Atmospheric Radiation Measurement Program Raman Lidar at Southern Great Plains: New Measurement Capabilities

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Introduction

The Atmospheric Radiation Measurement Program (ARM) Raman Lidar (CARL) was designed and deployed for the purpose of collecting a long-term observational data set that can be used to study and improve the understanding of processes that affect atmospheric radiation and the description of these processes in climate models [1]. It operates as an unattended, turn-key system for profiling tropospheric water vapor, aerosol and clouds around-the-clock [2]. It has been in continuous operation since February 1998 and a unique set of over 45,000 hours (over 5 years) of data is now available. The uptime for CARL since February 1998 is shown in Figure 1. The main down periods are associated with refurbishments and upgrades of the system.

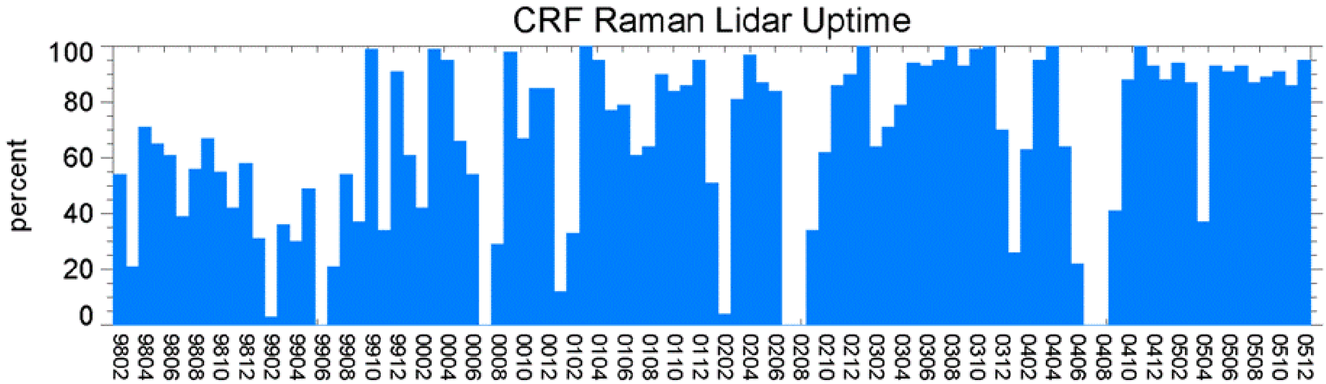

Figure 1. Histogram of the percentage of time when the Raman lidar was operational for each month for the period February 1998 through December 2005.

Automated algorithms are used to routinely derive profiles of water vapor mixing ratio, relative humidity, aerosol/cloud scattering ratio, aerosol/cloud backscatter coefficient, aerosol extinction coefficient, linear depolarization ratio and cloud boundaries [3]. Integrated products, such as total precipitable water vapor and aerosol/cloud optical thickness are routinely computed as well. The accumulated data set has been utilized in climatological as well as intensive observational period (IOP) studies of the indirect effect of aerosol on cloud formation, the effect of aerosol on the clear-sky radiative flux, the evolution of the planetary boundary layer (PBL), and the role of ice supersaturation in cirrus cloud formation (e.g., 4,5,6,7,8).

Recently, new measurement capabilities were added to CARL – the ability to profile atmospheric temperature and liquid water content/ice water content (LWC/IWC). These new capabilities will allow us to improve the quality of some of the derived products, which currently use temperature from other sources, and will promote such studies as investigation of the formation and persistence of ice clouds over the SGP and validation of co-located sensors.

Instrument and Measurements Overview

CARL is situated at the SGP central facility in north-central Oklahoma (36.61N, 97.49W). The system uses a frequency tripled Nd:YAG laser, transmitting nominally 350 mJ pulses of 355 nm light into the atmosphere at 30 Hz. The outgoing laser beam is expanded 15 times to achieve eye safety. The eye safety is an important consideration for an automated system and the reason why the fundamental and the second harmonic wavelengths of the laser are not transmitted. The backscattered light is collected with a 61-cm telescope. The system measures backscattered light at the laser wavelength (aerosol return), as well as 408 and 387 nm (water vapor and nitrogen Raman shifted returns, respectively). The aerosol return is split into copolarized and cross-polarized channels with respect to the laser's output in order to compute the linear depolarization ratio. Additional details on the configuration of the Raman lidar can be found in [2] and [9].

The "original" Raman lidar, which began its continuous autonomous operation in early 1998 was collecting data with vertical resolution of 39-m in photon counting mode. The data were typically averaged for approximately 1740 laser shots, which corresponds to 1-min datasets. Unfortunately, the Raman lidar began degrading in early 2002. This loss of sensitivity, which affected all observed variables, was very gradual and thus was not identified until the autumn of 2003. The degradation and its impact on Raman lidar data are reported in [10] and [11].

New Capabilities

In an attempt to restore CARL's sensitivity back to its nominal level, a variety of optical components were replaced and the original photon counting electronics were replaced with new detection electronic system, that combines photon counting (PC) and analog (AD) detection electronics into a single package. This combination of PC and AD electronics extend the dynamic range of each channel to over 500 MHz, and thus allowed for the neutral density filters (used to keep the photon counting signal level in the range where it can be successfully corrected for photon pile-up) to be removed or reduced [11]. The new electronics also increased the maximum vertical resolution of the raw data from 39 m to 7.5 m.

In order to use the data from the new detection electronics, however, the AD and PC profiles 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. More details on the way we apply the gluing to the Raman lidar data can be found at [12].

The removal of the neutral density filters greatly improved the signal-to-noise (SN) ratio and thus allowed for measurements with increased vertical and temporal resolution. Figure 2 shows the evolution of the PBL during the afternoon (in the water vapor mixing ratio (top) and aerosol scattering ratio (bottom) data), captured with the new 10 sec resolution. The black circles represent the cloud base. High resolution observations such as these have the potential for helping us understand boundary layer processes such as fair weather convection, structure of atmospheric boundaries (fronts, dry lines, etc.), boundary layer growth / decay, aerosol and cloud interactions, etc. It should be noted, however, that the resolution used in this example is the maximum possible resolution and we still may need to trade off either the vertical or the temporal resolution to reduce random error.

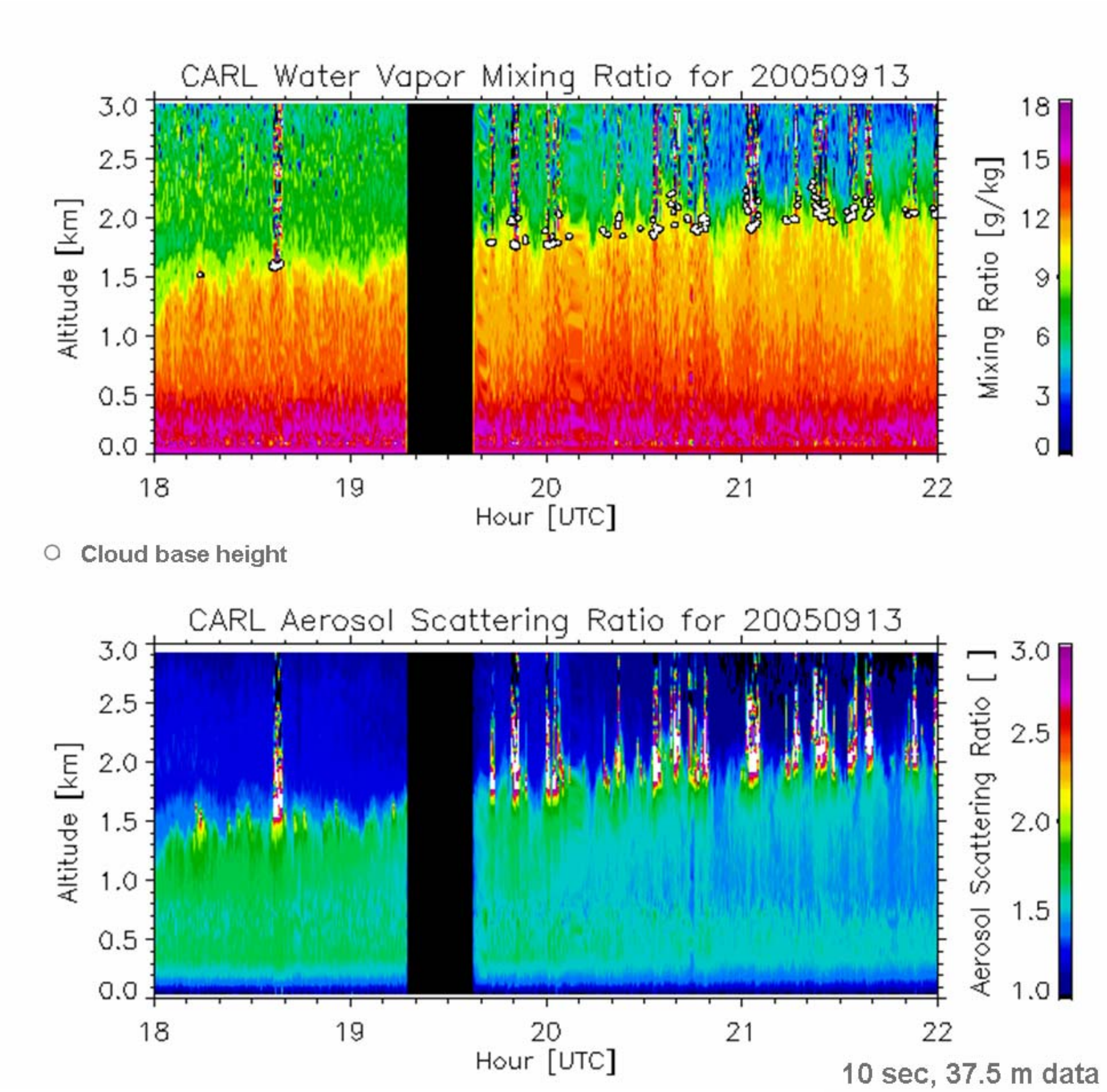

Figure 2. High resolution water vapor mixing ratio and aerosol scattering ratio derived from Raman lidar measurements on September 13, 2005. The vertical resolution is 37.5 m. The temporal resolution is 10 seconds. The cloud base height is represented by oval symbols.

Since November 2005, CARL measures the Raman shifted return from the liquid or ice water (403 nm) and the rotational Raman returns at 353 and 354 nm (for temperature measurements). An example of the temperature profiles derived from the Raman lidar and compared to a collocated radiosonde is shown on Figure 3. The Raman lidar data is averaged for 1.2 hours and 60 m. The agreement between the Raman lidar and the radiosonde is better than 2 degrees throughout the troposphere.

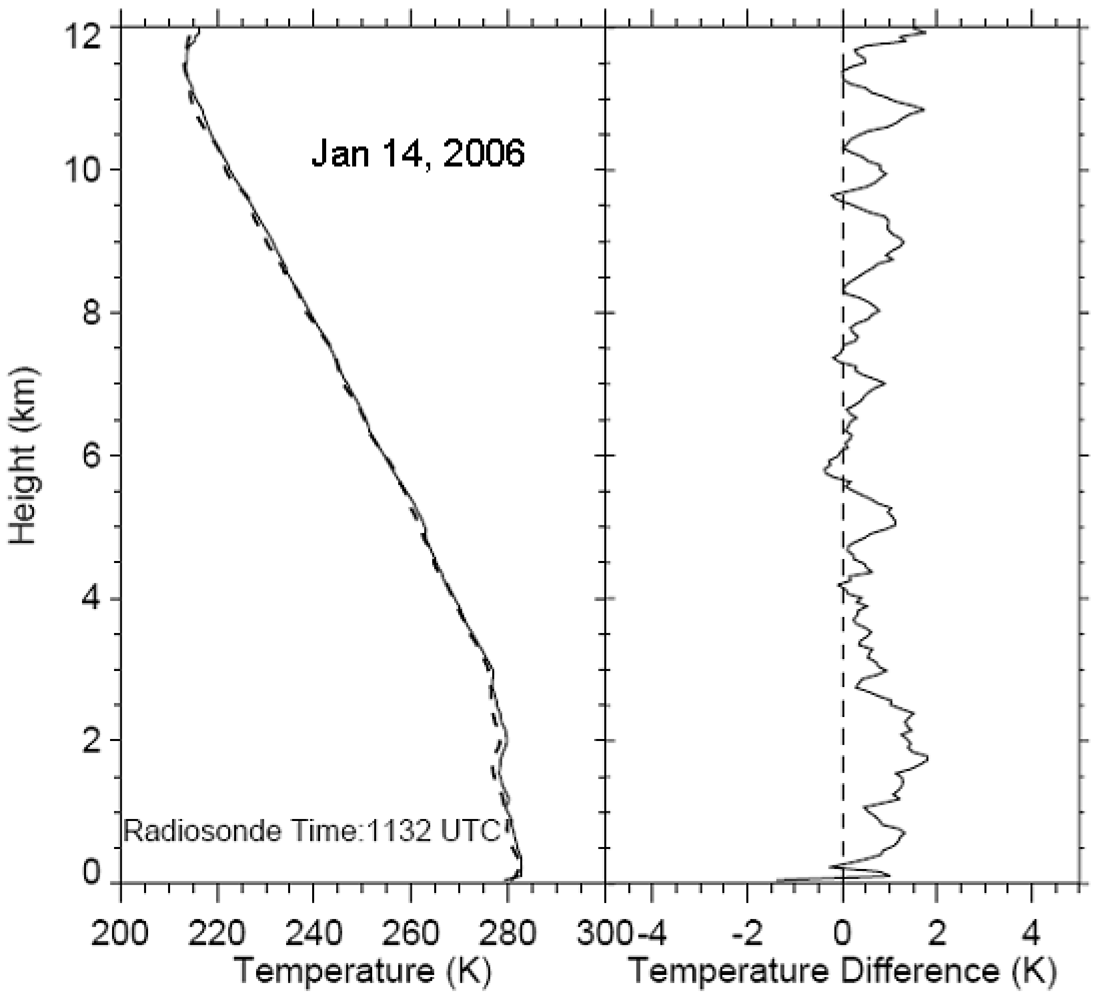

Figure 3. (top) Comparison of radiosonde (solid line) and Raman lidar (dashed line) temperature profiles at 5:32 local time on January 14, 2006 and (bottom) the difference temperature from lidar minus temperature from sonde.

Initial results for derived ice (or liquid) water ratio for a cirrus cloud are shown in Figure 4. A single channel is used for detection of the liquid and ice water and the discrimination between the ice and the liquid water is based on the value of the observed depolarization ratio. The ice (or liquid) water ratio is defined as the ratio of the "ice (or liquid) water" signal to the nitrogen signal and is proportional to the ice or liquid water mixing ratio. The signal in the ice (liquid) channel is rather weak, however, and the ice (liquid) water ratio could be derived only for the first couple hundred meters above the cloud base, as can be seen from Figure 4 (bottom). Initial calculations suggest that this is probably the best penetration depth we would be able to achieve with the averaging applied for this case (1 min and 90 m). As can be seen from the same figure, the day time measurements (12-24UTC) of ice or liquid water are hindered by the strong solar background, which results in a very low SN ratio.

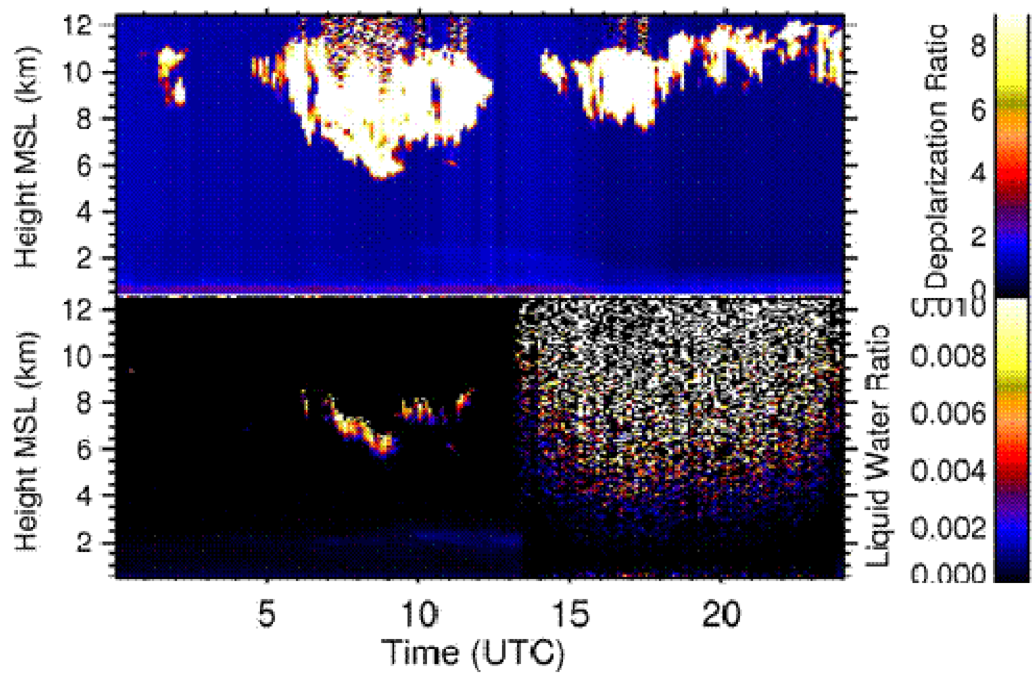

Figure 4. Depolarization ratio (top) and ice (or liquid) water ratio in relative units (bottom) derived from Raman lidar measurements on December 31, 2005. The vertical resolution is 60 m. The temporal resolution is 10 minutes.

Future

The refurbishments and the upgrade of the Raman lidar with new detection electronics and new channels for detection of liquid or ice water and temperature measurements greatly improved CARL's performance and its measurement abilities. Our current efforts are concentrated on releasing the data set accumulated since September 2004 (after the upgrade) to the public and developing algorithms to derive the new products - temperature and liquid (ice) water content. Future improvement to the system will include implementation of new automatic alignment system from Licel, GbR. (Berlin, Germany).

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References

1. Stokes, GM and SE Schwartz. 1994. "The Atmospheric Radiation Measurement (ARM) Program: Programmatic background and design of the cloud and radiation test bed." *Bulletin of the American Meteorological Society*, 75:1201-1221.

2. Goldsmith, JEM, et al. 1998. "Turn-Key Raman lidar for profiling atmospheric water vapor, clouds, and aerosols." *Applied Optics*, 37:4979-4990.

3. Turner, D, et al. 2002. "Automated retrievals of water vapor and aerosol profiles over Oklahoma from an operational Raman lidar." *Journal of Atmospheric and Oceanic Technology*, 19:37-50.

4. Pahlow, M, et al. 2006. "Comparison between lidar and nephelometer measurements of aerosol hygroscopicity at the Southern Great Plains Atmospheric Radiation Measurement site." *Journal of Geophysical Research*, 111:D05S15, doi:10.1029/2004JD005646.

5. Ghan, SJ, et al. 2006. "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." *Journal of Geophysical Research*, 111:D05S10,doi:10.1029/2004JD005752.

6. Comstock, JM, TP Ackerman, and DD Turner. 2004. "Evidence of high ice supersaturation in cirrus clouds using ARM Raman lidar measurements." *Geophysical Research Letters*, doi:10.1029/ 2004GL019705.

7. Turner, DD, RA Ferrare, and LA Brasseur. 2001. "Average aerosol extinction and water vapor profiles over the Southern Great Plains." *Geophysical Research Letters*, 28:4441-4444.

8. Ferrare, RA, et al. 2001. "Raman lidar measurements of the aerosol extinction-to-backscatter ratio over the Southern Great Plains." *Journal of Geophysical Research*, 106:20333-20348.

9. Turner, DD and JEM Goldsmith. 1999. "Twenty-four- hour Raman lidar measurements during the Atmospheric Radiation Measurement program's 1996 and 1997 water vapor intensive observation periods." *Journal of Atmospheric and Oceanic Technology*, 16:1062-1076.

10. Ferrare, R, et al. 2006. "Evaluation of daytime measurements of aerosols and water vapor made by an operational Raman lidar over the Southern Great Plains." *Journal of Geophysical Research*, 111:D05S08, doi:10.1029/2005JD005836.

11. Turner, D and J Goldsmith. 2005. "The Refurbishment and Upgrade of the Atmospheric Radiation Measurement Raman Lidar." Presented at the *Fifteenth ARM Science Team Meeting Proceedings*, Daytona Beach, Florida, March.

12. Petty, D and D Turner. 2006. "Combined Analog-to-Digital and Photon Counting detection utilized for continuous Raman lidar measurements." In the *Proceedings (the electronic version) of the 23d International Laser radar Conference,* Nara, Japan.