Observations of a Cold Front With Strong Vertical Undulations During the ARM RCS-IOP

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Passage of a cold front was observed on the night of April 14-15, 1994, during the Atmospheric Radiation Measurement (ARM) Remote Cloud Sensing (RCS) Intensive Observations Period (IOP) at the Southern Great Plains Cloud and Radiation Testbed (CART) site near Lamont, Oklahoma. This front produced severe thunderstorms on a line from Wisconsin to southeastern Oklahoma (OK). The series of water vapor profiles obtained by the Goddard Space Flight Center (GSFC) Scanning Raman Lidar (SRL) captures well the dramatic sequence of events at the CART site (Figure 1). The SRL site (Figure 1). The SRL was operated in alternating vertical and near-horizontal pointing modes, each with 1-minute dwell, where the former yielded high vertical resolution (75 m) profiles from 165 m to above 8 km and the latter provided ultra-high vertical resolution profiling from near the surface. Details of the SRL and modes of operation may be found in Melfi et al. (this volume).

The initial observations show a fairly sudden deepening of the boundary layer with progressive moistening after

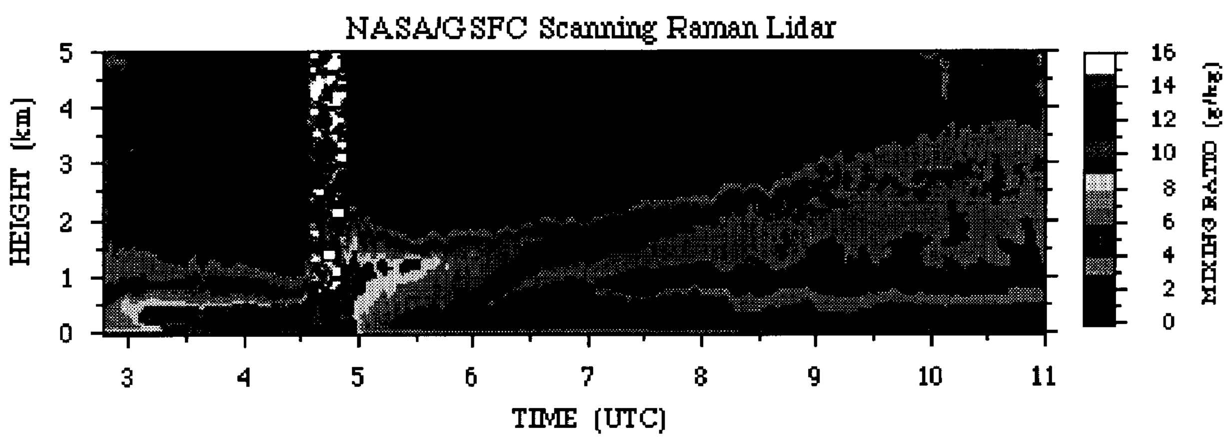

Figure 1. Observations of water vapor mixing ratio profiles by the GSFC Scanning Raman Lidar on 15 April during the 1994 ARM RCS IOP.

about 0300 UTC. At about 0430 UTC, very rapid growth in the planetary boundary layer (PBL) was observed with strong apparent wave activity. The vertical banding in the data indicate the presence of an attenuating cloud capping the first and second wave peaks (also indications of haze or very tenuous cloud on the third wave peak). Our real time display (and a strong wind gust) induced us to quickly make a visual observation and two roll clouds were sighted. Very high resolution observations by the University of Utah Polarization-Diversity Cloud Lidar revealed a sculpted cloud base (sloping upward) while the Penn State 95-GHz Doppler Radar showed turbulent dust plumes extending upward from the surface and alternating regions of strongly upward and downward motion in association with these waves.

This was followed by a change to a drier boundary layer capped by an upward sloping frontal surface. It should be noted that undulations, though more moderate, continued to be observed in the elevated frontal zone (note that the wave at 0340 UTC is purely an artifact of a brief 10-minute data lapse and processing for graphical display). Further analyses (not shown) show a fairly well-mixed layer extending from above the PBL or frontal zone to about the 5-km level where relative humidity reached a maximum. Our interpretation is that this is a dry "high-plains" PBL from the preceding day. Clouds developed just above the 5-km level after 1000 UTC with light showers reaching the surface after lidar operations were terminated at 1120 UTC. This mid-level cloudiness was observed by satellite (Geostationary Operational Environmental Satellite) as a cloud band oriented parallel to (and well behind) the surface front and was tracked by satellite and National Weather Service (NWS) radar from western Kansas.

An interesting structure is also seen in the post-frontal cold air mass where there is an indication of a developing PBL (moistening) near the surface. The moisture pattern around the 1-km level is suggestive of roll circulations (0900-1000 UTC). Rawinsonde data at 0900 UTC indicate this minimum level in water vapor mixing ratio was associated with an internal stably stratified layer that separated the developing PBL (becoming well-mixed) from the upper region of the post-frontal air mass that is also fairly well-mixed and capped by the stable frontal zone.

The vertical profile data obtained by the Sandia Raman Lidar (Goldsmith et al., this volume) at 1-minute temporal resolution yields an even better picture of the wave structure associated with the frontal passage (Figure 2). These observations indicate a displacement amplitude of about 1 km or more for the first wave diminishing to about 400 m by the fourth wave. The period of the first two waves was about 9 minutes, while the trailing waves appeared shorter (about 7 minutes). Assuming propagation at about the same speed as the cold front (15 m s^{-1}) yields wavelengths of about 8 and 6 km, respectively. Our interpretation of this wave phenomena is that it is an undular bore induced by the piling up (deepening) of the moist pre-frontal boundary layer immediately ahead of and resulting from the propagation of the cold front. This interpretation is supported by observations of a sudden strong pressure jump, surface wind gust and direction shift, and the rolling cloud bands (Stull 1988). Bores have been previously observed in association with thunderstorm outflow boundaries (Koch et al. 1991) and propagating sea breeze fronts (Smith et al. 1982).

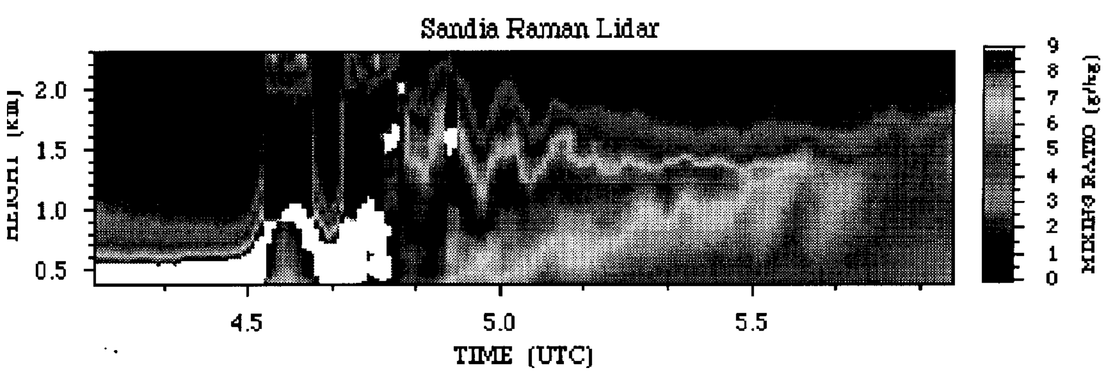

Figure 2. Observations of water vapor mixing ratio profiles (preliminary calibration) by the Sandia National Laboratory Raman Lidar on 15 April during the 1994 ARM RCS IOP.

Ancillary Observations - A Key to Understanding

Interpretation of even continuous high-resolution vertical-profile data may be ambiguous in complex situations as on this night. The Oklahoma Mesonet, a unique dense network of more than 110 automated surface stations making routine 5-minute observations, provides a wealth of complimentary meteorological data. In comparison, there are 16 NWS surface stations (half-hourly) and 3 ARM surface sites (1-minute data) in the state of Oklahoma (plus 2 ARM sites in southern Kansas). These surface data, together with data from the ARM rawinsonde sounding sites and the NWS profiler network, may be used to greatly enhance understanding of phenomena observed at the CART site. This case illustrates the high utility of these data (all available through the ARM data system).
Lidar observations indicated strong moistening and a rapid increase in the depth of the boundary layer about 2 hours prior to the frontal passage (left of Figure 1) when lidar operations were just commencing. Comparison to the 0300 UTC rawinsonde sounding (launched at 0230 UTC) more clearly shows the strong change. The next sounding (0600 UTC) was after the frontal passage (soundings not shown). Thus, even with the enhanced 3-hourly soundings at the CART site, this significant change in the pre-frontal boundary layer was not resolved. A strong thunderstorm with copious lightning was also visible during this time on the northeastern horizon from the CART site. Initially, the dramatic passage of the leading edge of the frontal zone with strong wind gusts and roll clouds could easily have been mistaken for a thunderstorm outflow boundary.

Analysis of the mesonet data provides a clear picture of what occurred (Figure 3). Shown are streamline analyses of the surface wind observations superposed on an analysis of the observed dew point temperatures (°F). We have added our analysis of frontal position and also indicated the locations of the ARM sites. At 0100 UTC, the cold front was just penetrating into extreme northwestern OK. A convergence line is evident with a roughly N-S orientation through west-central OK and with southerly flow to the east. Also very evident is a strong moisture gradient through central OK that was oriented SSW-NNE with dew points near 70 °F to the east transitioning to values near 50 °F to the west and lower still (30 °F) in the far west. The change to a more moist and deeper pre-frontal boundary layer seen in the Raman lidar observations (Figure 1) is a reflection of the northward movement of the moisture gradient on the southerly flow in advance of the front (Figure 3 at 0430 UTC). The 0600 UTC sounding from Morris in east-central OK shows the deep moist and warm boundary layer momentarily seen at the

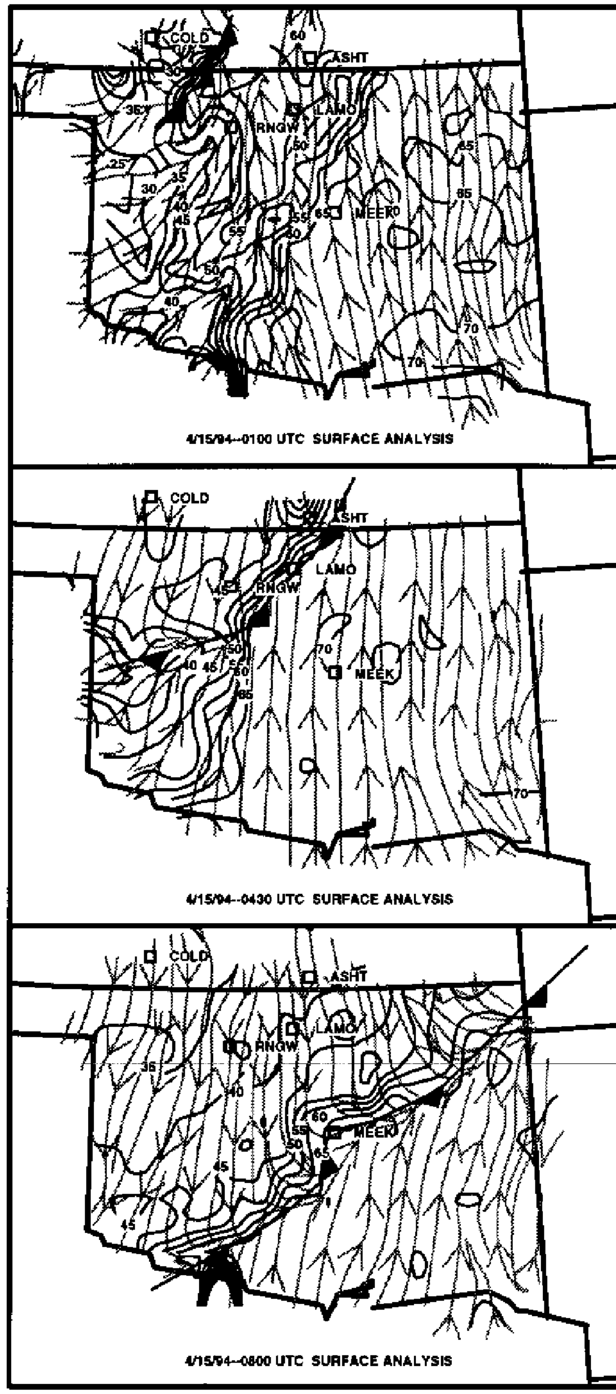

Figure 3. Streamline and dew point temperature (°F) analysis of surface observations from the Oklahoma Mesonet, NWS, and ARM stations on 15 April 1994.

CART site. The intrusion of the moist boundary layer did not extend much to the north or west of the CART site. It is apparent that the subsequent coincidence of the convergence zone, the moisture gradient, and the front (wind shift and temperature gradient) in central OK evolved from three distinct and separate earlier features. Thus, our influenced the observations at the CART site, although the frontal propagation speed was enhanced in northeastern OK (from about 15 m s^{-1} to 20 m s^{-1}).

Characterization of Structure

One goal of this project is to develop quantitative descriptions of subgrid-scale water vapor structure and variability in relationship to large-scale parameters (e.g., static stability and wind shear) that would be useful for validating or improving parametric treatments of subgrid-scale cloudiness or latent heat flux employed in mesoscale models or general circulation models. The rawinsonde and wind profiler data from the ARM and NWS networks enable characterization of the large-scale environment, while the Raman lidar provides a high-vertical and high-temporal resolution description of the water vapor field.

Because of the well-developed wave structure evident in the water vapor field (Figure 2), the 15 April case is very useful for evaluating techniques to quantify variability. Spectral analysis of the water vapor mixing ratio time series data at various levels does not reveal strongly dominant wavelengths. Minor peaks were found at periods of just greater than 7 and just less than 9 minutes. Wavelet analysis (Weng and Lau 1994) yields a very useful alternative characterization of the wave structure (Figure 4). Here, the results depict the relative amplitude of local water vapor undulations (averaged over a 375-m layer about the 0.69-km level) as a function of time and wavelength delineated by frequency octave where a period of 12.5 minutes corresponds to the zero octave and doubles (halves) for unit octave increment. Very apparent is the wave structure at a period of 8.5 minutes seen in the alternating pattern of highs and lows between the 0 and -1 octaves that is especially strong around 0430 UTC (peak/high near 4.5 hours). This phenomena persists, though with moderated amplitude, until 0600 UTC. The period of the higher frequency but weaker wave structure (between the -1 and -2 octaves) corresponds to the sampling interval (2 minutes). The power seen at lower frequencies (between octaves 1 and 3) corresponds to the gross changes associated with the transition from the relatively dry pre-frontal conditions at this level to the very moist bore zone to the frontal zone itself, and then to the post-frontal air mass. Analyses at other altitudes yield very similar results, but with some low-frequency differences depending on the sequence of gross events at the level, and with indications of a second important oscillation period of about 18 minutes at higher levels.

Other techniques, including a combined spectral analysis, structure function analysis, and singular measure analysis to derive a multifractal characterization (Davis et al. 1994) of water vapor variability and textural measures of variability have been applied to data from this case and others observed during the ARM RCS IOP and the 1991

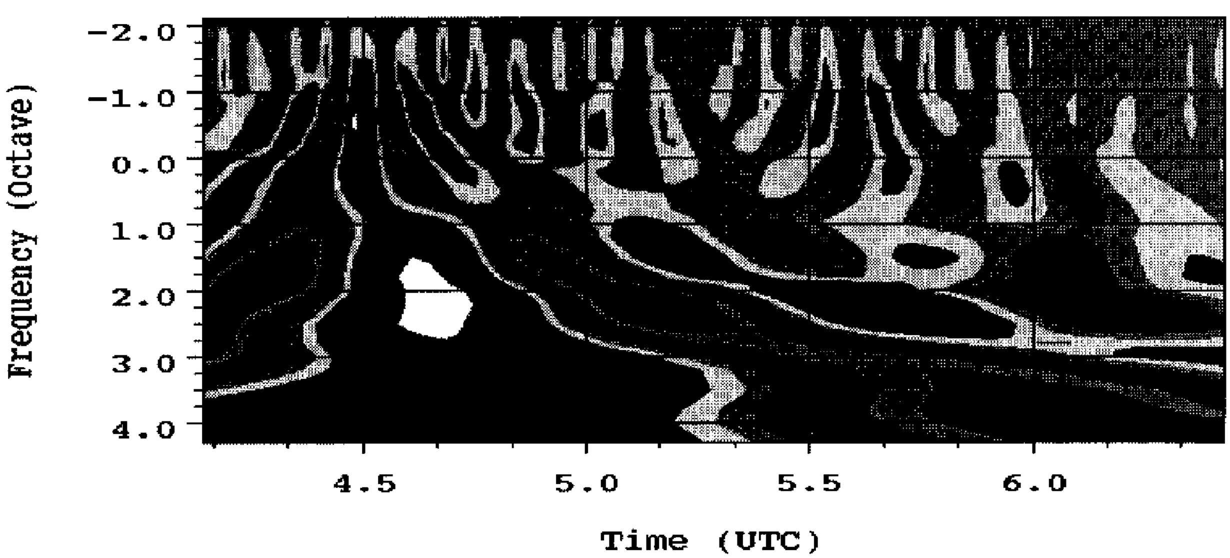

Figure 4. Wavelet analysis of GSFC Raman lidar water vapor mixing ratio observations, vertically averaged over 375-m layer centered on a height of 0.69 km (Figure 1), around the time of a cold front passage on 15 April 1994 at the ARM CART site in Oklahoma during the ARM RSC IOP (see text).

First International Satellite Cloud Climatology Project Regional Experiment/Spectral Radiance Experiment field campaign in Coffeyville, Kansas, in conjunction with analysis of the sonde and profiler data. The preliminary results (shown on poster) are encouraging. Specifically, the derived measures (stationarity or smoothness and intermittency or singularity) are found to encompass a limited but potentially useful range of the parameter space (i.e., the measures of variability do vary between cases or with altitude or with time which is requisite for producing a useful model of water vapor variability as a function of large-scale environmental conditions).

References

Davis, A., A. Marshak, W. Wiscombe, and R. Cahalan. 1994. Multifractal characterizations of nonstationarity and intermittency in geophysical fields: Observed, retrieved, or simulated, *J. Geophys. Res.*, **94**, 8055-8072.

Goldsmith, J.E.M., S. E. Bisson, and F. H. Blair. 1996. Implementation of a Raman lidar for profiling atmospheric water vapor and aerosols at the SGP CART site, this volume.

Koch, S. E., P. B. Dolan, R. Ferrare, S. H. Melfi, W. Skillman, and D. Whiteman. 1991. Structure of an internal bore and dissipating gravity current as revealed by Raman lidar, *Mon. Wea. Rev.*, **119**, 857-887.

Melfi, S. H., D.O'C. Starr, D. Whiteman, R. Ellingson, R. A. Ferrare, and K. Evans. 1996. Raman lidar measurements of water vapor and aerosols during the ARM RCS IOP, this volume.

Smith, R. K., N. Crook, and G. Roff. 1982. The morning glory: An extraordinary atmospheric undular bore, *Quart. J. Roy. Met. Soc.*, **108**, 937-956.

Stull, R. B. 1988. *An Introduction to Boundary Layer Meteorology*. Kluwer Academic Press, Dordrecht.

Weng, H., and K.-M. Lau. 1994. Wavelets, period doubling, and time-frequency localization with application to organization of convection over the tropical western Pacific, *J. Atmos. Sci.*, **51**, 2523-2541.