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Title: Cloud and Radiation Testbed (CART) Raman Lidar Measurements of Atmospheric Aerosols for the Atmospheric Radiation Measurement (ARM) Program

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Description of the objective of the report:

Vertical profiles of aerosol extinction are required for determination of the effects of aerosols on the clear-sky radiative flux. Since recent studies have demonstrated the inability to compute these profiles from surface aerosol measurements alone, vertical profiles of aerosol optical properties must be acquired to compute aerosol radiative effects throughout the entire atmospheric column. Following the recommendation of the ARM Aerosol Working Group, the investigator developed, evaluated, and implemented

algorithms for the CART Raman Lidar to provide profiles of aerosol extinction and backscattering. By virtue of its ability to measure vertical profiles of both aerosol extinction and water vapor simultaneously in the same scattering volume, we used the resulting profiles from the CART Raman Lidar to investigate the impact of water vapor and relative humidity on aerosol extinction throughout the column on a continuous and routine basis. The investigator used these the CART Raman Lidar aerosol extinction and backscattering profiles to evaluate the vertical variability of aerosol extinction and the extinction/backscatter ratio over the ARM SGP site.

Description of the approach employed in the project:

Algorithms developed for use with the Goddard Space Flight Center Scanning Raman Lidar (SRL) were examined for use with the CART Raman Lidar taking into account differences in systems such as overlap function photon pulse pileup and daytime and nighttime operation differences. Comparisons between the profiles from each instrument and with aircraft and surface based measurements during IOPs provided the source of further assessments and improvements.

Results:

We have developed a series of Value Added Procedures (VAPs) to use the CART Raman lidar data to routinely produce several data sets for use in characterizing the clear-sky state over the SGP site. This operational lidar acquires aerosol measurements during both daytime and nighttime operations. The procedures start by using the Raman nitrogen signal and the signal detected at the laser wavelength to compute profiles of the aerosol scattering ratio. This ratio is defined as the ratio of aerosol+molecular scattering to molecular scattering. These algorithms are designed to continually monitor the calibration of the aerosol scattering ratio and to account for the periodic automatic system realignments. 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. The atmospheric density profiles are computed using temperature profiles derived from a physical retrieval algorithm that uses measurements from both the SGP CART Atmospheric Emitted Radiance Interferometer (AERI) and Geostationary Operational Environmental Satellite (GOES) satellite. Aerosol extinction cross section profiles are computed from the derivative of the Raman nitrogen signal with respect to range. The aerosol backscattering and extinction profiles derived in this manner are then used to measure the aerosol extinction/backscattering ratio. Aerosoloptical thicknesses are derived by integration of the aerosol extinction profiles with altitude.

Because relative humidity is a key parameter affecting aerosol scattering and extinction, automated routines have also developed and implemented to simultaneously retrieve profiles of water vapor mixing ratio and relative humidity. These routines also use the (AERI+GOES) temperature retrievals.

These VAPs were implemented to run routinely at the Dept. of Energy Atmospheric Radiation Measurement (ARM) Experiment Center. The output products from these VAPs included a series of netCDF files that include the profile results as well as several quick look GIF images to show the results of this processing. These VAPS include:

- MR VAP (water vapor mixing ratio and relative humidity profiles)
- ASR VAP (aerosol scattering ratio and backscatter coefficient profiles)
- EXT VAP (aerosol extinction coefficient and extinction/backscatter ratio)
- DEP VAP (depolarization and cloud mask profiles).

Automated algorithms to derive aerosol scattering ratio, backscattering, and extinction profiles from the SGP CART Raman Lidar data were recently upgraded to improve performance during conditions of low aerosol loading. The corresponding VAPs discussed above were also updated at the ARM Experiment Center. These aerosol and water vapor profiles (Raman lidar) and temperature profiles (AERI+GOES) have been combined into a single "best estimate" (BE) VAP that takes advantage of both active and passive remote sensors to characterize the clear sky atmospheric state above the CART site. The products included in this BE VAP are profiles of water vapor mixing ratio, relative humidity, aerosol backscatter coefficient (at 355 nm), aerosol extinction coefficient (at 355 nm), temperature (from AERI+GOES retrievals), potential temperature (from AERI+GOES retrievals), total precipitable water vapor, aerosol optical thickness (at 355 nm), linear depolarization ratio, cloud mask. This BE VAP has also been implemented to run routinely at the ARM Experiment Center. The "best estimate" algorithms have been used to derive profiles for the following periods September 1996 (Water Vapor IOP #1), September-October 1997 (Water Vapor IOP#2, Aerosol IOP), April 1998 through present (August 2002). A web site showing these results for the periods listed above has been established at http://yard.arm.gov/~turner/raman_lidar_quicklooks.html. These data files are available from the ARM archive (http://www.archive.arm.gov/data/ordering.html). Best estimate products are being produced on a routine basis by automated software at the DOE ARM Experiment Center.

As part of the routine diagnostics, the CART Raman Lidar (CARL) water vapor mixing ratio profiles were compared with water vapor profiles measured by Vaisala radiosondes launched at the SGP site. Over 500 lidar/radiosonde profile comparisons examined between April 1998 and October 1999 showed that the unscaled radiosondes were about 3-5% drier than the lidar. When the radiosonde water vapor mixing ratio was scaled to match the microwave precipitable water vapor amount, the scaled radiosonde and lidar water vapor profiles agreed generally within 1-2%. The AERI+Model temperature profiles were also compared with temperature profiles measured by Vaisala radiosondes. Over 450 AERI+model/radiosonde profile comparisons showed that rms temperature differences were less than 1 K, with the AERI+Model slightly (~0.25 K) warmer.

Aerosol optical thicknesses (AOT), which are computed by integrating the Raman lidar aerosol extinction profiles between 0-6 km, have been compared with simultaneous and independent measurements of AOT made by a Cimel sun photometer at the SGP CART site. The lidar and sun photometer AOT values generally agree, with about a 5% bias difference. Of this difference, 3.5% can be explained by the wavelength dependence of aerosol extinction between the two wavelengths (340 nm vs. 355 nm). The CARL

AOT also generally show good agreement with the Cimel AOT when compared as a function of season. Comparisons of aerosol optical depth derived using these algorithms with a collocated CIMEL sun photometer for clear-sky days over an approximate 2-yr period show a slope of 0.90 with a correlation coefficient of 0.884. Furthermore, comparing the aerosol extinction profile retrieved from this system with that from the National Aeronautics and Space Administration (NASA) Goddard Space Flight Center's scanning Raman lidar agrees within 10% for the single available case.

The Raman lidar aerosol extinction, water vapor, and relative humidity profiles have been used to examine the vertical variability of aerosols and water vapor. Average aerosol and water vapor profiles derived from SGP CART Raman lidar measurements over two years (1998 and 1999) show significant differences in the vertical variability of aerosols and water vapor. Average aerosol extinction profiles were computed as a function of optical thickness to characterize the vertical distribution of aerosols. Similarly, average water vapor mixing ratio profiles were computed as a function of precipitable water vapor to characterize the vertical distribution of water vapor. The aerosol profiles show a large variability with seasons as well as with AOT. The average water vapor profiles do not show as much variability with season or precipitable water vapor. The aerosol scale height was between 1.0-1.2 km during the winter but rose to nearly 2 km in the summer. This behavior is in contrast to the scale height for water vapor mixing ratio, which remained nearly the same (2.0-2.5 km) during winter and summer. These results demonstrate the variability of the aerosols as a function of season, AOT and time of day, and suggest that assuming a constant profile and scaling it to agree in AOT can result in large errors between the assumed profile versus a true profile over this mid-latitude continental site.

The CARL aerosol extinction profiles also show that considerable aerosol loading often existed in elevated layer above the boundary layer. One example occurred when smoke from fires in Central America were observed over the ARM SGP CART site. Of particular importance in this case is the profile of the aerosol extinction/backscatter ratio (S_a) derived from the CARL data. Since S_a varies with changes in the aerosol size distribution and/or aerosol composition, variations in the vertical profile of S_a indicate that the aerosol size distribution and/or aerosol composition varied with altitude. In this example, the value of $S_a = 55$ sr observed for the boundary layer aerosols is typical of the aerosols observed over the SGP site. In contrast, the value of $S_a = 90$ sr observed for the elevated aerosol layer between 3-6 km is typical for biomass burning aerosols. We used aerosol size distributions derived from the Cimel Sun photometer sun and sky radiance measurements to show that the biomass burning aerosols are consistent with the CARL S_a measurements.

We examined the aerosol extinction/backscattering profiles derived from the CARL measurements to determine the how often aerosol optical and physical characteristics vary with altitude as in the case described above. In this study, we computed the standard deviation (due to atmospheric variability) of S_a in a vertical column. For cases when the AOT at 355 nm was greater than 0.3, for data acquired between April 1998 and April 1999, in about 30% of the cases the standard deviation of S_a due to atmospheric variability was greater than 10 sr (or 15%). This type of variability is similar to that described above for the smoke aerosols. In these cases of high S_a variability, the aerosol size distribution and/or composition varied significantly with altitude. These results suggest that column averages may not accurately represent the true aerosol characteristics in a significant number of cases. This implies that significant variability in the vertical distribution of the aerosol size distribution, shape, and/or composition often occurs. A subset of these cases showed that these lidar ratios are linearly correlated with the aerosol fine mode effective radius and volume ratio of fine/coarse particles. These ratios were also found to increase slightly with aerosol optical thickness and relative humidity. These measurements are important for remotely characterizing the vertical variability of aerosols over the SGP site as well as for developing parameterizations for space-based lidar retrievals of aerosol extinction and optical thickness.

The CARL retrievals of S_a were compared with the aerosol size parameters derived from coincident sun and sky radiance data measured by a Cimel Sun photometer data. An inversion procedure, which has been developed by Oleg Dubovik at NASA/GSFC, uses the Cimel direct solar and the sky brightness measurements to derive column-averaged aerosol size distribution, complex refractive index, and single scattering albedo, as well as the aerosol extinction/backscatter ratio. The CARL S_a values are linearly correlated with the fine (accumulation) mode volume median radius as well as the volume ratio (fine/coarse). This shows that the CARL S_a measurements may be used to indicate particle sizes. The aerosol extinction/backscattering ratio S_a often indicates variations in either the size and/or composition of the aerosols. As the aerosol Angstrom exponent decreases from -1 to -2, aerosol particle sizes decrease and S_a tends to increase.

The CARL data have also been used to investigate how aerosol extinction and the aerosol extinction/backscatter ratio vary with relative humidity and observe the increase in aerosol extinction with relative humidity near the top of the daytime boundary layer. We have examined measurements from several of these days to show the dependence of aerosol extinction and S_a on relative humidity. The ratio of aerosol extinction at RH=80% to that at RH=30% is about 1.9 +/- 0.4 which is not inconsistent with the values derived from the SGP surface in situ measurements. The increase in S_a with relative humidity is consistent with that modeled for "continental aerosols".

Deliverables:

The algorithms and code used to derive the profiles of aerosol extinction, backscattering, optical thickness, water vapor mixing ratio, and relative humidity have been delivered to the ARM Experiment Center. A web page showing images of aerosol extinction, aerosol backscatter, water vapor mixing ratio, relative humidity, total precipitable water vapor, aerosol optical thickness, temperature, linear depolarization ratio, and cloud mask data has been created at http://playground.arm.gov/~turner/raman_lidar_quicklooks.html. Web pages have also been created to provide more details about the algorithms used in this study. These pages are most easily accessed through the related homepage http://playground.arm.gov/~turner/EOS_validation/.

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