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Validation of long-term measurements of water vapor from the midstratosphere to the mesosphere at two Network for the Detection of Atmospheric Composition Change sites

Gerald E. Nedoluha,[1] R. Michael Gomez,[1] Helen Neal,[2] Alyn Lambert,[3] Dale Hurst,[4] Chris Boone,[5] and Gabriele Stiller[6]

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[1] We present measurements from the Water Vapor Millimeter-wave Spectrometer (WVMS) instruments at Table Mountain, California (34.4°N, 242.3°E), and Mauna Loa, Hawaii (19.5°N, 204.4°E), and highlight the extended altitude range of the measurements at these sites, which now provide measurements down to 26 km. We show that this extended altitude range has been acquired without disturbing the existing long-term WVMS data set at Mauna Loa. Validation of the successful transition is provided by comparing WVMS measurements with coincident satellite measurements from the Aura Microwave Limb Sounder (MLS), the Atmospheric Chemistry Experiment, and the Michelson Interferometer for Passive Atmospheric Sounding. At the lowest altitudes where WVMS measurements are possible, we also compare with frost-point hygrometer balloon measurements. The water vapor mixing ratios measured at 50 km over Mauna Loa are the highest ever reported in the WVMS (since 1996) or MLS (since 2004) time series. Particularly encouraging for the new 26 km WVMS measurements is that they indicate an increase between 2010 and 2011 that is comparable to that observed by other instruments. This shows that these measurements are sensitive to variations at this altitude and that the instrumental baseline remains stable.

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1. Introduction

[2] Water vapor in the middle atmosphere is important because of its role in ozone chemistry as the reservoir of odd hydrogen, and there are indications that it is an important driver of decadal-scale global surface climate change [*Solomon et al.,* 2010]. There are several physical mechanisms that drive changes in middle-atmospheric water vapor on interannual and longer time scales. Variations in Lyman-α radiation over the period of the solar cycle change the amount of water vapor in the upper mesosphere [e.g., *Hervig and Siskind,* 2006; *Nedoluha et al.,* 2009]. Increasing surface methane emissions will slowly increase the amount of water vapor in the stratosphere and mesosphere due to methane oxidation [*Le Texier, Solomon and Garcia,* 1988]. Changes in middle-atmospheric dynamics alter the amount of water vapor produced from methane oxidation at any particular location [e.g., *Nedoluha et al.,* 1998a, *Nedoluha et al.,* 1998b]. Finally, unique among long-lived tracers, the amount of water vapor entering the middle atmosphere is sensitive to variations in the temperature at the tropical tropopause [e.g., *Randel et al.,* 2004, 2006].

[3] The Water Vapor Millimeter-wave Spectrometer (WVMS) instruments have been measuring water vapor since 1992 from sites of the Network for the Detection of Atmospheric Composition Change (NDACC). Measurements have been made nearly continuously since 1993 from Lauder, New Zealand, and since 1996 from Mauna Loa, Hawaii. These measurements make use of the pressure broadening of the 22 GHz water vapor emission line to obtain a vertical profile of water vapor.

[4] Newly available technologies, including phase-locked dielectric resonator oscillators, improved room temperature low-noise amplifiers, and 16,384 channel digitizers that use fast Fourier transform firmware to create a spectrometer have made it possible to extend the measurement capabilities to lower altitudes. Because of the need to preserve continuity

[1]Remote Sensing Division, Naval Research Laboratory, Washington, D. C., USA.
[2]Computational Physics, Inc., Springfield, Virginia, USA.
[3]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, USA.
[4]Cooperative Institute for Research in Environmental Sciences, University of Colorado, Boulder, Colorado, USA.
[5]Department of Chemistry, University of Waterloo, Waterloo, Ontario, Canada.
[6]Karlsruhe Institute of Technology, Institute for Meteorology and Climate Research, Karlsruhe, Germany.

Corresponding author: G. E. Nedoluha, Remote Sensing Division, Naval Research Laboratory, 4555 Overlook Avenue, SW, Washington, D. C. 20375, USA. (nedoluha@nrl.navy.mil)

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in the long-term data sets, such new developments are first tested on the WVMS4 instrument at the NDACC site at Table Mountain, California. Recent developments at this site have been discussed in *Nedoluha et al.* [2011] and *Gomez et al.* [2012]. In this paper, we will focus first on the measurements since June 2010 at Table Mountain and particularly on the stability of the retrievals down to 26 km. Measurements in stratosphere down to this altitude are particularly difficult because of the need to maintain instrumental baseline stability over a broad frequency range. We will also compare measurements from Table Mountain with coincident satellite measurements in the mesosphere.

[5] We will then show measurements from the new WVMS5 instrument at Mauna Loa, which has been providing retrievals for the long-term data set since November 2010. We will show that, at those altitudes where measurements were possible with the previous instrument at Mauna Loa (WVMS3), there is no discernible change in measured mixing ratios that accompanies the transition from WVMS3 to WVMS5. We will also compare the new WVMS5 measurements in the lower stratosphere with coincident measurements.

2. Coincident Measurement Data Sets

[6] Throughout this paper we will reference coincident water vapor measurements where they are available. Satellite measurements come from the Aura Microwave Limb Sounder (MLS), from the Atmospheric Chemistry Experiment (ACE) mission taken with the Fourier transform spectrometer (FTS) on board the Scisat-1 satellite (ACE-FTS), and from the Michelson Interferometer for Passive Atmospheric Sounding (MIPAS) on board the Envisat research satellite. We also show frost-point hygrometer (FPH) measurements to compare with the lowest altitude WVMS measurements.

[7] The ACE-FTS instrument (hereafter referred to simply as ACE) is a high-resolution (0.02 cm^{-1}) FTS that 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, using high sun measurements to calculate atmospheric transmittances. The transmittance spectra are fitted to obtain profiles of temperature, pressure, and more than 20 atmospheric trace gases [*Boone et al.,* 2005]. The altitude sampling of the ACE 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 to 4 km. ACE is in a circular, low Earth (650 km altitude) orbit with an inclination of 74 degrees 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 spaceborne 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 further supported by a recent study by *Wrotny et al.,* 2010, which shows consistency between H_2O and CH_4 variations within and between different pressure levels.

[8] The MIPAS is a limb emission spectrometer measuring in the midinfrared (4.15–14.6 μm, i.e., 2410 to 685 cm^{-1}) from the Environmental Satellite (Envisat) platform in a sun-synchronous orbit at about 780 km altitude [*Fischer et al.,* 2008]. Spectra of the atmospheric infrared emission are taken for the 7 to 72 km altitude range at step widths of 1.5 km in the Upper Troposphere/Lower Stratosphere (UTLS) and increasing toward 4.5 km in the lower mesosphere with 0.0625 cm^{-1} spectral resolution (unapodized). For the MIPAS operation mode applied during the period relevant to comparison here, about 1300 profiles with 27 altitude steps each along 14.4 orbits per day were obtained. After level-1 processing from the raw data to calibrated and geo-located radiances done by European Space Agency (ESA) [*Nett et al.,* 1999], the spectral radiances were fitted within selected microwindows to derive global vertically resolved fields of temperature, cloud coverage, and up to 30 trace species. Details of the applied Tikhonov-constrained retrieval approach can be found in von *Clarmann et al.* [2009]. In this study, we use the IMK/IAA V5R_H2O_220 water vapor product from the Institute for Meteorology and Climate Research (KIT). This product has a vertical resolution of 2.5 to 4.5 km in the relevant altitude range. The precision of another data version with identical retrieval approach but based on an earlier spectra version has been assessed at about 7% for a single profile, whereas the total accuracy including systematic (mainly spectroscopic errors) was between 13% (at 40 km) and 19% (at 25 km) [*von Clarmann et al.,* 2009]. The MIPAS IMK H_2O data have been validated within the Measurements of Humidity in the Atmosphere and Validation Experiments 2009 campaign [*Leblanc et al.,* 2011] by comparison to a number of ground-based, balloon-borne, and satellite instruments. The deviation of MIPAS was within ±10% of all other instruments, with a slight tendency toward a systematic high bias of less than 10% between 35 and 45 km, and a low bias of ≥10% above 55 km [*Stiller et al.,* 2012]. Similar to ACE, the study by *Wrotny et al.,* 2010] supported the high quality of MIPAS data by demonstrating the consistency between H_2O and CH_4 variations within and between different pressure levels.

[9] The balloon-borne National Oceanic and Atmospheric Administration FPH has made routine vertical profile measurements of water vapor in the UTLS over Boulder, Colorado, since 1980 (*Oltmans et al.,* 2000). The fundamental measurement technique, unchanged since 1980, is to grow and maintain a thin, stable layer of frost on a temperature-controlled mirror. Stability of the frost layer, indicative of equilibrium between the ice surface and overlying water vapor, permits direct calculation of the water vapor partial pressure from the mirror (frost-point) temperature. Volume mixing ratios are determined by dividing the water vapor partial pressure by ambient pressure. The only requisite calibrations are of the mirror thermistors; no water vapor calibration standards or scales are required. Stratospheric measurements are made with 4% precision (*Hurst et al.,* 2011) and an accuracy of better than 10% (*Vömel et al.,* 1995). Long-term UTLS water vapor monitoring programs similar to Boulder were initiated at Lauder, New Zealand, and Hilo, Hawaii, in 2004 and 2010, respectively.

[10] The Aura MLS H_2O water vapor product is retrieved from the radiances measured by the radiometers centered near 190 GHz [*Lambert et al.,* 2007; *Read et al.,* 2007].

The instrument began producing science observations on 13 August 2004. The version 3.3 (v3.3) stratospheric and mesospheric water vapor data used in this study are the latest update to the v2.2 version, which is validated and described by *Lambert et al.* [2007]. The MLS v3.3 data have significant improvements for a number of species [*Livesey et al.,* 2011], including the H_2O product. Correlative measurement comparisons show a fine-scale oscillation in the v2.2 H_2O retrievals, and this retrieval artifact has been eliminated in the v3.3 retrievals. The accuracy is estimated to be 0.2 to 0.5 ppmv (4–11%) for the pressure range 68 to 0.01 hPa. The scientifically useful range of the H_2O data is from 316 to 0.002 hPa.

[11] Extended comparisons between WVMS and MLS data have been presented in many previous studies, and the measurements have always shown good agreement in temporal variations on time scales of months to years [*Nedoluha, G. E., et al.,* 2007, *Nedoluha et al.,* 2009, *Nedoluha et al.,* 2011]. The Aura MLS data are particularly valuable to this study because daily measurements throughout the WVMS altitude range are available coincident with both Mauna Loa and Table Mountain. We can therefore use these data to provide a daily seasonal climatology for both water vapor and temperature. With the exception of the lower stratosphere (where National Centers for Environmental Prediction (NCEP) data are used) and the thermosphere (where the Mass Spectrometer Incoherent Scatter Radar (MSIS) model is used), this temperature climatology provides the required background temperature for the retrieval.

3. Water Vapor Millimeter-Wave Spectrometer Measurements From Table Mountain

[12] Water vapor measurements with the WVMS instruments were made at Table Mountain, California, from 1992 to 1997. From 1997 to 2008, measurements from this site were made on an intermittent basis primarily to test upgrades of the WVMS instruments before deploying these upgrades at the NDACC sites at Mauna Loa, Hawaii, and Lauder, New Zealand. From December 2008 until May 2009, measurements were taken from this site using the new WVMS4 instrument. This instrument contained many improvements [*Gomez et al.,* 2012], including the replacement of the filter banks with an FTS. *Nedoluha et al.* [2011] showed that stable stratospheric measurements could be made down to 26 km over a period of 5 months. Between May 2009 and June 2010, further improvements were made to this instrument, and with the exception of minor repairs, the WVMS instrument has been kept in a stable configuration since June 2010. As shown in *Gomez et al.* [2012], the instrumental baseline was considerably further improved between May 2009 and June 2010, and it is data from this improved instrument that will be shown in this paper.

[13] The WVMS4 instrument at Table Mountain has been operational nearly continuously since June 2010. Although no major changes were made to the WVMS instrument at Table Mountain since then, it was necessary in January 2012 to replace the aging reference absorber bar that is used to noise balance the measurements [*Nedoluha et al.,* 1995]. Previous tests had shown that having the reference bar far away from the feedhorn reduced the sensitivity of the instrumental baseline to changes in the precise positioning of the mirror relative to this reference bar, and this bar had been installed more than 1 m from the feedhorn. As we show below, this change had no apparent effect on the retrievals. The ability to make such changes without disturbing the 26 km time series is important to our ability to provide a stable, long-term water vapor measurement at this altitude.

[14] WVMS retrievals for this study use an optimal estimation technique [*Rodgers,* 1976] and use a seasonally varying a priori water vapor profile based on an MLS climatology [*Nedoluha et al.,* 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 data from 2005 to 2011. By using a climatology as an a priori, we can better study interannual variations, because the resultant retrieval will be less sensitive to any changes in the signal to noise of the measurements [*Nedoluha et al.,* 2009].

3.1. Weekly Retrievals

[15] In Figure 1, we show the spectrum and retrieved profile taken from 500 measurement scans on 1–7 June 2011 at Table Mountain. The 500 scan retrieval period is generally

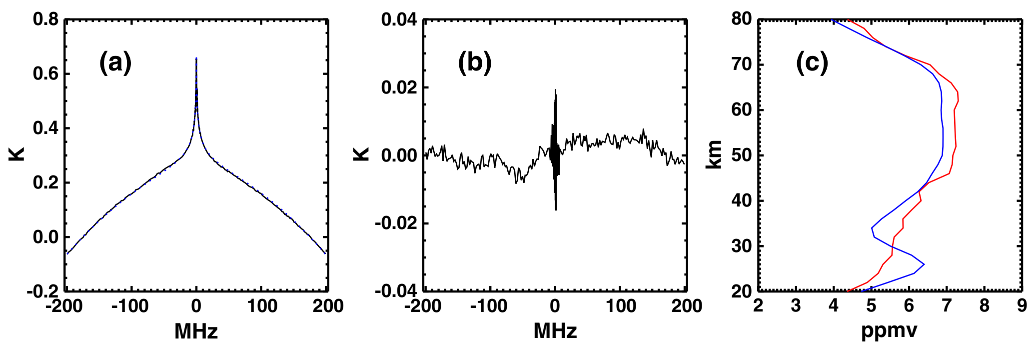

Figure 1. WVMS and MLS measurements from Table Mountain, 1–7 June 2011. (a) WVMS spectrum (black) and spectrum fit from retrieval (blue, but nearly indistinguishable on this scale). A linear slope has been removed. (b) Difference between measured and fitted spectra. The spectrum appears less noisy away from line center because more channels are binned together at these frequencies. (c) Water vapor profile retrieved from WVMS measurements (blue) and from coincident MLS measurements (red). This MLS profile has not been convolved with the WVMS averaging kernel.

~1 week but can represent a somewhat longer period when the measurements are temporarily interrupted (usually due to bad weather). The spectrum in Figure 1a is the difference of a measurement taken at a low elevation angle and a second measurement taken at a higher elevation angle with a reference absorber in the beam (Dicke switching). The spectrum shown has not had any baseline removed except for a linear slope and represents a dramatic improvement over what was possible a decade ago over such a spectral range [e.g., *Forkman et al.,* 2003]. The channels of the WVMS4 spectrometer are averaged into increasingly larger bins away from line center (see *Gomez et al.,* 2012, for details); hence, the residuals near line center are noisier. Measurements farther than ±6.33 MHz from line center are averaged over ~2 MHz (67 channels). The residual has been significantly improved over that which was possible in 2009 (compare with Figure 4 of *Nedoluha et al.,* 2011). The steps taken to reduce the instrumental baseline to this level are discussed in *Gomez et al.* [2012]. There remains, however, a broad structure (at the few mK level) that is most visible on the positive frequency offset side of the spectrum. Comparisons with spectra shown in *Motte et al.* [2008] and *DeWachter et al.* [2009] are difficult because of the noise and scale of the figures shown there, but the baseline wave structure in the residual shown in Figure 1b appears to be at least as good as, if not better than, any 22 GHz measurement system. Also shown is the average coincident H_2O profile for these days from Aura MLS measurements taken within ±30° longitude and ±2° latitude of Table Mountain. The retrieval also has a peak at 26 km, which is not apparent in the MLS measurements.

[16] In Figure 2, we show a retrieval for the same period as in Figure 1. In this case, we have allowed the retrieval to fit a single sine-wave baseline in additional to fitting the water vapor profile. The resultant residual is clearly better, and the retrieved water vapor profile shows a much smaller peak in the lower stratosphere, in better agreement with the MLS measurements. That the addition of an additional fitting parameter provides a closer fit to the MLS measurements in the lower stratosphere is not surprising, because these are closer to the a priori calculated from the MLS climatology. Although the addition of the single sine-wave baseline to the retrieval produces both a flatter residual and a more physically realistic looking water vapor profile, it comes at a cost; such a retrieval has limited sensitivity to true variations in water vapor in the lower stratosphere because the spectral shape of a sine-wave baseline may be very similar to that of the water vapor emission from this region.

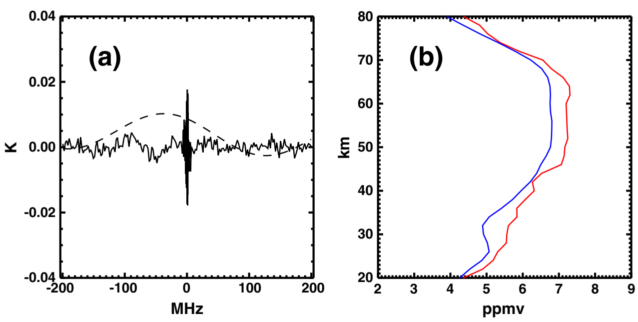

Figure 2. Measurements from Table Mountain, 1–7 June 2011 (same dates as Figure 1). (a) Residual from WVMS measurements and (b) water vapor mixing ratio profiles from WVMS (blue) and MLS (red). The WVMS retrieval shown here allows for the fitting of a single sine-wave baseline (indicated by dashed line).

[17] If we wish to perform useful retrievals in the lower stratosphere, we can therefore not include a variable baseline fit in the retrieval scheme. Sensitivity to H_2O variations in the lower stratosphere is, however, maintained if we add the same sine wave to all retrievals and then perform retrievals without a sine-wave baseline fit. This, of course, assumes that the sine wave is constant, an assumption that can only be confirmed by studying residuals over an extended period and validating H_2O variations with an independent data source.

[18] In Figure 3, we show a retrieval from 500 measurement scans taken from 11–16 December 2010. The same sine wave (identical in amplitude, frequency, and phase) that was added to improve the fit in the data shown in Figure 2 has been added to the spectrum shown in Figure 3. The residual in Figure 3 shows no clear sine-wave feature and no peak in the retrieval near 26 km. Because the sine-wave fit is not included in the retrieval process, measurements in the lower stratosphere remain sensitive to variations in H_2O.

[19] In Figure 4, we show 500 scan retrievals in the mesosphere from WVMS4, together with coincident satellite data from MLS (daily averages within +2° latitude and +30° longitude) and ACE (average of measurements within ±5° latitude for an overpass period). This is the only figure in which the retrievals have not been calculated using an a priori based on the MLS climatology. This has been done here to emphasize that the WVMS measurements do accurately reproduce the seasonal variation even with a constant a priori. All of the WVMS retrievals shown in Figure 4 have at least a 75% measurement contribution at 70 km as calculated from $\Sigma_j A_{i,j}(x_a)_j/x_i$, where A is the averaging kernel, x is the retrieved water vapor mixing ratio profile, and x_a is the a priori water vapor profile [*Connor et al.,* 1991]. At 50 and 60 km altitudes, the measurement contribution is generally greater than 90%. The FWHM of the averaging kernels at these altitudes is ~15 km [see Figure 1 in *Nedoluha et al.,* 2011].

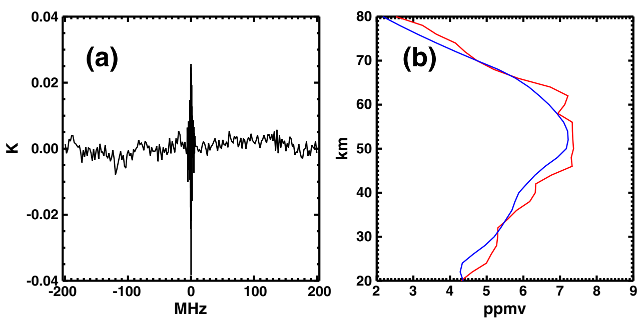

Figure 3. Measurements from Table Mountain, 11–16 December 2010. (a) Residual from WVMS measurements and (b) water vapor mixing ratio profiles from WVMS (blue) and MLS (red). The baseline sine wave that was calculated from the fit to the 1–7 June 2011 WVMS measurements (Figure 2) has been added to this WVMS retrieval and continues to successfully remove the largest instrumental baseline component.

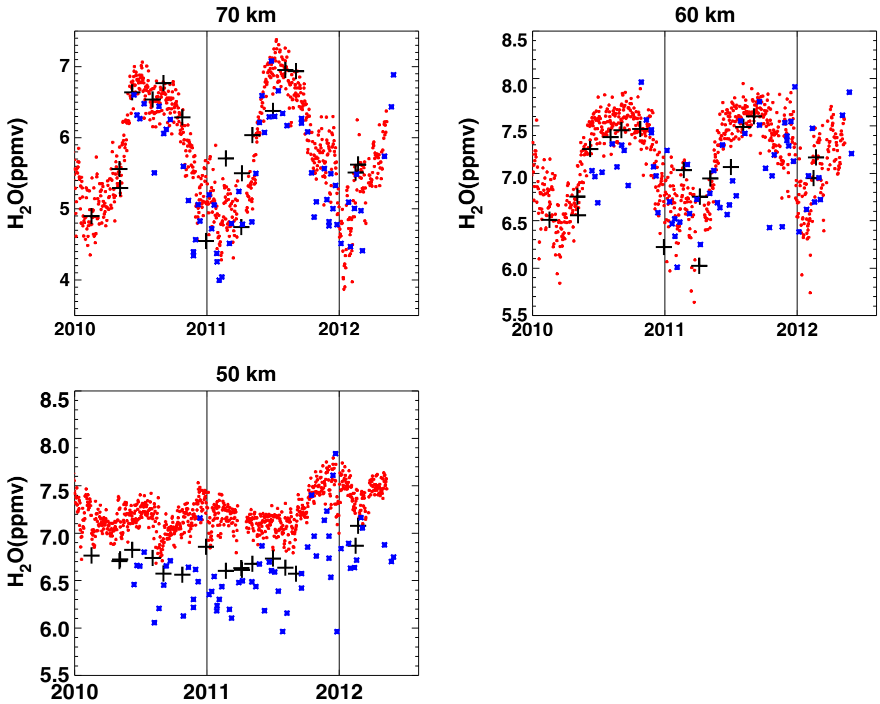

Figure 4. WVMS (blue) and coincident MLS (red) and ACE (black) measurements for Table Mountain. Satellite measurements have been convolved with the averaging kernels from the WVMS retrievals.

At 50 km, all measurements show an increase at the end of 2011 so that the measurements at the beginning of 2012 are somewhat higher than during the same season in 2011.

3.2. Six Hour Retrievals

[20] Retrievals based on 500 measurement scans, as shown in Figures 1–4, are ideal for long-term studies of the mid and upper mesosphere, and for precise determination of a long-lived baseline wave. In the stratosphere, adequate signal to noise can be obtained in a few hours, but, as mentioned earlier, accurate retrievals in the stratosphere do require a very stable baseline. The most common source of instrumental baseline disturbance is water and/or ice in the feedhorn or on the external absorber that is used to noise balance the measurements (see *Gomez et al.,* 2012). In many cases, these effects are easily recognized and the scans are discarded, but even slightly disturbed baselines can cause unphysical and difficult to detect changes in the retrieved mixing ratios, and these effects are not removed by averaging together large numbers of scans into a retrieval.

[21] To mitigate the effect of a few bad scans, we perform retrievals over short periods (6 hours) and then report a median of these retrievals over an extended period (1 month). Only 6-hour retrievals that have at least a 75% measurement contribution at 26 km are included; higher altitudes in the stratosphere always have a larger measurement contribution than the 26 km retrieval. From June 2010 to July 2012, there are between 12 and 90 retrievals per month that meet this criterion, with the smallest number in part caused by some instrumental problems in April 2012. The standard deviation of measurements in a typical month is ~0.3 to 0.4 ppmv, a variation that is probably primarily instrumental and not geophysical (the MLS

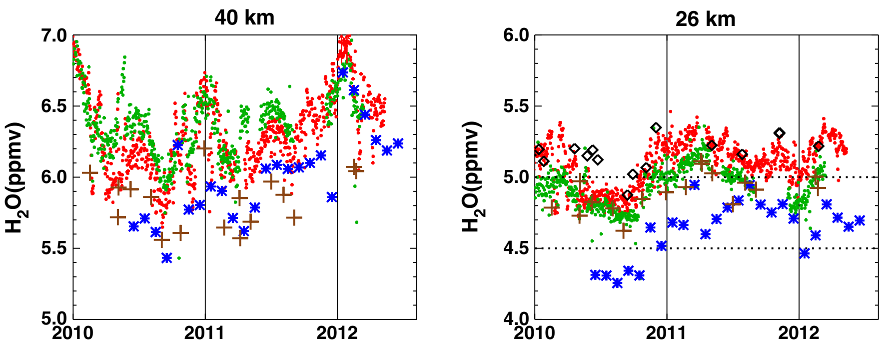

Figure 5. WVMS (blue) and coincident MLS (red), MIPAS (green), and ACE (brown) measurements for Table Mountain. Balloon measurements (black) are from Boulder, Colorado. The satellite and balloon measurements have been convolved with the averaging kernels from the WVMS retrievals. Dotted lines are included to aid in visually quantifying the variation.

measurements show greater stability). WVMS monthly median retrievals obtained by this method are shown in Figure 5.

[22] Also shown in Figure 5 are daily coincident measurements from MLS, MIPAS, and ACE. The average of the relatively sparse ACE solar occultation measurements within ±5° latitude are shown whenever there is a coincident overpass period. MIPAS measurements are shown as daily averages within ±2° latitude. MLS measurements are shown as daily averages within ±2° latitude and ±30° longitude. The satellite measurement profiles are convolved with the WVMS averaging kernels.

[23] In addition to the satellite measurements, we show FPH measurements. These measurements are not coincident with Table Mountain but are taken ~6° further North, at Boulder, Colorado (40°N, 255°E). Because of the need to apply the WVMS averaging kernels for this comparison, only balloons for which measurements are available up to at least 28 km have been included in Figure 5, thus eliminating about half of the profiles. To provide values for the convolution above the highest balloon measurements, we used the MLS climatological a priori.

[24] Although the values of the WVMS measurements at 26 km are lower than those of the other data sets, the variation is very similar. As mentioned in section 3.1, this systematic offset is dependent on exactly what constant baseline is applied to the data. The fact that the offset remains consistent shows that the instrumental baseline is constant. The fact that the WVMS retrievals vary interannually in the same way as the other instruments shows that the WVMS retrievals are sensitive to changes in water vapor at this altitude. We also note that the 26 km retrievals show no indication that the changes made to the reference bar in January 2012 disturbed the time series.

[25] All of the measurements in Figure 5 show an increase at both 26 and 40 km from 2010 to 2011. The water vapor mixing ratios at 26 km in 2012 remain similar to those in 2011, whereas at 40 km, there is another increase. An increase from 2011 to 2012 was also apparent in the 50 km data. To which extent these changes are due to changes in water vapor entering the stratosphere and to which extent they are due to dynamically driven variations is under investigation.

4. Water Vapor Millimeter-Wave Spectrometer Measurements from Mauna Loa

[26] In November 2010 we replaced the WVMS3 instrument at Mauna Loa with the WVMS5 system. The system has been operational nearly continually since November 2010, with the exception of a gap in August and September 2011. The new instrument should, just as at Table Mountain, provide measurements down to ~26 km. However, unlike at Table Mountain, the first priority at Mauna Loa was to ensure that, at altitudes where the WVMS3 instrument was providing good water vapor retrievals, the water vapor time series was disturbed as little as possible.

[27] Measurements for the WVMS3 system are reported down to 40 km, but the long-term stability of the 40 km measurements is not as good as those from ~50 km and above. The long-term stability of these measurements has been documented in several studies [*Haefele et al.,* 2009; *Nedoluha et al.,* 2007, *Nedoluha et al.,* 2009]. In this section, we will therefore first show how, at measurements where the long-term time series is most reliable, the measurements have been extended without disturbing the existing time series. As in section 3, we will examine the stratospheric retrievals from this site.

4.1. Weekly Retrievals

[28] We show in Figure 6 the annual anomalies for the entire WVMS Mauna Loa measurement time series, as well as for the halogen occultation experiment (HALOE), ACE, and MLS measurements. Each point shown represents an annual average difference from the MLS climatology. Annual averages are shown for 1 January to 31 December and from 1 July to 30 June; thus, each measurement is included in two annual averages.

[29] The measurements from the new WVMS5 instrument are shown in the final three WVMS data points. Given the many differences between the WVMS5 instrument and the WVMS3 instrument, it is very encouraging to see that there is no abrupt change in measured mesospheric water vapor accompanying this changeover. The mixing ratios measured by both WVMS systems are a few percent smaller than those measured by MLS, with the exact value dependent on altitude. A somewhat surprising finding is that ACE, MLS, and WVMS show increasing water vapor at 70 km during a period where Lyman-α is increasing following the solar minimum in 2009. It is also interesting that the 60 km values for 2012 are the highest observed at Mauna Loa throughout the entire WVMS, ACE, and MLS time series.

[30] Figure 6 highlights the importance of maintaining a continuous time series of measurements. Although the instruments generally show good agreement in interannual variations, there are ~5% to 10% differences in the average values of the measured mixing ratios. Any gap in the measurement time series could therefore lead to a very large uncertainty in trends inferred over such a gap.

4.2. Six Hour Retrievals

[31] Just as at Table Mountain, we use 6-hour integrations for retrievals in the lower stratosphere at Mauna Loa. There is, however, an important difference between the setup of the WVMS5 instrument and that of the WVMS4 instrument at Table Mountain, which is relevant to the 6 hour retrievals. In an effort to improve the continuity of the measurements, the WVMS5 instrument was first deployed with the absorber bar and feedhorn in a configuration very similar to that of the old WVMS3 instrument, with the bar closer to the feedhorn than at Table Mountain. As mentioned in section 3, however, tests later showed that having the reference bar closer to the feedhorn makes the baseline more sensitive to changes in the position of the reference bar in the beam. In January 2012 there was a change in the angle at which the absorber bar is observed, and this resulted in a change in the instrumental baseline. The reference bar for the Mauna Loa measurements has now been raised, but none of the measurements shown here is made with a raised reference bar.

[32] We have therefore performed the lower stratospheric (6-hour) retrievals using two slightly different instrumental baselines: one for the period November 2010 through December 2011, and a second one beginning in January 2012, when the reference angle was changed. The 2010 to 2011 baseline is derived from a baseline fit to measurements from 1–10 June 2011, whereas the 2012 baseline is

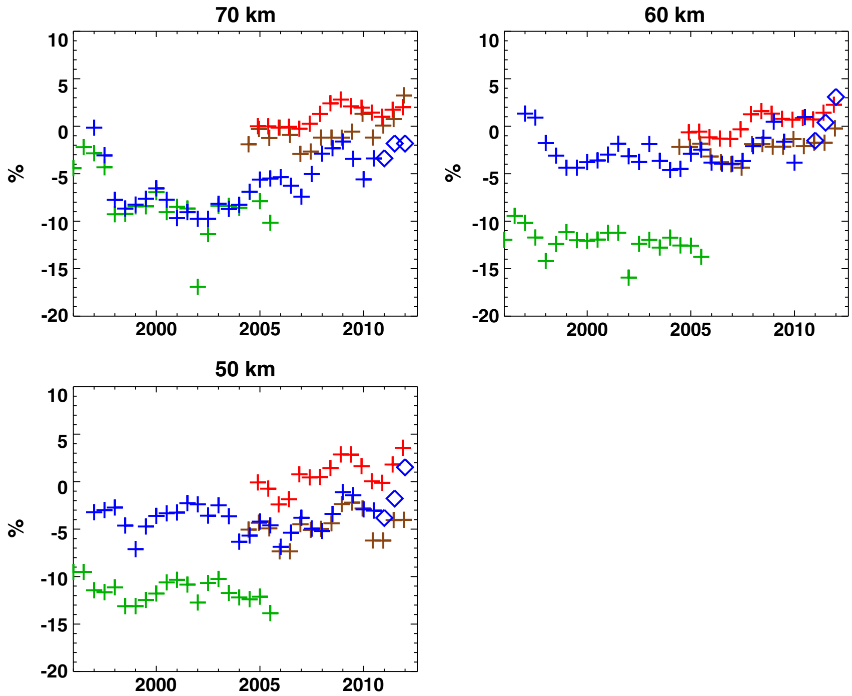

Figure 6. Water vapor measurements over Mauna Loa, Hawaii (19.5°N, 204.4°E). Each symbol represents the annual average difference from an MLS climatology. Symbols are shown for January to December and July to June; thus, each measurement is included in two annual averages. Measurements are from HALOE (green), WVMS (blue), ACE (brown), and MLS (red). WVMS3 (filter bank) data are shown with crosses; WVMS5 (FTS) data are shown with diamonds. Satellite data have been convolved with WVMS averaging kernels.

derived from a baseline fit to measurements from 1–7 June 2012. Both baselines are similar in amplitude to that used at Table Mountain.

[33] To test the sensitivity of retrievals at all altitudes to this baseline change, we retrieved the 2012 data using both baselines in weekly retrievals. The difference between 26 km retrievals for the 2012 measurements with the two baselines is 0.37 ppmv, with a standard deviation of 0.05 ppmv. Measurements at 26 km between these periods are therefore not directly comparable, but variations within each period are valid. At 40 km, retrievals in 2012 with the two different baselines differ by only 0.02 ppmv, with a standard deviation of 0.03 ppmv. Retrievals above 40 km are even less affected by the baseline change. Hence, retrievals at 40 km and above from 2012 are comparable with earlier retrievals.

[34] In Figure 7, we show the 26 and 40 km measurements from Mauna Loa, together with coincident satellite measurements and balloon measurements from nearby Hilo (19.7°N, 205°E). The good absolute agreement at 26 km is coincidental, as it depends on the precise choice of baseline. Although there is an increase in H_2O at 26 km from November 2010 until mid-2011, this increase, unlike that at Table Mountain, appears to be primarily seasonal. There

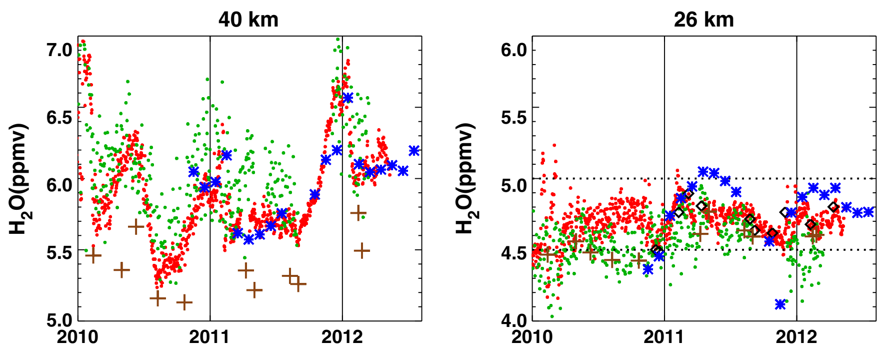

Figure 7. WVMS (blue) and coincident MLS (red), MIPAS (green), and ACE (brown) measurements for Mauna Loa. Balloon measurements (black) are from Hilo, Hawaii. The satellite and balloon measurements have been convolved with the averaging kernels from the WVMS retrievals. Because of instrumental baseline differences, 26 km WVMS measurements from January 2012 onward are not directly comparable with those from November 2010 to December 2011.

is, however, an increase relative to H_2O values in early 2010, before 26 km WVMS measurements were available. At 40 km there is a clear increase between 2011 and 2012. This increase is almost certainly caused primarily by dynamic variations in the stratosphere that can cause interannual variations in the CH_4 oxidation in this region.

5. Discussion

[35] We have shown that the new WVMS instruments at Mauna Loa and Table Mountain can measure variations in stratospheric water vapor down to 26 km. These retrievals are successful because of successful efforts to reduce the instrumental baseline and because that baseline that remains is nearly constant. This remaining baseline can be adequately fit with a constant single sine wave. Because the precise choice of constant baseline is somewhat arbitrary, the average value of the retrieved water vapor at 26 km is not well determined, but the measurement is sensitive to variations at this level. Comparisons at Table Mountain show that the variations observed at 26 km by WVMS are consistent with other data sets since 2010. With increasing altitude this instrumental baseline term quickly becomes much less important.

[36] The WVMS time series at Mauna Loa, which has been ongoing since 1996, has been successfully extended without any apparent discontinuity with the new WVMS5 instrument. We have also shown that the new instrument can make stratospheric measurements down to 26 km, but the baseline fit for this time series, which affects the 26 km retrievals (but not those at ~40 km or above) will probably need to be adjusted once more before beginning long-term monitoring at this altitude.

[37] The WVMS instrument at Lauder has now also been recently upgraded. Although it is not expected that conditions at Lauder will allow for useful retrievals down to 26 km, we are currently studying the altitude range over which it will be possible to perform useful retrievals with this new instrument.

[38] The 2010 to 2012 period shows some interesting variations at both Mauna Loa and Table Mountain. There is an increase in the brief 2010 to 2012 Table Mountain data set at 26 and 40 km, and in the 40 km Mauna Loa data set (because of baseline changes in the 26 km Mauna Loa data set, interannual variations cannot be determined at 26 km for this site). The 26 km increase occurs primarily between 2010 and 2011, whereas the 40 km increase appears to occur gradually over the entire time period. At 50 and 60 km over Mauna Loa, the 2012 water vapor values are the highest ever observed by WVMS (since 1996). They are also the highest values observed in the Aura MLS time series (since 2004). We are currently investigating the extent to which these water vapor variations can be attributed to dynamically driven changes in the amount of CH_4 oxidation, and to which extent they may be due to changes in water vapor entering the middle atmosphere.

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