Distribution of water vapor in the stratosphere

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Cargèse International School
Water vapour in the Climate System (WAVACS)
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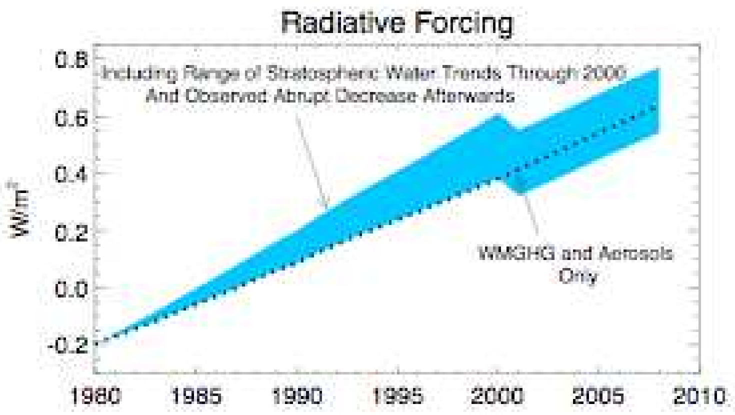
Lecture 1 of 4

Why are we interested in stratospheric water vapor?

It impacts radiative processes including stratospheric temperature (potentially even impacting surface temperatures)

It impacts ozone chemistry in the stratosphere (via influence on OH chemistry, but also impacting polar stratospheric clouds)

From measurements of the mean distribution and variations we can infer something about temperatures and stratospheric motions.



radiation and chemistry examples for significance of stratospheric water vapor.

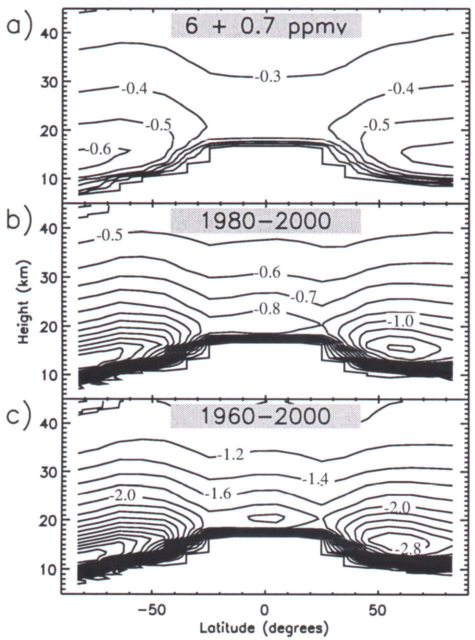


Figure 2. The annually averaged FDH stratospheric temperature change (in K) calculated by the NBM as a function of latitude for: (a) a 0.7 ppmv increase in SWV, from a 6 ppmv background value; (b) a 1 ppmv increase from a 1980 background, to simulate the 1980–2000 change in SWV and (c) a 2 ppmv increase from a 1960 background, to simulate the 1960–2000 change in SWV. (a) and (b) have a contour interval of 0.1 K and (c) a contour interval of 0.2 K.

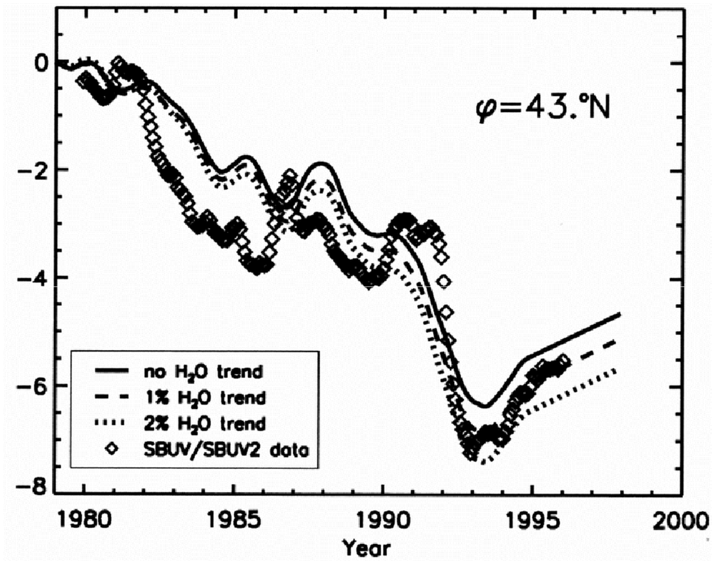


Figure 3. Column ozone change for the 1979-1997 period relative to 1979, in percent, for the scenarios with unperturbed water vapor (solid curve), and the imposed stratospheric water vapor trend of 1% per year (dashed curve) and 2% per year (dotted curve) at northern midlatitudes. *WMO* [1999] emissions and SAGE II aerosols are used. Ozone anomaly derived from SBUV/SBUV2 observations is also shown (diamonds).

Brief history of stratospheric water measurements

First stratospheric water measurements.

Brewer, MRF, 1943, manually operated FP

FP Balloon measurements first reported in the 1960s

discovered the problems with balloon out gassing on ascent (Mastenbrook, NRL, 64-79, handed over to NOAA in 1980)

Lyman-alpha (balloon) introduced in the late 1970s (Kley)

First global satellite water measurements: LIMS, 1978

showed hygropause was a global feature

combined with SAMS CH_4 gave global total water distributions

Long-term satellite measurements started with SAGE II (1986), currently a number of satellites are measuring stratospheric water vapor, included MLS, ACE and MIPAS.

First UTLS measurements were made to assess conditions where contrails may form (to determine how to avoid them during WW-II)

Used an aircraft frost point instrument above the UK (Brewer, Weather 1946, page 38-40) originally on a B-17 (up to 38K ft) then on Mosquito aircraft (up to 44 kft, or ~160 mb)

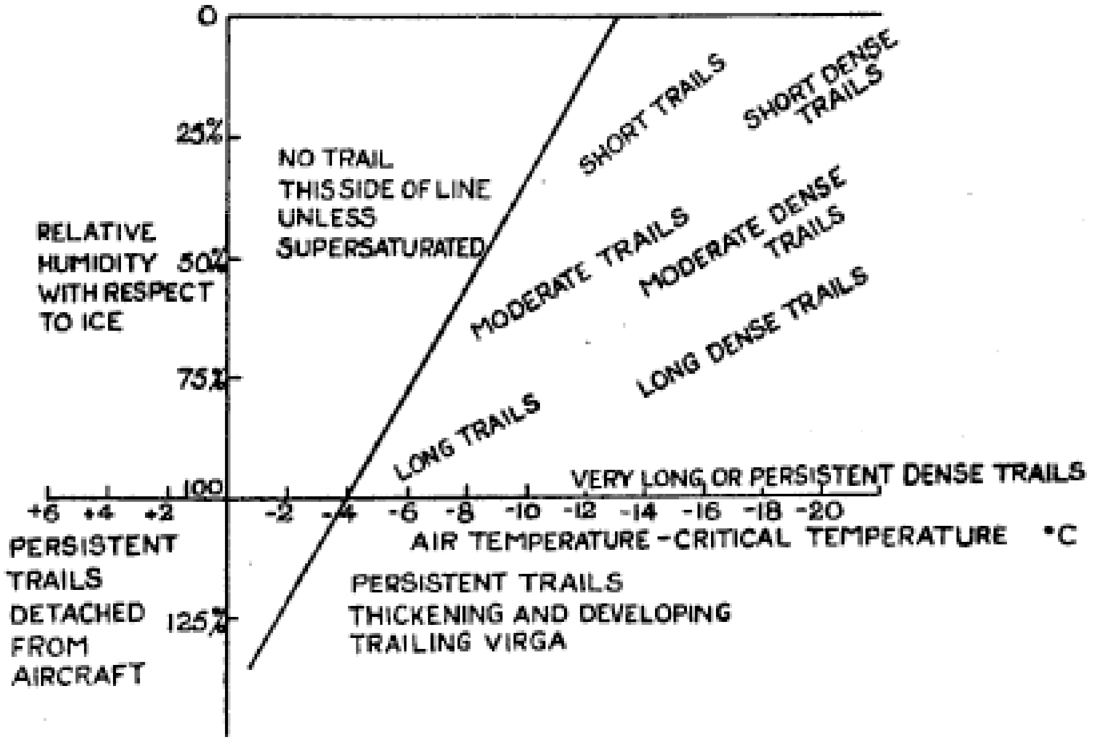


Fig. 3. The variation of condensation trail length with humidity and the depression ir temperature below the calculated critical temperature.

CONDENSATION TRAILS

By A. W. Brewer, M.Sc.

In the process, also found measurements of supersaturation in the upper troposphere.

551.571.7

NOTES ON UPPER AIR HYGROMETRY.—II

On the Humidity in the Stratosphere

(Communicated by Dr. G. M. B. Dobson)
By E. GLUCKAUF, Dr.-Ing., M.Sc., D.I.C.
University Science Laboratories, Durham

[Manuscript received May 16, 1945]

Quarterly Journal of the Royal Meteorological Society Vol. 71, 1945, pages 110-115

TABLE I.—Temperatures at and Relative Humidities with respect to Ice Saturation below the Tropopause during April, 1939

Date	T	% R.H. (Ice)	Date	T	% R.H. (Ice)
1	215·0	160	16	214·5	52
3	218·5	130	19	222·0	48
4	217·5	171	20	218·0	69
5	221·0	84	21	211·5	92
6	217·5	43	22	213·0	60
7	217·0	54	23	218·5	154
8	206·0	162	24	229·5	67
10	215·0	117	25	220·5	107
11	215·5	113	29	221·0	124
12	214·0	64	30	223·0	134
14	221·0	74			

Data from UK balloon ascents, supersaturated 10 days out of 30.

551.510.5

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)

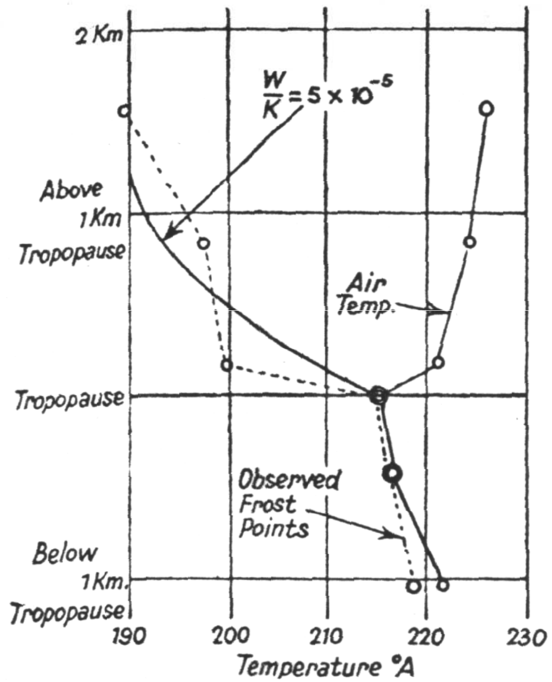
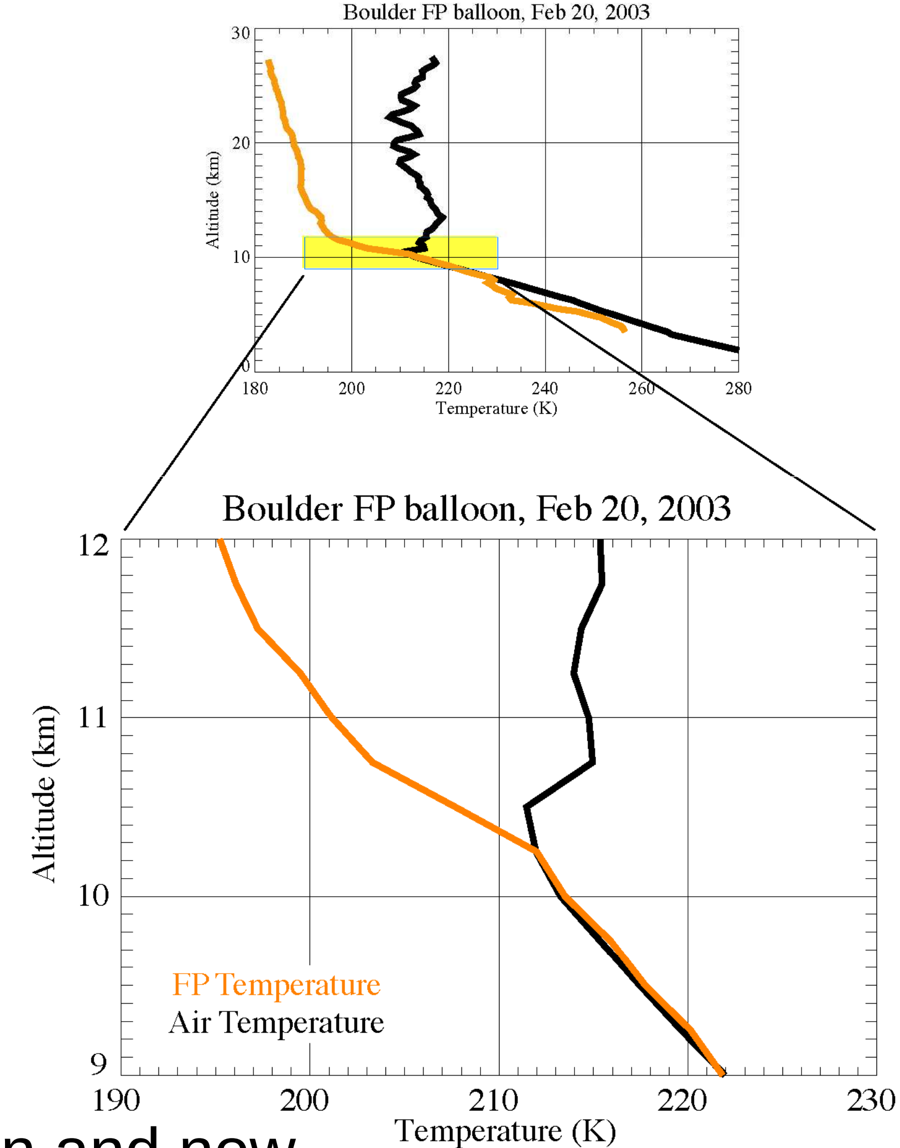


FIG. 1. 30 May 1945. Tropopause ht 33,400 ft.

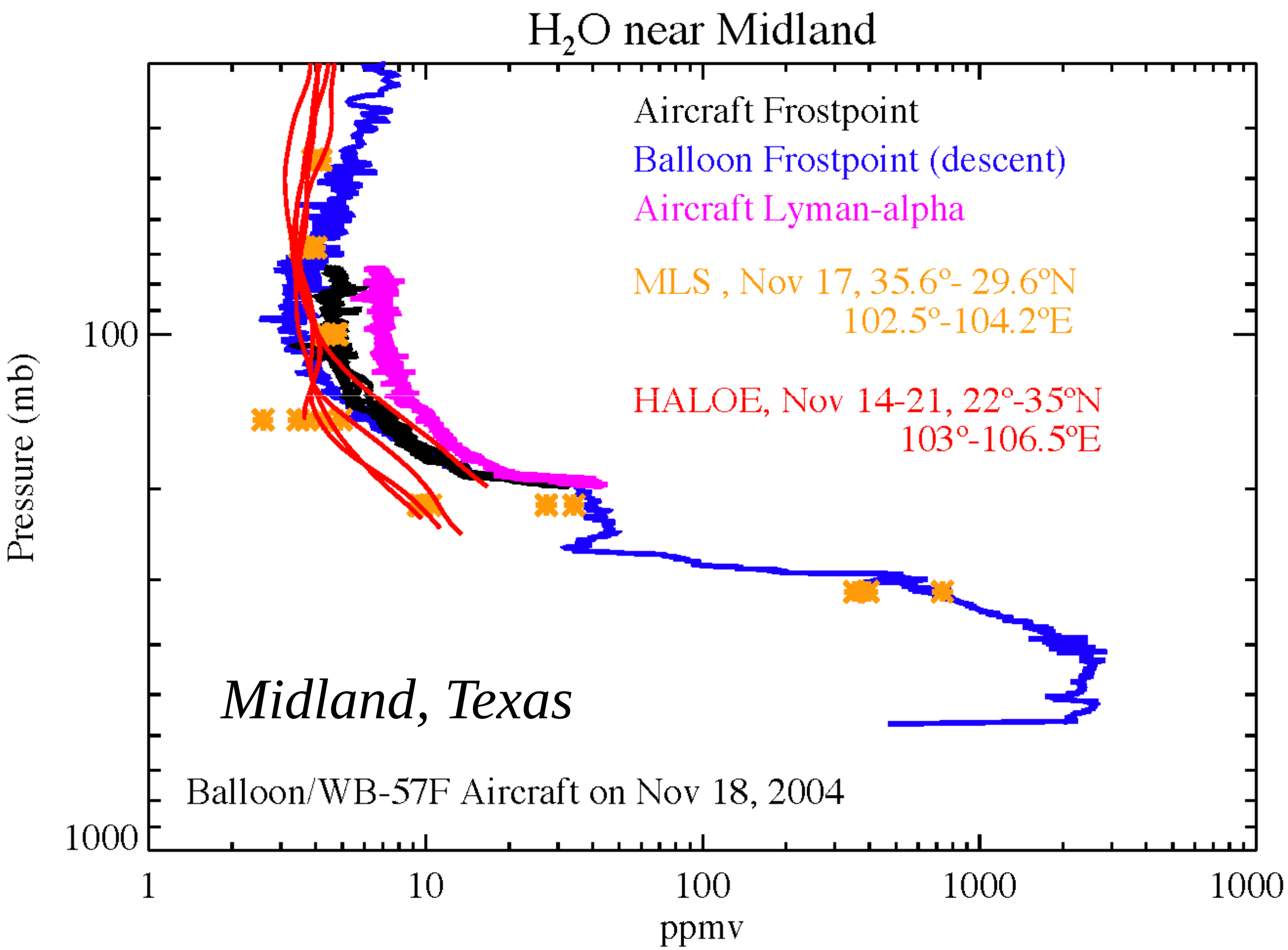
~50°N, 1945, Southern England

~40°N, 2003, Boulder, CO

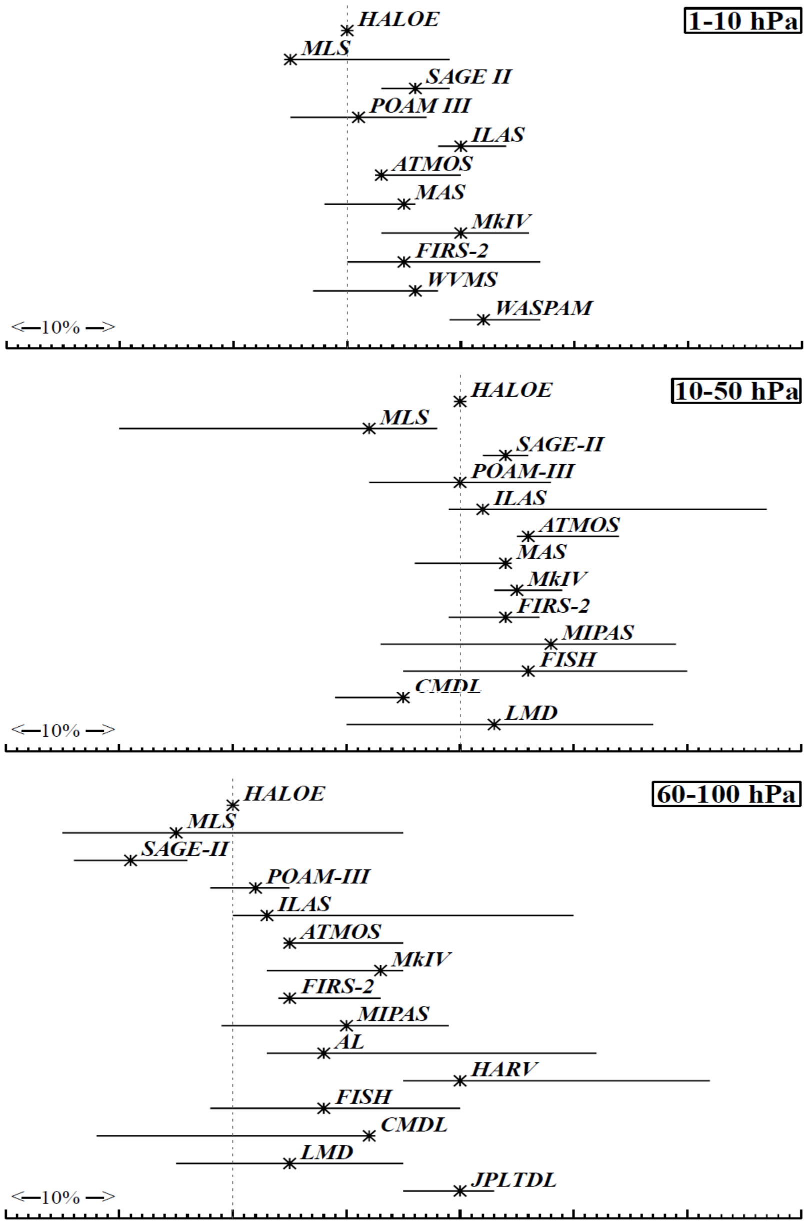


Example of vertical profiles, then and now.

Example of a mid latitude profile in units of mixing ratio: note the stratospheric values (in this case, above 200 mb) are quite small, on the order of 5 ppmv.



Mid latitudes: Near coincidence between aircraft and balloon, satellite within 10° and 1 day.



From SPARC 2000.

Aside: accuracy is an issue for some things, affects determination of whether air enters the stratosphere at 100% RHice (or greater), and have there been any long term changes in that fraction.

The problem is that there are large uncertainties in water vapor measurements, in particular at low values. (highlighted in previous figure)

Typical model assumption is that air enters the stratosphere at 100% RHi for the coldest temperature encountered. If it enters at different degrees of supersaturation, that could produce model representation issues.

Brewer (1949) using water and ozone measurements, first deduced the sense of the mean meridional circulation in the stratosphere.

Key points:

1) water vapor values over the UK in the stratosphere were lower than could be explained by the coldest temperatures encountered locally.

2) explains high ozone values observed at high latitudes, away from the photochemical source region. (see Dobson, 1956)

At the time of Brewer's paper, the stratosphere was thought to be turbulent, but without "steady vertical movements".

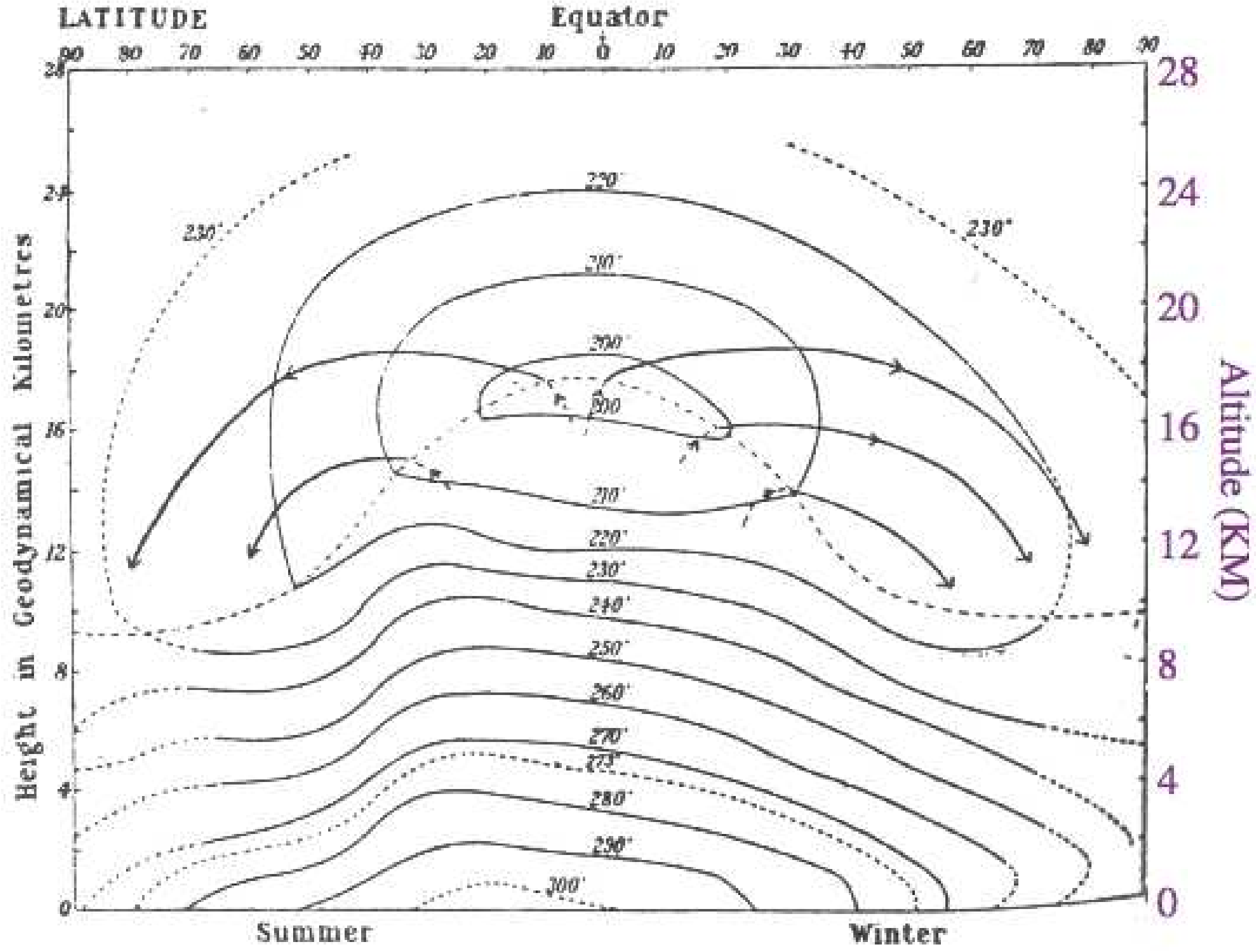
This would imply that at any given latitude, the dryest that air could be would be ice saturation at the coldest temperature at that latitude.

There are a variety of formulations for ice saturation vapor pressure; these are a function of temperature, and a recent summary of the expressions used for approximating both ice and liquid saturation vapor pressure is given by Murphy and Koop, 2005 (QJRMS, 131, 1539-1565, doi:10.1256/qj.04.94) To convert to mixing ratio, one also needs to know pressure.

At 250 mb, 215K (not unusual midlatitude coldest values), qsatmix = 55.5 ppmv (using the goff-gratch approx), much greater than the ~5 ppmv observed in the stratosphere.

The observed distributions can be explained by the existence of a circulation in which air enters the stratosphere at the equator, where it is dried by condensation, travels in the stratosphere to temperate and polar regions, and sinks into the troposphere. The sinking, however, will warm the air unless it is being cooled by radiation and the idea of a stratosphere in radiative equilibrium must be abandoned. The cooling rate must lie between about 0·1 and 1·1°C per day but a value near 0·5°C per day seems most probable. At the equator the ascending air must be subject to heating by radiation.

From *Brewer* [1949]



Isotherms over the Globe

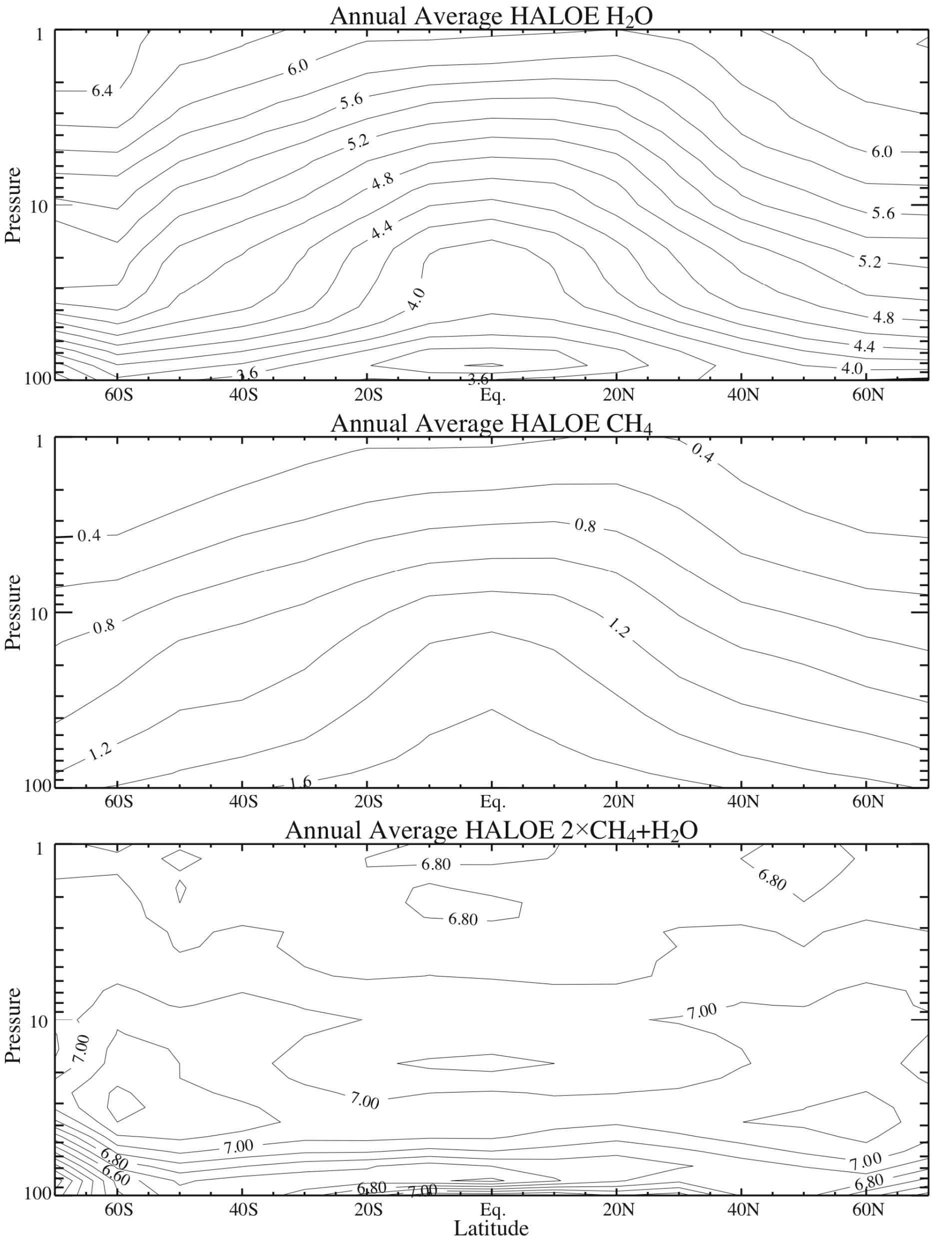
So, based on observations of water vapor over the UK, combined with global knowledge of the ozone and temperature distributions, Brewer (1949) formulated the concept of the Brewer-Dobson Circulation.

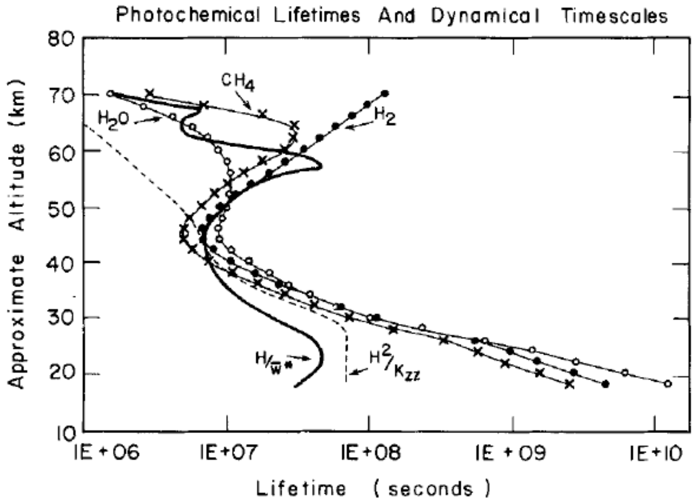
The B-D circulation represents Lagrangian-mean motion. It can be approximated with the Transformed-Eulerian Mean circulation, which can be expressed as:

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

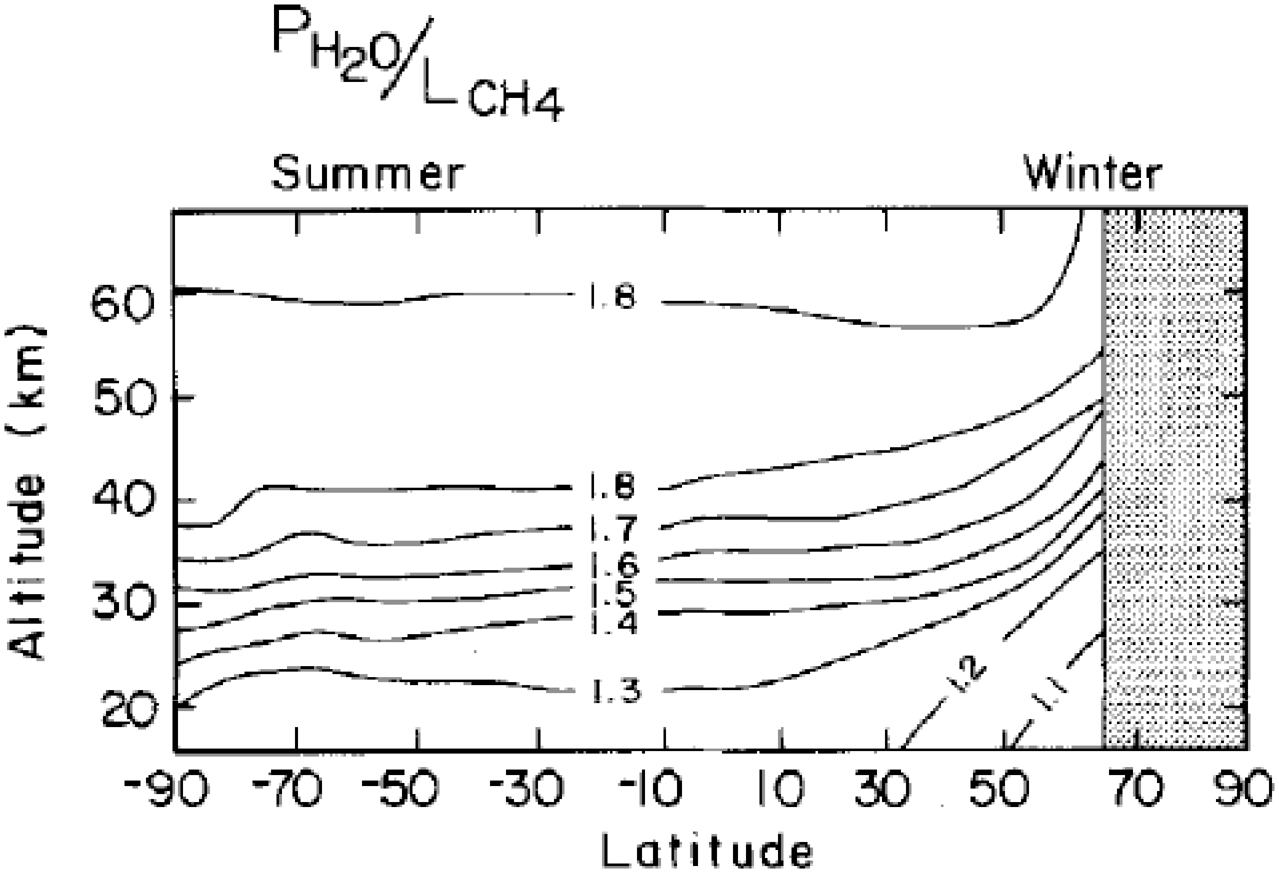
$$\bar{w}^* = \bar{w} + \frac{1}{a\cos\phi}\frac{\partial}{\partial\phi}\left(\cos\phi\,\overline{v'\theta'}/\bar{\theta}_z\right).$$

What does the overall zonally averaged distribution look like?

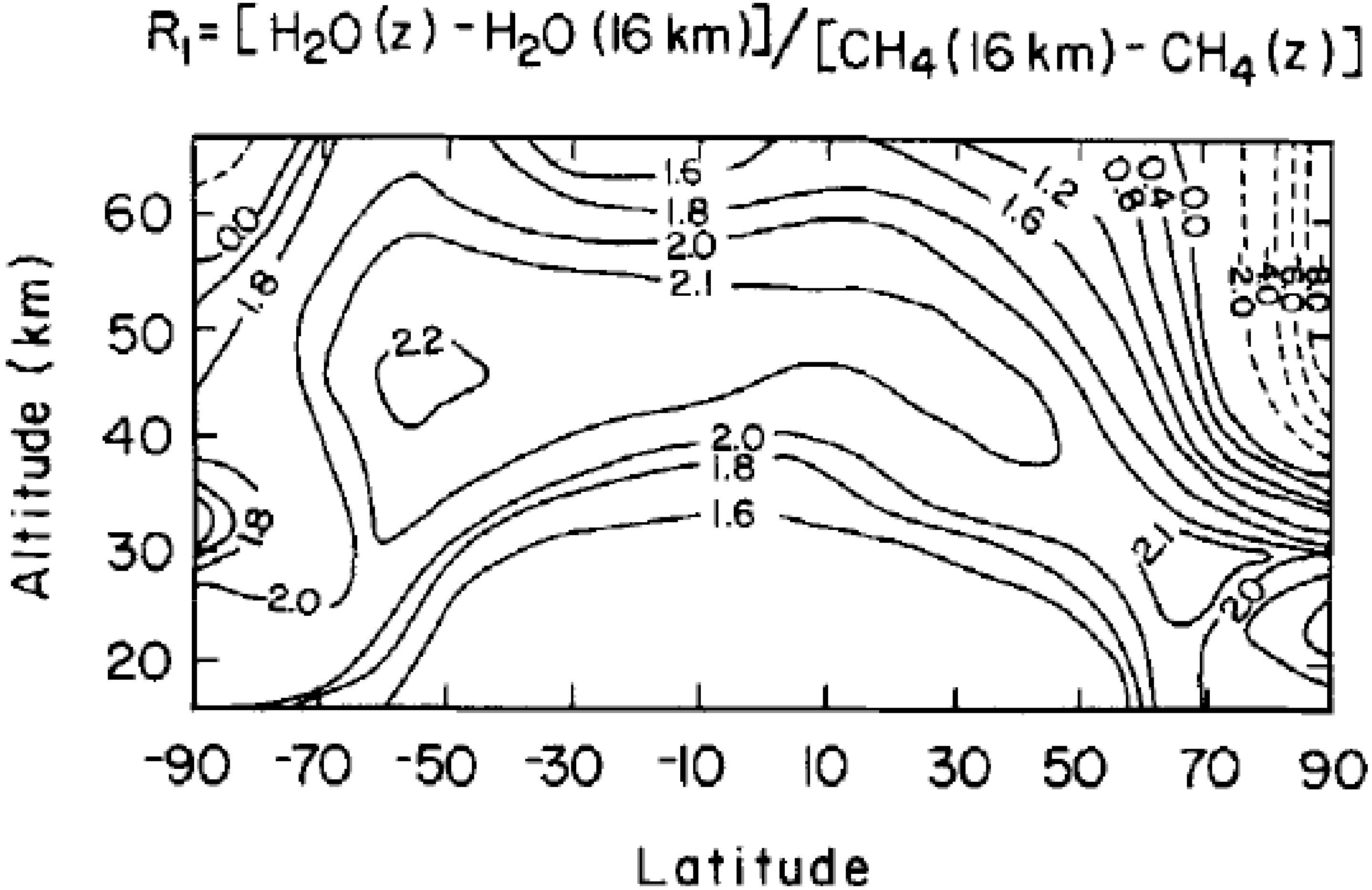




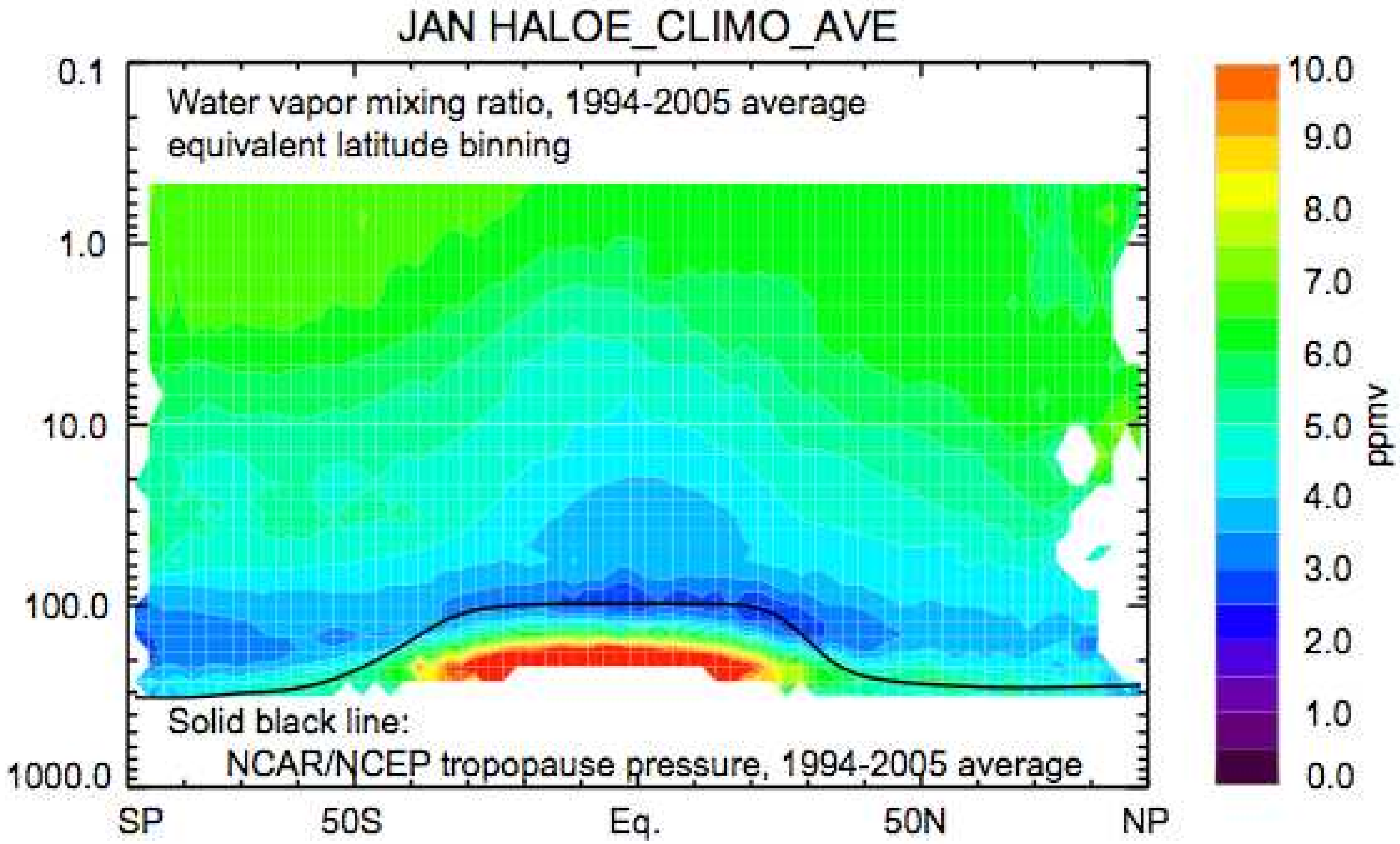
In the mesophere, there is photolysis of water vapor, so the vertical gradient reverses. That's above the levels ploted in the figure at the left.



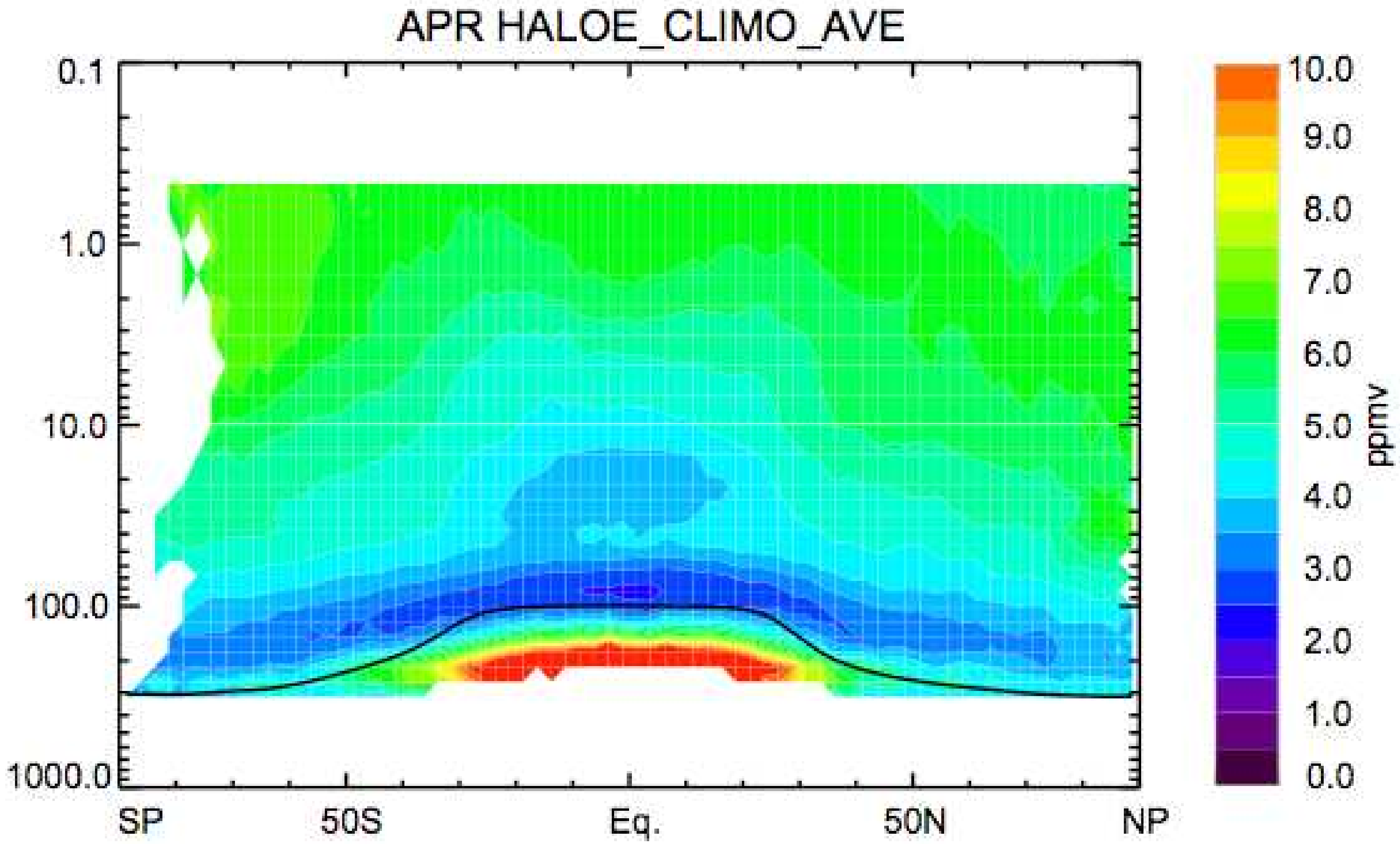
shows how many water molecules come from the destruction of 1 methane molecule as a function of latitude/altitude, from LeTexier et al, 1988

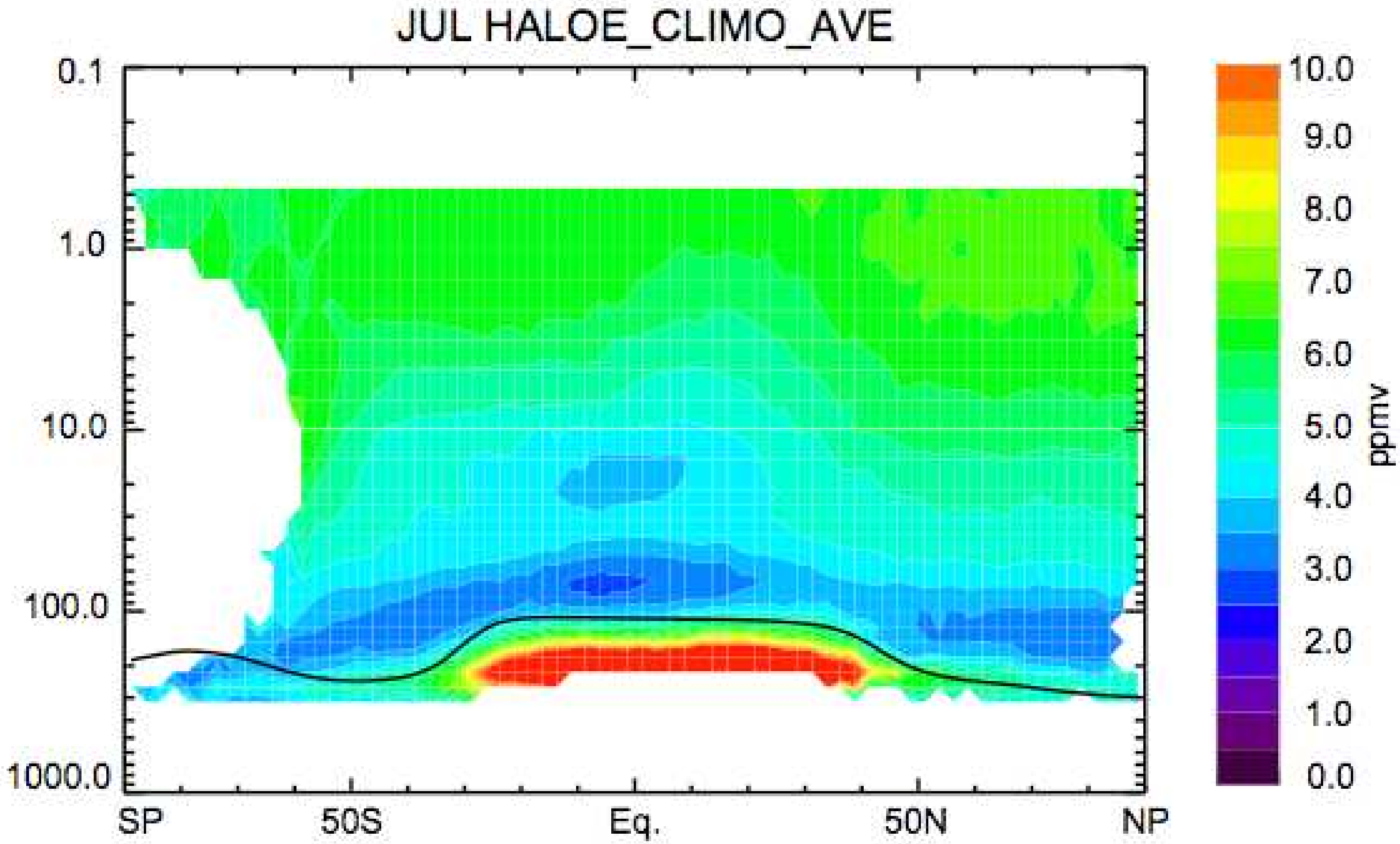


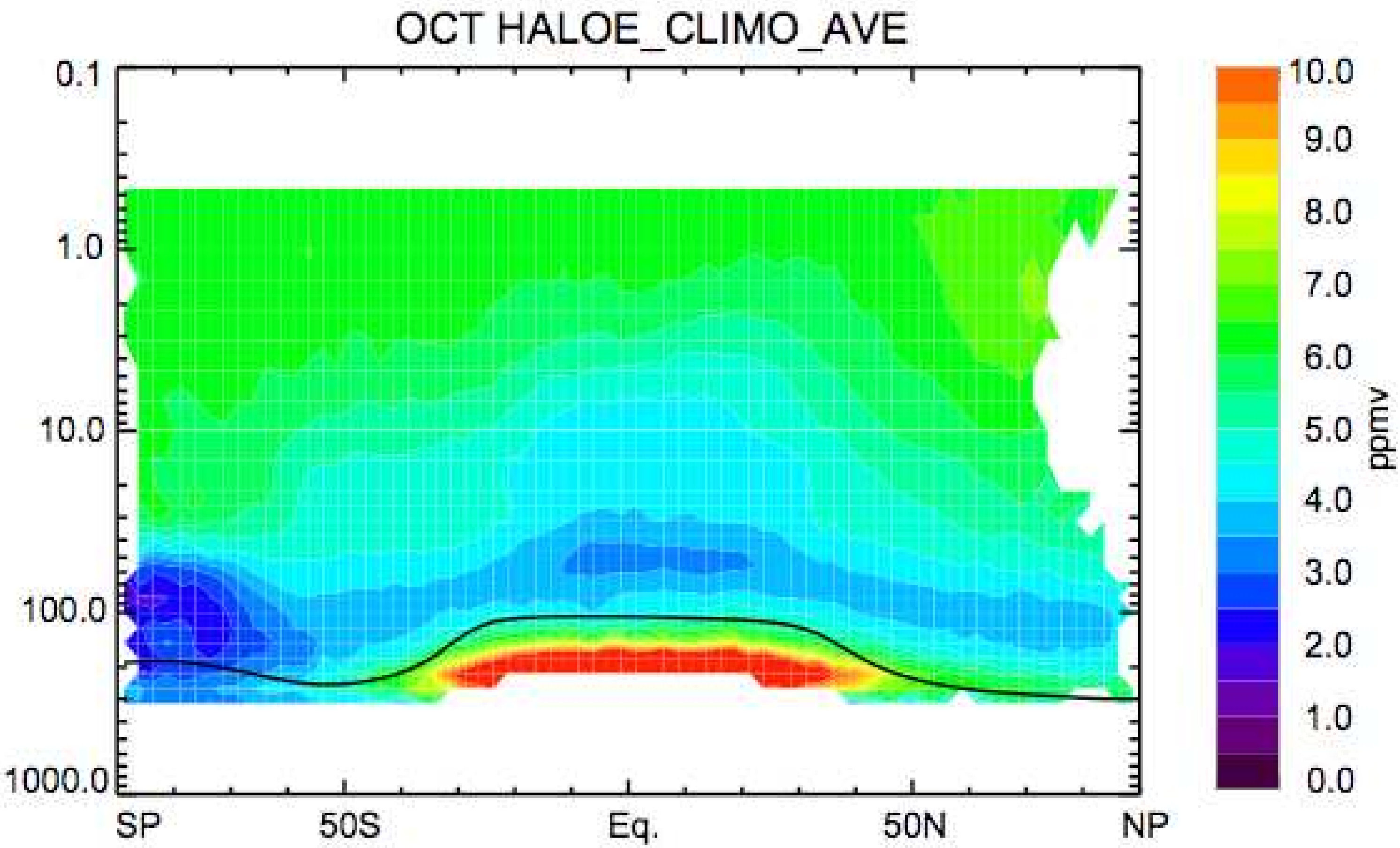
Methane yield, from Le Texier et al, 1988. Stratosphere is largely below 50 km. Where values are greater than 2, that means that molecular hydrogen produced by the methane oxidation has itself oxidized.



JAN HALOE_CLIMO_AVE
Water vapor mixing ratio, 1994-2005 average
equivalent latitude binning
Solid black line:
NCAR/NCEP tropopause pressure, 1994-2005 average
0.1
1.0
10.0
100.0
1000.0
SP
50S
Eq.
50N
NP
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
ppmv


APR HALOE_CLIMO_AVE
0.1
1.0
10.0
100.0
1000.0
SP
50S
Eq.
50N
NP
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
ppmv


JUL HALOE_CLIMO_AVE
0.1
1.0
10.0
100.0
1000.0
SP
50S
Eq.
50N
NP
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
ppmv


OCT HALOE_CLIMO_AVE
0.1
1.0
10.0
100.0
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SP
50S
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10.0
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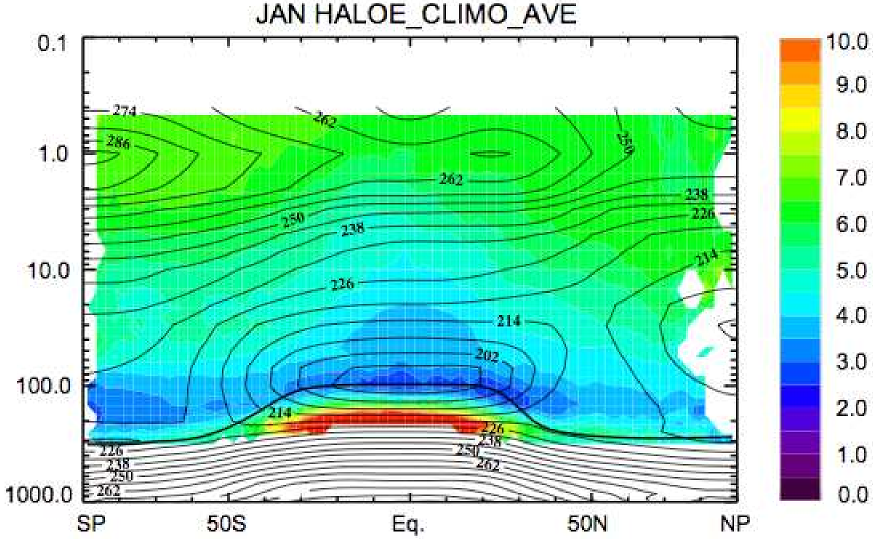
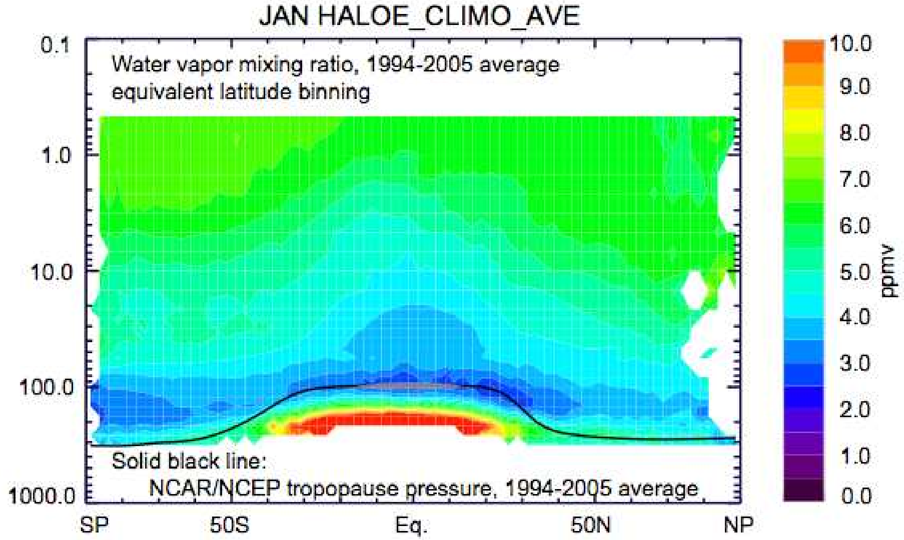
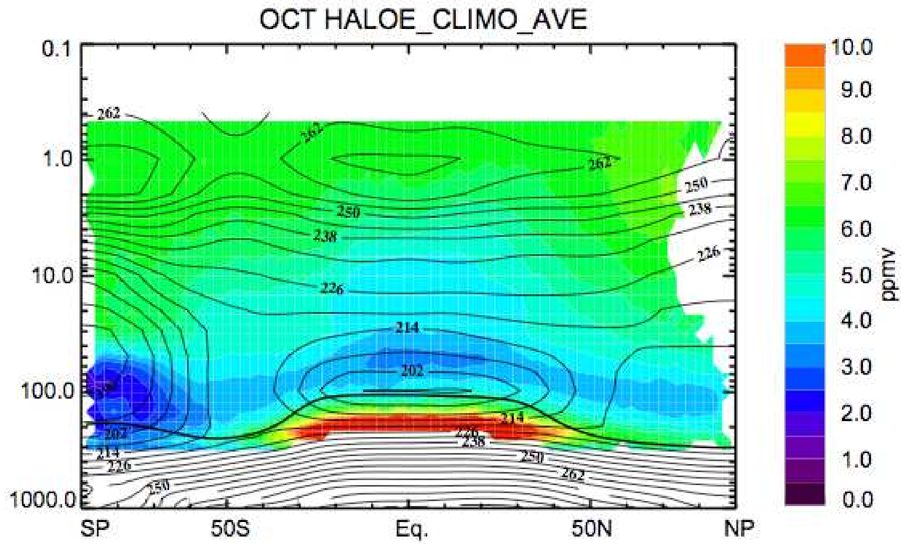
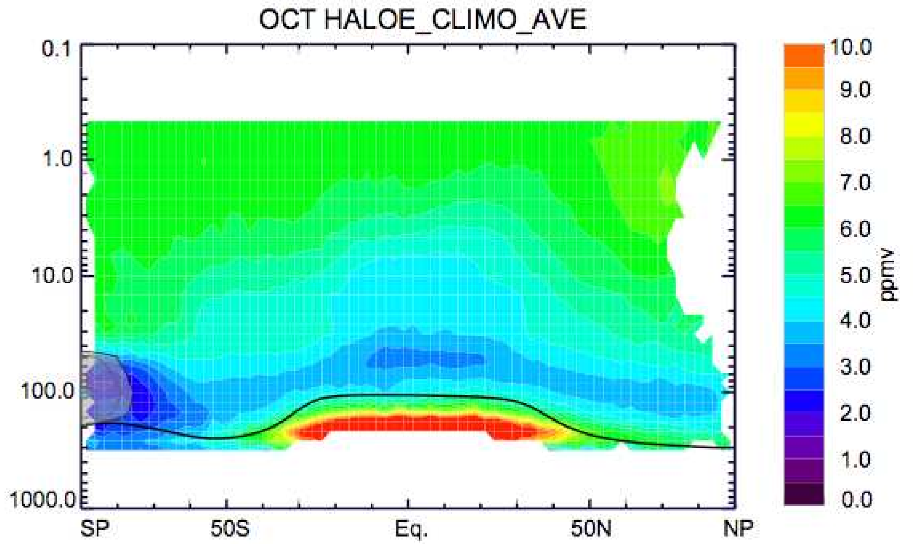
ppmv



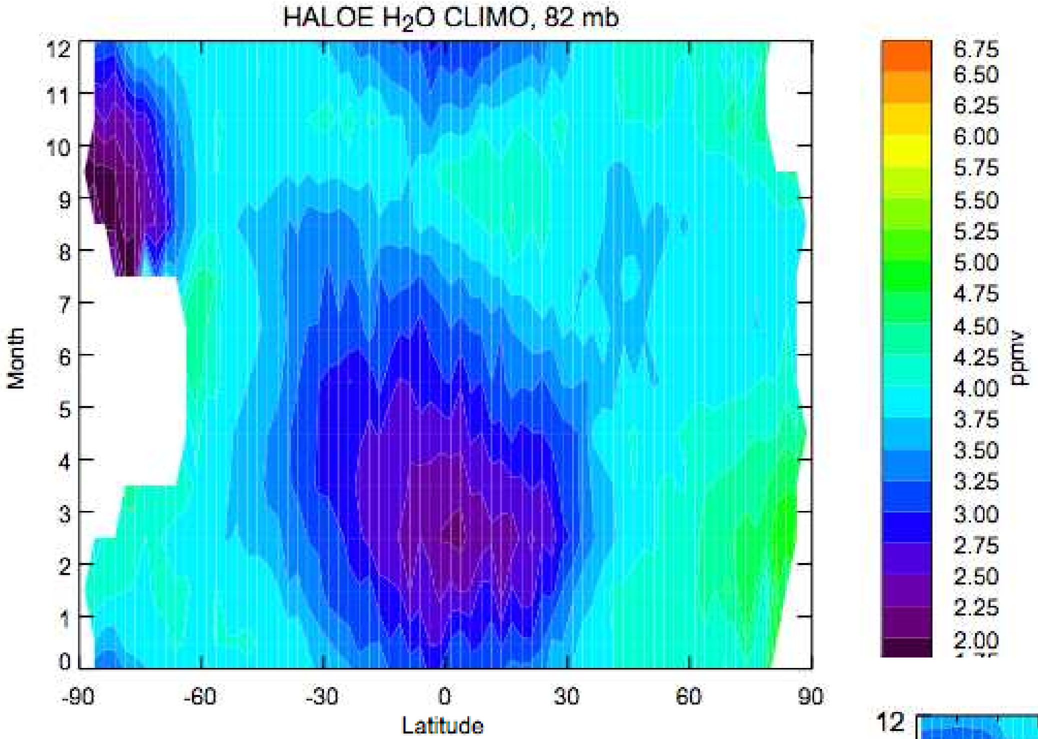


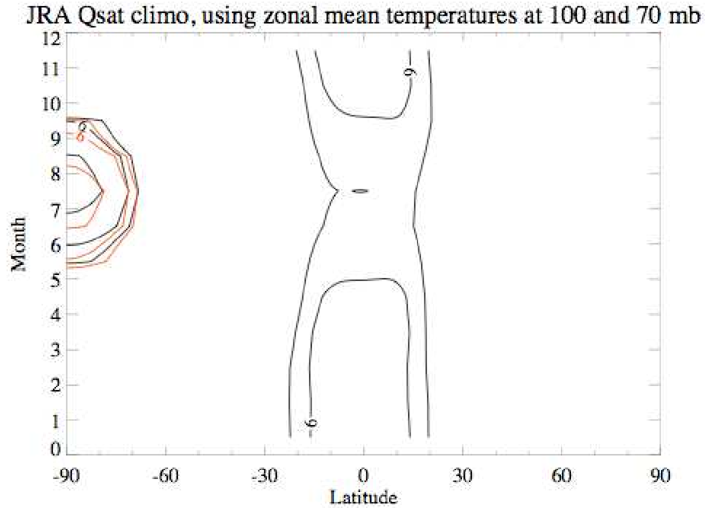


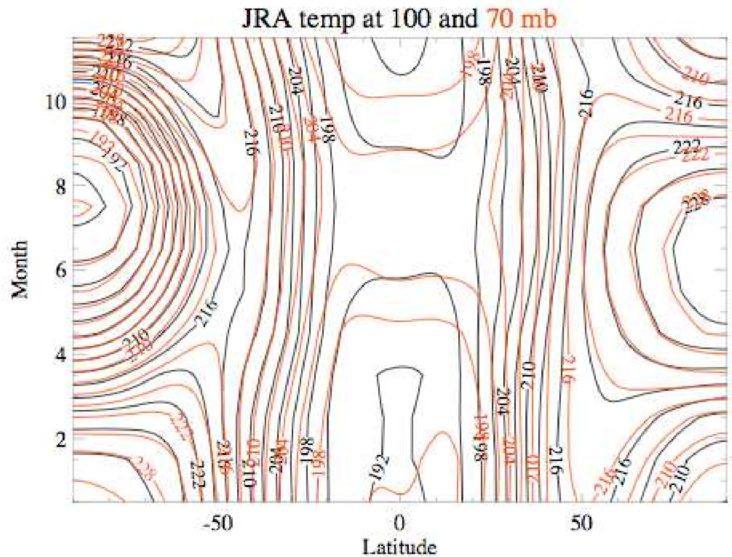


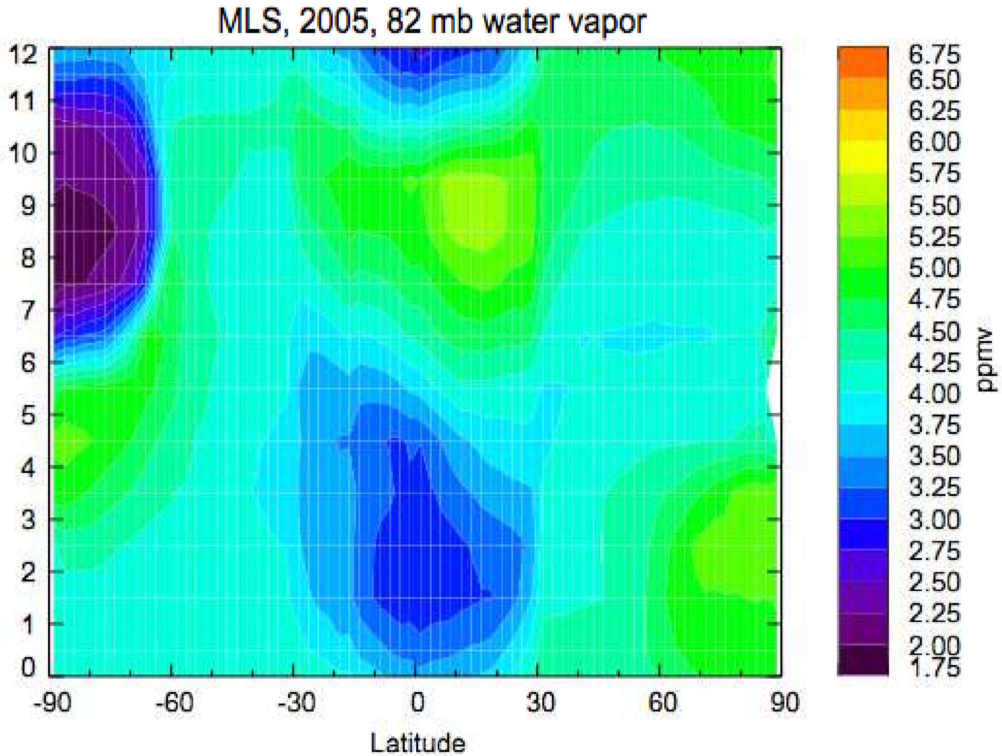
JRA temps overlaid on HALOE water

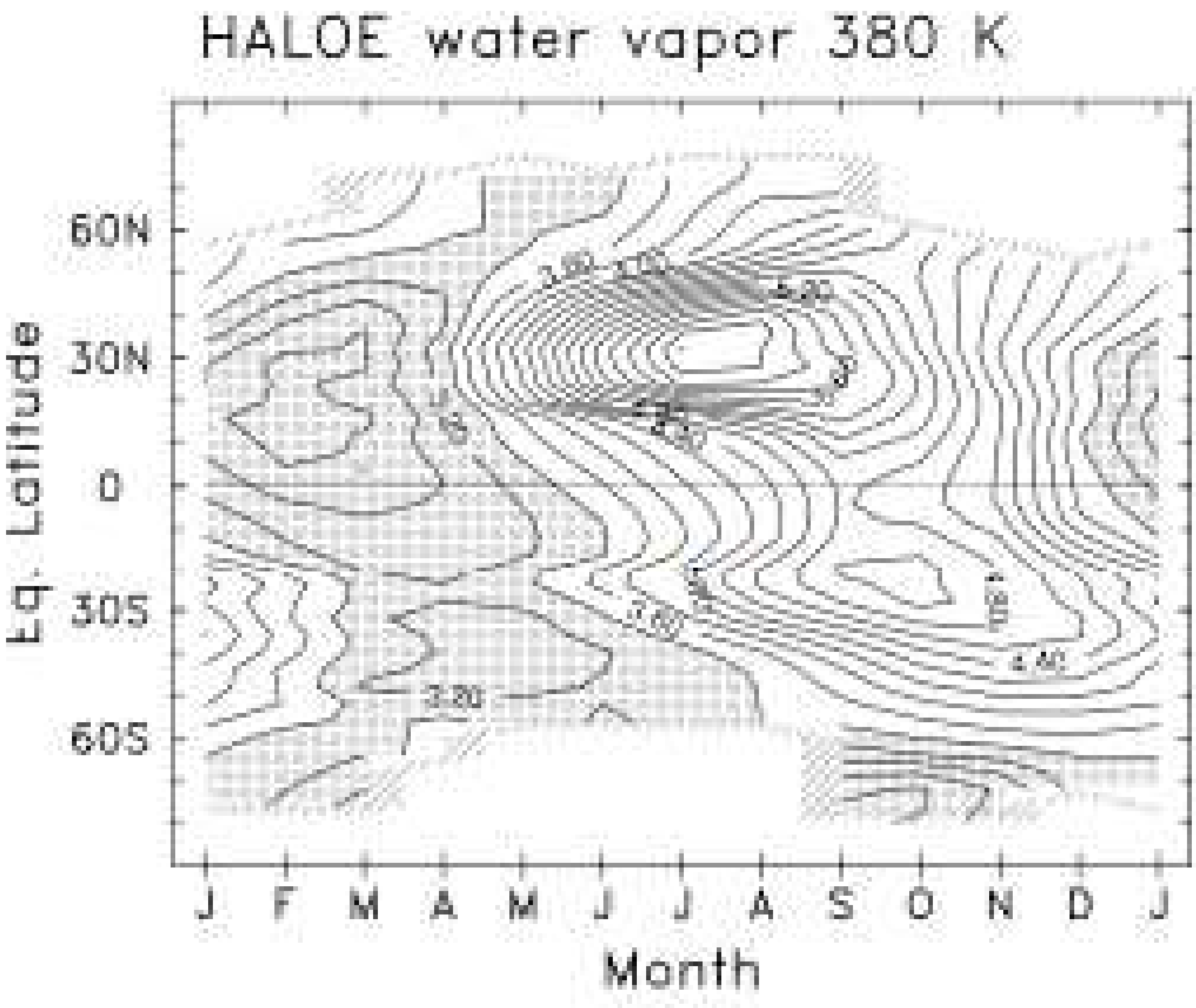
shaded grey region is where qsat using monthly mean temps is less than 6 ppmV

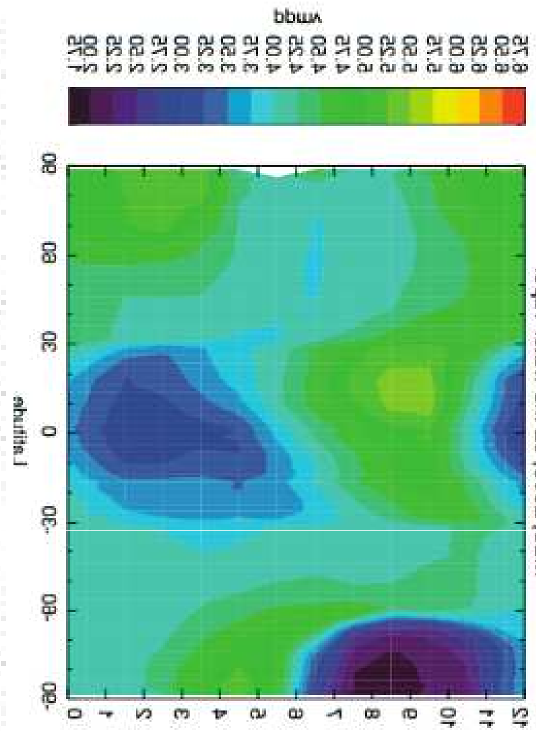

HALOE H_2O CLIMO, 82 mb
Month
Latitude
ppmv


JRA Qsat climo, using zonal mean temperatures at 100 and 70 mb
Month
Latitude


JRA temp at 100 and 70 mb
Month
Latitude


MLS, 2005, 82 mb water vapor
Latitude
ppmv



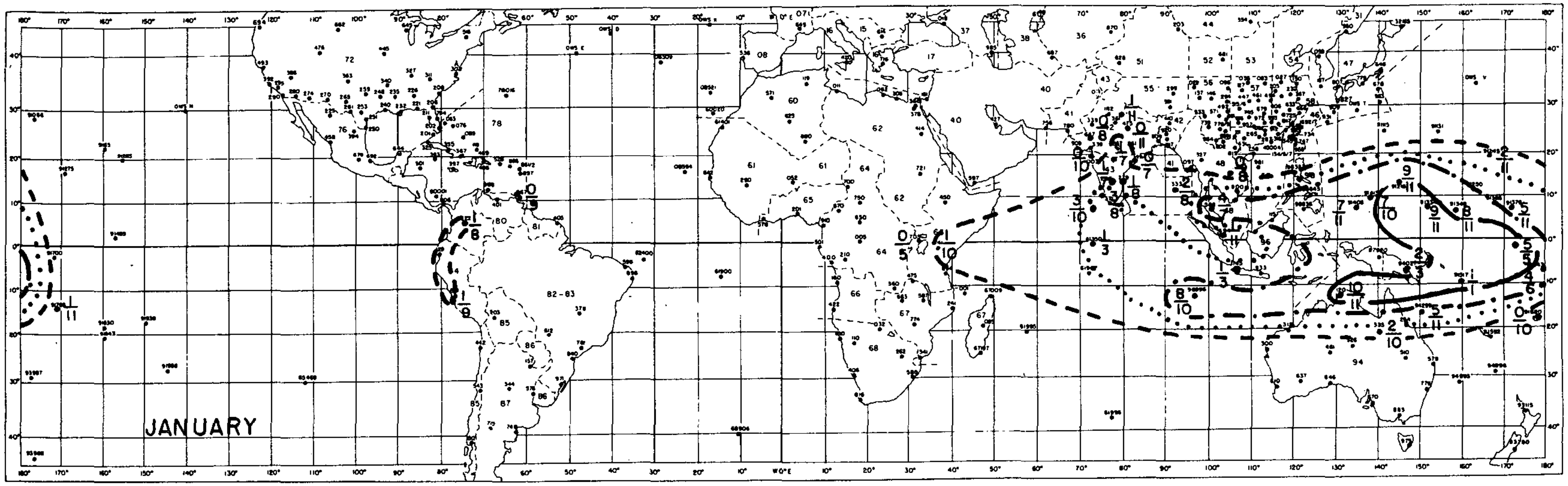


similar MLS image

From SPARC 2000

And to really get cold enough: longitude matters

Based on measured mixing ratios corresponding to frostpoints of -84^{o}C, *Newell and Gould-Stewart* [1991] concluded that air could only enter the stratosphere atspecific geographic locations by analyzing 100 mb temperatures. They called the region of entry a "stratospheric fountain."



However, ones needs to remember that air doesn't just move upward. Heating rates, and average vertical motions are very small near the tropopause, so parcels can move horizontally through the coldest regions in the tropics where dehyration can occur.

Holten and Gettelman, 2001

Consequently, the small region identified by Newell can impact the entire globe.

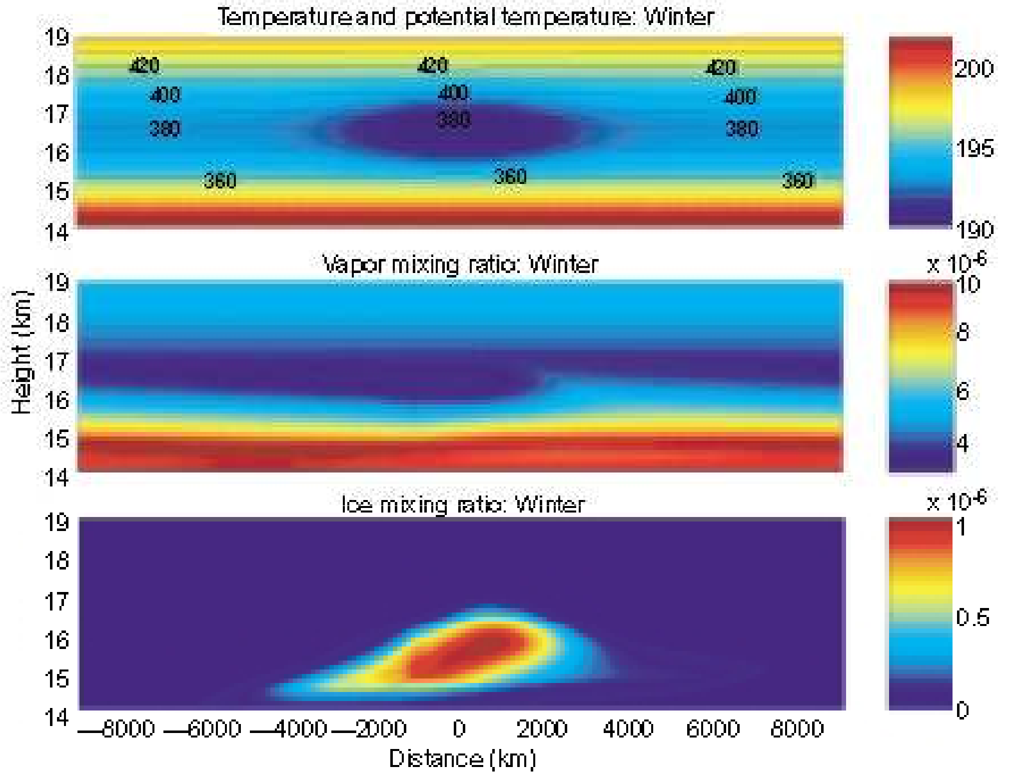
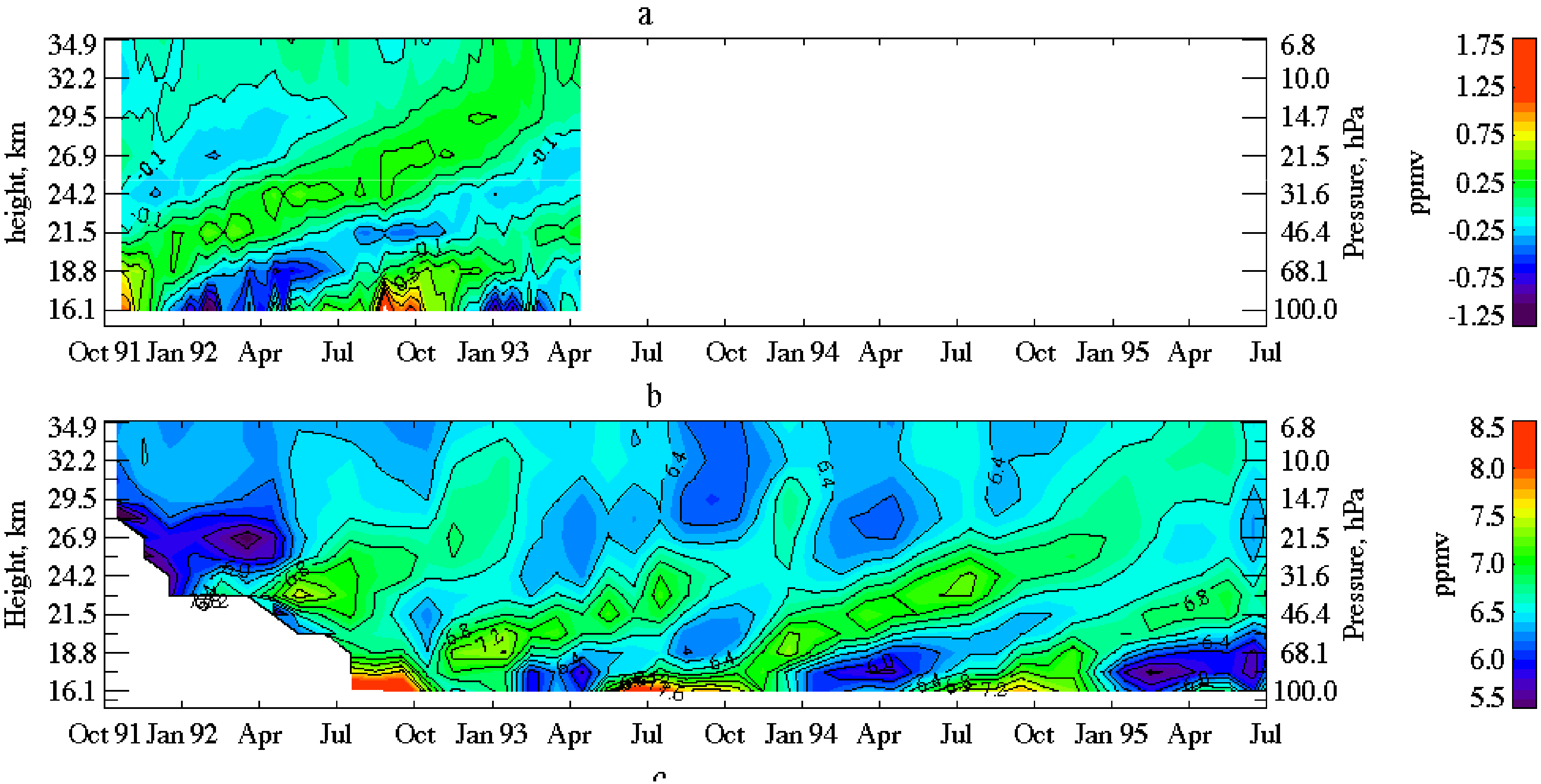
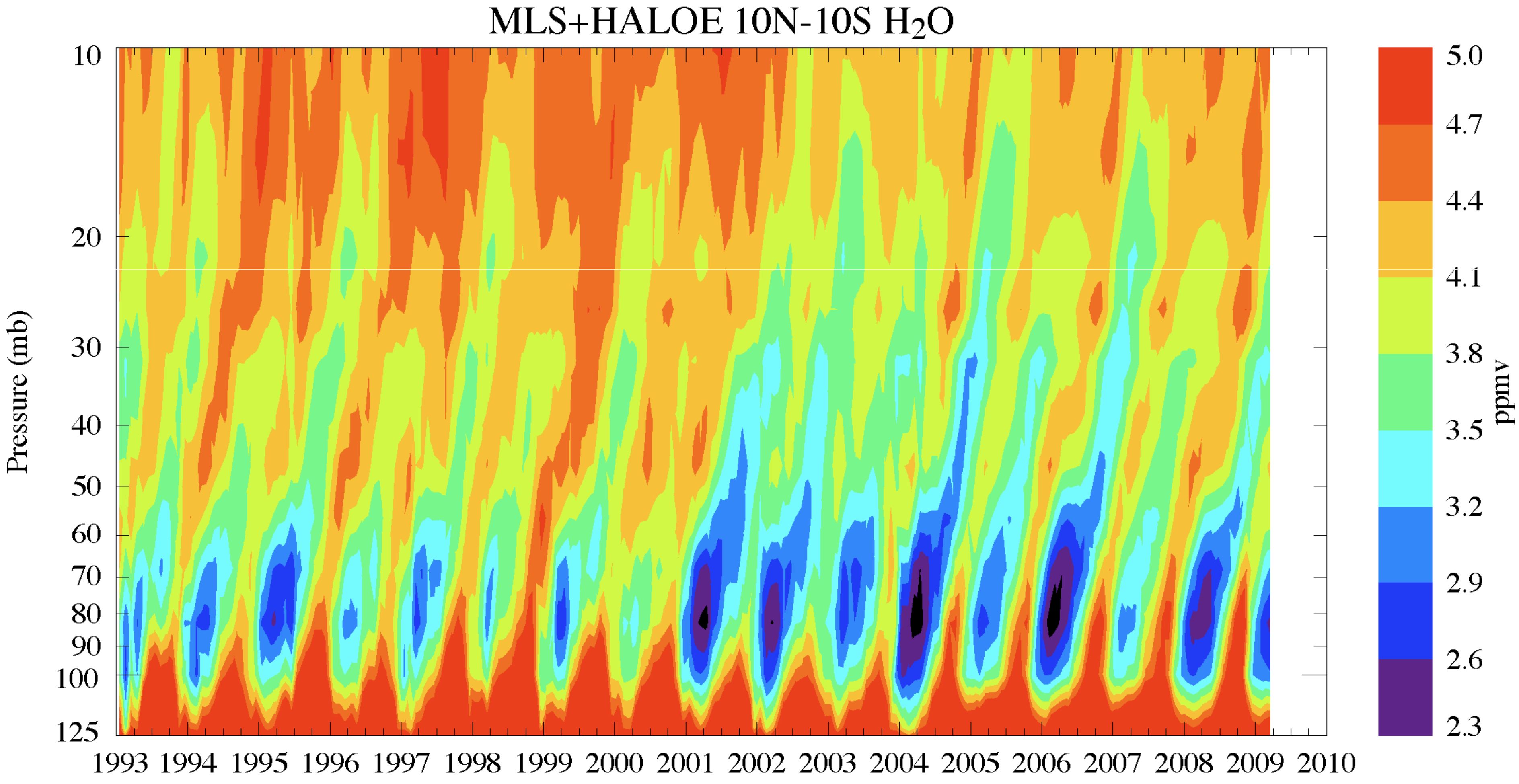


Plate 1. Longitude-height cross sections showing the specified temperature distribution (color), potential temperature (isolines, K), water vapor mixing ratio (ppmv), and ice mixing ratio for Northern Hemisphere winter.

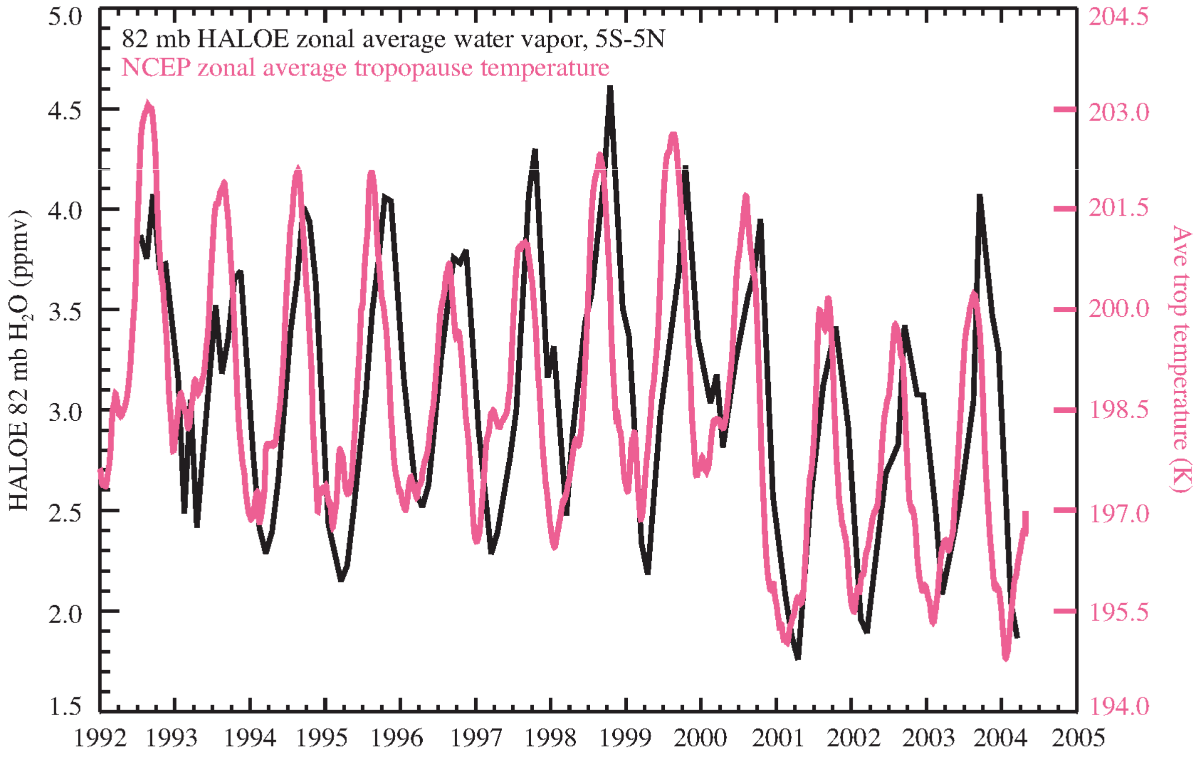
Using water vapor measurements, we can also assess something about the seasonal cycle of the mean meridional motion in the stratosphere, in particular the upwelling in the tropics. This can be done with other constituents as well, but was first done with water vapor.



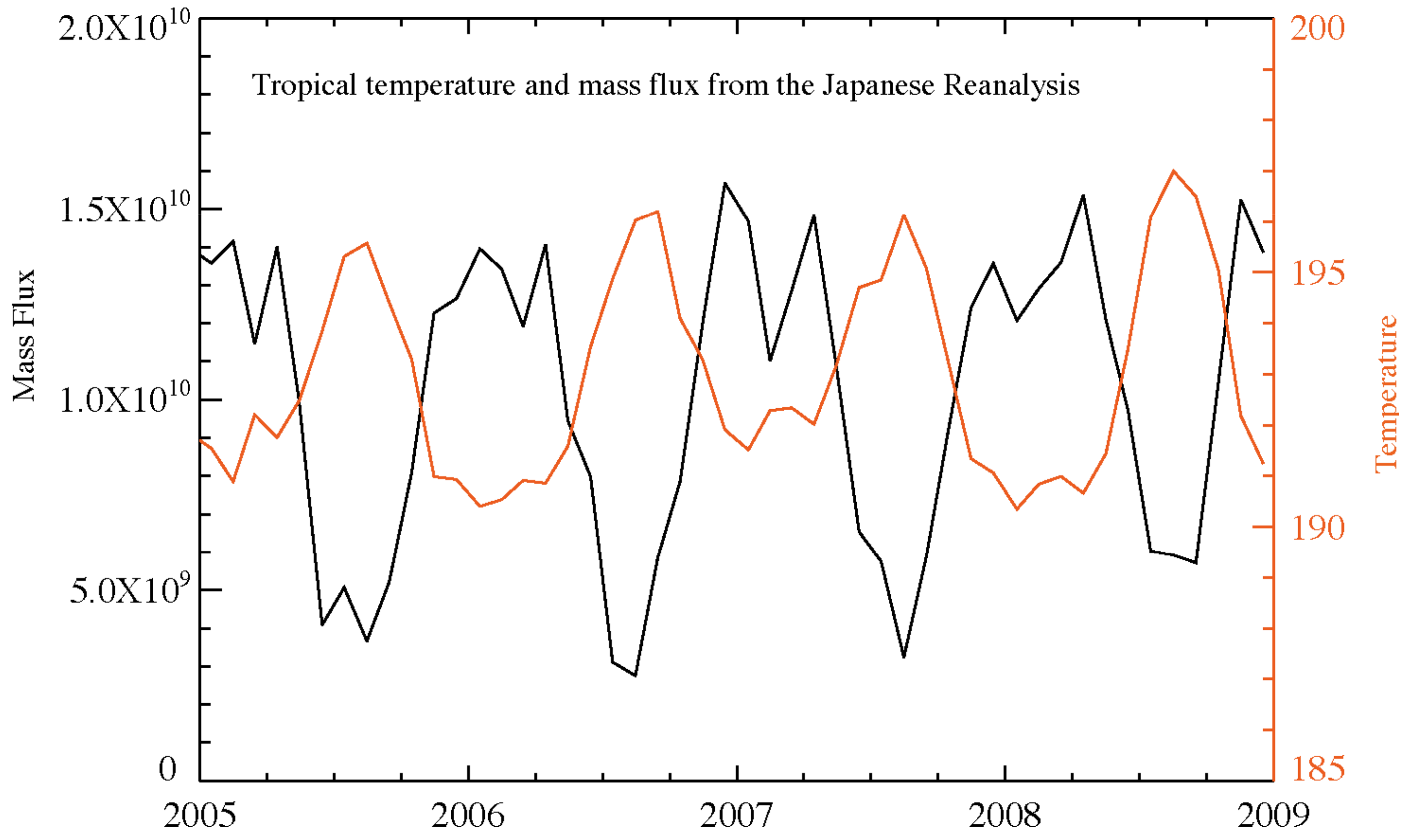
Why is there an annual cycle in the entry of water vapor into the stratosphere?



We see an annual cycle in the entry value of water vapor because there is an annual cycle in tropical cold point (or near tropopause temperatures). Yuleava et al. 1994, Randel et al. 2008.)



The minimum tropical cold point temperatures correspond to a time period when upwelling is a maximum...related to hemispheric assymetries in the seasonal cycle of stratospheric wave driving, or what has been referred to as the extratropical pump.



If we combine information from temperature and upwelling, we can reproduce something similar to the water vapor observations in the tropics.

This shows (From Mote et al, 1996) a modeled version of the tape recorder using minimum saturation vapor pressure mixing ratios estimated from NCEP, and velocities estimated from a radiative heating rate calculation.

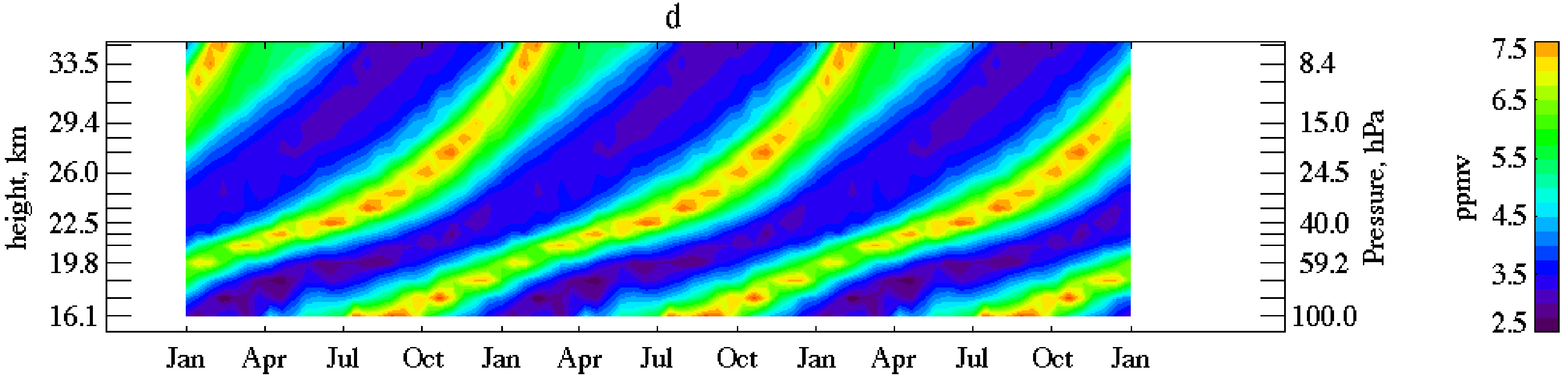


Figure 1

Why does the tape recorder maintain itself from the cold point up to ~10 mb?

There is a region in the tropics that is relative isolated from in mixing from higher latitudes in the lower stratosphere. Tracer-tracer from aircraft measurements relationships were originally used to deduce this (see references in Plumb 1996). This has been referred to in the literature as the tropical pipe.

Plumb, 1996

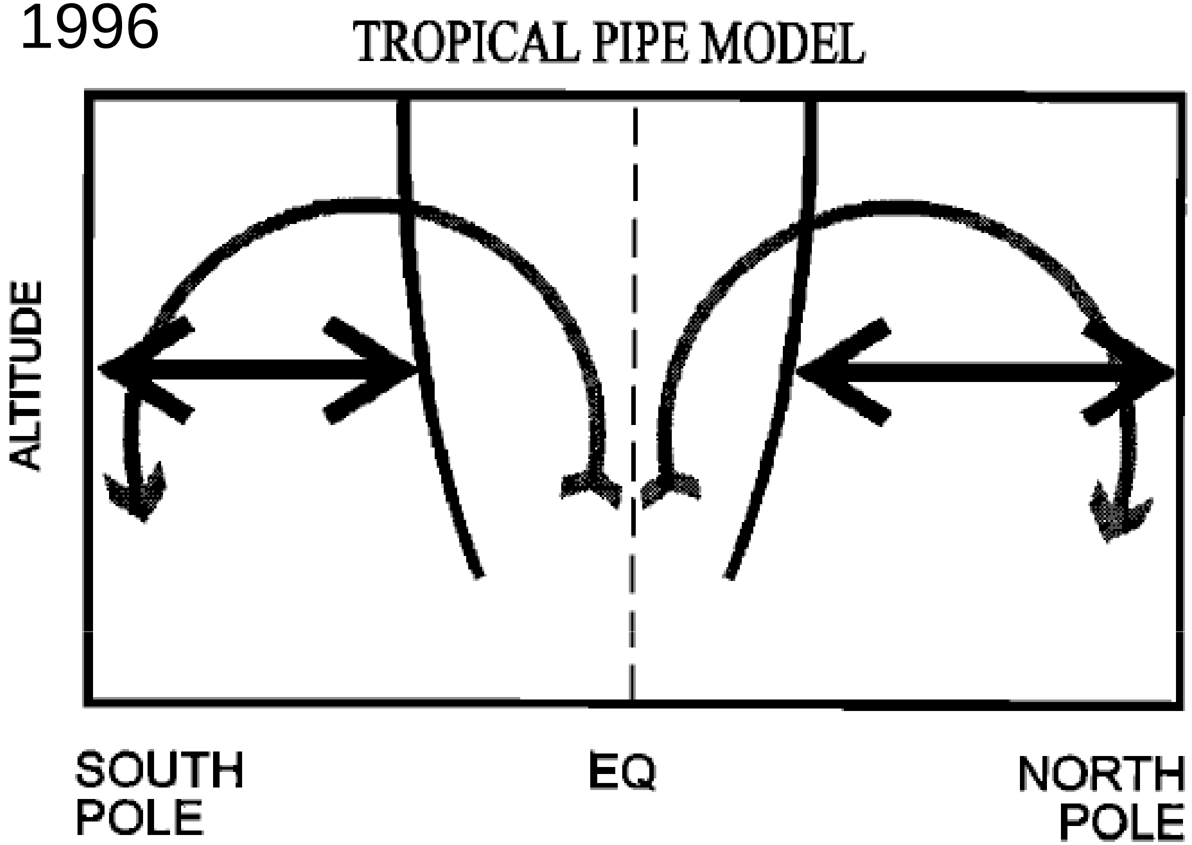


Figure 1. Schematic figure illustrating (top) the "global mixing" model discussed by *Plumb and Ko* [1992], in which the "surf zones" overlap, and (bottom) the "tropical pipe" model, in which there is a "tropical pipe" region isolated from the mixing. Double arrows represent isentropic mixing, and single arrows the meridional circulation. Heavy lines in the bottom figure mark the edges of the "tropical pipe."

Such observations can be used to deduce more about the the mean meridional circulation. Schoeberl et. al, 2008 recently exploited the vertical propogation of the annual cycle in tropical water vapor to estimate Lagrangian mean vertical velocities.

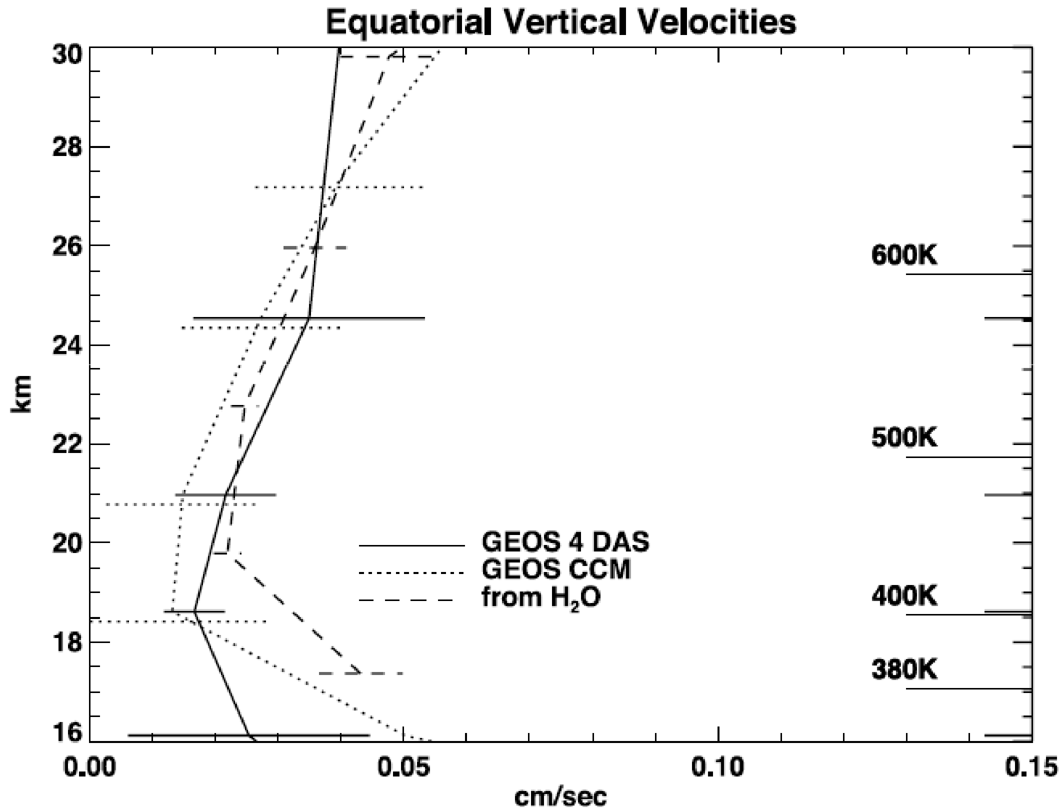


Figure 2. Comparison between time mean GCM vertical velocities and vertical velocities derived from the upward propagation of water vapor anomalies. Horizontal lines represent one standard deviation from the time mean vertical velocity. GEOS CCM uses the GEOS-4 GCM. "From H_2O" is the vertical velocity diagnosed from the GEOS CCM using the water vapor tape recorder simulation. Right-hand tick marks show the potential temperature levels. Long unlabeled tick lines on the right show the model levels.

Velocities were estimated by using lag correlation between levels in the vertical following a method described in Niwano et. al 2003.

SCHOEBERL ET AL.: STRATOSPHERIC MEAN VERTICAL VELOCITY

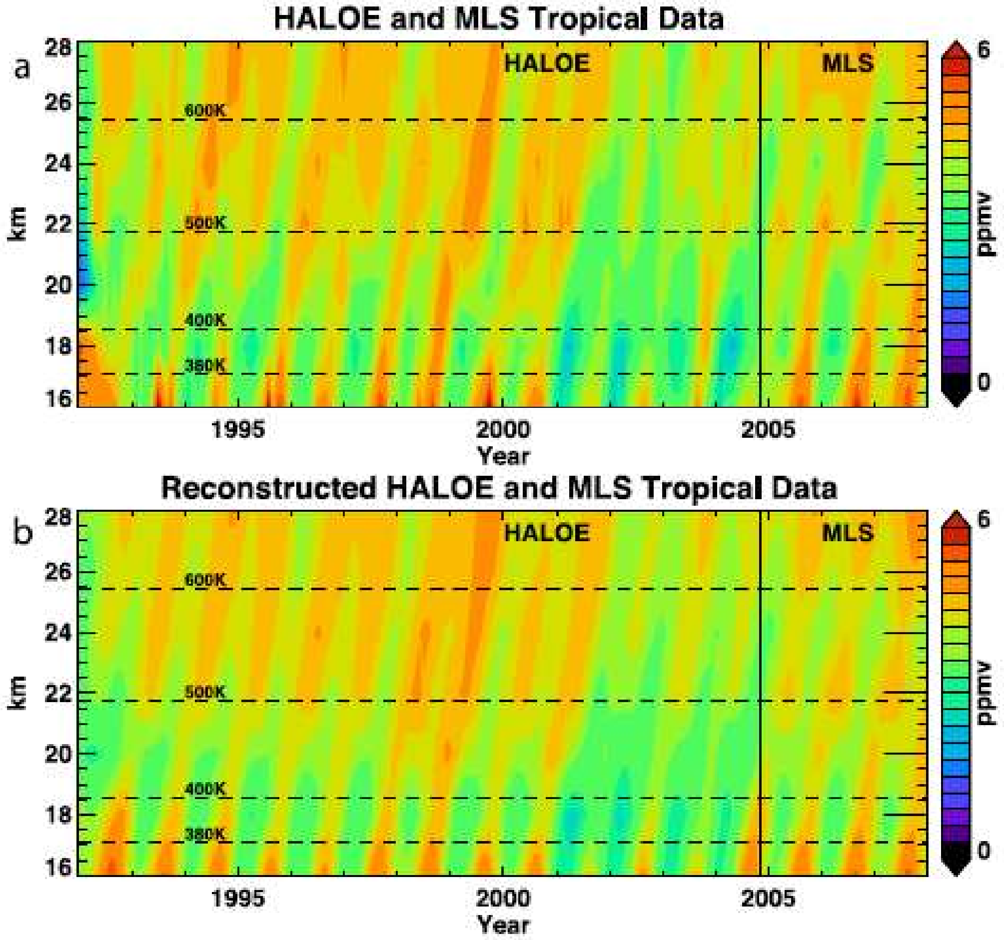
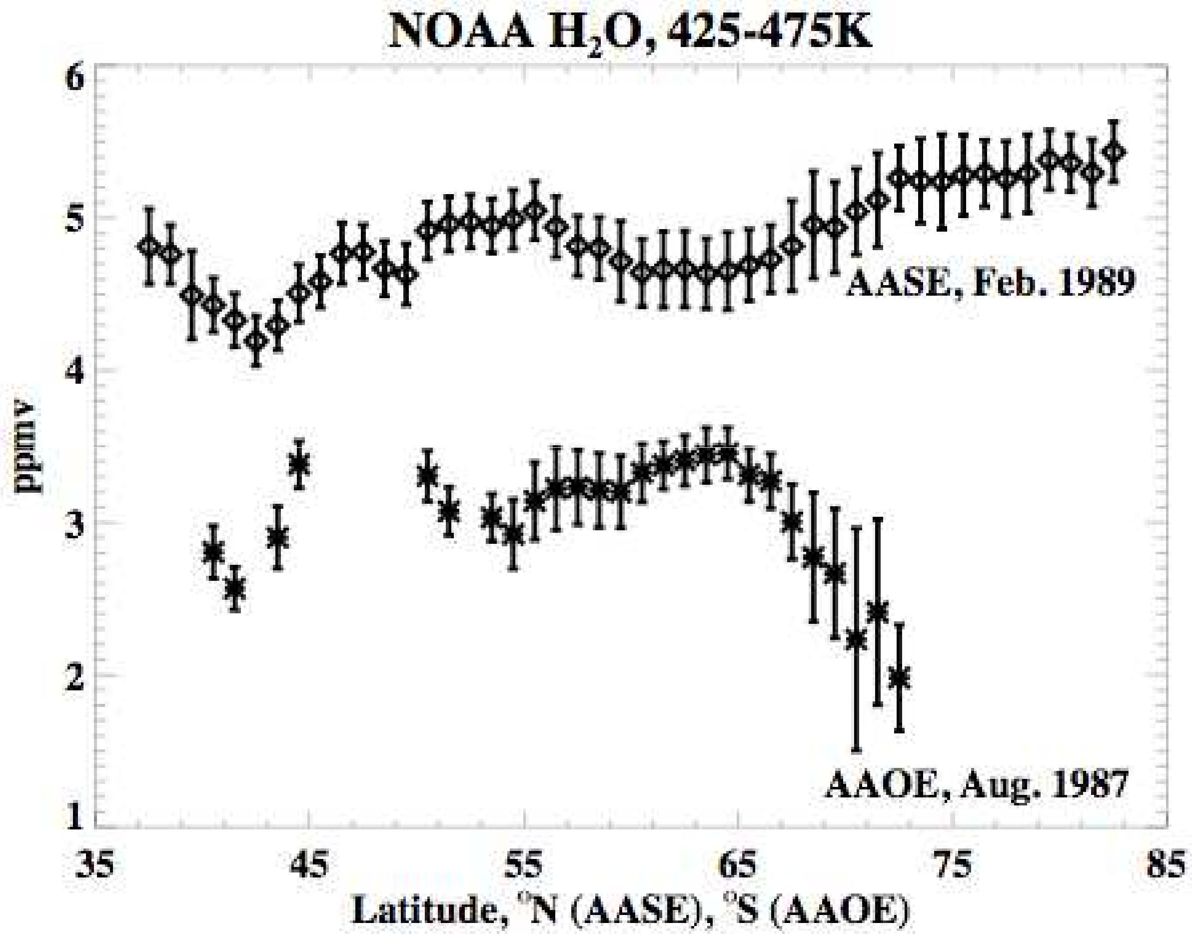
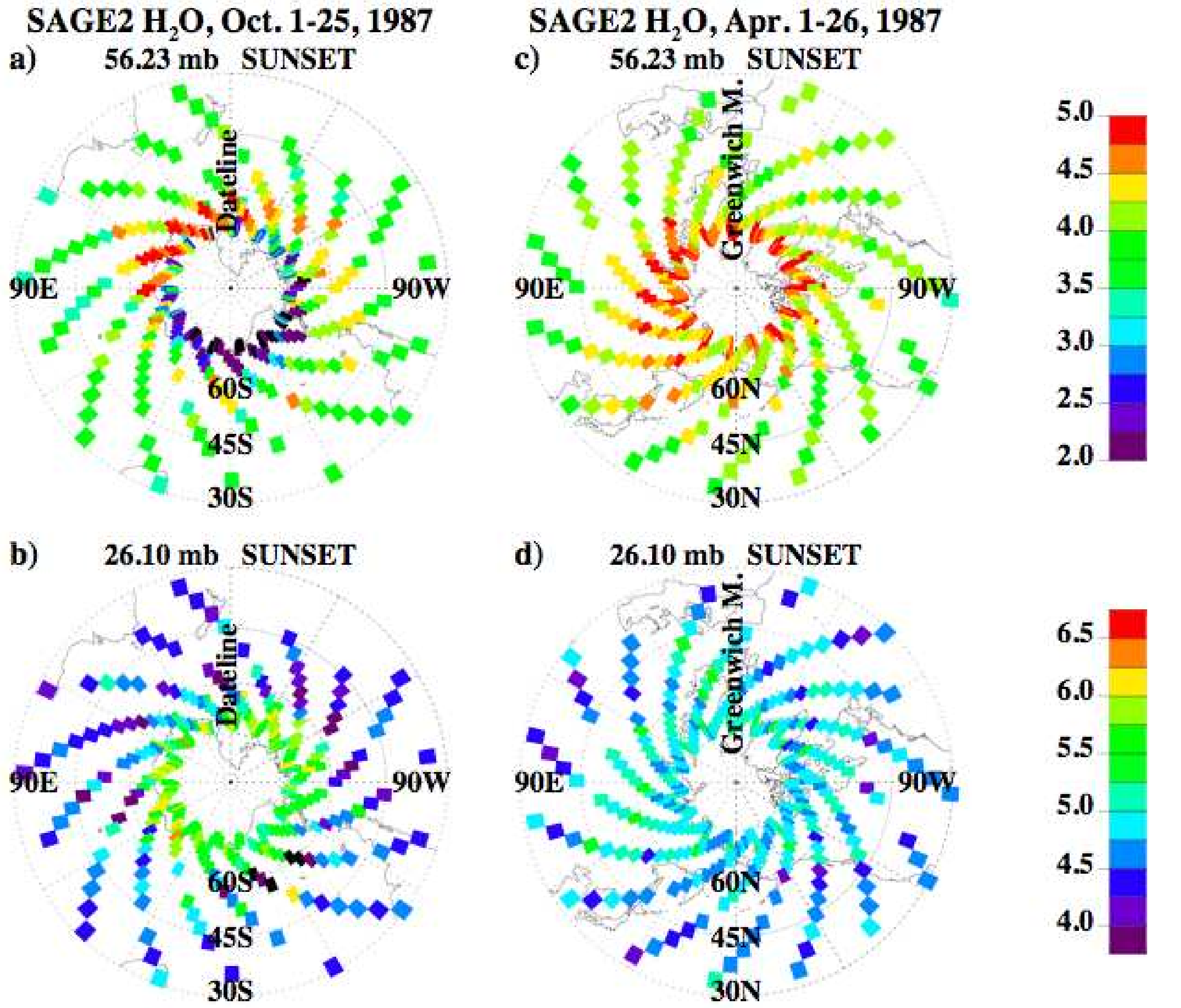


Figure 3. (a) Combined Halogen Occultation Experiment (HALOE) and Microwave Limb Sounder (MLS) water vapor time series at the equator. (b) Reconstructed data set using multiple parameter fit of the data to reduce the noise as described in text. Approximate potential temperature levels are shown as dashed lines. Long tick lines on the right show the model levels.

Hemispheric differences in lower stratospheric water vapor



Aircraft measurements from the same instrument in both NH and SH (NASA ER-2) In tropics, differences are quite small.



SAGE2 H_2O, Oct. 1-25, 1987
SAGE2 H_2O, Apr. 1-26, 1987
a)
56.23 mb SUNSET
c)
56.23 mb SUNSET
b)
26.10 mb SUNSET
d)
26.10 mb SUNSET
Dateline
Greenwich M.
90E
90W
60S
45S
30S
60N
45N
30N
5.0
4.5
4.0
3.5
3.0
2.5
2.0
6.5
6.0
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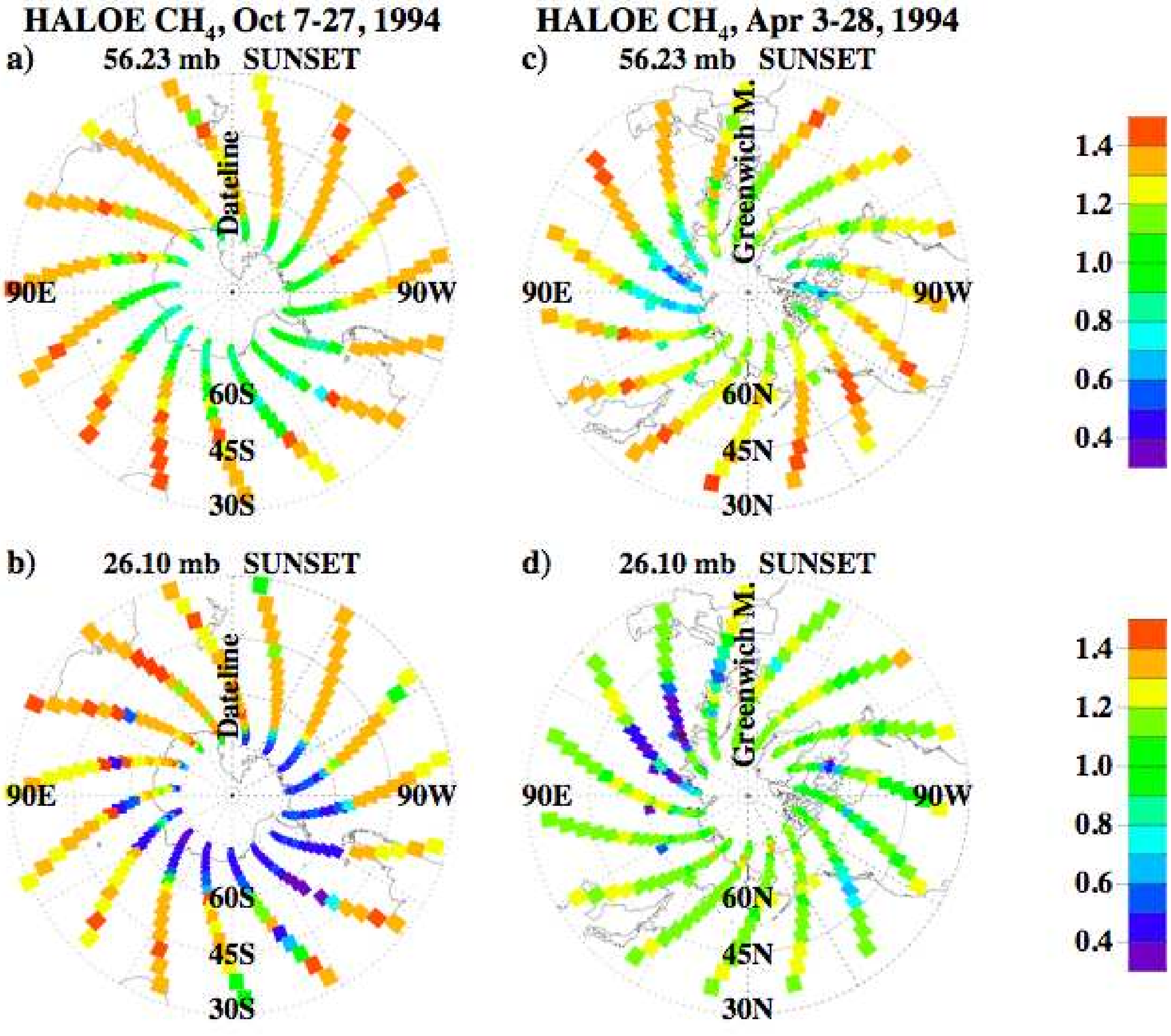
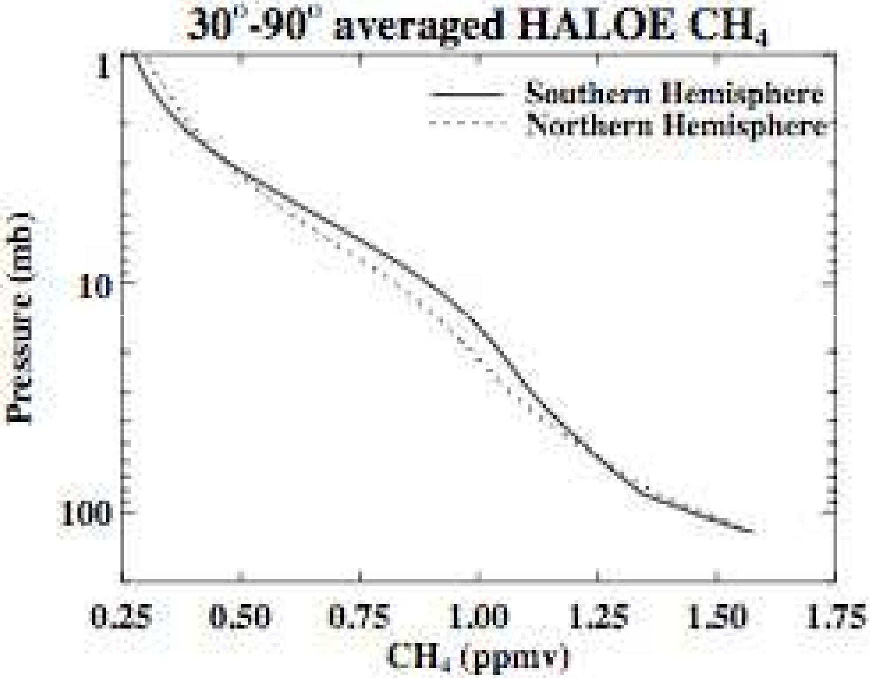
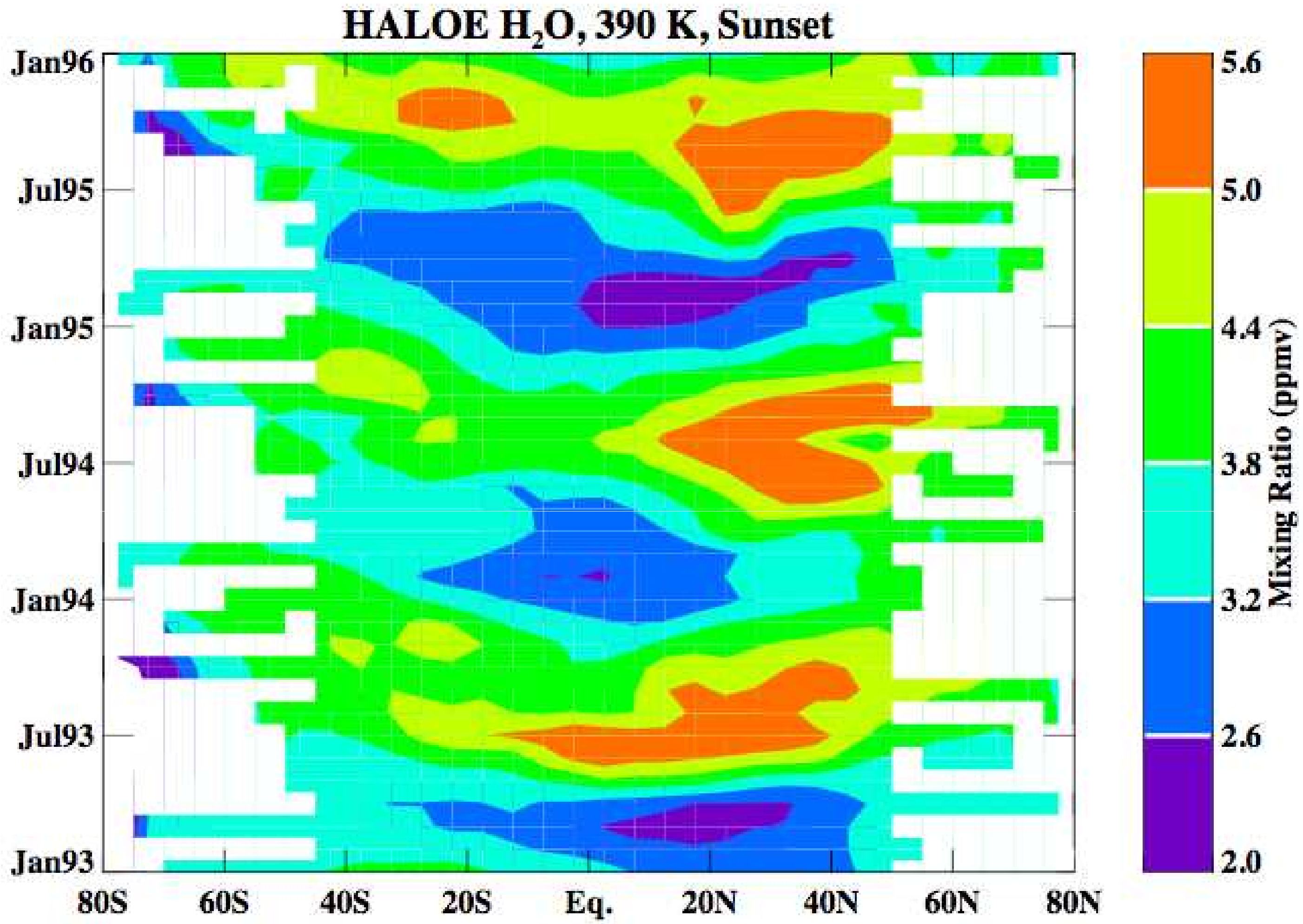
5.0
4.5
4.0



HALOE CH$_4$, Oct 7-27, 1994
HALOE CH$_4$, Apr 3-28, 1994
a)
56.23 mb SUNSET
Dateline
90E
90W
60S
45S
30S
c)
56.23 mb SUNSET
Greenwich M.
90E
90W
60N
45N
30N
b)
26.10 mb SUNSET
Dateline
90E
90W
60S
45S
30S
d)
26.10 mb SUNSET
Greenwich M.
90E
90W
60N
45N
30N
1.4
1.2
1.0
0.8
0.6
0.4
1.4
1.2
1.0
0.8
0.6
0.4


30°-90° averaged HALOE CH_4
Southern Hemisphere
Northern Hemisphere
Pressure (mb)
1
10
100
0.25
0.50
0.75
1.00
1.25
1.50
1.75
CH_4 (ppmv)
30°-50° averaged HALOE H_2O
Southern Hemisphere
Northern Hemisphere
Pressure (mb)
1
10
100
3
4
5
6
H_2O (ppmv)


HALOE H_2O, 390 K, Sunset
Jan96
Jul95
Jan95
Jul94
Jan94
Jul93
Jan93
80S
60S
40S
20S
Eq.
20N
40N
60N
80N
5.6
5.0
4.4
3.8
3.2
2.6
2.0
Mixing Ratio (ppmv)

We could only explain observations with a combination of input from the SP dehydration and convolution with the seasonal cycle in tropical upwelling. (Rosenlof et al. 1997)

We concluded that:

Above 450K, seasonal variations in the strength of the Brewer-Dobson circulation control the water vapor distribution.

Stratosphere can be well represented by zonal averages (2D) Transport barriers tend to be strong (with isolated vortex and tropical regions.)

Below 450K, recent entry tropical air controls the water vapor seasonal cycle.

Stratospheric air is relatively young

There is significant mixing between tropics and middle latitudes, and moderate leakage of air out of polar regions.

From SPARC 2000 report:

The concentration of stratospheric water vapor in the "overworld" (where Theta is greater than ~380 K) is determined by

1) dry air upwelling through the tropical tropopause
2) methane oxidation in the stratosphere
3) transport by the poleward-and-downward (Brewer-Dobson) mean circulation and wave-induced isentropic mixing
4) in the lowest few km of the stratosphere, an upward extension of tropospheric circulations is important as well.
5) Nearly all the air above 380K has been freeze dried in the vicinity of the tropical tropopause.

6) Some of this dry air rises slowly in the tropics, but most spreads poleward, primarily in the lowest few kilometres of the stratosphere.

7) Below approximately 380K, the extratropical lower stratosphere is moistened by air transported from the tropical upper troposphere horizontally across the subtropical tropopause at the location of the subtropical jet.

Take home message:

1) Nominal stratospheric values of water vapor set by the tropical cold point temperature

2) Water vapor increases with altitude in stratosphere (then decreases in the mesosphere). This is due to production of water vapor via methane oxidation. (and other hydrogen chemistry in the mesosphere.) Molecular hydrogen oxidation can't be ignored, it produces deviations from the value of 2 for the methane yield (see, LeTexier et. al, 1988, QJRMS, 114,pp. 281-295)

3) There is a hygropause: which is the location of the minimum value of water vapor in the profile, first observed in balloon profiles (see Kley et al., 1979, JAS, 36, pp. 2513-2524). Was confirmed by LIMS measurements to be a global phenomena. Original tropical balloon observations showed the minimum was above the local tropopause In the tropics, the tape recorder explains that. Hygropause at higher latitudes is a consequence of transport from the tropical cold regions.

4) Local dehydration occurs in the SH polar regions, and it does impact the hemispheric differences in lower stratospheric water vapor. Monsoon does as well...should be explained later in the course.