A Two Year Climatology of Water Vapor and Aerosols in the Lower Troposphere Measured by a Raman Lidar

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ABSTRACT

A wide variety of water vapor and aerosol products are automatically and routinely retrieved from the operational ground-based Raman lidar which is deployed at the DOE ARM Southern Great Plains (SGP) CART site in north-central Oklahoma, USA. These products include profiles of water vapor mixing ratio, relative humidity, aerosol extinction and backscatter coefficients, depolarization ratio, and cloud mask. In addition, integrated products such as total precipitable water vapor and aerosol optical thickness are computed. From April 1998 – January 2000 this lidar, which is able to profile the lower troposphere both during the nighttime and daytime, has operated more than 50% of the time, and has run more than 90% of the time during some recent months. During this 2-year period, almost 7500 hours of data have been collected and processed, and climatological statistics have been generated.

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A wide variety of water vapor and aerosol products are automatically and routinely retrieved from the operational ground-based Raman lidar which is deployed at the DOE ARM Southern Great Plains (SGP) CART site in north-central Oklahoma, USA. These products include profiles of water vapor mixing ratio, relative humidity, aerosol extinction and backscatter coefficients, depolarization ratio, and cloud mask. In addition, integrated products such as total precipitable water vapor and aerosol optical thickness are computed. From April 1998 – January 2000 this lidar, which is able to profile the lower troposphere both during the nighttime and daytime, has operated more than 50% of the time, and has run more than 90% of the time during some recent months. During this 2-year period, almost 7500 hours of data have been collected and processed, and climatological statistics have been generated.

1. Introduction

The U.S. Department of Energy's Atmospheric Radiation Measurement (ARM) program has fielded an operational Raman lidar at its Southern Great Plains (SGP) Cloud and Radiation Testbed (CART) site in north-central Oklahoma (36.61 N, 97.49W). This turn-key lidar has operated over 50% of the time during both daytime and nighttime between April 1998 and January 2000, providing almost 7500 hours of water vapor and aerosol data during this time period. During October and December 1999, the lidar was operational over 98% and 91% of the time, respectively. We have developed and implemented automated routines to retrieve profiles of water vapor mixing ratio, relative humidity, aerosol extinction and aerosol backscatter coefficients, linear depolarization ratio, and a cloud mask. Additionally, integrated products, such as total precipitable water vapor and aerosol optical thickness, are also routinely computed. These Raman lidar profiles are important for determining the clear-sky radiative flux, research of synoptic features such as cold fronts, and validating the retrieval algorithms associated with satellite sensors. We discuss the lidar system, the algorithms, and show seasonal mean profiles of water vapor and aerosol as a function of the integrated quantities for this two-year period.

2. Instrumentation

The CART Raman Lidar (CARL) was specifically designed for the ARM program to be able to profile water vapor and aerosols throughout the diurnal cycle and to operate autonomously [1]. It uses a tripled Nd:YAG laser, operating at 355 nm with 350-400 millijoule pulses at 30 Hz. 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. These signals are recorded as one-minute sums with a vertical resolution of 39 meters. 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 large uninterruptible power supply (UPS) was added in February 1999 to eliminate the effect of short power interruptions (on the order of fractions of a second) that occur rather frequently in rural Oklahoma, which were shutting down the lidar by tripping the laser interlock. Additional system details are given in [1].

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 the lidar's water vapor mixing ratio profiles and the temperature profiles derived using a physical retrieval from the high resolution downwelling longwave radiance data observed by the Atmospheric Emitted Radiance Interferometer (AERI) [2]. The CARL water vapor mixing ratio profiles are automatically calibrated using the coincident nighttime measurements of precipitable water vapor (PWV) from the collocated microwave radiometer (MWR) [3]. Data from three consecutive nights are used to determine this height-independent calibration factor for the center day. This calibration factor has been found to vary by about 3-4% over this 2-year period. The water vapor profiles are usually limited by the solar background to altitudes below approximately 3-4 km during the daytime, but typically extend to 10-12 km at night.

Profiles of total scattering ratio, which is defined as the aerosol plus molecular scattering divided by the molecular scattering, are derived using the signal detected at the laser wavelength and the Raman nitrogen signal. This profile is automatically calibrated by normalizing it to unity in a clear-air (cloud and aerosol free region) between 6-9 km. Aerosol volume backscattering cross section profiles are then computed using the aerosol scattering ratio and molecular

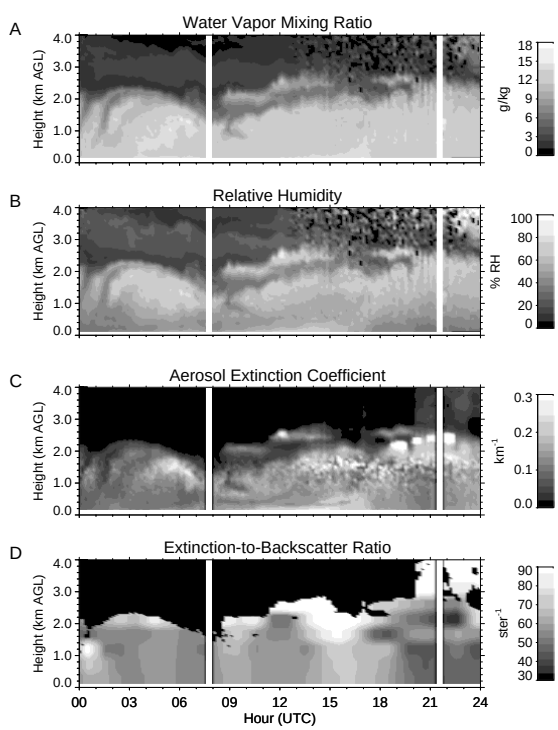

Figure 1. Water vapor mixing ratio (A), relative humidity (B), aerosol extinction coefficient (C), and extinction-to-backscatter ratio (D) calculated from CARL data collected on 29 August 1999.

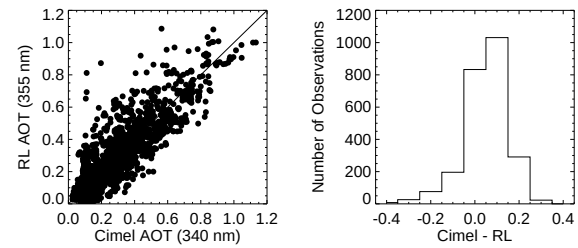

Figure 2. (Left) Scatterplot of 2485 aerosol optical thickness (AOT) samples from April 1998 – January 2000 from the CIMEL sunphotometer (340 nm) and the Raman lidar (355 nm). The slope and intercept of the regression line is 0.928 and 0.018, respectively, with a correlation coefficient of 0.73. (Right) Histogram of the CIMEL – CARL AOT differences. The mean and standard deviation are 0.00 and 0.100, respectively.

scattering cross section profiles derived from atmospheric density data calculated from the AERI retrieval data. Aerosol extinction coefficient profiles are computed by taking the derivative of the log of the Raman nitrogen signal with respect to range. However, this technique only works where the overlap function for the nitrogen channel is unity (which occurs at about 800 m for the wide field-of-view channel). Aerosol extinction profiles from near the surface to this level of complete overlap are derived from the aerosol-to-backscatter ratio data from 800-1000 m together with the backscatter profile, which extends to 60 m above the surface. Aerosol optical thickness values are then computed by integrating the extinction coefficient profile from the surface to 7 km (or cloud base, whichever is lower). Additional details on how these aerosol quantities are derived are given in [4].

3. Measurements

The high-resolution Raman water vapor and aerosol measurements, together with the AERI temperature measurements, provide a much more detailed representation of the atmospheric state than can be achieved using radiosondes or other in-situ measurements alone. Figure 1 provides an example of the water vapor and aerosol measurements made on 29 August 1999. These data were processed with 10-minute averages, and the vertical resolution was about 78 m for the water vapor and 300 m for the aerosol profiles. Note the large variability of these fields, both in space and time. High-resolution data such as this are used to investigate synoptic features such as drylines and cold fronts [5], radiative transfer applications, the interaction between water vapor and aerosols [6], and ice supersaturation in the upper troposphere [7].

While the Raman lidar's water vapor measurements have been compared to other measurements of water vapor in [3] and [5], there were no other routine measurements of aerosol profiles currently available to use for validation at the CART site. Therefore, to validate the aerosol retrievals, comparisons of aerosol optical thickness (AOT) with the CIMEL sunphotometer have been performed. A scatterplot of the AOT from the 340 nm channel of the CIMEL against the Raman lidar's AOT (at 355 nm) and a histogram of the differences are given in figure 2. The slope is 0.928, but the expected slope would be approximately 0.95 due to the differences in wavelength between the two measurements. Interestingly, the mean bias is zero, although the standard deviation about the mean difference is 0.100.

Aerosol optical thickness data between the two instruments was compared as a function of season. AOT data from all of the CIMEL channels sensitive to aerosol are shown, and that a comparison of the Raman lidar to the 340 nm channel of the CIMEL is meaningful. As shown in figure 3, the Raman lidar's mean AOT agrees very well with the mean Ångstrom relationship derived from the CIMEL data, with the exception of the winter season. This season has the smallest mean optical thickness, indicating that perhaps there is a bias in the Raman lidar retrievals in relatively clean conditions. This season is relatively undersampled as compared to the other seasons (225 coincident samples versus more than twice that for the other seasons), but it is doubtful that this would significantly change with more samples.

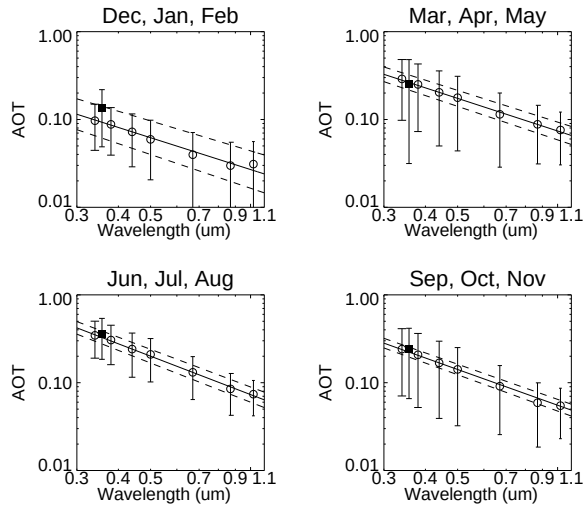

Figure 3. Comparisons of mean AOT from coincident samples from the CIMEL sunphotometer (open circles) and CARL (solid squares) as a function of season. There were 225, 571, 562, and 1127 points in the winter, spring, summer, and fall seasons, respectively. The solid lines represent the mean Ångstrom relationship, while the dotted lines are three times the standard deviation about this mean.

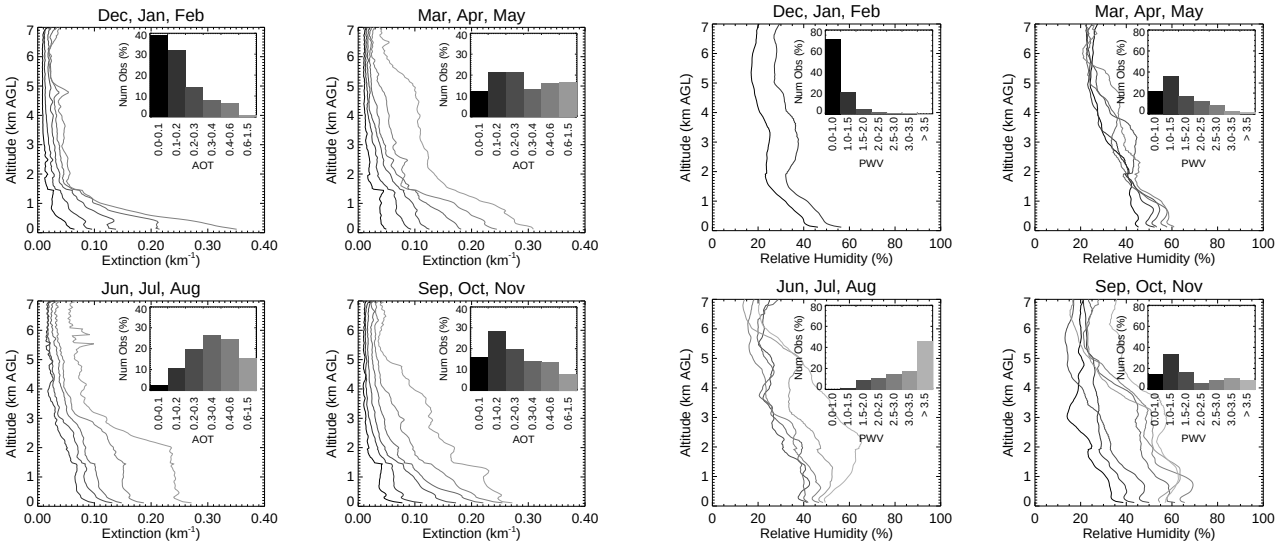

Figure 4. Seasonal mean profiles, derived from data collected by the Raman lidar from April 1998 – January 2000, of aerosol extinction coefficient (left) and relative humidity (right), as a function of aerosol optical thickness (AOT) and total precipitable water vapor (PWV), respectively. The inset plots indicate the fraction of the total number of samples for that season that was in the given bin. Profiles where not plotted for bins with less than 5% of the total samples for the season.

Average aerosol extinction profiles were computed as a function of optical thickness and season to characterize the vertical distribution of aerosols. The left-hand panels in figure 4 show the distribution of the percentage of samples in each AOT bin, as well as the mean extinction profile for that bin. These profiles demonstrate that there is a large seasonal variability both in AOT as well as the vertical distribution of the aerosols. The right-hand panels of figure 4 provide a similar look at how relative humidity varies as a function of season and total precipitable water vapor (PWV).

We have begun using these lidar profiles of aerosol and water vapor to investigate the lidar extinction-to-backscatter ratio (S_a), and the relationships among water vapor mixing ratio, relative humidity, aerosol extinction, and the extinction-to-backscatter ratio for hydroscopic aerosols. CARL data often show that the aerosol extinction increases significantly when the relative humidity increases above 60-70% near the top of the boundary layer. Moreover, the CARL retrievals of S_a as a function of altitude show large (> 20%) variations of S_a occur approximately 25% of the time. This information is important since passive retrievals of aerosol size and composition based on ground or space-based measurements provide only column integrated values, and thus typically have to assume some mean profile.

4. Summary

We have implemented algorithms to compute aerosol extinction and relative humidity profiles using CART Raman lidar data and AERI temperature retrievals. Together with Raman lidar water vapor mixing ratio, cloud mask, and depolarization retrievals, these aerosol and relative humidity profiles form a suite of products that are retrieved using automated remote sensing instruments and can be used to characterize the clear sky state over the SGP site at high vertical and temporal resolution. We are using these Raman lidar aerosol and water vapor measurements to investigate the relationships among water vapor and aerosols.

5. Acknowledgements

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