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# Lower stratospheric water vapor measured by UARS MLS

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**Abstract.** We present zonal mean time series of water vapor in the lower stratosphere as measured by UARS MLS. The data are taken from a development version known as V104; we demonstrate that this version behaves in a physically realistic manner at 100 and 68 hPa, lower altitudes than are useful in previous versions of the data. The 100 hPa data show that the annual cycle in tropical lower stratosphere water vapor is driven by the northern hemisphere. Both low and high mixing ratios spread from the northern hemisphere tropics into the southern hemisphere tropics and into the mid-latitudes with transport out of the tropics being greater at 100 hPa than at 68 hPa. Transport into mid-latitudes is greater in the northern hemisphere and greater in spring than in fall. At 46 hPa, the tropical annual cycle is strongly confined to low latitudes.

## 1. Introduction

Water vapor plays many important roles throughout the atmosphere. In the lower stratosphere it is a powerful tracer for atmospheric motions and is the source of the hydroxyl radical. Hence, its study has important implications for our understanding of the chemistry and dynamics of the lower stratosphere. Measurements of water vapor in the lower stratosphere are difficult to obtain. In situ measurements from balloon and aircraft are limited in their spatial and temporal coverage. Satellites have been increasingly exploited to provide better data coverage in this region. In this paper we present results of an interim prototype retrieval from the Microwave Limb Sounder (MLS) on the Upper Atmosphere Research Satellite (UARS) [*Pumphrey,* 1999]. This version is known informally as version 104.

The phenomenon now known as the "tape recorder" effect was first reported in two papers: *Mote et al*, [1995] and *Mote et al*, [1996]. This term describes how the zonally averaged water vapor content of air rising through the lower stratosphere is controlled by the seasonal cycle of temperatures at the tropical tropopause coupled with the rate at which air is moved upwards by the Brewer-Dobson circulation. The region of the stratosphere between 100 hPa and 14 hPa and within 25° of the equator, where the air moves slowly upwards without being mixed outwards to higher latitudes, is often referred to as the "tropical pipe" [*Plumb,* 1996]. In this paper we show that the zonal distribution of water vapor in the lower stratosphere is consistent with these theories and therefore that the new data behave in a physically realistic manner, even in regions of the lower stratosphere not reached by the version 4 and 5 retrievals.

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## 2. Data

The UARS sat *Reber,* 1993] is in an almost circular orbit at an altitude of 585 km and an inclination of 57° to the equator. It makes about 15 orbits a day, giving a longitudinal resolution between 12° and 24°. The MLS instrument [*Barath et al.*, 1993] observes the Earth's limb in a direction perpendicular to the UARS orbit path. One scan across the limb is performed every 65.5 seconds. The distance traveled along the orbit during this time is such that the latitudinal resolution is about 4°. Latitudinal coverage changes from between 80°N and 34°S to 34°N and 80°S about every 36 days due to the satellite making a yaw manœvre. Daily measurements (barring instrument failures) are available from 19 September 1991 to 22 April 1993.

The measurements of limb radiance from one scan are used to deduce profiles of temperature and of the mixing ratio of various species; the profiles are retrieved on a fixed pressure grid. Versions 3 and 4 of the MLS data used a grid with 3 levels per pressure decade – approximately one level every 5-6 km. The version used here has 6 levels per pressure decade – approximately one level every 2.5-3 km. In the lower stratosphere this is close to the achievable vertical resolution of the instrument. The retrievals used in this version also extend the usable vertical range from 46 hPa down to 68 hPa and 100 hPa.

It is shown by *Pumphrey* [1999] that, although the version 104 data used here are an improvement on previous versions, the values in the lower stratosphere must be used with some caution. The data show almost no bias compared to frost-point hygrometer data, but are up to 0.5 ppmv drier than the HALOE and ATMOS instruments and up to 1 ppmv drier than aircraft-mounted Lyman-alpha instruments. The a priori used in the retrieval process is a monthly zonal mean derived from SAGE-II data [*Pumphrey et al.*, 1998]. At 100 hPa in particular the retrieved data depend to a noticeable extent on the a priori, this effect may be seen in Figure 1. This problem is worst at low latitudes – its most obvious effects are spurious changes in the data at the end of calendar months and it may also be responsible for the dry bias mentioned above. Finally, the MLS antenna suffers changes in temperature in the few days either side of a UARS yaw manœvre. These can cause uniformly low retrieved water vapor values at certain pressure levels at these times. This problem is particularly noticeable at 68 hPa.

Version 104 was a prototype used in the development of MLS version 5. Version 5 has only recently become available. We have chosen not to use it for this study because it appears to have more problems than version 104 in the lowest part of the stratosphere. This is demonstrated by the time series of daily zonal means of MLS water vapor shown for both version 5 (grey) and version 104 (black) in Figure 1. The zonal means are for the tropical region at 46 hPa (top),

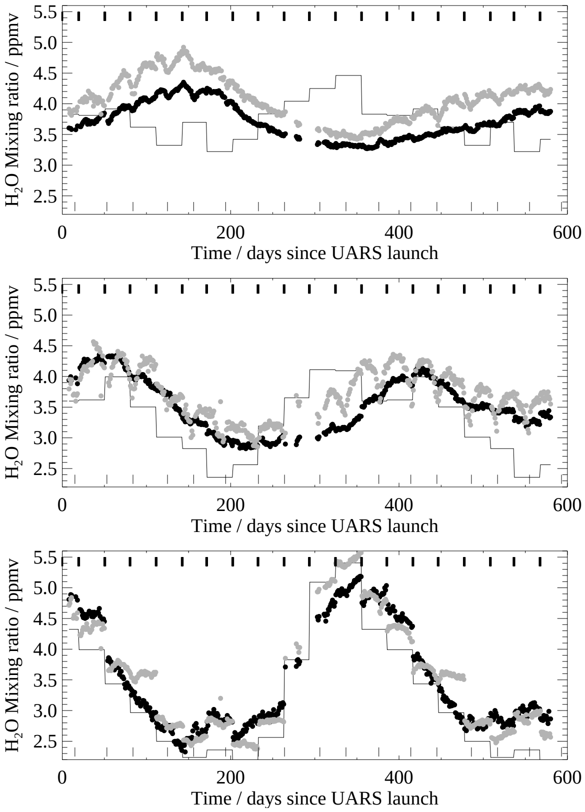

**Figure 1.** This figure shows evidence that the V104 data set used in this paper is superior to version 5 in the lower stratosphere. Each panel shows a time series of MLS $H_2O$ at the equator. The panels are, from top to bottom, 46 hPa, 68 hPa and 100 hPa. Black points are V104; grey are V5. The thin line is the a priori used in both retrievals. The row of ticks at the top of each panel are calendar month ends and the row at the bottom are UARS yaw days. Note that V5 has much larger dependence on the yaw cycle at 68 hPa and on calendar month (and hence the a priori) at 100 hPa than does V104.

68 hPa (middle) and 100 hPa (bottom). The row of ticks at the top of each panel are calendar month ends and the row at the bottom are UARS yaw days. The dependence on the yaw cycle at 68 hPa and on calendar month boundaries at 100 hPa is much worse in version 5 than in version 104. Version 5 is more closely constrained to the a priori (shown as a thin line), partly because of the a priori covariance chosen. Another reason is that while both versions have a criterion for rejecting radiances with too large a tangent pressure or opacity, this criterion is stricter in version 5. The yaw cycle dependence is caused by variations in the antenna temperature. These contribute to an offset or baseline which must be removed from the radiance measurements. Version 104 uses a simpler method of doing this [*Pumphrey* 1999] than do versions 4 and 5. At 68 hPa this simpler method appears to be more successful. For these reasons we use V104 data throughout this paper.

## 3. Results and discussion

Figure 2 shows the zonal mean water vapor at 100 hPa from September 1991-April 1993. We show this figure to give an impression of what the raw data are like and to emphasize the data coverage available. In all subsequent figures the data gaps have been filled by interpolation and the data have been smoothed with a Kalman filter. These data gaps are filled solely to allow the eye to follow the seasonal cycles more easily – we do not claim to make any detailed inference about the state of the atmosphere in the data gaps. The smoothed version of the 100 hPa data is shown in Figure 3. Figure 4 shows the a priori at 100 hPa processed and plotted in exactly the same way as was done with the retrieved product in Figure 3. By comparing Figures 3 and 4 it may be seen that MLS provides a considerable amount of information at 100 hPa, particularly at higher latitudes.

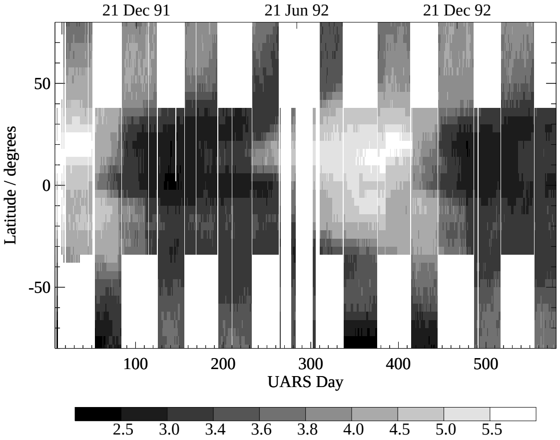

**Figure 2.** Zonal mean water vapor (ppmv) at 100 hPa. The entirely white areas indicate where there are no data, either due to the UARS yaw cycle or to operational problems. Note that the grayscale levels are not evenly spaced.

The tape recorder signal can be seen clearly in Figure 3; the maxima and minima are offset from the equator. The two maxima, occurring in August-September, lie at about 20°N and reflect moistening by the Asian monsoon. The minima in February-March lie at 5-10°N, nearer to the equator than the maxima. At 68 hPa (Figure 5), the first appearance of moist air is also displaced off the equator into

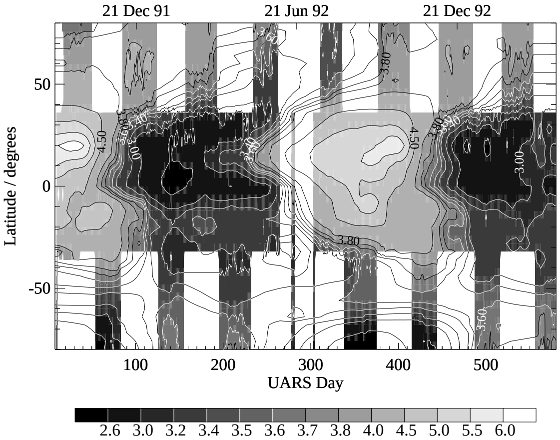

**Figure 3.** Zonal mean water vapor (ppmv) at 100 hPa, with the gaps seen in Figure 2 filled and the data smoothed. The areas with no greyscale indicate where data gaps longer than a few days have been filled. Note that the contour levels are not evenly spaced.

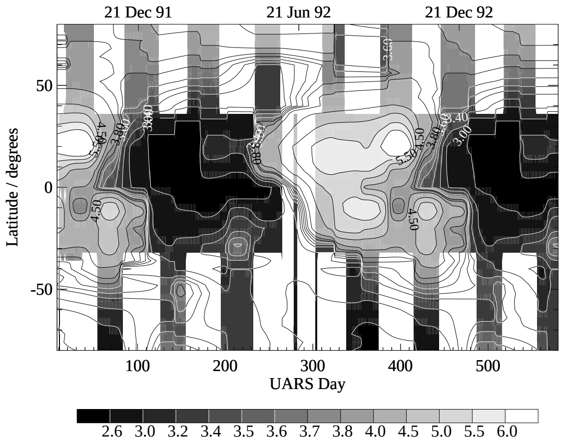

**Figure 4.** As Figure 3, but shows the a priori used for the retrieval. Exactly the same filtering has been applied to the a priori as to the retrieved product.

the northern hemisphere but by a smaller distance than at 100 hPa. The dry air at 68 hPa is more or less on the equator. Finally, at 46 hPa (Figure 6) both the maxima and minima are centered on the equator. Similar results were seen by *Randel et al.*, [1998] who noted that the annual cycle in water vapor observed by HALOE is centered over the equator at and above 68 hPa but in the NH sub-tropics at 100 hPa. We note that the a priori used in the retrieval does not have a clear tape recorder signal except at 100 hPa. This is an artefact in the SAGE-II data used to construct the climatology, these data are affected by stratospheric aerosols between 70 and 20 hPa. The signal seen in the retrieved product above 100 hPa is therefore coming from the instrument and not from the a priori.

Evidence for transport from the tropics to mid-latitudes is visible at 100 hPa (Figure 3) and to a lesser extent at 68 hPa (Figure 5). In Figure 3, the contour lines between 35°N and 70°N slope to the right, implying that water vapor is transported from 35°N to 70°N on a time-scale of about 130 days. This pattern is not as clearly discernible in the southern hemisphere and insofar as it exists, penetrates only to 50°S. In both hemispheres the pattern is clearer in spring than in fall. We infer that air appears to move into the mid-latitudes more quickly and with less mixing in the northern hemisphere than in the southern hemisphere. This was also noted (but for a different time period to that which we show here) by *Rosenlof et al.*, [1997] in a zonal mean of HALOE data (from 1993-1996) on the 390 K isentropic surface.

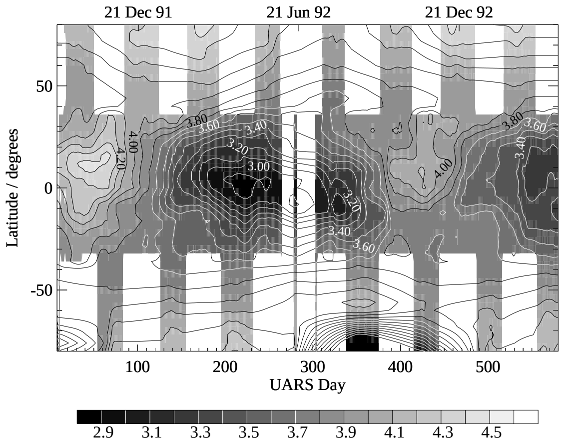

**Figure 5.** As Figure 3 but for 68 hPa. Note different contour values.

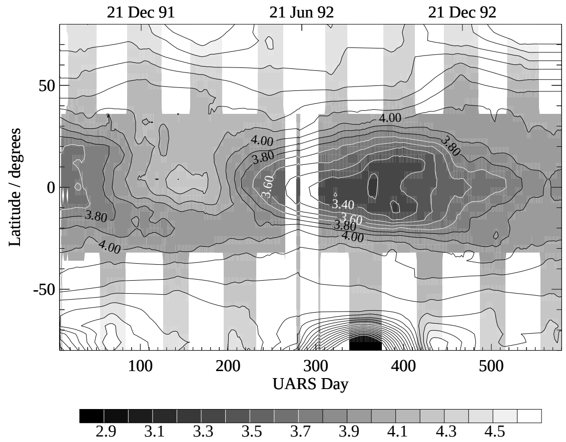

**Figure 6.** As Figure 5 but for 46 hPa.

At 68 hPa (Figure 5) there still appears to be some transport out of tropics, but only to about 40°S and 50°N. As at 100 hPa, we see more rapid poleward transport in the northern hemisphere than in the southern. By 46 hPa (Figure 6), there is little horizontal spreading and the tape-recorder signal remains confined between 30°N and S. Again this behavior is similar to that seen in HALOE data [*Randel et al.*, 1998] which showed strong transport into the northern hemisphere middle and high latitudes at 100 hPa but little latitudinal spreading at 68 hPa and above with the annual cycle remaining within 30°N-S.

More limited spreading to mid-latitudes takes place at 68 hPa than at 100 hPa due to the upward advection in the tropical pipe being much more rapid than the horizontal mixing [*Plumb,* 1996]. The tropical pipe appears more leaky in the tropopause region, and transport to mid-latitudes is more evident at 100 hPa than above. *Trepte and Hitchman* (1992) analyzed the dispersal of volcanic aerosol and found that poleward transport occurred readily at altitudes within a few kilometers of the tropopause but that in the altitude range 21-28 km (∼ 46 hPa and above), aerosols remained within 20° of the equator.

Interannual variability is evident, both in the degree of drying seen at 100 hPa, and the degree of moistening seen at 68 and 46 hPa. We suggest the change in phase of the QBO in November 1991 from easterly to westerly and the eruption of Mount Pinatubo in June 1991 as two possible causes of this interannual difference. From the data presented here, it would be difficult to determine the relative importance of these two influences. We hope that future research will be able to address these issues.

## 4. Conclusions

The MLS stratospheric water vapor product is shown to have geophysically reasonable behavior in the lower stratosphere, between 100 and 46 hPa. The zonal mean at 100 hPa shows that the annual cycle in water vapor is initiated in the northern hemisphere. Both low and high mixing ratios spread from the northern hemisphere tropics into the southern hemisphere tropics and into the mid-latitudes. Transport is more rapid into the northern hemisphere mid-latitudes and remains relatively unmixed. Spreading out of the tropics is much greater at 100 hPa than at 68 hPa due to the tropical pipe being more leaky at lower altitudes. The data set shows some interannual variability but is not long enough to show unambiguously whether this is due to the QBO, the eruption of Mount Pinatubo or to some other cause. Results agree well with zonal means from HALOE presented by *Randel et al.*, [1998] and *Rosenlof et al.*, [1997]. In addition to useful zonal mean information we find that the data used here contain interesting longitudinal information, even at 100 hPa. We describe this in a later paper.

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