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# Characterizing the Vertical Distribution of Aerosols Over the ARM SGP Site

**Final Report for period 12/15/2001-12/14/2007**

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## Executive Summary

This project focused on: 1) evaluating the performance of the DOE ARM SGP Raman lidar system in measuring profiles of water vapor and aerosols, and 2) the use of the Raman lidar measurements of aerosol and water vapor profiles for assessing the vertical distribution of aerosols and water vapor simulated by global transport models and examining diurnal variability of aerosols and water vapor.

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 relative humidity. The water vapor mixing ratio profiles generally showed smaller variations with altitude between day and night.

We also compared simultaneous measurements of relative humidity, aerosol extinction, and aerosol optical thickness derived from the ARM SGP Raman lidar and in situ instruments on board a small aircraft flown routinely over the ARM SGP site. In contrast, the differences between the CARL and IAP aerosol extinction measurements are considerably larger. Aerosol extinction derived from the IAP measurements is, on average, about 30-40% less than values derived from the Raman lidar. The reasons for this difference are not clear, but may be related to the corrections for supermicron scattering and relative humidity that were applied to the IAP data.

The investigators on this project helped to set up a major field mission (2003 Aerosol IOP) over the DOE ARM SGP site. One of the goals of the mission was to further evaluate the aerosol and water vapor retrievals from this lidar system. Analysis of the aerosol and water vapor data collected by the Raman lidar during the 2003 Aerosol IOP indicated that the sensitivity of the lidar was significantly lower than when the lidar was initially deployed. A detailed analysis after the IOP of the long-term dataset demonstrated that the lidar began degrading in early 2002, and that it lost approximately a factor of 4 in sensitivity between 2002 and 2004. We participated in the development of the remediation plan for the system to restore its initial performance. We conducted this refurbishment and upgrade from May-September 2004. This remediation lead to an increase in the signal-to-noise ratio of 10 and 30 for the Raman lidar's water vapor mixing ratio and aerosol backscatter coefficient data, respectively as compared to the signal strengths when the system was first deployed. The DOE ARM Aerosol Lidar Validation Experiment (ALIVE), which was conducted during September 2005, evaluated the impact of these modifications and upgrades on the SGP Raman lidar measurements of aerosol extinction and optical thickness. The CARL modifications significantly improved the accuracy and temporal resolution of the aerosol measurements.

Aerosol extinction profiles measured by the Raman lidar were also used to evaluate aerosol extinction profiles and aerosol optical thickness (AOT) simulated by aerosol models as part of the Aerosol module inter-Comparison in global models (AEROCOM) (http://nansen.ipsl.jussieu.fr/AEROCOM/aerocomhome.html) project. There was a wide range in how the models represent the aerosol extinction profiles over the ARM SGP site, even though the average annual AOT represented by the various models and measured by CARL and the Sun photometer were in general agreement, at least within the standard deviations of the averages. There were considerable differences in the average vertical distributions among the models, even among models that had similar average aerosol optical thickness. Deviations between mean aerosol extinction profiles were generally small (~20-30%) for altitudes above 2 km, and grew considerably larger below 2 km.

**Project goals:**

1) Remotely identify aerosol type as a function of altitude using the continuous lidar measurements of aerosol intensive[1] parameters

2) Investigate the use of Raman and MPL data to remotely characterize the aerosol humidification factor

3) Improve the characterization of the vertical distribution of aerosol properties over the SGP site used for modeling radiative fluxes and heating rates

4) Assess the ability of the aerosol transport models to simulate the contribution to aerosol extinction profile and aerosol optical thickness made by major aerosol types

**Accomplishments vs. Goals**

We feel that goals 3 and 4 were successfully addressed in the work. The project description that follows will describe these accomplishments in some detail. Because of the problems associated with the degradation of the Raman lidar data, goals 1 and 2 could not be fully addressed. Our work had to focus more on determining the extent of the degradation of the Raman lidar, the impact on the data, determining and implementing appropriate repairs/upgrades to the system, and assessing the impact of these modifications and repairs. Consequently, we were unable to complete items 1 and 2. However, as part of our current DOE ARM project, we have demonstrated how the Raman lidar measurements of aerosol backscatter and extinction, and relative humidity can be used to investigate aerosol humidification.

**Results:**

**Aerosol and Water Vapor Variability**

CARL aerosol and water vapor profiles acquired over 946 days between March 1, 1998 and December 31, 2001 were used to characterize diurnal variability. During this period, CARL operated an average of about 55% of the time. 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 were examined. 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. The highest aerosol extinction was generally observed close to the surface during the nighttime just prior to sunrise. The high values of aerosol extinction were 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 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. The diurnal variability of both AOT and integrated water vapor for winter and summer was also examined. 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.

[1] *Intensive* aerosol properties (e.g. phase function, Angstrom exponent, single scatter albedo, depolarization) depend on the type of aerosol and not on the total number concentration of aerosols. *Extensive* aerosol properties (e.g. extinction, scattering, absorption, optical thickness) depend on both the aerosol type and concentration.

We also compared simultaneous measurements of relative humidity, aerosol extinction, and aerosol optical thickness derived from the ARM SGP Raman lidar and in situ instruments on board a small aircraft flown routinely over the ARM SGP site. The comparisons use data acquired between March 2000 and December 2001. In this comparison, the CARL aerosol extinction measurements were scaled to 550 nm using the aerosol scattering wavelength dependence from the IAP measurements. The CARL and IAP relative humidity measurements generally agreed within about 5%. In contrast, the differences between the CARL and IAP aerosol extinction measurements were considerably larger. Aerosol extinction derived from the IAP measurements was, on average, about 30-40% less than values derived from the Raman lidar. The reasons for this difference are not clear, but may be related to the corrections for supermicron scattering and relative humidity that were applied to the IAP data. Note also that the Raman lidar measurements of aerosol extinction below about 800 m were derived by assuming that the aerosol extinction/backscatter ratio measured above 800 m also applies below this level.

Raman lidar profiles of water vapor mixing ratio, relative humidity, aerosol backscattering, and aerosol extinction acquired over a few years were used to study the variability of aerosols and water vapor over the ARM SGP site in northern Oklahoma. The Raman lidar measurements were combined with back trajectory analyses to assess how the vertical profiles of water vapor and aerosol extinction vary with these transport patterns, and to show the relationships between these transport patterns and aerosol optical thickness and precipitable water vapor. Four-day back trajectories were computed using the NOAA Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT4) model (http://www.arl.noaa.gov/ready/hysplit4.html, NOAA Air Resources Laboratory, Silver Spring, MD). These trajectories were computed at several altitudes every three hours for the period between January 2000 and December 2002. A cluster analysis method was used to objectively group these trajectories and to discriminate distinct flow patterns and large scale circulation patterns. Clusters of backtrajectories computed at 600 m above the surface for the summer (June, July, and August) months were evaluated during this period. Over two-thirds of the trajectories show air parcels originating southeast of the SGP site; most of these trajectories originated over the Gulf of Mexico and were also confined to altitudes below about 1.5 km. Few (<15%) of the trajectories were observed to originate northwest of the SGP site. In contrast, during the winter months nearly two-thirds of the trajectories originated to the west or northwest of the SGP site; less than 5% of the trajectories originated from southeast of the site.

Profiles of average aerosol extinction and water vapor mixing ratio corresponding to the various trajectory groups were computed from the CARL data. Trajectory clusters computed for high aerosol optical thickness and precipitable water vapor show that air parcels originating from the east and southeast typically occurred during the summer and had the highest aerosol extinction and water vapor amounts, while those trajectories originating from the west and northwest typically occurred during the winter and had the lowest aerosol extinction and water vapor amounts. These observations of high aerosol extinction and water vapor amounts associated with southeasterly and easterly trajectories is consistent with increased aerosol extinction associated with hygroscopic growth of aerosol particles as with the transport of air masses from urban/industrial areas.

We have also begun examining the aerosol and water vapor variability using a time series of over 54,000 CARL profiles acquired during 2000 and 2001. Examination of a series of 10- averaged water vapor measurements acquired at an altitude of 0.47 km during this period clearly showed the annual, mesoscale, and diurnal variabilities. First and second order temporal structure functions were computed as a function of altitude. Changes in the slopes of these structure functions at around 8-10 hours indicate a scale break that corresponds to a spatial scale of about 180-360 km for wind speeds of 5 to 10 m/s. This scale break is associated with the transition to a stationary regime also found from the Multi-Filter Rotating Shadowband Radiometer (MFRSR) aerosol optical thickness measurements. The power law spectral slope $\beta = \zeta(2) + 1$ varied between 1.8-2.0, similar to the range found using aircraft in situ water vapor measurements acquired in the extratropical free troposphere. In contrast to these lidar data, their spectral exponent increased with altitude. Changes in the slopes of these aerosol structure functions at around 6-8 hours indicate a scale break that corresponds to a spatial scale of about 200-280 km for wind

speeds of 5 to 10 m/s. The power law spectral slope $\beta = \zeta(2) + 1$ varied between 1.6-1.8 and also decreased with altitude.

Autocorrelation functions for water vapor mixing ratio, relative humidity, aerosol backscattering, and aerosol extinction were computed at various altitudes using the 10-minute resolution CARL data acquired during 2000 and 2001. Water vapor shows less variability than aerosol backscattering and 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.

**Evaluation of Global Aerosol Models**

The CARL measurements of aerosol extinction and AOT acquired during 2000 were used to evaluate the performance of the Georgia Tech/Goddard Global Ozone Chemistry Aerosol Radiation and Transport (GOCART) model for this same period. The comparisons for September 2000 show that the GOCART average aerosol optical thickness (AOT) was about half that measured by the Raman lidar and Sun photometer. The average GOCART aerosol extinction profile was also significantly less than the corresponding average Raman lidar profile. The excellent agreement between measured and modeled relative humidity profiles indicates that the disagreement between measured and model aerosol extinction and AOT was probably not associated with errors in the simulated relative humidity fields and the resulting humidification of hygroscopic aerosols. These differences may be due to: an underestimate of sulfates caused by an overestimate of the wet removal rate of sulfate and sulfur dioxide, an underestimate of the sulfur dioxide oxidation rate, and/or an underestimate of the amount of dust over the SGP site during the summer. Examination of aerosol Angstrom exponents derived from Sun photometer AOT measurements and dust amounts from model results for previous years suggest that the model may have underestimated the amount of dust during the summer of 2000.

The agreement between the modeled and measured AOT for November 2000 was much better. However, note that while the AOT comparison shows good agreement this month, the GOCART and CARL aerosol extinction profiles show significant disagreement throughout the lower troposphere. These initial comparisons show that the model simulations of aerosol extinction in the lowest 1-2 km are significantly (>50%) smaller than the Raman lidar measurements. This case illustrates that good agreement between measured and modeled AOT does not necessarily mean that the model correctly represents the vertical distribution of aerosols. Note that in the case of absorbing aerosols, differences in the vertical distributions of aerosols can have large impacts on calculations of radiative heating rates and radiative forcing. In both September and November 2000 cases, the average GOCART aerosol extinction profiles show much less vertical variability than the corresponding CARL profiles, and considerably smaller values near the surface that the lidar profiles.

Aerosol extinction profiles measured by the Raman lidar were also used to evaluate aerosol extinction profiles and aerosol optical thickness (AOT) simulated by aerosol models as part of the Aerosol module inter-Comparison in global models (AEROCOM) (http://nansen.ipsl.jussieu.fr/AEROCOM/aerocomhome.html) project. This project seeks to diagnose aerosol modules of global models and subsequently identify and eliminate weak components in aerosol modules used for global modeling; AEROCOM activities also include assembling data sets to be used in the evaluations.

There was a wide range in how the models represent the aerosol extinction profiles over the ARM SGP site, even though the average annual AOT represented by the various models and measured by CARL and the Sun photometer were in general agreement, at least within the standard deviations of the

averages. There were considerable differences in the average vertical distributions among the models, even among models that had similar average aerosol optical thickness. Deviations between mean aerosol extinction profiles were generally small (~20-30%) for altitudes above 2 km, and grew considerably larger below 2 km. Similar results were found when comparing the aerosol extinction profiles derived from the EARLINET Raman lidar measurements for 2000 over Europe and the corresponding Interaction with Chemistry and Aerosols (INCA) (http://www.ipsl.jussieu.fr/~dhaer/inca/) model results. One possible explanation may be that there is no evolution of the PBL in the model. Additional impacts of this limitation were also evident when comparing the average diurnal variations of aerosol extinction as measured by CARL and represented by the INCA model. The largest values of aerosol extinction derived from the CARL data are typically found near the surface around sunrise (10-12 UT). Since the highest average values of relative humidity were also normally found at this location and time, this maximum in the aerosol extinction was most likely due to the hygroscopic growth of the aerosol particles. In contrast, the INCA model showed minimum values of aerosol extinction at this location and time.

Some indication of potential reasons why the models have different average distributions may be found by examining the contributions to the total aerosol optical thickness made by the various aerosol components (sulfate, black carbon, sea salt, particulate organic matter, dust) as represented by the various models. For example, one particular model showed a much higher concentration of dust throughout than any of the other models and, perhaps as a result, shows higher overall levels of aerosol extinction and optical thickness than the other models. These results indicate that there were differences in how the models represent the contributions made by the various aerosol components, and that these differences may help to explain some of the differences between the measured and modeled values of aerosol extinction and optical thickness.

We performed similar studies by using the CARL profiles to evaluate the aerosol extinction and water vapor profiles produced by the Lawrence Livermore Integrated Massively Parallel Atmospheric Chemical Transport (IMPACT) model. Average annual aerosol optical thickness values were in good agreement with the corresponding values measured by the Cimel Sun photometer and CARL for 2001. The average aerosol extinction profile derived from the IMPACT simulations for 2001 over the ARM SGP site showed generally smaller aerosol extinction values than the corresponding average annual CARL profile near the surface, with better agreement found above the surface. Bias differences between CARL and the IMPACT model aerosol extinction values were about 0.02 $km^{-1}$ (~30%); rms differences were about 0.035 $km^{-1}$ (~60%). This behavior is consistent with several other global aerosol model and Raman lidar comparisons that were performed for 2000 and 2001. Dr. Ferrare hosted the 5$^{th}$ AEROCOM Workshop that was held in Virginia Beach, VA in October, 2006 (http://nansen.ipsl.jussieu.fr/AEROCOM/webvb06.html). Approximately 50 attendees presented talks and posters dealing with various aerosol measurements and aerosol modeling activities.

**May 2003 Aerosol IOP**

Several comparisons were made using data acquired during the Aerosol IOP to assess the Raman Lidar water vapor and aerosol extinction retrievals. Some comparisons used measurements acquired from an extensive suite of instruments deployed on board the Center for Interdisciplinary Remotely-Piloted Aircraft Studies (CIRPAS) Twin Otter aircraft. The Twin Otter performed 16 daytime research flights over the SGP site during the IOP. The aircraft carried instrumentation to perform in-situ measurements of aerosol absorption (Particle Soot Absorption Photometer (PSAP)) and scattering (nephelometer) and water vapor density (chilled mirror). Aerosol extinction and water vapor density were measured with the NASA Ames Airborne Tracking 14-channel Sun photometer (AATS14). Additional measurements were acquired as part of the ARM In Situ Aerosol Profiling (IAP) measurement program. The IAP instrument suite includes a Vaisala Humicap 50Y capacitive sensor to measure ambient relative humidity. Additional IOP water vapor comparisons include both the standard Vaisala RS-90 radiosonde water vapor profiles, as well as the radiosonde water vapor profiles that have been scaled to match the PWV measured by the ARM SGP microwave radiometer (MWR). These MWR scaled radiosonde profiles have been adopted

by ARM because this scaling has significantly reduced the sonde-to-sonde variability and has reduced the residuals between measurements and models of high spectral infrared radiance. These water vapor comparisons were performed for altitudes between 0.1-3.0 km to match the nominal daytime altitude range of the Raman lidar.

The Raman lidar profiles were generally in good (<5% bias difference) agreement with the Microwave Radiometer (MWR) scaled radiosonde measurements but were 5-17% wetter than the other measurements. The largest differences were generally found for low relative humidity conditions. The reasons for such large differences are not presently clear, but may be related to the use of the MWR PWV as a calibration standard since both the Raman lidar and scaled radiosonde water vapor profiles are calibrated to match the MWR PWV. Previous nighttime comparisons found that scaling Raman lidar water profiles to match a chilled mirror sensor on the SGP tower produced profiles that were 3-4% drier than the profiles scaled to match the MWR PWV. Previous comparisons have also found better agreement between the Raman lidar and IAP water vapor measurements. Note that the Aerosol IOP water vapor result that suggested that the MWR scaling produced results slightly too wet was supported by subsequent analyses that indicated that the MWR precipitable water vapor (PWV) since April 2002 is 3% too high due to use of older (Rosenkranz, 1998) 22.2 GHz line width instead of updated HITRAN line width.

The Raman lidar aerosol extinction profiles were also compared with aerosol extinction profiles derived from other IOP sensors. The Twin Otter in situ aerosol extinction profiles were derived by combining the nephelometer aerosol scattering measurements with the PSAP aerosol absorption measurements. The nephelometer aerosol scattering measurements were converted to ambient relative humidity using aerosol humidification factors derived from simultaneous aircraft measurements of aerosol scattering at high relative humidity. The aerosol absorption measurements represent dry (<40% RH) conditions. In order to compare to the Twin Otter and IAP aerosol extinction profiles, the Raman lidar aerosol extinction profiles at 355 nm were converted to 450 nm using Angstrom exponents computed from the aerosol extinction values derived from the in situ Twin Otter and IAP measurements. The Raman lidar aerosol extinction profiles were, on average, significantly (33-50%) higher than the other measurements. Additional analyses indicate that the largest differences were found for low (<0.05 $km^{-1}$) aerosol extinction values and that the differences were significantly less (~10%) for higher (0.15-0.3 $km^{-1}$) values of aerosol extinction. The aforementioned reduction in the Raman lidar sensitivity led to increased calibration errors, larger random errors, and greater uncertainties in maintaining proper alignment, all of which contributed to these large differences. The extensive modifications made to the Raman lidar automated algorithms reduced but could not eliminate these adverse effects.

**Raman Lidar Upgrades**

After the Aerosol IOP, several efforts were undertaken to characterize and modify the Raman lidar to restore and/or improve its sensitivity. These efforts included: 1) replacing the outside window, 2) replacing the lens on the beam expander telescope, 3) replacing the high power laser beam turning mirrors, 4) realigning the aft optics, 5) evaluating the photomultiplier tubes, 6) replacing the detection electronics with new Licel analog/photon counting electronics, 7) modifying the motor-driven mirror mount to improve the automated alignment tweaks, 8) refinishing the primary and secondary telescope mirrors, and 9) replacing the interference filters.

We helped conduct this refurbishment and upgrade from May-September 2004. This work included replacing many of the optics in the system, resurfacing the mirrors of the primary telescope, replacing the interference filters with new filters with higher transmittance, and upgrading the detection electronics. This remediation lead to an increase in the signal-to-noise ratio of 10 and 30 for the Raman lidar's water vapor mixing ratio and aerosol backscatter coefficient data, respectively as compared to the signal strengths when the system was first deployed.

Buoyed by the success of this refurbishment and upgrade, we proposed to the ARM Science team (via the working groups) to add additional channels to the Raman lidar to profile temperature and liquid water

content. By measuring temperature profiles with the same instrument as the water vapor mixing ratio, we can derive more accurate estimates of the relative humidity, which is a critical variable for investigating the hygroscopicity of the atmospheric aerosol. Furthermore, the addition of the liquid water channel will allow us to profile liquid water content, and potentially the effective size of the droplets, in the lowest portion of the liquid water clouds. This proposed second upgrade was endorsed by the Cloud Properties and Aerosol working groups, and the Infrastructure Management Board subsequently provided funding for the activity.

During 2004, the SGP Climate Research Facility (CRF) Raman lidar (CARL) was modified in several ways to increase its sensitivity and improve and/or extend the aerosol extinction and water vapor retrievals. As part of the upgrades, new detection electronics were added to the system; these detection electronics permit the detection of data in analog-to-digital mode (A/D) as well as in the photon counting (PC) mode. The A/D conversion capabilities of the Licel electronics permits the detection of much stronger signals than could be obtained with the photon counting electronics alone, so that the attenuating neutral density filters could be reduced in the case of the high and low elastic (i.e., aerosol) channels, and eliminated in the case of the nitrogen Raman channels. As a result, the signal strengths in the aerosol and Raman nitrogen channels increased by a factor of about 10 to 20. The use of the Licel electronics also increased the maximum vertical resolution from 39 m to 7.5 m and the maximum temporal resolution from 1 minute to 10 seconds.

The addition of these A/D data required extensive modifications of the CARL data analyses software forcing us to spend a considerable amount of time to develop, implement, and test changes to the CARL aerosol and water vapor retrieval algorithms. Many of these modifications have involved combining or "gluing" the A/D and PC data together to form continuous lidar return signals. In order to use the data from the new electronics the AD and PC profiles (both maintained within the instrument) need to be merged (or "glued" together) in some fashion to create a single backscatter profile for each channel. The process of gluing (or combining the AD and PC data) is straightforward if a couple of days or limited period of time has to be processed. However, it presents a significant challenge for CARL, which operates continuously and hence requires that the gluing coefficients be determined automatically. For example, the glue coefficients cannot be derived when there are clouds in the fit region or when the solar background is too high–for some of the channels the solar background can be more than 50 MHz during the day, which brings the photon counting data far out of its region of linearity. The A/D and PC data must be carefully combined in this process otherwise artifacts associated with the transition from A/D to PC data in the near field region may be introduced in the aerosol extinction and water vapor profiles.

**September 2005 Aerosol Lidar Validation Experiment (ALIVE)**

A major objective of the DOE ARM Aerosol Lidar Validation Experiment (ALIVE), which was conducted during September 2005, was to evaluate the impact of these modifications and upgrades on the SGP Raman lidar measurements of aerosol extinction and optical thickness using airborne data were collected by the NASA Ames Airborne Tracking 14 Channel Sunphotometer (AATS 14) flown aboard the Sky Research Jetstream 31 research aircraft. Another objective was to use the AATS 14 data to evaluate the aerosol extinction profiles derived from the ARM SGP MicroPulse Lidar (MPL).

After revising and implementing the CARL analysis algorithms, we computed aerosol extinction and water vapor profiles for the ALIVE period. We evaluated these profiles using the other measurements acquired during ALIVE. The aerosol extinction profile comparisons focused on comparisons with the aerosol extinction profiles acquired by the AATS 14; during ALIVE, there were 29 available profile comparisons over 7 days between the CARL and AATS 14 measurements. These profile comparisons show that the CARL aerosol extinction measurements (355 nm) were about 0.011 to 0.015 $km^{-1}$ (21 to 36%) higher than the AATS14 aerosol extinction profiles. This bias was about a factor of two smaller than the bias derived from the May 2003 Aerosol IOP measurements. Note also that this bias is about 10% of the annual median value of aerosol extinction (355 nm) within the lowest kilometer. These initial

comparisons indicate that the CARL modifications significantly improved the accuracy and temporal resolution of the aerosol measurements.

Our investigations examined the impacts of the corrections required to address these issues on the aerosol and water vapor profiles acquired during the DOE ARM Aerosol Lidar Validation Experiment (ALIVE), which was conducted during September 2005. Our results show that these algorithm modifications to account for diurnal variation in glue coefficients, PC count rate threshold, and PC "deadtime" corrections significantly affected the instantaneous aerosol and water vapor profiles; however, these modifications caused only minor (1-2%) impacts on the average aerosol extinction profiles. These modifications caused more significant (~10%) impacts on the average water vapor profiles.

Using these algorithm modifications, the key findings from ALIVE that were reported previously were confirmed. For aerosol extinction, our investigations found that these upgrades significantly improved the accuracy and temporal resolution of the aerosol measurements. The CARL aerosol extinction bias was about a factor of two lower than the bias observed during the May 2003 Aerosol IOP (AIOP). During ALIVE, the bias was 0.011-0.14 $km^{-1}$ (20-30%) higher than the AATS14 aerosol extinction (355 nm); this bias is about 10% of the annual median value of aerosol extinction within the lowest kilometer over the ARM SGP. The average relative differences between the CARL and AATS14 values are generally comparable to the differences observed with other instruments.

CARL water vapor profiles are calibrated such that the integrated precipitable water vapor derived from the CARL profiles acquired at night matches the PWV derived from the microwave radiometer. ALIVE results show that, on average, CARL water vapor measurements were within +/-3% of the water vapor measurements from the scaled and unscaled radiosondes and airborne in situ measurements. This result showed that the daytime Raman lidar water vapor measurements had a much smaller bias relative to both in situ water vapor observations and microwave-radiometer scaled radiosonde profiles than the Raman lidar water vapor observations collected during the AIOP.

The ALIVE comparisons also revealed a diurnal variability in the CARL water vapor measurements; the CARL water vapor measurements acquired near mid-day were about 13% drier than measurements acquired at other times. We believe that this result is due to the inability of the automated routines to fully account for the diurnal nature of the A/D to PC "glue" coefficients. We are working with the ARM instrument mentor to modify these merge routines accordingly.

We have also modified the CARL water vapor calibration routines to use the daytime microwave radiometer (MWR)-scaled radiosonde data as well. The MWR-scaled radiosonde water vapor profiles have been shown to significantly reduce the sonde-to-sonde variability and consequently improve the overall radiosonde accuracy. The modified routines scale the Raman lidar water vapor profiles to match the water vapor profiles from the MWR-scaled radiosondes. This procedure has been used successfully for processing data from a test period (June 2006) and is currently being implemented for the CARL data acquired during the CLASIC/CHAPS (June 2007) experiment.

**Deliverables:**

1. Science Plan for DOE ARM Aerosol IOP (http://www.tap.bnl.gov/arm_acp_aerosol_iop/Aerosol_IOP_SciencePlan.pdf)
2. Revised algorithms for Raman lidar aerosol and water vapor retrievals to reduce impacts of loss of sensitivity (includes report discussing these changes - Turner, D.D., R.A. Ferrare, and M.B. Clayton, Summary of the processing of the aerosol data from the ARM Raman lidar for the 2003 ARM Aerosol IOP, http://iop.archive.arm.gov/arm-iop-file/2003/sgp/aerosol/ferrare-raman/2003_aerosol_iop_summary.pdf, 2003a.)
3. Revised Raman lidar Aerosol IOP data set for the May 2003 Aerosol IOP (see http://iop.archive.arm.gov/arm-iop/2003/sgp/aerosol/ferrare-raman/)

**Publications:**

1. Andrews E., P. J. Sheridan, J. A. Ogren, and R. Ferrare, In Situ Aerosol Profiles over the Southern Great Plains CART site, Part I: Aerosol Optical Properties, *J. Geophys. Res.,* 109, D06208, doi:10.1029/2003JD004025, 2004.
2. Ferrare, R.A., D.D. Turner, M. Clayton, B. Schmid, J.Redemann, D. Covert, R. Elleman, J. Ogren, E. Andrews, J.E.M.Goldsmith, H.H. Jonsson, Evaluation of Daytime Measurements of Aerosols and Water Vapor made by an Operational Raman Lidar over the Southern Great Plains, J. Geophys. Res. 111, D05S08, doi:10.1029/2005JD005836, 2006.
3. Gasparini, R., R. Li, D. R. Collins, R.A. Ferrare, V.G. Brackett, Aerosol hygroscopicity and volatility measured at the ARM SGP site and their application to investigate composition and evolution, J. Geophys. Res. 111, D05S13, doi:10.1029/2005JD006092, 2006.
4. Ghan, S.J., T. A. Rissman, R. Elleman, R.A. Ferrare, D.D. Turner, C. Flynn, J. Wang, J. Ogren, J. Hudson, H.H. Jonsson, T. VanReken, R.C. Flagan, J. H. Seinfeld, Use of In Situ Cloud Condensation Nuclei, Extinction, and Aerosol Size Distribution Measurements to Test a Method for Retrieving Cloud Condensation Nuclei Profiles from Surface Measurements, J. Geophys. Res. 111, D05S10, doi:10.1029/2004JD005752, 2006.
5. Hallar, A.G., A.W. Strawa, B. Schmid, E. Andrews, J. Ogren, P. Sheridan, R. Ferrare, D. Covert, R. Elleman, H. Jonsson, K. Bokarius, A. Luu, ARM Aerosol Intensive Operating Period: Comparison of aerosol scattering during coordinated flights, J. Geophys. Res., 111, D05S09, doi:10.1029/2005JD006250, 2006.
6. Pahlow, M., G. Feingold, A. Jefferson, E. Andrews, J. A. Ogren, J. Wang,Y.-N. Lee, R. A. Ferrare and D.D. Turner, Comparison between lidar and nephelometer measurements of aerosol hygroscopicty at the Southern Great Plains Atmospheric Radiation Measurement site. J. Geophys. Res., 111, D05S15, doi:10.1029/2004JD005646, 2006.
7. Schmid B., R. Ferrare, C. Flynn, R. Elleman, D. Covert, A. Strawa, E. Welton, D. Turner, H. Jonsson, J. Redemann, J. Eilers, K. Ricci, A. G. Hallar, M. Clayton, J. Michalsky, A. Smirnov, B. Holben, J. Barnard. How well do state-of-the-art techniques measuring the vertical profile of tropospheric aerosol extinction compare? J. Geophys. Res. 111, D05S07, doi:10.1029/2005JD005837, 2006.
8. Wang, Jian, D. Collins, D. Covert, R. Elleman, R.A. Ferrare, R.Gasparini, H. Jonsson, J. Ogren, P. Sheridan, S. C. Tsay, Temporal variation of aerosol properties at a rural continental site and study of aerosol evolution through growth law analysis, J. Geophys. Res., to be submitted, 2005.
9. Ferrare, R.A., Feingold, G., S. Ghan, J. Ogren, B. Schmid, S. Schwartz, P. Sheridan, Preface to special section on the DOE ARM May 2003 Aerosol Intensive Operations Period (IOP), J. Geophys. Res., 111, D05S01, doi:10.1029/2005JD006908, 2006.

**Presentations:**

1. "Evaluation of Terra aerosol and water vapor measurements using ARM SGP data", Ferrare, R.A., Brasseur, L.H., Clayton, M.B., Turner, D.D., Remer, L., and Gao, B.C., 11th Conference on Atmospheric Radiation, preprints, Ogden, Utah, June, 2002, 130-133. "Raman lidar profiling of aerosols and water vapor over the Southern Great Plains", R.A. Ferrare, D. Turner, M.B. Clayton, L. Brasseur, T. Tooman, J. Goldsmith, John Ogren, E. Andrews, M. Chin, International Geoscience and Remote Sensing Symposium (IGARSS'02), Toronto, Canada, June 27, 2002.
2. "Raman lidar profiling of aerosols over the central U.S.; diurnal variability and comparisons with the GOCART model", R. A. Ferrare, M. Chin, M. Clayton, and D. Turner, 21st International Laser Radar Conference, Quebec City, Canada, July 8-12, 2002, Proceedings, pp. 563-566.
3. "Comparisons of Raman lidar and aircraft in situ measurements over the ARM SGP site", M. B. Clayton, R. A. Ferrare, L. H. Brasseur, E. Andrews, D. D. Turner, and J. A. Ogren, 21st International Laser Radar Conference, Quebec City, Canada, July 8-12, 2002, Proceedings, pp. 211-214.
4. "Comparison of Raman Lidar and MicroPulse Lidar Aerosol Measurements", Felicita Russo, Belay Demoz, Igor Veselovskii, David N. Whiteman, James Campbell, Richard Ferrare, 21st International Laser Radar Conference, Quebec City, Canada, July 8-12, 2002, Proceedings, pp. 599-602.

5. "DOE ARM Aerosol Experiments", R. Ferrare, J. Ogren, S. Schwartz, S. Ghan, G. Feingold, B. Schmid, DOE ARM Instantaneous Radiative Flux Working Group Meeting, Albany, New York, October 8-10, 2002.
6. Raman Lidar Profiling of Aerosols and Water Vapor over the Southern Great Plains, Ferrare, Turner, Clayton, Ogren, Andrews, Chin, and Brackett, Presentation at Laser Radar Technology and Applications VIII (OR07) at AEROSENSE 2003, Orlando, FL, April, 2003.
7. Vertical Variability of Aerosols and Water Vapor over the Southern Great Plains, Ferrare, R.A., Turner, D.D., Clayton, M., Brackett, V., Tooman,T.T., Goldsmith, J.E.M., Ogren, J.A., Andrews,E., Welton, E.J., Campbell,J.R., and Chin, M., Presentation at DOE ARM Science Team Meeting, April, 2003.
8. "Intensive Airborne and Surface Measurements of Aerosol Microphysical and Optical Properties Planned for the Aerosol IOP", Rich Ferrare, Steve Schwartz, John Ogren, Beat Schmid, Steve Ghan, Pete Daum, Graham Feingold, Pat Sheridan, Haf Jonsson, Jens Redemann, Presentation at DOE ARM Science Team Meeting, April, 2003.
9. "Lidar Characterizations of Water Vapor Measurements over the ARM SGP Site", R. A. Ferrare, E. V. Browell, S. Ismail, J. Barrick, G. Diskin, S. Kooi, L.H. Brasseur, V.G. Brackett, M. Clayton, B. Lesht, L. Miloshevich, J. Podolske, F. Schmidlin , D. D. Turner, AMS Conference on "Observing and Understanding the Variability of Water in Weather and Climate", Feb. 2003.
10. Ferrare, R., John Ogren, Steve Schwartz, Pat Sheridan, Beat Schmid, Graham Feingold, Steve Ghan, Pete Daum, Dave Covert, Anthony Strawa, Pat Arnott, DOE ARM Aerosol Measurements, Cloud/Aerosol/Precipitation Workshop, Ventura, CA, Aug. 5-7, 2003.
11. "Airborne DIAL and Ground-Based Raman Lidar Measurements of Water Vapor over the Southern Great Plains", R. Ferrare, E. Browell, S.Ismail, S. Kooi, V.G. Brackett, M. Clayton, A. Notari, C. F. Butler, J. Barrick, G. Diskin, B. Lesht, F.J. Schmidlin, D. Turner, D. Whiteman, L. Miloshevich, SPIE Annual Meeting, San Diego, CA, August, 2004.
12. Ferrare, R.A., M. B. Clayton, W. Feltz, J. A. Ogren, E. Andrews, D. D. Turner, Measurements of Water Vapor and Aerosol Profiles over the ARM SGP Site, 6th International Symposium on Tropospheric Profiling, Leipzig, Germany, September 15-19, 2003.
13. Ferrare, R.A., D.D. Turner, M.B. Clayton, B. Schmid, J. Welton, ARM CART Raman lidar (CART) Measurements of Aerosols and Water Vapor during the May 2003 Aerosol IOP, DOE ARM Aerosol IOP Workshop, Dec. 2003.
14. Ferrare, R.A., D.D. Turner, M.B. Clayton, B. Schmid, J. Redemann, D. Covert, R. Elleman, E.J. Welton, V.G. Brackett, J.A. Ogren, E. Andrews, J.E.M. Goldsmith, SGP CART Raman Lidar Measurements during the May 2003 Aerosol IOP", Fourteenth ARM Science Team Meeting, Albuquerque, NM, March 2004. http://www.arm.gov/publications/proceedings/conf14/extended_abs/ferrare-ra.pdf
15. Ferrare, R.A., D. Turner, M. Clayton, J. Goldsmith, Growing with the automated DOE CART Raman lidar (CARL): Single laser wavelength aerosol studies, First International Raman Lidar Techniques Workshop, NASA Goddard, May 2004. http://www.ecotronics.com/events/nasa/secure/materials/index.htm
16. Ferrare, R., David Turner, Marian Clayton, Vince Brackett, Beat Schmid, Jens Redemann, David Covert, Robert Elleman, John Ogren, Elizabeth Andrews, John Goldsmith, Haf Jonsson, Ian Brooks, Raman Lidar Measurements of Aerosols and Water Vapor over the Southern Great Plains, 22nd International Laser Radar Conference, Matera, Italy, 2004.
17. Ferrare, R.A., D. Turner, M. Clayton, B. Schmid, J. Redemann, D. Zcovert, R. Elleman, J. Ogren, E. Andrews, J. Goldsmith, H. Jonsson, I. Brooks, M. Chnin, S. Guibert, M. Schulz, Raman lidar measurements of aerosols over the Southern Great Plains, IEEE Workshop on Remote Sensing of Atmospheric Aerosols, Tucson, AZ, April 2005.
18. Ferrare, R.A., D. Turner, M. Clayton, B. Schmid, J. Redemann, D. Zcovert, R. Elleman, J. Ogren, E. Andrews, J. Goldsmith, H. Jonsson, I. Brooks, M. Chnin, S. Guibert, M. Schulz, Raman lidar measurements of aerosol profiles over the Southern Great Plains during the May 2003 Aerosol IOP,

Hyperspectral sensing of the Environment, Optical Society of America, Washington, D.C., January, 2005.

19. Ferrare, R.A., D. Turner, M. Clayton, S. Guibert, M. Schulz, M. Chin, Sarah Guibert, Michael Schulz, Mian Chin, The Vertical Distribution of Aerosols Over the Atmospheric Radiation Measurement Southern Great Plains Site: Measured vs. Modeled, Fifteenth ARM Science Team Meeting, Daytona Beach, FL, March 2005. http://www.arm.gov/publications/proceedings/conf15/extended_abs/ferrare_r.pdf
20. Turner, D.D., and J.E.M. Goldsmith, 2005: The Refurbishment and upgrade of the ARM Raman lidar. Proceedings of the 15th ARM Science Team meeting, Daytona Beach, FL. Available at http://www.arm.gov/publications/proceedings/conf15/extended_abs/turner_dd1.pdf.
21. Ferrare, R.A., D. Turner, M. Clayton, S. Guibert, M. Schulz, M. Chin, Sarah Guibert, Michael Schulz, Mian Chin, The Vertical Distribution of Aerosols Over the Atmospheric Radiation Measurement Southern Great Plains Site: Measured vs. Modeled, Fourth AEROCOM Workshop, Oslo, Norway, June 2005.
22. Flynn, C.J., Mendoza, A, Remote Sensing of Aerosols with Micropulse Lidar: Slant-Path Measurements at NEAQS-ITCT 2004. IEEE Workshop on Remote Sensing of Atmospheric Aerosols, Tucson, AZ, April 2005
23. C. J. Flynn, A. Mendoza, D. D. Turner, J. Comstock, S. A. McFarlane, and J. Mather, Observation of Clouds and Aerosol with Elastic Backscatter Depolarization LIDAR During the Mixed-Phase Arctic Cloud Experiment, San Diego, CA, January 2005
24. J.M. Comstock, C.J. Flynn, C.N. Long, R.T. Marchand, J. H. Mather, S.A. McFarlane, A. Mendoza, D. D. Turner, K. Widener, Microphysical Properties of Arctic Mixed-Phase Clouds Using Ground-Based Remote Sensors. San Diego, CA, January 2005
25. Connor Flynn, Jason Christy and Sherman Beus, Autonomous Retrieval of Cloud and Aerosol Properties from ARM Micropulse Lidar, Proceedings of the 15th ARM Science Team meeting, Daytona Beach, FL
26. C. J. Flynn, A. Mendoza, D. Hopkins, MPL Hardware Upgrades and New Measurement Capabilities, Proceedings of the 15th ARM Science Team meeting, Daytona Beach, FL
27. Ferrare, R. A., M. Clayton, D. Turner, M. Chin, S. Guibert, M. Schulz, B. Andrews, V. Brackett, C. Butler, E. Browell, Vertical Distribution of Aerosols over the ARM SGP, Measured vs. Modeled, Fourth AEROCOM Workshop, June 2005, Oslo, Norway, http://nansen.ipsl.jussieu.fr/AEROCOM/weboslo05.htm#VERTICAL DISTRIBUTION
28. Ferrare, R.A., D. Turner, M. Clayton, M. Chin, S. Guibert, M. Schulz, C. Chuang, M. Krol, S.E. Bauer, X. Liu, G. Myhre, O. Selund, D. Fillmore, S. Ghan, S. Gong, P. Ginoux, T. Takemura, The Vertical Distribution of Aerosols: Lidar Measurements versus Model Simulations, Sixteenth ARM Science Team Meeting, Albuquerque, New Mexico, March 2006. http://www.arm.gov/publications/proceedings/conf16/author.stm#F
29. Ferrare, R. A., David D. Turner, Connor Flynn, Diana Petty, Albert Mendoza, Marian Clayton, and Beat Schmid, Raman lidar and MPL Measurements during ALIVE, 7th International Symposium on Tropospheric Profiling, Boulder, CO, June 2006.
30. Ferrare, R.A., Aerosol Profiling needs for climate and air quality research, 7th International Symposium on Tropospheric Profiling, Boulder, CO, June 2006.
31. R. A. Ferrare, E.V. Browell, J.W. Hair, S. Ismail, D. D. Turner, M. Clayton, C.F. Butler, V.G. Brackett, M.A. Fenn, A. Notari, S.A. Kooi, S. Burton, M. Chin, S. Guibert, M. Schulz, C. Chuang, M. Krol, S. E. Bauer, X. Liu, G. Myhre, O. Seland, D. Fillmore, S. Ghan, S. Gong, P. Ginoux, T. Takemura, The Vertical Distribution of Aerosols: Lidar Measurements vs. Model Simulations, 23rd International Laser Radar Conference, Nara, Japan, July 2006.
32. Determination of vertical profiles of aerosol extinction, single scatter albedo, and asymmetry parameter at Barrow. C. Sivaraman, C. Flynn, and D. Turner. 16th ARM Science Team meeting, Albuquerque, NM, March, 2006.

33. Combined analog-to-digital and photon counting detection utilized for continuous Raman lidar measurements. D. Petty and D.D. Turner. 23rd International Laser Radar Conference, Nara, Japan, July, 2006.
34. C. J. Flynn, A. Mendoza, Invited Speaker, MPL-PS, Polarization is not a Post-Script, OPTEC Conference, Bozeman MO, Sept 2006.
35. R. A. Ferrare, E.V. Browell, J.W. Hair, S. Ismail, D. D. Turner, M. Clayton, C.F. Butler, V.G. Brackett, M.A. Fenn, A. Notari, S.A. Kooi, S. Burton, M. Chin, S. Guibert, M. Schulz, C. Chuang, M. Krol, S. E. Bauer, X. Liu, G. Myhre, Ø. Seland, D. Fillmore, S. Ghan, S. Gong, P. Ginoux, T. Takemura, The Vertical Distribution of Aerosols: Lidar Measurements vs. Model Simulations, Fifth AEROCOM Workshop, June October 2006, Virginia Beach, VA, http://nansen.ipsl.jussieu.fr/AEROCOM/webvb06.html
36. Ferrare, R.A., D. Turner, M. Clayton, D. Petty, C. Flynn, B. Schmid, Aerosol and Water Vapor Measurements Acquired by the Upgraded SGP Raman Lidar During ALIVE, Albuquerque, New Mexico, March 2006. http://www.arm.gov/publications/proceedings/conf17/index.php?sort=author#F
37. Bedka, S., and D.D . Turner, Characterization of Dust Type and Properties at Niamey, Niger, Using AERI Downwelling Infrared Radiance Data, 17th ARM Science Team Meeting, Monterey, CA, March 2007.
38. Russo, F., D.N. Whiteman, and D.D. Turner, Measurements of Liquid Water Content with the Atmospheric Radiation Measurement Program Raman Lidar at the Southern Great Plains, 17th ARM Science Team Meeting, Monterey, CA, March 2007.
39. McComiskey, A., G. Feingold, S. Frisch, Q. Min, D. Turner, and M. Miller, Aerosol/Cloud Interactions at Point Reyes, California, 17th ARM Science Team Meeting, Monterey, CA, March 2007.
40. Flynn, C., A. Mendoza, R. Ferrare, D. Turner, D. Petty, M. Clayton, B. Schmid, R. Johnson, and M. Truong, Comparison of Aerosol Extinction Profiles from Micropulse Lidar, Raman Lidar, and NASA Ames Airborne Tracking Sunphotometer During the 2005 Aerosol Lidar Validation Experiment (ALIVE) at SGP, 17th ARM Science Team Meeting, Monterey, CA, March 2007.