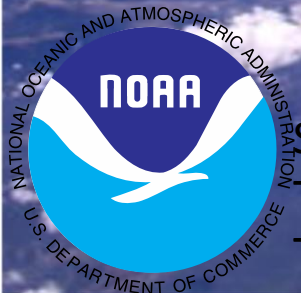


Stratospheric constituents and circulation

Karen H. Rosenlof
NOAA ESRL CSD
Boulder, CO
USA



SPARC 2014 General Assembly, Queenstown, New Zealand
Thursday, Jan 17, 2014

Theme 4: Observational datasets, reanalyses and attribution studies



What long-term stratospheric changes are important?

- 1) Radiatively active trace species
 - a) Ozone & ODSs
 - b) Water
 - c) Well mixed GHGs (CO_2 , CH_4 , N_2O)
- 2) Aerosols
- 3) Temperature
- 4) Circulation*

What long-term stratospheric measurements exist for assessing changes?

For trace species and temperature: ground based (remote and balloon borne) and satellite

For circulation: only inferences from species or temperature measurements can be made, changes in mass flux can't be measured directly

SPARC activities concerned with constituent trends

Ozone: SPARC Report 1 (1998)

Water Vapor: SPARC Report 2 (2000)

Aerosol: SPARC Report 4 (2006)

Models: SPARC Report 5 (2010)

Trace gases: New SPARC Report (2014)

Current and emerging activities

SI²N

WAVAS-II

Temperature trends

CCMI

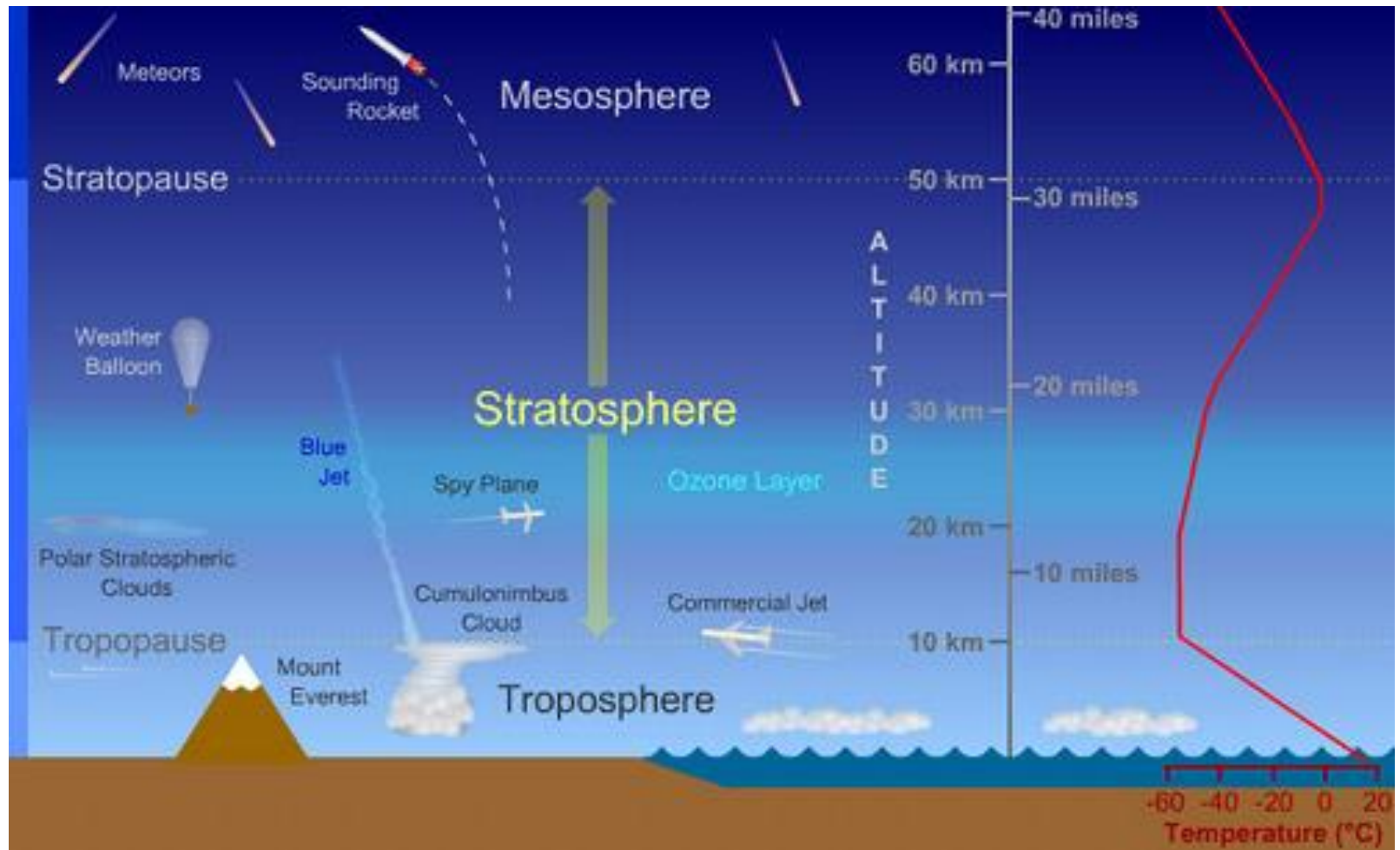
SSiRC

S-RIP

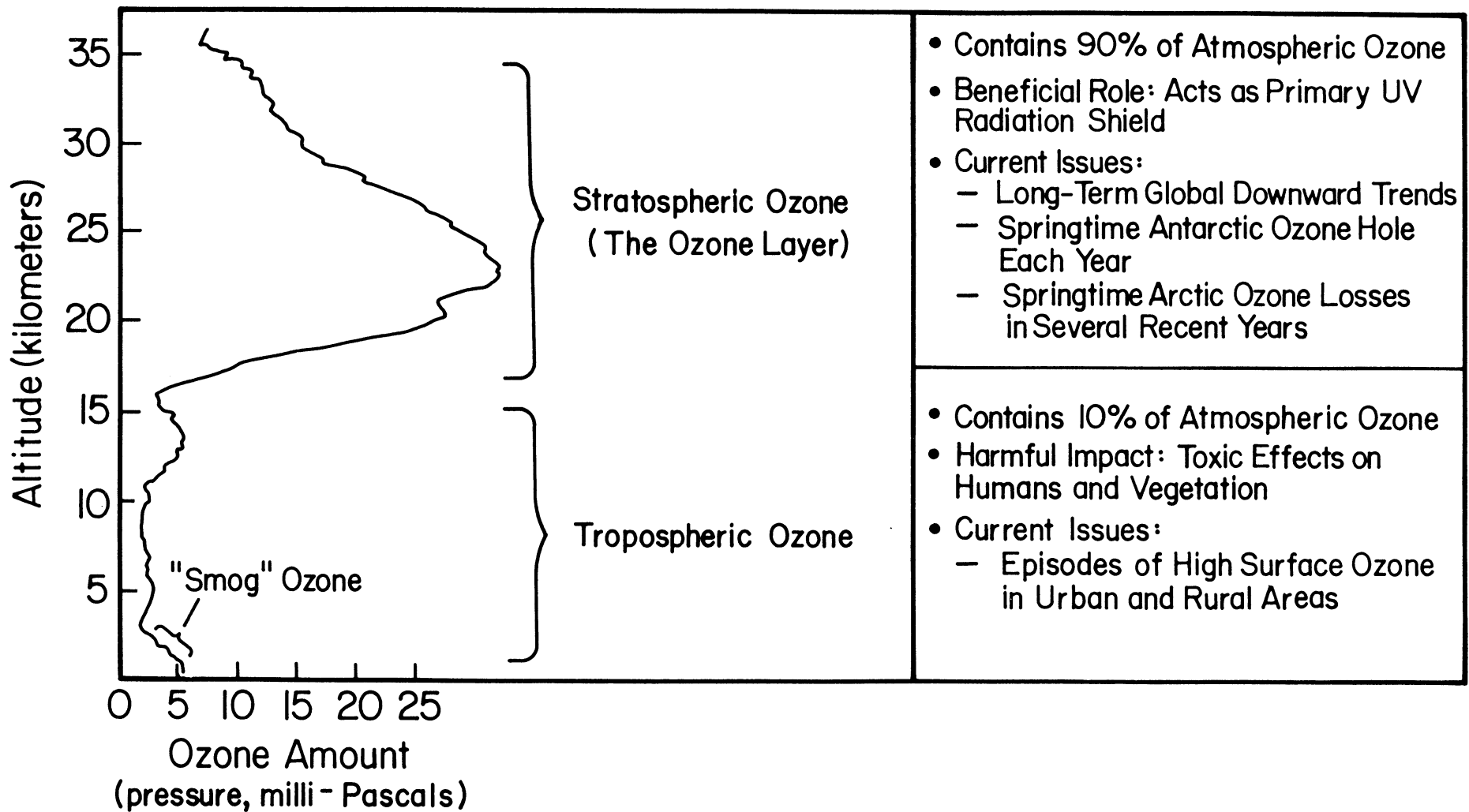
Today I'll focus on the stratospheric mean meridional circulation (tracer transport circulation, Brewer Dobson Circulation, BDC, diabatic circulation, residual circulation), and how we can use constituent measurements to learn about that circulation.

Key measurements: Water, ozone, temperature

Why do we care about stratospheric mean meridional circulation?



Because changes can affect ozone.

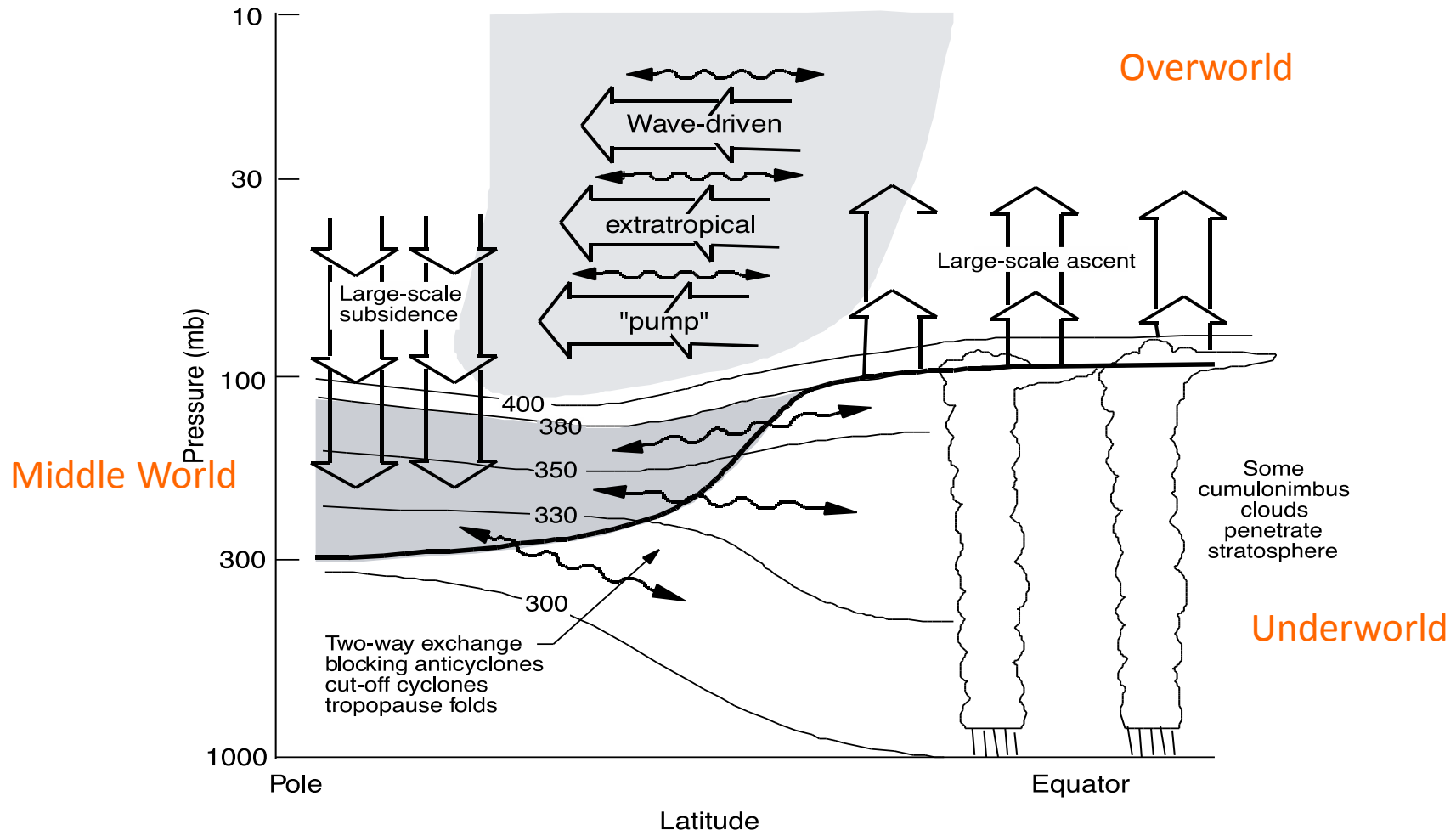


From NOAA info page

<http://www.ozonelayer.noaa.gov/science/basics.htm>

What is the stratospheric mean meridional circulation?

It is commonly referred to in the literature as the Brewer-Dobson circulation.



Schematic from Holton et al., 1995, Review of Geophysics

Fundamentally, the BDC is a **transport circulation**. We're interested in it (and how it changes in a changing climate) because it transports trace species into and out of the stratosphere.

An important thing to note is that it is a Lagrangian-mean circulation, and cannot be directly measured.

Trace species measurements are how the BDC was first inferred.

Prior to taking many measurements in the stratosphere, the general view was that the stratosphere was essentially free from vertical motions, and transport of trace species was a diffusional process.

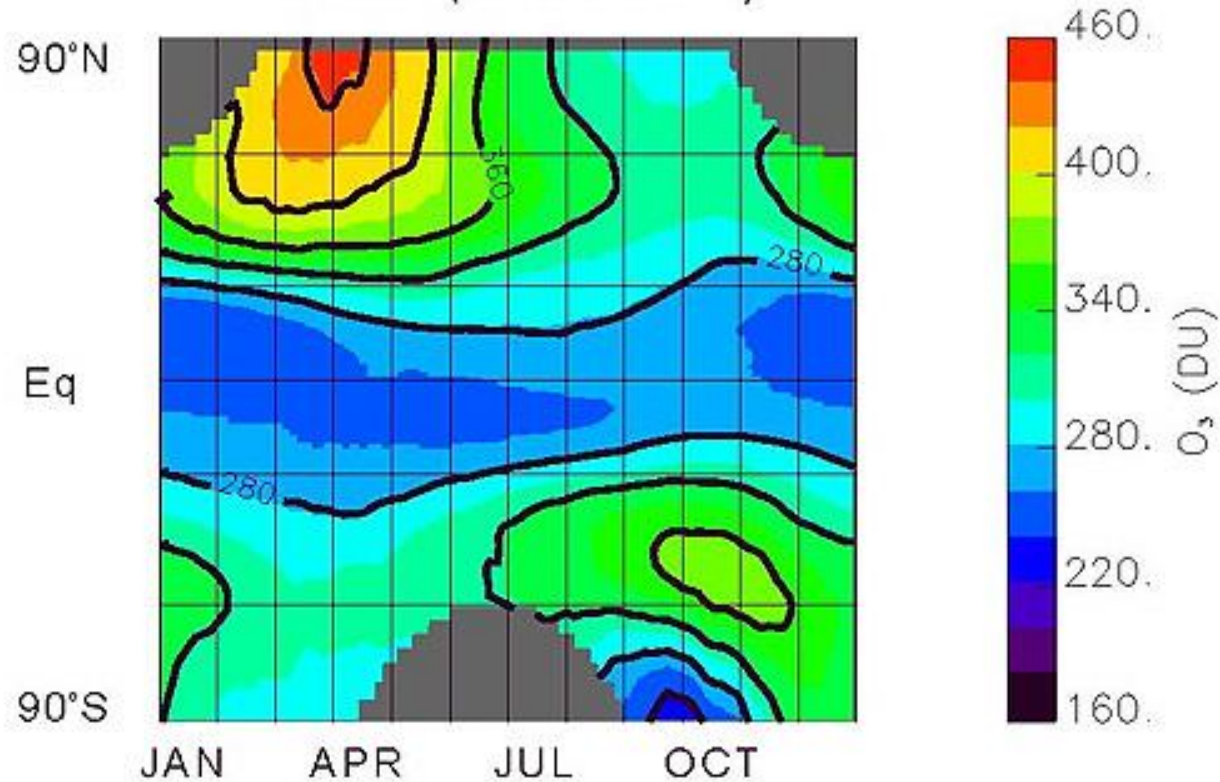
However, this picture was not consistent with the latitudinal gradients in total ozone, or vertical profiles of water vapor taken during the first half of the 20th century.

First line of evidence showing there is a circulation in the stratosphere

Although produced in the tropics, ozone columns are larger at mid to high latitudes.

Also, Dobson (1956) noted high ozone in the lower polar stratosphere, far from the source region.

Mean Annual Cycle of Ozone TOMS (1978-1993)



484 G. M. B. Dobson, D. N. Harrison and J. Lawrence.

troposphere, the observations will not support the hypothesis that the ozone is chiefly formed by sunshine. Again, the Abisko and Lerwick observations

From Dobson, Harrison and Lawrence, 1929, Proc. Roy. Soc. A

Second line of evidence for the sense of the stratospheric circulation: Water Vapor measurements

Alan Brewer developed an aircraft borne frost point hygrometer during WW-II specifically to assess conditions where contrails might form (to determine how to avoid making contrails). They flew on a B-17 (up to 38 Kft) and then a Mosquito (up to 44 Kft), and got just into the stratosphere over the UK.

CONDENSATION TRAILS

By A. W. BREWER, M.Sc.

Weather, 1946, pg 38-40

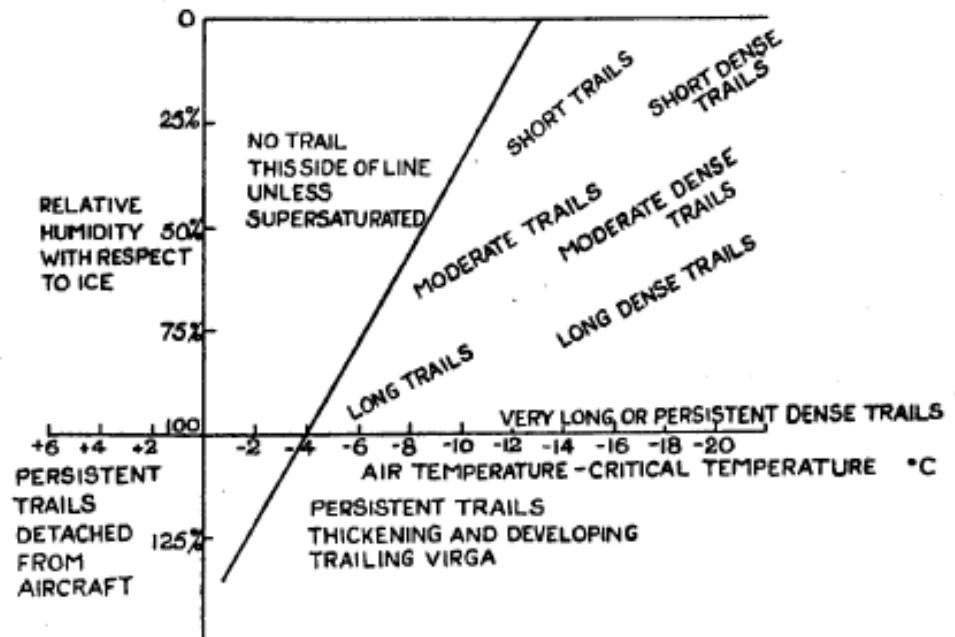


Fig. 3. The variation of condensation trail length with humidity and the depression of the air temperature below the calculated critical temperature.

EVIDENCE FOR A WORLD CIRCULATION PROVIDED BY THE MEASUREMENTS OF HELIUM AND WATER VAPOUR DISTRIBUTION IN THE STRATOSPHERE

By A. W. BREWER, M.Sc., A.Inst.P.

(Manuscript received 23 February 1949)

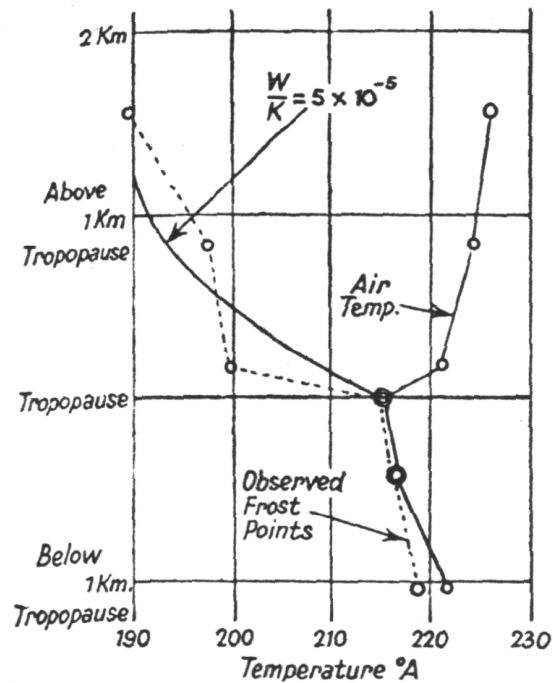
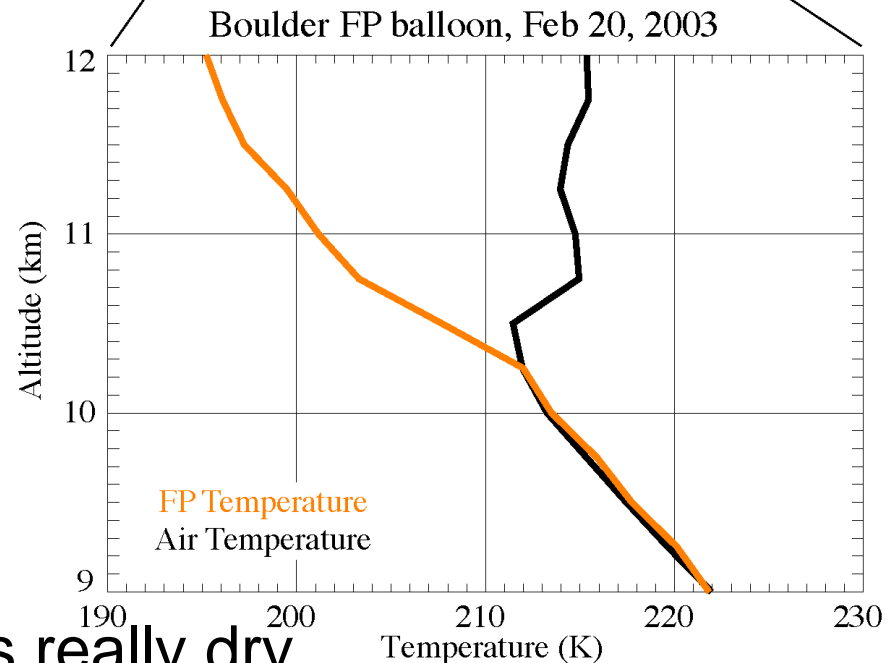
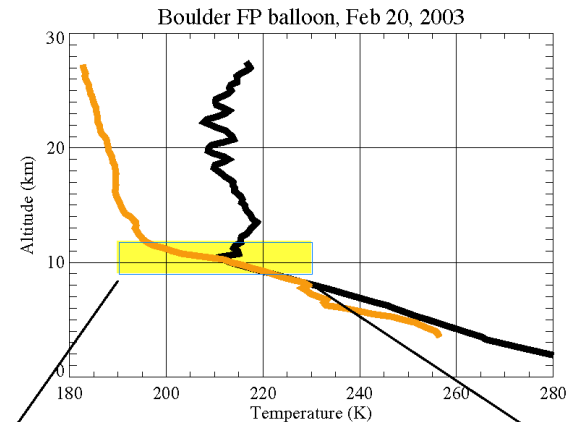


FIG. 1. 30 May 1945. Tropopause ht 33,400 ft.

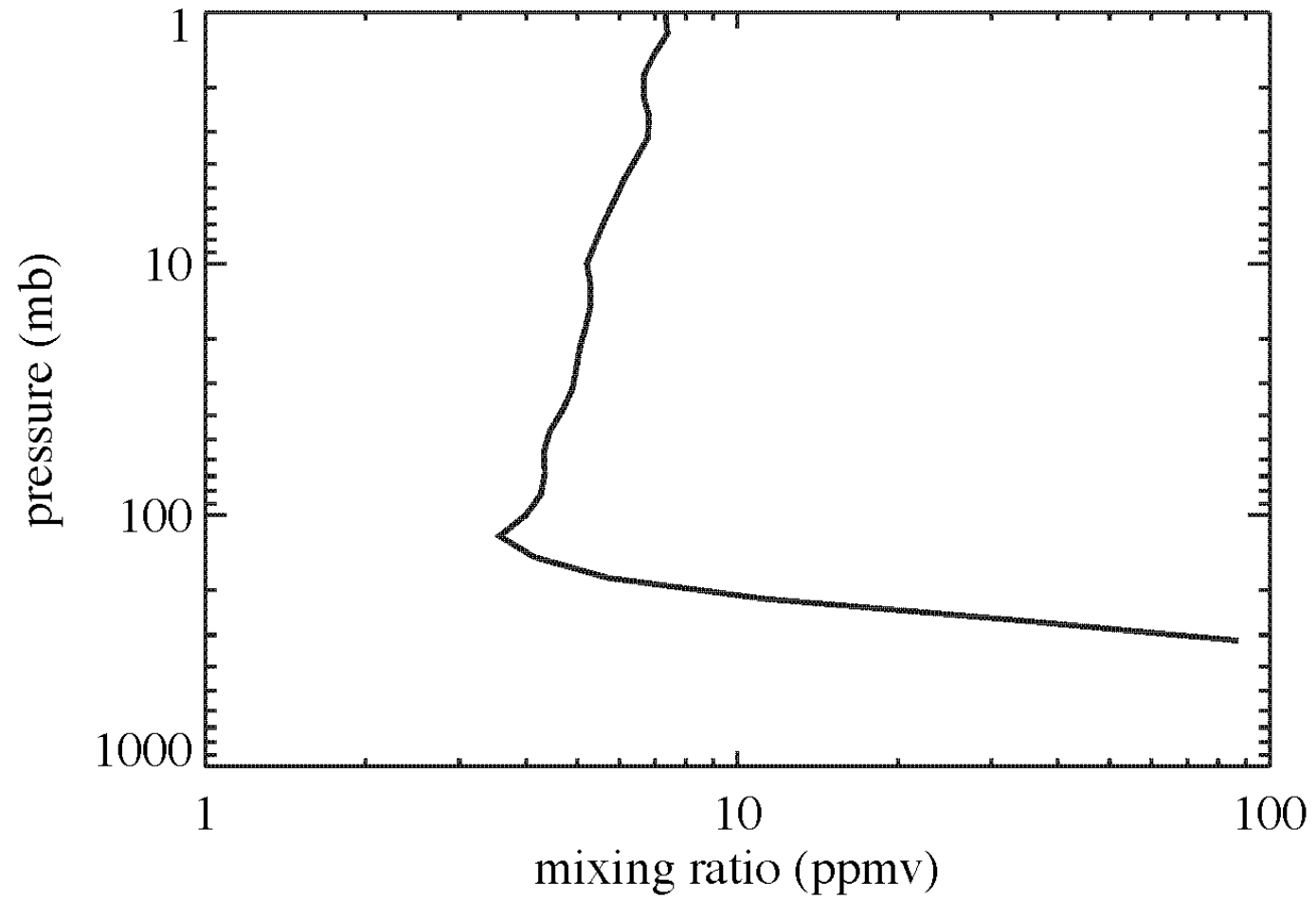
~50°N, 1945, Southern England

~40°N, 2003, Boulder, CO



Bottom line, the stratosphere is really dry.

Jan 2009 35N MLS H2O

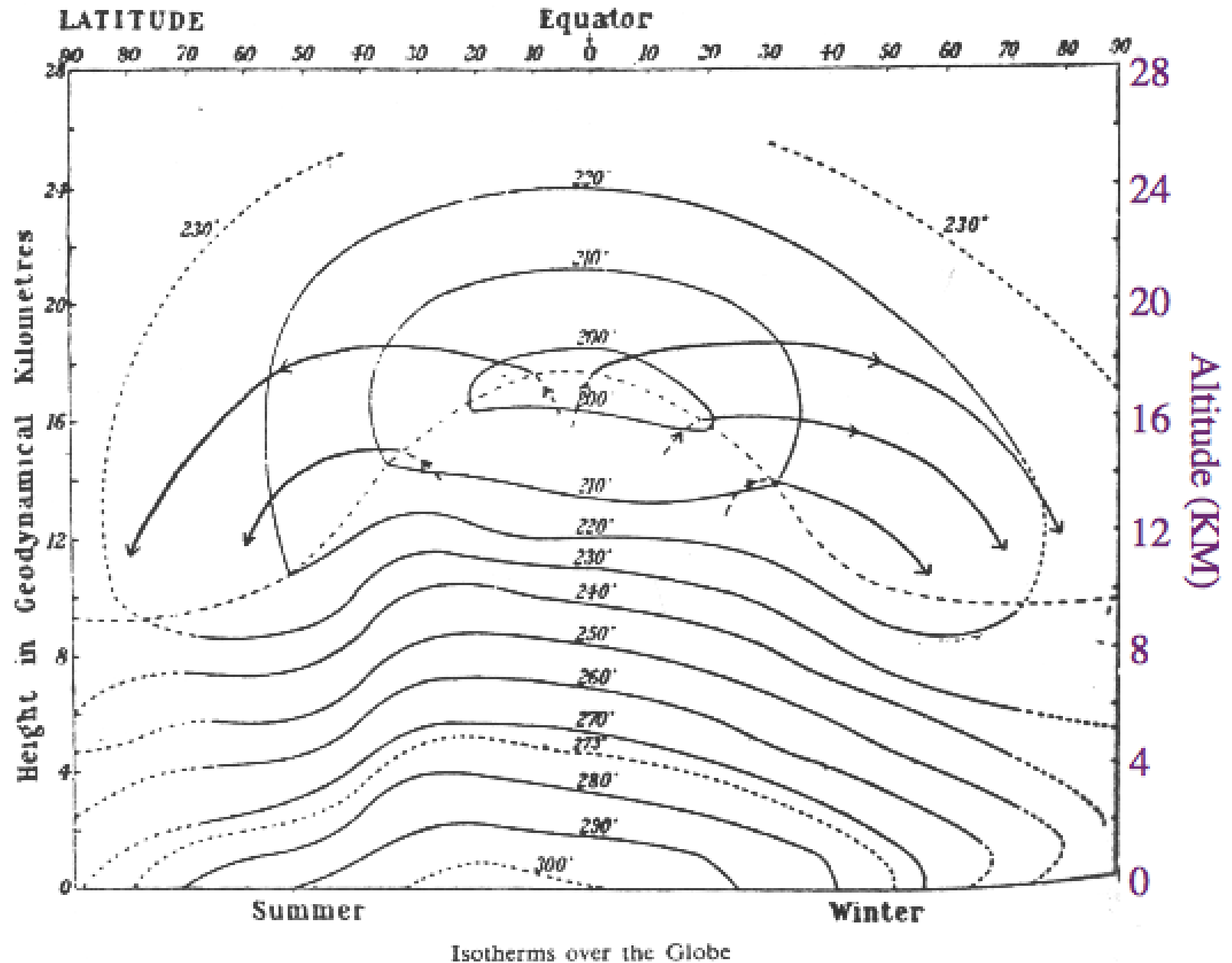


Brewer (1949) noted that the stratosphere sampled over the UK in the lower stratosphere was much drier ($\sim 3\text{-}5$ ppmv) than the local minimum temperatures would produce (~ 50 ppmv).

Because this air was drier than ice saturation over the UK, that implied that air came from someplace else.

The only location Brewer knew of where temperatures were cold enough was near the tropical tropopause. (This was further refined by R. Newell and S. Gould-Stewart (1981) who looked at specific cold regions in the tropics.)

The mean meridional circulation from Brewer 1949



Murgatroyd and Singleton (1961) calculated what's come to be known as the diabatic circulation, and obtained similar results. The idea fell out of favor during the 60s when a more Eulerian-based viewpoint was popular.

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R. J. MURGATROYD and F. SINGLETON

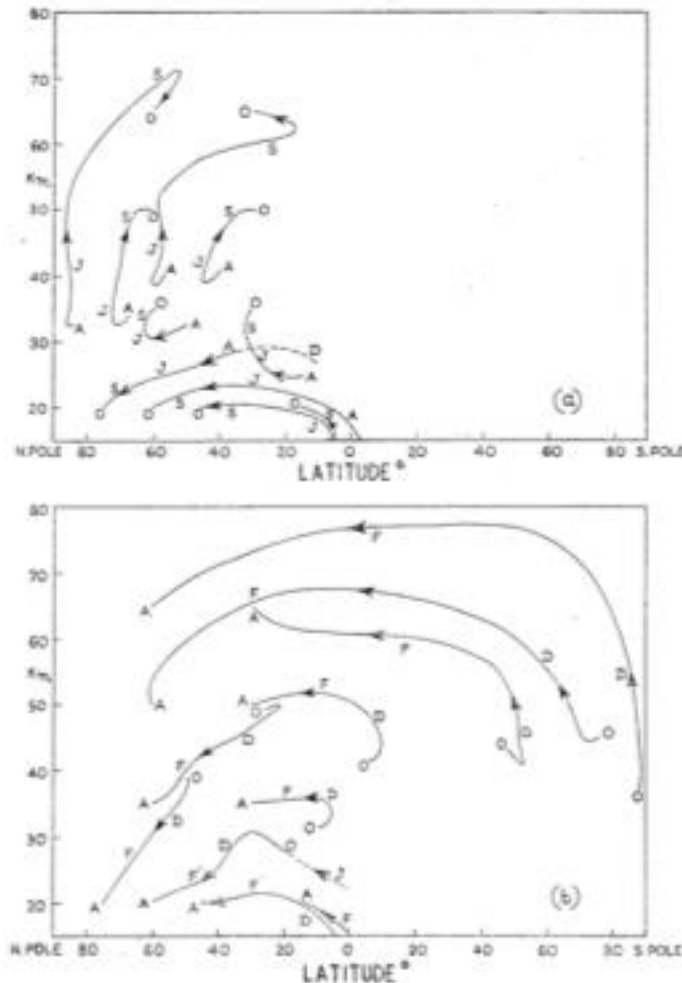


Figure 3. Selected air trajectories over six-monthly periods. Upper diagram shows trajectories ending in summer, lower in spring in northern hemisphere. Dashed lines indicate movement in preceding six months. F denotes February position, A April, J July, S September, O October, D December.

A problem remained that tracers indicated a thermally direct cell from equator to pole, but observations (ie Vincent (1968), showed flow in the opposite direction at midlatitudes.

Dunkerton, 1978, JAS, Volume 35, “On the Mean Meridional Mass Motions of the Stratosphere and Mesosphere

ABSTRACT

Using a simplified, approximate “Lagrangian-mean” dynamical formulation, the mean meridional mass circulation of the stratosphere and mesosphere is discussed. Under solstice conditions, it is shown that this Lagrangian-mean circulation may be inferred, as a first approximation, from the Eulerian-mean diabatic heating. Diabatic heating rates for the solstices, originally derived by Murgatroyd and Goody (1958), result in Lagrangian-mean rising motion at the tropical tropopause, subsidence across the extra-tropical tropopause, and a very strong summer-to-winter pole flow in the mesosphere. This circulation is exactly that obtained by Murgatroyd and Singleton (1961) for the solstices. Those authors, however, attempted to identify this circulation as the Eulerian-mean motion, and were later criticized for their neglect of the meridional eddy heat flux in the calculation, which proved to be extremely important in the winter hemisphere. The present study, nevertheless, indicates that Murgatroyd and Singleton’s circulation may in fact be representative of actual air parcel motions in the stratosphere and mesosphere.

Key point: You don’t need to know the heat and momentum fluxes to ascertain the zonal mean mass transport (Lagrangian quantity), but do to deduce the zonal mean Eulerian circulation.

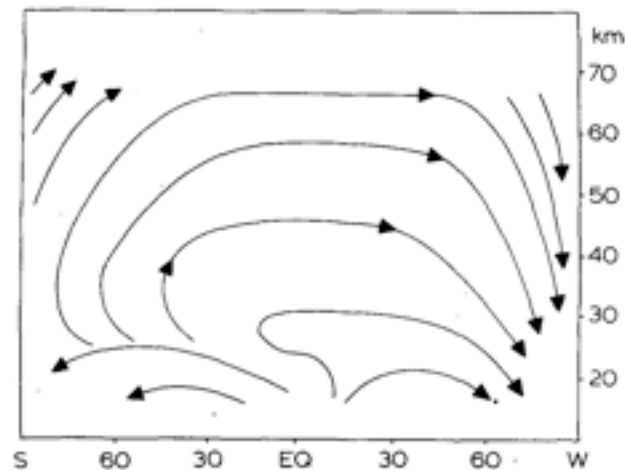


FIG. 4. Streamlines associated with Lagrangian-mean velocities.

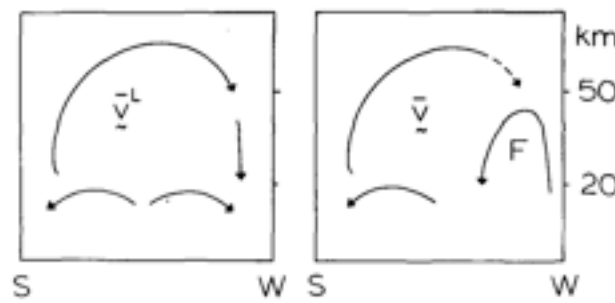


FIG. 6. The fundamental distinction between Lagrangian (left) and Eulerian (right) mean meridional circulations at the solstices. The Eulerian circulation includes a wave-induced Ferrel cell (F) which has little relevance to mass transport, since it is opposed by the Stokes’ drift due to the eddies.

Tracer observations ultimately led to our understanding of the mass transport in the stratosphere, elegantly interpreted by Alan Brewer in 1949.

This represents Lagrangian-mean motion. It can be approximated with the Transformed-Eulerian Mean Residual circulation (from Andrews and McIntyre), which can be expressed as:

$$\bar{v}^* = \bar{v} - \frac{1}{\rho_0} \frac{\partial}{\partial z} (\rho_0 \overline{v' \theta'} / \bar{\theta}_z)$$

$$\bar{w}^* = \bar{w} + \frac{1}{a \cos \phi} \frac{\partial}{\partial \phi} (\cos \phi \overline{v' \theta'} / \bar{\theta}_z).$$

Dunkerton's realization that this is effectively the same as the diabatic circulation first estimated by Murgatroyd and Singleton allowed the formulation of the middle atmosphere 2D models used in ozone depletion calculations.

How does the BDC vary?

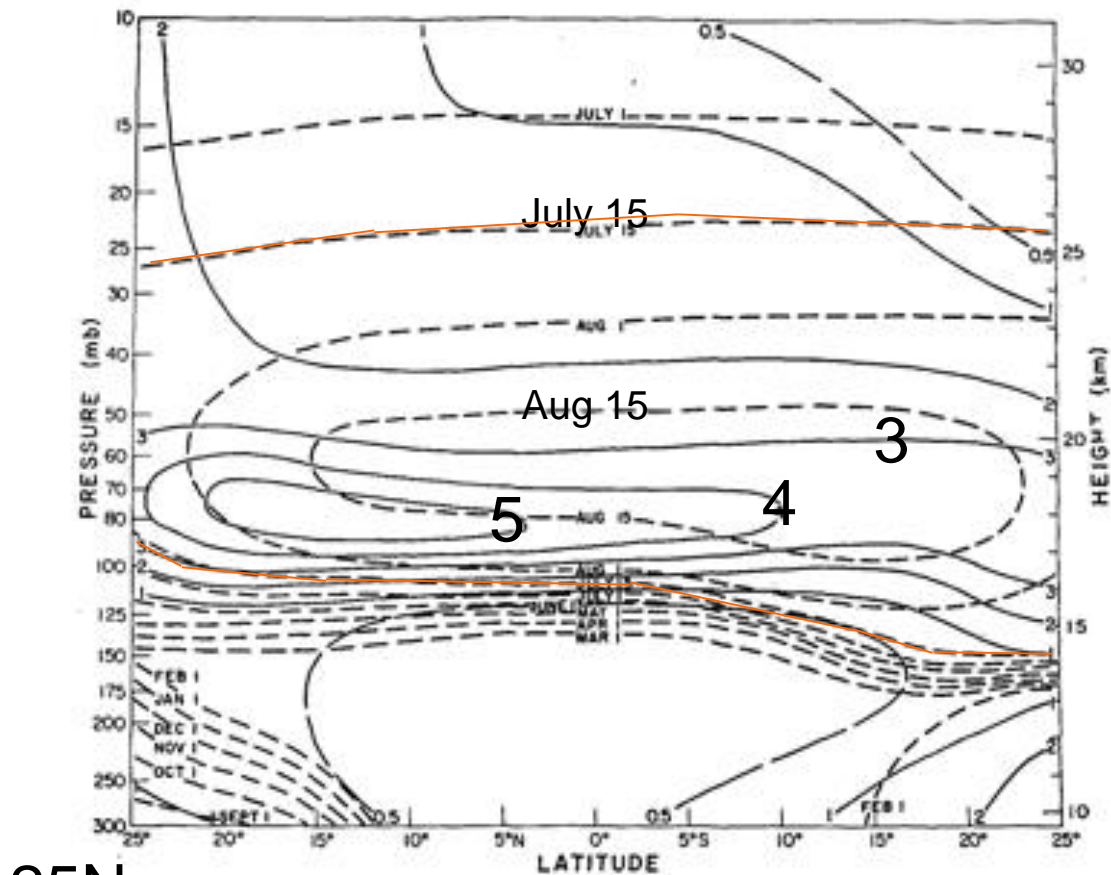
Because the BDC is not directly measurable, and global wind and flux measurements are hard to come by, tracers and temperature have been used to look at trends and variability.

Annual cycle in tropical cold point temperatures:

10 mb

100 mb

300 mb



Based on
radiosonde
record

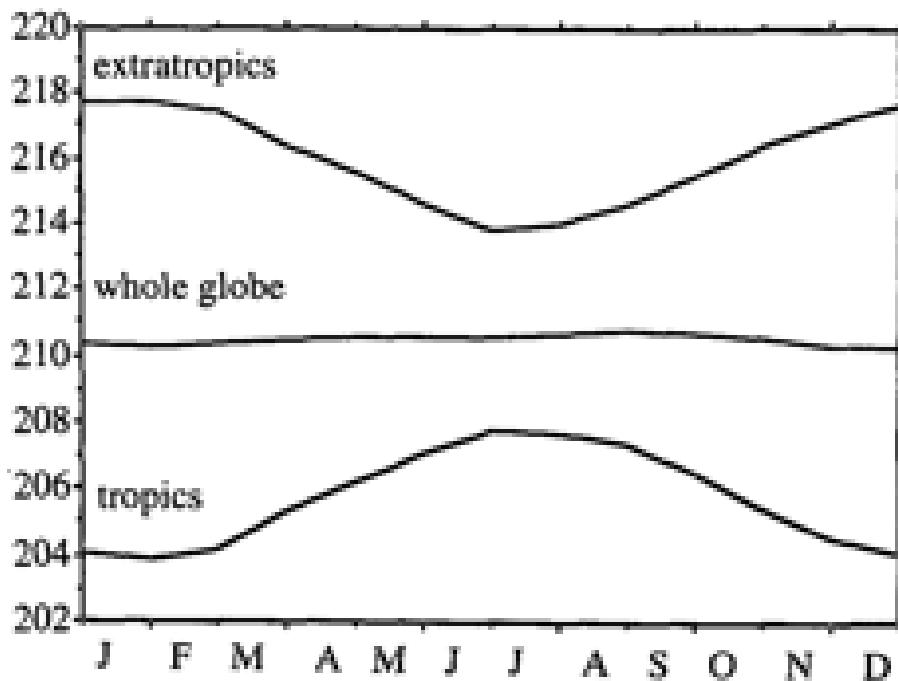
25N

25S

FIG. 1. Amplitude and timing of the peak of the annual temperature cycle as a function of latitude and height, based on harmonic analysis of extended records of radiosonde data. After Reed and Vleck (1969).

related to the annual variation in strength in the Brewer-Dobson circulation (from Reed and Vleck, 1969)

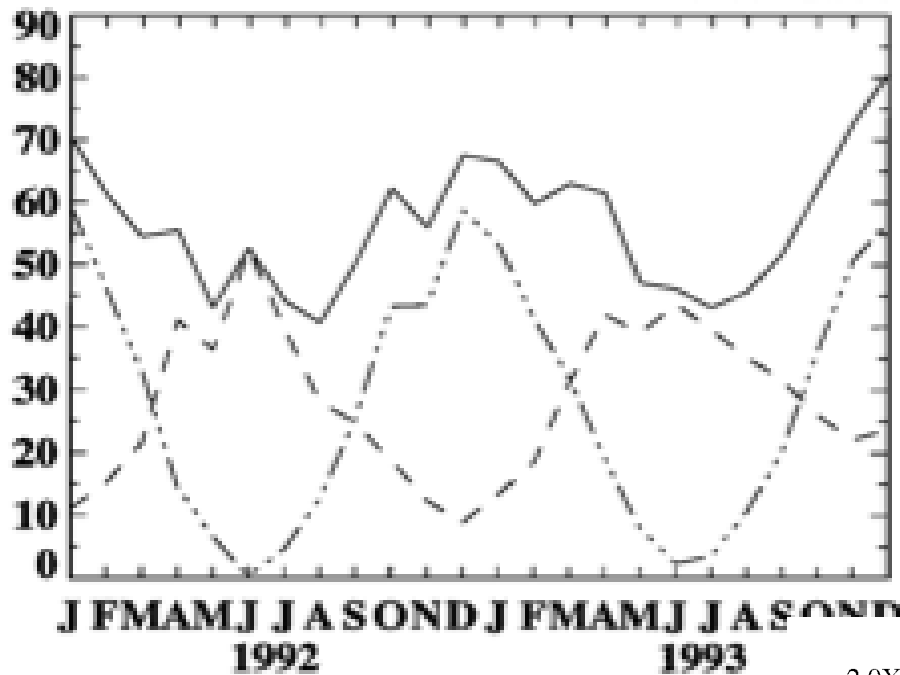
Yuleava et al, 1994 studies this in more detail. They concluded that the annual variation in lower stratosphere tropical temperatures was due to an annual variation in tropical upwelling in the BDC.



MSU Channel 4
Temperature
data centered at
around 70 mb

FIG. 2. Climatological mean annual march of lower-stratospheric temperature based on MSU-4 data for the period 1979-91, averaged over the tropics (30°S - 30°N), the extratropics (poleward of 30°S and 30°N), and the entire globe.

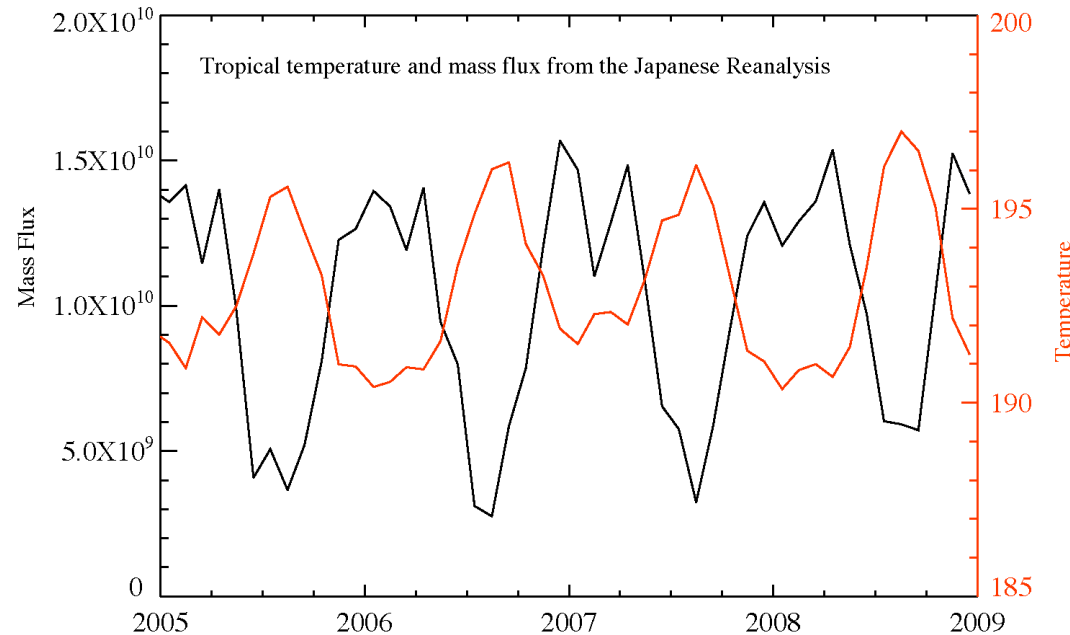
Mass flux across the 70 mb surface



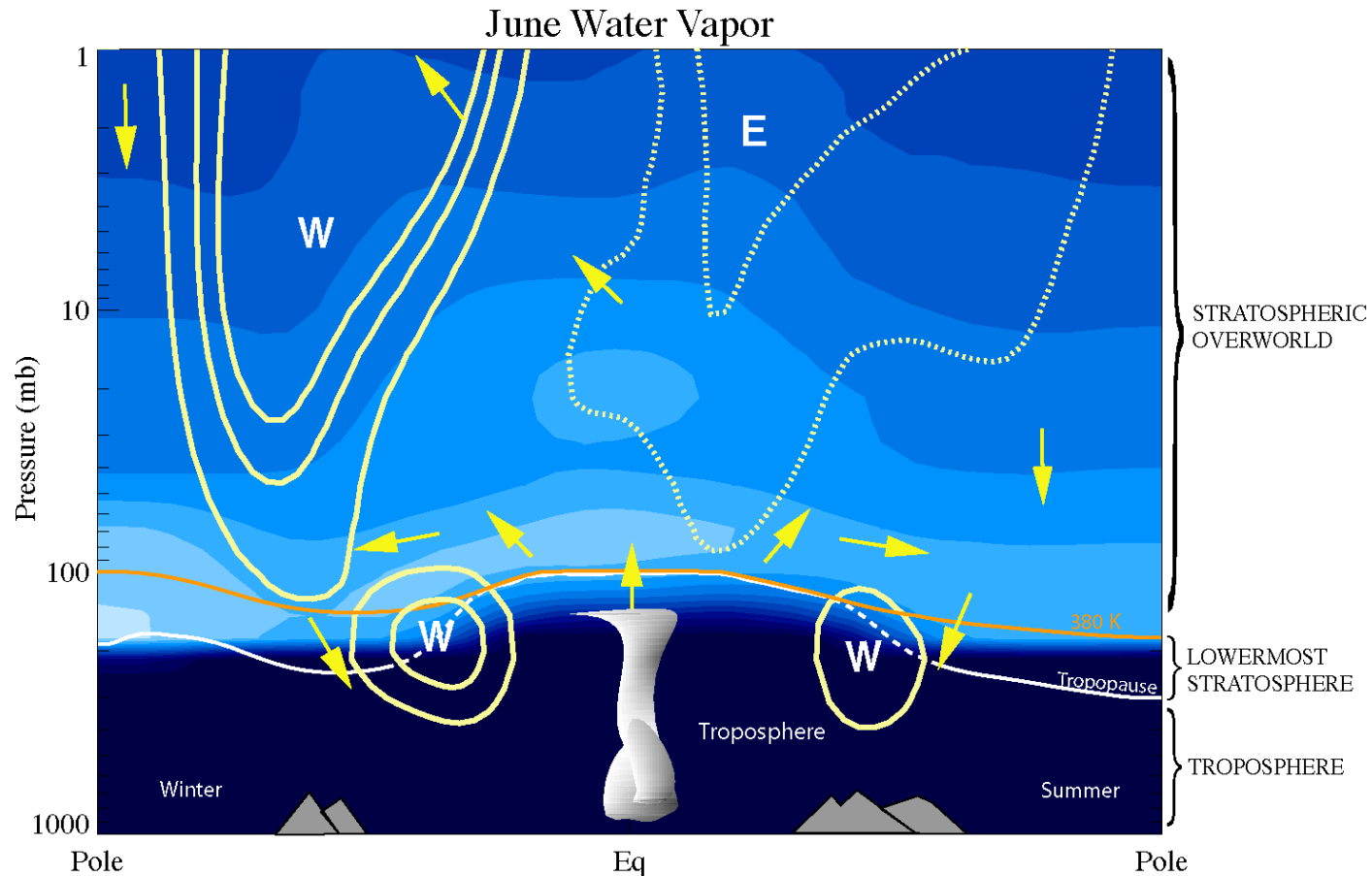
Below: shows mass flux and temperature relationship

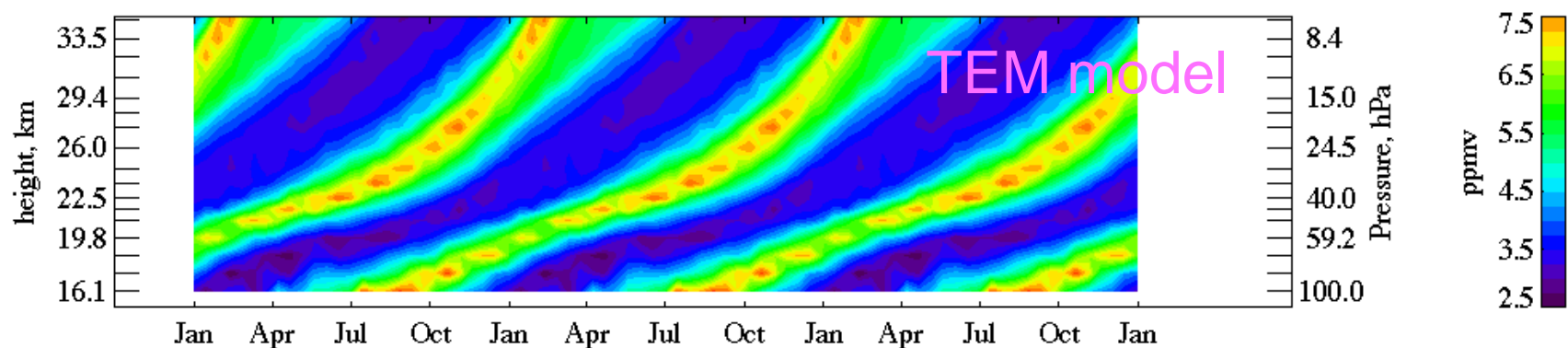
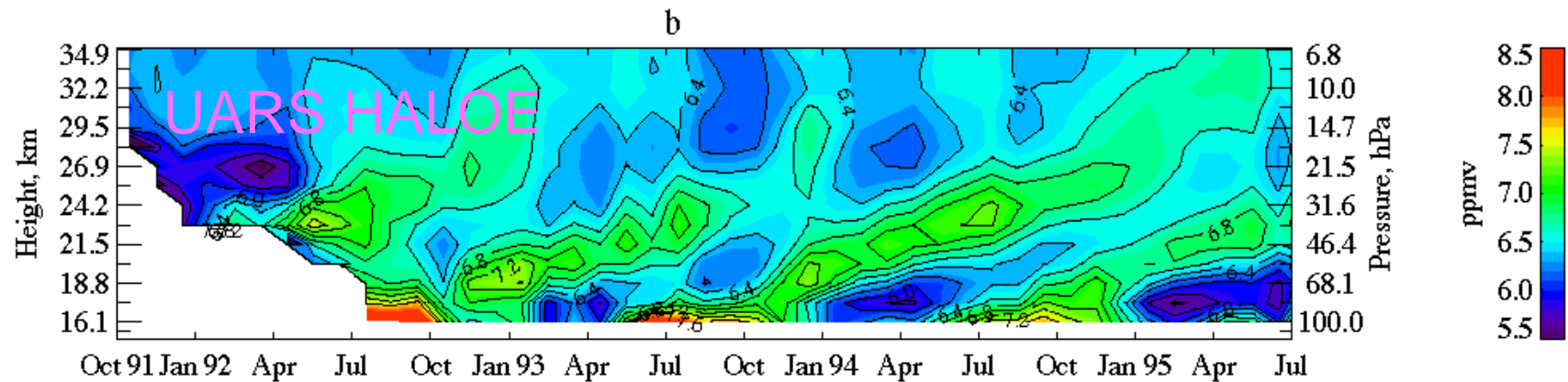
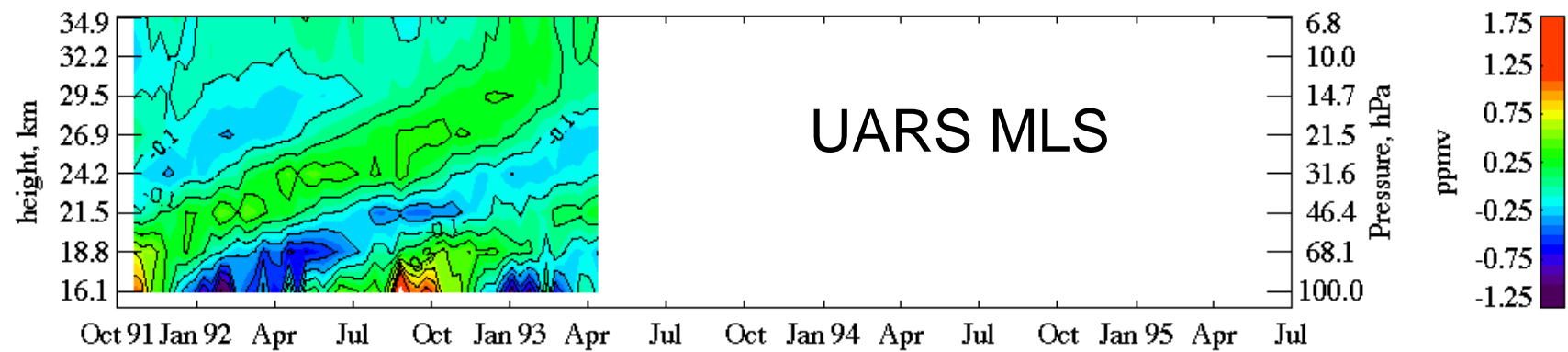
Figure 14. Time series of mass flux across the 70 mb surface in units of 10^8 kg/s computed from the stream function. Solid curve is the net upward flux; dotted-dashed curve is downward flux into the Northern Hemisphere; dashed curve is downward flux into the Southern Hemisphere.

Seasonal cycle lower stratospheric mass flux



Water vapor is impacted on the annual cycle both via cycles in tropical cold point temperature (entry values) and via variations in the global Lagrangian mean circulation (at higher latitudes and higher altitudes)



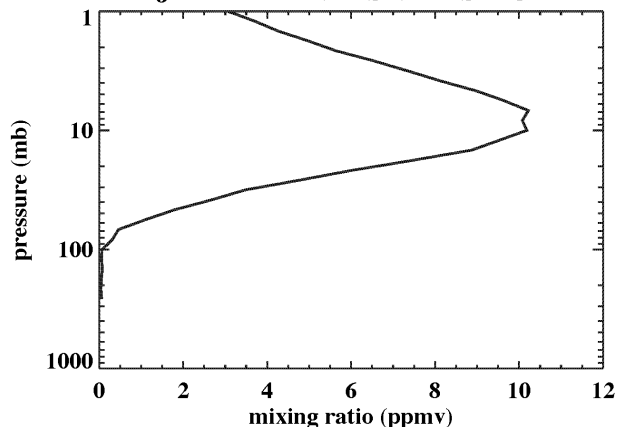


Tropical tape recorder, Mote et al, 94&95

Ozone in the lower stratosphere also shows variability related to BDC strength as well...ie, annual cycle

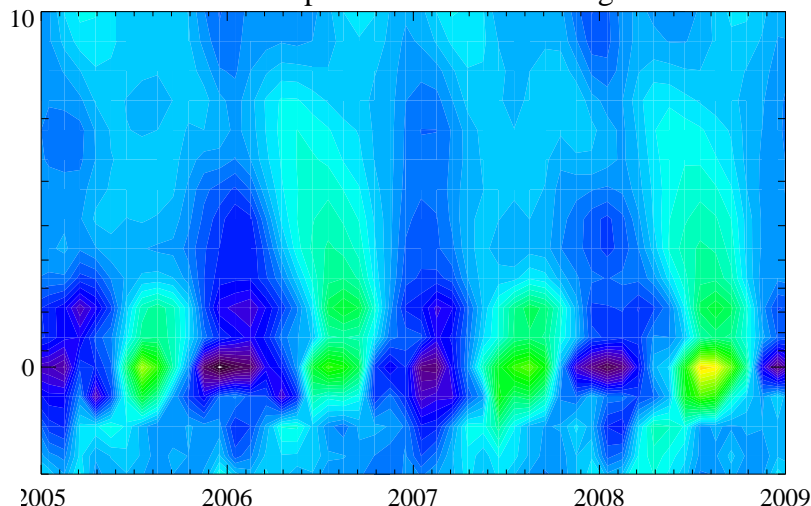
Essentially a flux related pattern

Jan 2009 10N-10SN MLS HO3



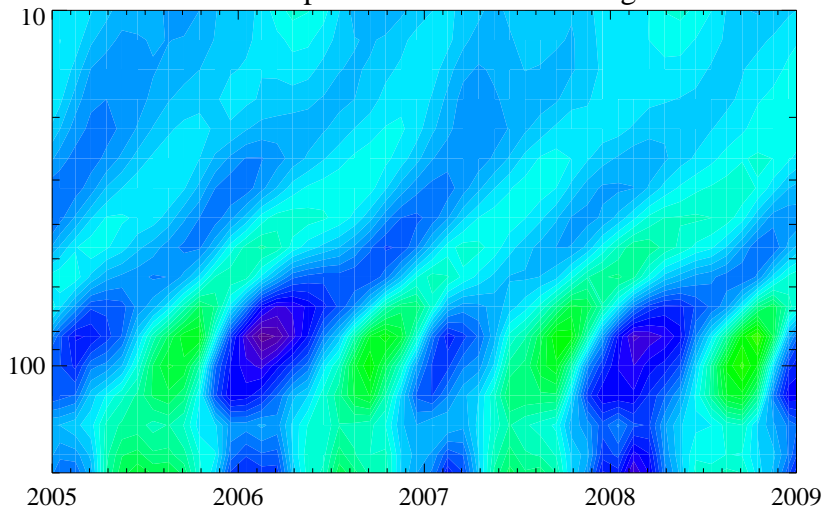
Essentially a temperature related pattern.

MLS tropical O3/annual average



MLS O3
normalized

MLS tropical H2O/annual average



MLS H2O
normalized.

Observational evidence of a BDC change

Case Study: change at the end of 2000

(Rosenlof and Reid, JGR, 2008)

Note: this is a step change, not a gradual GHG related change implied in model studies.

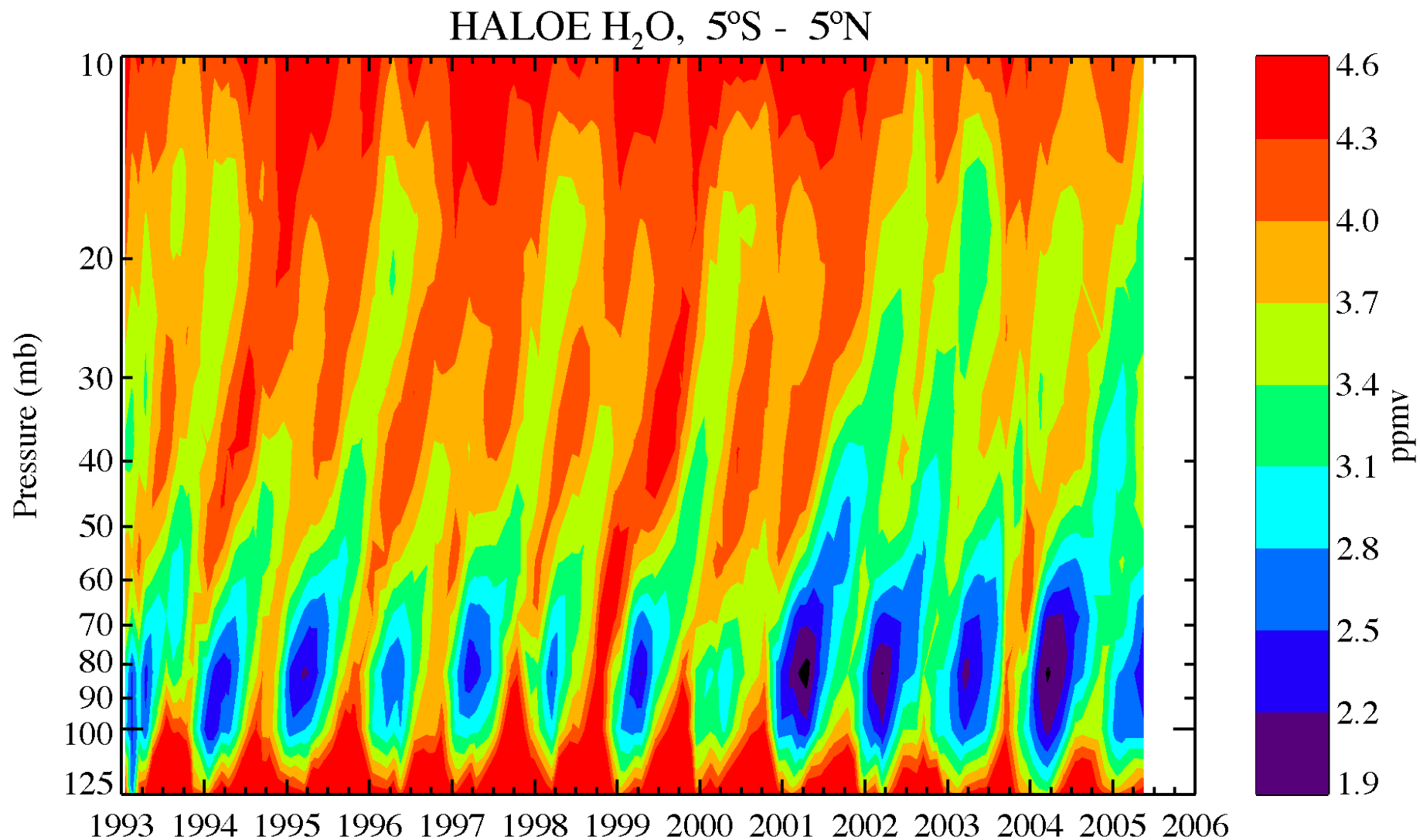
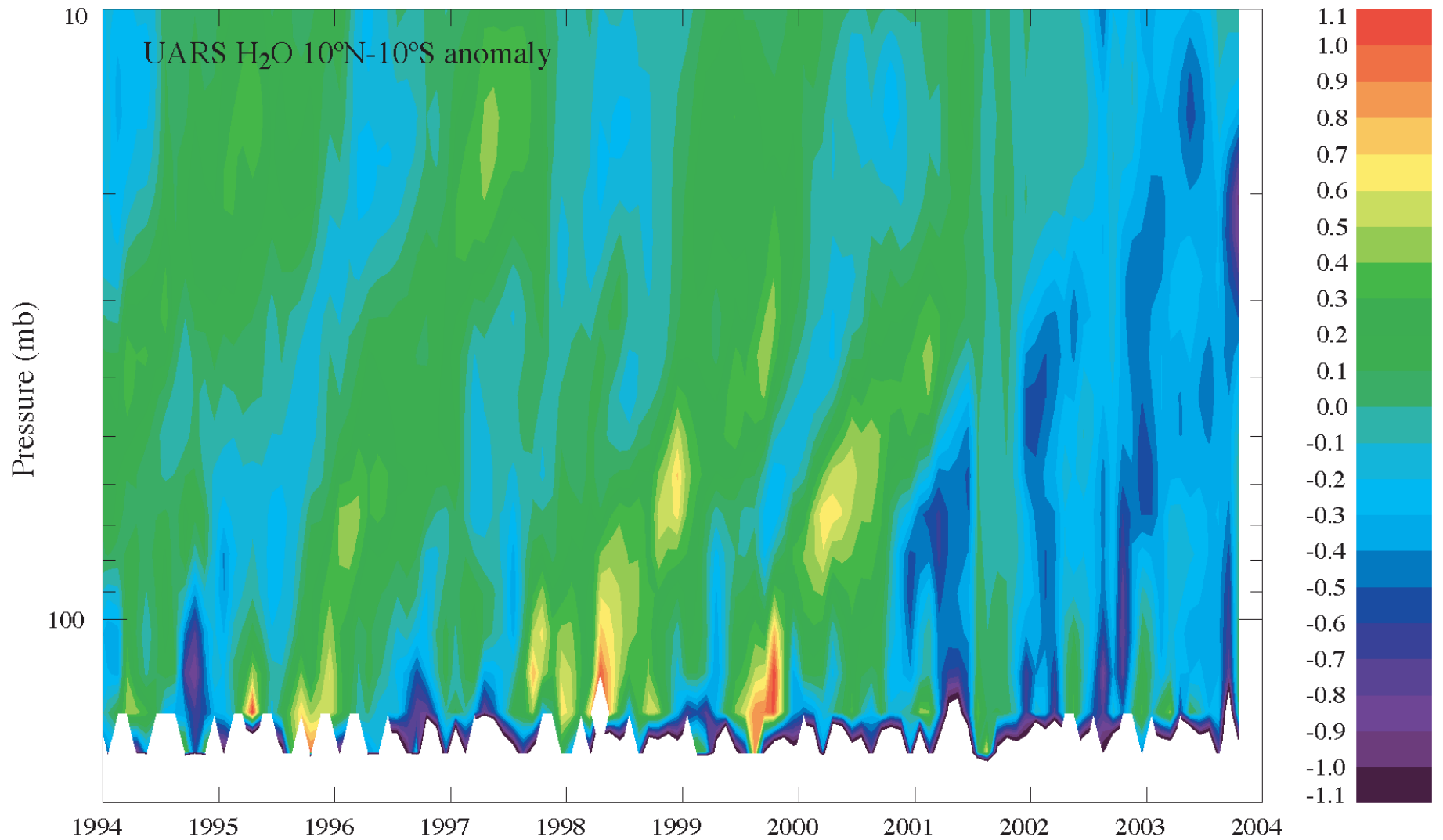
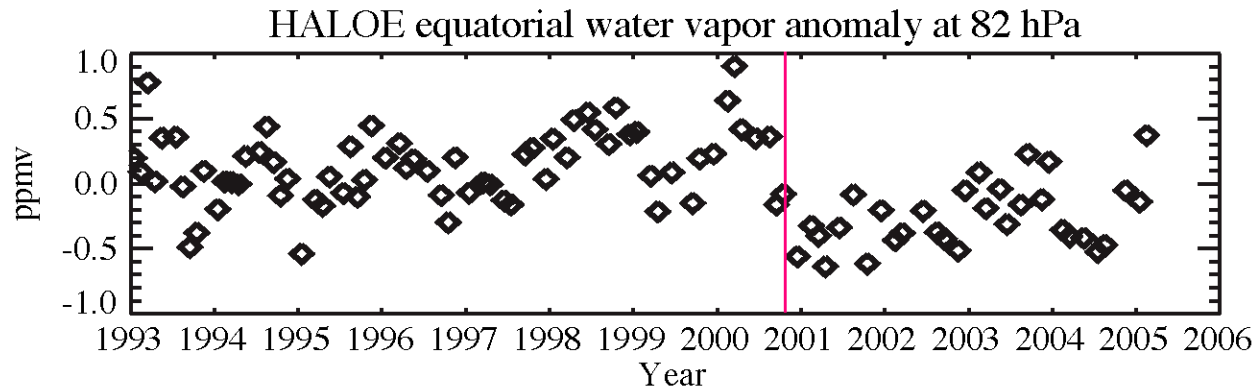


Figure 10. Tropical HALOE water vapor (tape recorder), 5°S-5°N, plotted versus time. Note the change to lower values of the hygropause at the end of 2000, and the upward propagation of those lower values in subsequent years.

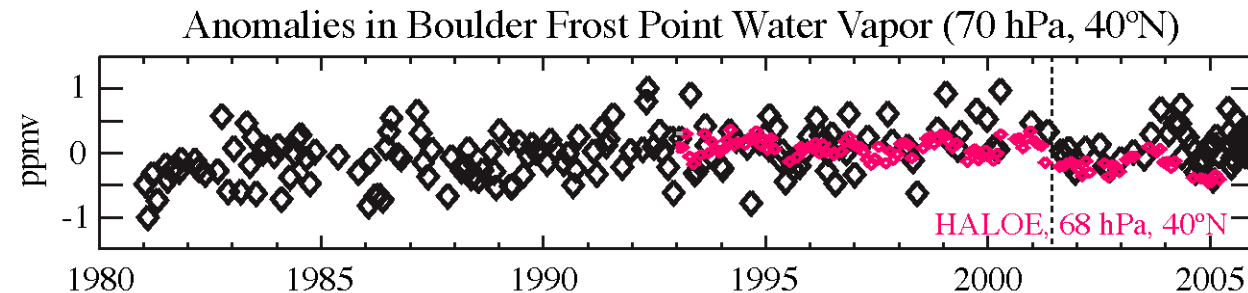
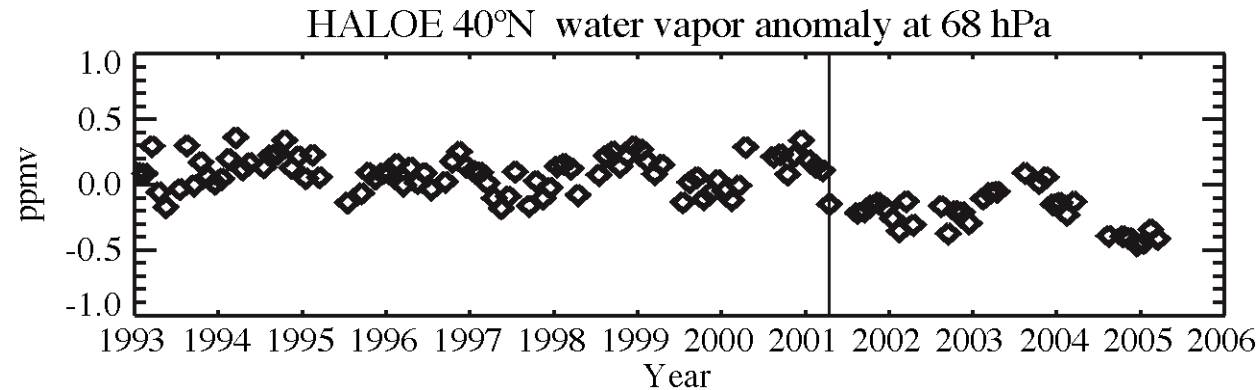


Tropical water vapor anomalies, HALOE

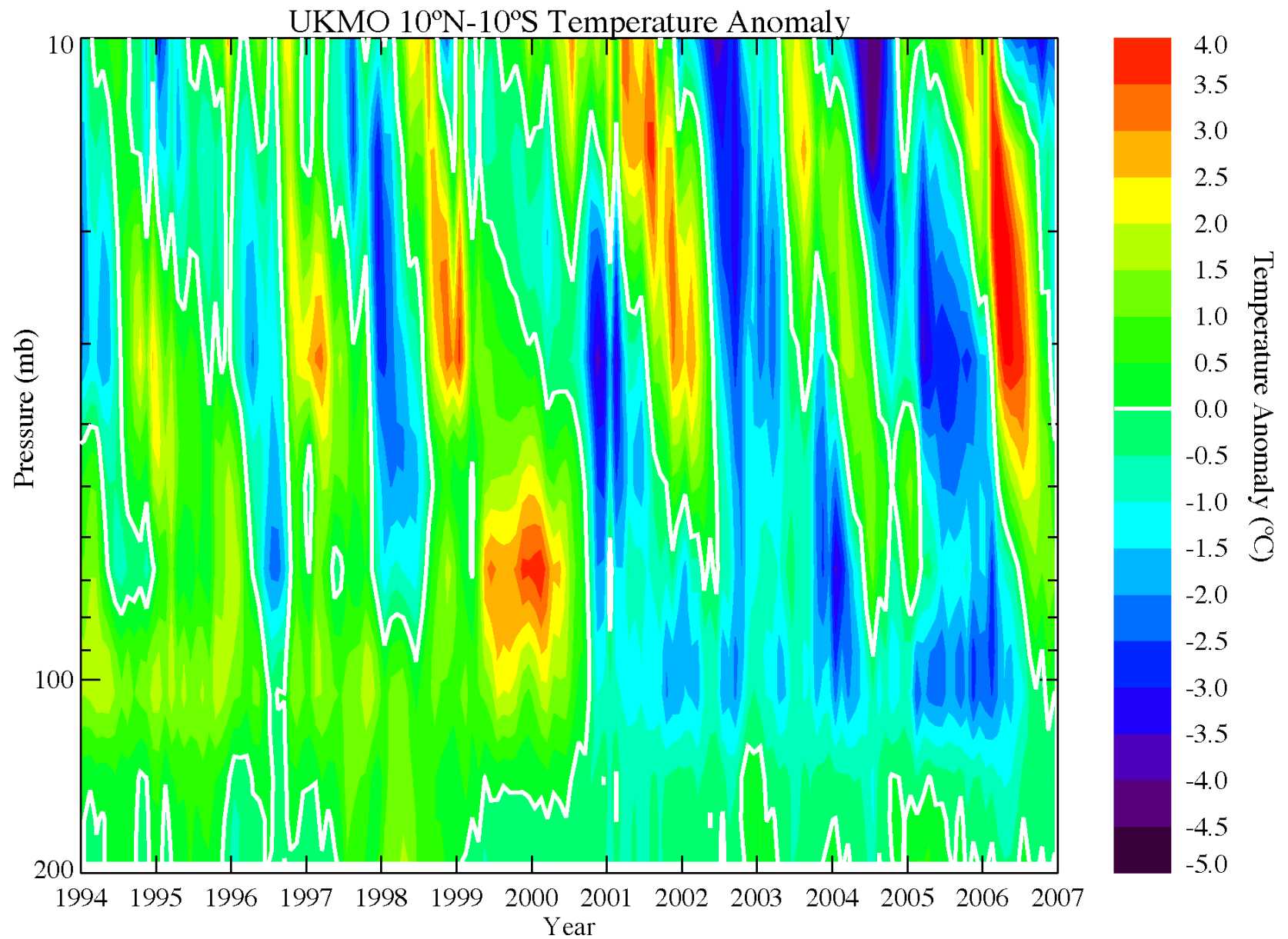
tropics



40N



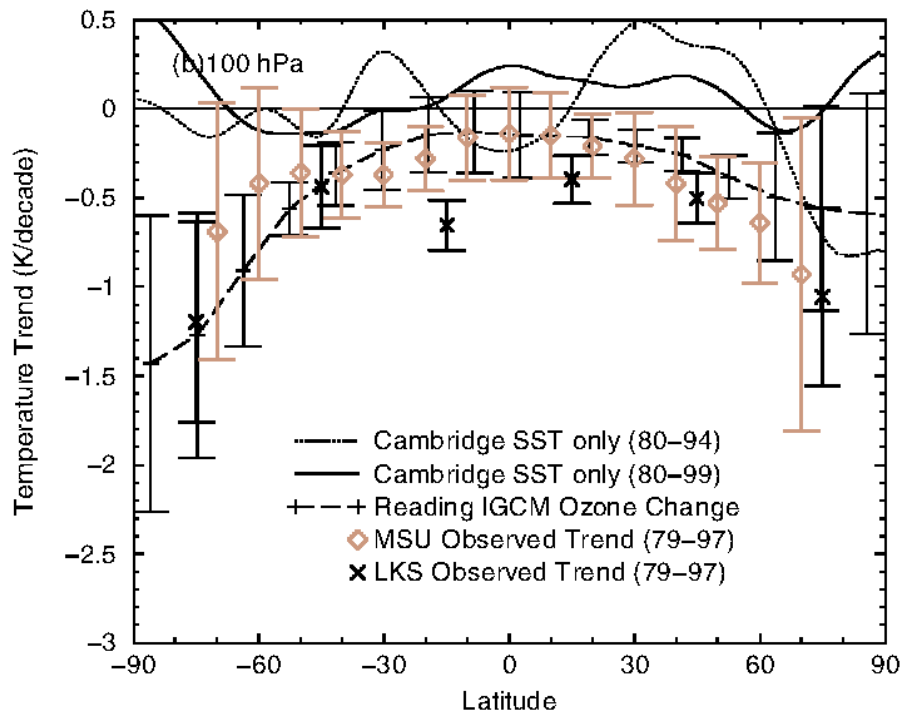
Propagates poleward and present in multiple data sets.



Tropical temperature anomalies

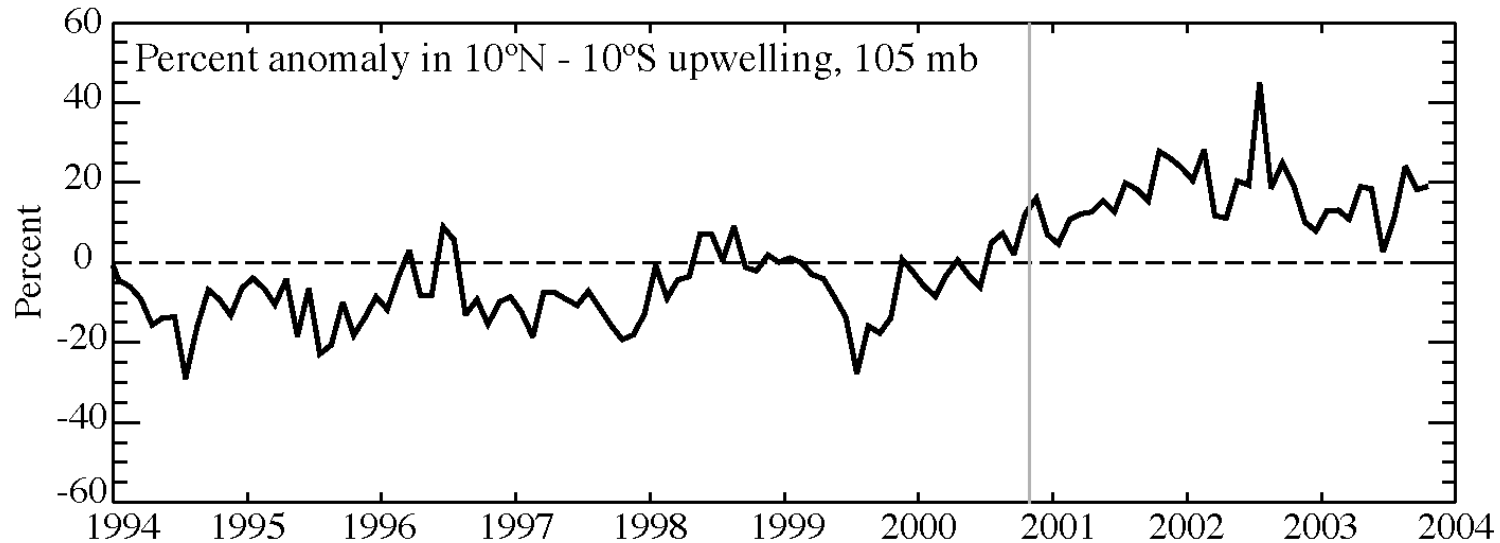
In a zonally averaged sense it is clear that

1) Temperatures dropped at the tropical cold point at the end of 2000. The drop is on the order of 2°C zonally averaged. As comparison, the annual cycle has a peak to peak amplitude at the tropopause of $5\text{-}6^{\circ}\text{C}$.



from Shine et al (2003), shows temperature trends per decade at 100 mb (larger trends at higher levels in the stratosphere)...changes modeled here are due to ozone and greenhouse gas changes

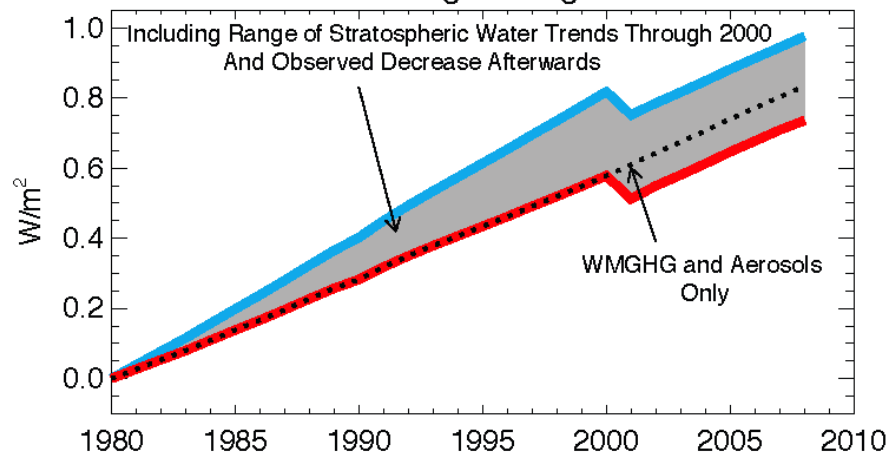
LKS = Lanzante, Klein and Seidel, J. Climate, 2003



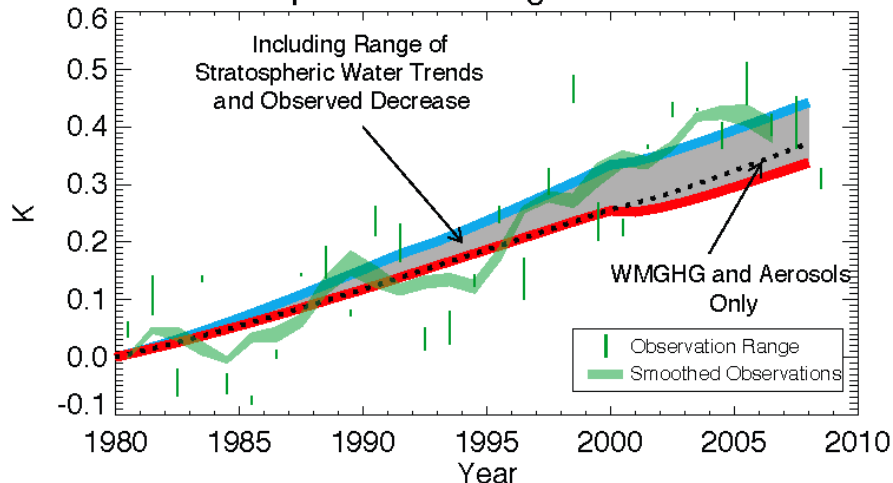
Associated with the temperature change was a change in the strength of the BDC near the tropical tropopause.

Could this have an impact on climate?

Radiative Forcing Change From 1980



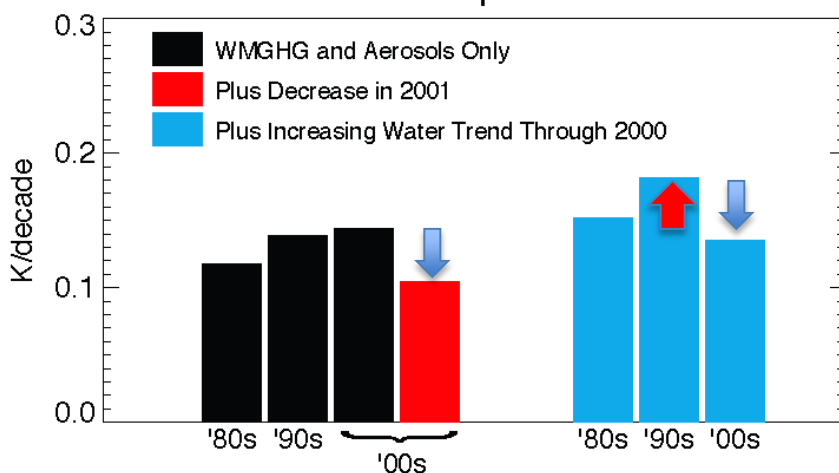
Temperature Change From 1980



Small...but did provoke some additional work on stratospheric water vapor feedback

- 25% less warming in the 00s (lots of data)
- 30% more warming in the 90s (Data uncertainties)
- significant effects on decadal changes in global warming
- Climate feedback or natural variability?

Impact of Stratospheric H₂O Changes on Decadal Temperature Trends



Impose H₂O RF from the obs
in the Bern 2.5cc EMIC

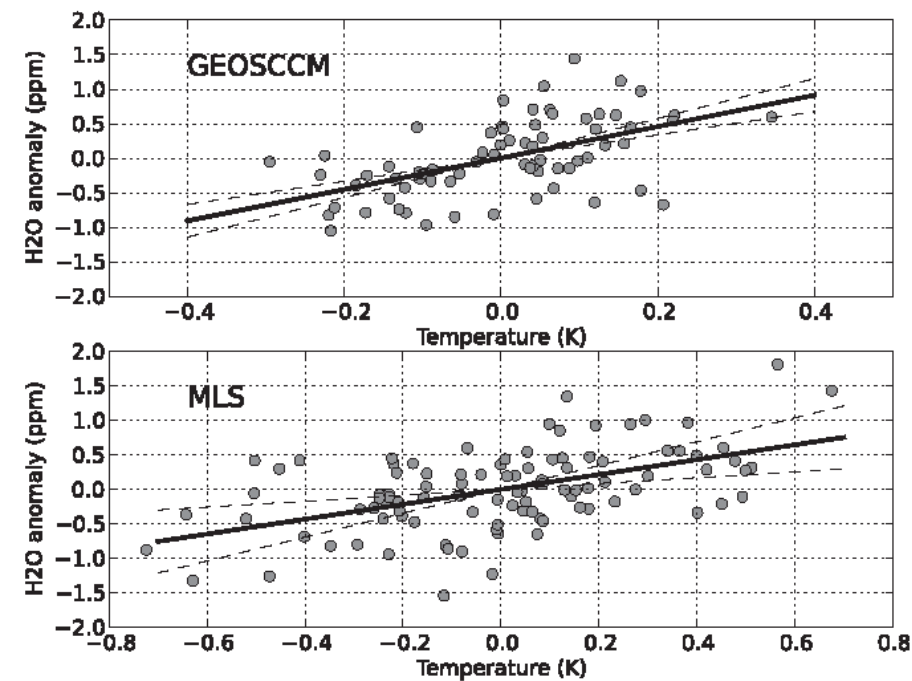


Fig. 3. Scatter plots of (*Upper*) GEOSCCM annual-average lowermost stratospheric H₂O (200-hPa mixing ratio, averaged between 50°N and 90°N) vs. extratropical tropospheric temperature (500-hPa temperature, averaged between 30°N and 90°N) and (*Lower*) the corresponding scatterplot of MLS monthly average H₂O vs. MERRA temperatures. For these plots, the GEOSCCM data have been filtered to remove long-term (>10 y) variations. The solid line is the least-squares fit, and the dashed lines are the 95% confidence interval.

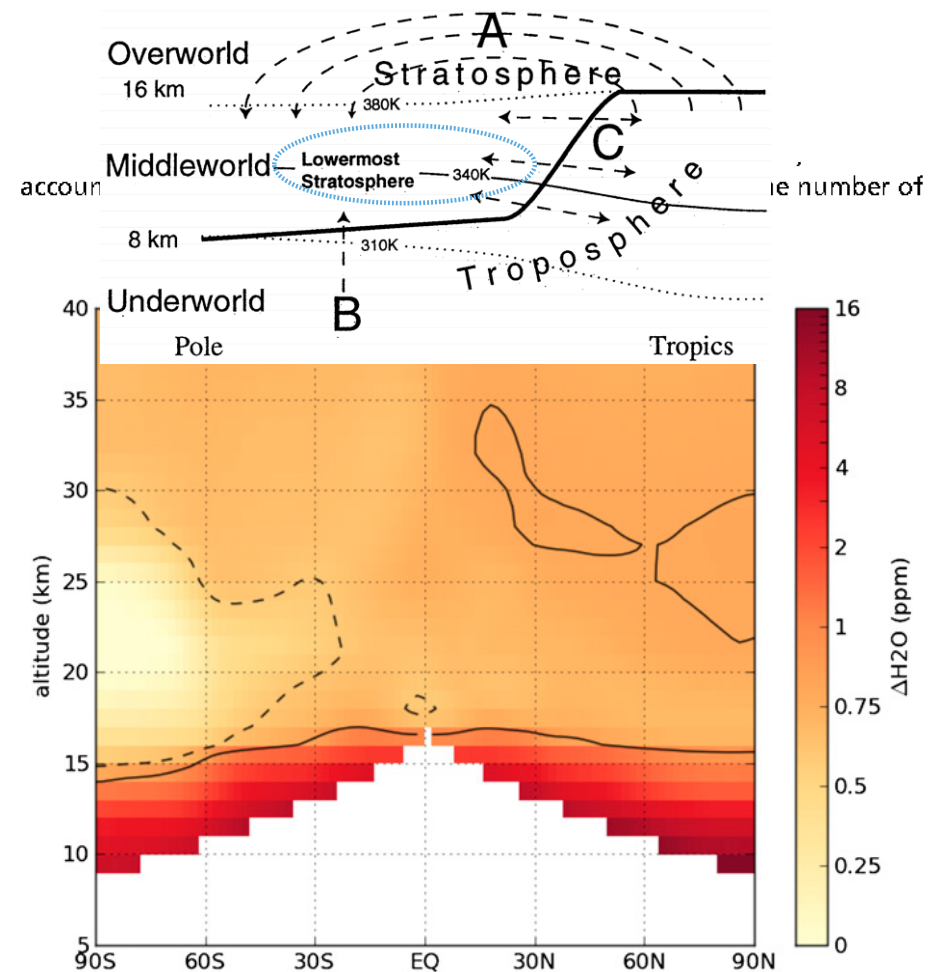


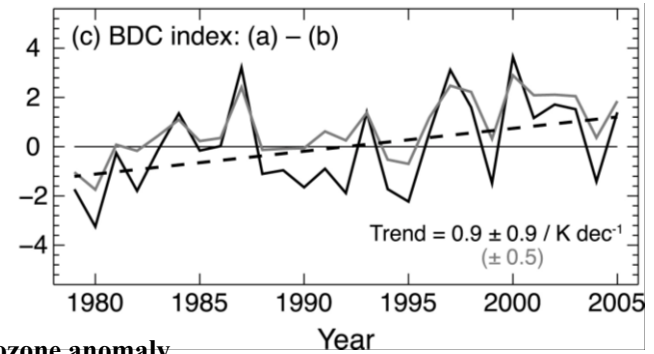
Fig. 4. Change in zonal average stratospheric H₂O in ppm over the 21st century from the GEOSCCM; the contribution from methane oxidation has been subtracted. Note that the color scale is nonlinear; white areas indicate the troposphere. The dashed and solid lines are the 0.6 and 0.8 ppm contours, respectively.

Dessler et al., 2013, PNAS, Stratospheric water vapor feedback

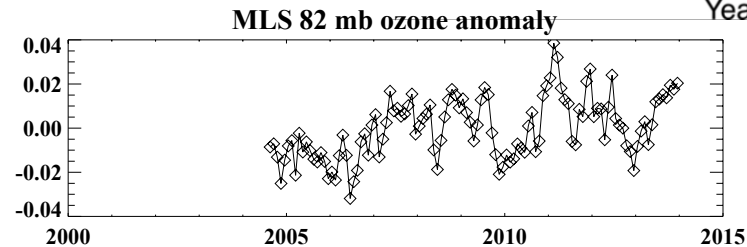
Also, poster by Bob Portmann on Monday

How can we monitor BDC changes

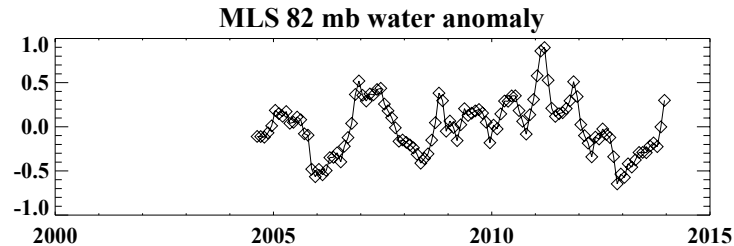
1) Temperature (P. Young, 2011)



2) Ozone



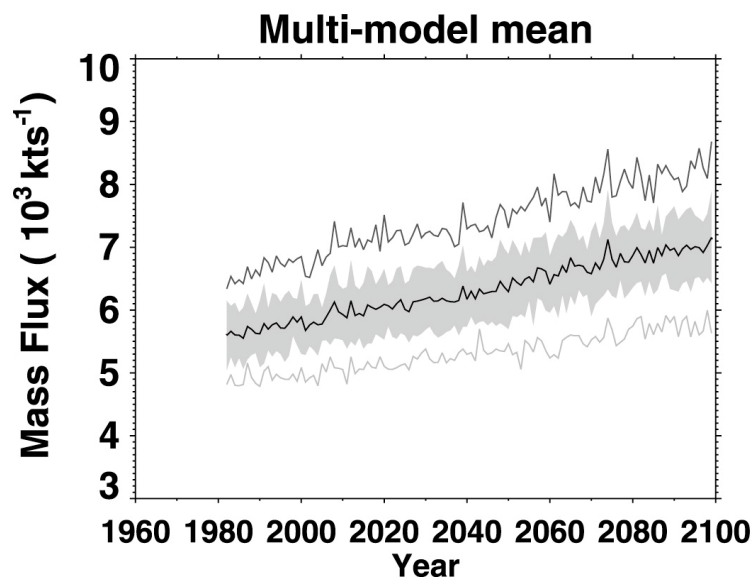
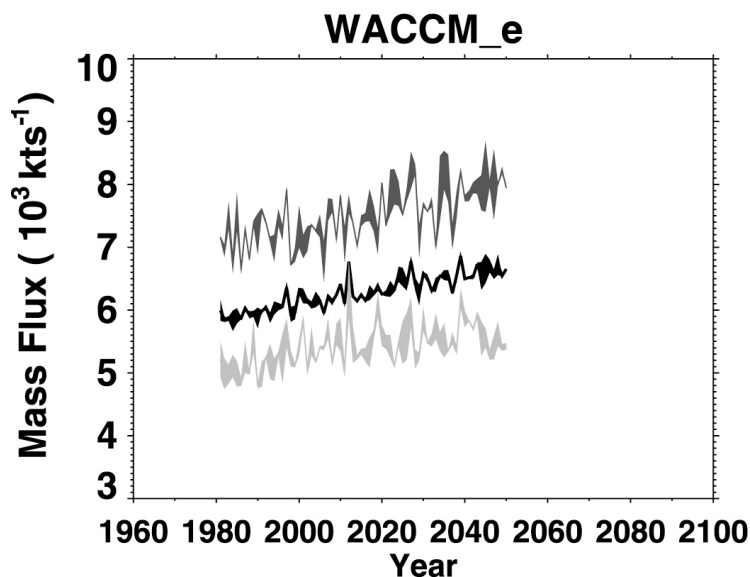
3) Water vapor



4) We'd like to be able to monitor "age of air"

Proposal: A cost effective trace gas measurement program for long term monitoring of the stratospheric circulation
(Moore, Ray, et al., BAMS, 2014)

Model world trends



Tropical upwelling 70 mb mass flux

Butchart et al., 2010: *“There is a strengthening of the Brewer–Dobson circulation throughout the depth of the stratosphere, which reduces the mean age of air nearly everywhere at a rate of about $0.05 \text{ yr decade}^{-1}$ in those models with this diagnostic. “*

Using “age of air” to infer BDC changes

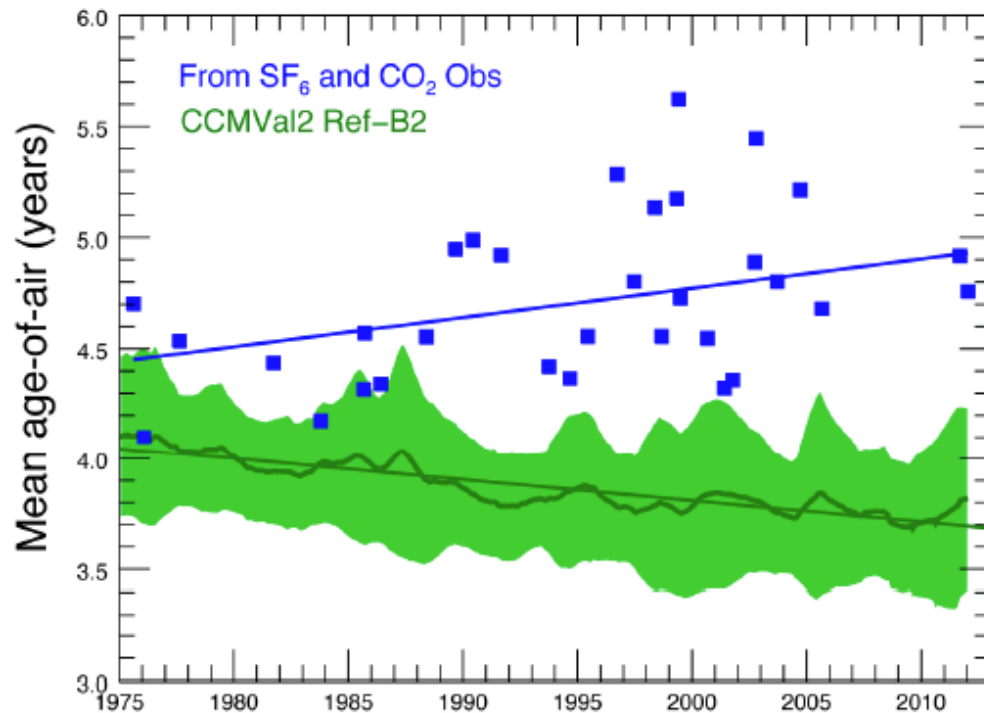
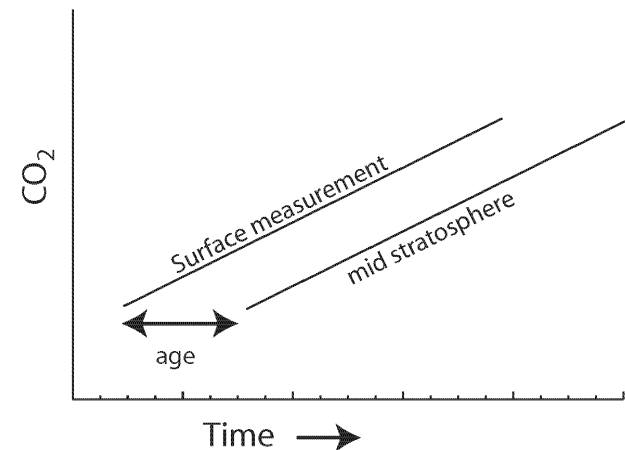


Figure 2: Modeled and measured mean age of stratospheric air, averaged over 25-35 km and 30°N – 50°N. The blue squares and blue line show the balloon-based age-of-air measurements and linear trend, respectively. The green timeseries and shaded region show the CCMVal2 ensemble mean age-of-air timeseries for the REF-B2 scenario, which includes natural and anthropogenic forcings such as greenhouse gasses and ozone depleting substances. Figure adapted from Ray et al. (2010) and Moore et al. (in press).

Compute effective residence time in the stratosphere by using long-lived tracers with known trends in the tropospheric source. Here, we use SF_6 and CO_2



At present, stratospheric trace gas measurements are sporadic in time and/or place, primarily associated with localized aircraft or balloon campaigns or relatively short-lived satellite instruments.

We can't reconstruct the past, but we may be able to start monitoring in the near future.

A proposed program would make use of the relatively low cost AirCore and sonde techniques, allowing more frequent measurements of key species than currently available.

Recent and Future “In Situ” Stratospheric Profile Measurements - AirCore



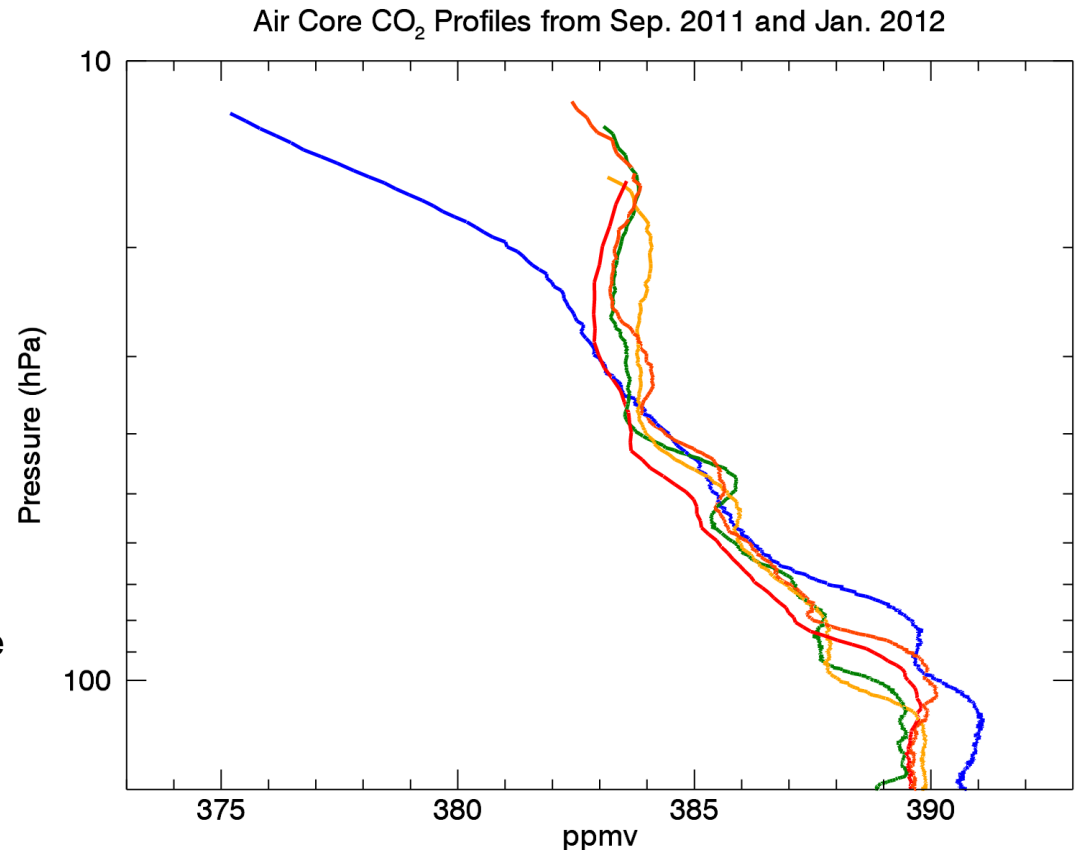
FIG. 1. The AirCore with magnesium perchlorate driers and shut-off valves attached on each end.

Roughly a dozen flights with the AirCore have been flown in the last two years by the NOAA GMD Carbon Cycle Group.

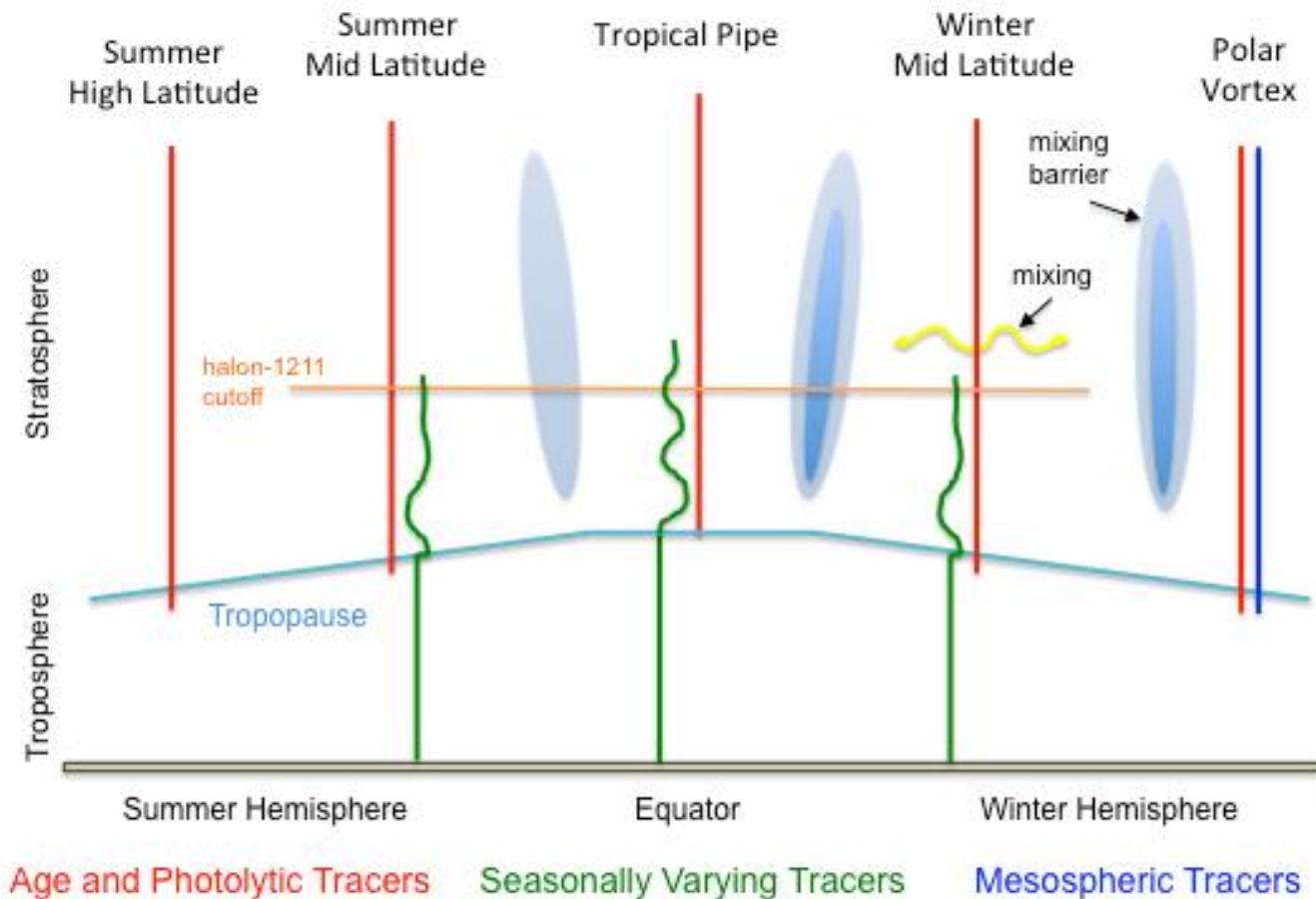
Additional AirCore measurements of SF_6 and photolytic trace gases by NOAA GMD HATS group are soon to come.

Big potential to increase understanding of stratospheric transport variability.

(CO_2 , SF_6 , N_2O , CFC-12, CFC-113, CFC-11, and halon-1211 + H_2O and O_3)



Profile Locations for Stratospheric Circulation Data Set



Summary

Tracers and temperature give us information on the strength of stratospheric mean meridional circulation.

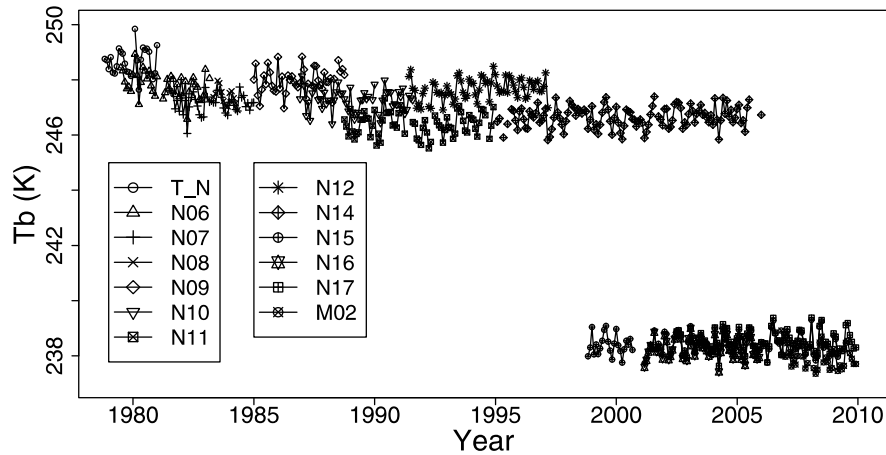
Similarly, changes in the mean meridional circulation (and assorted forcings) will impact measured tracer distributions which can then have subsequent climate impacts.

We need a better understanding of the BDC in present climate and we need to understand how the stratospheric circulation will change in a future with changed greenhouse gases or changes induced by SRM.

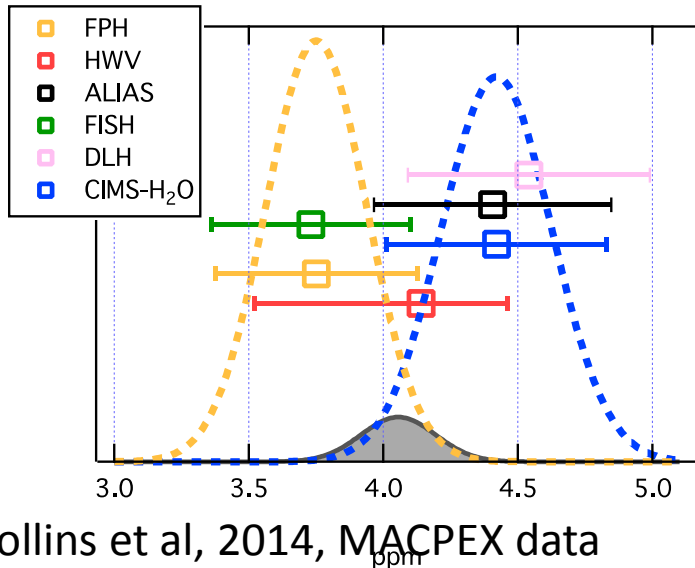
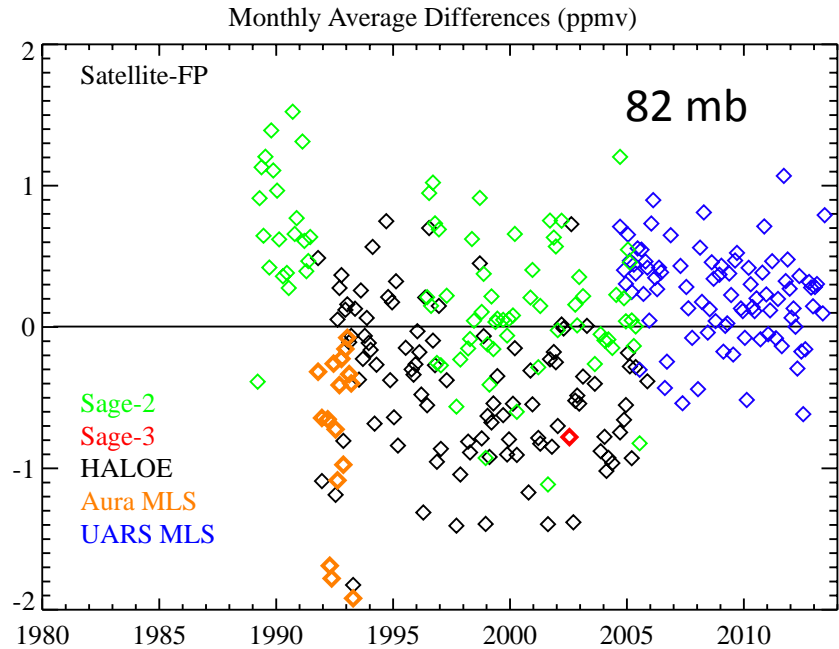
and how it affects the troposphere in regards to climate (temp/precip) and air quality

This requires consistent, continuous trace species and temperature measurements (CDRs) (to serve as ground truth for model simulations)

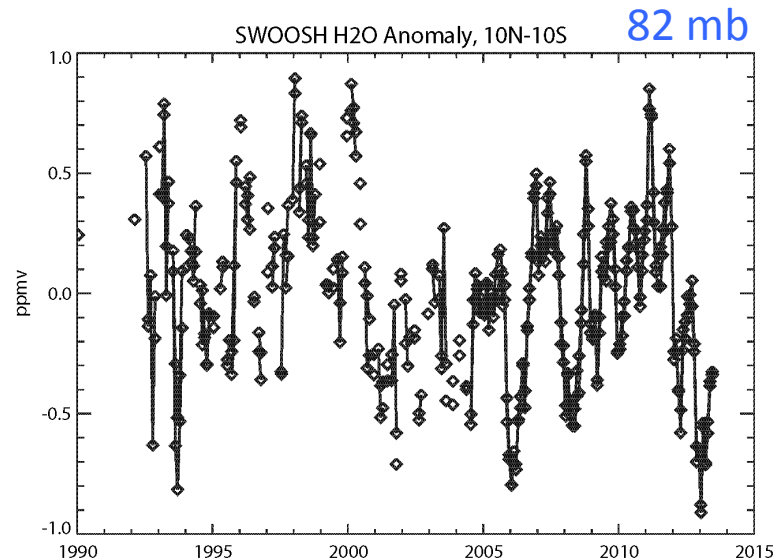
Water measurements



30N-30S brightness T, HIRS UTH, Shi and Bates, 2011



Rollins et al, 2014, MACPEX data



In spite of 90ish years of stratospheric ozone/water/circulation research, there are many things that we still don't understand about stratospheric mean meridional circulation variability.

Global observations of stratospheric trace species and temperature are still needed to test climate models.

CDRs of these species are critical and more work is needed at this point to really homogenize these records and to understand why differences exist between different platforms.

Continued measurements and attention to discrepancies between past measurements are important!

