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Water vapor measurements in the mesosphere from Mauna Loa over solar cycle 23

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[1] The Water Vapor Millimeter-wave Spectrometer (WVMS) system has been making measurements from the Network for the Detection of Atmospheric Composition Change site at Mauna Loa, Hawaii (19.5°N, 204.4°E), since 1996, covering nearly the complete period of solar cycle 23. The WVMS measurements are compared with Halogen Occultation Experiment (HALOE) (1992–2005), Microwave Limb Sounder (MLS) (2004 to present), and Atmospheric Chemistry Experiment (ACE) Fourier transform spectrometer (2004 to present) measurements in the mesosphere. In the upper mesosphere Lyman α radiation photodissociates water vapor; hence, water vapor in the upper mesosphere varies with the solar cycle. We calculate fits to the WVMS and HALOE water vapor data in this region using the Lasp Interactive Solar Irradiance Datacenter Lyman α data set. This is, to our knowledge, the only published validation of the sensitivity of HALOE water vapor measurements to the solar cycle, and the HALOE and WVMS water vapor measurements show a very similar sensitivity to the solar cycle. Once the solar cycle variations are taken into account, the primary water vapor variations at all of these altitudes from 1992 to the present are an increase from 1992 to 1996, a maximum in water vapor in 1996, and small changes from 1997 to the present. Measurements from 2004 to 2008, which are available from WVMS, MLS, and ACE, show not only good agreement in interannual variations but also excellent agreement in their absolute measurements (to within better than 3%) of the water vapor mixing ratio from 50 to 80 km.

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1. Introduction

[2] Water vapor is photodissociated in the upper mesosphere by Lyman α radiation. As the Lyman α irradiance varies with the solar cycle there are maxima in upper mesospheric water vapor associated with the minima in Lyman α at the beginning and end of the solar cycle. There are two upper mesospheric water vapor measurement data sets available currently which span, or in one case nearly span, a complete solar cycle.

[3] The ground-based Water Vapor Millimeter-wave Spectrometer (WVMS) instruments have been measuring water vapor in the upper stratosphere and mesosphere nearly continuously since November 1996 from the Network for the Detection of Atmospheric Composition Change (NDACC) site at ~3400 m on Mauna Loa, Hawaii (19.5°N, 204.4°E). The WVMS measurements have been validated against numerous satellite data sets [e.g., *Harries et al.*, 1996; *Nedoluha et al.*, 1997; *Pumphrey*, 1999; *Lambert et al.*, 2007; *Nedoluha et al.*, 2007].

[4] In addition to WVMS measurements, we will show the coincident 14 years of Halogen Occultation Experiment (HALOE) measurements, as well as the shorter data records from the Microwave Limb Sounder (MLS) measurements on the Aura satellite, and measurements from the Atmospheric Chemistry Experiment (ACE) mission taken with the Fourier transform spectrometer (FTS) on board the SCISAT-1 satellite (ACE-FTS). The AURA-MLS data are particularly valuable to this study since daily measurements are available coincident with Mauna Loa. We can therefore use these data to provide a daily seasonal climatology for both water vapor and temperature. Although the MLS measurements are taken near the end of the solar cycle and are therefore biased slightly high with respect to a full solar cycle, the dominant variability at these altitudes is seasonal; hence the seasonal climatology represents a good first-order approximation to water vapor at these altitudes.

[5] Solar cycle 23 began in May 1996, and as of April 2009 there remains some question as to whether solar cycle 24 has begun. The WVMS measurements cover almost the complete period of solar cycle 23. The effects of the solar cycle are much smaller than the seasonal variation of water

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vapor in the mesosphere, so in order to obtain an estimate of the solar cycle effects we must accurately remove the seasonal variations. Although Lyman α radiation is clearly stronger in the summer hemisphere, dynamics play the dominant role in determining the seasonal cycle of mesospheric water vapor so that water vapor in the upper mesosphere increases in the summer because of upwelling of air that has experienced less photodissociation. On top of this annual cycle there is also a semiannual component which has been attributed to diffusive transport [*Bevilacqua et al.*, 1990; *Nedoluha et al.*, 1996].

[6] There have been a number of studies of solar cycle variations in water vapor which have used the HALOE measurements. The HALOE measurements cover the period 1991–2005 and, hence, cover the end of solar cycle 22 and much of solar cycle 23. Measurements from 1991 to 1996 were used to estimate the effects of solar cycle variations on mesospheric water vapor [*Chandra et al.*, 1997]. *Sonnemann and Grygalashvyly* [2005] calculated the effect of the solar cycle on water vapor in the COMMA-IAP model and reported good agreement with *Chandra et al.* [1997] results from HALOE. *Randel et al.* [2000] showed the global anomaly in the HALOE measurements at 0.01 hPa (~80 km) from 1992 to 1999 and showed the anticorrelation with Lyman α over that time period. *Marsh et al.* [2003] examined the response of mesospheric ozone to changes in water vapor and showed decreasing HALOE water vapor in the upper mesosphere from 1996 to 2001, consistent with an increase in Lyman α over that time period. *Hervig and Siskind* [2006] showed that at 80 km HALOE water vapor measurements at 67.5°N and 67.5°S near the summer solstice peaked in 1996, near the solar minimum.

[7] The *Hervig and Siskind* [2006] study focuses on high-latitude summer solstice water vapor, since there is an interest in understanding how water vapor affects the decadal variation in polar mesospheric clouds (PMCs). Many studies, such as *Gadsden* [1998] and *DeLand et al.* [2007] have shown correlations between PMC measurements and the solar cycle. *Rapp and Thomas* [2006] concluded from a microphysical modeling study that accurate humidity and temperature variations are both needed in order to accurately model PMC variations.

[8] We note that ground-based WVMS measurements are also being made from the NDACC site at Lauder, New Zealand (45.0°S, 169.7°E), since 1994 [*Nedoluha et al.*, 2007]. The measurements at Lauder are, however, not as sensitive to upper mesospheric variations, both because this instrument does not have the 50 kHz filters available at Mauna Loa and because of the lower altitude (and corresponding higher tropospheric optical depth) of that site. In addition, the larger seasonal cycle at Lauder makes it more difficult to isolate the solar cycle effects.

[9] In this study we will intercompare the ground-based measurements from Mauna Loa with satellite measurements to estimate and validate the variations in mesospheric water vapor caused by the solar cycle. We will also study the 1992–1996 period when there were large variations in mesospheric water vapor which do not appear to be caused by changes in Lyman α irradiance. As the time series of available mesospheric measurements lengthens, our ability to characterize the solar cycle variations should further improve, and we should therefore be able to better detect non–Lyman α related changes in upper mesospheric water vapor.

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

[10] The WVMS 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. The standard WVMS data analysis procedure uses the individual spectral scans integrated into 500 scan blocks (~1 week), with each 500 scan average spectrum then being 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 for measurements and is particularly important for retrievals in the upper mesosphere. Details of the instrumentation and the general retrieval technique are given by *Nedoluha et al.* [1995], but, as will be discussed in section 3, the retrieval technique used here differs slightly from the standard WVMS retrieval.

[11] 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 essentially self-calibrating and 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 third public release v19 retrievals.

[12] The Aura MLS H_2O water vapor product is retrieved from the radiances measured by the radiometers centered near 190 GHz [*Froidevaux et al.*, 2006]. The instrument began producing science observations on 13 August 2004. The version 2.2 (v2.2) water vapor product used here is validated and described by *Lambert et al.* [2007]. The accuracy is estimated to be 0.2–0.5 ppmv (4–11%) for the pressure range 68–0.01 hPa. The scientifically useful range of the H_2O data is from 316 to 0.002 hPa. Comparisons from *Nedoluha et al.* [2007] showed good agreement in temporal variations with the WVMS measurements from 2004 through early 2007.

[13] The ACE-FTS instrument (hereafter referred to simply as ACE) is a high resolution (0.02 cm^{-1}) Fourier transform spectrometer which measures atmospheric absorption spectra between 2.2 and 13.3 μm (750–4400 cm^{-1}). It performs solar occultation measurements from the midtroposphere up to 150 km [*Bernath et al.*, 2005]. The instrument is self-calibrating, employing high-Sun measurements to calculate atmospheric transmittances. The transmittance spectra are fitted to obtain profiles of temperature, pressure, and over 20 atmospheric trace gases [*Boone et al.*, 2005]. The altitude sampling of the ACE-FTS ranges from a measurement spacing of 6 km to a spacing of less than 2 km. However, for occultations with higher sampling rates, the altitude resolution is limited by the instrument's 1.25 mrad circular field of view, corresponding to 3–4 km. ACE is in a circular, low-Earth (650 km altitude) orbit with

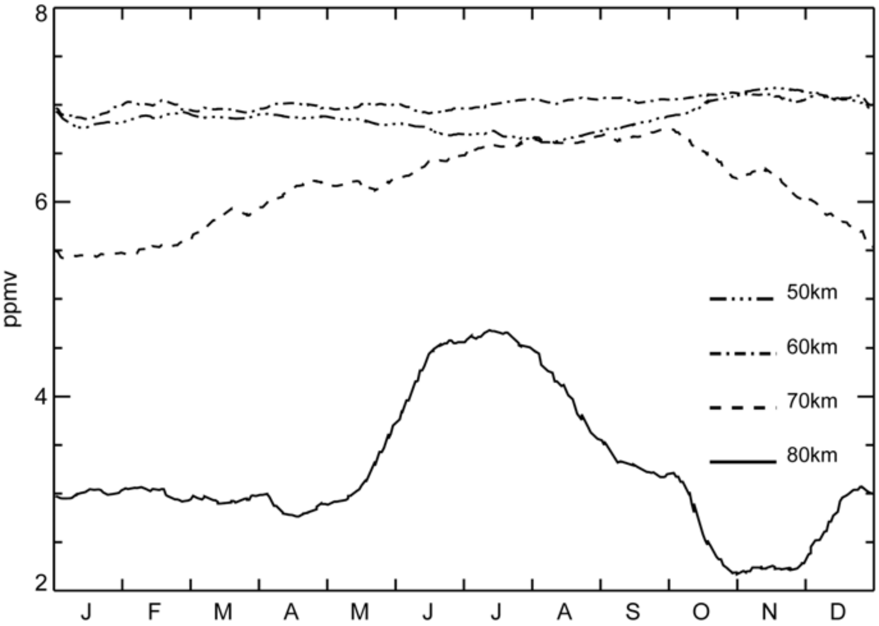

Figure 1. The average seasonal water vapor mixing ratio based on an MLS climatology at four altitude levels. The MLS climatology is based upon data with ±2° latitude and ±30° longitude of the Mauna Loa site taken from August 2008 until September 2009. The climatology is calculated by first finding an MLS daily median, then averaging all data within 5 days of the day of interest, and finally averaging together the values for the ~4 years of data.

an inclination of 74° resulting in near-global coverage approximately every 2 months. ACE measurements are available from February 2004 to the present, and the version 2.2 data are used for this study. The H_2O data from ACE have been validated by *Carleer et al.* [2008] by comparisons to H_2O measurements from several space-borne instruments. The repeatability of the measurement relative to correlative measurements and its high precision (<5%) make it very suitable to scientific studies and a good reference measurement. The accuracy of the ACE H_2O data is supported by a recent study of *Wrotny et al.* [2009], which shows consistency between H_2O and CH_4 variations within and between different pressure levels.

3. Retrievals in the Upper Mesosphere

[14] In previous studies WVMS retrievals have always been calculated using a constant a priori water vapor profile for the middle atmosphere. This is generally appropriate since the retrievals from the upper stratosphere to the midmesosphere are minimally affected by the a priori profile. It also ensures that all observed variations are driven by the data and not by the a priori.

[15] In this study we are interested in the deviation of the water vapor variations from the seasonal cycle, and we are focused on the upper mesosphere where the signal-to-noise limitations on the measurements are most severe. In an optimal estimation retrieval [*Rodgers*, 1976] noisy measurements experience a larger a priori influence than measurements with better signal to noise, so variations in the level of noise can themselves introduce variations in the retrieved water vapor. While every effort is made to minimize variations in signal to noise in the WVMS measurements, changes in tropospheric conditions can affect the signal to noise of the measurement and can therefore affect the retrieval in the upper mesosphere. The variation of the retrieval as a function of changes in the signal to noise of the measurement is approximately proportional to the difference between the true atmosphere and the a priori; hence, these signal to noise–induced variations can be minimized by choosing an a priori profile which represents a good first guess of the true profile. WVMS retrievals for this study, therefore, use a seasonally varying a priori water vapor profile based on an MLS climatology shown in Figure 1. The MLS climatology is based upon data with ±2° latitude and ±30° longitude of the Mauna Loa site taken from August 2004 until September 2008. The climatology is calculated by first finding an MLS daily median, then averaging all data within 5 days of the day of interest, and finally averaging together the values for the ~4 years of data. In Figures 3, 5, 6, and 7 we will show only deviations from this climatology.

[16] In addition to using a water vapor climatology based on MLS measurements, we also use a temperature climatology calculated from the MLS temperature measurements. This is derived using the same coincidence criteria and temporal smoothing and provides the background temperature profile required for the WVMS retrievals. In using the MLS temperature measurements to provide a seasonal climatology, we are clearly failing to incorporate any variations in mesospheric temperature which may be driven by the solar cycle. *Remsberg* [2007], updating the calculations of *Remsberg and Deaver* [2005], found an amplitude for a solar cycle–like term of 0.5 K at 10°N and 1.0 K at 20°N for the 0.01 hPa level, with the maximum temperatures occurring slightly (~1 year) after solar max. At 80 km a 1 K

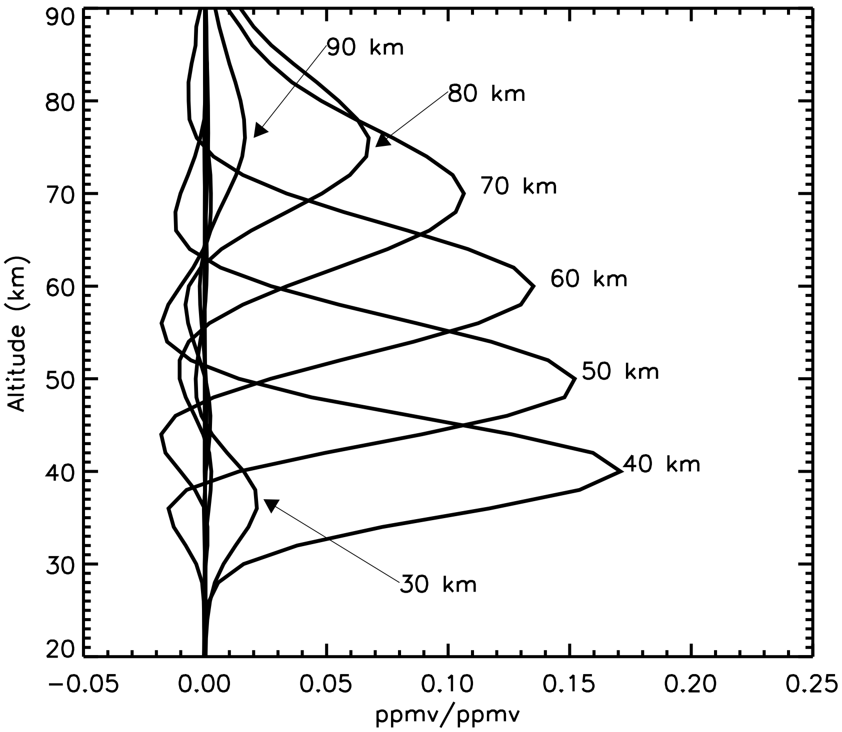

Figure 2. Averaging kernels for the WVMS measurements at Mauna Loa. Each line represents the sensitivity of the retrieval at the indicated altitude to perturbations over a range of 2 km altitude bins.

error in background temperature causes an error of ~0.5% in the water vapor mixing ratios retrieved in the WVMS measurements. If the assumed background temperature is higher than the true temperature (as will happen near solar minimum), then the water vapor mixing ratios retrieved from that level will tend to be too low. Hence, by neglecting the solar cycle variation in temperatures, the WVMS retrieval may underestimate the amplitude of the solar cycle in water vapor by ~0.5%.

[17] For the HALOE and ACE comparisons we have used all measurements with ±5° latitude of the Mauna Loa site. Since the MLS measurements are much more numerous, we limited the coincidence criteria to measurements taken with ±2° latitude and ±30° longitude the WVMS measurements. *Nedoluha et al.* [2007] showed that both average differences and standard deviations of differences between MLS and WVMS measurements were only minimally different for these different coincidence criteria.

[18] In order to make a comparison between WVMS and satellite measurements, we convolve the satellite measurements with the averaging kernels for the WVMS instrument. When we are using a satellite profile as taken from the database without convolution with these averaging kernels, we will refer to this as an unconvolved profile. The averaging kernel used for this convolution is shown in Figure 2. As is the case with any such convolution, calculated convolved results at a particular level are affected by measurements both above and below that level. As is shown in Figure 2, the peak sensitivity of the 80 km retrieval is actually at 76 km, but the retrieval is also sensitive to water vapor above 80 km. The satellite measurements also begin to degrade in the upper mesosphere, and in many cases retrievals are not available above 80 km. In order to provide convolved satellite profiles to compare with the WVMS profiles near the mesopause we have in some cases extended satellite retrievals to altitudes above those where data were available. For such altitudes, we take the ratio of measured water vapor to the a priori water vapor at the highest available altitude. We then apply this ratio to the a priori for all higher levels to obtain a satellite mixing ratio which is then convolved with the WVMS averaging kernels.

[19] The fraction of HALOE profiles with water vapor values for this set of coincidences drops from almost 100% at 78 km to 92% at 80 km and only about 27% at 84 km. The ACE water vapor profiles are nominally retrieved up to 90 km [*Carleer et al.*, 2008]; however, the actual upper altitude limit in a given occultation is governed by the location of the highest measurement below 90 km. Also, 98% of the ACE profiles from the coincidences used have retrieved water vapor up to 80 km. The percentage of water vapor profiles is 88% at 87 km and quickly drops off above this altitude. MLS water vapor measurements are almost always available up to 0.002 hPa, which corresponds to ~88 km.

[20] Convolution of satellite data in order to compare with WVMS results is correct under the assumption that the satellite data have a much finer vertical resolution than the WVMS retrieval and that there is very little sensitivity to the a priori used in the satellite retrieval itself. These assumptions are appropriate for the solar occultation instruments, but as is shown by *Lambert et al.* [2007], the MLS vertical resolution degrades with altitude so that is ~12–16 km (full width at half maximum (FWHM)) in the upper

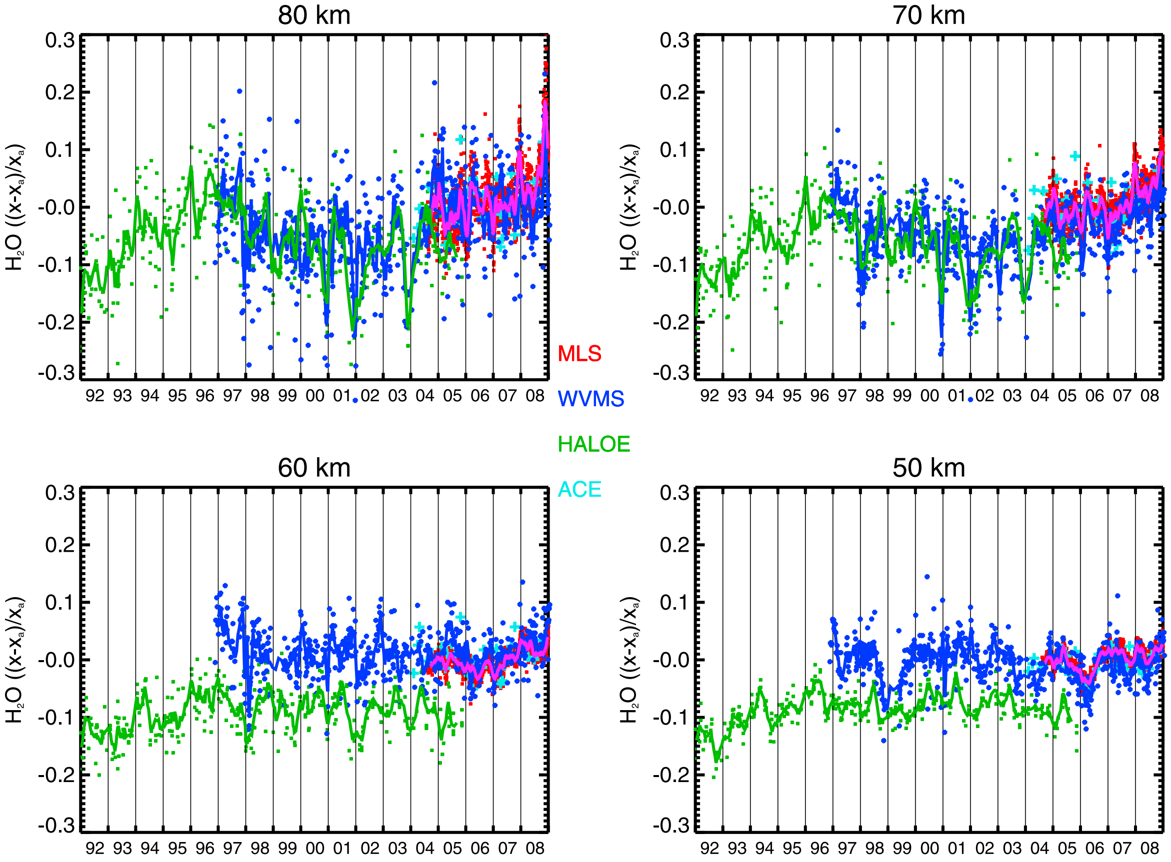

Figure 3. Water vapor measurements from HALOE, WVMS, MLS, and ACE, shown as a fractional difference from the MLS seasonal a priori. HALOE results are zonal averages. The lines for the HALOE and WVMS results represent a 5 point smoothing (~5 weeks for WVMS, ~2–3 months for HALOE), while the MLS line, shown in magenta, represents a 35 point smoothing (~5 weeks). All of the satellite data have been convolved with the averaging kernels shown in Figure 2.

mesosphere. This WVMS vertical resolution at 80 km is ~16 km (FWHM), so it is comparable to the reported MLS vertical resolution at this altitude. Unlike the MLS retrievals, which have little a priori dependence even at this altitude, the WVMS retrievals at 80 km have a 29% dependence on the a priori. It is therefore not clear for this analysis whether or not the comparison between MLS and WVMS is most appropriately performed with or without convolution of the MLS retrievals. Therefore, while all of the results to be shown here will make use of convolved MLS data, we have performed comparisons with unconvolved MLS measurements as well. We found only small differences (~1%) in the annual average anomalies at 50, 60, and 70 km. There were, however, significant differences at 80 km, and the agreement between MLS and both WVMS and ACE is clearly degraded when the unconvolved MLS retrievals were compared to the WVMS and ACE measurements.

4. Seventeen Year Water Vapor Time Series

[21] In Figure 3 we show time series of the WVMS and convolved satellite water vapor measurements. All results are shown as fractional differences from the seasonal a priori shown in Figure 1, so whereas water vapor at 80 km varies by almost a factor of 2, the variations from the seasonal climatology are almost always within ±20%. The largest deviations from the climatology generally occur at 70 and 80 km in December–January.

[22] Since the results are all shown as fractional differences from the MLS a priori, the MLS results must necessarily be centered near 0. However, the good agreement between MLS and the other instruments shows that in absolute terms, the water vapor mixing ratios measured by HALOE, ACE, and MLS are in good agreement. The only exception to this is that the HALOE results at 50 km and 60 km are somewhat lower than those measured by the other three instruments.

[23] It is apparent from the smoothed time series shown in Figure 3 that at 70 and 80 km, there was an increase in water vapor from 1992 to 1997, a subsequent decrease with a minimum around 2000–2002, and then a gradual increase until the end of the time series. At 50 and 60 km there is an increase in the early 1990s [*Nedoluha et al.*, 1998, *Evans et al.*, 1998], but the increase appears to be smaller than at the higher altitude levels. Since all results are shown relative to an MLS climatology, the HALOE measurements, which are consistently somewhat lower than the MLS measurements in the lower mesosphere [*Lambert et al.*, 2007], have a consistently negative fractional difference in this region.

[24] As was discussed in section 1, we would expect to observe an anticorrelation between water vapor and Lyman

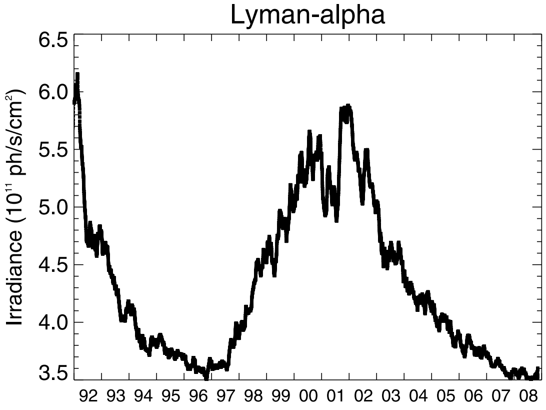

Figure 4. Composite Lyman α irradiance from the Lasp Interactive Solar Irradiance Datacenter.

α irradiance. In Figure 4 we show a composite Lyman α obtained from the Lasp Interactive Solar Irradiance Datacenter [*Woods et al.*, 2000]. This shows a minimum in the irradiance in 1996 and 2008, and a maximum in 2001–2002, consistent with the minimum in mesospheric water vapor near this time.

[25] In order to evaluate the relationship between Lyman α and the water vapor, we calculated the annual average difference from the MLS climatology for WVMS (1997–2008) and HALOE (1992–2005) measurements. The results for 80 km WVMS and convolved HALOE data are shown in Figure 5. Also shown in Figure 5 are fits to the WVMS and HALOE data based on a linear regression of the annual average Lyman α irradiance and the water vapor data sets. While there is a slight relative bias between the two sets of measurements, the water vapor in the WVMS and convolved HALOE data sets show a very similar sensitivity to Lyman α variations. We also have recalculated the fit after removing the 1992 data. In 1992 the irradiance was high and water vapor was low compared to later years even in the upper stratosphere and lower mesosphere, i.e., altitudes where Lyman α variations should have very little effect on water vapor. Removing the 1992 data does, therefore, slightly reduce the calculated sensitivity of fractional water vapor on Lyman α (from -0.051 ± 0.014 to -0.045 ± 0.014 (per 10^{11} ph s^{-1} cm^{-2}) at 80 km). Non–Lyman α related interannual variations certainly can affect the results somewhat, but in subsequent plots we will use the full (1992–2005) HALOE data set to calculate the sensitivity of water vapor to Lyman α.

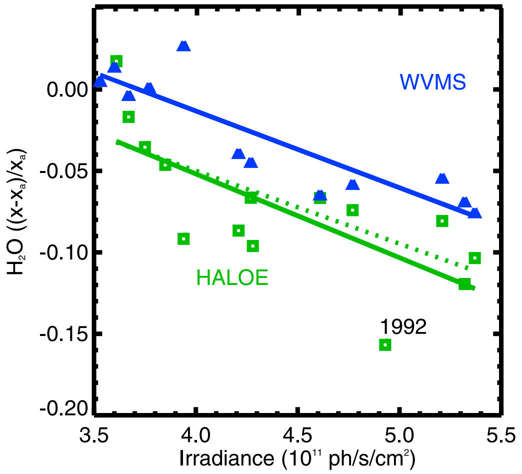

Figure 5. Water vapor at 80 km as an annual average fractional difference from the MLS climatology plotted against the annual average Lyman α irradiance. The lines represent linear regression fits to the data. The dotted line represents the fit to the convolved HALOE data without the 1992 data.

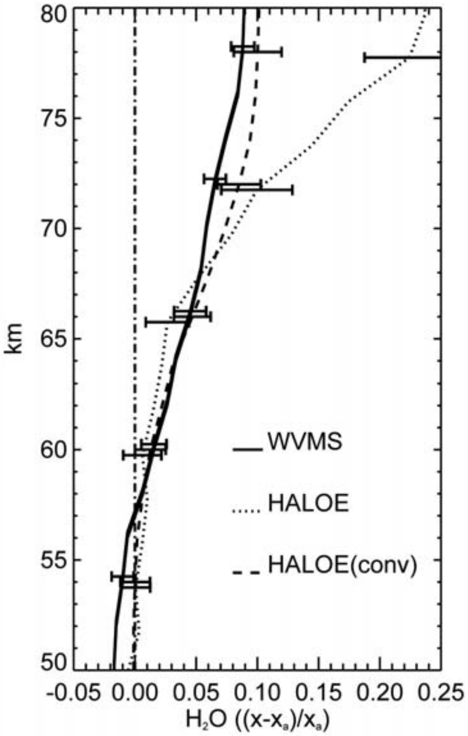

Figure 6. The total fractional change in water vapor as a function of altitude based upon a linear regression of annual Lyman α irradiances and water vapor. Error bars represent $\pm 1\sigma$. Results are shown for WVMS (solid), unconvolved HALOE (dotted), and convolved HALOE (dashed).

[26] In Figure 6 we show the calculated sensitivity of water vapor to Lyman α irradiance based on the types of fits shown in Figure 5 for the range 50 to 80 km. Results are shown here both for HALOE retrievals convolved with the WVMS averaging kernels and for the unconvolved HALOE data. The unconvolved HALOE data clearly show a higher sensitivity to Lyman α irradiance in the upper mesosphere than do the WVMS retrievals, and this sensitivity drops to values which are smaller than the WVMS values at altitudes below 68 km. The differences near 80 km are consistent with expectations given the averaging kernels shown for the WVMS instrument in Figure 2. These indicated a reduced sensitivity of the WVMS retrievals in this region, combined with a tendency for information to come from slightly below the retrieved altitude in this region. Once the HALOE water vapor data are convolved, the sensitivity to Lyman α is in very good agreement with the WVMS retrievals. The Lyman α sensitivity becomes statistically insignificant (at

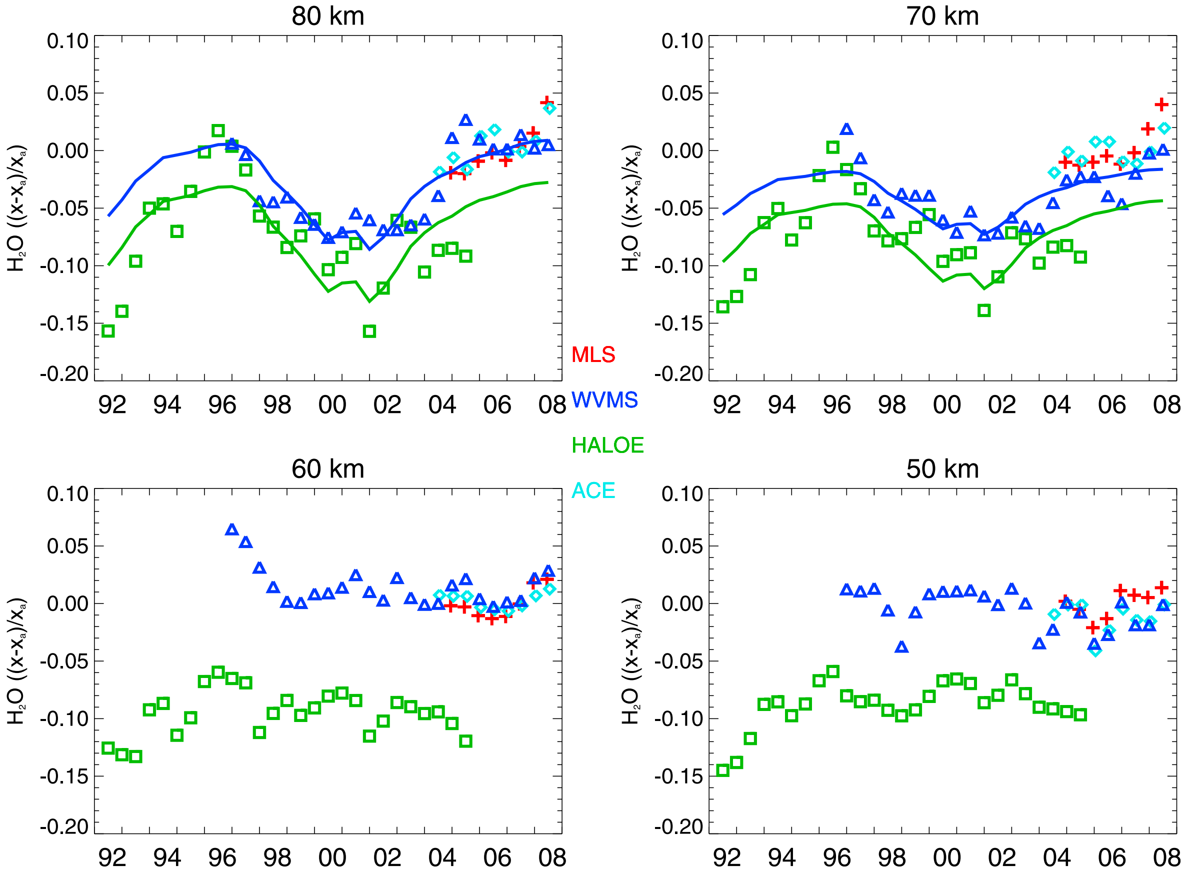

Figure 7. Water vapor given as an annual average fractional difference from the MLS climatology for WVMS (blue), convolved satellite measurements from MLS (red), HALOE (green), and ACE measurements (cyan). Also shown as lines are the fits to the convolved HALOE (green) and WVMS data (blue) based upon the annual average Lyman α irradiance. Annual averages are shown both centered on the middle of each year, and around the start of each year.

the 1σ level) at 64 km and below for the HALOE data, at 60 km and below for the convolved HALOE data, and at 58 km and below for the WVMS data. While the WVMS measurements are very useful for validating the sensitivity of the HALOE data to Lyman α irradiance, the unconvolved HALOE data certainly provides the best estimate of the true variations in water vapor caused by the solar cycle in the upper mesosphere.

[27] The annual average climatological mixing ratio shown in Figure 1 at 80 km is 3.2 ppmv, so the 21% variation shown in Figure 6 represents a total variation in water vapor from the solar cycle of ~0.7 ppmv. This is clearly smaller but not insignificant when compared to the seasonal cycle, for which the MLS climatology shows a variation of 2.4 ppmv.

[28] In Figure 7 we show a time series of the annual average water vapor anomalies for WVMS data and for convolved satellite data. In addition to the annual averages based on calendar years, we also show annual averages shifted by 0.5 year (i.e., starting on 2 July and ending on 1 July of the following year). An annual average point is included on Figure 7 only if there are measurements both before and after the time indicated on the plot, so, e.g., the WVMS point at 1997.0 indicates that measurements were made in both the 0.5 year before and after 1 January 1997. We will refer to these points as a 1996–1997 average. As in Figure 3, these anomalies are all referenced to an MLS climatology, so the excellent agreement between the MLS, ACE, and WVMS water vapor mixing ratios does reflect the fact that these instruments are, in absolute terms, measuring very similar water vapor mixing ratios from 50 to 80 km. In Figure 7 it is apparent that the HALOE measurements are lower than the others not just at 50 and 60 km, but are also slightly lower at 70 and 80 km. At 70 km the WVMS measurements are, on average, slightly lower than those of MLS and ACE (but still higher than HALOE). In Table 1 we show the average difference of the annual average WVMS and satellite anomalies over the indicated years at the four altitudes shown.

[29] Also shown Figure 7 are fits at 70 and 80 km to the WVMS and convolved HALOE anomalies based on the Lyman α irradiance as shown in Figures 5 and 6. While the fit to the Lyman α irradiance at 60 km is statistically significant, it represents only a small fraction of the observed variation. The 1992 and 1993 HALOE data clearly show that water vapor during this period is anomalously low at all altitudes even when solar cycle variations are taken into account. These low values are observed both at altitudes where the solar cycle effect is significant (i.e., 70 and 80 km) and at those where it is small (i.e., 50 and 60 km). In 1996 the HALOE and WVMS water vapor

Table 1. Overall Bias Between Ground-Based WVMS Measurements and Three Satellite Measurements[a]

Altitude (km)	HALOE-WVMS (1997–2005) (%)	MLS-WVMS (2005–2008) (%)	ACE-WVMS (2004–2008) (%)
80	−3.6	−0.6	0.2
70	−3.4	2.5	2.3
60	−10.7	−1.3	−0.6
50	−8.3	1.3	0.5

[a] The bias is calculated from the average differences of the annual median anomaly between the convolved satellite and WVMS measurements at Mauna Loa. The years used for the comparisons are shown in parentheses.

values are the largest at all four altitudes shown (with the exception of the 2005 WVMS water vapor at 80 km). The HALOE and WVMS values generally track each other very well. Both show a sharp drop from 1996 to 1998 at 70 and 80 km and a smaller drop over this time period at the lower altitudes. While the drop occurs just after solar minimum, the drop is faster than would be expected from the solar cycle fit. The largest variations in the WVMS-HALOE differences are at the end of the coincident time series. The standard deviations of the differences in the annual averages of the HALOE and WVMS measurements for the nine full calendar years of data (1997–2005) are 3.5% at 80 km, 1.6% at 70 km, 1.6% at 60 km, and 0.8% at 50 km.

[30] In Figure 7 we also show the convolved MLS and ACE data for the years 2004–2008. Given the as yet relatively short duration of these measurements we have not attempted to fit a solar cycle to the MLS and ACE measurements. There is only a short period of overlap in 2004 and 2005 between all four data sets. The large WVMS increase at 80 km from 2004 to 2005 is not observed in the HALOE or ACE data. On the other hand, at 70 km, the ACE and WVMS data seem to be in slightly better agreement, showing a slight increase from 2004 to 2005, while the HALOE data show a slight decrease.

[31] The excellent agreement in both the absolute terms and in the variations observed by ACE, MLS, and WVMS at 50 km and 60 km is particularly impressive. At 50 km most of the ACE values are nearly indistinguishable from the WVMS values. This is true even when there are changes of ∼4% from between points separated by 0.5 year (as is the case between 2005 and 2005–2006). The largest difference between ACE and WVMS at these altitudes is the 1.6% difference in 2008 at 60 km. Between MLS and WVMS at 50 and 60 km, the largest difference is 2.5% for 2004–2005 at 60 km.

[32] An interesting feature in the WVMS data is that there are local minima in the 50 km water vapor retrievals in 1998–1999, 2003–2004, 2005–2006, and 2007–2008. In all of these cases there was a maximum in the easterly 30 hPa winds at the equator in September–October according to the CPC reanalysis (available at http://www.cpc.noaa.gov/data/indices/), so perhaps these minima are related to the quasi-biennial oscillation.

5. Discussion

[33] The WVMS and HALOE measurements both approximately cover the period of a full solar cycle and both show very similar sensitivity to variations in Lyman α irradiance in the upper mesosphere. This is, to our knowledge, the only published validation of the sensitivity of HALOE water vapor measurements to the solar cycle. Since the early HALOE measurements include an increase in water vapor at all altitudes, studies which make use of only the first few years of HALOE measurements may overestimate the effect of the solar cycle; however, this early 1990s increase has only a small effect on the estimate of the sensitivity of water vapor to the solar cycle if a fit is calculated using the entire HALOE time series.

[34] Having derived an estimate of the solar cycle effect on upper mesospheric water vapor, and of the uncertainties in annual average variations based on comparisons between WVMS and HALOE, it is now possible to estimate to which extent the early 1990s increase in the upper mesosphere is related to the solar cycle, and to which extent it is similar to the same secular increase which is observed at lower altitudes. At 80 km the convolved HALOE water vapor increases by 17.4 ± 3.5% from 1992 to 1996, but 7.7 ± 1.5% of this can be attributed to the solar cycle. Taking the difference and adding the errors in quadrature leaves 9.7 ± 3.8% of the increase unexplained. At 70 km, after subtracting a 5.7 ± 1.2% solar cycle effect, 8.1 ± 2.0% of the increase remains. At 50 and 60 km where the solar cycle term is small, the increase from 1992 to 1996 is 8.6 ± 1.6% and 6.6 ± 0.8%, respectively. Hence, to within the uncertainties, the fractional increase in water vapor between 1992 and 1996 is the same at all of these altitudes.

[35] Any trends which might be derived from the observed variations are dependent upon the choice of start and end points. The start of the HALOE time series has the lowest water vapor values, whether or not the solar cycle variations are taken into account. The only exception is the 2001–2002 point at 70 and 80 km, but 2001–2002 has the highest annual average Lyman α, so this annual average water vapor is not as far below the solar cycle fit as the 1992 annual average water vapor.

[36] While a time series from the HALOE data beginning in 1992 and ending in 2005 shows a positive trend, the maximum in this time series occurs in 1996. The WVMS time series begins just after this, and the first point of the WVMS time series (1996–1997) is the maximum in the WVMS time series at every altitude. The only exception to this is the 80 km WVMS data for 2005, but the jump in the WVMS data preceding this maximum is inconsistent with that in either the ACE or HALOE data, so it may be unphysical. The trend from 1996 to 2005 will be negative at all altitudes in both the HALOE and WVMS data (except at 80 km in the WVMS data), even if the solar cycle is removed. If the WVMS time series is extended through the end of 2008 the trend will be negative at 60 and 70 km. This is because just as the HALOE time series started at an unusually low value in 1992, the WVMS time series started at an unusually high value (in agreement with HALOE) in 1996–1997.

[37] For the most recent years of the WVMS time series we show coincidences with ACE and MLS. Both the absolute agreement and the variations observed during the period of coincident WVMS, ACE, and MLS measurements are excellent. The largest bias is at 70 km, where the ACE and MLS retrievals show average water vapor values 2–3% higher than WVMS. At 60 km, which we believe to be the

optimal altitude for WVMS retrievals, the differences between the annual average ACE and WVMS retrievals are never larger than 1.6%.

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