JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 102, NO. D14, PAGES 16,647–16,661, JULY 27, 1997

A comparative study of mesospheric water vapor measurements from the ground-based water vapor millimeter-wave spectrometer and space-based instruments

Gerald E. Nedoluha,[1] Richard M. Bevilacqua,[1] R. Michael Gomez,[1] William B. Waltman,[1] Brian C. Hicks,[1] D. L. Thacker,[2] James M. Russell III,[3,4] Mark Abrams,[3] Hugh C. Pumphrey,[5] and Brian J. Connor[6]

Abstract. We compare water vapor measurements from the Naval Research Laboratory ground-based Water Vapor Millimeter-wave Spectrometer (WVMS) instruments with measurements taken by five space-based instruments. For coincident measurements the retrievals from all of the instruments show qualitatively similar altitude profiles. The retrieved mixing ratios from most instruments generally differ from an average calculated using retrievals from all of the instruments by <1 ppmv at most altitudes from 40 km to 80 km. Comparisons with the Microwave Limb Sounder (MLS) and the Halogen Occultation Experiment (HALOE) allow for the validation of observed temporal variations. The observed variations show similar annual and semiannual cycles. A comparison of several years of data from HALOE and WVMS also shows that the instruments are detecting similar interannual variations. A regression analysis of the WVMS and HALOE data sets shows that the observed variability is consistent within the estimated errors in the mesosphere and that in the upper stratosphere, where the natural variability is small, there is a positive correlation between the WVMS and the HALOE data.

1. Introduction

The timescales for chemical processes and transport make water vapor an ideal tracer of atmospheric transport. The primary sources and sinks are well understood and allow for the tracing of both altitudinal and latitudinal motion. Accurate measurements of water vapor can therefore provide useful constraints on middle atmospheric transport models [*Bevilacqua et al.,* 1990, *Nedoluha et al.,* 1996].

The Naval Research Laboratory ground-based Water Vapor Millimeter-wave Spectrometer (WVMS) instruments have been measuring middle atmospheric water vapor nearly continuously since January 1992. Measurements are made from two sites of the Network for the Detection of Stratospheric Change (NDSC). During these years there has been a tremendous increase in the available data on water vapor in the middle atmosphere. In addition to the WVMS measurements, contributions to this water vapor data set come from instruments aboard the Upper Atmosphere Research Satellite (UARS), including the Halogen Occultation Experiment (HALOE), the Microwave Limb Sounder (MLS), and the Improved Stratospheric and Mesospheric Sounder (ISAMS). Middle atmospheric water vapor measurements have also been made by instruments flown on the three NASA Atmospheric Laboratory for Application and Science (ATLAS) Spacelab shuttle missions, including the Millimeter-wave Atmospheric Sounder (MAS) and the Atmospheric Trace Molecule Spectroscopy Experiment (ATMOS).

In this paper we compare the WVMS measurements with several sets of space-based measurements. Opportunities exist during the ATLAS flights to make comparisons of coincident measurements between the WVMS instrument and as many as four space-based instruments. Such snapshot comparisons provide the best opportunity to estimate the true altitude dependence of a typical water vapor distribution. These comparisons also provide a good opportunity to estimate the accuracy of individual measurements.

In addition to these snapshot comparisons, we present time series comparisons between measurements from the UARS-based instruments and the ground-based measurements. These provide an opportunity to compare the observed variations in the water vapor profiles. In particular, comparisons between HALOE and WVMS are of great interest, as they allow for the study of several years of simultaneous measurements. Such comparisons help to ensure not only the accuracy of the observed seasonal variations but are also crucial in establishing a baseline from which long-term variations can be monitored.

2. The WVMS Instruments

The WVMS instruments make high spectral resolution measurements at 22.2 GHz, the emission frequency of the 6_{16}-5_{23} rotational line of H2O. Each WVMS instrument measures

[1]Remote Sensing Division, Naval Research Laboratory, Washington, DC.
[2]Interferometrics Inc., Vienna, Virginia.
[3]NASA Langley Research Center, Hampton, Virginia.
[4]Now at Hampton University, Hampton, Virginia.
[5]University of Edinburgh, Edinburgh, United Kingdom.
[6]National Institute of Water and Atmospheric Research, Lauder, New Zealand.

Paper number 97JD01095.
0148-0227/97/97JD-01095$09.00

the spectrum using several filterbanks, with the filters evenly spaced at frequencies symmetric about 22.2 GHz. The WVMS1 spectrometer contains twenty 200 kHz filters, twenty 2 MHz filters, and ten 40 MHz filters. The WVMS2 spectrometer contains ten 50 kHz filters, twenty 200 kHz filters, thirty 2 MHz filters, and thirty 14 MHz filters. None of the results shown here include measurements from the 14 and 40 MHz filters due to uncertainties in the baseline. The instruments operate 24 h/d, with interruptions only for maintenance, system failure, and tests. Details of the instrument and measurement techniques are presented by *Nedoluha et al.* [1995] and by *Thacker et al.* [1995].

The water vapor profiles shown here are obtained from measurements taken at the Jet Propulsion Laboratory (JPL) facility at Table Mountain, California, from January 1992 to October 1992 and from May 1993 to October 1995, and from the National Institute of Water and Atmospheric Research (NIWA) site in Lauder, New Zealand, from November 1992 to April 1993 and from January 1994 to October 1995. Measurements at both sites are nearly continuous during these periods. Details of the deployment history are given in Table 1.

The retrieval of water vapor profiles as a function of altitude (or pressure) relies upon the sensitivity of the observed spectrum to pressure broadening. Data from the National Centers for Environmental Prediction (NCEP; formerly NMC) is used to determine the relationship between pressure, temperature, and altitude up to 1 mbar. Above this altitude the temperature profile as a function of altitude is smoothly merged with the temperature from the MSISE90 model [*Hedin*, 1991]. Hydrostatic equilibrium is assumed everywhere above 1 mbar and is used to calculate a geometric altitude from the NCEP/MSISE90 temperature-pressure relationship.

While the WVMS instruments operate nearly continuously, the sensitivity of retrievals at altitudes above ≈70 km can be significantly improved by integrating the data obtained from several days of measurements. All of the retrievals shown here are therefore obtained from multi-day measurements, incorporating ≈500 scans of ≈15 min each (as in the work of *Nedoluha et al.* [1996]). By integrating data over this time interval, we can attain a signal-to-noise level that allows for useful retrievals up to ≈80 km.

An extended error analysis for the WVMS instrument is given by *Nedoluha et al.* [1995], with some updates by *Nedoluha et al.* [1996]. From these studies we find that the random measurement error component for the retrievals shown here is estimated at 4-7%, with the largest error at the highest altitudes to which the retrieval is sensitive. Uncertainties in instrumental calibration and pointing are found to be the largest source of systematic error in these measurements and introduce an altitude independent error of ≈5-10%. While the pointing and calibration are generally constant over long periods of time, they can change when improvements are made and when an instrument is moved to a new site. The largest change in pointing and calibration apparently occurred after the 1992 Table Mountain campaign. The retrievals from January to October 1992 indicate ~15% less water vapor than those from later measurements. Significant changes in the pointing techniques were introduced following this campaign, and the relative consistency of the retrievals since 1992 suggest that these changes have improved the pointing accuracy of the instrument. Subsequent incremental improvements have been made in both pointing and calibration, and the uncertainty in these parameters is now near the low end of the 5-10% range.

Additional sources of error considered include those resulting from baseline effects, errors in the calculated tropospheric attenuation, and uncertainties in the model used to estimate the atmospheric temperature. These error sources were estimated to contribute an uncertainty of <5% except at altitudes near 40 km, where the baseline effects introduce a somewhat larger error (usually ~5-10%). The total measurement error (assuming that the components add in quadrature) for most of the data is therefore ≈10%, with the smallest errors in the most recent data between ≈50 and 60 km, and the largest errors in the oldest data at the extremes of the 40-80 km retrieval range.

Retrievals from the two WVMS instruments were compared during a 3-month period in 1993 when they were colocated at Table Mountain. In this intercomparison campaign the instruments were able to accurately track changes in middle atmospheric water vapor on weekly timescales. During the last month, when both instruments operated continuously, the differences in the retrieved mixing ratios from simultaneous weekly retrievals were found to be <16% at 40 km and <5% above ≈45 km. The large difference at low altitudes was probably due to an uncharacterized baseline component. The <5% error at other altitudes for individual retrievals suggests that we may have overestimated the random error. This small difference also shows that the systematic difference between the two instruments is smaller than our estimated systematic error. Some of the results of this intercomparison are shown by *Nedoluha et al.* [1996].

In comparing the ground-based results from WVMS with those from the space-based instruments, we require not only an estimate of the errors but also an understanding of differences in the vertical resolution. In Figure 1 we show the averaging kernels for a typical WVMS retrieval. Each curve represents the sensitivity of the retrieved mixing ratio at a specific altititude to perturbations of the atmosphere at all altitudes. As can be seen from the figure, the resolution of the retrievals is much broader than the 2 km grid on which mixing ratios are retrieved, hence the retrieved mixing ratios at adjacent 2 km gridpoints are closely correlated. This oversampling of the atmospheric profile preserves as much of the information in the measurements as possible. The decreasing amplitude of the averaging kernels above ≈80 km and below ≈40 km is an indication of the drop in sensitivity of the retrievals outside this altitude range.

In January 1994 a set of 50 kHz filters was installed in the spectrometer at Table Mountain, thus increasing the spectral resolution by a factor of 4 near line center and thereby increasing the sensitivity of the retrieval to water vapor above ≈70 km. As a result of the increased sensitivity, the retrievals at Table Mountain show a larger seasonal variation above this altitude after January 1994. When comparing with high vertical resolution data sets this effect is taken into account by convolving the high-resolution data with the WVMS averaging kernels (see section 4).

3. Instruments Included in This Study

The WVMS retrievals are compared with retrievals from the HALOE, MLS, and ISAMS instruments aboard the UARS satellite and with the MAS and ATMOS instruments flown on the space shuttle.

3.1. HALOE

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], and a water vapor validation study is given by *Harries et al.* [1996]. HALOE has provided measurements since October 1991, hence the HALOE measurements span the entire range of dates covered by the WVMS experiment. Coincident measurements with the WVMS sites are available at least 10 times per year each for both sunrise and sunset observations. In the absence of any interruption to the data taking process, the intervals between data at the latitudes of the WVMS instruments should be no larger than ≈25 days. The results used here are obtained from retrievals processed with the version 17 production algorithm.

3.2. MLS

The MLS measurements are made using a limb-sounding technique in atmospheric emission [*Barath et al.*, 1993]. The water vapor retrievals are obtained from measurements at 183 GHz and are validated in *Lahoz et al.* [1996]. The results used here are taken from the version 3 retrievals obtained from the Goddard Distributed Active Archive Center. A daily average at each altitude is calculated by averaging coincident measurements for which the diagonal component of the error covariance matrix is <1.5 ppmv. At high altitudes the retrieved mixing ratio will therefore be determined from comparable contributions of the UARS climatology and of the measurement. The MLS team generally recommends that data not be used above 60 km; however, measurements above this altitude contain useful information on the variability of water vapor. Data are available for most of the period from September 1991 to April 1993, at which point the 183 GHz receiver failed. There is a gap in the data from June 3 to July 18 1992, when problems with the solar array limited the number of measurements. Because of the UARS yaw cycle, approximately once a month the MLS measurement range toggles between ≈80°S-32°N and ≈32°S-80°N. Thus until April 1993, measurements coincident with the Table Mountain site are almost always available, but measurements coincident with the Lauder site are only available approximately every other month.

3.3. ISAMS

The ISAMS measurements are taken from the 6.3 µm water vapor emission band. The results shown here are from the 3AT files obtained from the version 8 data on the UARS CDROMs, which provide water vapor mixing ratios for altitudes up to ≈70 km. Only nighttime measurements are included because of significant nonthermal daytime emission at this wavelength. A validation study of the ISAMS water vapor data is given by *Goss-Custard et al.* [1996]. Measurements coincident with the WVMS retrievals at Table Mountain are available from March 27 to June 2, 1992, and from July 19 to July 29, 1992.

3.4. MAS

The ATLAS MAS instrument is similar to the MLS instrument in concept and scientific capability. MAS measures the same microwave water vapor line (183 GHz) as that measured by MLS. A discussion of the MAS water vapor measurements is given by *Hartmann et al.* [1996]. During the ATLAS 1 mission the instrument observed from 40°S to 70°N, thus providing coincident measurements with the WVMS instrument operating at Table Mountain. Measurements were made during the ATLAS 2 flight from 70°S to 70°N, allowing for comparison with the WVMS measurements at Lauder. The instrument suffered a malfunction on the third day of the ATLAS 3 mission, allowing coverage only from 35°S-75°N, hence coincident measurements are available only with the Table Mountain site.

3.5. ATMOS

The ATMOS solar occultation instrument was also flown on the ATLAS space shuttle missions. The water vapor mixing ratio is calculated from spectral lines in the 1360-1980 cm^{-1} range (32-46 µm) [*Gunson et al.*, 1990]. Although the range of latitudes covered by solar occultation measurements during an ATLAS flight is necessarily limited, there are measurements coincident with the ground-based sites during both the ATLAS 2 and the ATLAS 3 mission.

Table 1. Deployment History

Measurement Site	Instrument	Measurement Period
Table Mountain, California (34.4°N, 117.7°W)	WVMS1	January 23 to October 13, 1992
Lauder, New Zealand (45.0°S, 169.7°E)	WVMS1	November 3, 1992 to April 21, 1993
Table Mountain, California (34.4°N, 117.7°W)	WVMS1	May 17 to November 9, 1993
Lauder, New Zealand (45.0°S, 169.7°E)	WVMS1	January 14, 1994 to present
Table Mountain, California (34.4°N, 117.7°W)	WVMS2	August 19, 1993 to present
Table Mountain, California (34.4°N, 117.7°W)	WVMS2 (with 50 kHz filters)	January 7, 1994 to present

WVMS, water vapor millimeter-wave spectrometer

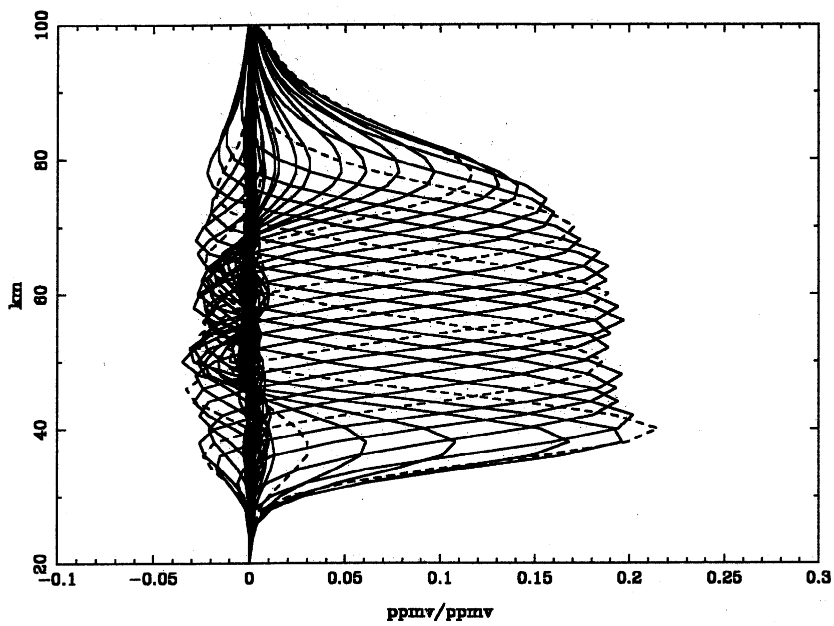

Figure 1. A typical set of averaging kernels for the Water Vapor Millimeter-wave Spectrometer (WVMS) instruments. Dashed lines indicate kernels at 10 km altitude increments. The kernels used in the comparisons are calculated separately for each retrieval.

4. Comparisons During ATLAS Missions

There was at least one WVMS instrument in operation during each of the three ATLAS missions. The WVMS retrievals shown here are obtained from single retrievals obtained by integrating several days of spectra taken during each ATLAS mission. Space-based retrievals are considered to be spatially coincident when the measurement is taken within ±5° latitude and ±30° longitude of the ground-based site. WVMS measurements coincident with the space-based microwave instruments were available during each of the ATLAS missions (except during ATLAS 3 when the 183 GHz receiver on the MLS instrument was no longer operational). ISAMS measurements coincident with the Table Mountain site are available during ATLAS 1; however, the instrument was not operational during the ATLAS 2 and ATLAS 3 missions. Since the occultation measurements necessarily cover a more limited latitudinal range during a given time period, it is not always possible to make a useful comparison with ATMOS. When HALOE measurements near the WVMS sites are not available during an ATLAS mission we show spatially coincident HALOE retrievals that are separated by up to about a week from the other retrievals.

The retrieved water vapor profiles necessarily depend upon the resolution and sensitivity of the observing instrument. In comparing measurements we therefore wish to minimize any differences due to these well-understood instrumental limitations. In order to present a more useful comparison between the WVMS measurements and those of HALOE and ATMOS, we therefore show HALOE and ATMOS results convolved with averaging kernels (**A**) calculated for each WVMS retrieval. In general, the values of the averaging kernels are very similar to those of the typical WVMS averaging kernel shown in Figure 1. The data are convolved using the equation

$$\mathbf{x}_c = \mathbf{x}_a + \mathbf{A}(\mathbf{x}_h - \mathbf{x}_a) \tag{1}$$

[*Connor et al.*, 1994] where $\mathbf{x}_c$ is the convolved profile, $\mathbf{x}_a$ is the WVMS a priori profile, and $\mathbf{x}_h$ is the original high-resolution profile. Such a convolution is appropriate only because the resolution of the HALOE and ATMOS instruments is much higher than that of the WVMS instruments, and because in the altitude range of interest, the HALOE and ATMOS retrievals are nearly independent of any a priori constraints. In comparisons with WVMS retrievals we can therefore treat $\mathbf{x}_h$ as a fully resolved atmospheric profile.

The effect of the convolution on the resolution of the HALOE and ATMOS profiles can be clearly seen in Figure 2. Any features on scales smaller than ≈15 km are not present in the convolved data. Convolving the HALOE and ATMOS profiles with the WVMS averaging kernels also limits the sensitivity of these retrievals at high altitudes. Thus while the retrieved mixing ratios at 80 km in the unconvolved HALOE and ATMOS results are ≈0.5-1 ppmv below the values retrieved by WVMS, this difference may be entirely attributable to the greater high-altitude sensitivity of the HALOE and ATMOS instruments, rather than to a measurement error in any of the three experiments.

We have not attempted to convolve measurements from MAS, MLS, or ISAMS with the WVMS averaging kernels, as these retrievals have a somewhat coarser resolution than the solar occultation measurements. Although the retrievals from these instruments have a higher resolution than the WVMS measurements, it is not clear that the assumptions required for the correct application of (1) are met. It is therefore difficult to quantify the effect of differences in resolution on differences between the MAS, MLS, ISAMS, and WVMS retrievals.

In Plate 1 we show mixing ratio profiles obtained during or near the time of the ATLAS missions. In addition to the profiles we show the fractional differences from the average mixing ratio, which is calculated from all of the profiles

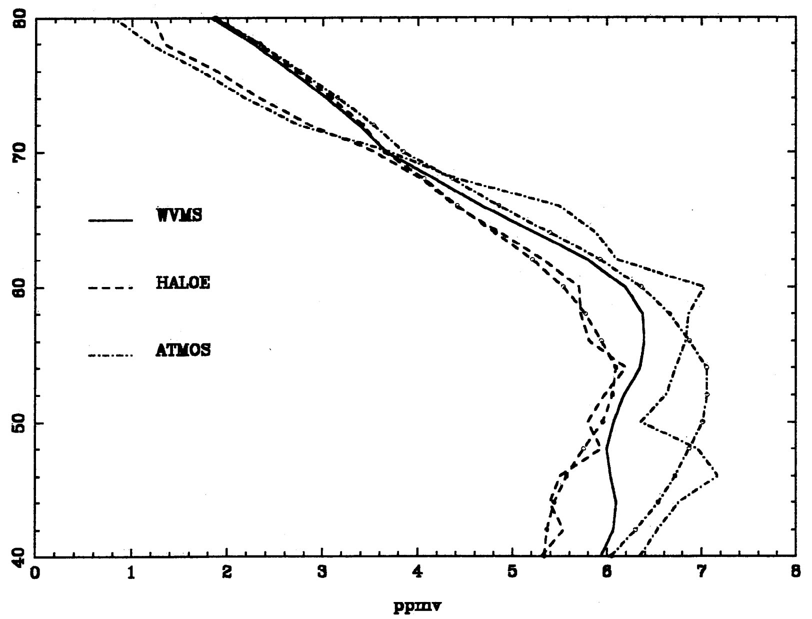

Figure 2. Water vapor retrievals during the period of ATLAS 2 showing the effect of differences in resolution and sensitivity. The Halogen Occultation Experiment (HALOE) and the Atmospheric Trace Molecule Spectroscopy Experiment (ATMOS) profiles are shown both before (line only) and after (line with circles) convolution with the WVMS averaging kernels.

except those of the unconvolved HALOE and ATMOS measurements and those from ISAMS, which do not cover the entire altitude range shown. We also show, at selected altitudes, error bars (1σ) for the total measurement error of the WVMS retrievals.

4.1. ATLAS 1

During the ATLAS 1 mission (March 24 to April 2, 1992) the WVMS 1 instrument was deployed at Table Mountain. Because of severe weather during this period the only good coincident WVMS measurements are from March 24, 29, and 30. The coincident MAS, MLS, and ISAMS profiles shown are taken from retrievals obtained from March 27 to 31. HALOE measurements near the Table Mountain site were made about a week before the ATLAS mission, from March 15 to 17. There is no ATMOS data coincident with the Table Mountain site during this mission.

The WVMS data during this mission is in good agreement with the HALOE and MAS data at most altitudes, while the MLS and ISAMS mixing ratios are generally somewhat larger. Although the profiles retrieved from HALOE, MAS, and WVMS measurements during this period are very similar, we note that the mixing ratios retrieved from WVMS measurements during 1992 at Table Mountain are generally somewhat smaller than those retrieved during subsequent observations.

4.2. ATLAS 2

In Plate 1 we also show the retrievals obtained during the ATLAS 2 mission (April 9-15, 1993) when the WVMS 1 instrument was deployed at the Lauder site. Measurements which fit the criterion for coincidence with Lauder are available from three of the space-based instruments (MAS, ATMOS, and MLS) between April 9 and 11. The HALOE measurements are from April 19 and 20.

The mixing ratios of the five instruments span a range of only ≈1 ppmv over most of the altitudes shown except for the MLS "notch" between 60 and 70 km. The WVMS retrievals are generally near the average for all of the retrievals and never differ from the average by more than 10%.

4.3. ATLAS 3

During the ATLAS 3 mission (November 3-14, 1994) WVMS instruments were operational at both sites, but coincident measurements are available only with the Table Mountain site. In Plate 1 we show HALOE, MAS, and WVMS measurements taken between November 2-4, and ATMOS profiles from November 7-9. In the mesosphere the shapes of the profiles from all four instruments are similar, with the WVMS mixing ratios <13% above the average. The high mixing ratios retrieved from the WVMS measurements at the lowest altitudes are probably due to an unusually large baseline error.

5. Long-term Comparisons Between WVMS and the UARS Instruments

5.1. Long-term Averages and Variability

The availability of a long set of continuous observations from the UARS-based instruments and from WVMS allows us to determine both the magnitude and the variability of the water vapor profiles. In Figure 3 we compare the profiles calculated from HALOE, MLS, and ISAMS retrievals coincident with WVMS measurements. The UARS averages and standard deviations are calculated by averaging all the measurements coincident with each 500-scan WVMS

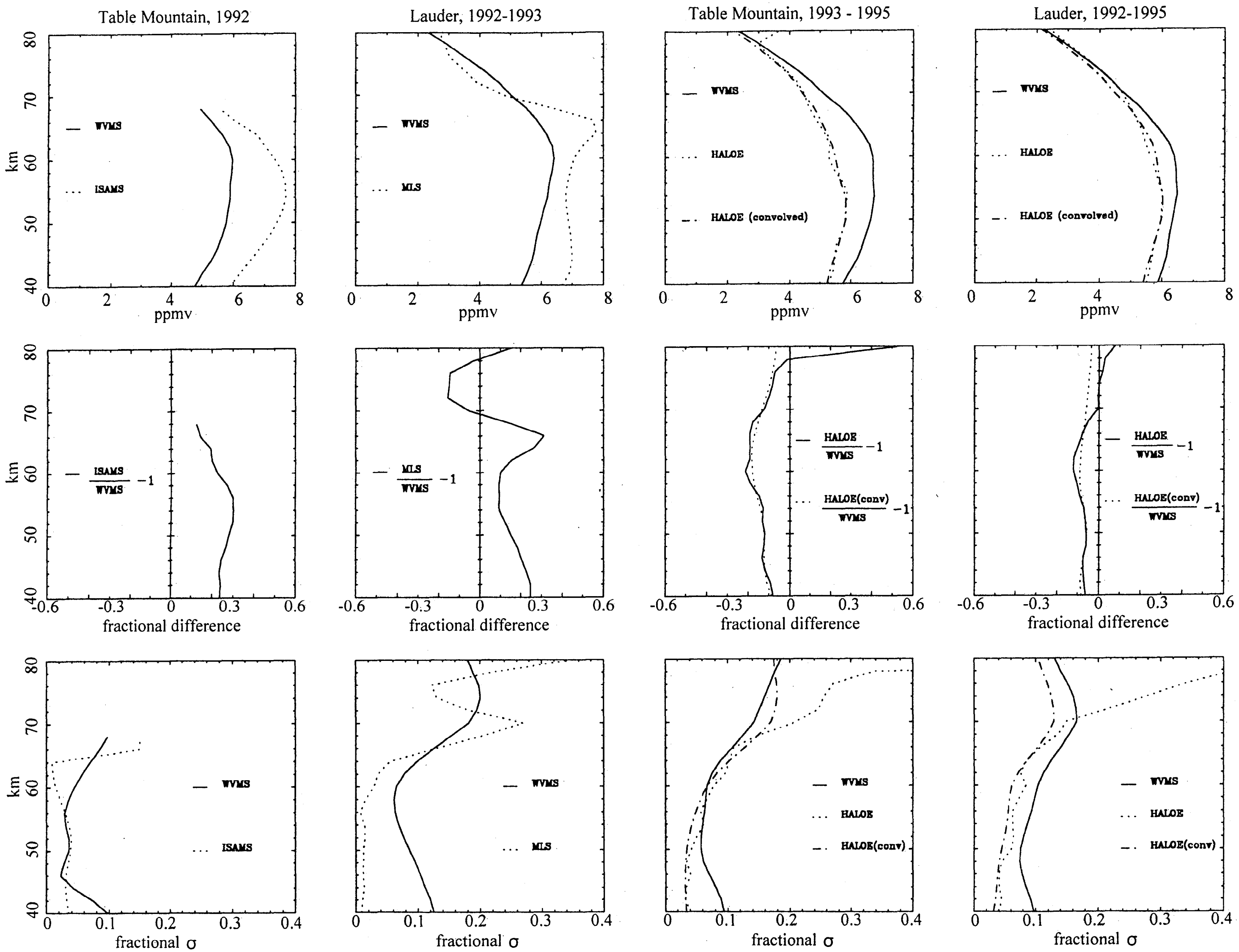

Figure 3. A comparison of sets of retrievals from the HALOE, Microwave Limb Sounder (MLS), and Improved Stratospheric and Mesospheric Sounder (ISAMS) instruments coincident with retrievals from the WVMS instrument. From left to right the panels show comparisons for ISAMS and WVMS from March 27 to June 2, 1992 and July 19-29, 1992, for Table Mountain, MLS and WVMS from November 3, 1992 to April 15, 1992 for Lauder, and HALOE and WVMS at Table Mountain (since May 1993), and at Lauder (since November 1992). (Top) Average profiles from coincident measurements. (Middle) Fractional difference in the average profiles ($\langle x_{UARS}\rangle/\langle x_{WVMS}\rangle$-1). (Bottom) Fractional standard deviations of the retrievals at each altitude. Since only coincident measurements between each UARS instrument and the WVMS instruments are used, the WVMS data points used in the comparison are different for each of the two UARS instruments.

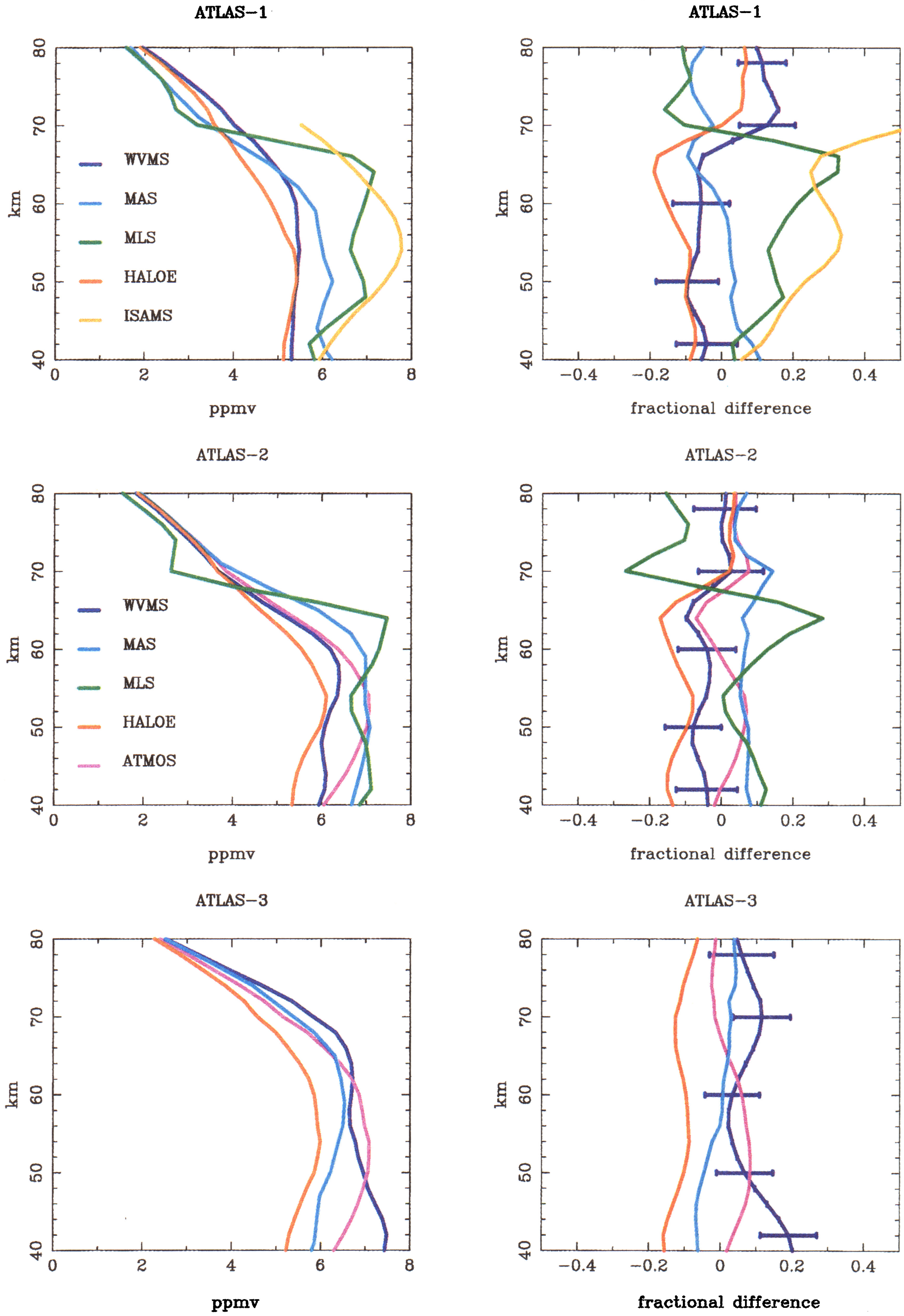

Plate 1. (Left) Water vapor profiles from five instruments during or near the time of the ATLAS missions. The HALOE and ATMOS retrievals shown have been convolved with the WVMS averaging kernels. (Right) Fractional differences $((x_{meas}-x_{avg})/\ x_{avg})$, where x_{avg} is calculated from the average of the profiles shown, but does not include the ISAMS profile. Also shown are 1σ error bars for the total measurement error of the WVMS retrievals at selected altitudes. (Top) Retrievals during ATLAS 1 (March 24 to April 2, 1992) coincident with Table Mountain (34.4°N, 117.7°W). (Middle) Retrievals during ATLAS 2 (April 9-15, 1993) coincident with Lauder (45.0°S, 169.7°E). (Bottom) Retrievals during ATLAS 3 (November 3-14, 1994) coincident with Table Mountain.

retrieval. For the ISAMS comparison we use WVMS data taken from Table Mountain during 1992, while for the HALOE and MLS comparisons, we only use WVMS retrievals obtained since November 1992. The 1992 Table Mountain measurements are the only WVMS measurements available for comparisons with the ISAMS data; however this data set is not used in comparing WVMS retrievals with data from HALOE and MLS because of the larger uncertainty in the systematic error for the WVMS measurements during this period.

The average profiles show that for altitudes below ≈70 km the average mixing ratios retrieved by WVMS are clearly larger than those retrieved by HALOE and smaller than those retrieved by MLS and ISAMS. We note that the ISAMS measurements are compared with the WVMS measurements from 1992 at Table Mountain and that the water vapor mixing ratios retrieved from WVMS measurements during this campaign are ~15% lower than in subsequent years. Part of the difference between ISAMS and WVMS may therefore be due to an error in the pointing of the WVMS instrument in 1992, but over most of the altitude range, the difference is larger than 15%. The difference between the average ISAMS and WVMS profiles is between 24 and 30% from 40 to 58 km and then drops to 12% at 68 km. The decreasing difference between the WVMS and ISAMS retrievals above ≈60 km may be, in part, due to the decreasing sensitivity (and therefore increasing dependence on the a priori profile) of the ISAMS measurements above this altitude.

The difference between the average MLS and WVMS profiles shows a larger variation with altitude than the difference between the average HALOE and WVMS profiles. Most striking is the "notch" in the MLS profiles at ≈65-70 km. The MLS team generally recommends that water vapor retrievals near and above this altitude not be used; however, the higher-altitude retrievals do seem to contain useful information about seasonal variations (see section 5.2).

The shapes of the HALOE and WVMS profiles are remarkably similar. At both sites the peaks in the both convolved HALOE and the WVMS profiles are at 52-54 km. The nearly constant fractional difference between the HALOE and WVMS profiles within the altitude range shown suggests that much of the difference between the two sets of measurements is due to an overall calibration offset. The convergence of the profiles in the upper mesosphere is, in part, a result of the decrease in sensitivity of the WVMS (and convolved HALOE) measurement at high altitudes. The WVMS and convolved HALOE profiles therefore both approach the same a priori profile at these altitudes. The rate of convergence with increasing altitude is, however, faster than that which would result solely from the change in sensitivity. In addition, the fractional difference shows some altitude dependence in the lower mesosphere and upper stratosphere, a region in which there is no significant variation in sensitivity. Thus while much of the difference between the average WVMS and HALOE profiles is probably due to an overall calibration error, there remain systematic differences in the shapes of the profiles that cannot be attributed to such a calibration error. In particular, we note that at both sites the largest difference in the profiles occurs at 60-62 km. This maximum difference occurs because the HALOE profile falls slightly more sharply with increasing altitude above the peak in the profile at 52-54 km.

Figure 3 also shows the variability of the measurements as a function of altitude. At ≈60 km and below, the standard deviation of the WVMS retrievals is larger than that of the UARS instruments. The MLS retrievals show almost no variation at altitudes below 60 km, and then display a sharp increase at altitudes near the "notch." The striking increase in the variability of the ISAMS retrievals above 64 km is primarily due to a sharp increase that occurred in retrievals at all latitudes on April 15. The WVMS variability in the ISAMS comparison is, at most altitudes, smaller than in the other comparisons because of the shorter time period available for coincident measurements. Both the convolved and the unconvolved HALOE retrievals at Table Mountain show slightly more variability than the WVMS retrievals at most altitudes above 60 km, while at Lauder, the convolved HALOE profiles at all altitudes show a standard deviation which is everywhere ≈3-7% less than that observed by WVMS. The WVMS, HALOE, and MLS retrievals all show that there is an abrupt increase in variability with increasing altitude near ≈60 km.

5.2. Seasonal Variations

A detailed study of the seasonal variations observed in the WVMS retrievals and a comparison with transport models is given by *Nedoluha et al.* [1996]. Briefly, the mixing ratio of water vapor above ~60 km is primarily determined by the competition between transport and photodissociation. Vertical transport is generally characterized in terms of advective and diffusive contributions. The upward advective transport at midlatitudes peaks near the summer solstice, thus in a primarily advective atmosphere, mixing ratios above the maximum in the mixing ratio profile should be largest near the summer solstice and smallest near the winter solstice. The diffusive transport rate is thought to increase near both the winter and summer solstice. The presence of diffusive transport would therefore be indicated by a secondary maximum in the water vapor mixing ratio above ~60 km near the winter solstice.

In Figure 4 we show the water vapor mixing ratios retrieved by the HALOE, MLS, and WVMS instruments at 70 km. We also show curves derived by smoothing the data using a Gaussian filter with a (1/e) width of 25 days. The individual HALOE and MLS retrievals shown are derived from daily averages from measurements within ±5° latitude and ±30° longitude of the WVMS sites.

From Figure 4 it is clear that while the solar occultation technique used by HALOE necessarily results in some gaps in the data, there is adequate data to describe the seasonal variations. As in the work of *Nedoluha et al.* [1996], the WVMS retrievals used here are obtained from equal integration intervals of ≈500 scans each, resulting in approximately one retrieval per week when the instrument is operating continuously. During the periods for which the smooth curve is derived, there are no large gaps in the WVMS measurements which are likely to have a significant effect on the measured seasonal variation. Given the high temporal density and small daily variation in the MLS retrievals shown in Figure 4, the 25-day Gaussian filter used to smooth the retrievals is clearly not optimal for estimating the variations measured by MLS. Nonetheless, such a smoothing is helpful in understanding the HALOE and WVMS data sets, hence we also apply it to the MLS retrievals.

The consistency of the amplitude of the HALOE data near Table Mountain from 1992 to 1993 suggests that most of the

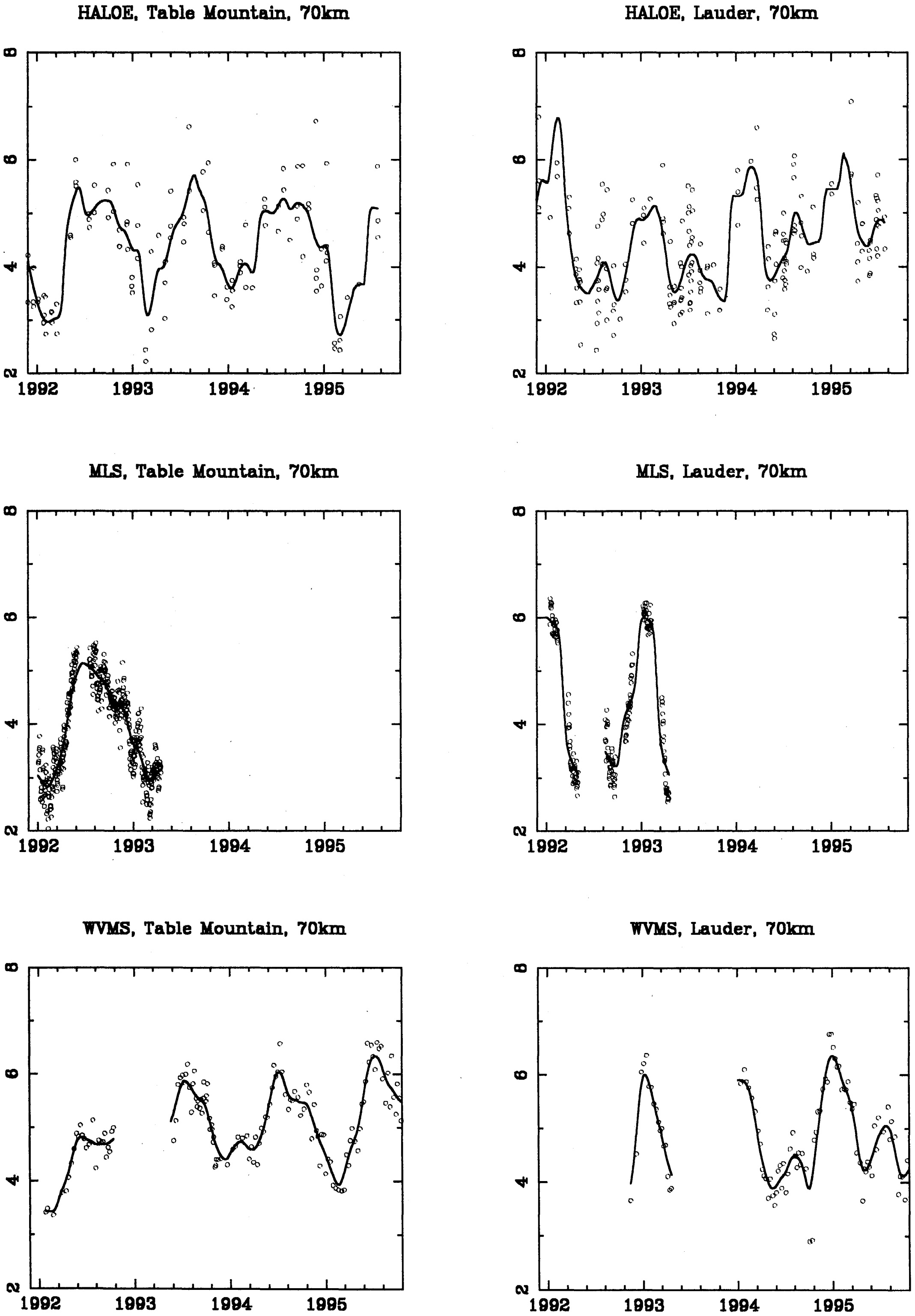

Figure 4. Water vapor retrievals at 70 km from HALOE (top), MLS (middle), and WVMS (bottom). The left-hand (right-hand) panels give measurements coincident with Table Mountain (Lauder). The curves represent data smoothed with a 25-day Gaussian filter.

increase in mixing ratio observed by WVMS between 1992 and 1993 is due to an instrumental change, probably primarily related to an error in the pointing of the instrument in 1992. Such an error would introduce a nearly constant fractional error in the mixing ratios retrieved at all altitudes. Improvements in the pointing of the instrument have been made since the 1992 Table Mountain campaign.

In Plate 2 we show superimposed retrievals from HALOE, MLS, and WVMS at three altitudes smoothed with a 25-day Gaussian filter. All three instruments show a clear annual

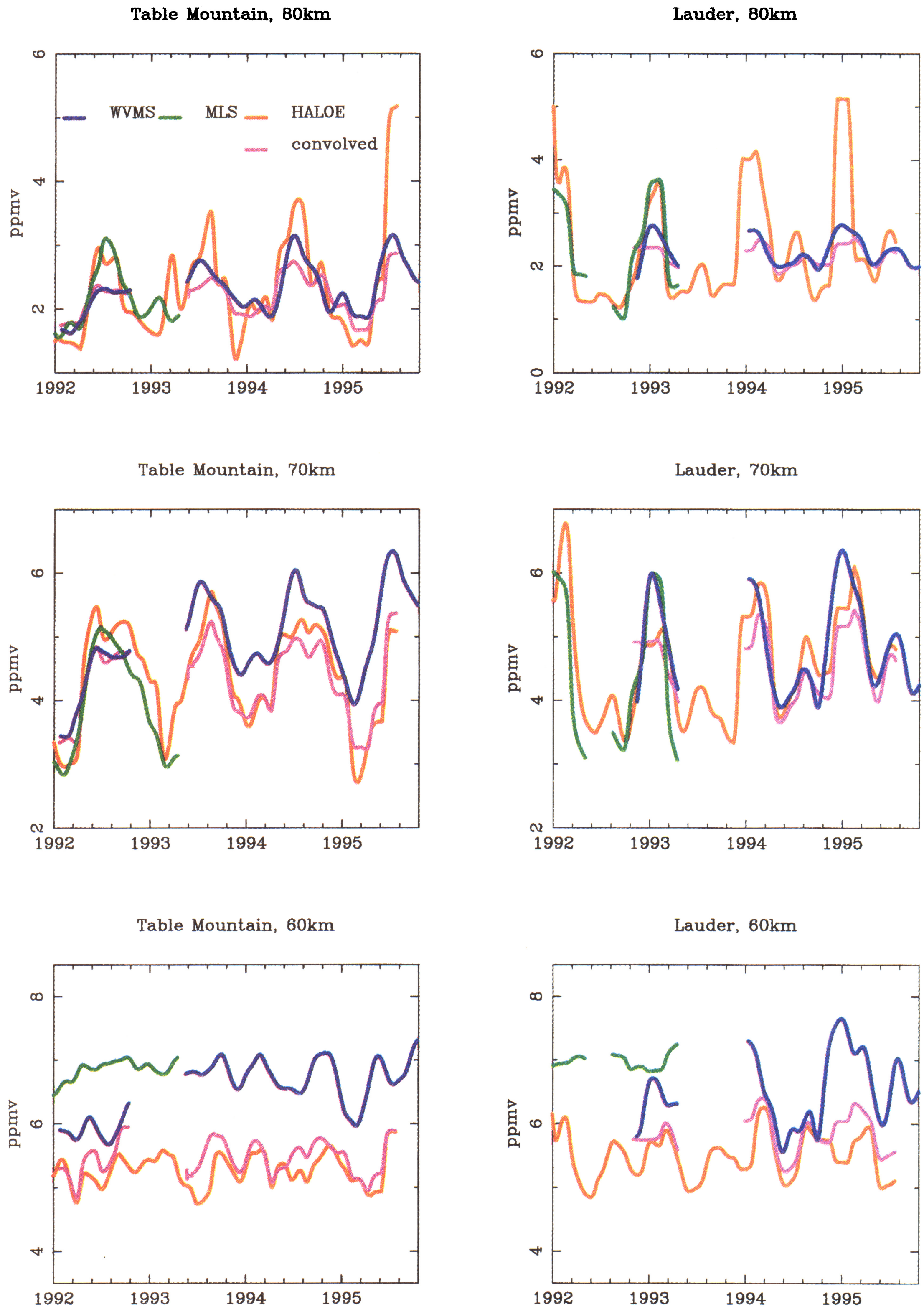

Plate 2. Water vapor retrievals at 80 km (top), 70 km (middle), and 60 km (bottom). The left-hand panels show results for Table Mountain, while the right-hand panels show results for Lauder. The curves represent data smoothed with a 25-day Gaussian filter.

cycle at both sites. The HALOE retrievals at 80 km vary by about a factor of 3, even after the data is smoothed. This is a much larger seasonal variation than has hitherto been reported from any set of water vapor observations. Such a large variation is not inconsistent with the ground-based results. At this altitude, ground-based microwave measurements suffer from decreasing signal to noise. The low pressure also causes the Doppler broadening of the lines to become comparable with the pressure broadening, thus making it impossible to correlate linewidth with altitude. The WVMS results at 80 km are therefore strongly influenced by the a priori profile, which has no seasonal variation in the WVMS retrievals. When the HALOE measurements are convolved with the WVMS averaging kernels, the seasonal variations observed by the two instruments show similar amplitudes.

The MLS mixing ratios at 80 km also indicate a large seasonal variation, though not quite as large as the variations observed by HALOE. The smaller amplitude of the seasonal variations retrieved by MLS may be due to tighter a priori constraints, as is the case for the WVMS retrievals. The MLS retrievals are performed with a seasonally varying a priori profile; however, the variation of the a priori profile is much smaller than the observed variation both at this altitude and at 70 km. The UARS a priori profile for water vapor at 80 km varies by ≈0.7 ppmv at 34°N, and by ≈0.8 ppmv at 45°S, while at 70 km the range is ≈1.2 ppmv at 34°N and ≈0.9 ppmv at 45°S.

The 80 km HALOE retrievals near Table Mountain show an increase in water vapor at this altitude since the start of the UARS mission, as do the zonally averaged retrievals near 34.4°N. While the 80 km WVMS retrievals from Table Mountain also show an increase during this period, the observed trend may be attributable to instrumental effects. The increase from 1992 to 1993 may be the result of a pointing error in 1992, while the increase from 1993 to 1994 is due to the increased sensitivity at 80 km resulting from the 50 kHz filters installed in January 1994. When the measurements are retrieved without the 50 kHz filters, the 80 km summer peaks are ≈0.4 ppmv smaller, while the minima remain similar. The HALOE data at Lauder also indicate an increase from 1993 to 1995; however, the 1995 summer peak in the mixing ratio is calculated from a small number of good measurements, and there is no clear indication of an increase in the WVMS retrievals. There is also no indication of an increase in the zonally average mixing ratio retrieved by HALOE near 45°S. It is therefore not possible, from the data shown here, to infer any clear trend in the water vapor mixing ratio at 80 km.

In addition to the annual cycle observed at 80 km by all of the instruments, the WVMS and HALOE retrievals at Lauder also show a clear semiannual cycle, with a secondary peak near the winter solstice. Unfortunately, MLS retrievals near the 1992 austral winter solstice are unavailable. The nature of the semiannual variation near Table Mountain is somewhat more complex. The HALOE measurements show no clearly repeated winter pattern, while the WVMS and MLS retrievals show a small maximum soon after the winter solstice. Given the small amplitude of the variation near the winter solstice, however, these differences are probably not significant. What is clearly indicated by all of the measurements is that there is generally no minimum near the winter solstice analogous to the maximum near the summer.

Measurements from all three instruments at 70 km should be better than at 80 km as the increase in water vapor with decreasing altitude provides an increase in the signal strength. The WVMS retrievals are also better at this altitude due to the increasing importance of pressure broadening relative to Doppler broadening with decreasing altitude. The WVMS retrievals (and the HALOE retrievals convolved with the WVMS averaging kernels) are therefore much less constrained by the a priori profile. While there remain some differences between the convolved and unconvolved HALOE retrievals, these differences are much smaller than at 80 km. The amplitudes of the seasonal cycles observed by WVMS, HALOE, and MLS are similar, with the amplitudes of the seasonal variations retrieved by WVMS and MLS appearing to be somewhat larger than those observed by HALOE. The average WVMS mixing ratios retrieved at 70 km from both Lauder and Table Mountain are slightly larger than those retrieved by HALOE, with the largest differences occurring in the summer.

The retrievals from the MLS and WVMS instruments show that the amplitude of the 70 km seasonal cycle at Lauder is generally larger than that at Table Mountain. This is consistent with the general trend in the HALOE retrievals which shows that the amplitude of the seasonal variation gradually increases with increasing latitude. While the zonally averaged HALOE retrievals near the latitudes of these two sites show a larger amount of variability near 45°S than near 34.4°N, from the measurements shown here there appears to be no clear difference in the observed variability at the two sites. Nevertheless, the general shape of the annual variations measured by HALOE and WVMS show a marked similarity. Both instruments show that the decrease in mixing ratios following the summer solstice is generally much slower at Table Mountain than at Lauder.

Particularly encouraging in the comparison between HALOE and WVMS are the coincidences and amplitudes of secondary minima and maxima. We note that at Table Mountain, even small interannual variations in the amplitude of the seasonal cycles are consistent. Both instruments show broader mixing ratio peaks at 70 km in the summers of 1992 and 1994 than in the summer of 1993 and a lower minimum in the winter of 1994-1995 than in the winter of 1993-1994. Between 1994 and 1995 at Lauder both instruments observe an increase in the mixing ratio, with the minima becoming more shallow and the maxima becoming larger.

At 60 km, there is a clear offset in the average observed mixing ratio, with the MLS retrievals indicating more water vapor than is measured by WVMS, while the HALOE retrievals indicate a smaller mixing ratio. While the offset between the WVMS and the HALOE mixing ratios at 60 km is larger than at the other two altitudes shown, the fractional difference at the three altitudes is comparable. All of the instruments show that there is less variability observed in the smoothed data at 60 km than is observed at 70 km, however, there is some disagreement as to the magnitude of this variability. The annual variability of the MLS data covers a range of ≈0.5 ppmv, while the HALOE data vary over ≈1 ppmv, and the WVMS data vary by up to ≈2 ppmv at Lauder. The HALOE and WVMS data both show more seasonal variability at Lauder than at Table Mountain. At Lauder the mixing ratio peaks in the WVMS retrievals generally coincide with the peaks observed at 70 km. Since the retrieval at 60 km is affected by mixing ratios over a range of altitudes (see Figure 1), some of the variation observed by WVMS at 60 km is the result of the large variations observed at higher altitudes. For example, near the end of 1994 the HALOE data at 70 and 80 km show rapidly increasing mixing ratios, while at 60 km there is a small (~7%) decrease in mixing ratio. When these data are convolved with the coarse resolution WVMS averaging kernels, the 60 km decrease is not resolved. Rather, there is a small (~5%) increase in the mixing ratio at 60 km. In general, however, the convolved and unconvolved

60 km HALOE data are very similar. While there is no clear seasonal cycle in the HALOE and WVMS data at Table Mountain, there is good agreement in both the amplitude and the time of the observed variations. This agreement is very encouraging given the small magnitude of these variations. No time series comparisons are presented for altitudes below 60 km, as the variability continues to decrease with decreasing altitude, and there is no clear indication of a seasonal cycle at 40 and 50 km.

5.3. Regression Analysis

In order to better quantify the difference in the variability observed in the HALOE and WVMS measurements and to provide a check on the accuracy of the WVMS error estimates, we have performed a linear regression analysis using all of the coincident data points. Since the errors in the HALOE and WVMS measurements are comparable, a standard linear regression technique is inadequate, as it implicitly assumes that there is no error in the dependent variable (*i.e.*, $\sigma_x=0$). We therefore calculated the slope of the best-fit straight lines using the FITEXY routine by *Press et al.* [1992]. The routine calculates a best fit line, $y(x)=a+bx$ by minimizing

$$\chi^2(a,b)=\sum_i \frac{(y_i-a-bx_i)^2}{\sigma_{yi}^2+b^2\sigma_{xi}^2} \qquad (2)$$

where y_i and σ_{yi} represent the WVMS measurements and errors, while x_i and σ_{xi} represent the HALOE measurements and errors. The slope of this line provides an extremely sensitive test not only of the variability of the retrievals but also of the accuracy of the error estimates. If there is no difference in the observed variability and if we have a good estimate of the errors in the retrieval, the slope of the best fit line will be ≈1. However if, for example, the WVMS errors are underestimated or the HALOE errors are overestimated, then the calculated best fit will indicate that the WVMS instrument is retrieving water vapor profiles that show greater variability than those retrieved by the HALOE instrument.

In Figure 5 we show all of the coincident retrievals since November 1992 from HALOE (convolved with WVMS averaging kernels) and WVMS at 70 km. A similar comparison with the MLS data is not attempted here since it is not clear how to quantify resolution differences between the MLS and the WVMS instruments and because of the shorter time span of available comparative data. As in Figure 3, we have averaged all of the HALOE retrievals coincident with each WVMS retrieval. We determine the HALOE errors by calculating an average standard deviation at each altitude and site from those periods during which there are at least six HALOE measurements overlapping the WVMS retrieval. We then used $\sigma/\sqrt{n}$ as the error in the HALOE data for each set of overlapping measurements. This error estimate clearly includes variability due to instrumental effects and to the spatial and temporal variations within the 10°x60° area which we consider to be coincident with the approximately weekly WVMS measurements. The standard WVMS errors are calculated using the methods discussed by *Nedoluha et al.* [1995]. Since the WVMS instrument measures at only one point within the area used for the comparison, there is clearly some additional error in extrapolating this measurement to the entire area (as we must do if we are to make a comparison with HALOE). We therefore also perform calculations in which we add the standard deviation calculated from the HALOE data to the standard WVMS errors. This second error estimate is an overestimate of the error incurred by extrapolating the WVMS data to the entire area, since a WVMS retrieval should provide a better estimate of the

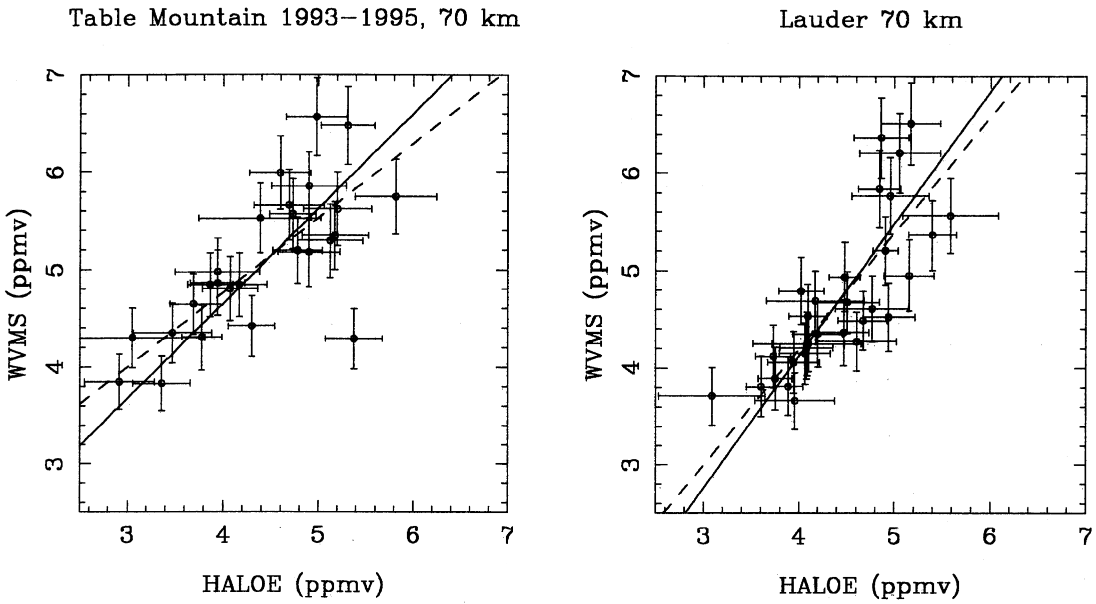

Figure 5. Mixing ratios retrieved by HALOE (convolved with WVMS averaging kernels) and WVMS at 70 km for Table Mountain (34.4°N, 117.7°W) since May 1993 (left) and Lauder (45.0°S, 169.7°E) since November 1992 (right). The error bars shown for the WVMS retrievals include only the standard WVMS errors. Results are shown with (dashed) and without (solid) an error added to the standard WVMS error to account for uncertainties in applying the WVMS measurements to the entire comparison region.

average mixing ratio within the area during the week than a short HALOE measurement and since some of the variability in the HALOE data is instrumental. The steeper line in Figure 5 is obtained using the standard WVMS errors, while the less steep line is obtained when we attempt to account for the error in using the WVMS data to approximate the water vapor in the comparison area. The slope of the line at Table Mountain is ≈1 for the standard WVMS errors and <1 in the large WVMS error case. At Lauder, both cases give a slope >1, indicating that more variability is present in the WVMS retrievals than in the HALOE retrievals.

In Figure 6 we show the slope of the best-fit straight lines for both sites at a range of altitudes and also show normalized χ^2 values for each altitude. Values of $\chi^2 \approx 1$ indicate that the estimate of the total error for the two sets of measurements are reasonable. Adding the HALOE standard deviation to the WVMS error results in values of $\chi^2 < 1$ at most altitudes, indicating, as expected, an overestimate of the combined error. The χ^2 value for this estimate of the error is particularly small at high altitudes, where it is probably inappropriate because of significant noise in the HALOE retrievals. While the χ^2 values provide a good indication that the combined error is reasonable, they provide no information on the relative errors.

If we make no provision for the error in comparing the WVMS retrievals with the HALOE data, then the slope of the best fit straight line for Lauder is >1 for all of the altitudes shown. The slope differs from 1 by more than 2σ from 58 to 68 km, and at 40 to 42 km. At Table Mountain the slope $=1\pm\sigma$ at all altitudes above 48 km. Of the 42 altitude increments shown in Figure 6, the measurements at 21 altitudes are best fit by a line with a slope within the range $1\pm\sigma$. For another 11 altitudes the slope of the best fit straight line is within the range $1\pm2\sigma$, while for the remaining 10 altitudes the slope falls within the range $1\pm3\sigma$. For a Gaussian distribution 29 of the 42 points should lie within $\pm1\sigma$ of the slope=1 value. Adding the HALOE standard deviation to the WVMS error leaves only nine altitudes with a slope differing from 1 by more than σ, again suggesting that this is an overestimate of the error in the comparison.

A disproportionately large fraction of the points for which the best fit lines appear to differ from 1 by more than the expected error occur at low altitudes. This suggests that there are changes in the WVMS baseline which affect retrievals at these altitudes. Such baseline errors are not easily characterized as required for the linear regression comparison. Not only is the magnitude of the baseline error for an individual retrieval difficult to estimate, but because baseline errors that affect the low altitudes tend to remain constant over many retrievals before changing, the error is neither completely random (as assumed here) nor completely systematic. Despite these difficulties and the small magnitude

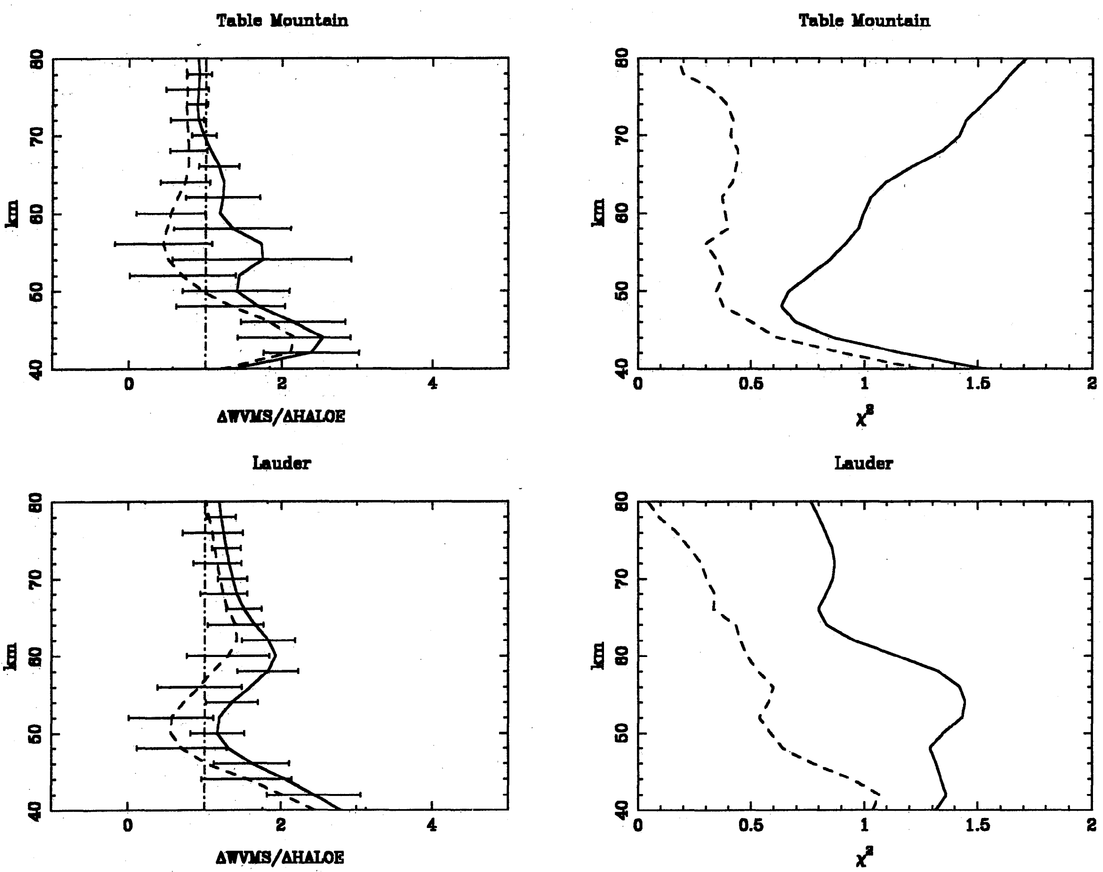

Figure 6. Slopes of lines and normalized χ^2 values derived from a least squares fit between WVMS measurements and coincident HALOE measurements that have been convolved with the WVMS averaging kernels. The top panels show the best fit Table Mountain measurements since May 1993, and the bottom panels show the best fit to Lauder measurements since November 1992. Results are shown with (dashed) and without (solid) an error added to the standard WVMS error to account for uncertainties in applying the WVMS measurements to the entire comparison region.

of the variability of atmospheric water vapor in the upper stratosphere, we note that there is a positive correlation between the convolved HALOE and the WVMS retrievals over the entire range of altitudes measured by the WVMS instrument.

In principle, the slopes of the best fit straight lines combined with the offset resulting from the calculation could be used to determine systematic calibration and offset differences between the WVMS and the HALOE instruments. With the data sets currently available for this comparison, however, the uncertainties in estimates of slopes remain much larger than the estimates of the calibration errors. The overlap of most of the error bars with a slope =1 does, however, show that the differences in the water vapor variations observed by the two instruments are generally not significant. This suggests that no changes have occurred in the HALOE and WVMS instruments since November 1992 which would result in significant instrumentally induced variations in the retrieved water vapor mixing ratio; and that the errors given in section 2, which are calculated by using the methods discussed by *Nedoluha et al.* [1995], provide a good estimate of the error in the WVMS retrievals. The stability of the WVMS measurements is particularly encouraging given the improvements that have been made to the WVMS instruments during this period.

6. Other Water Vapor Data Sets

We have investigated the possibility of including measurements from the CLAES instrument aboard UARS in this comparison, but these measurements are considered to be most useful only at altitudes below the range investigated here. There is little historical data on the variability of water vapor in the lower mesosphere and upper stratosphere. One instrument that has provided such data is the Stratospheric and Mesospheric Sounder (SAMS). While there have been problems calculating the vertical structure of the water vapor profiles observed by SAMS, it has been possible to obtain information on the average latitudinal and seasonal variations from January 1979 to December 1981 [Munro and Rodgers, 1994]. This shows a seasonal cycle at 0.1 mbar (≈65 km) with an amplitude >1.2 ppmv at 35°N and >2 ppmv at 45°S. These amplitudes are somewhat larger than the amplitudes of the zonally averaged seasonal cycles observed by HALOE at this altitude and are comparable to but slightly smaller than the amplitudes of the seasonal cycles observed by the WVMS instruments.

7. Conclusions

Water vapor profiles retrieved by the six instruments included in this study generally differ from an average calculated by using retrievals from all of the instruments by <1 ppmv throughout most of the upper stratosphere and mesosphere. The profiles generally show a mixing ratio peak between ≈50 and 60 km, with a sharp drop at higher altitudes. For all of the ATLAS missions the difference between the average of the coincident measurements and the WVMS profile is well within the estimated WVMS error at most altitudes. When long-term average comparisons are possible, we find that the mixing ratios retrieved from the WVMS data are smaller than those retrieved by MLS (by 6-25% below 65km) and larger than those retrieved by HALOE (by 10-20% at Table Mountain and 5-9% at Lauder between 40 and 80 km). Thus the present comparisons do not suggest any systematic bias in the WVMS retrievals, and no adjustment in the data is warranted at either site. The ratios of the mixing ratios retrieved by HALOE and WVMS are not a strong function of altitude, with the peak in the long-term average mixing ratio profiles from the two instruments agreeing to within 2 km at both sites. This suggests that much of the difference between the WVMS and the HALOE data is the result of altitude independent bias. This bias is reduced in the version 18 HALOE retrievals, which generally show slightly larger water vapor mixing ratios.

The annual variations observed by the HALOE, MLS, and WVMS instruments are all similar in phase, with a maximum in upper mesospheric water vapor near the summer solstice. The HALOE and WVMS retrievals also show a semiannual variation at Lauder, where a secondary peak in the water vapor mixing ratio occurs near the winter solstice. Such a secondary peak is also apparent in the MLS and WVMS measurements at Table Mountain. A regression analysis shows that the mesospheric water vapor mixing ratio variations measured by HALOE and WVMS throughout a 3-year period are generally consistent within estimates of the errors. There is some disagreement in the upper stratosphere, where the error in the WVMS measurements is most difficult to characterize, and where the small magnitude of the natural variability increases the difficulty of making comparisons of the instrumental sensitivity to this variability. Nevertheless, there is a positive correlation between mixing ratio variations observed by HALOE and WVMS over the entire 40 to 80 km range of altitudes retrieved by the WVMS instruments. The general agreement of the observed variations in the water vapor profile shows that these measurements can provide useful information for studies of middle atmospheric chemistry and transport.

Acknowledgments. We wish to thank P. Marsden, who obtained and helped organize the HALOE profiles used in this comparison and to M. Daehler for calculating the coincident MAS retrievals. Our thanks also go to P. R. Schwartz for his help in initiating the WVMS project and to R. Tate for his engineering assistance. We also thank M. Schmoe-Hennop and the Table Mountain staff and B. McNamara and the Lauder staff for their technical assistance. Thanks also to P. Newman's group at NASA Goddard and the Climate Prediction Center (CPC) of the National Centers for Environmental Prediction (NCEP) for providing daily temperature and pressure data. The MLS data were obtained from the NASA Goddard Distributed Active Archive Center (DAAC). This project was funded by NASA under the Upper Atmospheric Research Program and by the Strategic Environmental Research and Development Program (SERDP).

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M. Abrams, NASA Langley Research Center, Hampton, VA.

R. M. Bevilacqua, R. M. Gomez, B. C. Hicks, G. E. Nedoluha, and W. B. Waltman, Remote Sensing Division, Naval Research Laboratory, Code 7227, Washington, D. C., 20375. (e-mail: nedoluha@wvms.nrl.navy.mil)

B. J. Connor, National Institute of Water and Atmospheric Research, Private Bag 50061, Omakau, Central Otago, New Zealand.

H. C. Pumphrey, Department of Meteorology, The University of Edinburgh, Mayfield Road, Edinburgh EH9 3JZ, Scotland, U. K.

J. M. Russell III, Department of Physics, Hampton University, Hampton, VA 23668

D. L. Thacker, National Radio Astronomy Observatory, Suite 219, 2015 Ivy Road, Charlottesville VA 22903-1733

(Received August 13, 1996; revised February 27, 1997; accepted April 10, 1997.)