Final Technical Report for Interagency Agreement No. DE-SC0006898
"Lidar Investigations of Aerosol, Cloud, and Boundary Layer Properties Over the ARM ACRF Sites"

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OBJECTIVE: Project goals:

- Characterize the aerosol and ice vertical distributions over the ARM NSA site, and in particular to discriminate between elevated aerosol layers and ice clouds in optically thin scattering layers.
- Characterize the water vapor and aerosol vertical distributions over the ARM Darwin site, how these distributions vary seasonally, and quantify the amount of water vapor and aerosol that is above the boundary layer.
- Use the high temporal resolution Raman lidar data to examine how aerosol properties vary near clouds
- Use the high temporal resolution Raman lidar and Atmospheric Emitted Radiance Interferometer (AERI) data to quantify entrainment in optically thin continental cumulus clouds
- Use the high temporal Raman lidar data to continue to characterize the turbulence within the convective boundary layer and how the turbulence statistics (e.g., variance, skewness) is correlated with larger scale variables predicted by models.

Accomplishments:

Development of the Raman Lidar (RLID) temperature derivation algorithm Value-Added Product (VAP) – The RLID was upgraded in 2005 to include channels sensitive to the rotational Raman scattering of nitrogen and oxygen molecules. During this period, we worked with the RLID instrument mentor (Rob Newsom) to develop an automated algorithm to derive ambient temperature profiles from these new observations. This algorithm [Newsom et al. 2013] had to overcome two significant challenges in order to run in an autonomous mode: a robust method to determine the near-field overlap correction to allow the temperature profile to be measured below the region of full optical overlap (i.e., below 4 km), and a method to calibrate the derived profile. The latter method needed to account for the solar background, as the change in the signal-to-noise in the rotational Raman channels over the diurnal cycle impacted the absolute calibration. The algorithm was implemented as a Value Added Product (VAP) in the ARM Data Management Facility, and is currently producing both 10-min and 60-min resolution data.

Development of the AERIoe retrieval algorithm – The infrared radiance observations made by the AERI are very sensitive to the profile of the temperature and humidity in the BL, and early ARM investigators developed a retrieval algorithm called *AERIprof* to derive thermodynamic profiles from these observations and use them in a range of studies [e.g., Feltz et al., 1998, 2003]. However, the *AERIprof* algorithm was only able to provide data when the sky overhead was cloud free, and thus only provided retrievals approximately 35% of the time (depending on site and season). We have developed a new algorithm, called *AERIoe* [Turner and Löhnert 2014], which is able to retrieve thermodynamic profiles in both clear and cloudy scenes, and thus is able to provide boundary layer profiles over 95% of the time. The *AERIoe* algorithm simultaneously retrieves the thermodynamic profiles with the cloud properties (in cloudy scenes), and also provides a full error characterization (i.e., posterior covariance matrix and 1-sigma error bars) for each of the retrieved profiles. The accuracy of the retrieved temperature and humidity profiles in clear vs. cloudy scenes (below cloud base) is very similar [Turner and Löhnert 2014], and the data are being used in a wide range of studies (e.g., to investigate the role of stability in the evolution of low level jets [Klein et al. 2014]). The algorithm is also able to provide estimates of the column amounts of CO_2, CH_4, and N_2O, and work is currently underway to evaluate the accuracy of these trace gases.

Evaluation of the turbulent profiles observed by the SGP RLID with aircraft observations – Turbulence is a stochastic process that is often described using statistic moments of various variables that can be assumed to be a tracer for atmospheric motion (such as water vapor mixing ratio (q), in the absence of condensation and precipitation). After the upgrade of the RLID with new detection electronics in 2005 [Ferrare et al. 2006], the system became much more sensitive and able to provide profiles of q throughout the CBL at 10-s, 75-m resolution. An initial study was performed that demonstrated that the SGP RLID had the proper sensitivity to derive profiles of the second- and third-order moments, and thus also the skewness, of the q profile in the CBL [Wulfmeyer et al. 2010]. The technique [Lenschow et al. 2000] used to derive the second- and third-moment profiles of q that accounts for and removes the contribution from the random instrument noise; this is important because the RLID q observations in the daytime are quite noisy due to the high solar background in the detection channel sensitive to the Raman scattering by water vapor molecules. To ensure that the technique we were using to derive the variance and skewness profiles of q were accurate, we derived variance and skewness value of q from in-situ aircraft observations of q during level legs during RACORO [Vogelmann et al. 2012]. Data from two of these flights demonstrated that our techniques to separate instrument noise from atmospheric variance and skewness worked well [Turner et al. 2014a], giving us confidence to analyze these turbulence profiles over a much larger dataset.

Development of a 300-case dataset 2nd and 3rd order moment water vapor profiles – We selected 300 cases from the RLID data record from 2005-2011 to develop a climatology of the variance and skewness of q in the CBL, and to investigate relationships between the magnitude of the variance and skewness (especially in the entrainment zone at the top of the CBL) and geophysical variables that are predicted by large-scale models (e.g., water vapor gradient at the top of the CBL, surface parameters such sensible and latent heat flux, etc.). This study [Turner et al. 2014b] demonstrated that there is a good correlation between the magnitude of the q variance at the top of the CBL and the vertical gradient in q at this level, and that the magnitude of the variance of q at the top of the CBL can be used to predict the shape of the third-moment and skewness profile from the middle-to-top of the CBL.

Characterization of the Darwin RLID, and development of an aerosol and water vapor profile climatology – Eighteen months of data from the Darwin RLID were used to develop an aerosol and water vapor climatology in the Darwin region. Darwin experiences three distinct climate patterns annually, comprising of 1) a dry continental regime, 2) a wet monsoon season, and 3) a transition period between the dry and wet seasons. The RLID observations were separated into different synoptic classes using the technique developed by Evans et al. [2012], and the mean and standard deviation profiles of water vapor mixing ratio and aerosol properties during these three distinct climate regimes were derived. These profiles show that the variability in water vapor and aerosol extinction profiles is smallest during the wet season (Austral summer) and largest during the dry season (Austral winter) [Mishra et al. 2014a]. Average aerosol extinction/backscatter "lidar ratio" profiles increase with altitude in several cases indicating that the aerosol type often varies with altitude. This variation may be associated with the presence of sea salt aerosol near the surface and biomass burning smoke aloft. The distribution of water vapor and aerosols is in alignment with the synoptic classification scheme based on ECMWF classification.

BL height retrieval algorithm development over the SGP and Darwin – In order to provide a better representation of the BL height during the diurnal cycle, we developed algorithms that use potential temperature profiles derived from a combination of RLID and AERI measurements. The AERI potential temperature profiles were spliced onto the bottom of the RLID potential temperature profiles. This combination of measurements was used to take advantage of the different performance characteristics of the RLID and AERI instruments. The BL heights computed for the SGP site for the period 1 Jan 2009 through 31 Dec 2011 were submitted to the ARM archive and are now available as a PI product (under SGP/Ferrare). The BL heights computed using the RLID and AERI measurements were compared with those in the new BL height VAP being developed by the ARM infrastructure (http://www.arm.gov/data/eval/58). The BL height VAP computes BL heights with several different methods that use radiosonde measurements of temperatures and winds. Overall the comparisons showed that the differences among the results were due primarily to the differences in the BL techniques rather than the sources of the potential temperature profiles. The BL heights computed from the RLID and AERI potential temperatures were generally in better agreement with the corresponding heights computed from the radiosonde data than were the mixed layer heights computed using the Raman lidar water vapor and aerosol profiles [Ferrare et al. 2013].

Comparison of mixed-layer heights from airborne HSRL with WRF-Chem during CARES – The NASA LaRC airborne High Spectral Resolution Lidar (HSRL) was deployed to California on board the NASA LaRC B-200 aircraft to aid in characterizing aerosol properties during the Carbonaceous Aerosol and Radiative Effects Study (CARES) field campaign in 2010. The HSRL ML heights were used to evaluate the performance in simulating the temporal and spatial variability of ML heights from the Weather Research and Forecasting Chemistry (WRF-Chem) community model. Hourly WRF-Chem simulations were extracted along the HSRL flight track using the Aerosol Modeling Testbed software tools. Scarino et al. [2013] demonstrated that the WRF-Chem under-predicted the ML heights when the ML height was low, but tended to over predict when the ML height was large. There was generally good agreement over the flat terrain in the Central Valley, but on certain days WRF-Chem did not correctly represent the diurnal growth of the mixed layer and distributed aerosol over a much taller ML than measurements indicated, up to twice the measured ML height. In contrast, the complex terrain and bodies of water in the San Francisco Bay and Sierra Nevada regions introduced larger uncertainties in the simulated interaction of surface fluxes, boundary layer mixing, and ambient winds or there were local variations in the ML depth that the model did not resolve using a grid spacing of 4 km. The HSRL aerosol ML heights provided additional information for validating and improving model ML heights by providing the means to distinguish between biases due to BL parameterizations from those due to other factors such as interaction with synoptic meteorology.

Utilized observations of skewness and kurtosis in CBL to characterize turbulence – In 2012, the University of Wisconsin – Madison deployed an HSRL (which is very similar to the ARM HSRLs) in Norman, Oklahoma, as part of the DC3 field experiment. This provided a unique opportunity to evaluate the utility of HSRL measurements to characterize turbulent motions in the continental CBL. The extremely low noise in the HSRL measurements allowed us to derive profiles of the second-, third-, and fourth-moment of aerosol backscatter from the HSRL, and hence we were able to derive profiles of variance, skewness, and kurtosis [McNicholas and Turner 2014]. The lidar was deployed for over 2 months, from which we identified 17 cases for our analysis. The relative humidity for these cases was always below 80% in the CBL, as observed by NWS-launched radiosondes in Norman, and thus we were able to neglect the impact of hygroscopic growth on these higher order moment profiles. The results demonstrated that the aerosol backscatter skewness profile crossed from negative to positive values just below the top of the CBL, matching the results seen in the q skewness results from Turner et al. [2014b]. Furthermore, the skewness and kurtosis profiles demonstrated that the turbulent motions are not Gaussian at any height in the upper portion of the CBL through the entrainment zone (Figure 4), but that a simple two-scale mass-flux model does fit the observations well [McNicholas and Turner 2014].

Lower Atmospheric Boundary Layer Experiments (LABLE-I and –II) – Two small, low-cost, field experiments were conducted at the SGP site in the fall of 2012 and summer of 2013 wherein multiple Doppler lidars were deployed to evaluate novel scanning strategies to characterize the turbulent motions in the lowest 2 km across the diurnal cycle [Klein et al. 2014]. Another unique aspect of these experiments was the lead role of graduate students in the design and execution of the experiment, and analysis of the resulting datasets. The analysis has focused on development of low level jets, their interaction with mesoscale disturbances, and the spatial variability (across scales of hundreds of meters) of the turbulence in the CBL. A unique event that was sampled during LABLE-I was an extremely intense dust storm on 18 Oct 2012, which led to multiple accidents on Interstate Highway 35 between Wichita and Ponca City [Mishra et al. 2014b]. Data from these experiments, which have been uploaded to the ARM IOP data archive, have contributed to two PhD dissertations and one MS thesis at the University of Oklahoma.

NSA HSRL measurements of aerosols and ice clouds – Ground-based High Spectral Resolution Lidar (HSRL) measurements of particulate backscatter and depolarization were used to discriminate and identify ice, liquid water, and aerosol (e.g. dust, pollution) using a classification scheme developed at the University of Wisconsin [Bourdages et al. 2009]. High values of depolarization correspond to nonspherical particles such as dust and ice while low values correspond to spherical particles (e.g. haze, liquid water). High values of backscatter correspond to clouds. The HSRL measurements were also combined with data from the Ka-band ARM zenith radar (KAZR) to help study the distributions and properties of clouds over the NSA. KAZR reflectivity measurements were combined with the HSRL backscatter measurements to compute backscatter color ratios, which were then used with the HSRL depolarization measurements to classify the aerosols and clouds over the NSA. Classifications were performed for selected days in May, June, and August 2011 and February 2013. Aerosol extinction/backscatter ratios were computed using the HSRL integrated backscatter profiles and column aerosol optical thicknesses provided by the ARM Sun photometer and MFRSR instruments as well as by NOAA Carter-Scott Sun photometers. These lidar ratios were used to compute aerosol extinction profiles and optical thickness. The aerosol extinction/backscatter ratios typically varied around 60 sr, which is a value often associated with biomass burning smoke.

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