5.9 RAMAN LIDAR MEASUREMENT OF WATER VAPOR MIXING RATIO AND AEROSOLS DURING A BORE-FRONT CASE.

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1. INTRODUCTION

Water vapor concentration, expressed as a mass mixing ratio (g kg^{-1}), is conserved in all meteorological processes except condensation and evaporation. This property makes it an ideal choice for visualizing many of the atmosphere's dynamic features. In fact, the water vapor mixing ratio across an air-mass boundary often remains distinct even when the temperature difference is indistinct.

Ground based lidar remote sensing of water vapor, in particular Raman lidars, have been making steady progress. An example of such a lidar is the NASA/GSFC Scanning Raman Lidar (SRL). Development of the SRL has been in progress for a number of years. The SRL system measures high temporal and spatial resolution profiles of aerosol backscattering/extinction and water vapor mixing ratio profiles at night and more recently also during the daytime. Extensive data sets exists now from several field campaigns and investigations of the atmosphere. These data sets have proven very useful in advancing our understanding of a variety of mesoscale phenomena; including atmospheric frontal structures, gravity and bore waves, thunderstorm outflows, drylines and many other mesoscale features.

In this study, we present recent improvements in the Raman lidar technology measurement capabilities and instrument improvements planned in the future and their atmospheric applications. As an example of SRL measurement capability, a classic gust front and solitary wave event that passed the Northern Oklahoma region on 23 September 2000 is presented. We discuss the contribution of the SRL measurement in forecast diagnostics and its use in mesoscale atmospheric structures analysis and summarize the role of Raman lidars in advancing our understanding of these structures. A summary of how the SRL compares to the "standard" water vapor sensing instruments will also be presented. The data presented here were collected at the Department of Energy Atmospheric Radiation Measurement (DOE/ARM) Cloud and Radiation Testbed (CART) site in north-central Oklahoma by NASA/GSFC Raman lidar. It was collected during the Water Vapor Intensive Comparison Project 2000 (WVIOP2000). Water Vapor IOP 2000 held in September-October was concerned with water vapor measurements in the lower atmosphere while the ARM FIRE Water Vapor Experiment (AFWEX) dealt with upper tropospheric measurements. The SRL participated in both of these campaigns.

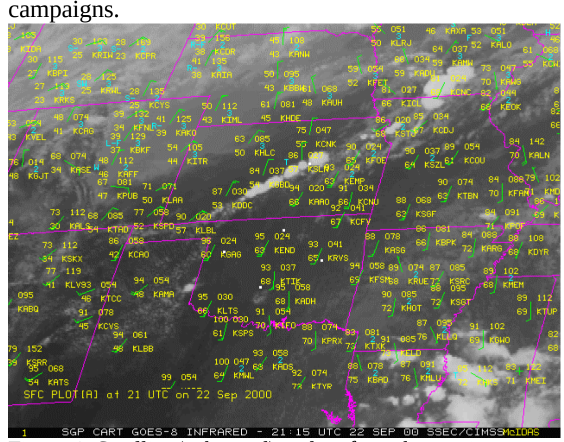

Figure 1. Satellite (enhanced) and surface observations at 21:15 UTC, on 22 September 2000. The DOE ARM sites are denoted by white dots over OK; the north most location in OK is the CART site.

2. CASE STUDY: 23 SEPTEMBER 2000

We commence by giving brief details of the synoptic and station observations made on 23 September 2000.

2.1. Synoptic and Upper Air Observations

During the early morning hours of 22 September 2000 a surface low pressure area moved into northwestern Kansas. As the day progressed, satellite images showed thunderstorms triggered along a line that extended from the Texas-Oklahoma panhandle to north east Kansas (Fig.1). This front, associated with the low pressure system, moved southeast toward the northern Oklahoma border.

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Increasing south to southeasterly winds ahead of the cold front resulted in dew-point temperatures near 21° C in Oklahoma and Kansas. The local forecast for that day called for ***"a low layer of thick clouds will trail the front generally by about 100 miles and this is where the truly chilly air will be [emphasis added]."*** This clearly identifies the line where the thunderstorms formed (Fig.1), and that passed over CART at 0400 (all times are UTC), as the cold front..

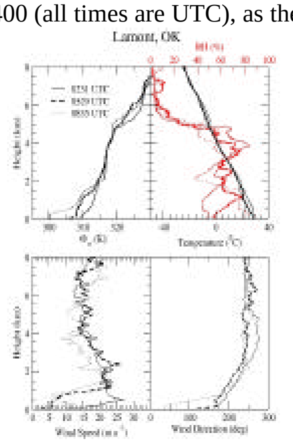

Figure 2. Soundings launched at 0231, 0529, and 0835 on 23 September 2000 at the DOE-ARM CART site in Oklahoma.

2.2 *Upper Air Soundings*

Soundings taken at Topeka, Kansas, in the afternoon of 22 September 2000 revealed a moist stable layer from the surface up to 1 km capped by an inversion layer (1.2km) and a 20 m s^{-1} increase in wind speed within the lowest 500 m. At Amarillo, Texas, a relatively unstable layer that aided in the development of scattered low level convection seen in the satellite images over the Texas Panhandle. Soundings at CART were taken every 3-hours. The soundings at 0230 (just prior to the arrival of the cloud lines seen in Fig.1), 0530 (just after the cloud lines), and 0835 all showed a well mixed layer extending from 2km to about 4km and a stable layer near the surface. Wind speeds below 2km increased from a value of 5-10 m/sec to between 20 and 25 m/sec at 2km altitude. In the same altitude range, wind direction changed from south to southwesterly and low level moisture continuously increased with time. *Note that the 3-hr resolution sonde profiles, while detecting the broad change in moisture, can not capture the sharp transitions in moisture associated with the air-mass boundaries that is crucial to characterizing the details of the dynamics and local convective response.*

2.3 *Surface Observations*

Surface observations for this day are plotted in Fig.3. An increasing (decreasing) trend of pressure (temperature) was associated with the approaching front. Embedded in the pressure trend were several small pressure jumps which are not seen in the 5-minute average data in Fig. 3. The strongest of the jumps, an increase of about 2mb, followed by some oscillations, occurred around 0400. ***This pressure jump occurred five and half hours ahead of the frontal clouds and a persistent and sharper drop in temperature.*** It was also associated with a spike in relative humidity, a dip in temperature and with the start of several wave oscillations in wind speed and direction (Fig.3). Often, these wave-like features in the pressure and temperature record are indicative of nearby frontal systems, convection and/or air-mass boundary changes. Indeed, this was the case on 23 September 2000. A dynamic interpretation of these surface signatures, however, is often complicated and requires knowledge of temporal evolution of the vertical structure.

In the next section, Raman lidar profile data are used to characterize the flow structure over CART and simplify the dynamic interpretation of these signatures.

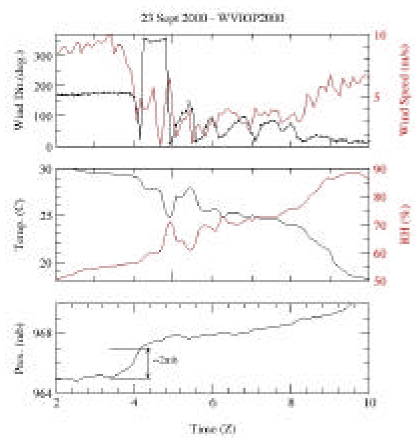

Figure 3. Time series of wind speed, wind direction, temperature, relative humidity and pressure on 23 September 2000 at the DOE-ARM CART site in Northern Oklahoma.

3. THE SCANNING RAMAN LIDAR

The NASA/GSFC Scanning Raman Lidar is a mobile system contained in a single environmentally controlled trailer. It includes two lasers (XeF excimer and Nd:YAG), 0.76 meter telescope and large aperture scanning mirror. Using Raman scattering from atmospheric molecules, it measures water vapor, nitrogen, oxygen and Rayleigh-Mie signals. Derived products from the system include water vapor mixing ratio, aerosol scattering ratio and extinction, cloud optical depth and cloud base height. UV transmission windows 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 water vapor; one of the main focuses of the IOP.

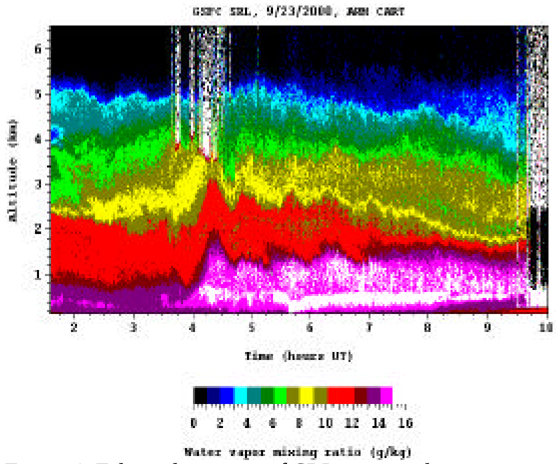

Figure 4. False color image of SRL measured water vapor mixing ratio (g kg^{-1}) profiles observed on 23 September 2000 showing the details of location of clouds (cloud bases correspond to bases of the white attenuation spikes between 0530 and 1700 UTC) and moisture structure of a bore wave and the boundary layer ahead of a front.

3.1 SRL Water Vapor Mixing Ratio Observations.

SRL-measured time-height profiles of water vapor mixing ratio on 23 September are plotted in Fig. 4. The figure consists of high resolution data; 10sec temporal and 7.5m vertical profiles of a gust front (solitary wave) triggered by a cold front in the Oklahoma Panhandle. The image clearly defines that the 0400 location as a moisture front rather than a temperature front. It also shows the arrival of the "rope" cloud visible on the GOES imagery of Fig.1, riding the wave crest at a height of 3.5 km. The low level moisture increased by about 2g/kg after 0400, which is contrary to what is expected during a passage of a front. On the other hand, the arrival of the clouds at 0930, the associated low level decrease in water vapor mixing ratio, and the steeper drop in temperature are all superior indicators of a frontal passage. ***Thus, surface frontal passage should be located at about 0930 - trailing the gust front by 6 hours, not at 0400.***

3.1 SRL Error Characterization.

Accurate measurements of moisture are required for successful modeling and characterization as well as prediction of convection. Crook (1996) reports that "a 1g/kg variation in the accuracy of the moisture measurements can make the difference between no initiation and intense initiation." Given this sensitivity, a highly accurate measurement system is a must. We present an error analysis plot for the data collected on 23 September 2000 in Figure 5.

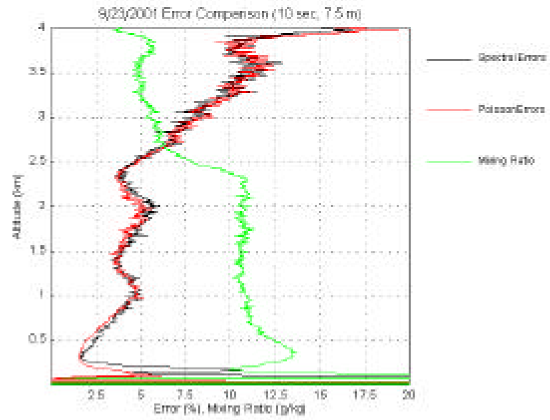

Figure 5. Error characterization of the nighttime SRL measurements on 23 September 2000. See text for details

Figure 5 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% random error up to altitudes beyond 3 km. At 1-minute and 30m average, the profiles extend to 8km with less than 10% error. Therefore, quantification of boundary layer turbulence at extremely high spatial and temporal resolution – measurements that are important for studies of energy transport, convection and dissipation - are possible using the SRL.

4. SUMMARY AND CONCLUSION

We have presented and discussed a high temporal resolution Raman lidar water vapor profile data set collected during a cold frontal passage in the central United States. The data set is unique in that it captures the development and structure of the boundary layer associated with a cold front, resulting into an accurate and correct diagnosis of the mesoscale interaction.

5. ACKNOWLEDGEMENT

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6. REFERENCES

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