A comparison of middle atmospheric water vapor as measured by WVMS, EOS-MLS, and HALOE

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[1] We compare middle atmospheric water vapor measurements from the Halogen Occultation Experiment (HALOE), Water Vapor Mm-wave Spectrometer (WVMS), and Earth Observing System (EOS) Microwave Limb Sounder (MLS) instruments from 40 to 70 km. The ground-based WVMS measurements shown here were taken at Network for the Detection of Atmospheric Composition Change (NDACC) sites at Mauna Loa, Hawaii (19.5°N, 204.4°E), and Lauder, New Zealand (45.0°S, 169.7°E). A comparison of measurements where HALOE, MLS, and WVMS are all available shows that the average HALOE water vapor retrievals are lower than those from MLS at all altitudes from 40 to 70 km and lower than the WVMS retrievals everywhere except above 64 km at Lauder. The average difference between all coincident WVMS and MLS water vapor profiles is within 0.2 ppmv over almost the entire 40–70 km altitude range, both at Lauder and Mauna Loa. The standard deviation of the difference between weekly WVMS retrievals and coincident MLS retrievals is ~0.2 ppmv at Mauna Loa and ~0.3–0.4 ppmv at Lauder. The interannual correlation between water vapor observed by MLS and WVMS is slightly improved by the use of MLS temperature measurements in the WVMS retrievals. The MLS and WVMS profiles at Mauna Loa show particularly good interannual agreement, including a clear QBO signature.

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1. Introduction

[2] The ground-based Water Vapor Millimeter-wave Spectrometer (WVMS) instruments have been measuring water vapor in the upper stratosphere and mesosphere nearly continuously since 1992. These instruments are deployed at Network for the Detection of Atmospheric Composition Change (NDACC) sites in Lauder, New Zealand (45.0°S, 169.7°E), Mauna Loa, Hawaii (19.5°N, 204.4°E), and Table Mountain, California (34.4°N, 242.3°E). The WVMS measurements have been validated against numerous satellite data sets [e.g., *Harries et al.*, 1996; *Nedoluha et al.*, 1997; *Pumphrey*, 1999]. During 2005 several of the satellite instruments which had been providing measurements of middle atmospheric water vapor, including the Halogen Occultation Experiment (HALOE) which had provided measurements since 1991, ceased to operate. Fortunately in 2004 the Earth Observing System (EOS) Microwave Limb Sounder (MLS) measurements became available, so there was some overlap of measurements between HALOE and MLS and it was possible to maintain an uninterrupted record of water vapor from 1991 to the present with just these two satellite instruments. Nevertheless, ground-based measurements such as are available from the WVMS instruments in the upper stratosphere and mesosphere, and in the lower stratosphere from balloon based measurements [*Oltmans et al.*, 2000], are important for ensuring the long-term consistency of water vapor data sets.

[3] In this paper we will primarily compare WVMS measurements to the MLS measurements. Comparisons between WVMS and HALOE measurements will also be shown in order to provide a benchmark for the WVMS-MLS comparisons. WVMS and HALOE measurements of water vapor have been used in several trend detection studies [*Nedoluha et al.*, 1998, 2000, 2003]. One of the goals of this paper is to evaluate the interannual consistency of the WVMS and MLS measurements in order to determine whether differences in interannual variations observed by these instruments can be used as a check on instrumental trends. Such cross checks are invaluable for long-term trend studies.

2. EOS-MLS, HALOE, and WVMS Data Sets

[4] The EOS MLS instrument began producing science observations on 13 August 2004, and scientific results based

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on the water vapor data have already been presented [e.g., *Jimenez et al.*, 2006]. The version 1.5 (v1.5) water vapor retrievals, which will be used in this paper, are described by *Livesey et al.* [2006], and initial validations of these retrievals have been shown by *Froidevaux et al.* [2006]. The retrievals showed a positive bias with respect to HALOE water vapor at all pressures. In the middle and upper stratosphere the bias was ~5–10%, consistent with the ~5% apparent dry bias in HALOE water vapor reported in *Stratospheric Processes and Their Role in Climate* [2000] In the middle mesosphere the MLS v1.5 wet bias relative to HALOE increases to ~10–15%. We have used here MLS v1.5 measurements for pressures <0.1 hPa even though at these mesospheric pressure levels the precision values have been flagged because the retrieved precision is >50% of the a priori precision. We note, however, that the contribution of the a priori to the v1.5 retrievals remains <20% at 0.01 hPa, and is <5% at all pressure levels between 70 hPa and 0.03 hPa. We therefore expect that the a priori used in the MLS retrievals will have only a minimal influence on the comparisons shown here from 40 to 70 km. A subset of the EOS-MLS data has been reanalyzed and is now available as version 2.2 (v2.2), which has better precision above the stratopause [*Lambert et al.*, 2007]. The largest difference between the mean of the v2.2 and v1.5 MLS stratospheric and mesospheric water vapor retrievals is at 1 hPa, where the v2.2 retrievals are ~0.5 ppmv larger. At most pressure levels in the middle atmosphere the difference are smaller than 0.2 ppmv [*Lambert et al.*, 2007].

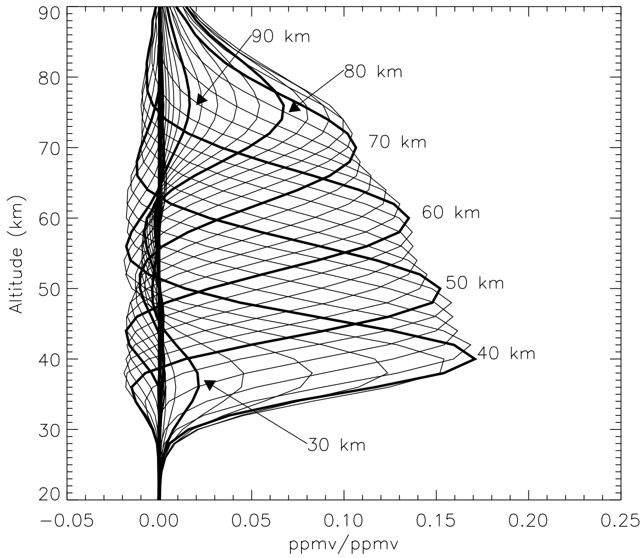
[5] The HALOE instrument uses a solar occultation technique and operates between 2.45 and 10.0 μm. A full description of the design and operation is given by *Russell et al.* [1993]. Since the measured quantity is the fractional absorption of solar radiation, the experiment is highly precise; making the data well suited to long-term trend studies. HALOE provided measurements from October 1991 through November 2005. The results shown here use the HALOE 3rd public release v19 retrievals.

[6] The MLS and HALOE instruments will be compared here with the ground-based WVMS instruments. These instruments make spectrally resolved measurements of the 22 GHz water vapor absorption line in emission. Since this line is predominantly pressure-broadened in the middle atmosphere, the measured shape of the spectral line can be deconvolved to retrieve the water vapor profile. In the standard WVMS data analysis procedure, the individual spectral scans are integrated into 500 scan blocks (which takes ~1 week) and each 500 scan average spectrum is then inverted to retrieve the water vapor profile. Therefore the temporal resolution of each individual WVMS measurement shown here is ~1 week. The ~1 week long integration is necessary for improving the signal-to-noise ratio for measurements, and is particularly important for retrievals in the upper mesosphere. Details of the instrumentation and retrieval technique are given by *Nedoluha et al.* [1995].

[7] The WVMS measurements shown here have been taken from Lauder, New Zealand, and from Mauna Loa, Hawaii. Results from the WVMS instrument at Table Mountain, California will not be shown here. The Table Mountain instrument operated from 1992 to 1997, and has now been continuously operational since September 2006, but it was undergoing upgrades during the first 2 years of the EOS-MLS operations and was only intermittently operational during this period. The WVMS instruments deployed at Lauder and Mauna Loa are very similar. The WVMS1 instrument, now deployed in Lauder, was deployed at Table Mountain and compared with the WVMS2 in 1993 [*Nedoluha et al.*, 1996]. The WVMS3 instrument, now deployed at Mauna Loa, underwent a similar intercomparison campaign in 1995–1996 [*Nedoluha et al.*, 1999]. The most important instrumental difference is the presence of an additional narrow-band spectrometer (with 50 kHz channels) on the WVMS3 instrument at Mauna Loa. This additional spectrometer provides a factor of 4 higher spectral resolution at line center compared with the Lauder instrument. The higher spectral resolution makes the retrievals from this instrument more sensitive to variations in water vapor above ~70 km. The Mauna Loa instrument also has thirty 2 MHz channels as opposed to the twenty 2 MHz channels present in the Lauder instrument, which improves sensitivity in the stratosphere. In addition to these instrumental differences there is also an important difference in the quality of the data from Lauder and Mauna Loa because of the altitude of these two sites. The Mauna Loa measurements are taken from ~3400 m, where the median 22 GHz tropospheric optical depth for measurements taken nearly continuously since 19 November 1996 is 0.035, while for the Lauder site, which is at ~370 m, the median optical depth for measurements since 16 October 1994 is 0.092. This difference in tropospheric optical depth increases the signal-to-noise ratio of the Mauna Loa measurements relative to those at Lauder measurements (which affects primarily the higher-altitude measurements) and also reduces problems related to instrumental baseline (which affects primarily measurements in the upper stratosphere).

3. HALOE/MLS/WVMS Comparisons

[8] In Figure 1 we show the averaging kernels for the WVMS instruments at Lauder and Mauna Loa. When not specified otherwise, all of the HALOE and MLS measurements shown in comparison with a WVMS measurement will be convolved with the WVMS averaging kernels for the appropriate site. This convolution has two major effects on the satellite data: it degrades the vertical resolution at all altitudes, and it decreases the sensitivity above ~70 km and below ~40 km. We note that in applying such a convolution we are making the assumption that the satellite retrievals are insensitive to their assumed a priori, and have infinite resolution relative to the WVMS measurements. For the case of MLS v1.5 data the assumption of insensitivity to the a priori is reasonable for the altitudes to be compared in this study. However, for retrievals in the upper mesosphere the vertical resolution degrades from a FWHM of ~4 km at 1 hPa to ~10 km at 0.1 hPa, so the assumption of infinite resolution relative to the WVMS measurements is not strictly correct. An incorrect assumption of altitude resolution of the MLS water vapor measurements could certainly cause errors for comparisons near the tropopause, where water vapor values change quickly and nonlinearly with altitude, but all comparisons shown here are well away from the tropopause. Sudden jumps in the water vapor mixing ratio as a function of altitude are not expected in ~1 week long measurements of water vapor in the tropical and



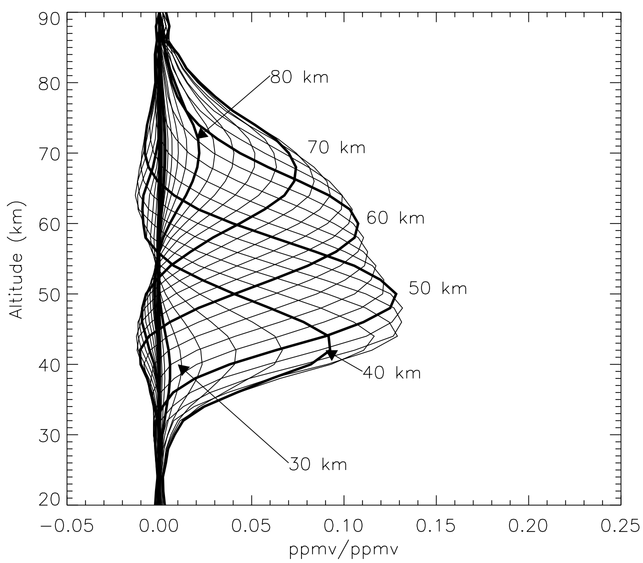


Figure 1. Averaging kernels for the WVMS instruments at (top) Mauna Loa and (bottom) Lauder. Each line represents the sensitivity of the retrieval at a given altitude to perturbations over a range of 2 km altitude bins. Lines in bold indicate the sensitivity of the retrieval at labeled altitude levels.

midlatitude upper mesosphere, hence the assumption of infinite MLS vertical resolution should not cause large errors in these comparisons.

3.1. Three-Satellite Coincidences

[9] In Tables 1 and 2 we show all coincidence periods for which there are a minimum of five profile measurements from both the HALOE and MLS instruments within ±5° latitude of the WVMS site and occurring during a ~1 week period WVMS retrieval period (we use any satellite measurement within ±3.5 days of the average time of that WVMS integration period). These criteria give us 10 coincidence weeks at Mauna Loa and 14 coincidence weeks at Lauder. Details are provided in Tables 1 and 2. We then calculate the median of the satellite measurements for each of those coincidences to establish a coincident satellite data set (with 10 profiles at Mauna Loa and 14 at Lauder). Figure 2 shows the overall profile comparison for the periods given in Tables 1 and 2. All of the satellite data in Figure 2 have been convolved with the WVMS averaging kernels for the appropriate site. Note that the standard deviations shown in Figure 2 are not representative of the standard deviation of the difference between WVMS measurements and single satellite measurements, but between the WVMS measurements and their associated coincident satellite data sets.

[10] Figure 2 shows that the average MLS and WVMS profiles are in better agreement with each other than with HALOE, except in the mid to upper mesosphere at Lauder where the MLS mixing ratio is as much as 0.54 ppmv higher than the WVMS and HALOE values. As is indicated in Table 2 there are only 14 WVMS retrievals for Lauder included here, and as we will show in Figure 3 the agreement improves when all of the MLS and WVMS coincidences are included. The error bars shown in Figure 2 indicate the formal uncertainty in the bias based on the standard deviations and number of measurements (i.e., $\sigma/n^{1/2}$) from this WVMS-HALOE-MLS coincident data set, and are not obtained from estimated biases reported for the individual measurement data sets. Note that the HALOE-MLS differences in Figure 2 are, within the standard deviation, consistent between the two WVMS measurement sites; hence the difference in the satellite-WVMS comparisons at the two sites is not indicative of a latitudinal dependence in the satellite biases. The expected bias from WVMS instruments has been estimated at ~5–10% [*Nedoluha et al.*, 1997], an estimate which is comparable to the systematic difference between the WVMS instruments and coincident satellite measurements in previous investigations [*Nedoluha et al.*, 1997], and between coincident measurements by two WVMS instruments [*Nedoluha et al.*, 1999].

[11] Some of the differences in measured water vapor made by instruments at different frequencies may be caused by spectroscopic uncertainties. While the uncertainties in line center frequency and intensity are typically negligible for atmospheric studies, there are nonnegligible uncertainties in line broadening parameters (B. Drouin, private communication, 2007). *Harries et al.* [1996] give an uncertainty of 8% in the retrieved H_2O mixing ratio from HALOE based on the H_2O line parameters. *Lambert et al.* [2007] give an uncertainty of ~3% in the MLS retrieved water vapor due to uncertainty in the water vapor spectral line width at 183 GHz. *Cazzoli et al.* [2007] made spectroscopic measurements in the 4–36 GHz frequency range relevant to the WVMS measurements, and estimated that the experimental accuracy was ~3–4%.

[12] In Figure 2 we also show that the standard deviations of the differences between the satellite and WVMS measurements are very similar for HALOE and MLS. This similarity between the WVMS-HALOE and WVMS-MLS standard deviations suggests that either (1) the two satellite coincidence data sets have very similar noise levels (despite, as shown in Tables 1 and 2, the large difference in number satellite measurements included in each coincidence), (2) that the standard deviations of the differences are caused primarily by geophysical variability, or (3) that the standard

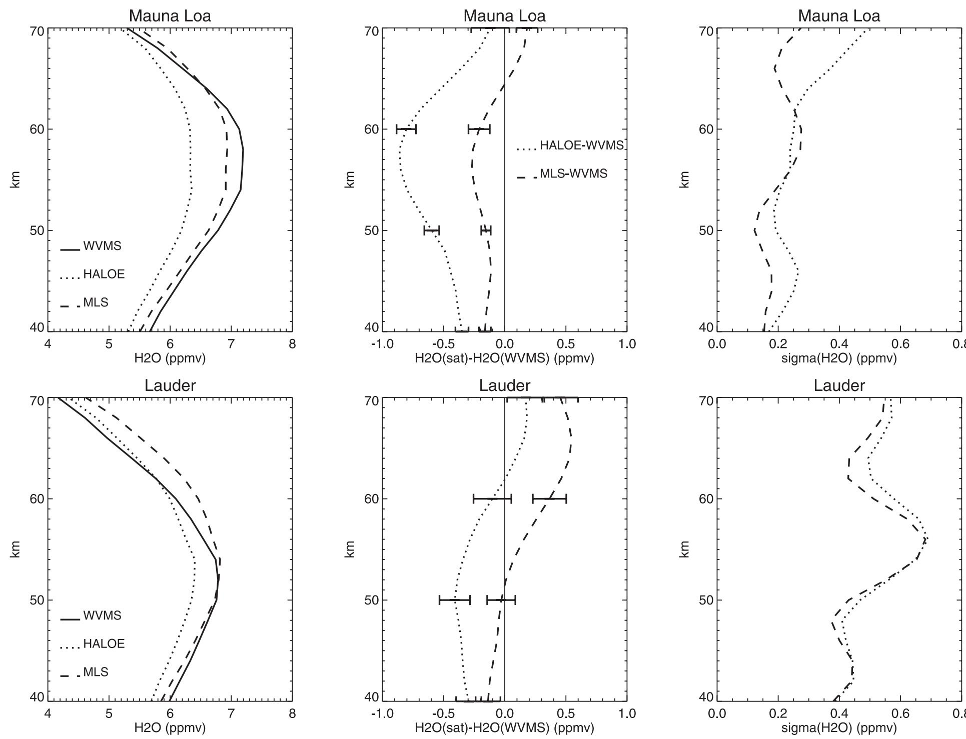


Figure 2. (left) Averages for all coincident profiles (all longitudes within ±5° latitude of the WVMS site. (middle) Average differences between the satellite and WVMS measurements. Error bars indicate statistical uncertainty in the bias (i.e., $\sigma/n^{1/2}$). (right) Standard deviation of the difference between the satellite and WVMS measurements. Results for (top) Mauna Loa and (bottom) for Lauder.

deviation of the difference is caused primarily by noise in the WVMS measurements. The higher standard deviations at Lauder could be caused by the higher expected noise in the WVMS measurements at this site because of the much larger tropospheric optical depth, or they could be caused by higher geophysical variability at this site.

3.2. WVMS-MLS Coincidences

[13] In Figure 3 we show results for all of the WVMS-MLS coincidences. Since a HALOE coincidence is not required, these are clearly much larger data sets than the three-instrument coincidence data sets. While in general the results are similar to those shown in Figure 2, the magnitude of the average WVMS-MLS difference from 60 to 70 km at Lauder is much smaller given this larger data set. Given the small number (14) of WVMS measurements used in the Figure 2 comparisons it is not surprising that there are differences between the comparisons shown in Figures 2 and 3. The difference between Figures 2 and 3 at 60–70 km is in part because the seasonal variation in the mesospheric WVMS measurements is slightly larger than that of the MLS measurements, and 10 of the 14 comparisons used in the Figure 2 comparison occur between April and July when water vapor mixing ratios are particularly low in this region. Where there are differences between the WVMS and MLS retrievals, the differences tend to be similar at the two sites, with the WVMS retrievals slightly higher than the MLS retrievals between 50 and 60 km, and slightly lower near 70 km. The standard deviations of the WVMS-MLS differences are ~0.2 ppmv for most altitudes at Mauna Loa, while at Lauder these differences increase with altitude from ~0.3 ppmv at 40 km to ~0.4 ppmv at 70 km. These standard deviations show generally much less variation with altitude than in Figure 2, with the large increase at Lauder near ~55 km being notably absent.

[14] In Figure 3 we also examine the effects of changing geographical coincidence criteria for MLS-WVMS comparisons. The MLS comparisons are shown for loose coincidence criteria of ±5° latitude from the WVMS site regardless of longitude, for tighter criteria of ±2° latitude and ±30° longitude, and for even tighter criteria of ±2° latitude and ±5° longitude. The tightest criteria result in an average of ~15 MLS measurements for comparison with each ~1 week long WVMS measurement. As is shown in the panels, the averages and standard deviations of the differences for all three sets of coincidence criteria are very similar for comparisons with ~1 week long WVMS measurements. The absence of sensitivity implies not only that the geophysical variations within this range are insignificant for the ~1 week average, but that averaging together more

Table 1. Coincidence Periods at Mauna Loa

Dates	Number of HALOE Measurements	Number of MLS Measurements
17–24 Nov 2004	58	1362
24–31 Jan 2005	53	1403
24 Feb to 3 Mar 2005	11	1365
10–18 Mar 2005	23	1395
4–11 May 2005	30	1171
17–24 May 2005	14	718
24–31 May 2005	17	945
13–20 Jul 2005	15	1044
20–27 Jul 2005	15	1239
7–15 Nov 2005	28	1332

Table 2. Coincidence Periods at Lauder

Dates	Number of HALOE Measurements	Number of MLS Measurements
22–28 Aug 2004	37	1093
28 Aug to 5 Sep 2004	8	1076
21–28 Sep 2004	40	1124
19–25 Apr 2005	37	931
15 Apr to 1 May 2005	35	915
7–13 May 2005	49	1151
19–24 May 2005	13	701
24–31 May 2005	64	941
6–12 Jun 2005	65	1326
29 Jun to 6 Jul 2005	31	1291
6–11 Jul 2005	47	1299
17–23 Jul 2005	33	1269
17–23 Aug 2005	62	1307
11–18 Nov 2005	14	1149

than ~15 convolved MLS measurements does not result in any significant reduction in noise relative to the WVMS measurements. Hence the noise in ~15 convolved MLS measurements must be significantly smaller than that of the ~1 week WVMS retrieval.

[15] We have and will, throughout this manuscript, work with WVMS retrievals based on ~1 week integration periods. Since we have just concluded that the standard deviation of the MLS-WVMS differences were dominated by the noise in the WVMS measurements this choice seems reasonable. Nevertheless, a ~1 week integration period does necessarily combine measurements taken under a range of tropospheric conditions, and this combination of measurements might itself cause additional noise in the retrieval. MLS-WVMS comparisons were therefore also investigated for daily WVMS retrievals (both with and without the use of MLS temperatures as will discussed in section 4), and it was found that the standard deviation of the difference was larger at all altitudes than in the results shown in Figure 3. We emphasize that this does not mean that there are no situations in which a daily WVMS variation may well reproduce a large daily local variation in water vapor, but for the purpose of validating instrumental data sets taken over a prolonged period it is statistically preferable to use the weekly WVMS retrievals when possible. We note that, for the 40 to 70 km altitude range shown here, observed diurnal variations in water vapor are small. Studies with WVMS data at Mauna Loa have shown diurnal variations of approximately ±0.03 ppmv at 70 km, with smaller variations at lower altitudes.

3.3. Time Series Comparisons

[16] In Figures 4 and 5 we show time series of HALOE, MLS, and WVMS measurements coincident with Lauder and Mauna Loa from 2002 to 2007. Here and in subsequent figures we use the MLS data within ±2° latitude and ±30° longitude of each WVMS site. The Lauder plots in Figure 4 show good agreement in the seasonal variation observed by the three instruments, with the WVMS and MLS data showing seasonal variations of similar amplitude and phase at 50, 60, and 70 km. While the HALOE measurements during austral summer are quite sparse during these years, the seasonal variations do show reasonably good agreement with the WVMS measurements. Results for 40 km are not shown in Figure 4 since the WVMS retrievals at this altitude show variations which are thought to be caused by instrumental baseline artifacts. The effect of these artifacts drop off rapidly with increasing altitude, and simulations of the inferred baseline error have shown that it does not affect results at 50 km and above. A seasonal feature which is well reproduced in the retrievals from all three of the instruments at Lauder is the midwinter local maximum at 70 km. This feature has been reported before in WVMS measurements from Table Mountain [*Nedoluha et al.*, 1996], and is thought to be caused by increased vertical diffusion resulting from gravity wave breaking in the winter mesosphere.

[17] The amplitude of the annual variations observed by both instruments at Mauna Loa is ~1/2 as large as those at Lauder at 70 km, and proportionally even smaller at 60 km. These smaller annual cycles are due to the lower latitude of the Mauna Loa site. This latitudinally dependent difference is actually somewhat underrepresented at 70 km because of the higher sensitivity of the WVMS Mauna Loa instrument at this altitude (see Figure 1). The measured seasonal cycles at Mauna Loa are generally in good agreement, especially at 70 km, where the similarity of the amplitude of the HALOE, MLS, and WVMS seasonal cycles is most apparent. Unlike for Lauder, we do show the WVMS measurements at 40 km for Mauna Loa since we believe these are generally of good quality. However, we have included three measurements at

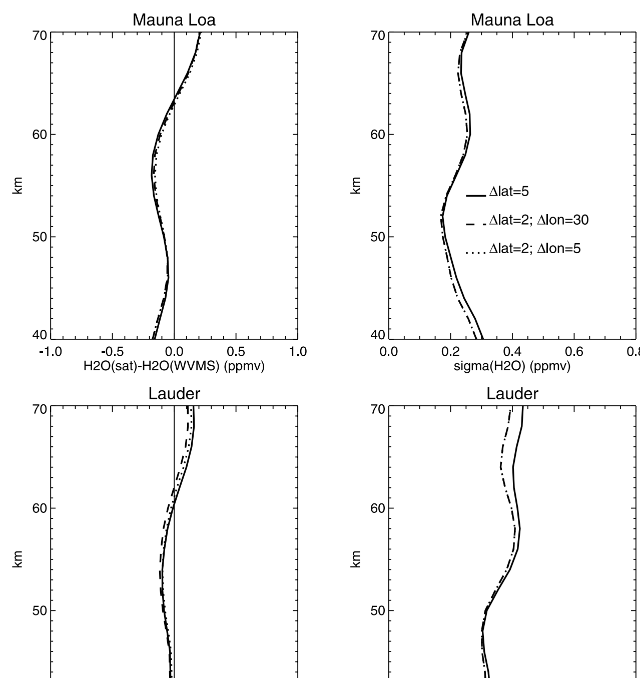


Figure 3. (left) Average differences for all coincident WVMS and MLS profiles. Different lines show results for several coincidence criteria (solid indicates ±5° latitude and any longitude, dashed indicates ±2° latitude and ±30° longitude, and dotted indicates ±2° latitude and ±5° longitude). Note that the results shown by dotted and dashed lines are often very similar, resulting in what appears to be a dot-dashed line. (right) Standard deviation of the differences between the MLS and WVMS measurements. Results (top) for Mauna Loa and (bottom) for Lauder.

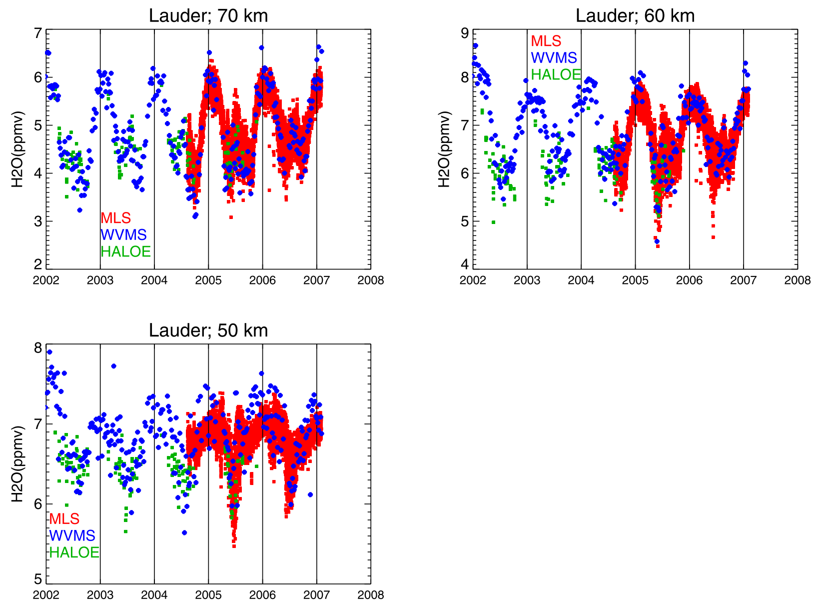


Figure 4. Water vapor measurements from WVMS at Lauder (blue) and from coincident MLS (red; individual measurements within ±2° latitude and ±30° longitude) and HALOE (green; daily zonal average within ±5° latitude) measurements. The satellite data have been convolved with the WVMS averaging kernels.

40 km toward the end of 2003 which we believe are affected by baseline problems and which show unusually low water vapor values. We include these in order to emphasize the point that, even when there are WVMS retrieval problems in the stratosphere, these problems generally do not affect retrievals at 50 km and above.

[18] A feature of particular interest in Figure 5 is the sudden decrease in water vapor which begins each year in late December at 50 km and in early January at 40 km (the feature is not apparent in 2003/2004 because of a gap in the WVMS measurements). In Figure 6 we show plots of MLS water vapor measurements from December and January for 3 years. These show that from December to January dryer tropical air is replacing the older, wetter, air between 40 and 50 km throughout the tropical upper stratosphere, including the latitude of Mauna Loa (19.5°N). Both the WVMS and MLS instruments indicate that this decrease is larger in

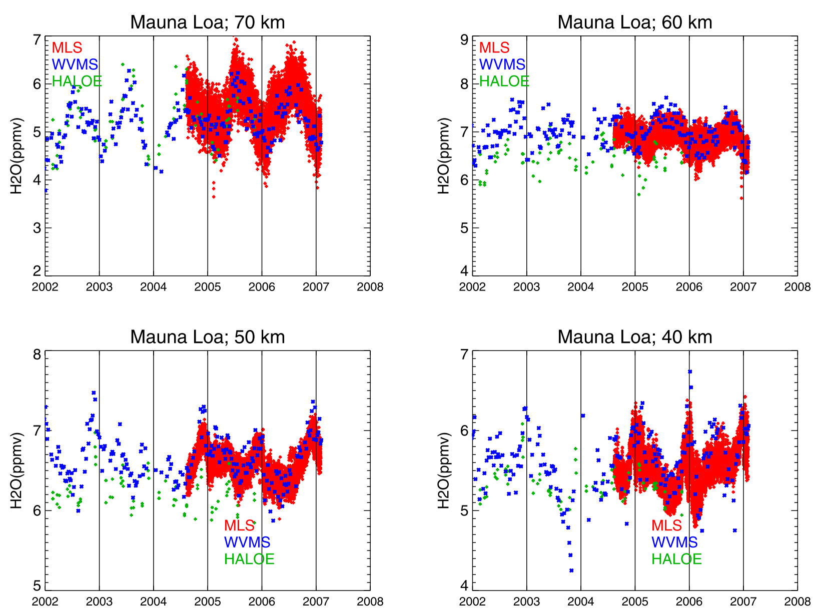


Figure 5. Water vapor measurements from WVMS at Mauna Loa (blue) and from coincident MLS (red; individual measurements within ±2° latitude and ±30° longitude) and HALOE (green; daily zonal average within ±5° latitude) measurements. The satellite data have been convolved with the WVMS averaging kernels.

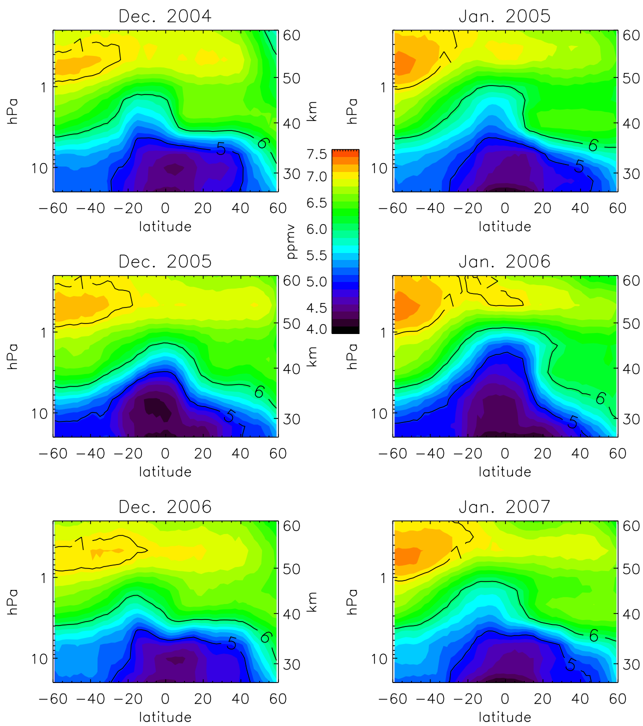


Figure 6. MLS water vapor monthly averages calculated in 2° latitude bands for December and January. These data have not been convolved with WVMS averaging kernels. The altitude scale is approximate.

2006 than in 2005 or 2007 suggesting a QBO influence on water vapor at these altitudes.

3.4. Seasonal Comparisons

[19] In Figures 7 and 8 we show 3-month profile comparisons between the WVMS and MLS data. In order to ensure that the comparisons are only minimally affected by any differences in the temporal sampling, we first divide each 3 month period into six ~2 week long intervals. We then show the average of all of the ~2 week intervals which contain both WVMS and MLS measurements. Ranges indicated on the plots show the mean absolute deviation of the differences calculated from each set of (usually 6) ~2 week WVMS and MLS measurements periods.

[20] The 3-month average profiles in Figure 7 show the seasonal variations in 2005 and 2006 for the WVMS and MLS measurements at Lauder. The a priori mixing ratio, which remains constant for all of the WVMS retrievals at both sites, is included in these plots to emphasize that these seasonal variations are obtained solely from the measurements. The overall seasonal variation is clearly captured well by both instruments, with mixing ratios at ~60 km decreasing from ~7.3 ppmv in January–March 2006 to ~6.1 ppmv in July–September 2006. With the exception of the comparisons in April–June near 40 km (altitudes where there are known to be baseline artifacts in the WVMS retrievals), the 2006 comparisons are within 0.2 ppmv everywhere. Figure 7 does show, however, that there are some 3-month periods in 2005 where instrumental differences are as large as 0.5 ppmv at certain altitudes. For instance, the WVMS-MLS difference is particularly large at ~55 km in January–March and October–December 2005. Since these are seasons when the tropospheric optical depth is generally high and hence ground-based measurements particularly difficult, we reanalyzed the comparisons by screening out those WVMS profiles taken under conditions of particularly high tropospheric optical depth. However, we found that this produced no clear improvement in the WVMS-MLS agreement, and we continue to investigate possible causes of this difference. We do note that the mean of the v2.2 MLS retrievals is ~0.5 ppmv higher at 1 hPa and ~0.2 ppmv higher at 0.1–0.2 hPa [*Lambert et al.*, 2007], and thus these MLS retrievals would, at least in 2005, agree more closely with the WVMS data at some altitudes, but it seems unlikely that a comparisons to the v2.2 MLS retrievals would result in a decrease in the interannual difference between the WVMS and MLS retrievals. Encouragingly, both instruments do detect an increase in the average April–June mixing ratio at Lauder between 2005 and 2006, an interannual agreement that is improved by the WVMS reanalysis in section 4.

[21] The seasonal variations at Mauna Loa data are clearly much smaller than at Lauder, but, as is shown in Figure 8, there is nevertheless generally good agreement in the magnitude of the seasonal variation. Figure 8 has been plotted to emphasize not just seasonal but interannual differences. Both instruments show that the July–September 2006 water vapor mixing ratios are slightly lower at ~55–60 km than those from 2005, while from ~40 to 45 km the July–September 2006 values are higher than in 2005. For January–March both instruments show that the mixing ratios at all altitudes in 2006 are either lower or equal to those in 2005. This good agreement in interannual variations is encouraging for future QBO and trend studies.

4. Effect of Improved Temperature Profiles on WVMS Retrievals

[22] Retrievals of water vapor profiles from microwave measurements require an estimate of the atmospheric temperature. The primary effect of underestimating the temperature at a particular level is to cause the retrieval to overestimate the water vapor mixing ratio required to emit the observed signal. As was shown by *Nedoluha et al.* [1995], a 5 K error introduced over an 8 km scale height results in an error of ~0.1 ppmv in the mixing ratio retrieved from WVMS measurements. The background

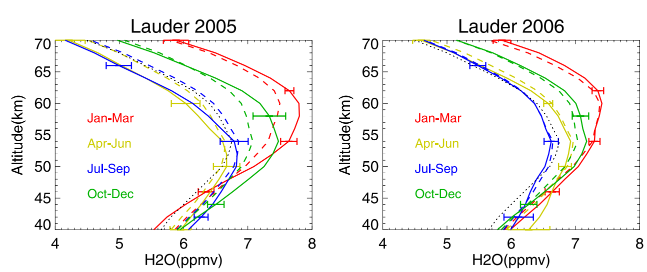


Figure 7. Three-month average profiles for Lauder from WVMS (solid line) and MLS (within ±2° latitude and ±30° longitude; dashed line). Results are shown for (left) 2005 and (right) 2006. Bars represent the mean absolute deviation of the difference calculated for each 3-month average (see text). Also shown is the a priori used in the WVMS retrievals (dotted line).

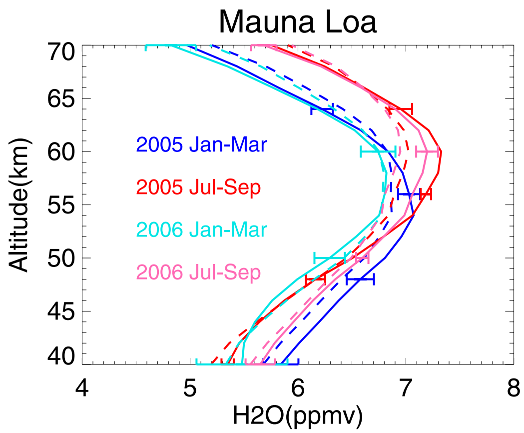


Figure 8. Three-month average profiles for Mauna Loa from WVMS (solid line) and MLS (dashed line). Bars represent the mean absolute deviation of the difference calculated for each 3-month average (see text).

temperatures for the WVMS retrievals are calculated on the basis of the local NMC temperatures in the lower stratosphere, the MSISE90 [*Hedin*, 1991] climatology in the mesosphere, and a smoothed combination of these two in the upper stratosphere. Hydrostatic equilibrium is assumed for the conversion of the temperature-pressure profile to altitude.

[23] The MLS temperature measurements provide a mesospheric temperature data set which can, when available, be used to provide a temperature background for the WVMS retrievals. A comparison of WVMS retrievals performed with a temperature background provided by the MLS measurements with retrievals performed with the standard background temperatures should help to provide an estimate of the error in WVMS retrievals resulting from temperature uncertainties. An early validation of the MLS temperature measurements is given by *Froidevaux et al.* [2006]. Comparisons with several other satellite instruments show biases of <5 K and standard deviations ~5 K near the stratopause. The vertical resolution is ~4 km in the middle stratosphere, but degrades to worse than ~12 km in the mesosphere.

[24] In Figure 9 we show reanalyzed WVMS water vapor retrievals at Lauder for which the background temperature has been taken from MLS measurements. In this case we take all of the MLS temperatures within ±5° latitude and ±30° longitude of each the WVMS site, calculate a daily average, and then use these values to provide an average background temperature for the reanalyzed WVMS retrievals. In general the effect of this change is small, and the agreement between MLS and WVMS water vapor retrievals based on MLS temperatures is certainly not always better (e.g., the size of the January–March WVMS-MLS difference is larger everywhere above 54 km when the reanalyzed retrievals are used). However, the interannual consistency is generally better when the MLS temperatures are used in the WVMS retrievals. Most clearly, there is an improvement in the July–September interannual consistency above ~50 km. MLS temperatures in July–September 2005 (and to a lesser extent in April–June 2005) are ~10 K colder in the upper mesosphere than in 2006. When the MLS temperatures are used in the WVMS retrievals the July–September 2005 water vapor mixing ratio increases by ~0.2 ppmv, bringing these WVMS measurements into much better agreement with the MLS water vapor measurements at ~60–70 km. From ~50 to 60 km the July–September 2005 and 2006 comparisons for the reanalyzed WVMS retrievals show that the WVMS mixing ratios are now consistently slightly higher than those for MLS. The April–June comparisons with the reanalyzed WVMS retrievals are very similar to the July–September comparisons, showing very good agreement from ~60 to 70 km in both 2005 and 2006, and slightly higher WVMS mixing ratios at ~50–60 km. The interannual consistency of the January–March and October–December comparisons are marginally improved with the reanalyzed WVMS retrievals. The reanalyzed WVMS retrievals at Lauder are now consistently slightly higher than the MLS retrievals everywhere above 50 km, but the differences near the peak mixing ratios of the profiles remain larger in 2006 than in 2005.

[25] A similar reanalysis of WVMS retrievals at Mauna Loa does not introduce changes to any particular season that are comparable to the differences observed at Lauder. Nevertheless, some differences are observed, and in Figure 10 we show the overall effect of the MLS temperatures on WVMS retrievals at both Mauna Loa and Lauder. Figure 10 shows the average difference and the standard deviation of the difference between MLS and WVMS both for standard WVMS retrievals and for WVMS retrievals with MLS temperatures. The average difference is generally not reduced by the use of the MLS temperatures, which is not surprising given that the seasonal profiles shown in Figure 9 show that the reanalyzed WVMS Lauder retrievals are now consistently higher than the MLS retrievals at ~50–60 km. In any case, the agreement between WVMS and MLS retrievals is already well within the ~5–10% estimated systematic WVMS errors [*Nedoluha et al.*, 1997]. Encouragingly, almost all altitudes show an improvement in standard deviation of the difference, with a decrease in this difference of as much as 0.08 ppmv (more than 20%) for the 60 km comparison at Lauder. The improvement in standard deviation shown in Figure 10 and the better agreement between WVMS and MLS in the winter mesosphere at Lauder both show the value of accurate background temperatures for WVMS retrievals. Unfortunately, since MLS temperatures are clearly not available for the entire WVMS data set it is

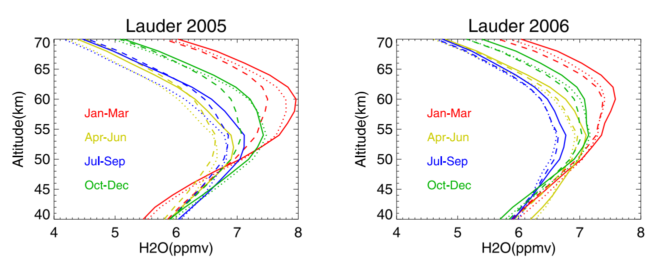


Figure 9. Three-month average profiles for Lauder from WVMS retrievals calculated using coincident temperatures measured by MLS (solid lines), standard WVMS retrievals using MSISE90/NMC temperatures (dotted line) and MLS (within ±2° latitude and ±30° longitude (dashed line). Results are shown for (left) 2005 and (right) 2006.

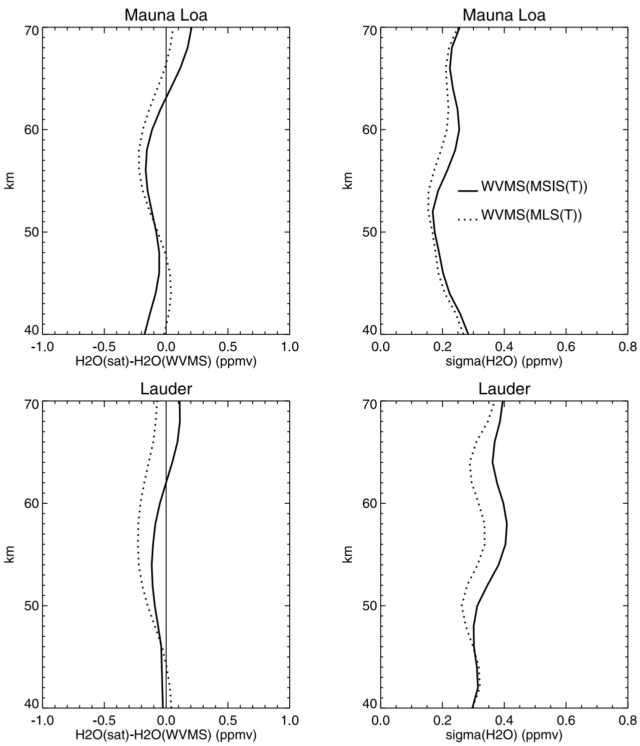


Figure 10. (left) Average difference between MLS and standard WVMS retrieval (solid lines), and between MLS and WVMS retrievals with MLS temperatures (dotted lines). (right) Standard deviation of difference between MLS and standard WVMS retrieval (solid lines), and between MLS and WVMS retrievals with MLS temperatures (dotted lines). Results are shown for (top) Mauna Loa and (bottom) Lauder.

not possible to reanalyze all of the WVMS data using MLS temperatures.

5. Discussion

[26] WVMS and MLS water vapor profiles in the 40–70 km altitude range show good agreement. The average difference for all coincident profiles is within 0.2 ppmv at almost all altitudes in this range, both over Lauder and Mauna Loa. This difference is within the estimated 5–10% systematic bias expected in the WVMS measurements. Over most of this altitude range (but not above ~55 km at Lauder) there is better agreement between WVMS and MLS than between either of these instruments and HALOE. The standard deviation of the difference of the WVMS and MLS profiles is within 0.2 ppmv for most of the 40–70 km range at Mauna Loa, and varies from ~0.3 to ~0.4 ppmv at Lauder.

[27] The WVMS and MLS measurements at Lauder and Mauna Loa show good agreement both in the seasonal variations and in the interannual variations. The good interannual agreement, especially at Mauna Loa, is encouraging not only because it allows us to study QBO variations, but also because it provides a good indication of the stability of the MLS measurements and hence, hopefully, an indication of their utility for long-term trend detection.

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