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Ground-based microwave measurements of water vapor from the midstratosphere to the mesosphere

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[1] We present 5 months of retrievals from a new Water Vapor Millimeter-wave Spectrometer (WVMS) instrument that has been deployed at Table Mountain, California (34.4°N, 242.3°E). The single most important improvement over previous WVMS instruments is that instead of a set of 90 filters, this instrument has a fast Fourier transform spectrometer that provides 16,384 channels across 500 MHz, with a channel bandwidth of ~30 kHz. The additional information provided by this spectrometer makes it possible to extend the altitude range of the WVMS measurements from the current ~40–80 km range to ~26–80 km. We present details of the retrieval scheme and study the effects on the retrieved profiles of fitting instrumental baseline components. We compare the retrievals to coincident measurements from the NASA Aura Microwave Limb Sounder (MLS) instrument with a particular emphasis on understanding the stability of the 26 km retrievals. While the retrieval is sensitive to variations at this altitude, neither the MLS-retrieved water vapor mixing ratios nor those retrieved by WVMS show much variation over the 5 month period: a good indication of the stability of both instruments.

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1. Introduction

[2] Ground-based microwave spectroscopy, using the water vapor rotational transition absorption line at 22.235 GHz, is now a mature and well proven and validated technique for measuring the water vapor profile in the mesosphere and upper stratosphere [e.g., *Nedoluha et al.*, 2007; *Haefele et al.*, 2009]. The physical basis for the measurement is the fact that the 22 GHz line is pressure broadened up to an altitude of about 80 km. Therefore, the measured line shape contains information on the distribution of water vapor as a function of pressure or, equivalently, altitude up to 80 km. Further, the 22 GHz line is sufficiently optically thin that the core of the line, resulting from middle atmospheric water vapor, can be observed even from moderate tropospheric opacity sites. The upper limit measurement altitude of the technique is governed by the altitude at which the spectral line is predominantly Doppler, rather than pressure broadened, which occurs at approximately 80 km for this water vapor transition, above which there is no longer a strong dependence of the line shape on altitude. However, the lower limit altitude for retrievals is governed by instrumental considerations and not the physics of the measurement. Roughly speaking, this is given by the altitude at which the pressure broadened half width of the line is equal to the spectral measurement bandwidth because emission from water vapor at lower altitudes is essentially unresolved by the measurement. On the basis of the success of this technique for monitoring mesospheric and upper stratospheric water vapor, there has been a large impetus in the community to increase the measurement spectral bandwidth and, thereby, extend the measurements down into the lower stratosphere [e.g., *Deuber et al.*, 2005]. There are two major difficulties associated with this extension: instrumental spectral baseline issues, and the large variability of the tropospheric water vapor profile.

[3] An important issue limiting accuracy of ground-based millimeter-wave retrieval is the instrumental spectral baseline. Among the many possible causes of instrumental baseline structure are reflections in the RF and/or IF chain. In addition, standing waves in the noise balancing of the measurement can be important [*Deuber and Kämpfer*, 2004]. Retrieval errors resulting from instrumental baseline artifacts become increasingly important with decreasing retrieval altitude because an increasingly larger measurement spectral bandwidth is required to extend the lower limit measurement altitude into the middle and lower stratosphere.

[4] Tropospheric water vapor will affect the retrieval of upper stratospheric and mesospheric water vapor, but the pressure broadened emission from tropospheric water vapor is sufficiently broad that it is essentially frequency independent over the measurement bandwidth required for such measurements. However, for the portion of the spectrum

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sensitive to water vapor in the lower stratosphere, the contribution to the line shape from tropospheric water vapor becomes nonnegligible, and there is no longer a clean separation between the tropospheric and middle atmospheric retrievals. This difficulty is accentuated by the much larger water vapor abundances in the troposphere compared to the very dry middle atmosphere. Thus, for retrievals down into the midstratosphere and lower stratosphere, tropospheric water vapor needs to be treated much more carefully than for retrievals extending down only into the upper stratosphere. In this case, minimizing middle atmospheric water vapor retrieval errors, resulting from tropospheric water vapor uncertainties, becomes a major retrieval challenge. We note that the useful retrieval of stratospheric water vapor down to ~26 km is made easier because of the high altitude (2300 m) and low tropospheric humidity at the Table Mountain site. It is not clear whether such a measurement can be duplicated under conditions of higher tropospheric humidity, and indeed *Haefele et al.* [2009] showed results suggesting that low tropospheric optical depths were very important in obtaining good comparisons between ground-based and satellite water vapor measurements.

[5] We have developed the ground-based Naval Research Laboratory (NRL) Water Vapor Millimeter-wave Spectrometer (WVMS) instrument, which has been operationally measuring the water vapor profile from ~40–80 km since the early 1990s as part of the Network for the Detection of Atmospheric Composition Change (NDACC). We presently have instruments operational at the Mauna Loa, Hawaii (19.5°N, 204.4°E), and Lauder, New Zealand (45.0°S, 169.7°E) NDACC sites. We also have intermittent measurements from the JPL facility at Table Mountain, California (34.4°N, 242.3°E) which has served primarily as a test site for new instruments. The long databases acquired with these instruments have established that ground-based millimeter techniques are excellent for long-term trend detection [e.g., *Nedoluha et al.*, 2009], and the precision and accuracy of the measurements are well documented. However, within the framework of the NDACC, it is desirable to develop a capability to monitor important shorter-term water vapor variations which frequently occur in the lower stratosphere (such as, e.g., the large-scale decrease in stratospheric water vapor observed in 2001 [*Randel et al.*, 2006]). Motivated by this consideration, we have developed a prototype of the next generation WVMS instrument. This instrument was designed with the specific objective of extending the ground-based millimeter-wave technique measurement range into the lower stratosphere. As such, every effort has been made to minimize and stabilize instrumental baseline structure. Perhaps most importantly, the filter bank spectrometer used in the operational WVMS instruments has been replaced with a state-of-the-art fast Fourier transform (FFT) spectrometer, which provides 16384 spectral channels across a 500 MHz measurement bandwidth (±250 MHz from line center), giving a spectral resolution of approximately 30 kHz. This measurement bandwidth gives the potential to measure water vapor down to about 26 km, while the high spectral resolution throughout the measurement bandwidth allows more complete characterization of residual instrumental baseline structure.

[6] The first measurement tests of this WVMS prototype instrument were performed at Table Mountain, California over the period 2 December 2008 to 11 May 2009. In this paper we present the results of those measurements. We will provide a detailed description of the new retrieval methodology developed to treat the tropospheric/middle atmospheric water vapor interaction issues discussed above. Also, the middle atmospheric retrievals obtained from these measurements will be compared with coincident measurements from the Microwave Limb Sounder (MLS) instrument aboard the NASA Aura satellite. This 5 month data set represents an important step to the establishment of a long-term data set of ground-based microwave measurements down to 26 km.

2. WVMS Instrumentation and Data Acquisition

[7] The WVMS instrument used in this study is, in general, similar to the WVMS instruments now operational at both Lauder and Mauna Loa as described by *Nedoluha et al.* [1995], but with some significant differences. The cryogenic amplifier has been replaced with a room temperature amplifier, and the 90 channel filter bank spectrometer has been replaced with an FFT spectrometer similar to the one described by *Müller et al.* [2009]. Using Agilent's 32K point fast Fourier transform analyzer firmware this spectrometer provides 16384 channels across 500 MHz, with a channel bandwidth of ~30 kHz, centered on the resonant frequency of the water vapor line.

[8] The data acquisition scheme is also similar to that used for other WVMS instruments and is described in detail by *Nedoluha et al.* [1995]. A Dicke switching scheme is used in which a reflector plate switches the beam between the sky viewed at a low elevation angle (~20° above the horizon; signal) and the zenith sky (reference). An absorber bar is placed partially in the zenith sky path field of view in order to achieve a total power balance between the signal and reference positions which is, in turn, important in minimizing instrumental baseline structure. Because the signal observation angle required to achieve this balance is a function of tropospheric opacity (the lower the opacity the lower the observation angle), before each scan the instrument performs an automatic balance procedure in order to determine the optimal observation angle. Since retrievals involve a series of measurements at slightly different signal angles, the air masses of all of these measurements are averaged and then converted to a single signal angle which is used for the retrieval. Also as described by *Nedoluha et al.* [1995], a tipping measurement, consisting of a series of measurements taken at observation elevation angles from 15° to 45° above the horizon, is performed every 30 min to determine the total optical depth. Given the extremely dry stratosphere and mesosphere, the total optical depth is nearly identical to the tropospheric optical depth.

3. WVMS Retrieval Methodology

[9] We combine the spectral measurements with the tropospheric optical depth from the tipping measurement, and then retrieve a water vapor profile with an optimal estimation retrieval [*Rodgers*, 1976] in a manner similar to that described by *Nedoluha et al.* [1995]. The tropospheric optical depth for a particular retrieval is calculated by linearly interpolating between tipping measurements to estimate an optical depth for each spectral measurement, and then averaging these

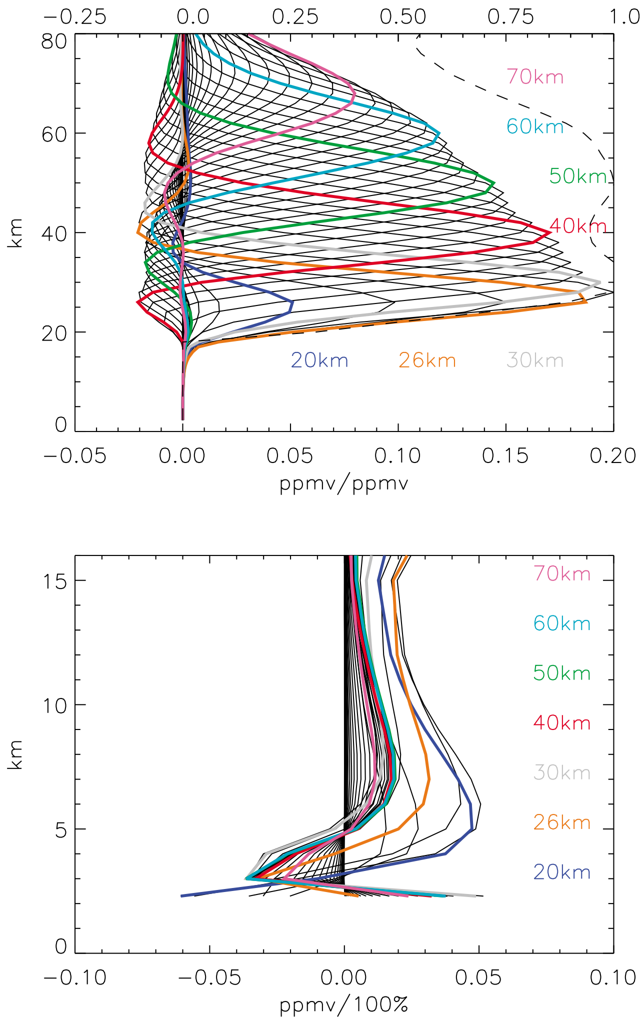

Figure 1. Measurement sensitivity for 24 h of WVMS measurements on 28 January 2009. (top) Each curve shows standard averaging kernels, given as the response of the retrieval at the indicated altitude (shown for 17–100 km) to 1 ppmv perturbations from 0 to 80 km. The dotted curve (axis label at top) indicates the contribution of the measurement to the mixing ratio profile (see text). The scale for this line is given at the top of the plot. (bottom) The sensitivity of the 17–100 km retrievals to perturbations of 100% at each altitude from 0 to 16 km.

optical depths. The measurements for the retrieval are signal minus reference brightness temperatures ($T_b(\nu)$) obtained from the FFT spectrometer. The bandwidth of the spectrometer is 500 MHz, with a spectral resolution of approximately 30 kHz. However, the outer 50 MHz on each end of the spectrometer are not used in the retrieval because of instrumental artifacts near the edge of the available spectrum; hence the usable spectral range of the spectrometer is 22.035 to 22.435 GHz. Specifically, the inner 58 FFT channels are used individually, covering the spectrum out to ± 0.87 MHz from line center. Then, on each side of line center, we use 20 FFT channel pairs (out to ± 2.06 MHz), 20 sets of 7 FFT channels (out to ± 6.3 MHz), and 95 sets of 67 FFT channels (out to ± 200 MHz).

[10] We retrieve a water vapor profile from the surface to 100 km, but the measurement has little sensitivity above ~80 km. The retrieval is performed in 1 km increments up to 18 km, except for the first altitude which is set to the 2.3 km elevation of Table Mountain. From 18 km to 100 km water vapor is retrieved in 2 km increments. Since middle atmospheric water vapor changes slowly and over a relatively limited range, the retrieval model makes use of an a priori mixing ratio profile for the middle atmosphere which is constant in time. In the troposphere, which is much more variable, the a priori mixing ratio profile has a 2 km scale height between 2.3 km (the altitude of the site) and 13 km. Since the column optical depth near 22 GHz is primarily caused by water vapor (with a small correction for O_2 based on calculations by *Smith* [1982]), we can scale the a priori profile so that the optical depth matches the total optical depth calculated at that frequency from the tipping measurement. For most retrievals, this scaled a priori provides the tropospheric a priori, and ensures that we are sufficiently close to the solution that the linearity assumed in a noniterative optimal estimation retrieval is appropriate.

[11] If the retrieval does not pass certain criteria the tropospheric a priori is modified. The first criterion is that we require that the total optical depth of the retrieval differs from the optical depth calculated from the tipping measurement by no more than 0.005 (the estimated uncertainty in the average tropospheric optical depth for a single day; ~10% of a typical optical depth). If the retrieved total optical depth minus the optical depth from the tipping measurement is >0.005 (<−0.005) then the scale height of the tropospheric a priori profile is modified by +0.1 km (−0.1 km) until these two optical depths are within 0.005. In a very small number of cases the retrieved mixing ratio at the surface becomes negative; in these cases we also modify the scale height by +0.1 km. If the scale height goes above 3.4 km the tropopause is raised by 1 km and the calculation is repeated. The tropospheric mixing ratios in each level are then again scaled so that the total optical depth of the new a priori matches the optical depth of the tipping measurement.

[12] In Figure 1 we show a set of typical averaging kernels for these retrievals based on 24 h of measurements (in this case, 28 January 2009). Each curve represent the sensitivity of the retrieval at a given altitude to changes in water vapor at all other altitudes. Figure 1 (top) shows how water vapor changes at altitudes from 0 to 100 km affect the retrievals from 17 to 100 km. At the highest altitudes the measurements are limited by signal-to-noise, resulting in both a decrease in sensitivity and a broadening of the vertical resolution.

[13] The sensitivity improves down to ~26 km, at which point the 400 MHz bandwidth of the instrument begins to limit the ability to measure to lower altitudes. Also shown in Figure 1 (top) is the total measurement contribution to the retrieved mixing ratio, calculated using the equation $\Sigma j A_{i,j} (x_a)_j / x_i$ [*Connor et al.*, 1991]. The retrieval has <10% sensitivity to the a priori in the altitude range from 26 km to 62 km. Retrieval sensitivities above 62 km are primarily signal-to-noise limited and can therefore be increased by longer measurement integration, however above ~80 km the Doppler broadening of the line becomes comparable to the pressure broadening, and it is no longer possible to obtain altitude profile information from this measurement technique.

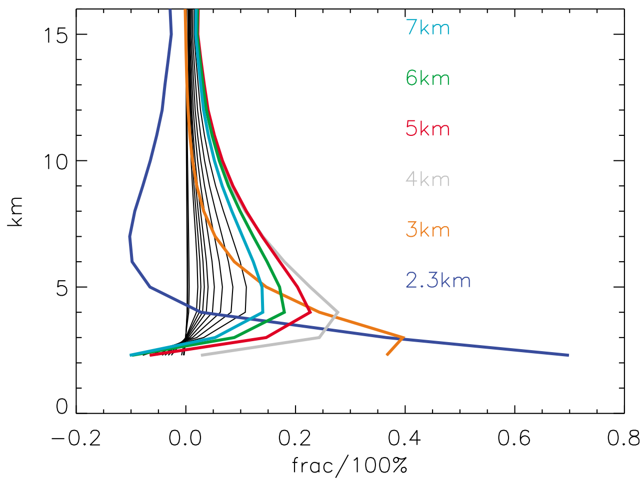

Figure 2. Sensitivity of the retrievals for 24 h of WVMS measurements on 28 January 2009. The response is calculated from the surface to 18 km for perturbations of 100% at each altitude from 0 to 16 km.

[14] As Figure 1 shows, the sensitivity of the stratospheric retrieval to changes in the troposphere of ~1 ppmv is very small, but water vapor in the troposphere is much more variable than in the stratosphere, both in a relative and in an absolute sense, so daily changes are $\gg$1 ppmv. By using the optical depth calculated from the tipping measurement to estimate the tropospheric a priori, we have incorporated most of this variability in the a priori. However, the same tropospheric optical depth can be obtained with different vertical distributions of water vapor. This distribution is particularly poorly constrained in the upper troposphere, where the contributions of changes in water vapor to the total column optical depth are small. While we do not propose here to accurately retrieve tropospheric profiles, we do need to quantify the effect of the tropospheric profile uncertainties on the stratospheric mixing ratios.

[15] To illustrate how uncertainties in the tropospheric profile can affect the stratospheric retrieval, consider a 100% difference between the a priori water vapor and the true water vapor at 6 km on 28 January 2009 (corresponding to ~560 ppmv increase). Such an increase would increase the column optical depth by only 0.0015 (~3% of the total optical depth). This is comparable to our estimated uncertainty in column optical depth from the tipping measurement (~0.005 on a typical day). In terms of the spectrally flat component of the tropospheric absorption of the middle atmospheric signal, a ~0.0015 change in the total column would have a negligible (<1%) effect on the middle atmospheric mixing ratio. However, the emission from this perturbation is not completely spectrally flat, and retrievals in the lower stratosphere are especially sensitive to such tropospheric variations. Figure 1 (bottom) shows the level of sensitivity of the stratospheric retrievals to changes of 100% in tropospheric water vapor at each level, so the curve labeled 20 km represents the sensitivity of the 20 km retrieval to a doubling of the mixing ratio at each of the altitudes shown on the *y* axis. These averaging kernels are calculated after the tipping measurement has been used to determine the tropospheric a priori profile. Unlike the averaging kernels for stratospheric perturbations, which are at least qualitatively similar to averaging kernels determined for any 22 GHz water vapor measurement [e.g., *Deuber et al.*, 2005; *Nedoluha et al.*, 1995], the averaging kernels for tropospheric perturbations will be sensitive to the uncertainty estimates based on local tropospheric conditions, and could vary greatly from site to site.

[16] Having estimated the sensitivity of the stratospheric retrievals to tropospheric uncertainties, we need to estimate the size of these tropospheric uncertainties. In order to estimate how the true water vapor profiles differ from the tropospheric a priori profiles used in the WVMS retrievals, we compared these a priori profiles with radiosonde measurements. The radiosonde data was taken at Edwards AFB (34.9°N, 242.1°E; ~60 km from Table Mountain) and Vandenberg AFB (34.7°N, 239.4°E; ~270 km from Table Mountain), which provided 168 usable sonde launches from 24 November 2008 to 1 June 2009. The data was obtained through the NOAA/ESRL database (www.esrl.noaa.gov/raobs). From these comparisons, we find that the standard deviation between the WVMS a priori and the radiosonde data in the midtroposphere and upper troposphere is typically ~100% (e.g., ~469 ppmv at 6 km). The 100% perturbations shown in Figure 1 therefore provide a good estimate of the sensitivity of the stratospheric retrievals to typical tropospheric uncertainties.

[17] As is shown in Figure 1, the sensitivity of the lower stratospheric retrievals to 100% perturbations in the troposphere begins to decrease below ~6 km. Also, since these lower layers of the troposphere contain most of the water vapor and hence determine the total optical depth, they are well characterized by the tipping measurement. Hence, most of the stratospheric uncertainty caused by tropospheric errors comes from ~6 km to the tropopause. We therefore estimate our stratospheric uncertainty assuming a correlated error in the tropospheric water vapor of ~100% from 6 to 13 km. If we sum these perturbations we find that the total error in the variations in the 26 km water vapor retrieval caused by variations in the troposphere is ~0.22 ppmv (~4%). This source of error can be compared with the formal precision for a daily retrieval (based on the signal-to-noise) in the stratosphere and lower mesosphere of ~1.5–2% (1σ). With respect to measurements of long-term change the variations in the upper tropospheric water vapor would not be expected to significantly affect calculations of trends at ~26 km, since any long-term changes in upper tropospheric water vapor will certainly be much smaller than the 100% uncertainty assumed here.

[18] The total column water vapor measurements from this WVMS instrument have been validated by *Leblanc et al.* [2010] for the NASA MOHAVE 2009 campaign, and show agreement in integrated precipitable water vapor of ~0.5 mm (~5%). Since the averaging kernels are calculated after having determined the tropospheric optical depth, they represent the ability to retrieve differences in profile shape after having fit for the tropospheric column. In Figure 2 we show averaging kernels for retrievals from the surface to 18 km. The kernels clearly change shape between the 2.3 km retrievals and those at 4 km, but above this there is only a very slow upward movement in the peak sensitivity which is closer to 4 km for the retrievals from 4 to 7 km, and is closer to 5 km for retrievals from 8 to 18 km. Thus, only between the surface and ~5 km is the tropospheric retrieval sensitive to variations

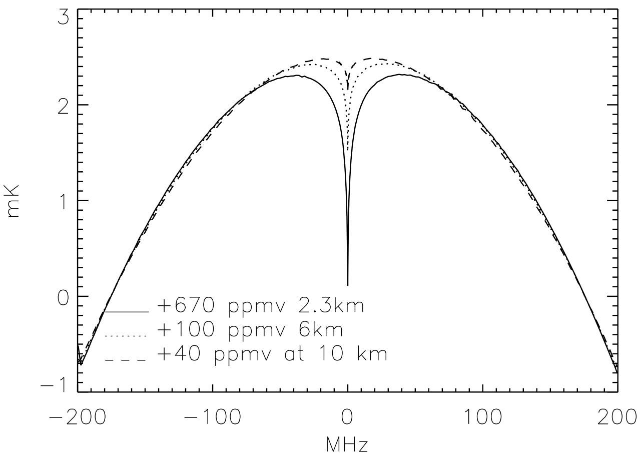

Figure 3. The effect of three different mixing ratio perturbations at several altitudes. Results are shown for signal minus reference spectra from which a linear baseline has been removed. While these three tropospheric perturbations have similar shapes over most of the spectrum, they differ greatly near line center in their absorption of the middle atmospheric signal.

in the shape of the vertical tropospheric profile away from the 2 km scale height used in the a priori.

[19] In order to better understand Figure 2, we show in Figure 3 the effect of water vapor perturbations in the troposphere on the spectrum observed by the WVMS instrument. Because the WVMS spectrum is obtained from the difference between the measurements in the signal and reference positions, it retains no useful information on the absolute power received in either the signal or the reference position measurements. Also, the presence of the absorber bar in the antenna beam is expected to introduce a baseline term which is linearly dependent on frequency. Because of these two effects, a linear baseline is been subtracted from the spectrum used in the retrievals. Without an absolute power measurement a 670 ppmv perturbation in water vapor in the 2.3–3 km layer has a very similar emission spectrum to 100 ppmv at 6–7 km or 40 ppmv at 10–11 km. Given the 400 MHz bandwidth of the WVMS measurements the emissions spectra of water vapor between the surface and ~26 km are nearly indistinguishable from each other. However, changes in water vapor at different altitudes within this range which produce similar spectra will differ in their absorption of the signal from the middle atmosphere. These differences in absorption are most pronounced in the lowest troposphere, since the large amount of water vapor in these levels dominates the total tropospheric optical depth. In the retrievals we have assumed an a priori uncertainty which is proportional to the mixing ratio in the lower and midtroposphere, hence these lower levels allow for the largest adjustment in mixing ratio which enables the retrieval to best match both the total optical depth measurement and the spectral measurement.

[20] Although Figures 2 and 3 suggest that the WVMS instruments can provide some information about the tropospheric profile shape, it has not yet been possible to confirm this with radiosonde validations. Both the mean and standard deviations of the differences between the WVMS and radiosonde retrievals are very similar to those between the WVMS and radiosonde retrievals when a 2 km scale height is assumed and the profile is scaled to fit the tipping measurements. For example, at 6 km the standard deviation between the radiosondes and the WVMS retrievals is ~464 ppmv (as compared to ~469 ppmv when assuming a 2 km scale height), and the mean difference is ~107 ppmv (as compared to ~106 ppmv when assuming a 2 km scale height). While these statistics do not show any tropospheric profile shape measurement capability, there is some similarity in the change in the seasonal cycle with respect to altitude. While neither the microwave measurements nor the radiosonde measurements showing any clear seasonal cycle at 2.3 km over the 5 months shown, at 6 km the water vapor mixing ratios from both sets of measurements tend to be lowest in February/March. A full validation of the ability of the WVMS instruments to measure the shape of the tropospheric profile will clearly require a large number of much more closely coincident measurements. Of course, deployment at a lower altitude site with larger tropospheric optical depths would probably improve the ability of the WVMS instruments to measure tropospheric profile shapes, but at the loss of measurement capability in the middle atmosphere.

[21] While we cannot fully validate the WVMS tropospheric profile shape retrievals, the comparisons with radiosondes do suggest that the tropospheric retrievals are not physically unreasonable. This is particularly important since we must retrieve tropospheric mixing ratios together with middle atmospheric mixing ratios, and unphysical tropospheric retrievals could indicate that variations in the instrumental baseline or in the stratospheric retrievals are being retrieved as incorrect tropospheric mixing ratios. Since the retrieved mixing ratios in the troposphere are similar to the a priori mixing ratios, we conclude that the error estimates presented above for the effect the troposphere on the lower stratosphere are reasonable.

[22] In Figure 4 we show a measurement and retrieval from 28 January 2009. The residual (modeled spectrum – measured spectrum) shown over the 400 MHz baseline clearly shows that there is a baseline component that cannot be fit by the modeled spectrum. The residuals become progressively less noisy away from line center, as larger numbers of channels are grouped together as was described above. This is a midwinter retrieval and the altitude of the peak of the mixing ratio near the stratopause is typical for this season at Table Mountain [*Nedoluha et al.*, 1998]. As was shown in Figure 1, the retrieval is dominated by the measurement from ~26–62 km.

[23] The retrieval in Figure 4 shows a case where the tropospheric profile deviates from the 2 km scale height of the a priori. As was shown in Figure 2, the measurement is sensitive to variations in the tropospheric profile shape in the lower troposphere, but in the upper troposphere the retrieval returns to the a priori. For the retrieval shown in Figure 4 a retrieved optical depth with a 2 km scale height which matches the optical depth calculated from the tipping curve would result in a spectral residual similar in shape to the broad component which is seen in the three curves shown in Figure 3. The retrieved profile for this date therefore has both a <2 km scale height and a retrieved zenith optical depth (0.0314) which is slightly smaller than the optical depth obtained from the tipping measurement (0.0328).

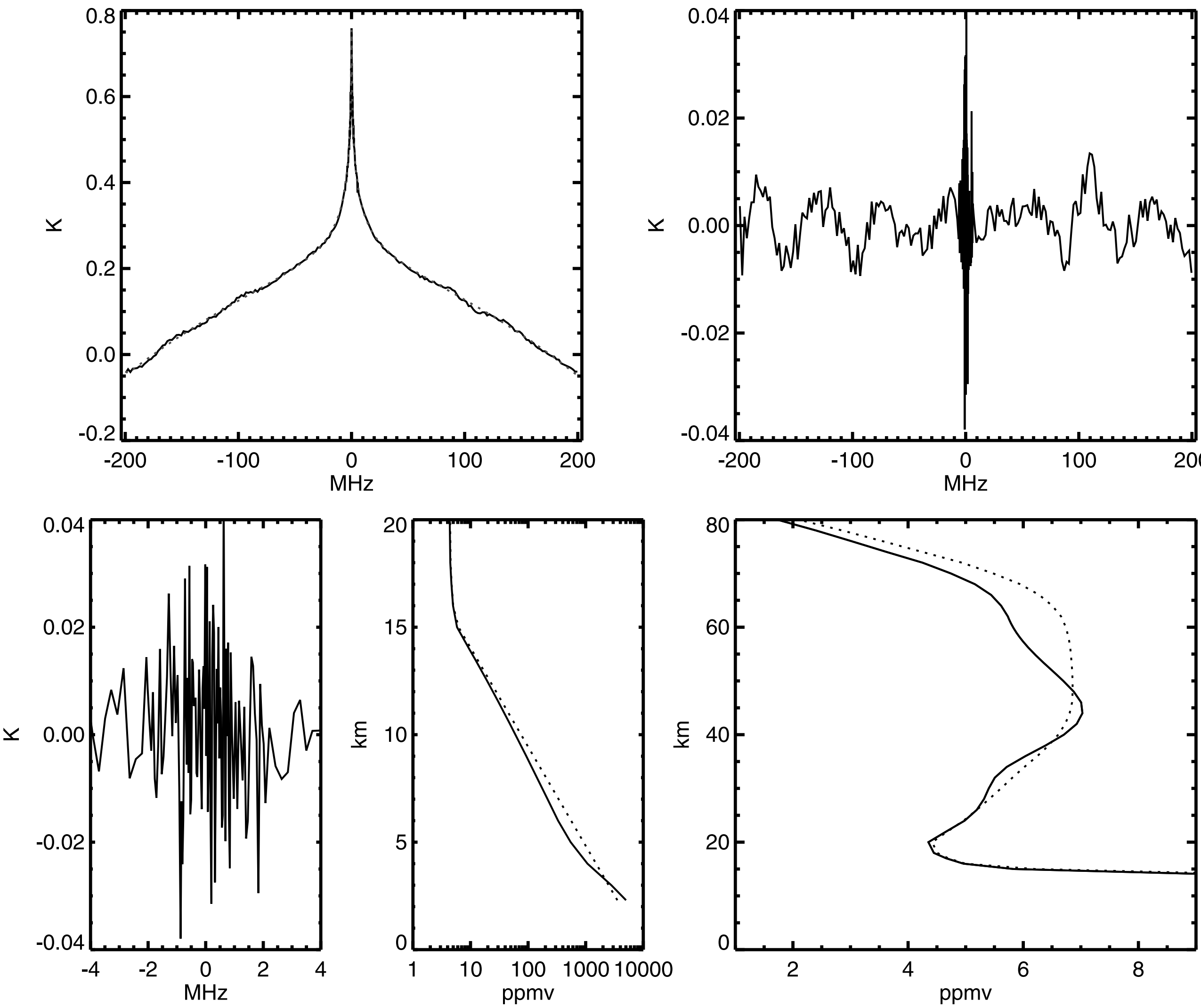

Figure 4. Spectrum (signal minus reference measurement) and retrieval from 28 January 2009. (a) The measured (solid curve) and (nearly indistinguishable) modeled spectrum (dotted curve). (b) The residual (model-measurement) for the ±200 MHz spectral range used in the retrieval. The residuals near line center are noisier because fewer FFT channels are grouped together in this region of the spectrum (see text). (c) Detail of the residuals near line center from Figure 4b. (d, e) The retrieval (solid curve) and a priori (dotted curve) for different altitude ranges.

[24] In Figure 5 we show a comparison of the WVMS optical depth calculated from the retrieval and the optical depth calculated from the tipping measurement. Since the optical depth from the tipping measurement is used to calculate the tropospheric a priori for the retrieval, these optical depths should be in good agreement. A consistent bias between these two optical depth measurements could be indicative of either a systematic instrumental baseline problem or a systematic error in the shape of the tropospheric profile, but there is no such clear systematic bias.

4. Stability of Averaging Kernels and Instrumental Baselines

[25] In previous studies with WVMS measurements we have assumed a baseline error and hence have limited the lower altitude sensitivity of the WVMS retrievals. Here we have not assumed a baseline uncertainty, and we have also (with the exception of the removal of an overall slope across the spectrum) not employed the commonly used technique of fitting either sine waves or polynomials as baseline components [e.g., *Forkman et al.*, 2003].

[26] Although we have not heretofore assumed a baseline error (except for the subtraction of the linear baseline term), instrumental baseline components certainly are present in the WVMS measurements, as is apparent from the periodic variations in Figure 4. For a given retrieval the addition of a baseline error term to the fit may result in a more optimal retrieval in the midstratosphere and lower stratosphere. However, fitting for baseline components in the retrieval complicates the interpretation of variations in the midstratosphere and lower stratosphere, since geophysical variations may be fit by a variation in the instrumental baseline. Figure 6 shows the contribution of the measurement (defined as in

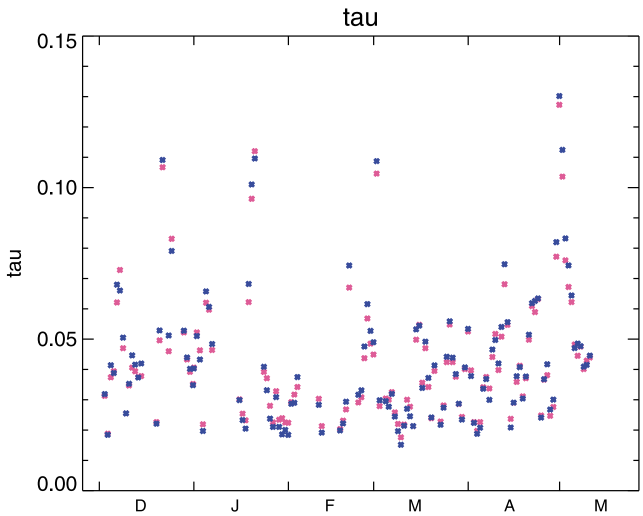

Figure 5. Total column optical depth as calculated from the WVMS spectral retrieval (blue) and from the tipping measurement.

Figure 1) for the 128 days retrieved here over a range of altitudes. The black crosses show the values for the retrieval without a baseline fit. The variation in the contribution of the measurement does decrease somewhat with increasing optical depth, but at 26 km the measurement contribution is >75% for 112 of the 128 measurements.

[27] The red crosses show the measurement contribution for a retrieval in which two sine-wave baseline terms have been included in the retrieval. As Figure 6 shows, the inclusion of a baseline fit in the retrieval generally reduces the measurement contribution in the lower stratosphere, and this effect is highly variable from day to day. Thus, daily comparisons with other instruments should be made with varying averaging kernels, making the comparisons difficult to interpret. Note that for higher-altitude retrievals, the choice of whether or not to include baseline terms makes little difference in the measurement contribution.

[28] Figure 7 shows why in some cases at 26 km the measurement contribution is affected by the baseline, while in other cases the measurement contribution to the mixing ratio retrieved at 26 km remains high. In cases where the baseline period is much shorter than the spectral range of the measurement, the baseline fit does not affect the retrieval because these shorter-period sine-wave terms which have multiple oscillations across the measured spectrum cannot be caused by atmospheric emissions. So in this case the inclusion of the baseline terms will result in smaller spectral residuals, but will have little effect on the retrieved atmospheric profile. Baselines with periods >200 MHz, however, can be fit by changing the water vapor profile, so spectral components with periods >200 MHz are partly fit by atmospheric variations and partly by baseline variations. As is shown in Figure 7, the amplitudes of the baselines increase when the periods exceed ~200 MHz, suggesting that the baseline is partially fitting atmospheric terms. We therefore conclude that, if these WVMS measurements are to provide useful retrievals of water vapor in the midstratosphere and lower stratosphere, then this must be done without including a baseline fit in the retrieval.

[29] We emphasize that this does not mean that there may not be situations for which a sine-wave baseline fit should be

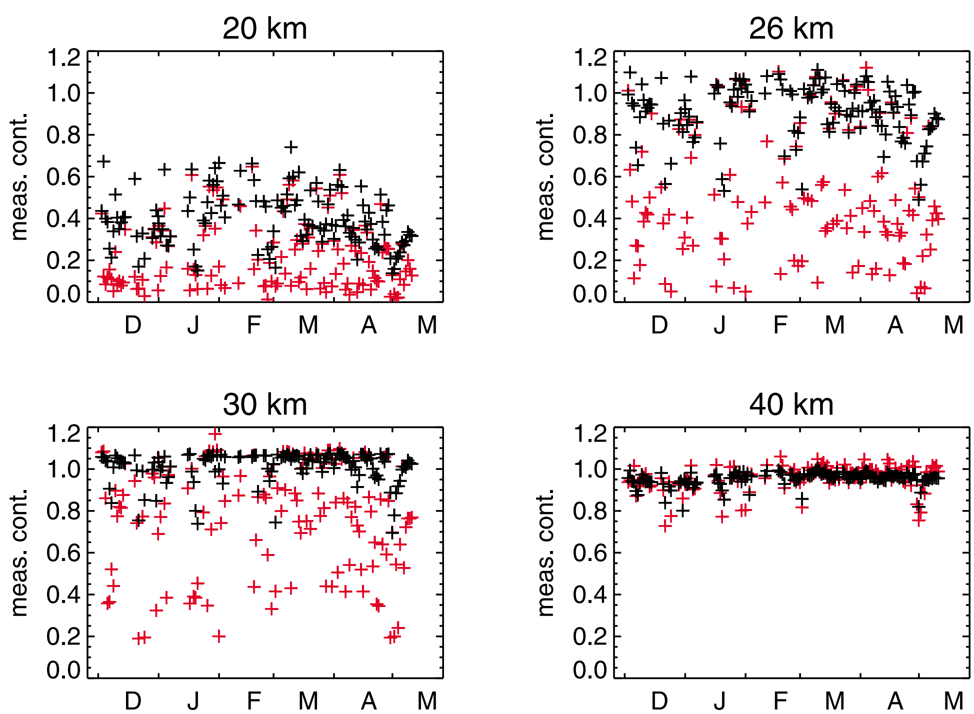

Figure 6. The contribution of the measurement at a given altitude (as defined in text) for daily retrievals from December 2008 to May 2009. Results are shown for without a baseline fit (black crosses) and for retrievals with a baseline fit (red crosses). Values near 1.0 indicate a measurement-dominated retrieval, while values near 0.0 indicate that the retrieved value is determined by the a priori mixing ratio profile.

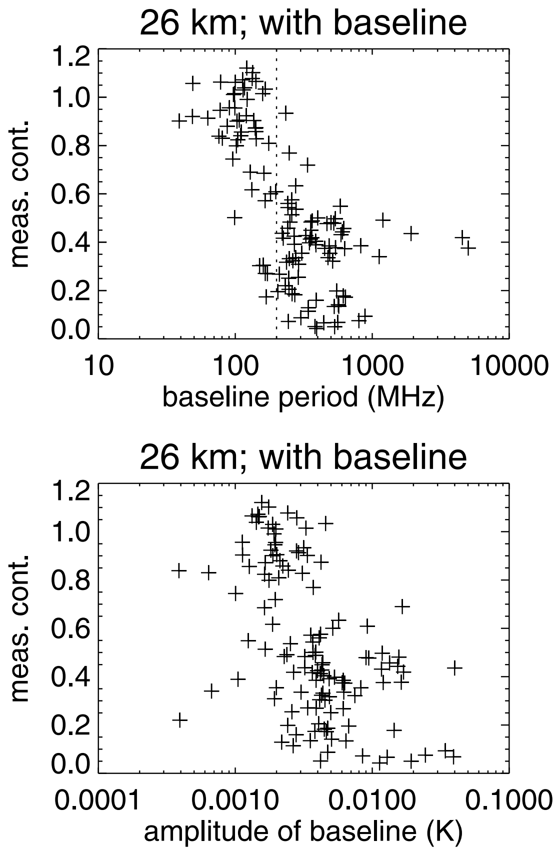

Figure 7. (top) The contribution of the measurement to the daily retrievals at 26 km from the baseline fit case in Figure 6. The measurement contribution is shown as a function of the longer of the two retrieved baseline periods. (bottom) The measurement contribution as a function of the amplitude of this baseline term.

included as part of a ground-based microwave retrieval, especially if there is a consistent and physically understood instrumental baseline component. However, if the period of such a fit is such that the spectral variations can be fit by atmospheric terms, then the effect of this fit on the sensitivity of the retrieval must be characterized. This requires that the baseline fit must be included as part of the optimal estimation routine, and must not be performed as part of a preretrieval data conditioning process.

5. Comparisons With Aura MLS in the Stratosphere and Mesosphere

[30] 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 in the work of *Nedoluha et al.* [2007, 2009] showed good agreement in temporal variations with the WVMS measurements at Mauna Loa and Lauder from 2004 through early 2008.

[31] In Figure 8 we show the average of the coincident WVMS and the MLS profiles convolved using the kernels shown in Figure 1. The WVMS retrievals and the convolved MLS retrievals are calculated with the same a priori, which is held constant in the middle atmosphere (shown in Figure 4). Each coincidence is calculated using a single WVMS retrieval and all MLS retrievals within ±2° latitude and ±10° longitude of Table Mountain taken within 1 day of the average time of the WVMS retrieval. This leaves only 2 of the 128 daily WVMS retrievals without matching MLS profiles. The ~5% average difference from 50 to 70 km is typical of WVMS-satellite retrievals, and is consistent with expected overall errors in calibration and pointing of the WVMS instrument. Such errors would be expected to remain nearly

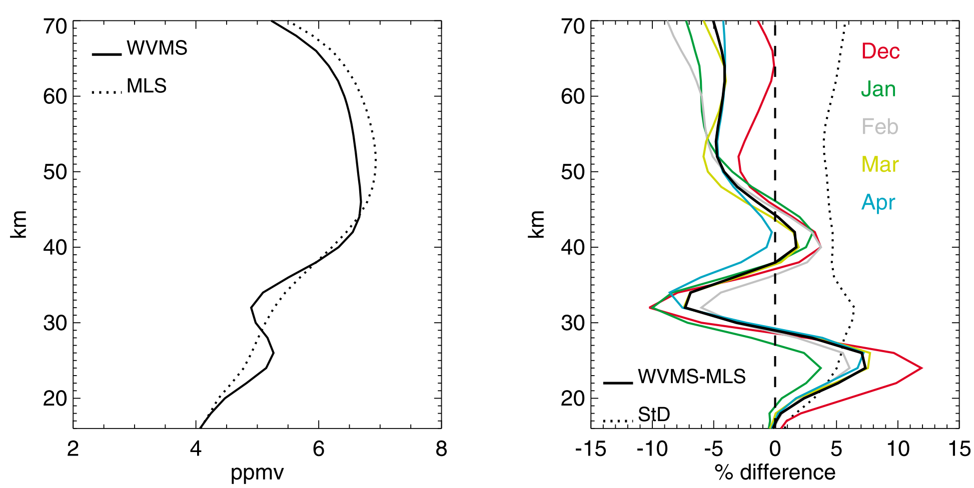

Figure 8. (left) The average WVMS (solid curve) and MLS (dotted curve) profiles for the period 2 December 2008 to 11 May 2009. (right) The fractional difference of the average WVMS and MLS profiles (solid curve) and the standard deviation of the daily differences. Also shown are the average differences for each month.

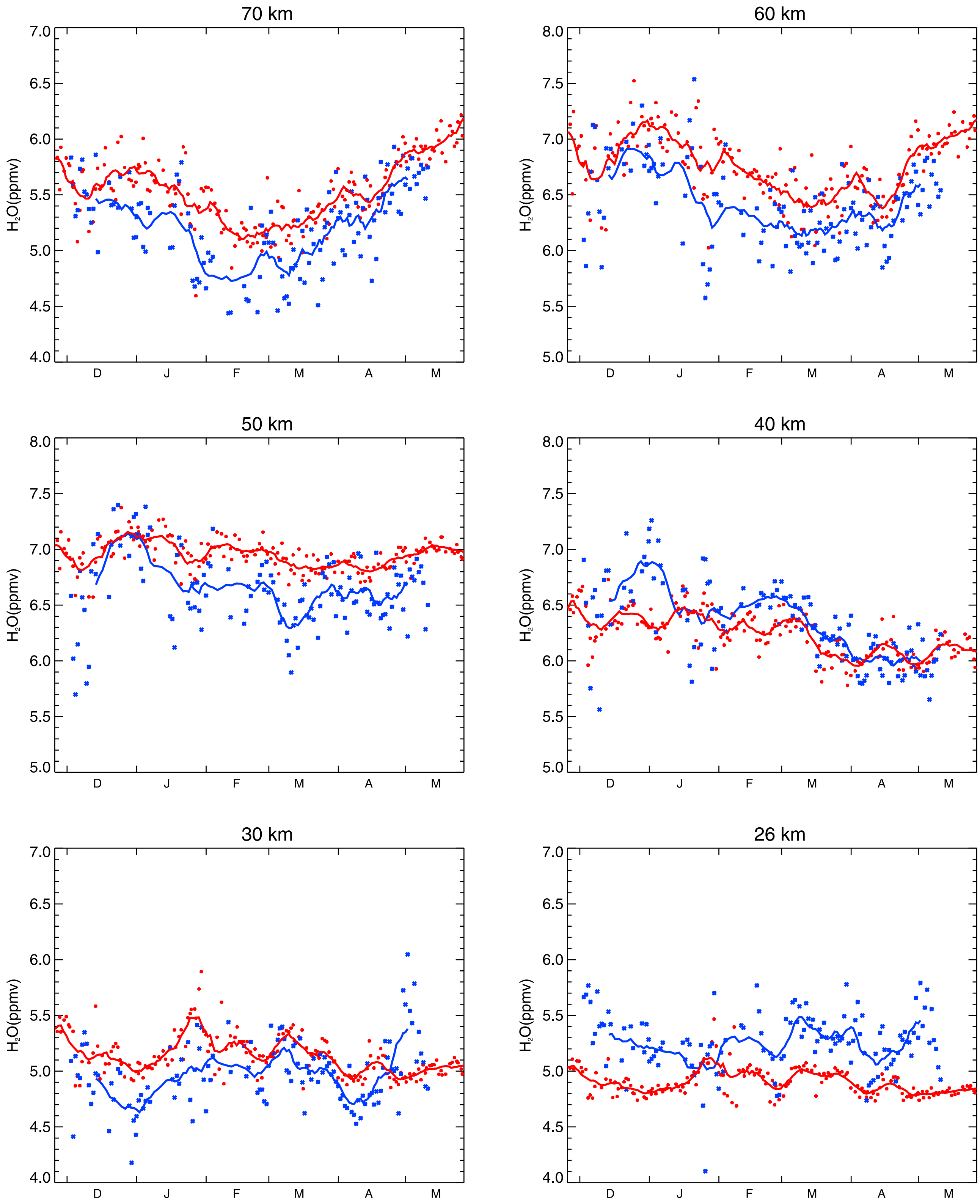

Figure 9. WVMS (blue) and convolved MLS (red) daily retrievals in the middle atmosphere over Table Mountain from December 2008 to May 2009. The lines show a 10-point smoothing.

constant over long periods, as was shown by *Nedoluha et al.* [2009].

[32] The oscillatory structure in the lower stratosphere is probably indicative primarily of an instrumental baseline in the WVMS measurements. This structure can be significantly reduced by allowing the retrieval to fit for the instrumental baselines, but, as discussed above, this comes at the cost of reduced and variable sensitivity in the retrievals. In addition

to the grand average coincident differences, we also show the differences for each month (each with between 15 and 30 WVMS retrievals). This shows that, while there is an overall bias between WVMS and MLS, the variation in difference profiles is generally consistent from month to month. This stability is encouraging, as it suggests that the instrumental baseline problem that is probably causing this oscillation is reasonably stable. Also shown is the standard deviation based on the daily WVMS retrievals for the entire comparison data set. The decrease in the standard deviation and the biases between 26 km and 16 km is caused by the decreasing measurement contribution below this altitude, which results in the convolved MLS profiles being drawn toward the WVMS a priori.

[33] In Figure 9 we show the daily water vapor in the stratosphere and mesosphere from MLS and WVMS. Here the MLS profiles are convolved daily averages of all retrievals within ±2° latitude and ±10° longitude of Table Mountain. In the mesosphere both instruments show the expected seasonal variations. The 70 km retrievals from both instruments show the effects of the descending peak of the water vapor profile, reaching a minimum in February/March, but these daily retrievals have a significant a priori dependence as can be seen from Figure 1. Note that most studies with mesospheric WVMS measurements use ~1 week integrations in order to reduce this a priori dependence. While there are some small consistent biases between the convolved MLS and WVMS retrievals, the variations over the season, and even some of the ~weekly-scale features are quite similar, although there are certainly some inconsistencies such as the increase that occurs in the WVMS retrievals (but not in the convolved MLS retrievals) at 40 km and 50 km at the end of December. At 30 km both instrument show a small, but similar, seasonal variation. At 26 km the variations are even smaller than at 30 km, and only 1 of the 128 WVMS retrieved mixing ratios at 26 km is outside the range 4.6–5.8 ppmv. Since, as is shown in Figure 1, there is very little a priori dependence at 26 km, this small variation shows the stability of the WVMS instrument. This stability must be maintained over an extended period in order to make it possible to detect long-term changes such as the ~0.3 ppmv decrease in water vapor mixing ratio which occurred in the stratosphere in 2001 [*Randel et al.*, 2004].

6. Discussion

[34] Microwave radiometry has been used to make continuous, long-term measurements of water vapor in the mesosphere and upper stratosphere since the early 1990s. Extending these measurements into the midstratosphere and lower stratosphere is difficult because retrievals at these lower altitudes are extremely sensitive to small changes in the instrumental baseline. In order to ensure the precision of such retrievals we therefore need to maintain an extremely stable baseline, and need to be able to adequately monitor this baseline.

[35] The incorporation in a WVMS instrument of an FFT spectrometer which provides measurements every 30 kHz over a ±200 MHz bandwidth extends the altitude range of the WVMS measurements from the current ~40–80 km range (where a multiday integration is needed for retrievals at the highest altitudes) to ~26–80 km. We have shown that, at this high-altitude site, errors in the daily retrieval at ~26 km caused by variations in the troposphere are ~4%. While an FFT spectrometer does provide the ideal instrumental back end for retrievals in the midstratosphere and lower stratosphere, the incorporation of such a spectrometer does not guarantee that such measurements will be sufficiently stable to provide a useful measure of variability at these altitudes. This study has shown that, over a 5 month period, this WVMS instrument was sufficiently stable to provide retrievals down to 26 km which, while biased (~7%) relative to retrievals from Aura MLS, remained stable relative to the Aura MLS retrievals over this period.

[36] Given correct error estimates, the technique of simultaneously fitting instrumental baseline terms together with water vapor mixing ratios in the retrieval will provide an optimal solution for a single profile. However, it has been shown that this technique is problematic when interpreting variability in the lower stratosphere. We concluded for this data set that, in order to understand variations in this region, we must not include fits for the instrumental baseline in the retrieval.

[37] In the coming years we plan to replace the existing WVMS instruments with these improved instruments. This will not only make it possible to begin to provide long-term change information at ~26 km, but will also, to the extent that even measurements in the upper stratosphere are affected by instrumental baseline components, improve the stability of the retrievals in the upper stratosphere.

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