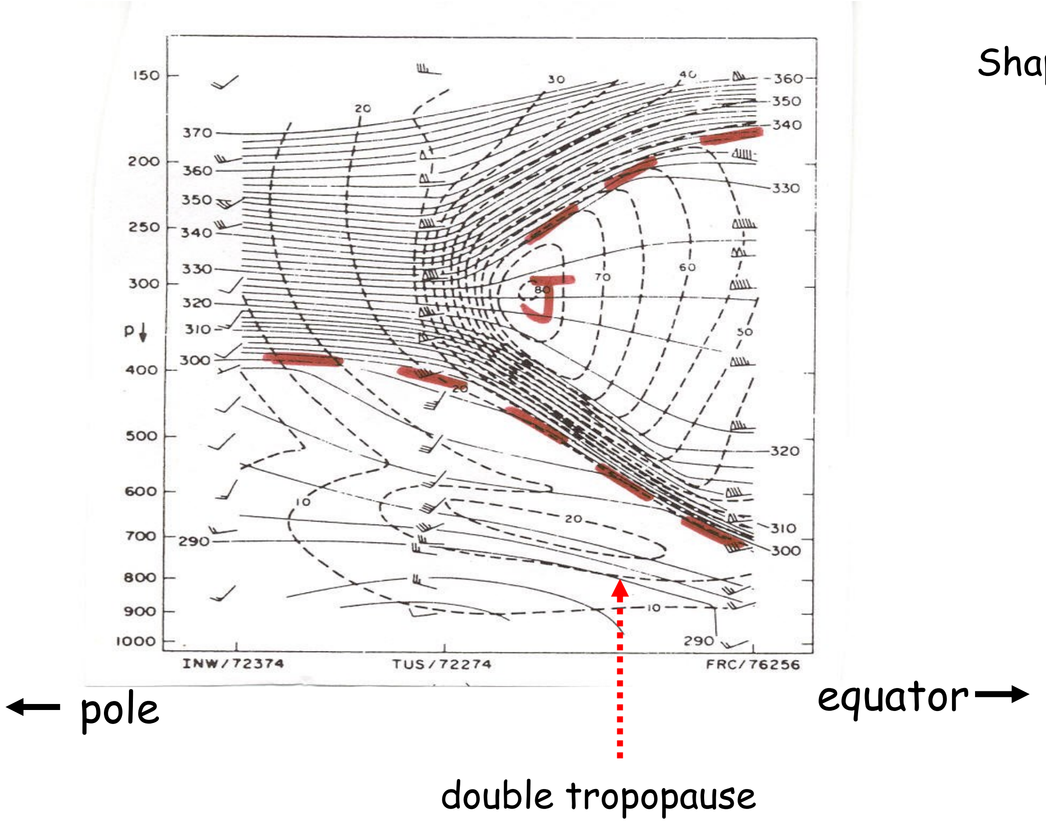


Randel et al., 2007, J. Geophys. Res.

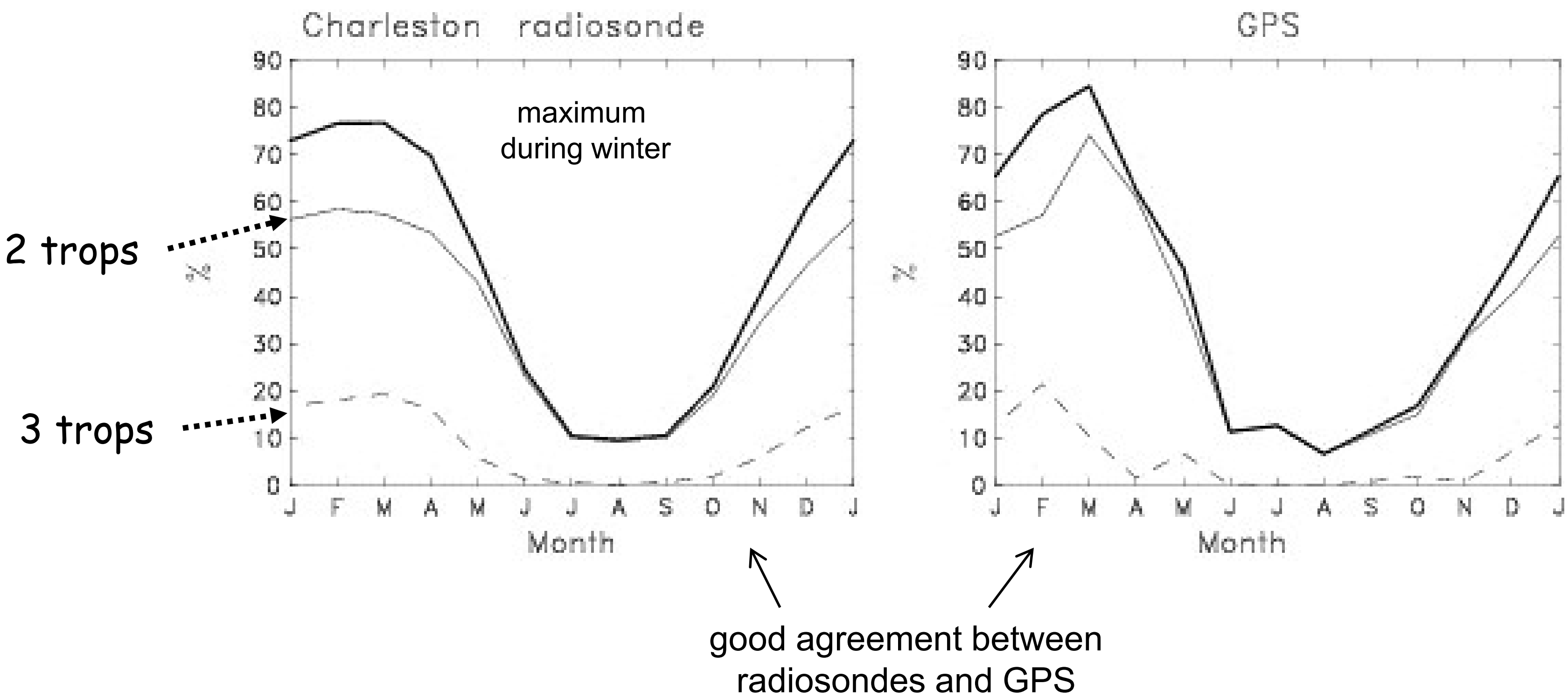
Not a new result: Bjerknes and Palmen (1937); Kochanski (1955); Shapiro (1978), ……

Tropopause structure associated with developing baroclinic wave

Shapiro, ~~1978~~ 1981



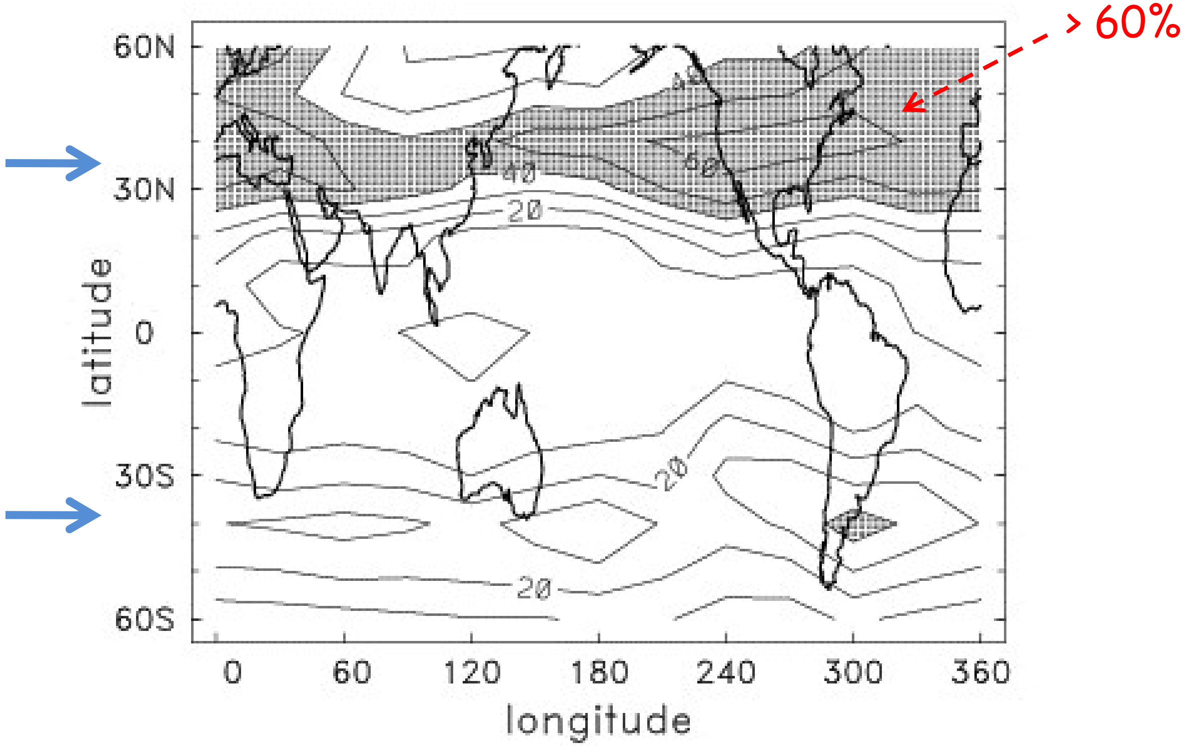
seasonal variation of profiles with multiple tropopauses



Randel et al, 2007., J. Geophys. Res.

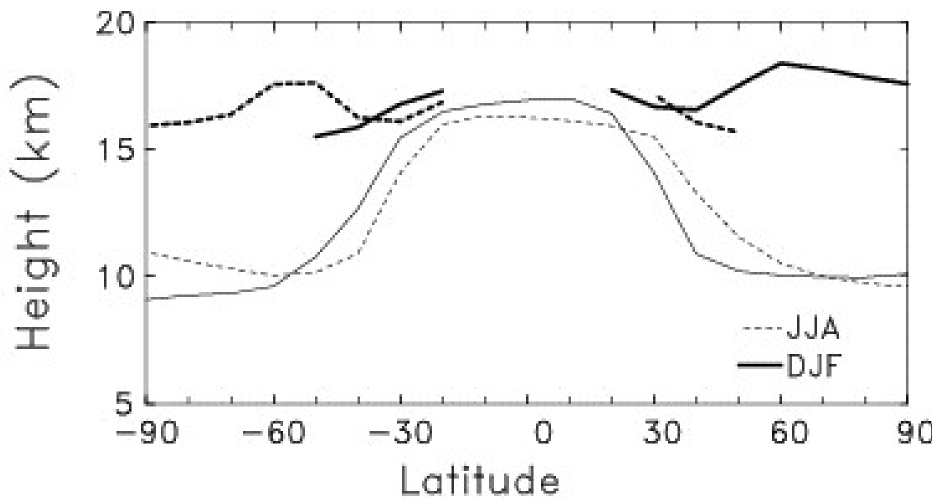
GPS climatology: percent of winter (DJF) soundings with a double tropopause

maximum in subtropics



Randel, Seidel and Pan, JGR, 2007

Climatological height of tropopauses from GPS data

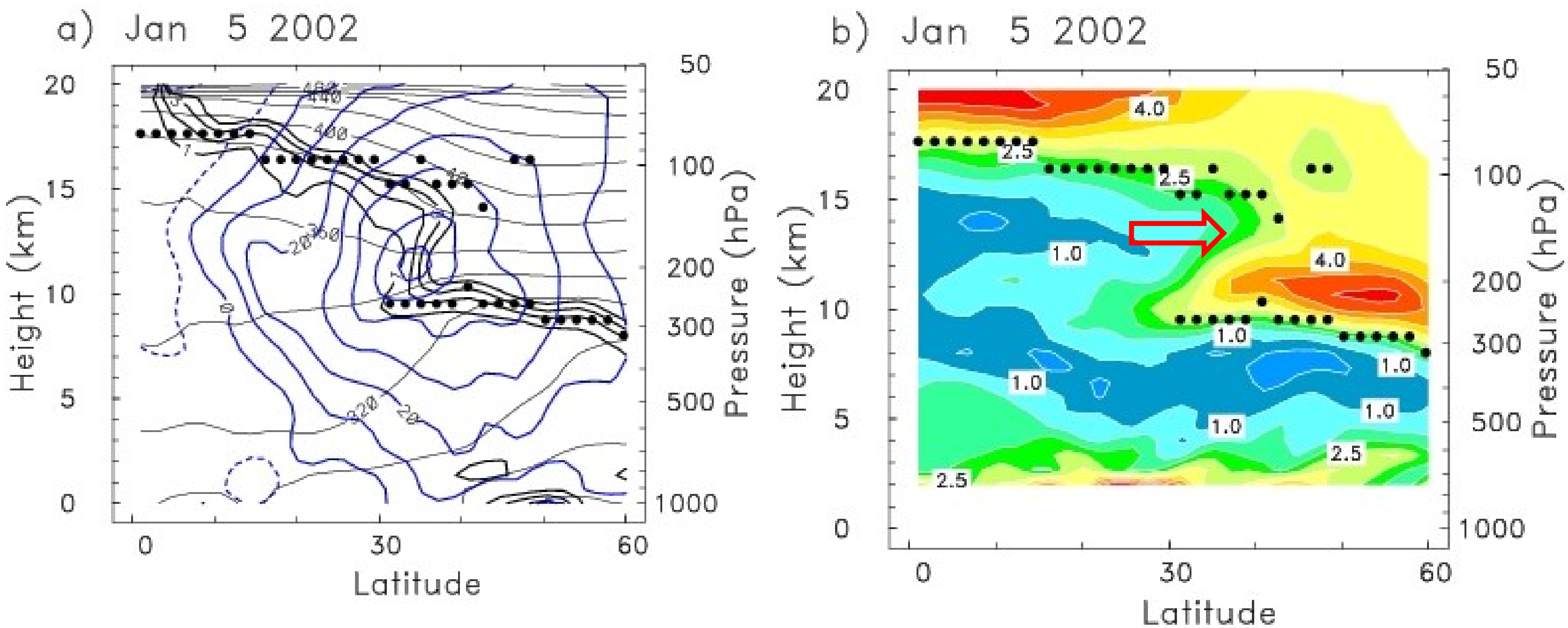


second
tropopause
close to
tropical cold point
~17 km

Randel et al., 2007, J. Geophys. Res.

Cross-section near Charleston

suggestive of transport from tropics



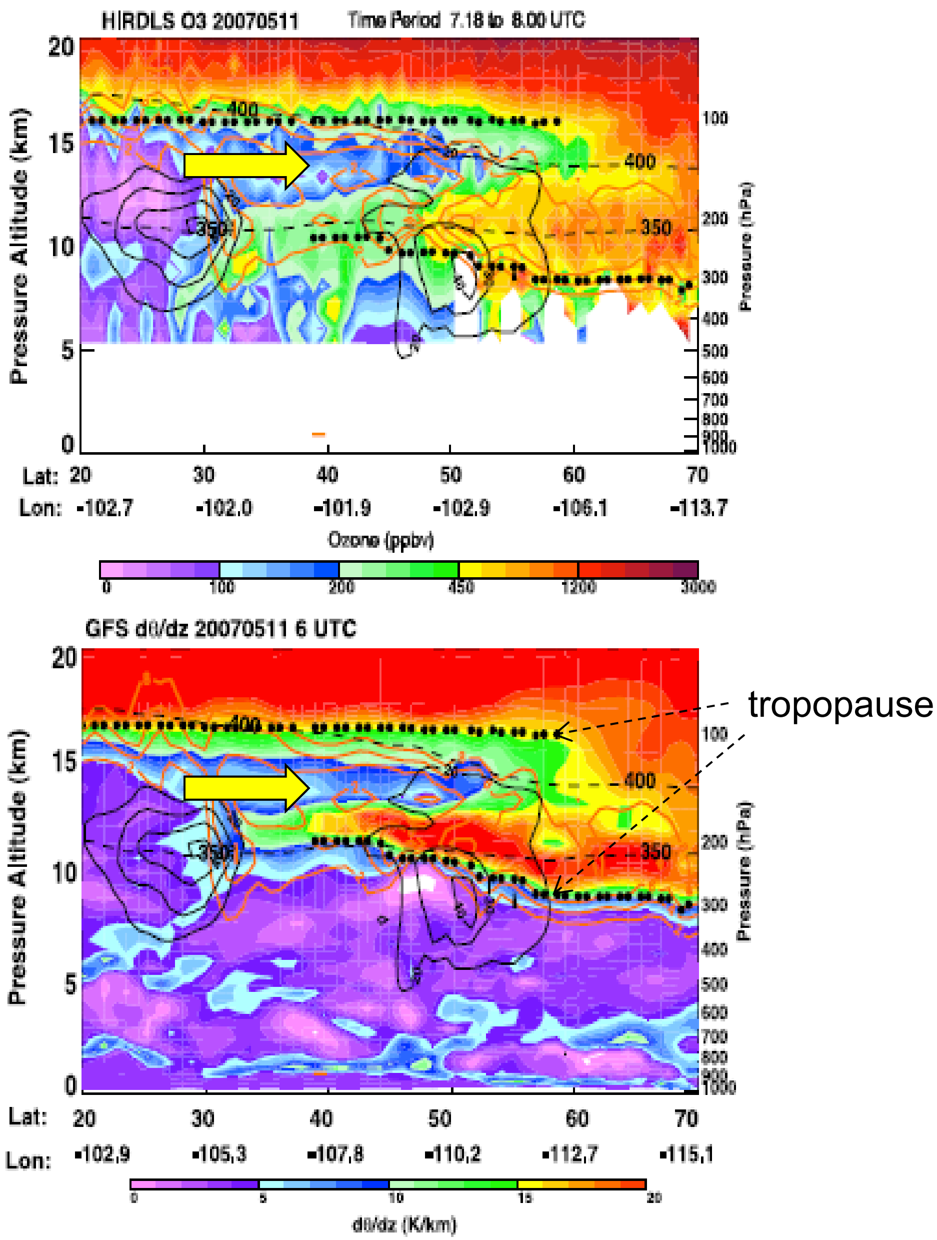
static stability N^2

Randel et al., 2007, J. Geophys. Res.

Double tropopauses and tropospheric intrusions

HIRDLS ozone

static stability

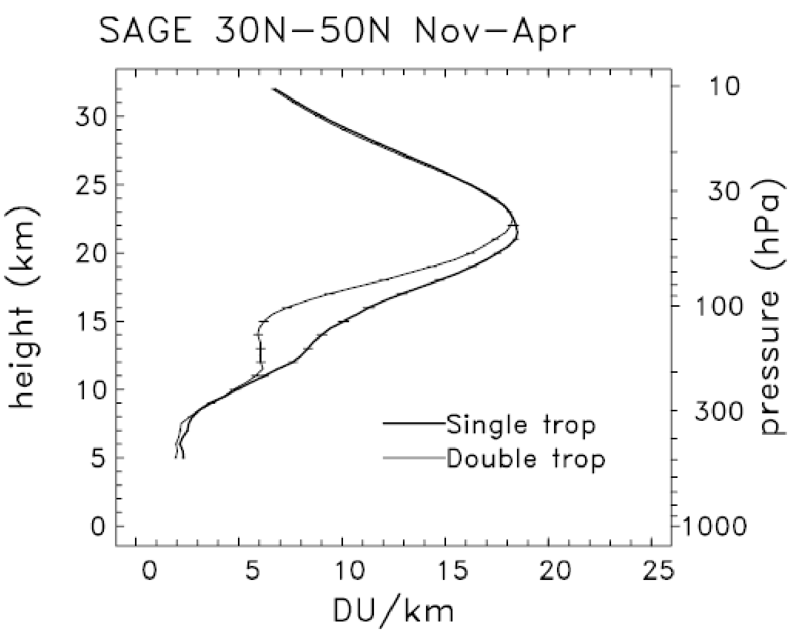


double tropopause linked to intrusion above subtropical jet

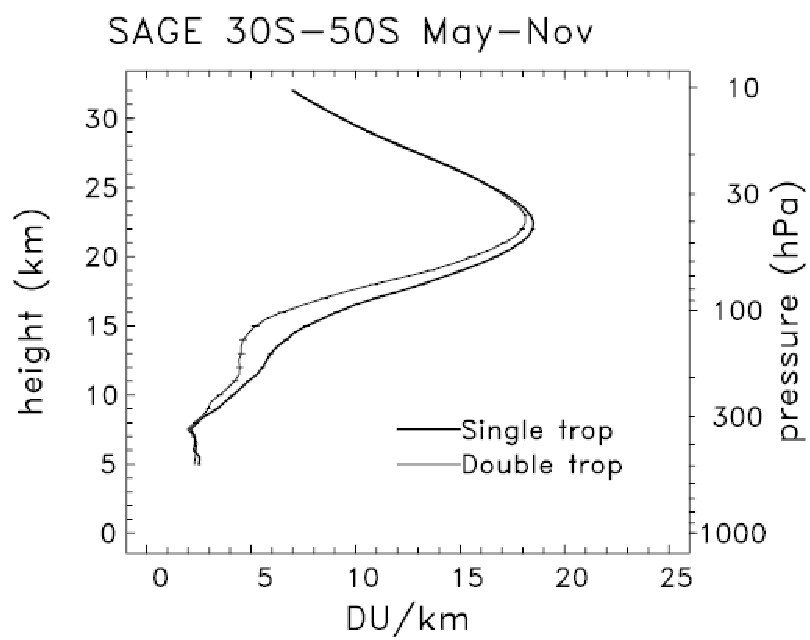
Pan et al, JGR, 2009

Differences in ozone for single vs. double tropopause derived from SAGE II satellite data

NH



SH

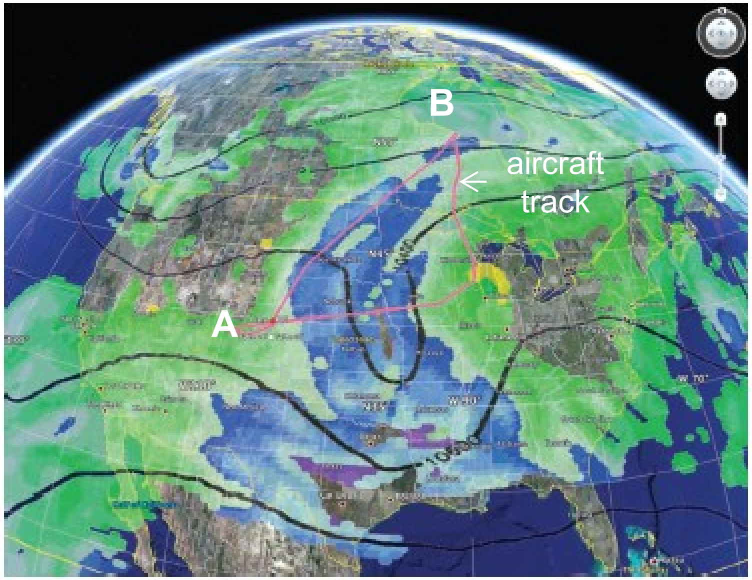


-> consistent pattern of less ozone for double tropopauses

Randel et al., 2007, J. Geophys. Res.

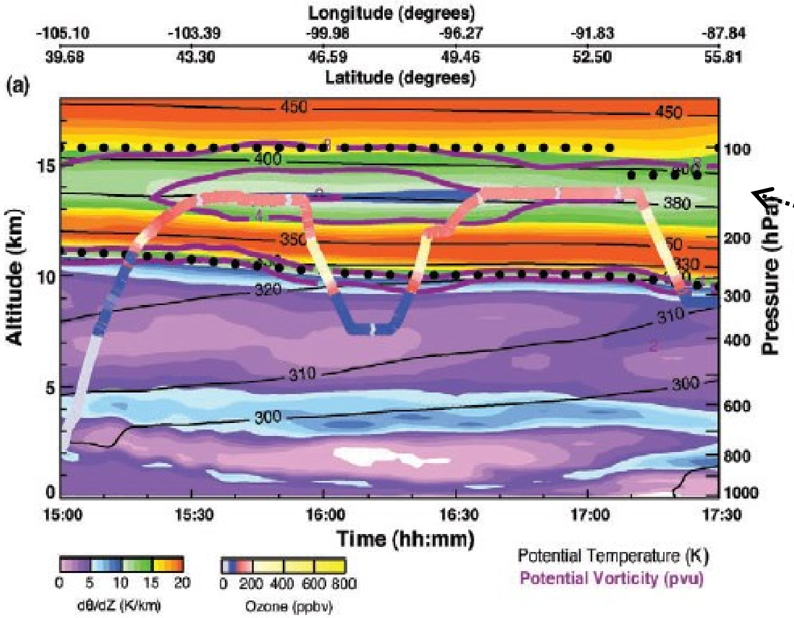
~~Pan et al 2009~~

Blue: region of tropospheric intrusion



Aircraft measurements
during START08 experiment:

section along A-B



double tropopause with low lapse rate
and low ozone

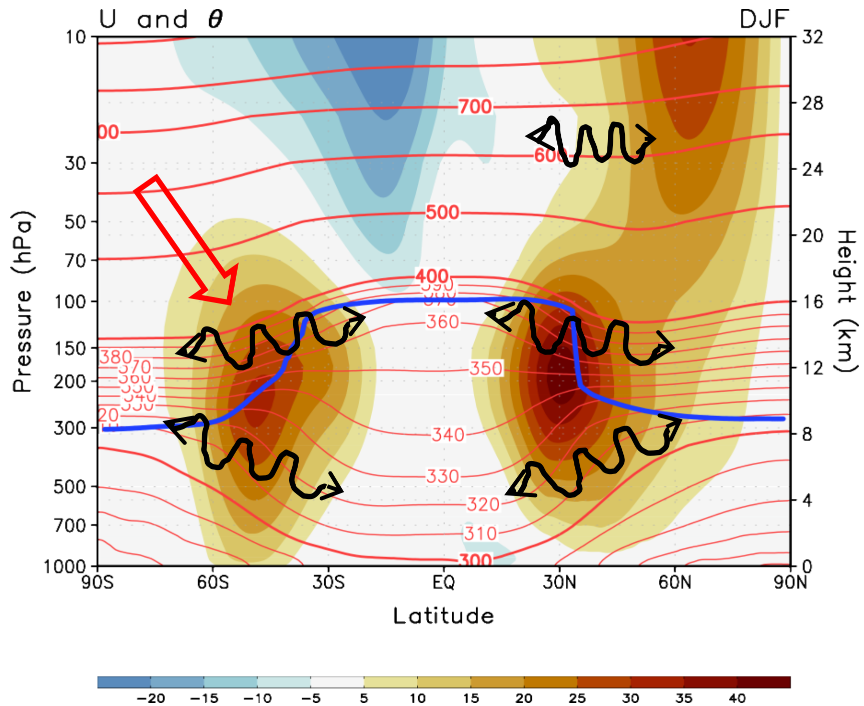
Pan et al., 2010, Bull. Amer. Meteor. Soc.

Key points:

•double tropopauses occur frequently in subtropics, especially during winter

•thermal and chemical structure consistent with intrusions from tropics above subtropical jets

transport above subtropical jets

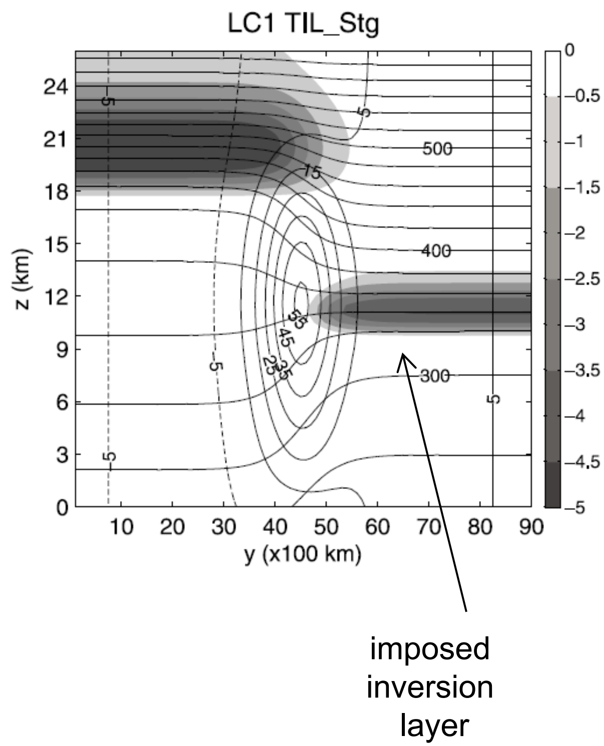


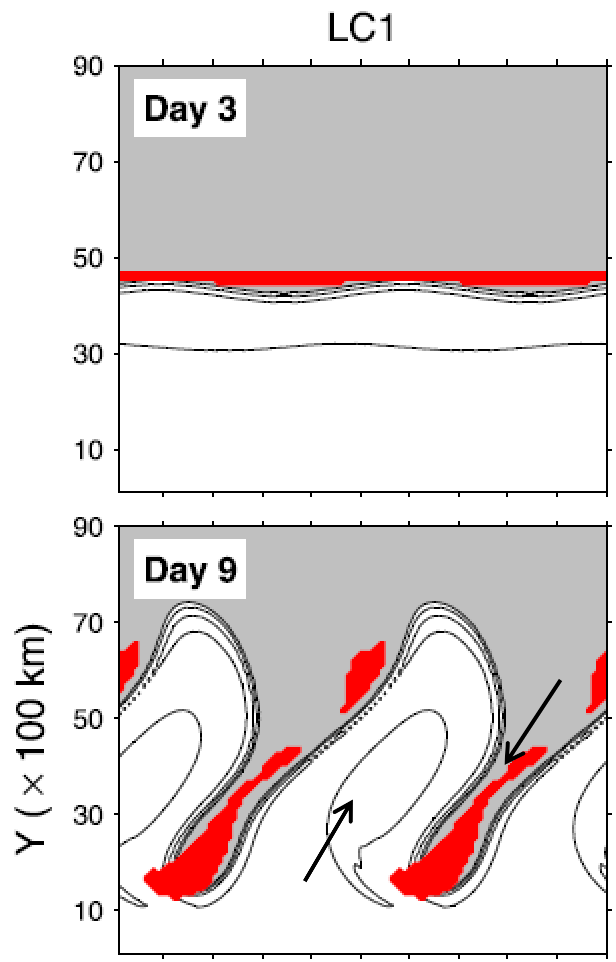
Double tropopause formation in idealized baroclinic life cycles: The key role of an initial tropopause inversion layer

JGR 2011

S. Wang[1] and L. M. Polvani[2]

Idealized LC1 life cycle





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

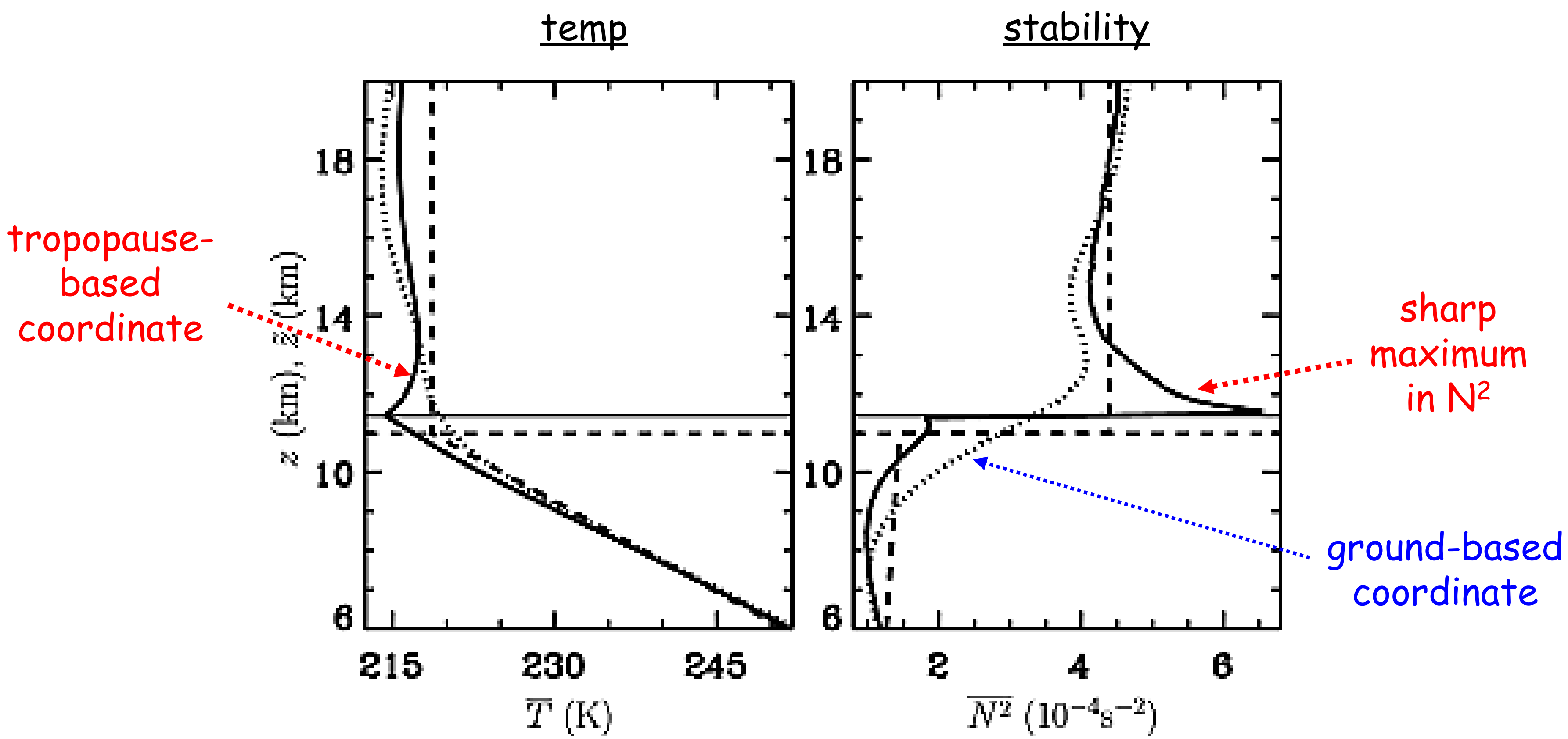
* different from observations

???

The tropopause inversion layer (TIL)

Birner, ~~2002~~ 2003 PhD Thethis, 2006 JGR

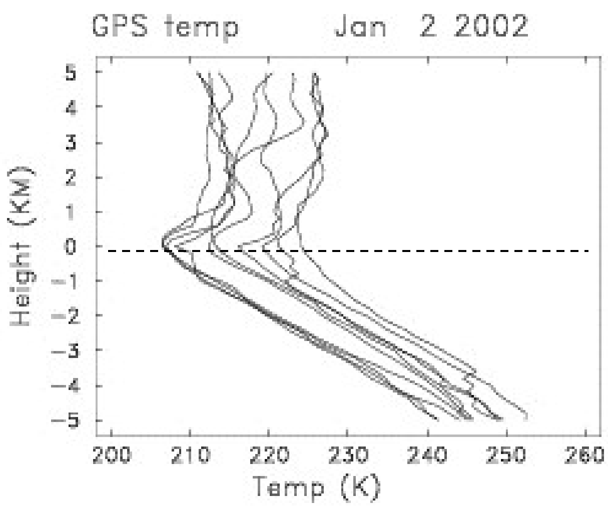
average vertical structure from high-resolution radiosondes near 45° N, calculated using ground-based and tropopause-based coordinates



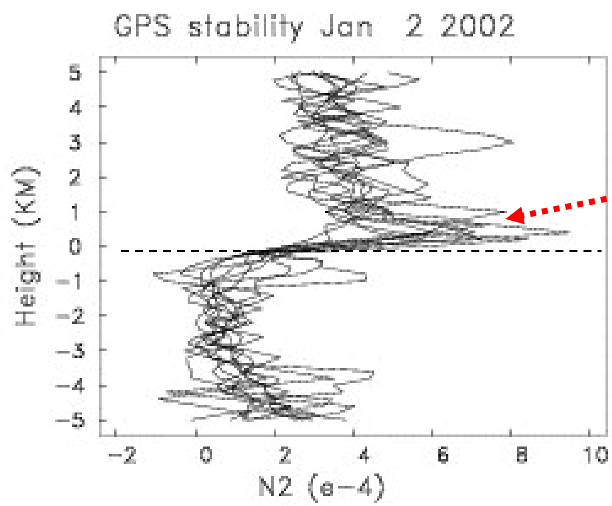
examples using GPS data in tropopause-based coordinate

height relative to tropopause

temp



stability



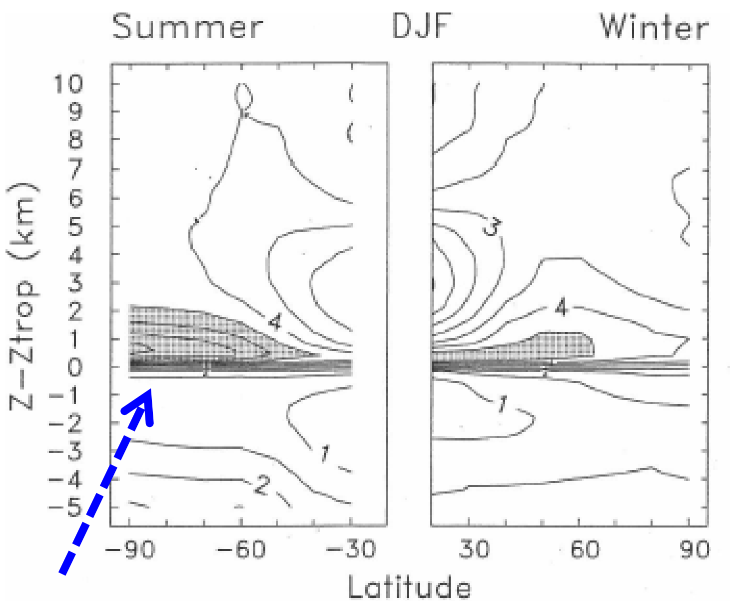
layer of high stability

Randel et al, JAS, 2007

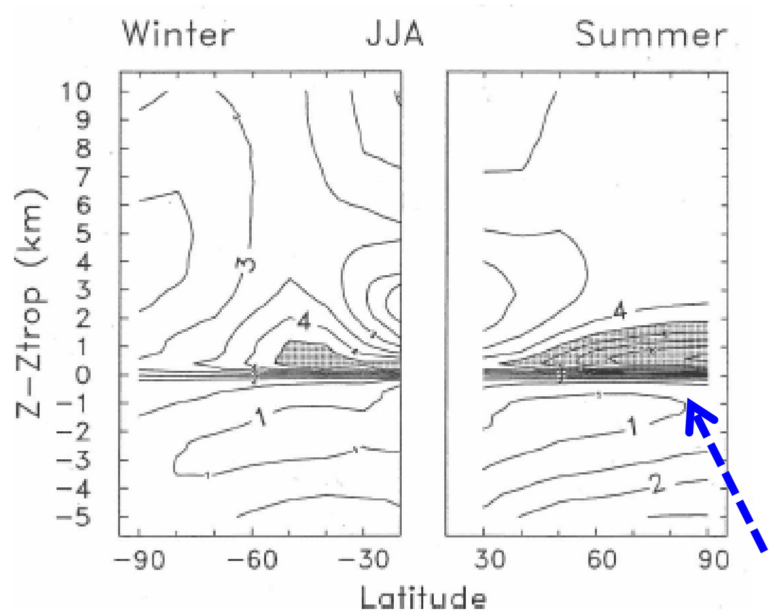
Climatology of inversion layer from GPS data

N^2 in tropopause coordinates

DJF



JJA



summer polar maximum

Randel et al, JAS, 2007

What causes the inversion layer?

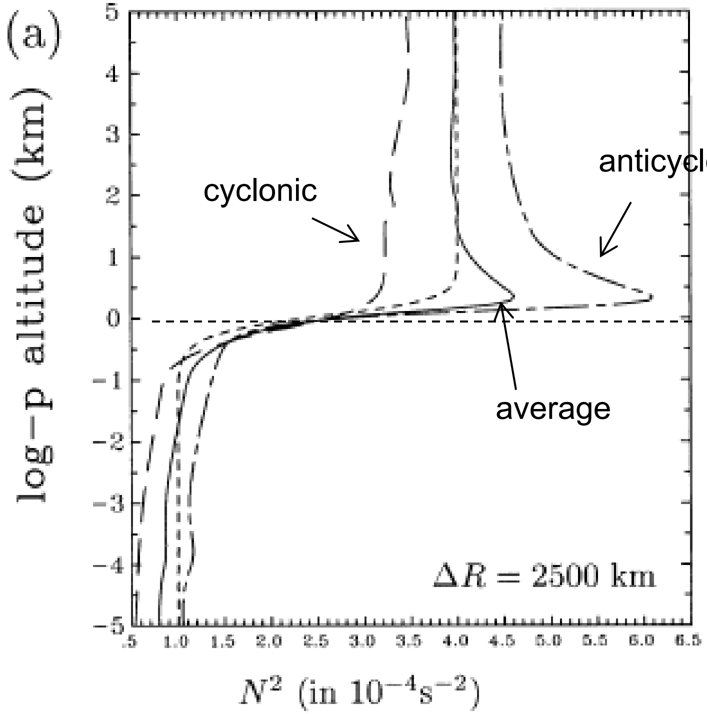
•dynamics?

•cyclone / anticyclones asymmetries?

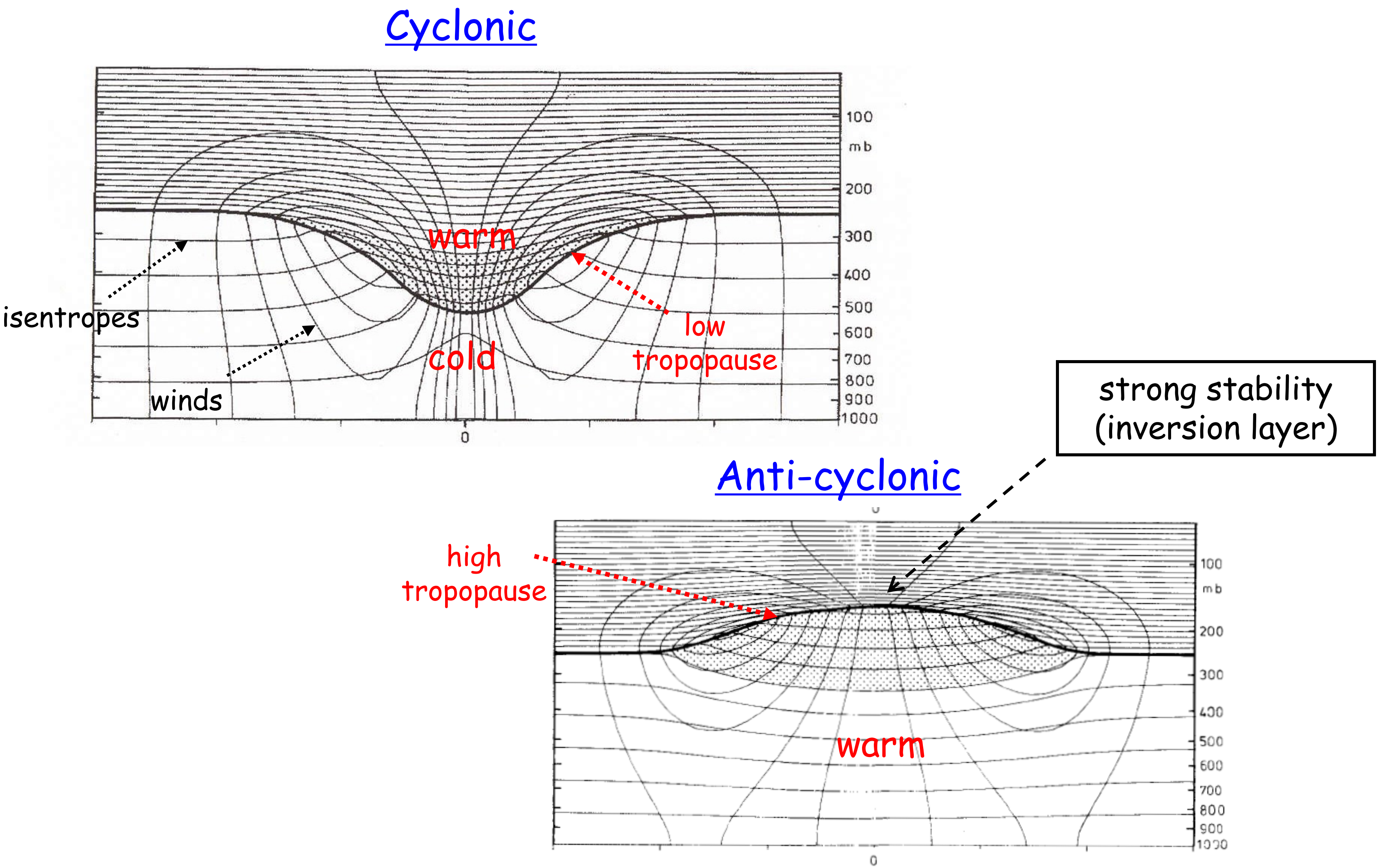
•radiation or other process?

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

Wirth 2003

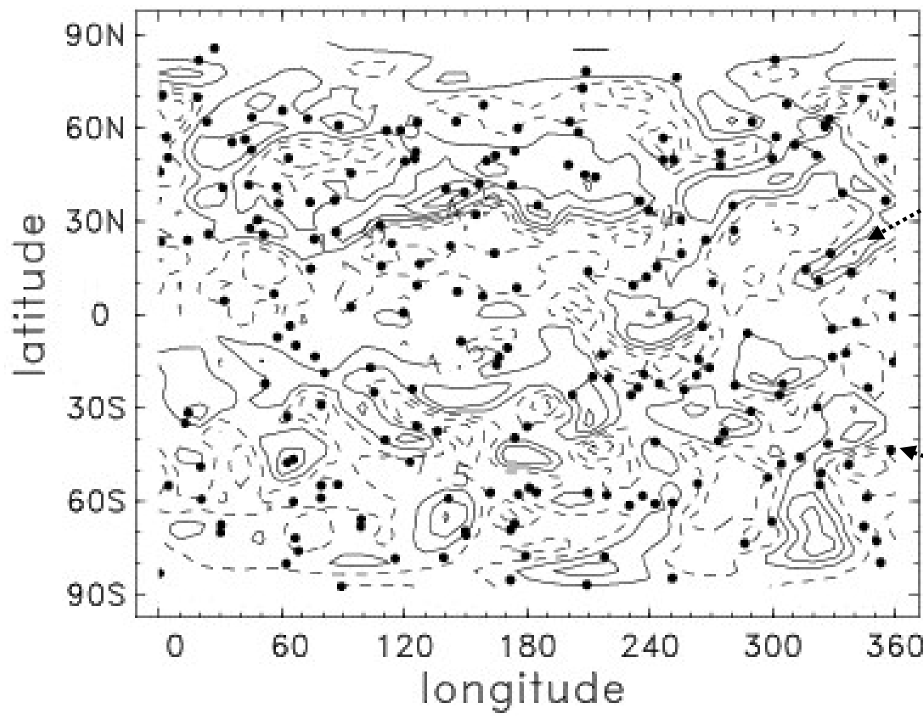


Balanced dynamical structure (Hoskins et al. 1985)



Study the dependence of tropopause statistics on UTLS circulation

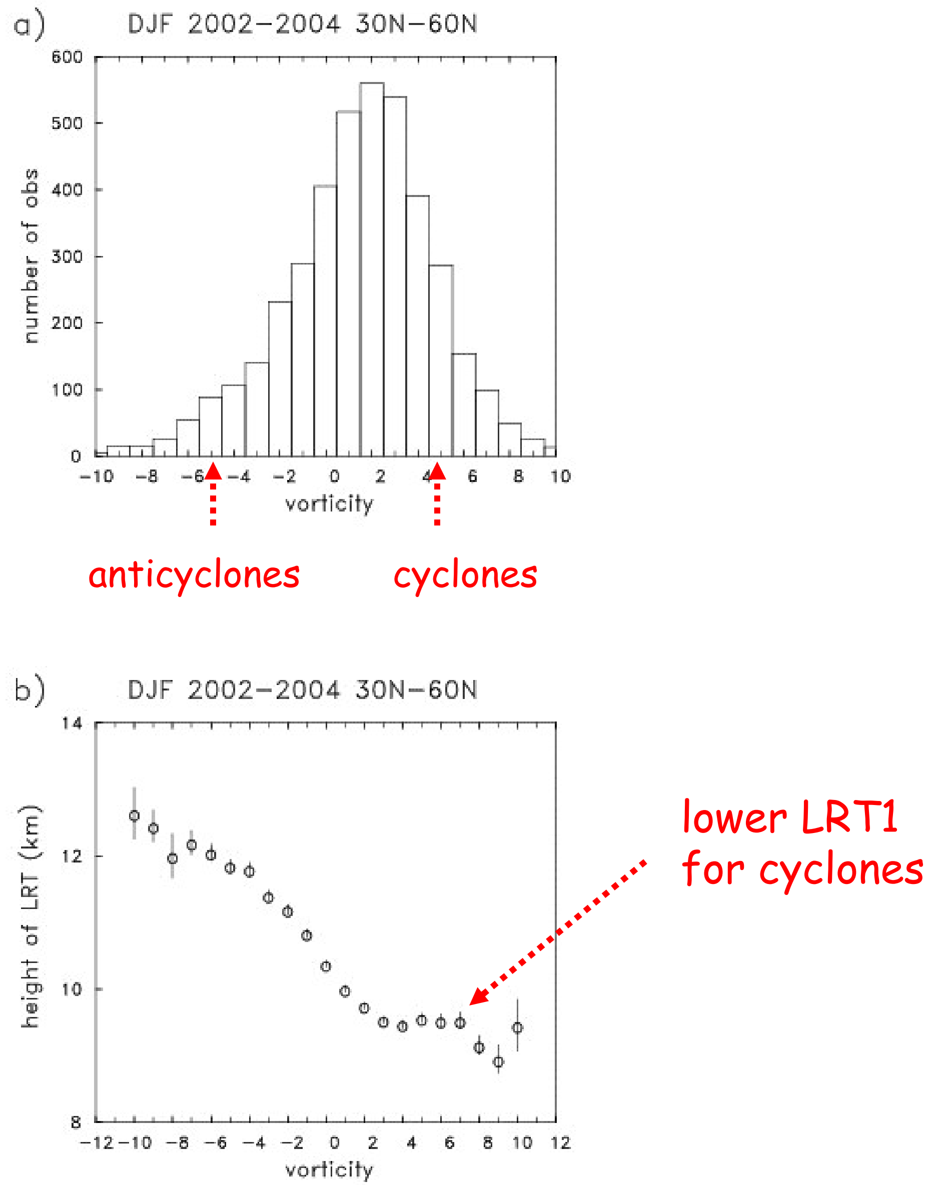
-> segregate GPS soundings according to 200 hPa vorticity



200 hPa relative vorticity Jan 2, 2002

GPS soundings

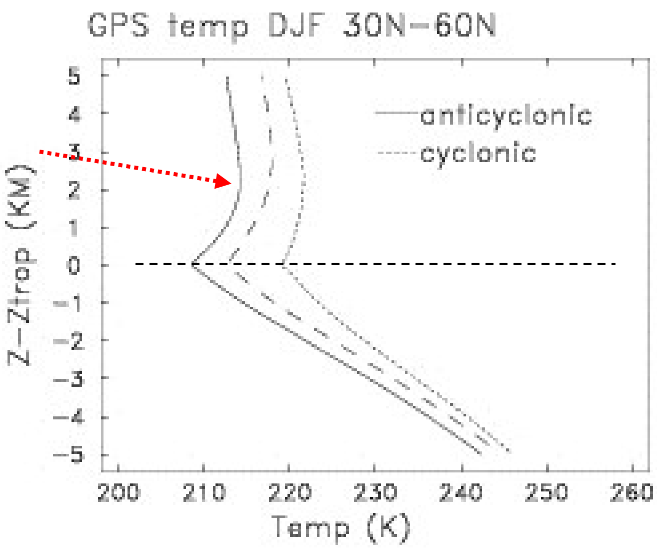
dependence of
tropopause height
on vorticity



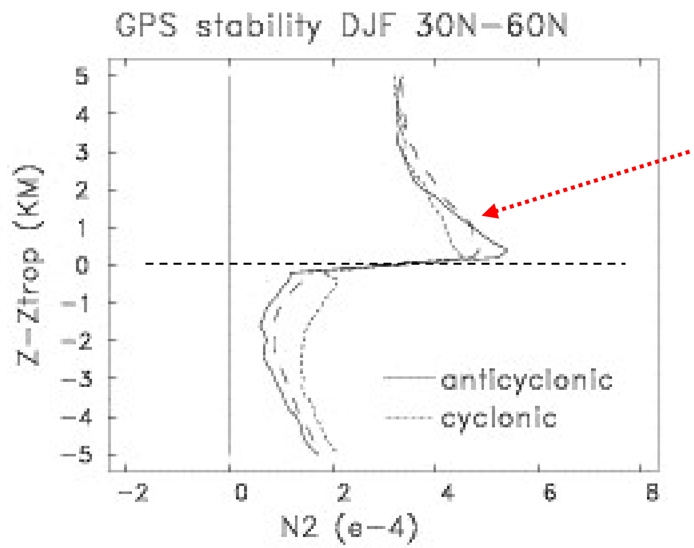
profiles binned according to vorticity (~2500 total)

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

<u>temp</u>



<u>stability</u>

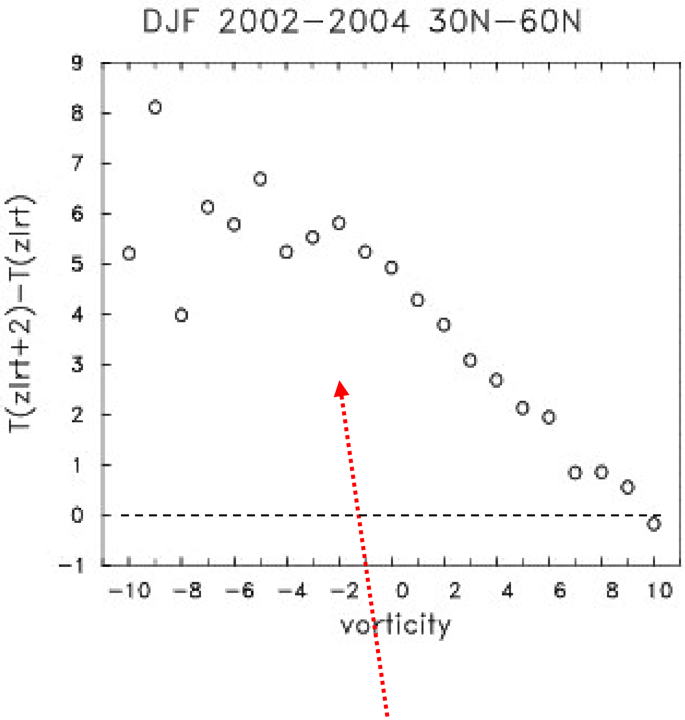


inversion
evident for
all circulation
types

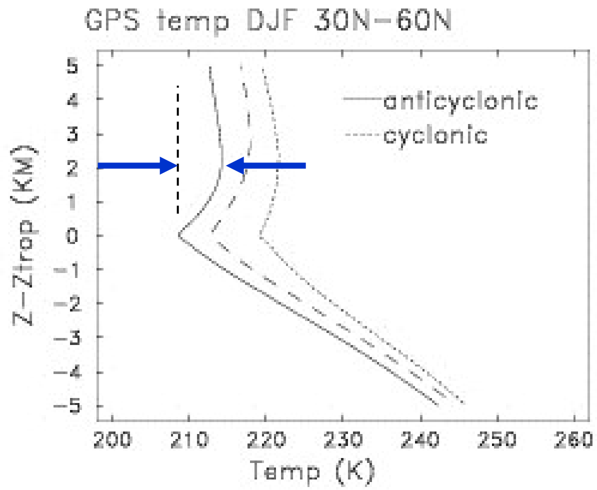
Randel et al., 2007, J. Atmos. Sci.

strength of the inversion vs. circulation

$T(Z_{LRT1}+2km) - T(Z_{LRT1})$



systematically stronger
for anticyclonic flow



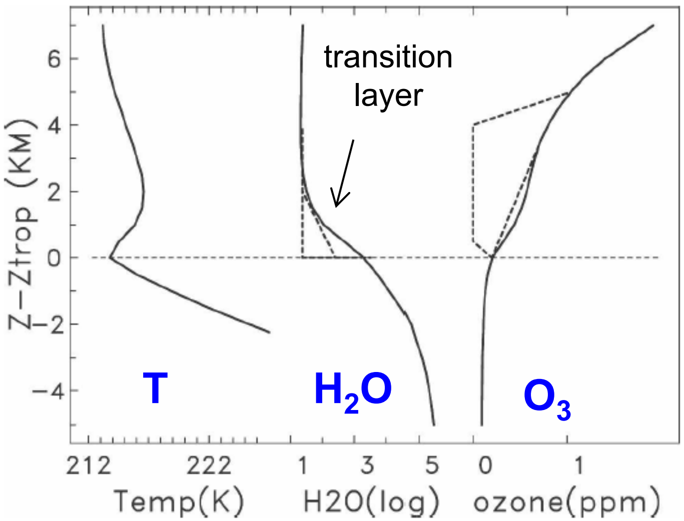
Result: inversion exists for cyclones (weaker)
and anti-cyclones (stronger)

Randel et al, JAS, 2007

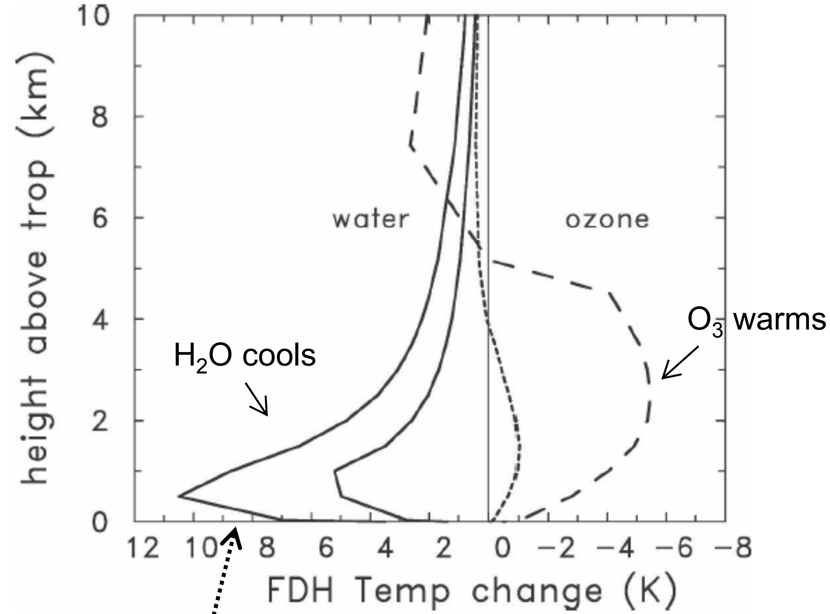
How do radiative processes contribute to the inversion layer?

What is the radiative effect of transition layer?

Vertical profiles in tropopause coordinates



temp changes due to observed H_2O and O_3
(compared to hypothetical dashed curves)



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

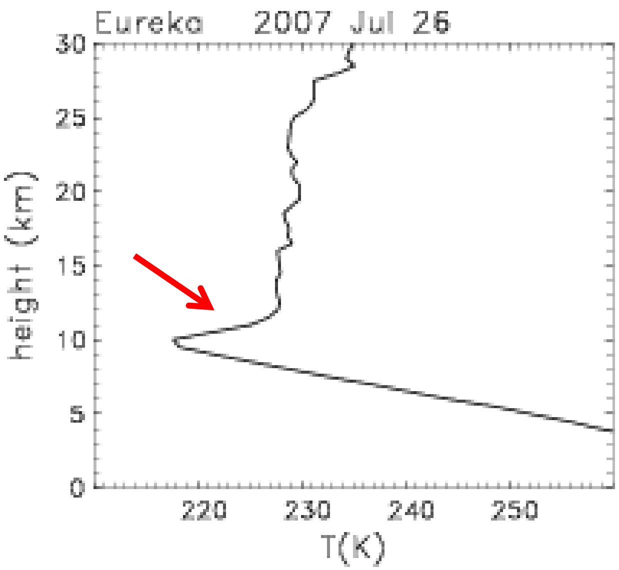
water vapor and ozone both influence thermal structure
(especially water vapor near tropopause)

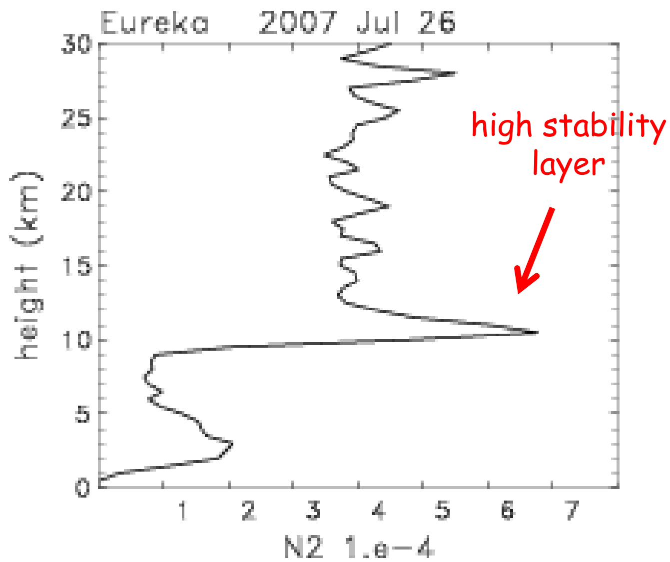
Randel et al., 2007, J. Atmos. Sci.

tropopause inversion layer during polar summer

Radiosonde at Eureka (80° N)

inversion
~ 8 K



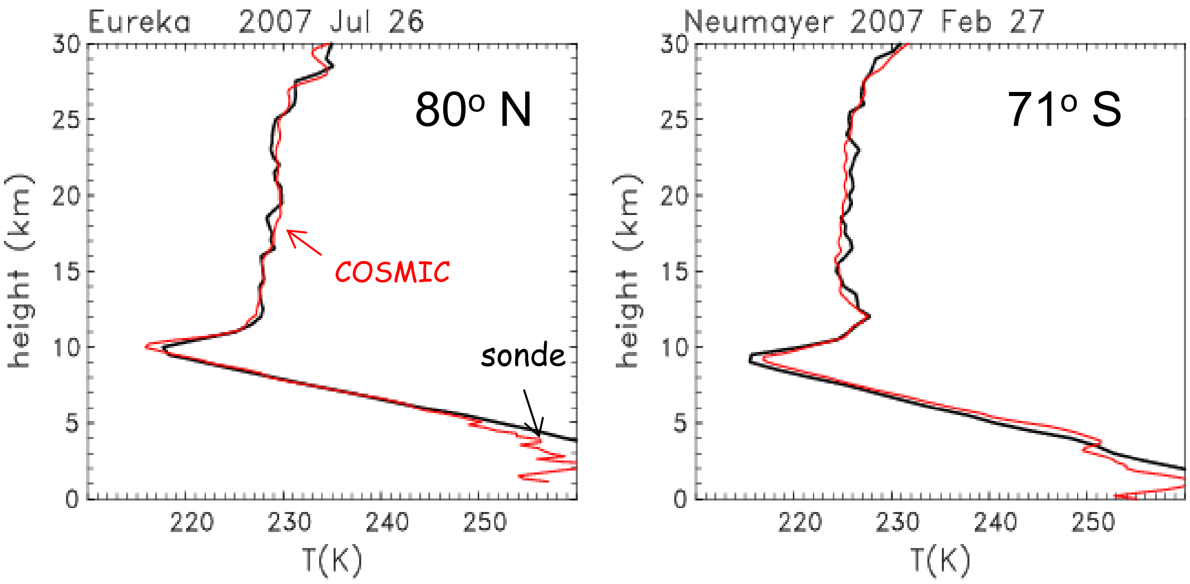


Static stability

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

Randel and Wu, 2010, J. Atmos. Sci.

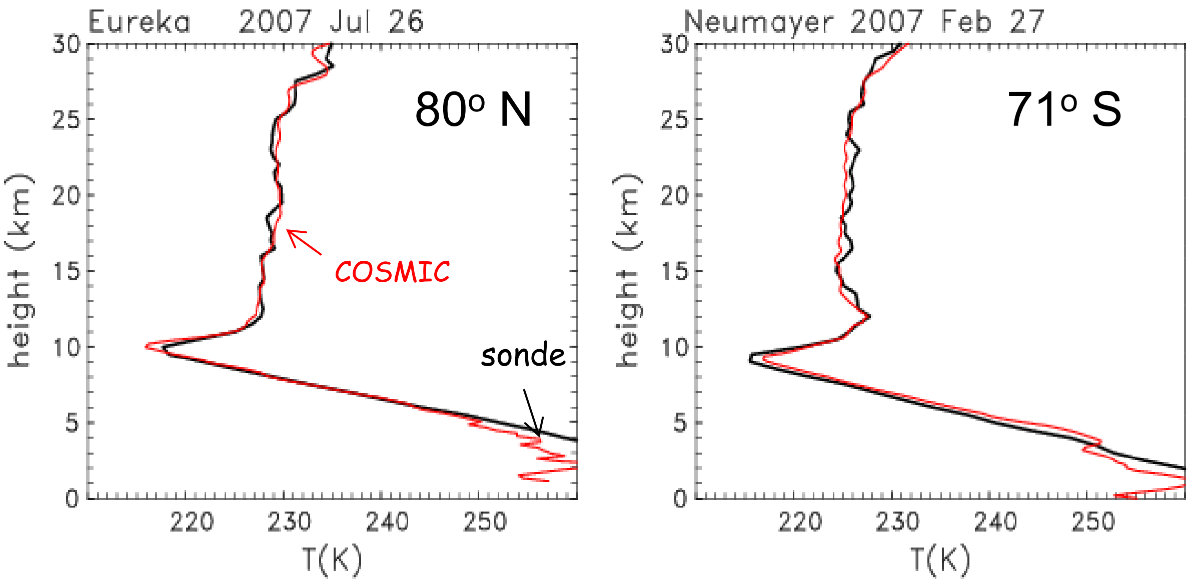
Radiosondes and nearby COSMIC soundings



Randel and Wu, 2010, J. Atmos. Sci.

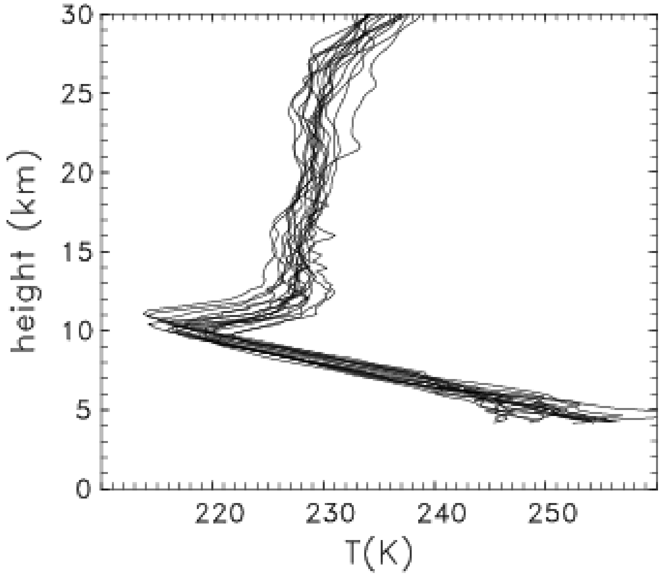
COSMIC allows ~100 times more observations than radiosondes, to study space-time variability of inversion layer

Radiosondes and nearby COSMIC GPS soundings



Randel and Wu, 2010, J. Atmos. Sci.

summer inversion is ubiquitous



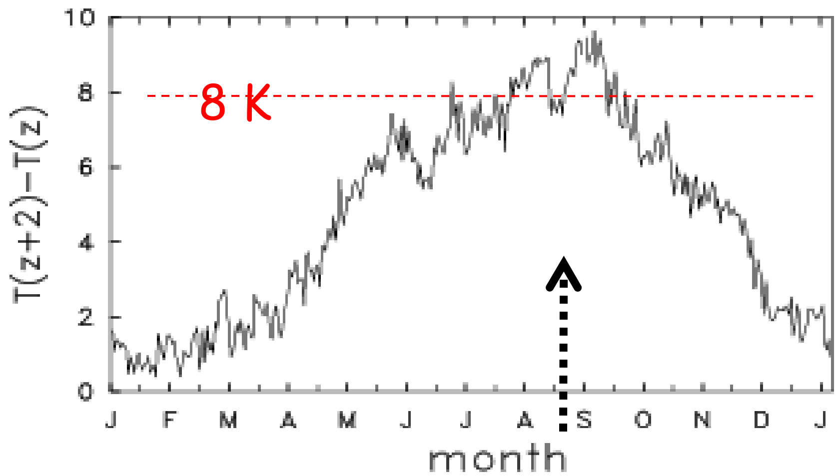
COSMIC allows ~100 times more observations than radiosondes, to study space-time variability of inversion layer

Strength of polar tropopause inversion

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

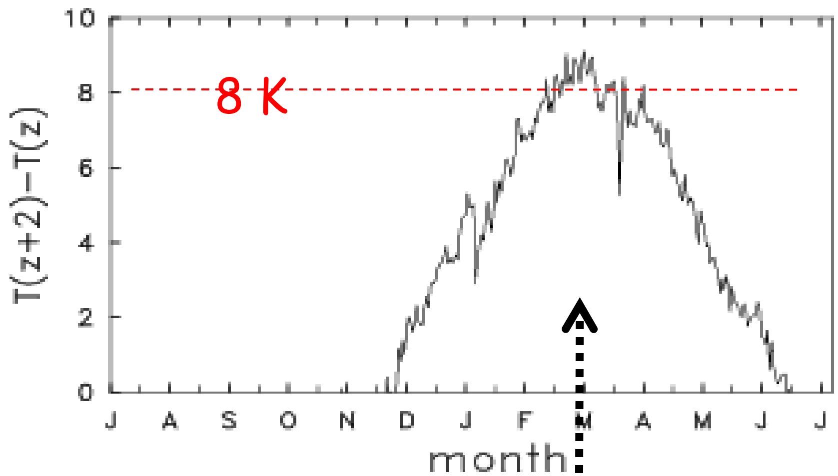
daily data from COSMIC, average over polar cap

COSMIC 70° - 90° N

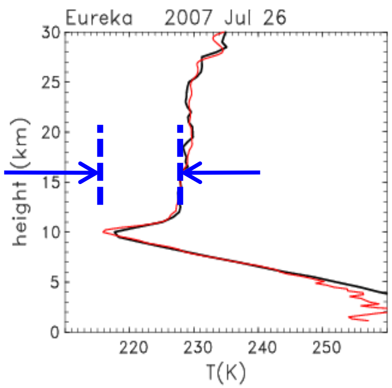


Arctic

COSMIC 70° - 90° S



Antarctic

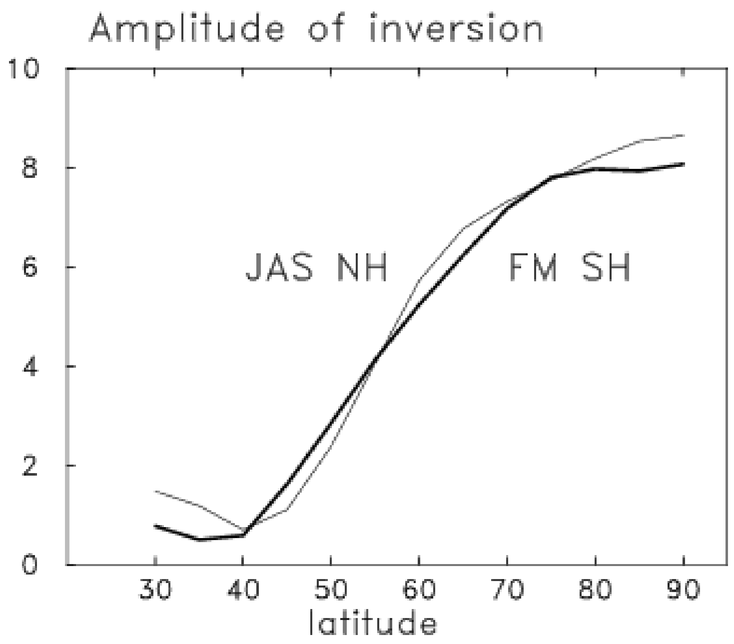


summer maximum
in both hemispheres

Randel and Wu, 2010, J. Atmos. Sci.

Latitudinal structure of summer inversion

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



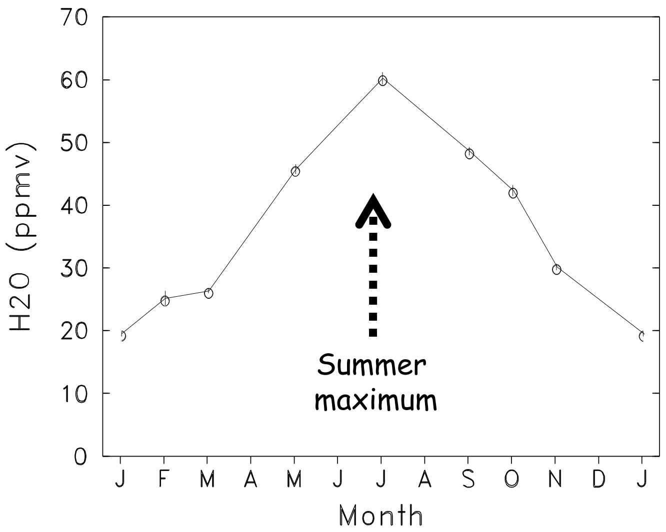
note the remarkable symmetry between hemispheres

Randel and Wu, 2010, J. Atmos. Sci.

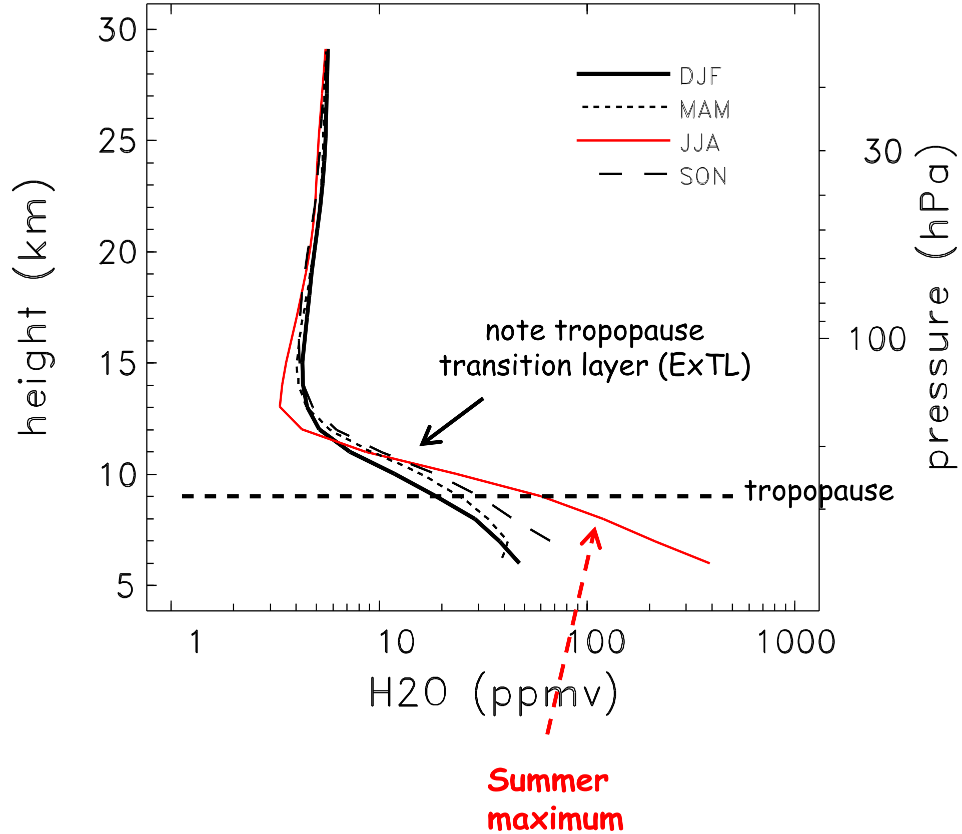
What causes the strong polar inversion layer?

*** Water vapor near the tropopause ***

Seasonal cycle at tropopause (9 km)



Seasonal vertical profiles



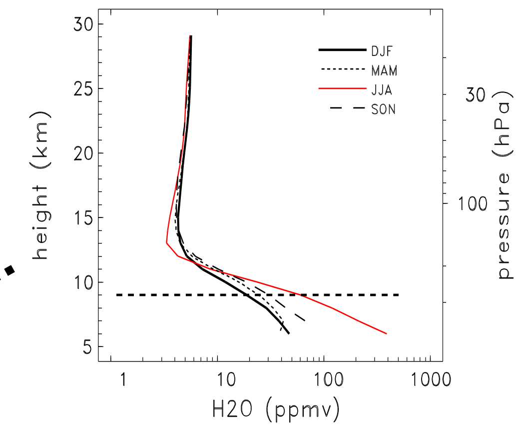
Polar water vapor measurements from ACE-FTS satellite

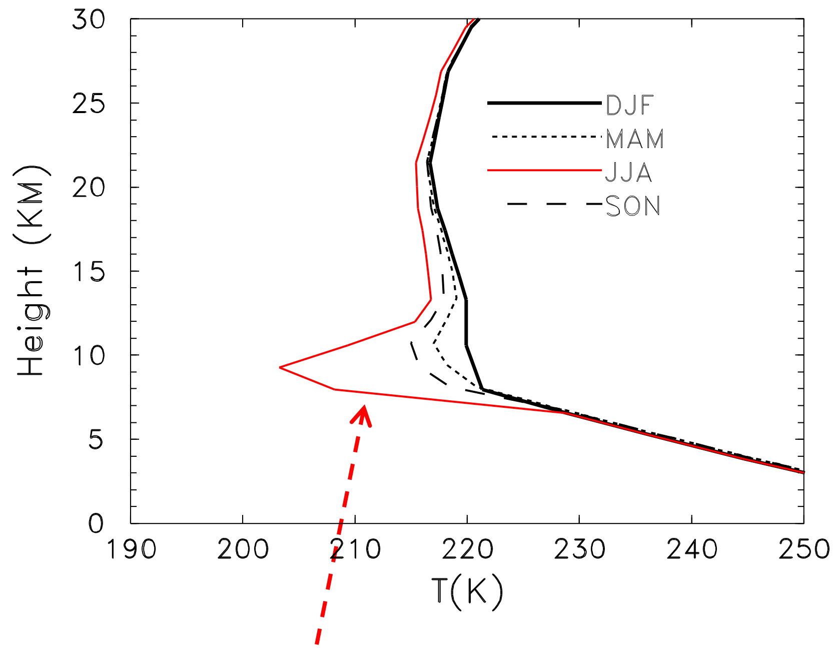
Randel and Wu, 2010, J. Atmos. Sci.

Radiative response to UTLS water vapor

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

ACE water vapor
(input to calculation)





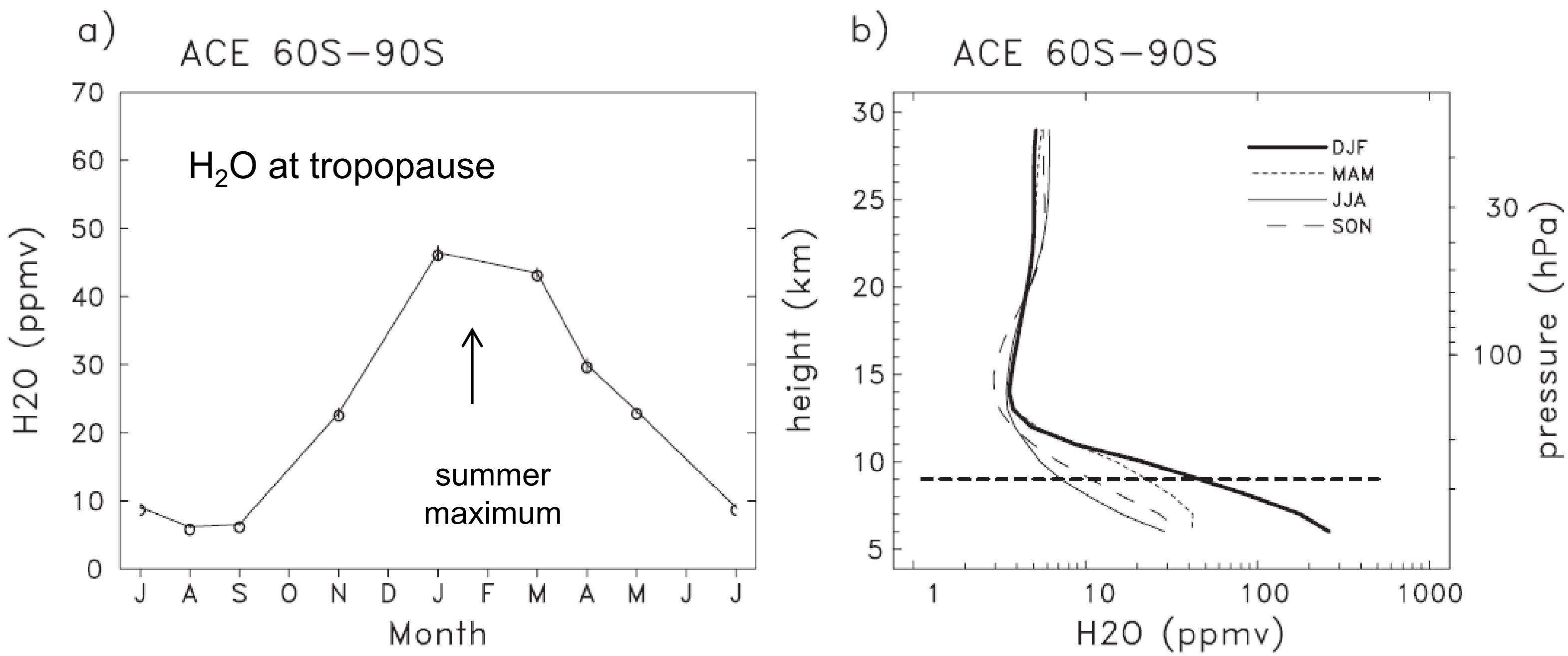
Calculated temperature profiles, changing only the H_2O

Enhanced water vapor leads to strong cooling near tropopause

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

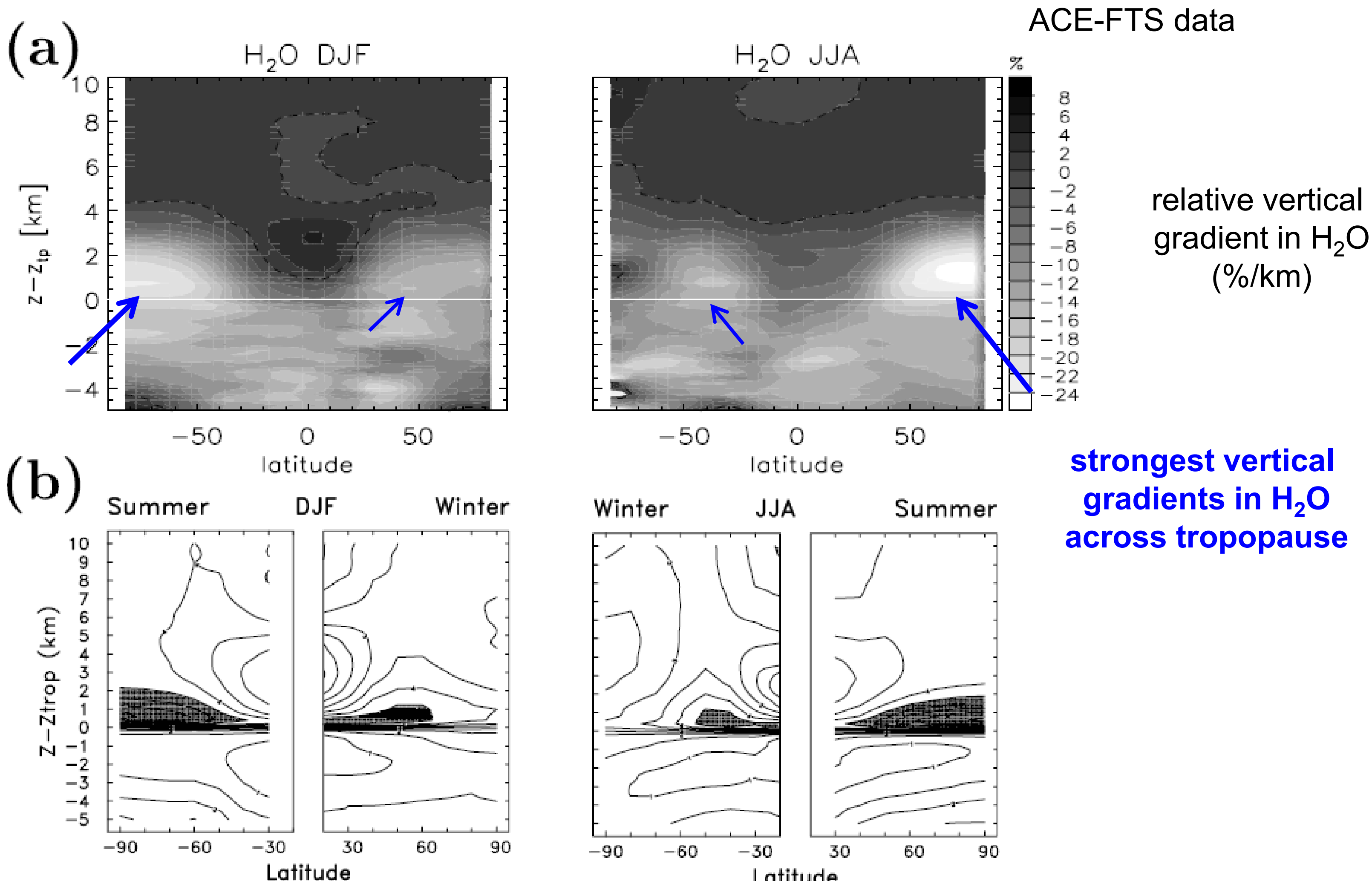
Randel and Wu, JAS, 2010

Similar H_2O behavior is seen in the Southern Hemisphere



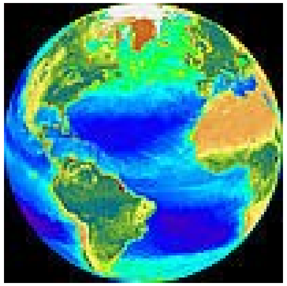
Randel and Wu, 2010, J. Atmos. Sci.

Why does this occur during polar summer?



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_2O gradients
 (and suggests this is a mechanism for other regions)

Reference1

- Birner, T., 2003: Die extratropische tropopausenregion, Ph. D. thesis, Fakult ät für Physik der Ludwig-Maximilians-Universit ät M ünchen, pp.129.
- Birner, T., 2006: Fine - scale structure of the extratropical tropopause region, J. Geophys. Res., 111, D04104.
- Bjerknes, J. and Palmèn, E., 1937: Investigation of selected European cyclones by means of serial ascents, Geophys. Publ. 12, 1-62.
- Boone, C. and Bernath, P., 2009: The atmospheric chemistry experiment: Status and latest results, 5th Atmospheric Limb Conference and Workshop (Helsinki, Finland, invited talk).
- Clerbaux, C., Boynard, A., Clarisse, L., George, M., Hadji-Lazaro, J., Herbin, H., Hurtmans, D., Pommier, M., Razavi, A., Turquety, S., Wespes, C. and Coheur, P.-F., 2009: Monitoring of atmospheric composition using the thermal infrared IASI/MetOp sounder, Atmos. Chem. Phys., 9, 6041-6054
- Forster, F. and Shine, K.P., 2002: Assessing the climate impact of trends in stratospheric water vapor, Geophys. Res. Lett., 29, 10-1-10-4.
- Gettelman, A., Hoor, P., Pan, L., Randel, W.J., Birner, T. and Hegglin, M., 2011: The extra tropical upper troposphere and lower stratosphere, Rev. Geophys., 49, RG3003.
- Haynes, P.H., Scinocca J.F. and Greenslade, M.D., 2001: Formation and maintenance of the extratropical tropopause by baroclinic eddies, Geophys. Res. Lett., 28, 4179-4182.

Reference2

- Hegglin, M.I., Boone, C.D., Manney, G.L. and Walker, K.A., 2009: A global view of the extratropical tropopause transition layer from Atmospheric Chemistry Experiment Fourier Transform Spectrometer O3, H2O, and CO, J. Geophys. Res., 114, D00B11.
- Hoor, P., Fischer, H., Lange, L., Lelieveld, J. and Brunner, D., 2002: Seasonal variations of a mixing layer in the lowermost stratosphere as identified by the CO-O3 correlation from in situ measurements, J. Geophys. Res., 107, ACL 1-1-ACL 1-11.
- Hoskins, B.J., McIntyre, M.E. and Robertson, A.W., 1985: On the use and significance of isentropic potential vorticity maps, Q.J.R. Meteorol. Soc., 111, 877-946.
- Kochanski, A., 1955: Cross sections of the mean zonal flow and temperature along 80 W, J. Meteorology., 12, 95-106.
- Pan, L., Bowman, K.P., Shapiro, M., Randel, W.J., Gao, R.S., Campos, T., Davis, C., Schauffler, S., Ridley, B.A., Wei, C. and Barnet, C., 2007: Chemical behavior of the tropopause observed during the Stratosphere-Troposphere Analysis of Regional Transport experiment, J. Geophys. Res., 112, D18110.
- Pan, L.L., Bowman, K.P., Atlas, E.L., Wofsy, S.C., Zhang, F., Bresch, J.F., Ridley, B.A., Pittman, J.V., Homeyer, C.R., Romashkin, P. and Cooper, W.A., 2010: The stratosphere - troposphere analyses of regional transport 2008 experiment, Bull. Amer. Meteor. Soc., 91, 327-342.
- Pan, L.L., Randel, W.J., Gary, B.L., Mahoney, M.J. and Hintsa, E.J., 2004: Definitions and sharpness of the extratropical tropopause: A trace gas perspective, J. Geophys. Res., 109, D23103.

Reference3

- Pan, L.L., Randel, W.J., Gille, J.C., Hall, W.D., Nardi, B., Massie, S., Yudin, V., Khosravi, R., Konopka, P. and Tarasick, D., 2009: Tropospheric intrusions associated with the secondary tropopause, J. Geophys. Res., 114, D10302.
- Park, M., Randel, W.J., Kinnison, D.E., Emmons, L.K., Bernath, P.F., Walker, K.A., Boone, C.D. and Livesey, N.J., 2013: Hydrocarbons in the upper troposphere and lower stratosphere observed from ACE-FTS and comparisons with WACCM, J. Geophys. Res. Atmos., 118, 1964-1980.
- Randel, W.J., Moyer, E., Park, M., Jensen, E., Bernath, P., Walker, K. and Boone, C., 2012: Global variations of HDO and HDO/H2O ratios in the UTLS derived from ACE-FTS satellite measurements, J. Geophys. Res., 117, D06303.
- Randel, W.J., Park, M., Wu, F. and Livesey, N., 2007: A large annual cycle in ozone above the tropical tropopause linked to the Brewer-Dobson circulation, J. Atmos. Sci., 64, 4479-4488.
- Randel, W.J., Wu, F. and Forster, P., 2007: The extratropical tropopause inversion layer: global observations with GPS data, and a radiative forcing mechanism, J. Atmos. Sci., 64, 4489-4496.
- Randel, W.J. and Wu, F., 2010: The polar summer tropopause inversion layer, J. Atmos. Sci., 67, 2572-2581.
- Shapiro, M.A., 1981: Frontogenesis and geostrophically forced secondary circulations in the vicinity of jet stream-frontal zone systems, J. Atmos. Sci., 38, 954-973.

Reference4

- Thuburn, J. and Craig, G.C., 2000: Stratospheric influence on tropopause height: The radiative constraint, J. Atmos. Sci., 57, 17-28.
- Vogel, B., Pan, L.L., Konopka, P., Günther, G., Müller, R., Hall, W., Campos, T., Pollack, I., Weinheimer, A., Wei, J., Atlas, E.K. and Bowman, K.P., 2011: Transport pathways and signatures of mixing in the extratropical tropopause region derived from Lagrangian model simulations, J. Geophys. Res., 116, D05306.
- Wirth, V., 2003: Static stability in the extratropical tropopause region, J Atmos Sci., 60, 1395-1409.
- World Meteorological Organization, 1957: Meteorology - A three-dimensional science: Second session of the Commission for Aerology, WMO Bulletin, 134-138.
- von Zahn, U., von Cossart, G., Fiedler, J., Fricke, K. H., Nelke, G., Baumgarten, G., Rees, D., Hauchecorne, A. and Adolfsen, K., 2000: The ALOMAR Rayleigh/Mie/Raman lidar: objectives, configuration, and performance, Ann. Geophys., 18, 815-833.