NASA/GSFC Scanning Raman Lidar Participation in WVIOP2000 and AFWEX

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Introduction

Due to the great radiative importance of water vapor (WV), its large variability on both time and space scales, and the difficulty of quantifying it, the U.S. Department of Energy (DOE) sponsored two major field campaigns in the fall of 2000 at the Southern Great Plains (SGP) Cloud and Radiation Testbed (CART) site focused on characterizing and improving atmospheric measurements of WV. Water Vapor Intensive Operational Period (WVIOP) 2000, held in September-October, was concerned with WV measurements in the lower atmosphere while the ARM-Fire (Atmospheric Radiation Measurement-First ISCCP [International Satellite Cloud Climatology Program] Regional Experiment) Water Vapor Experiment (AFWEX) dealt with upper tropospheric measurements. The National Aeronautic and Space Administration/Goddard Space Flight Center (NASA/GSFC) Scanning Raman Lidar (SRL) participated in both of these campaigns. We report here on measurements of WV, aerosols, and cirrus clouds using upgrades to the SRL that permitted significantly improved WV measurement performance. In addition, we present analysis of the SRL system noise using spectral techniques.

The Scanning Raman Lidar

The NASA/GSFC SRL is a mobile system contained in a single environmentally controlled trailer. It includes two lasers (XeF excimer and Nd:YAG), a 0.76-meter telescope and large-aperture scanning mirror. Using Raman scattering from atmospheric molecules, it measures WV, nitrogen, oxygen, and Rayleigh-Mie signals. Derived products from the system include WV mixing ratio, aerosol scattering ratio and extinction, cloud OD, and cloud base height. Windows that transmit in the ultraviolet (UV) permit measurements during rainfall. A more complete description of the SRL has recently been published (Whiteman and Melfi 1999). During the WVIOP, the SRL nighttime measurements were made predominantly with the excimer laser, which enabled scanning to be done for comparisons with the stationary sensors on the 60-m tower. The daytime measurements acquired during WVIOP were made with the Nd:YAG laser. During AFWEX, all measurements were made using the Nd:YAG laser, which provided improved upper tropospheric retrievals of WV, one of the main goals of the IOP.

SRL Upgrades Prior to WVIOP and AFWEX

Narrowband, narrow field-of-view measurements of WV in the daytime using the Raman Lidar technique are difficult due to high background light levels. Furthermore, much experience in the past in Raman Lidar development has demonstrated the general preference for photon-counting data acquisition versus analog to digital detection for small signal levels. Therefore, both the SRL and the DOE's CART Raman Lidar (CARL) were originally designed with only photon-counting data acquisition systems. This required that the WV signal strength be attenuated during the daytime by approximately a factor of 10 to permit the signals to be acquired using photon counting. However, new data acquisition electronics that combine analog and photon-counting detection technology now permit the x10 attenuation to be removed. They also provide 7.5-meter range resolution. The SRL was deployed to the SGP site with these new devices that, along with narrower bandpass filters, permitted significantly improved WV measurements during both daytime and nighttime. Examples of these measurements are shown in Figures 1 and 2. Figure 1 shows a comparison of the SRL and CARL measurements of WV during the daytime on October 2, 2000. The improved signal-to-noise of the SRL measurements (more than a factor of 2) compared to the CARL measurements is demonstrated by the improved consistency of the data above 3 km. Figure 2 shows a comparison of upper tropospheric WV measurements acquired by the SRL and CARL on the night of December 5, 2000. Both measurements used a 30-minute integration. The SRL errors are also plotted showing 10% random error for all altitudes less than 13 km. We believe that the SRL measurements shown in these figures represent some of the best WV measurements ever acquired by lidar.

Spectral Characterization of Noise

One of the research activities that has emerged from the WVIOP involves a comparison of simultaneous measurements from three WV lidar systems. The groups from NASA/GSFC, the Max Planck Institute, and Sandia National Labs have agreed to make a standard set of comparisons of each other's data to establish and validate techniques for doing such comparisons. A single dataset has been chosen to study the results of the different groups. This effort will focus on the following three comparisons:

1. Noise characterization using both spectral techniques and standard error propagation.

2. Comparison of profiles versus height.

3. Comparison of calibration constancy over time with the focus being the day/night transition period.

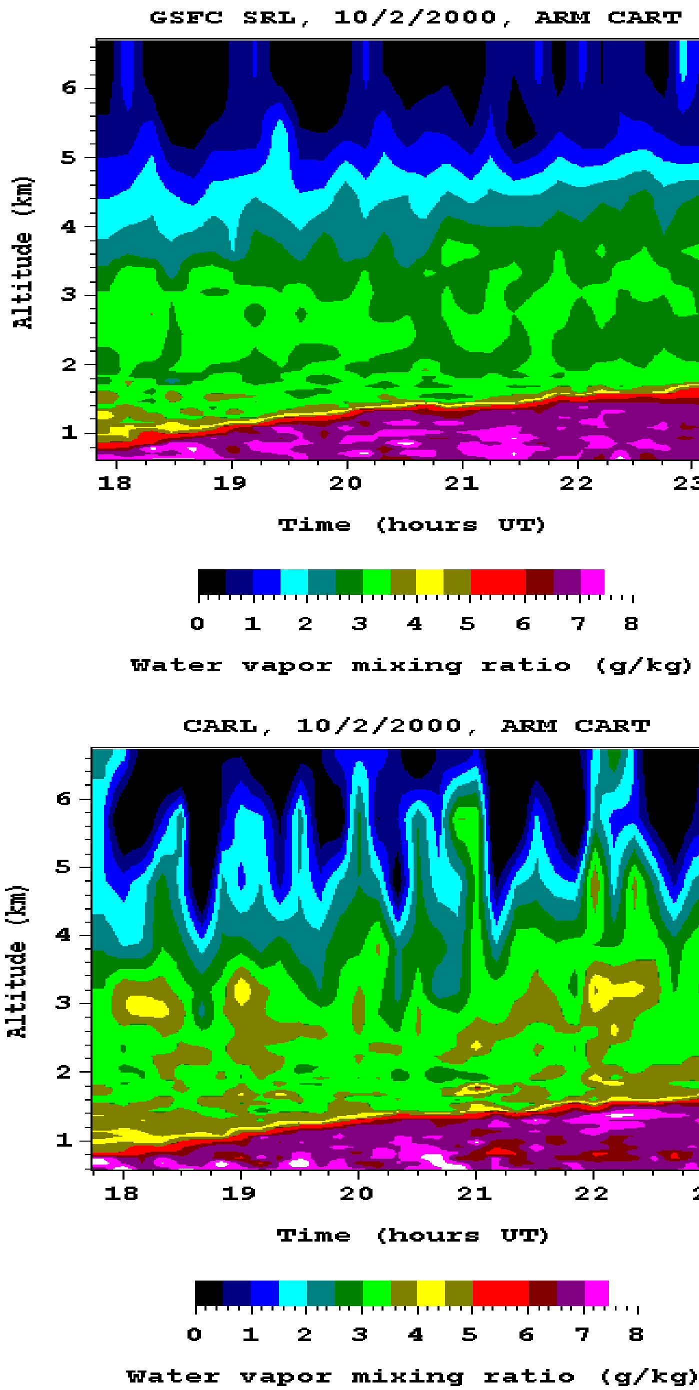

Figure 1. Comparison of daytime WV mixing ratio measurements of the SRL and CARL Raman Lidars on October 2, 2000, during the WVIOP2000 campaign. The increased signal strength of the SRL permitted significantly improved measurement, which can be seen in the greater consistency of the WV measurements above 3 km. A 10-minute average of data is used and the vertical resolution varies as follows: 75 m to 2 km, then 300 m to 4 km, 450 m to 5.5 km, and 900 m above this. The lower 600 meters of data are not shown because the SRL possessed only high-altitude channels for this deployment.

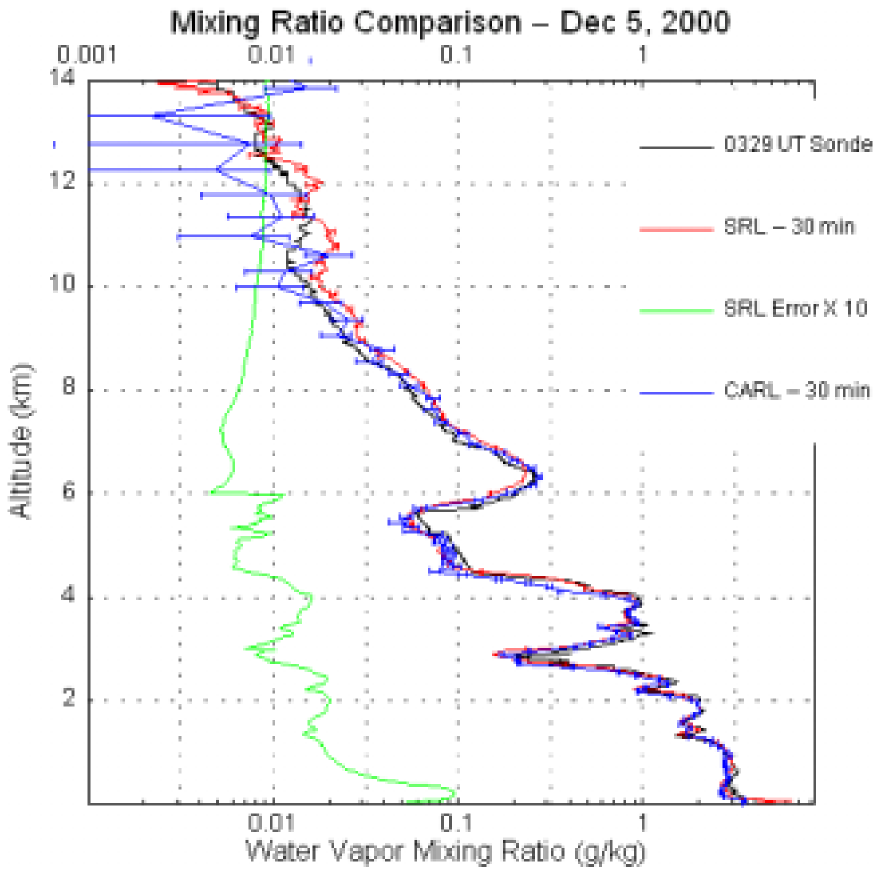

Figure 2. Comparison of Vaisala radiosonde, SRL and CARL WV mixing ratio measurements extending to 14 km on the night of December 5, 2000. The integration time for the lidars is 30 minutes. The vertical resolution of the lidar measurements is approximately 400 to 500 meters at the highest altitudes. Also plotted is the random error in the SRL measurements indicating less than 10 percent error for all altitudes below approximately 13 km. The increased signal strength of the SRL permits greatly improved upper tropospheric WV measurements compared to CARL. Improvements are underway that will improve the CARL Universal Time (UT) measurement capability.

In addressing comparison Item 1, the noise characteristics of the SRL have been studied for several cases including both daytime and nighttime conditions in a fashion similar to that of Linn et al. (Linn et al. 2000). Figure 3 shows an analysis of nighttime data acquired using the excimer laser with 10-second temporal resolution and 7.5-meter range resolution. This plot indicates that there is good agreement between the Poisson determination of noise and the results using spectral analysis validating the standard Raman Lidar error propagation techniques, which assume Poisson statistics. More importantly, it indicates that at 10-second temporal and 7.5-meter range resolution, the SRL measurements under these conditions possess less than 10 percent random error up to altitudes beyond 3 km. Therefore, quantification of boundary-layer turbulence at extremely high spatial and temporal resolution, measurements that are important for studies of energy transport and dissipation, are possible using the SRL.

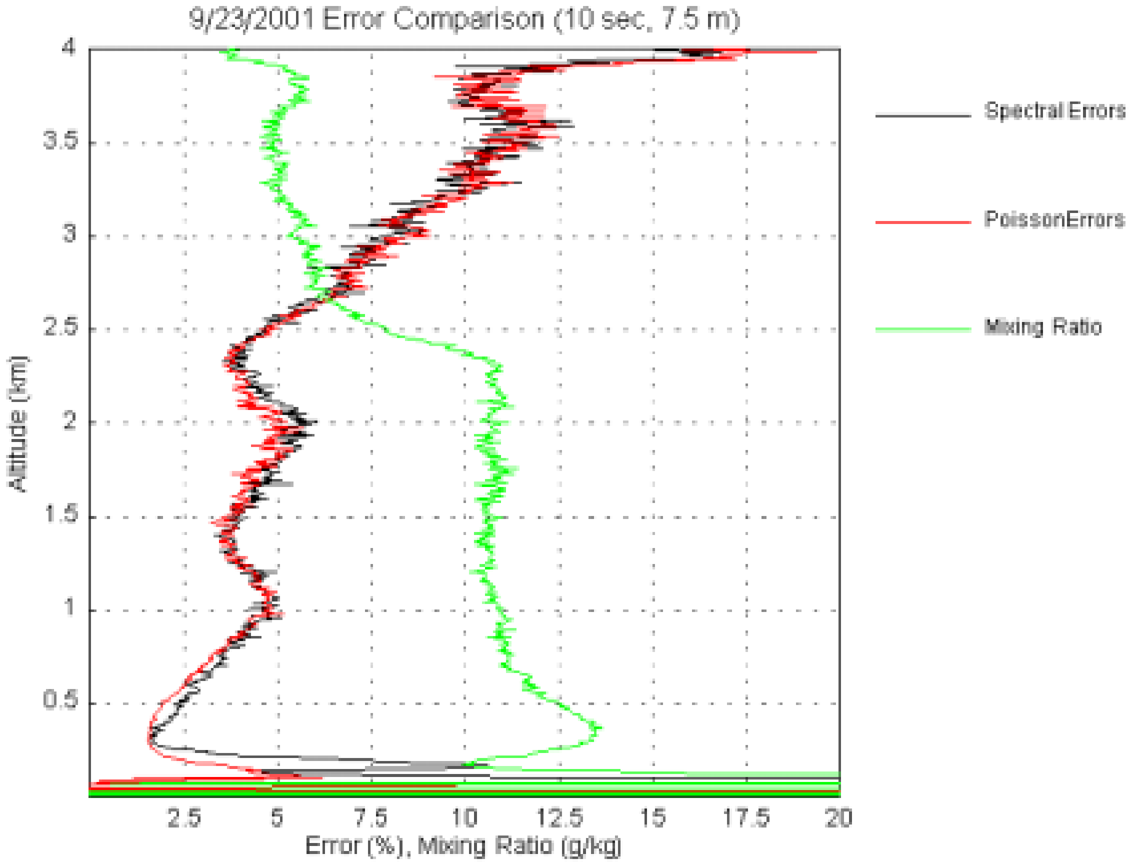

Figure 3. A comparison of errors in SRL nighttime measurements using data acquired September 23, 2000. Errors are calculated using the standard Poisson statistics and also using Fourier techniques. The agreement is excellent, which validates the Poisson approach to error propagation. More importantly, this figure demonstrates that the excimer-based SRL measurements are able to quantify WV mixing ratio with less than 10 percent error using 10-second integration and 7.5-meter range resolution. Such high-resolution WV measurements can permit the study of boundary-layer turbulence at scales not achievable using other remote sensing techniques.

Profile Comparisons from AFWEX

Small errors in the measurement of upper tropospheric WV can produce large errors in radiative balance calculations because of WV large radiative capacity, its very low concentration in the upper troposphere, and the ability of molecules in the upper troposphere to radiate directly to space. The prime focus of AFWEX was therefore to characterize WV measurement technologies in the upper troposphere. Figure 4 shows the mean percentage differences between the WV mixing ratio profiles measured by SRL, CARL, LASE (NASA/Langley Lidar Atmospheric Sensing Experiment), Vaisala, and chilled mirror sonde. The LASE data were selected to be within 0.05 degrees of the SGP site (~5 to 6 km). The lidar profiles use 30-minute integration. All available data satisfying these criteria were used. Also plotted are the statistics for SRL and CARL after applying a temperature correction due to the change in the Raman scattering spectrum of WV with temperature (Whiteman 2000). Standard deviation and 2x standard error bars are plotted for each curve. These comparisons indicate that there frequently are

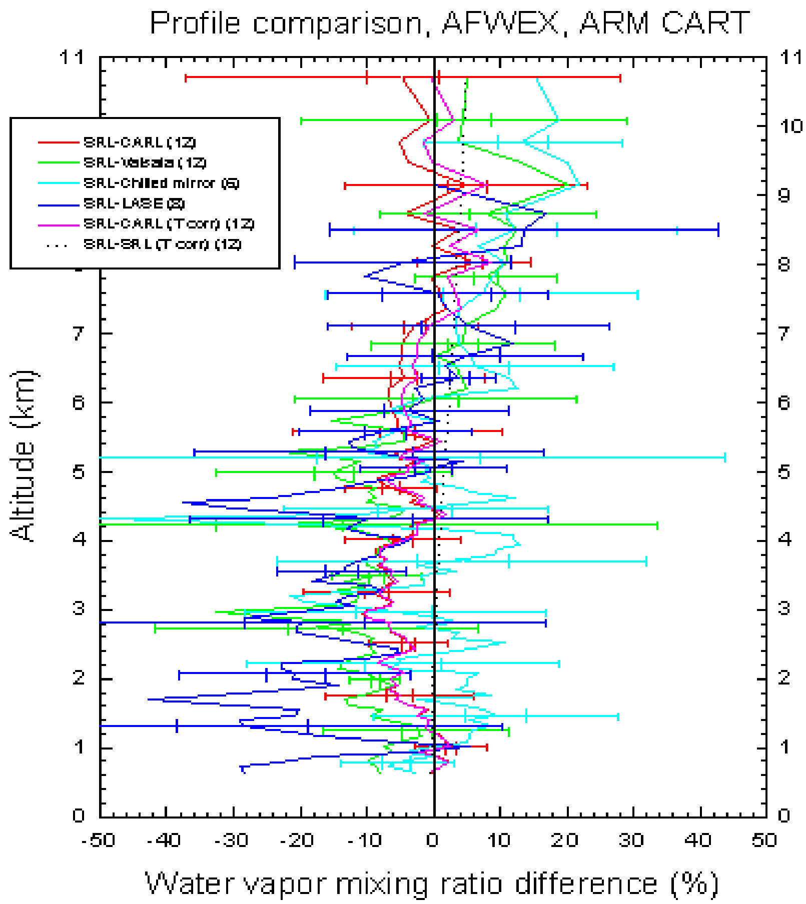

Figure 4. The WV mixing ratio measurements are compared from SRL, CARL, LASE, Vaisala, and chilled mirror sondes. These preliminary comparisons indicate considerable variation among the instruments from measurement to measurement. The ensemble statistics show better agreement, although there is a persistent bias that appears in the SRL data up to approximately 6 km. This is being studied.

statistically significant differences between the mean measurements of these sensors, particularly below 6 km. It is clear that there can be large differences among the various profilers from comparison to comparison, which is important to consider for the typical field campaign mode of data acquisition.

Thin Cirrus Optical Depth and Cirrus Supersatuation

The ability of the SRL to quantify thin cirrus optical depth (OD) and to study the influence of thin cirrus on satellite radiances has recently been demonstrated (Whiteman et al. 2000). Data acquired during the AFWEX campaign is being used to continue this study and also to compare the cirrus OD retrievals of SRL and CARL. The night of December 8, 2000, during AFWEX presented such an opportunity for comparisons. Figure 5 shows cirrus scattering ratio (top) on the night of December 8, 2000, and the corresponding OD calculations using both SRL and CARL (bottom). The vertical stripes in the image indicate attenuation of the laser beam due to thicker cirrus. The cirrus ranged in height from below 6 km to approximately 11 km.

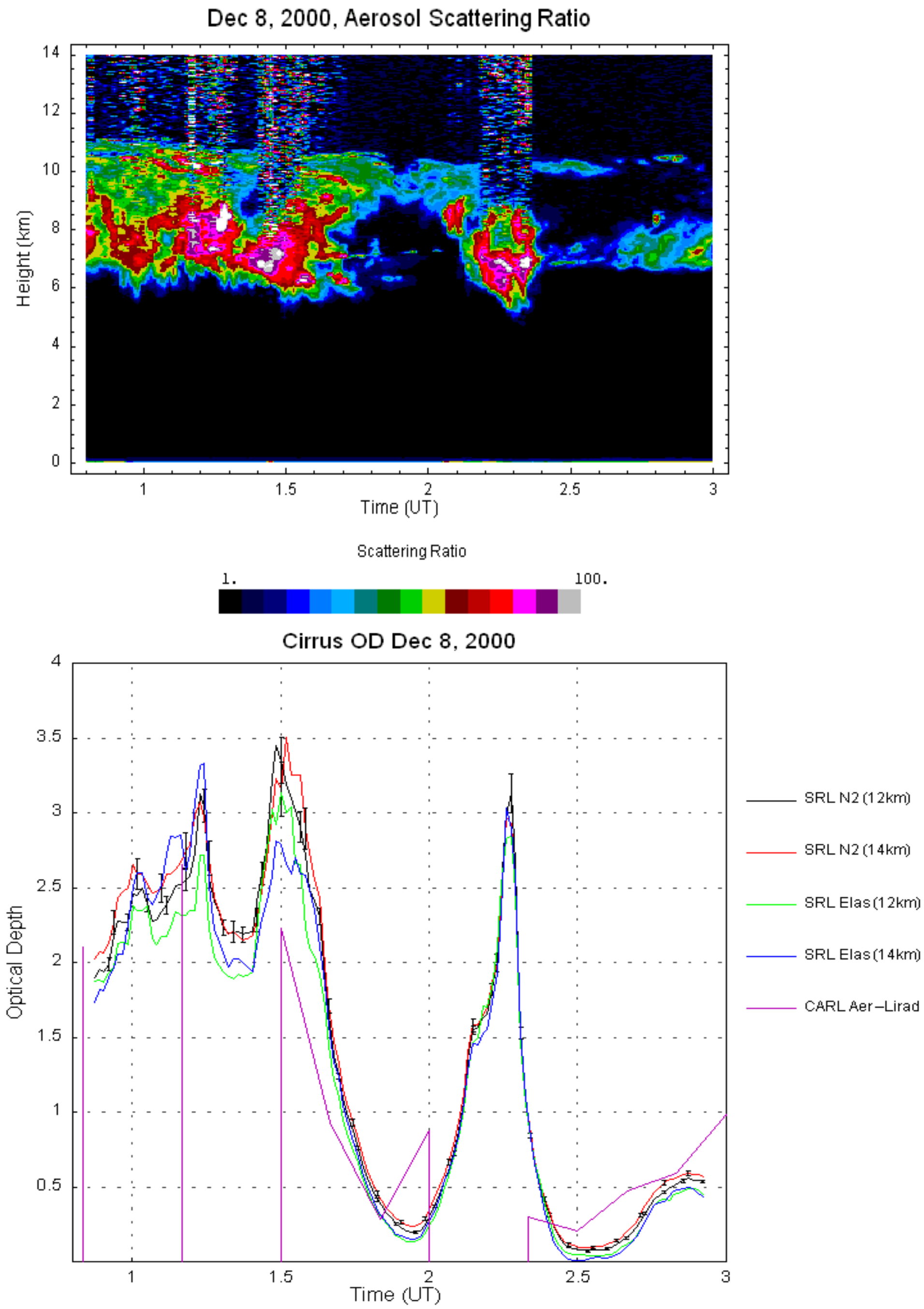

Figure 5. Cirrus scattering ratio (top) and cirrus OD (bottom) for the December 8, 2000, cirrus case. Optical depth is shown retrieved from both the SRL and CARL. The SRL retrievals are done using 4 techniques as a test for the presence of multiple scattering. The separation of the retrievals in the early part of the sequence indicates the likely presence of multiple scattering due to large cirrus particles. The absence of this effect later in the measurements indicates smaller cirrus particles. Particle size retrievals will be studied using these measurements in the future. The CARL retrieves OD using signals attenuated by approximately a factor of 20 compared to the SRL, which results in the poorer measurements shown.

Cirrus cloud OD measured by the SRL using 4 different methods and by the CARL using 1 method are shown. All retrievals from the SRL are in good agreement in the latter part of the image. The separation of the retrievals early in the dataset is consistent with a multiple scattering influence, which would indicate larger cirrus particles in the cloud than later in the measurement period. Such data have been used to quantify cirrus particle size (Whiteman et al. 2000). The same retrieval technique will be used on these data in future studies. The CARL nitrogen signals are attenuated by approximately a factor of 20 compared to the SRL and thus give noisier results. Efforts are underway that should permit this attenuation to be removed. This should enable CARL to quantify cirrus OD with similar quality to that demonstrated by the SRL.

Upper Tropospheric Humidification and Ice Super-Saturation

Figure 6 displays the WV mixing ratio that corresponds to the aerosol scattering ratio shown in Figure 5. This is a very interesting case of upper tropospheric humidification due to cirrus sublimation. The image reveals a moist layer that develops at the base of the cirrus and descends through the measurement period. Figure 7 shows the relative humidity with respect to ice, which indicates regions of super saturation above the base of the clouds and in the clouds. These measurements will be studied in the future as a test case for a NASA/GSFC cirrus cloud physics model.

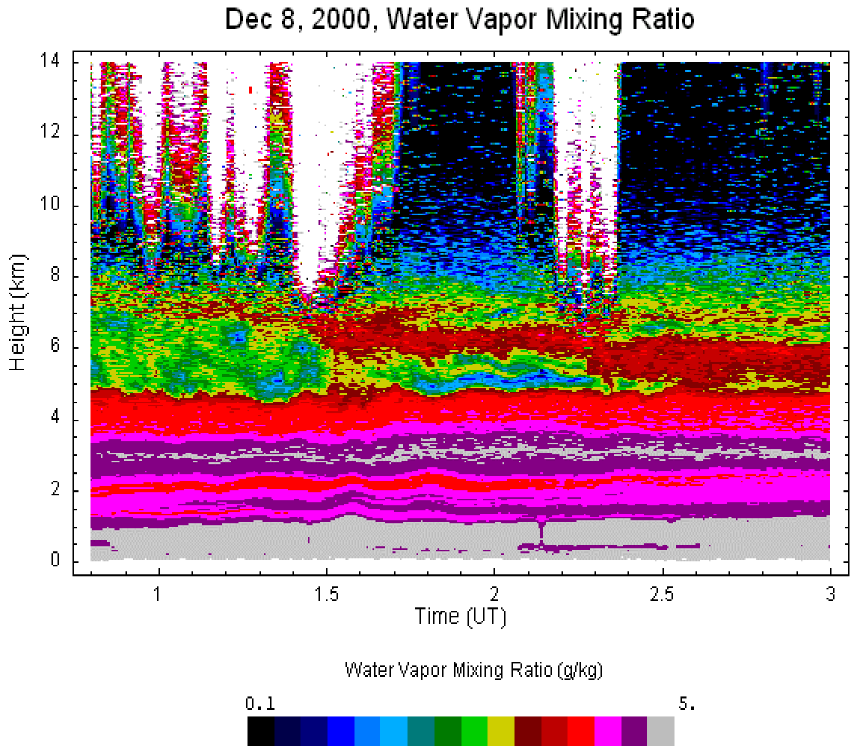

Figure 6. The WV mixing ratio measured by the SRL on the night of December 8, 2000, during the presence of the cirrus clouds shown in Figure 5. The image is showed using a logarithmic color scale to reveal features in the upper troposphere. The humidification of the upper troposphere at the base of the cirrus (likely due to cirrus sublimation) is apparent.

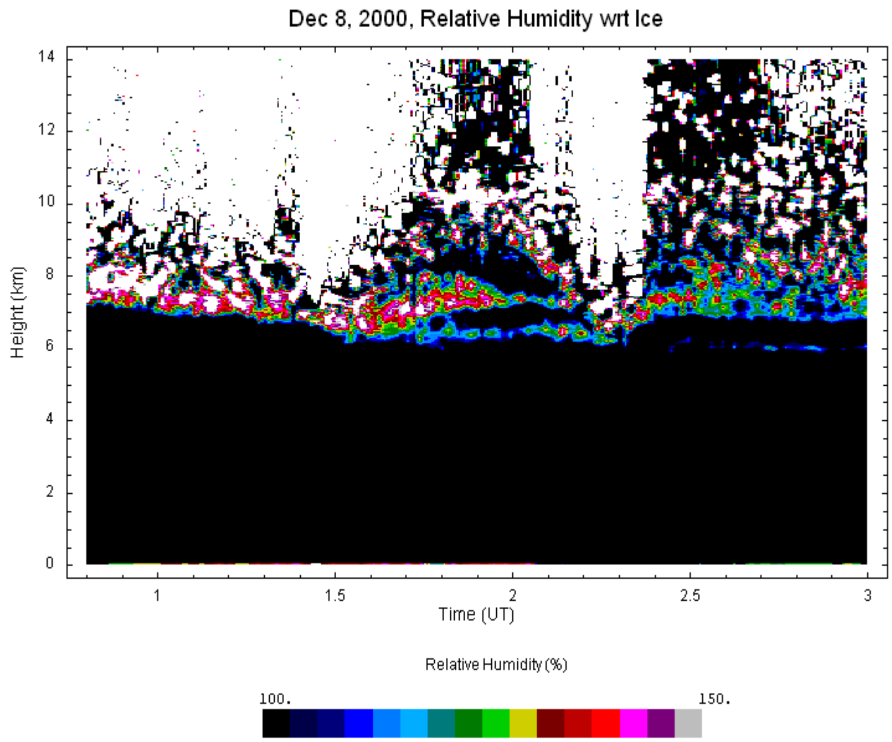

Figure 7. Relative humidity with respect to ice for the same December 8, 2000, cirrus case. A comparison of this figure with Figure 5 indicates significant regions of ice super saturation in and near the cirrus clouds.

Summary and Conclusions

The SRL participated in two DOE/ARM field campaigns devoted to characterizing WV measurement capability. The SRL demonstrated large improvements in Raman Lidar WV measurement capability for both the daytime and nighttime measurements. These measurements have been used for a number of studies to characterize measurement performance. An interesting test case from December 8, 2000, during the AFWEX field campaign was presented. The SRL revealed upper tropospheric humidification due to cirrus sublimation. The profile comparison of the different WV sensors from AFWEX indicates that from profile to profile, radiatively significant differences in WV measurements exist and require further study.

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