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Tropical stratospheric water vapor measured by the microwave limb sounder (MLS)

E. S. Carr,[1] R. S. Harwood,[1] P. W. Mote,[1] G. E. Peckham,[2] R. A. Suttie,[2]
W. A. Lahoz,[3] A. O'Neill,[3] L. Froidevaux,[4] R. F. Jarnot,[4] W. G. Read,[4]
J. W. Waters,[4] and R. Swinbank[5]

Abstract. The lower stratospheric variability of equatorial water vapor, measured by the Microwave Limb Sounder (MLS), follows an annual cycle modulated by the quasi-biennial oscillation. At levels higher in the stratosphere, water vapor measurements exhibit a semi-annual oscillatory signal with the largest amplitudes at 2.2 and 1hPa. Zonal-mean cross sections of MLS water vapour are consistent with previous satellite measurements from the LIMS and SAGE II instruments in that they show water vapor increasing upwards and polewards from a well defined minimum in the tropics. The minimum values vary in height between the retrieved 46 and 22hPa pressure levels.

Introduction

Air is believed to enter the stratosphere from below in low latitudes where it is desiccated by processes which are still not fully understood [*Danielsen*, 1982 & 1993 and *Robinson & Atticks Schoen*, 1987]. It is then transported vertically and polewards in the Brewer-Dobson circulation [*Dobson et al.*, 1946], while subject to quasi-horizontal mixing by breaking or dissipating planetary-scale waves [*Andrews & McIntyre*, 1976] and to a slow hydration due to methane oxidation. These processes result in a zonal mean water vapor distribution in which mixing ratios increase upwards and polewards in the stratosphere from the tropical tropopause [*Remsberg et al.*, 1984].

Processes which alter the strength of the Brewer-Dobson circulation, such as those associated with the quasi-biennial oscillation (QBO) and semi-annual oscillation (SAO) in equatorial winds and temperature can modify the distribution of atmospheric trace species such as ozone and water vapor [*Hyson*, 1983, *Mastenbrook & Oltmans*, 1983 & *Froidevaux et al.*, 1994]

In this paper we analyse seasonal scale changes in tropical water vapor distribution measured by the Microwave Limb Sounder (MLS) on the Upper Atmosphere Research Satellite (UARS) and relate them to the known dynamics.

Observations

The MLS water vapor measurements (version 3) used in this study are obtained from radiance measurements at a frequency of 183 GHz [*Waters*, 1993, *Barath et al.*, 1993]. Radiances are retrieved onto a grid regularly spaced in a log pressure height co-orinate with 3 points per decade of pressure, to give profiles of mixing ratio with horizontal and vertical resolution of approximately 400 km and 5 km respectively.

H_2O observations were obtained from 19th September 1991 (UARS day 8 - written hereafter as U8) to April 25 1993 (U582) when the 183 GHz radiometer failed. No data were available from 2 June 1992 - 15 July 1992 due to a UARS technical problem.

The precision and accuracy of individual measurements at 46, 22 and 10hPa are < 0.2 ppmv and ~15–20% respectively while at 4.6, 2.2 and 1hPa, they are < 0.3 ppmv and ~15–30% respectively (Lahoz et al., Data validation of 183 GHz UARS MLS H_2O measurements, submitted, 1994). Moreover a comparison at equatorial latitudes using a non-linear retrieval scheme shows similar shaped vertical profiles (from 46hPa upwards). The accuracies quoted are estimates based on comparisons of MLS H_2O data (version 3) with other UARS and correlative measurements. The estimated precisions are based on observed variability in latitude bands where meteorological variability is expected to be small, hence the true precisions may be somewhat better than these estimates.

The plots below (Figure 1) show zonally-averaged daily data for which the precision will be correspondingly better. Data were averaged in 4° latitude bins from 30°S to 30°N.

Meridional Distributions

In this section an overview of the changing meridional distribution of H_2O is given. In later sections we discuss the variation in more detail.

Figure 1 shows the zonal-mean water vapor distribution for selected days throughout the life of the 183 GHz radiometer. Also plotted is the zonal mean error ratio which is the ratio of the estimated uncertainty in the retrieved value to the assumed *a priori* uncertainty (2 ppmv everywhere). The data are generally regarded

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[1] Meteorology Department, University of Edinburgh, Edinburgh, UK

[2] Physics Department, Heriot Watt University, Edinburgh, UK

[3] Meteorology Department, Reading University, Reading, UK

[4] Jet Propulsion Laboratory, California Institute of Technology, Pasadena, USA

[5] CR Division, United Kingdom Meteorological Office, Bracknell, UK

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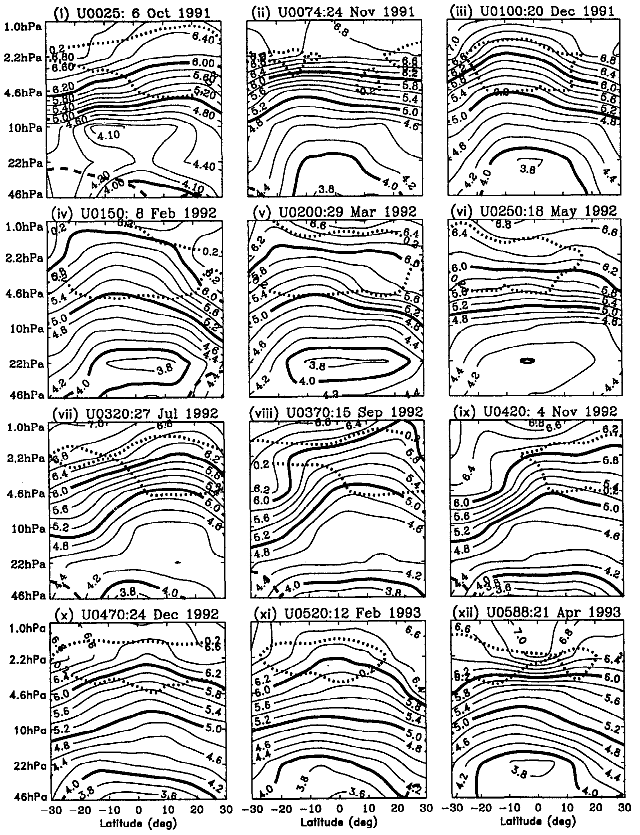

Figure 1. Zonal mean cross sections of MLS H_2O (ppmv) with contour intervals of 0.2 ppmv (note also the 4.1 ppmv contour in (i); 4.0, 5.0 & 6.0 contours are bold). Dashed contours represents error ratio(ER)= 0.5 ; dotted ER = 0.2

as satisfactory when this ratio is less than 0.5 (i.e. there is significant measurement information).

The distributions in Figure 1 show water vapor increasing upwards and polewards from the well-defined minimum in the tropics. This is consistent with the Brewer-Dobson circulation and water production by the oxidation of methane [*Jones et.al.*, 1986] and confirms previous measurements from LIMS [*Remsberg et al.*, 1984] and SAGE II [*Chiou et al.*, 1993].

Minimum MLS H_2O mixing ratios found in the tropical stratosphere generally occur at 22hPa (e.g. Figure 1(iii)-(vi) and (xii)) or at 46hPa (e.g. Figure 1(i), (ii) and (vii)). The movement of the minimum between these levels appears abrupt in the plots but this is to some extent an artifact of the retrieval grid having adjacent grid points at these positions. Inspection of HALOE data (not shown) which are retrieved on a finer grid indicate that the minimum sometimes occurs on the intermediate level at 32hPa.

Although the minimum in the MLS vertical profiles is occasionally at 22hPa (~ 26km), it is unlikely that this represents the true stratospheric minimum (or hygropause) since the majority of earlier measurements document a hygropause altitude several kilometres below this [e.g. *Remsberg et.al.*, 1984], in fact at altitudes where MLS H_2O retrievals are not currently available.

There is a large variability in the shape of the upwards bulge in the contours, as may be seen by fixing attention on the 5 ppmv contour, which sometimes is rather flat (e.g. Figure 1(vi)) and at other times is sharply curved possibly indicating a narrower region of ascent flanked by downwelling in the subtropics (e.g. Figure 1(vii)). In so far as the position of the maximum vertical velocities can be inferred from the latitude at which the minimum H_2O at a given height is found, Figure 1 gives evidence that the upward branch of the Brewer-Dobson circulation moves seasonally between the southern and northern hemisphere.

In Figure 1(i) (October 6 1991), as well as the 46hPa minimum in the tropics, there is a small region of minimum water vapor values (4.1 ppmv) over the southern tropics at 10hPa (~32km). Although there is an area of lessened measurement sensitivity in the lower stratosphere on this day we do not expect the 10hPa minimum to be an artifact of this as the *a posteriori* error estimate indicates satisfactory information content. Moreover surrounding days (not shown) have a similar appearance. The distribution is atypical and is possibly due to the lower stratospheric radiative perturbations following the eruption of Mount Pinatubo (15°N, 120°E) in June 1991 which enhanced the vertical transport in the mean meridional Brewer-Dobson circulation [*Kinne et al.*, 1992]. Aerosol measurements from SAGE II [*Trepte et al.*, 1993] are consistent with this, showing evidence of high extinction coefficient ratios at altitudes in excess of 30km, in the tropics, in the latter half of 1991 with a persistent high centered at ~15°S for several months following the eruption.

Variability

We now consider the temporal variations of tropical water vapor as observed by MLS, beginning with the lower stratosphere. In order to relate the panels of Figure 1 to each other, in Figure 2 we show the time-latitude variation of the zonal mean MLS water vapor at 22 and 46 hPa. At both levels, a well-defined

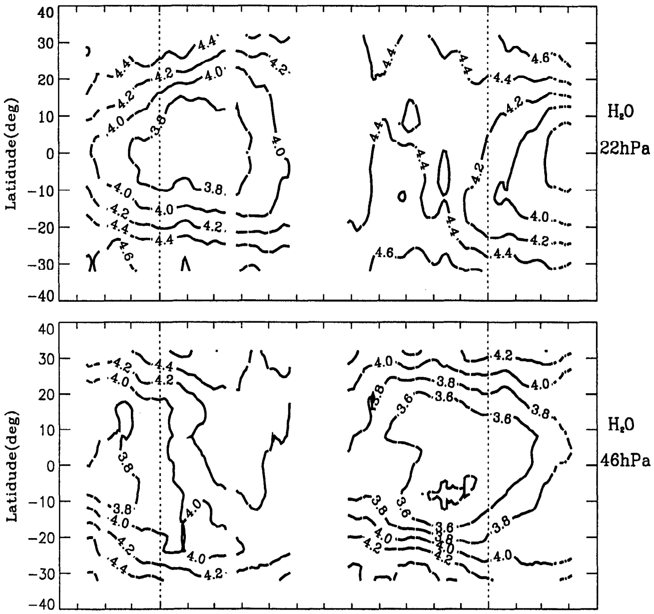

Figure 2. (i) Time-latitude series of MLS H_2O at 22hPa (data were averaged every 4° in latitude). (ii) As above but for 46hPa

tropical minimum is present in some months and is flanked by sharp gradients poleward of 10° or 20°. In other months, the well-defined tropical minimum and sharp gradients are not present (e.g. Figure 1(vii) and (viii) at 22 hPa). In their comparison of nitrous oxide between measurements from the CLAES instrument aboard UARS and a simulation with the NCAR community climate model (CCM2), *Randel et al.* [1994] noted that the subtropical region of sharp tracer gradient migrated equatorward and sharpened in winter at 10 hPa in a similar manner each year.

A repeatable annual cycle as noted by *Randel et al.* is not evident in the MLS H_2O at 22 hPa (Figure 2(i)), either in the position and intensity of the subtropical gradient or in the phase of the equatorial values. In 1992 mixing ratios are fairly constant at ~ 3.8 (ppmv) from January to March, while in 1993 the minimum occurs sometime after mid-March. Maximum mixing ratios are found around September 1992 (~ 4.5 (ppmv)) and sometime before October 1991. At 46 hPa, the variations more nearly follow an annual cycle. The gradient moves southward in the months of October to January in both years and then weakens after February. The equatorial minimum occurs in November or December in both 1991 and 1992 and the maximum occurs in early March 1992 and sometime after April 1993.

The quasi-biennial oscillation (QBO) is an aperiodic reversal in the tropical zonal winds in which the westerly and easterly regimes descend with time [*Reed*, 1965]. The QBO gives rise to thermal anomalies which are balanced by a tropical meridional circulation, such that when the mean westerly wind shear is increasing, a downward contribution to the circulation at the equator is produced. Such a circulation would have a signature in long-lived tracers and in aerosol [*Trepte and Hitchman*, 1993]. We suspected that the temporal variations shown in Figure 2 were caused by the QBO, and indeed we found that the equatorial 22 hPa water vapor was well correlated with the vertical shear of zonal mean zonal wind between 10 hPa and 50 hPa (using winds from the UK Met. Office assimilation which is part of the UARS correlative data base [*Swinbank and O'Neill*, 1994]). On further analysis, however, we found that water vapor in the lower stratosphere is very sensitive to the seasonal variations of tropopause temperature. The timing of features in Figure 2 is largely determined by the arrival of dry air which crossed the tropopause when it is at its coldest (January or February). These results will be presented elsewhere (Mote et al., The imprint of tropopause temperatures on stratospheric water vapor, manuscript in preparation, 1995). We also found that the role of the QBO is to delay or accelerate the arrival of a minimum; this explains why the variations at 22 hPa are farther from a pure annual cycle than the variations at 46 hPa.

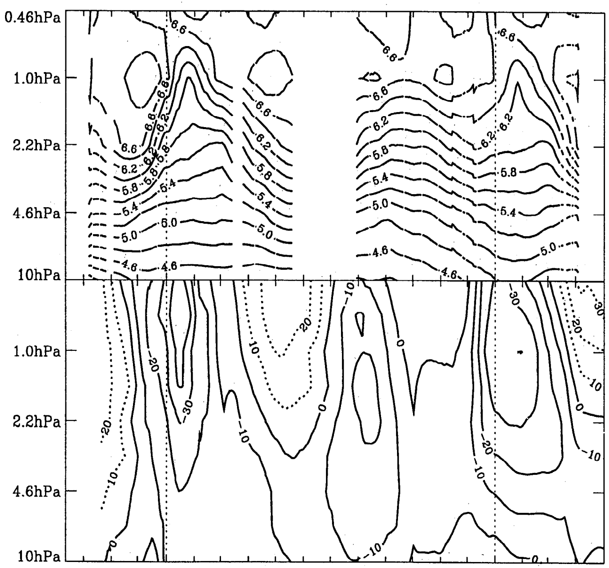

Figure 3. Time-$\log_{10}$[P/hPa] cross-section of equatorial MLS H_2O (upper panel, 0.2 ppmv contours) and United Kingdom Meteorological Office (UKMO) zonal-mean equatorial winds (lower panel, 5 ms^{-1} contours). Dotted vertical lines show January 1 for 1992 and 1993.

As with the QBO, the zonal accelerations which cause the semi-annual oscillation (SAO) in the upper stratosphere also produce thermal anomalies and a meridional circulation. This meridional circulation has a clear signal in MLS water vapor (Figure 3:upper panel) at four pressure levels and the largest amplitudes occur at 2.2 and 1hPa. The variations at each level correlate well with the corresponding variation in UKMO winds (Figure 3:lower panel) and cause the well-known equinoctial double peak in the zonal mean (Figures 1(v, viii, xii)). The MLS temperature and ozone measurements also exhibit this semi-annual oscillatory signal [*Ray et al.*, 1994].

Conclusions

The variability in lower stratospheric MLS zonal mean low latitude water vapor vapor, at 46 and 22hPa, appears to be that of a modulated annual cycle with the modulation arising from the modulation in the vertical velocity of the Brewer-Dobson cell. For the period of study it is possible that lower stratospheric heating perturbations following the eruption of Mount Pinatubo play a role also. In the upper stratosphere, the mixing ratios exhibit a semi-annual oscillation which is related to the oscillation in upper stratospheric UKMO winds.

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E. S. Carr, R. S. Harwood, and P. W. Mote,
Meteorology Department, University of Edinburgh,
Edinburgh, EH9 3JZ, UK

G. E. Peckham and R. A. Suttie, Physics Department,
Heriot Watt University, Edinburgh, EH14 4AS, UK

W. A. Lahoz and A. O'Neill, Meteorology Department,
Reading University, Reading, RG6 2AU, UK

L. Froidevaux, R. F. Jarnot, W. G. Read and J. W.
Waters, Jet Propulsion Laboratory, California Institute of
Technology, Pasadena, CA, USA 91109

R. Swinbank, CR Division, United Kingdom
Meteorological Office, Bracknell, RG12 2SZ, UK

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