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LIDAR CHARACTERIZATIONS OF WATER VAPOR MEASUREMENTS OVER THE ARM SGP SITE

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1. INTRODUCTION

Improving the parameterization of radiative processes in General Circulation Models (GCMs), which is a primary objective of the Department of Energy (DOE) Atmospheric Radiation Measurement (ARM) Program, requires an accurate specification of the atmospheric state. Water vapor measurements are especially important for this characterization because water vapor dominates clear sky emission in the atmospheric window region. Measurements obtained at the ARM Southern Great Plains (SGP) site (36.62 N, 97.5 W) have indicated that uncertainty in the routine water vapor measurements is the limiting factor in assessing the performance of infrared radiation models. The largest differences in water vapor profiles are found in the upper troposphere, where differences between operational Raman lidar and Vaisala radiosonde water vapor profiles often exceed 20% (Turner and Goldsmith, 1999).

ARM has conducted a series of experiments at the SGP site to characterize and ultimately improve the accuracy of water vapor measurements. The goal is to develop techniques to reduce uncertainties in upper tropospheric water vapor (UTWV) measurements to less than 10% (Tobin et al., 2002). As the latest in these series of experiments, the ARM-FIRE Water Vapor Experiment (AFWEX) was conducted at the SGP site during late November to early December 2000 to resolve differences in measurements of absolute water vapor amounts and to characterize the upper troposphere water vapor measurements acquired at the SGP site. During AFWEX, the NASA DC-8 aircraft was deployed and carried a suite of instruments to help characterize UTWV measurements. One such instrument was the Lidar Atmospheric Sensing Experiment (LASE) system, which provided absolutely calibrated water vapor profiles both above and below the aircraft. We discuss the LASE system and the LASE water vapor measurements acquired during AFWEX, and describe how these measurements have been used to assess and characterize UTWV measurements. We also describe how the Cloud and Radiation Testbed (CART) Raman lidar measurements have been used to examine the vertical and temporal variability of water vapor and aerosols over the ARM SGP site.

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2. INSTRUMENTATION

2.1 LASE SYSTEM

LASE is an airborne DIAL (Differential Absorption Lidar) system that was developed to measure water vapor, aerosols, and clouds throughout the troposphere. This system uses a double-pulsed Ti:sapphire laser, which is pumped by a frequency-doubled Nd:YAG laser, to transmit light in the 815-nm absorption band of water vapor. LASE operates by locking to a strong water vapor line and electronically tuning to any spectral position on the absorption line to choose the suitable absorption cross-section for optimum measurements over a range of water vapor concentrations in the atmosphere. For AFWEX, LASE operated using strong and weak water vapor lines in both the nadir and zenith modes, thereby simultaneously acquiring data both above and below the aircraft. Typical resolutions for water vapor profiles between 0.2 and 12 km AGL are 14 km (1-min) (horizontal) and 330 m (vertical) for nadir measurements. For zenith measurments, the horizontal and vertical resolutions are 70 km (3 min) and 990 m, respectively. Previous comparisons of water vapor measurements with other sensors showed the LASE water vapor mixing ratio measurements to have an accuracy of better than 6% or 0.01 g/kg, whichever is larger, across the troposphere (Browell et al., 1997).

2.2 CART RAMAN LIDAR

The CART Raman Lidar (CARL) uses a tripled Nd:YAG laser, operating at 30 Hz with 350-400 millijoule pulses to transmit light at 355 nm. A 61-cm diameter telescope collects the light backscattered by molecules and aerosols at the laser wavelength and the Raman scattered light from water vapor (408 nm) and nitrogen (387 nm) molecules. A beam expander reduces the laser beam divergence to 0.1 mrad, thereby permitting the use of a narrow (0.3 mrad) as well as a wide (2 mrad) field of view. The narrow field of view, coupled with the use of narrowband (~0.4 nm bandpass) filters, reduces the background skylight and, therefore, increases the maximum range of the aerosol and water vapor profiles measured during daytime operations.

A series of automated algorithms are used to derive water vapor and aerosol profiles (Turner et al., 2002). Water vapor mixing ratio profiles are computed using the ratio of the Raman water vapor signal to the Raman nitrogen signal. Relative humidity profiles are computed using these water vapor mixing ratio profiles and the temperature profiles from a physical retrieval algorithm that uses data from a collocated Atmospheric Emitted Radiance Interferometer (AERI). The water vapor mixing ratio profiles are integrated with altitude to derive precipitable water vapor (PWV). Profiles of aerosol scattering ratio, which is the ratio of aerosol+molecular scattering to molecular scattering, are derived using the Raman nitrogen signal and the signal detected at the laser wavelength. Aerosol volume backscattering cross section profiles are then computed using the aerosol scattering ratio and molecular scattering cross section profiles derived from atmospheric density data. These density profiles are computed using coincident pressure and temperature profiles. Aerosol extinction profiles are computed from the derivative of the logarithm of the Raman nitrogen signal with respect to range. Aerosol optical thickness (AOT) is derived by integration of the aerosol extinction profile with altitude.

3. LASE MEASUREMENTS DURING AFWEX

After the transit flight of the DC-8 to Tinker Air Force Base (AFB) (35.4 N, 97.38 W) on November 29, there was a total of six science flights of the DC-8 over the ARM SGP site between November 30 and December 10. LASE collected approximately 26 hours of data during these flights. The flight patterns typically consisted of a spiral ascent over the SGP site, followed by a series of level leg segments at several different altitudes in the upper troposphere, followed by a spiral down over the SGP site before the DC-8 returned to Tinker AFB. The spiral portions of each flight permitted the DC-8 in situ water vapor sensors to acquire a vertical profile over the SGP site. The level leg segments were performed at several altitudes between about 7.7 and 12.4 km above the SGP site. These segments, which were oriented both parallel and perpendicular to the wind at these altitudes, were approximately 10 minutes (140 km) in duration and were centered over the ARM SGP site.

4. AVERAGE WATER VAPOR COMPARISONS

Water vapor measurements acquired by two ground-based Raman lidars (CART Raman (CARL), NASA GSFC Scanning Raman Lidar (SRL)), three radiosonde sensors (Vaisala RS80-H, Sippican, Inc. (formerly VIZ Manufacturing Company) carbon hygristor, Snow White chilled mirror), and two DC-8 in situ sensors (NASA Langley diode laser hygrometer (DLH), cryogenic frost point hygrometer) were compared with the LASE profiles. Thirty minute average profiles from the two Raman lidars were compared with the UTWV measurements from LASE. The number of individual comparisons with the various sensors varied from 75 (LASE and CARL) to 16 (LASE and chilled mirror sonde).

Average differences between the LASE water vapor profiles and the profiles measured by the ground based lidars and radiosondes were computed as a function of altitude. Figure 1 shows the average difference (%) between the LASE water vapor values and the corresponding values from the other sensors as a function of altitude; the thick rectangles (boxes) represent +/- 2 standard error of the average, and error bars represent +/- 1 standard deviation of the measurements. There was generally very good agreement among the ground-based Raman lidars and LASE with average differences generally less than 10% for altitudes between 0-12 km. Both Raman lidars were calibrated such that the precipitable water vapor (PWV) derived by integrating their water vapor profiles matched the PWV measured by the ARM SGP ground based microwave radiometer (MWR). Additional comparisons with instruments on the SGP 60 m tower, radiosondes, and GSFC Raman lidar water vapor profiles revealed a slight altitude dependence of the CARL overlap correction. We developed a modification to this overlap correction that altered the CARL water vapor calibration slightly and reduced the CARL UTWV profiles by about 4%. This modification has only been applied to this AFWEX dataset and has not yet been applied to the CARL profiles available from the ARM archive. Recent work suggests that Raman lidar water vapor measurements are sensitive to large temperature variations such as those that occur between the lower

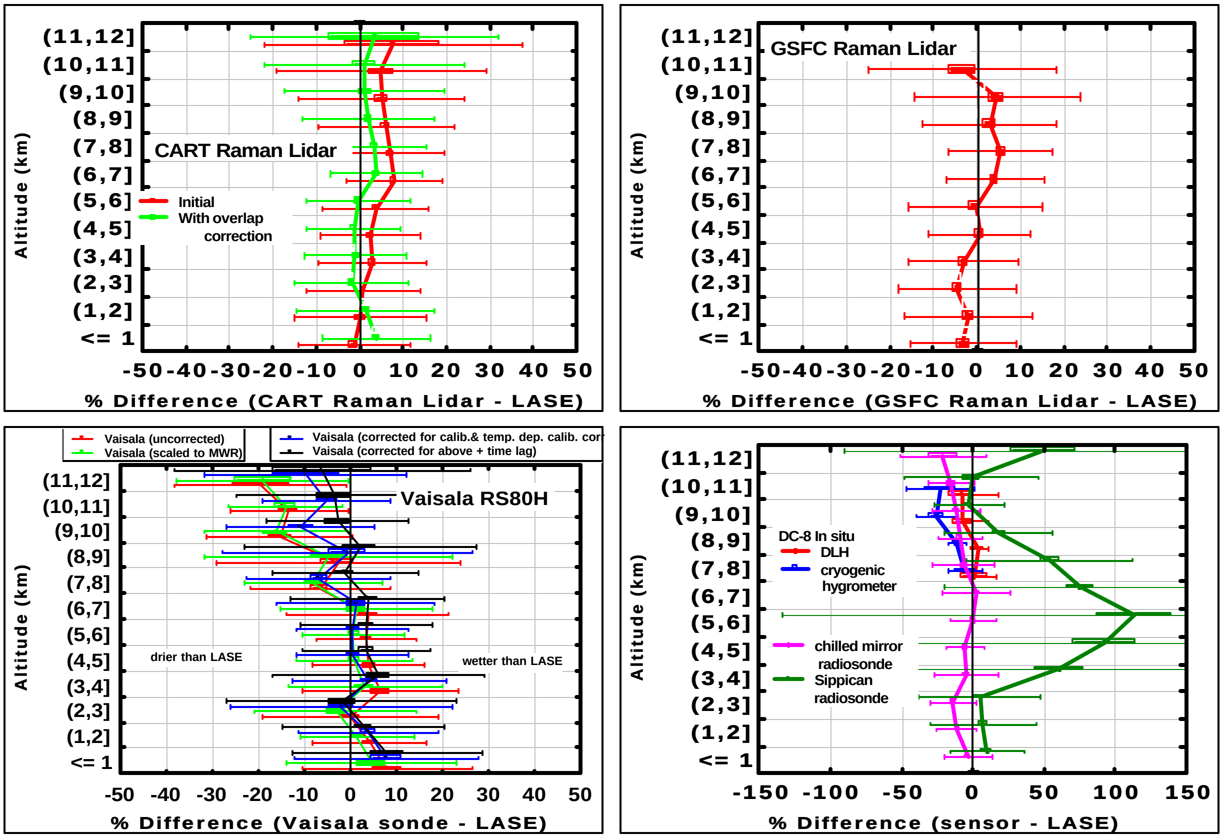

Figure 1. Average differences (%) in water vapor measurements between various AFWEX sensors and LASE. Thick rectangles (boxes) represent +/- 2 st. error of the average; error bars represent standard deviations of the measurements. Note the change in scale for the comparisons on the bottom right.

and upper troposphere so that the CARL and SRL profiles may require an additional altitude dependent correction (Whiteman et al., 2002). The temperature sensitivity and altitude correction are currently under investigation.

The Vaisala radiosonde UTWV profiles were about 8-10% drier than the LASE profiles. The average difference between LASE and the Vaisala radiosonde increased with altitude suggesting that the sonde dry bias increases with altitude. This dry bias is similar to what has been reported in previous UTWV comparisons (Soden et al., 1994). In an attempt to correct for this dry bias as well as to remove significant radiosonde batch-to-batch variability, ARM has pursued methods of correcting the water vapor profiles measured by the Vaisala RS80H radiosondes. One method applies a single, altitude-independent scaling factor to the radiosonde water vapor measurements such that the PWV computed from the resulting radiosonde water vapor matches simultaneous MWR PWV measurements (Turner et al., 2002a,b). The radiosonde water vapor mixing ratio profile is scaled by multiplying the ratio of the MWR PWV to the radiosonde PWV. Although this scaling generally moistens the lower troposphere and impacts the PWV, Figure 1 shows that this scaling does not significantly affect the Vaisala UTWV profiles.

Other correction schemes have been developed to account for the variability and dry bias of the Vaisala RS80H measurements. These schemes generally account for two sources of error: "bias" errors that produce a dry bias in the measurements, and a "time-lag" error that results from a slow response of the sensor to a changing ambient relative humidity field at cold temperatures (Miloshevich et al., 2002). A joint effort between Vaisala and the National Center for Atmospheric Research (NCAR) has produced a scheme that includes "bias error" corrections for chemical contamination, temperature-dependence, basic-calibration-model, ground check, sensor aging and sensor-arm-heating errors (Wang et al., 2002). Portions of this correction scheme were applied to the AFWEX data to account for the error in the basic RS80H calibration model, and to improve the representation of the temperature dependence of the RS80H calibration. (The AFWEX sondes were new and so no correction was applied to account for possible sensor contamination by outgassing of the plastic packaging material.) Figure 1 shows that this correction does increase the Vaisala UTWV profiles and bring them into closer agreement with the LASE and Raman lidar measurements. A correction for the "time-lag" error has also been developed that calculates the ambient humidity profile from the measured humidity and temperature profiles based on laboratory measurements of the sensor time-constant (63% response time) as a function of temperature (Miloshevich et al. 2001; 2002). Figure 1 shows that this correction also moistened the AFWEX Vaisala radiosondes and further reduced the average differences from about 8-10% to about 4-5% and within the goal of 10% in mean differences in UTWV. These results indicate that these corrections should be applied to the Vaisala RS80H water vapor measurements before using these data to quantitatively study upper tropospheric water vapor.

The UTWV profiles measured by the Sippican carbon hygristor radiosonde sensor exhibited poor agreement (>50% differences) with the other measurements. The radiosonde chilled mirror UTWV measurements were generally drier than the LASE UTWV measurements, but were still within about 10% on average.

Comparisons of the LASE and DC-8 in situ UTWV measurements are also shown in Figure 1. The in situ water vapor measurements acquired during level leg flights were averaged together and compared with the LASE nadir (zenith) water vapor measurements acquired when the DC-8 flew at a higher (lower) altitude either just before or after the in situ measurements. On each of five flights, 16 level leg comparisons were acquired on average at each 1 km altitude bin for a total of about 80 comparisons for each in situ sensor. The LASE and DLH water vapor measurements agreed within about 3% on average; however, the cryogenic frost point hygrometer values were about 14-17% less than the corresponding LASE and DLH measurements. This larger difference is most likely due to response characteristics dictated by physical properties (or restraints) of the chilled-mirror instrument and measurement technique. Previous comparisons between diode laser and cryogenic frost point hygrometers have also shown the tendency of cryogenic frost point hygrometers to measure smaller water vapor amounts than diode laser hygrometers (Sonnenfroh et al., 1998; Vay et al., 2000).

Figure 2 shows an overall comparison of UTWV measurements relative to the corresponding LASE measurements. Average differences between each sensor's measurements and the LASE measurements for altitudes between 7 km and the tropopause and for water vapor mixing ratio values below 0.2 g/kg are shown. Simultaneous temperature and ozone measurements indicated that tropopause altitudes varied between 10.5 and 13 km during these flights. The excellent agreement among the Raman lidars, which were calibrated using the MWR PWV, and LASE measurements indicates that the LASE absolute water vapor calibration agrees well with the MWR absolute water vapor calibration. This was verified by comparing PWV derived from the LASE water vapor profiles with the MWR PWV. When deriving PWV from the LASE profiles, two different methods were used to estimate the small (~10%) contribution to the PWV for altitudes between the surface and the lowest LASE water vapor measurement about 250 m above the surface. The first method interpolated through this region using the LASE water vapor profile above 250 m and the tower water vapor measurements at 25 and 60 m. The second method used an average of the LASE water vapor measurements between 250 and 400 m above the surface as an estimate of the average water vapor below 250 m. The average PWV computed from the LASE profiles using these methods were within 0.25% of each other and were only slightly higher (< 3%) than the MWR PWV.

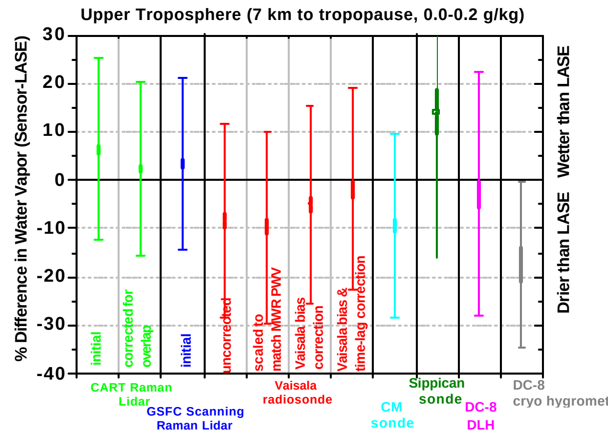

Figure 2. Average differences in UT water vapor measurements referenced to the LASE measurements. Thick black rectangles (boxes) represent +/- 2 st. deviations of the average and error bars represent standard deviations of the measurements.

5. MEASUREMENTS OF DIURNAL VARIABILITY

CARL profiles acquired over 946 days between March 1, 1998 and December 31, 2001 were used to characterize the diurnal variability of water vapor and aerosols. During this period, CARL operated an average of about 55% of the time. Figure 3 shows aerosol extinction, water vapor mixing ratio, and relative humidity profiles averaged over each hour of the day for both the winter (December-February) and summer (June-August) seasons. The average over the summer included CARL measurements from 205 days during these years, and the winter average included CARL measurements over 180 days. Cloudy samples were excluded from these averages. Times of average sunrise and sunset are also shown.

The highest aerosol extinction was generally observed close to the surface during the nighttime just prior to sunrise. The high values of aerosol extinction are most likely associated with increased scattering by hygroscopic aerosols, since the corresponding average relative humidity values were above 70%. After sunrise, relative humidity and aerosol extinction below 500 m decreased with the growth in the daytime convective boundary layer. The largest aerosol extinction for altitudes above 1 km occurred during the early afternoon most likely as a result of the increase in

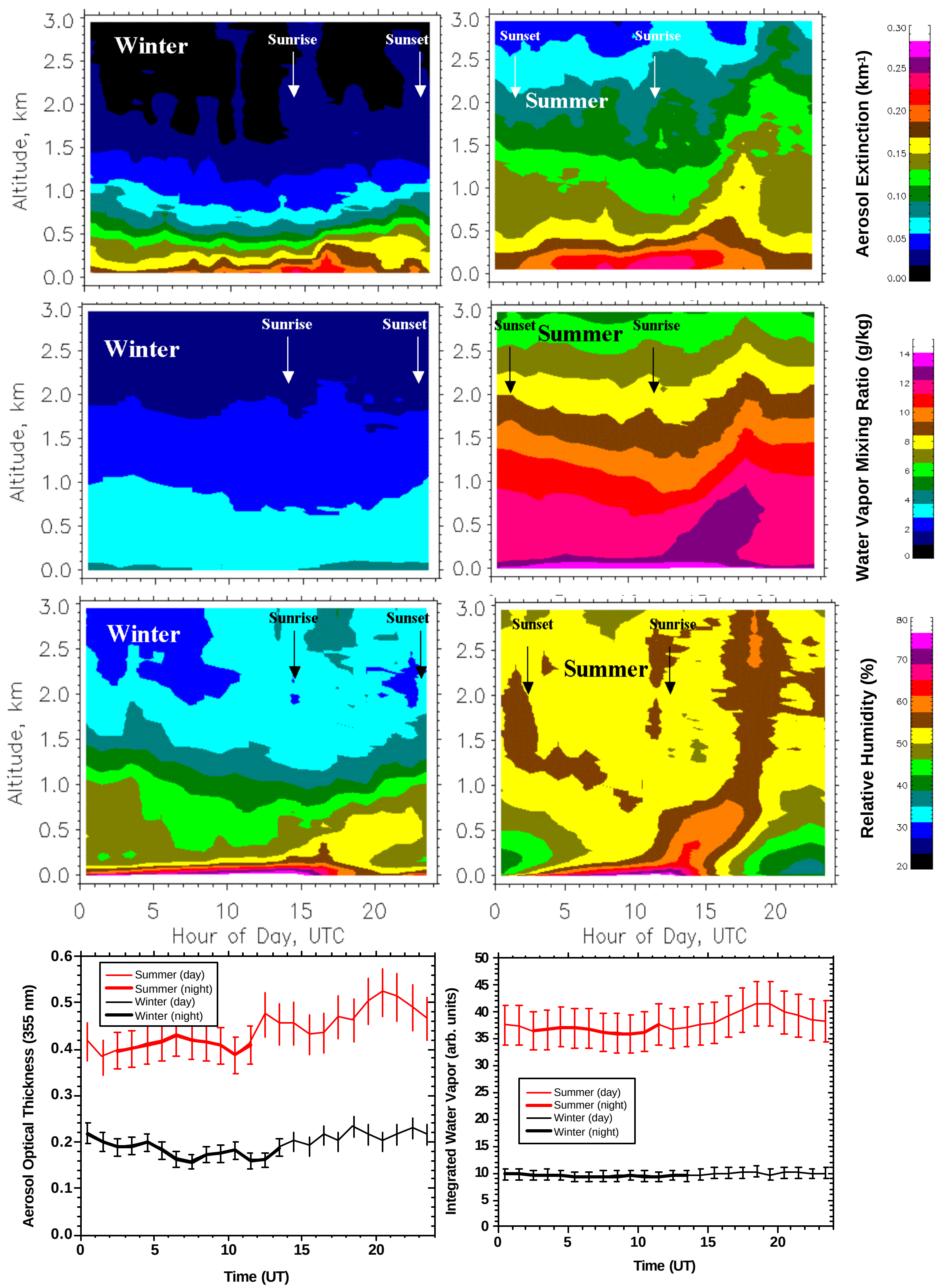

Figure 3. (top) Images showing average diurnal variation of aerosol extinction (top), water vapor mixing ratio (middle), and relative humidity (bottom) profiles measured by CARL for winter (left) and summer (right). (bottom) average AOT (left) and integrated water vapor (between 0 to 3 km) (right) for summer and winter.

relative humidity. The water vapor mixing ratio profiles generally showed smaller variations with altitude between day and night. The aerosol extinction profiles show that relatively large (10-25%) changes that occur in the average aerosol extinction profiles have a smaller impact on the AOT. Figure 3 also shows the diurnal variability of both AOT and integrated water vapor for winter and summer. The standard deviation of the AOT was about 10% of the daily average AOT during both summer and winter. In contrast, the water vapor profiles showed about half this variability for both the summer and winter cases.

Figure 4 shows autocorrelation functions computed for water vapor mixing ratio, relative humidity, aerosol extinction, and aerosol backscattering computed using CARL 10-minute resolution profile data acquired during 2000 and 2001. Autocorrelations are computed for several altitudes. These results also show that there was less variability in the water vapor than for aerosol extinction, particularly near the surface. Temperature variations apparently produce a large diurnal variability in the relative humidity, since there appears to be much less diurnal variability in the water vapor mixing ratio. This diurnal variability in relative humidity also leads to the diurnal variability in the aerosol extinction due to the hygroscopic growth of the aerosols as discussed above. For a given temporal lag and altitude, the autocorrelation function for water vapor is considerably larger than for aerosol backscattering and extinction, which indicates that there was less mesoscale variability in water vapor mixing ratio than aerosol backscattering and extinction. A recent study using ground, aircraft, and spaceborne measurements also found significant and general mesoscale variability in aerosol scattering (Anderson et al., 2002).

6. CONCLUSION

Initial comparisons with LASE upper troposphere water vapor (UTWV) measurements acquired during AFWEX showed the CART Raman lidar (CARL) UTWV profiles were about 6% wetter than LASE in the upper troposphere, and the Vaisala RS80-H and chilled mirror sondes were about 8-10% drier than LASE. The differences between the CARL and Vaisala radiosonde profiles are reduced to about 5% by accounting for an overlap correction of the CARL water vapor profiles, and by employing correction schemes designed to correct the Vaisala RS80-H calibration method and for the time response of this radiosonde water vapor sensor. The LASE and DC-8 in situ DLH UTWV measurements generally agreed to within about 3%, although the DC-8 in situ cryogenic hygrometer measurements were generally 10-20% drier than the LASE measurements. Precipitable water vapor (PWV) derived from the LASE profiles agrees within about 3%

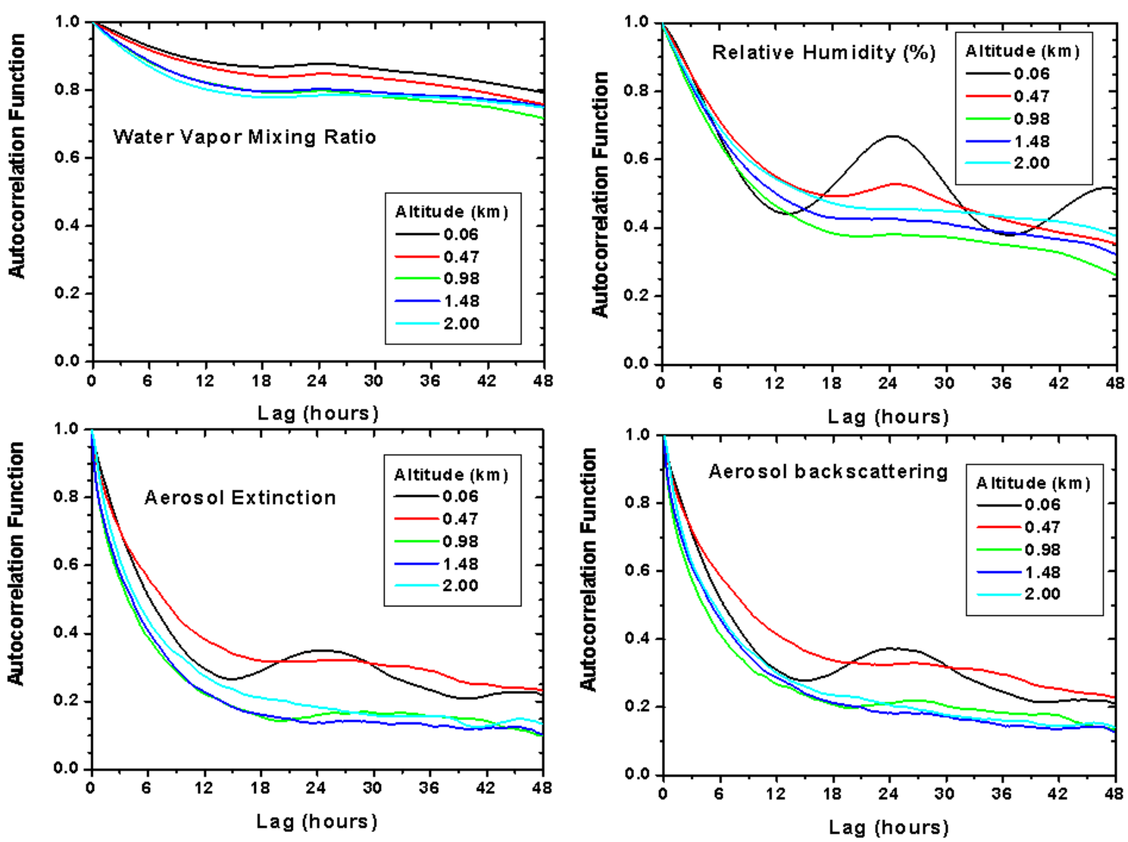

Figure 4. Autocorrelation functions computed using CARL data from 2000-2001.

on average with PWV derived from the ARM SGP microwave radiometer. The agreement between the LASE and MWR PWV and the LASE and CARL UTWV measurements supports the hypotheses that MWR measurements of the 22 GHz water vapor line can accurately constrain the total water vapor amount and that the CART Raman lidar, when calibrated using the MWR PWV, can provide an accurate, stable reference for characterizing upper troposphere water vapor. Examination of CARL water vapor and aerosol data shows that the water vapor mixing ratio and precipitable water vapor have smaller diurnal variabilities than aerosol extinction and aerosol optical thickness.

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