INVESTIGATION OF MICROPHYSICAL PROCESSES OF RAIN FORMATION USING UHF WIND PROFILERS AND S-BAND POLARIMETRIC RADAR

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1. INTRODUCTION

Unique opportunities to explore the characteristics of rain microphysics can be achieved using complementary data from wind profilers and polarimetric weather radars (e.g., May et al., 2001, 2002; May and Keenan, 2005). In a joint project involving the NOAA National Severe Storms Laboratory (NSSL) and the University of Oklahoma (OU), such measurements of precipitation are being conducted. One of the wind profilers used in the study is a 915-MHz radar operated through the OU Atmospheric Radar Research Center (ARRC) located at the Kessler Farm Field Laboratory (KFFL) (Chilson et al., 2007). We will refer to this radar as the OU profiler. Another wind profiler available for the study, which is also located at KFFL is part of the NOAA Profiler Network and produces estimates of the three dimensional wind profile every 6 minutes (Benjamin et al., 2004). The operating frequency of the NPN profiler is 404 MHz. Polarimetric radar data are obtained using the research platform WSR-88D (KOUN) operated by the NOAA National Severe Storms Laboratory (NSSL). KOUN has been shown to be an effective resource for precipitation studies (e.g., Ryzhkov et al., 2005).

The polarimetric parameters of radar reflectivity (Z_H), differential radar reflectivity (Z_{DR}), and cross correlation (ρ_{HV}) from KOUN are used to provide information regarding hydrometeors within the radar sampling volume. If a given form of the drop size distribution (DSD) of raindrops is assumed, then we can estimate the rain DSD using Z_H and Z_{DR} (e.g. Zhang et al. (2001); Brandes et al. (2004); Cao et al. (2007)). The characteristics of raindrops and snow below and around the freezing level are studied using DSDs estimated using the polarimetric radar together with the Doppler spectra measured with the OU profiler operating in a vertically pointing mode. Horizontal wind data are provided by the NPN profiler. An additional source of weather radar data is the KTLX WSR-88D located near Oklahoma City.

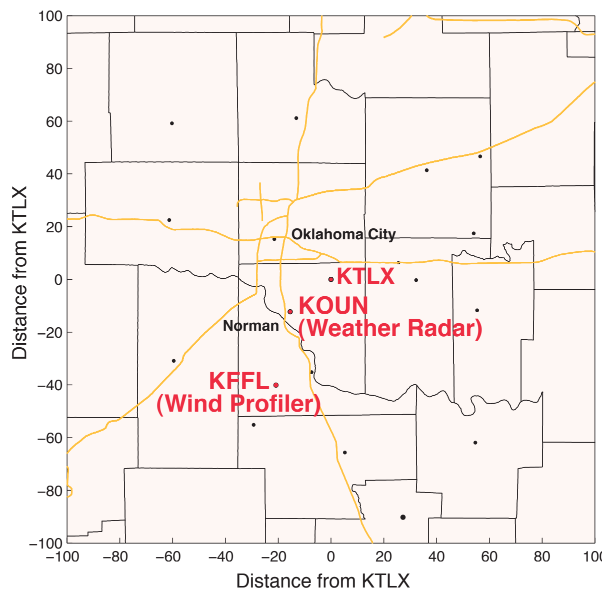

Figure 1: Map of central Oklahoma showing the locations of KTLX, KOUN, and KFFL.

The separation between KOUN and KFFL is approximately 30 km (see Figure 1), which means that KOUN and the OU profiler have similar sampling volumes. The range and angular resolutions of KOUN are 250 m and 1°, respectively. At a distance of 30 km the angular resolution of the radar corresponds to approximately 500 m. By comparison, the OU profiler has a beamwidth of 9°, and typical range resolutions are 100-200 m. Therefore, at an altitude of 2 km above ground level, the angular resolution is approximately 300 m.

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2. THE RETRIEVAL OF DSD AND VELOCITY SPECTRA FROM POLARIMETRIC VARIABLES

The DSD retrieval used here is based on Cao et al. (2007). It is assumed that the DSD has the form of a "constrained gamma" distribution

$$N(D) = N_o\, D^{\mu}\, \exp(-\Lambda D), \tag{1}$$

where D is the diameter of the raindrops, and parameters μ and Λ are related according to equations

$$\mu = \mu'(\Lambda) + C\, \Delta Z_{DR} \tag{2}$$

and

$$\mu' = -0.0104\Lambda^2 + 0.7692\Lambda - 1.79. \tag{3}$$

In (2), $C = 2$ and

$$\Delta Z_{DR} = Z_{DR} - Z_{DR}^{(a)} \tag{4}$$

$$Z_{DR}^{(a)} = 10^{f(Z_H)} \tag{5}$$

$$f(Z_H) = -5.01710 \times 10^{-4} Z_H^2 + 0.07401 Z_H - 2.0122, \tag{6}$$

where Z_H and Z_{DR} are expressed in dB. The parameter μ is constrained to be within the interval (0,6). Using this procedure, it has been possible to obtain estimates of the DSDs associated with the KOUN observations.

In order to compare the retrieved DSDs with measurements from the OU profiler, it is necessary to map the DSD spectra into equivalent Doppler spectra (fall speeds) using an assumed relationship between the the equivalent drop diameter and its terminal velocity. This can be done using

$$S_n = \frac{D^6 N(D)}{Z_h} \frac{dD}{dw}, \tag{7}$$

where Z_h is in linear units ($\mathrm{mm}^6\mathrm{m}^{-3}$), S_n is the normalized Doppler spectrum and dD/dw is the derivative of $D(w)$. Here it is assumed that the fall speeds of raindrops are related to their equivalent diameters according to

$$w(D) = 3.78\, D^{0.67} \quad (\text{if D} < 3\text{mm}) \tag{8}$$

$$= 9.65 - 10.3\, \exp(-0.6D) \quad (\text{if D} > 3\text{mm}). \tag{9}$$

The calculated terminal velocities were then corrected for differences in air density when considering the fall-speed of particles aloft (Foote and duToit, 1969).

3. CASE STUDY: MARCH 11, 2007

On March 11, 2007, a low pressure system moved from west to east across Oklahoma, and a large mesoscale convective system passed over central Oklahoma. This resulted in the formation of a line of strong convective clouds along a cold front, which extended in the north-south direction. The west side of the convective line was dominated by a region of trailing stratiform rainfall (Figure 2).

Both the OU and NPN profilers provided continuous measurements as the system passed through central Oklahoma. The OU profiler beam was directed vertically and the time and height resolutions during the observations were 20 seconds and 200 m, respectively. Figure 3 shows time-height intensity plots of the signal-to-noise ratio (SNR), Doppler velocity, and spectrum width from 11:00 to 13:00Z for the OU profiler. Negative velocity values indicate motion towards the radar. The observations indicate convection in the leading edge of the storm (before 11:30Z) and in the period between 11:50 and 12:10Z. The precipitation was predominantly stratiform in nature after 12:10Z. Although not shown here, wind data from the NPN profiler are available every 6 minutes and extend in height up to 16 km.

KOUN was operated in a Range-Height Indicator (RHI) scanning mode focused over the two wind profilers ($\sim$191° in azimuth) during the MCS event. RHI data were collected from 10:58 to 14:44Z, during which time the elevation angle was scanned in steps of 0.1° in order to support a detailed analysis of the rain microphysics. Plots similar to those shown in Figure 3 have been constructed from these KOUN RHI data. For each RHI scan, a height profile of several polarimetric parameters was created directly over the OU profiler. Then a time history of these profiles was created. The resulting time-height-intensity plots of Z_H, Z_{DR}, and ρ_{HV} are shown in Figure 4. In the stratiform rain region (after approximately 12:10Z), high reflectivity values associated with the bright band are found at a height of around 2.5 km. The differential reflectivity is roughly uniform in height below a height of 2 km and the general shape of the DSDs are considered to be be relatively similar during that period.

The temperature profile from the sounding data collected for Norman, OK (OUN) at 12Z on March 11 (Figure 5) shows the freezing level was located at approximately 3 km MSL. The polarimetric DSD retrieval was only applied to those KOUN data well below the freez-

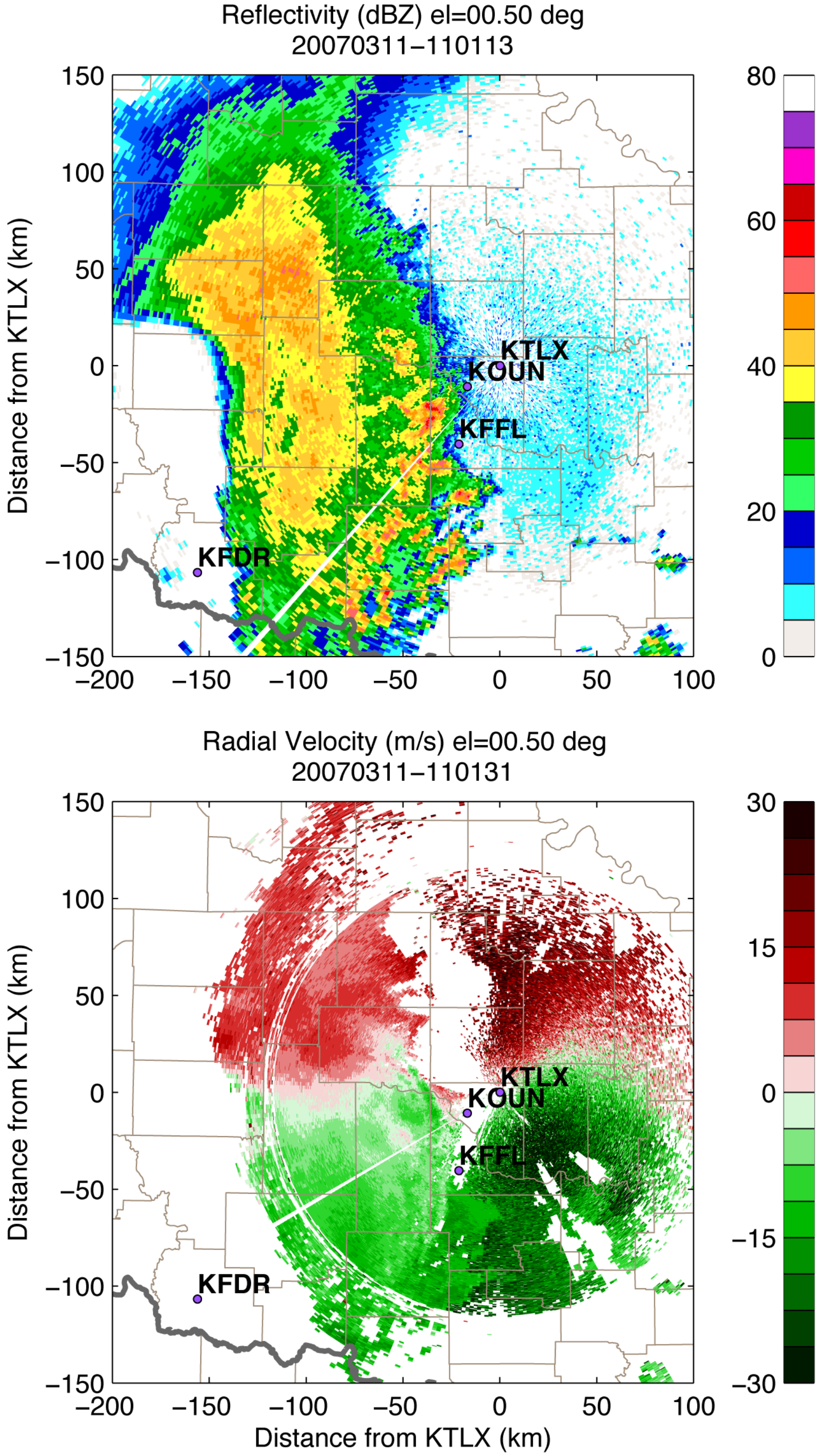

Figure 2: Horizontal distribution of radar reflectivity and Doppler velocity as observed by KTLX WSR-88D for a 0.5° elevation angle at 11:01Z on March 11, 2007.

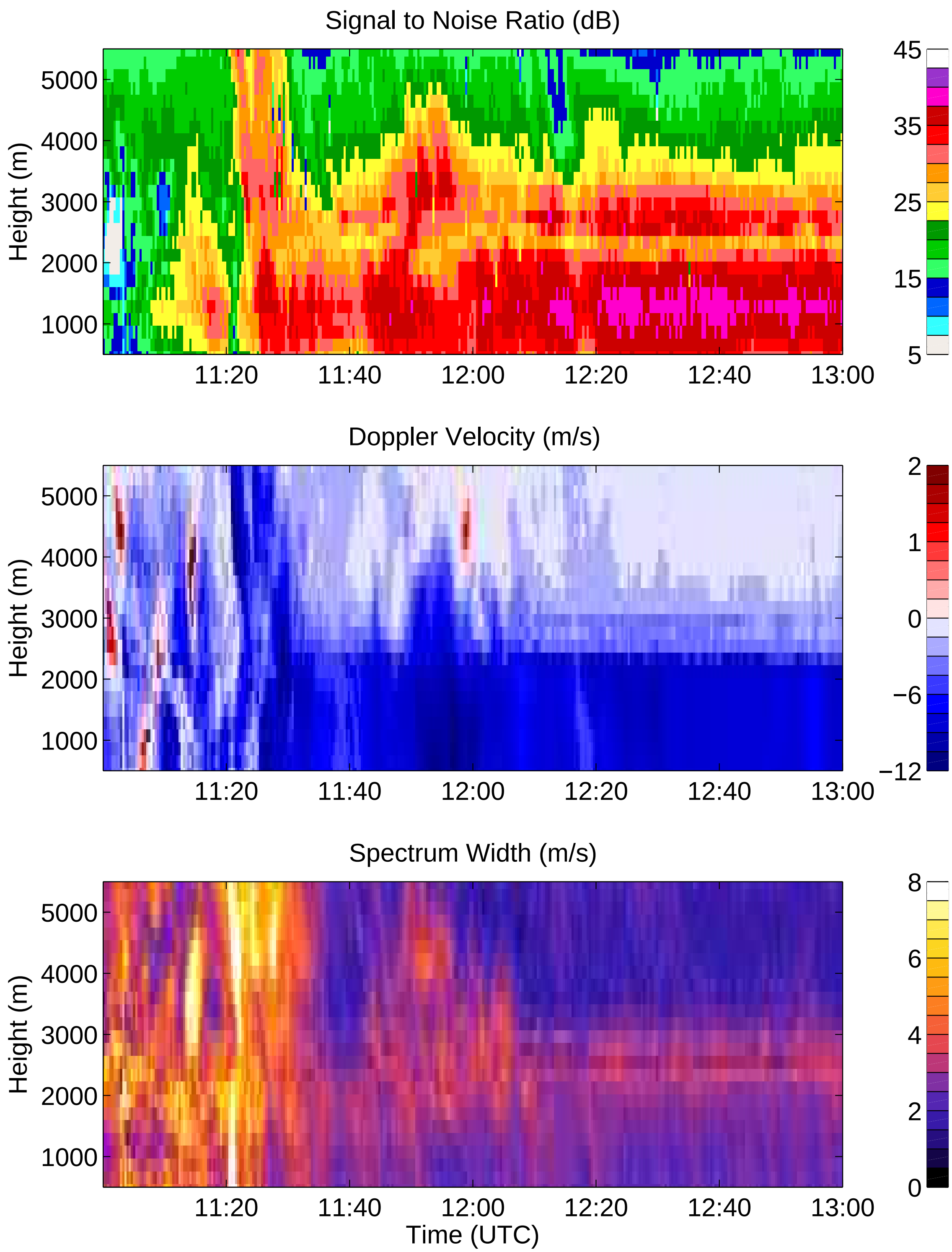

Figure 3: Time-height cross-sections of signal to noise ratio, Doppler velocity, and spectrum width observed with the OU profiler. Heights are given relative to Mean Sea Level (MSL).

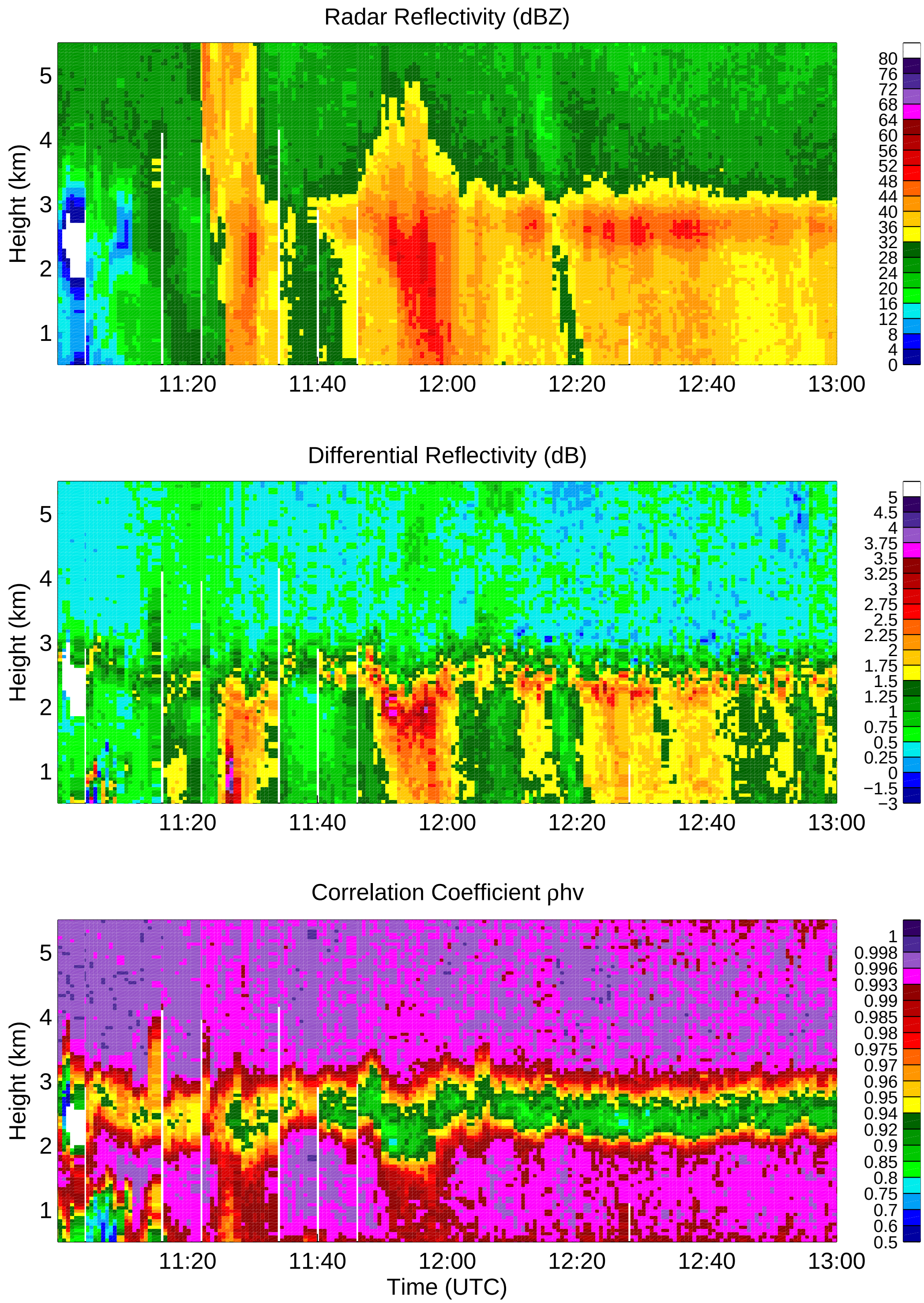

Figure 4: Time-height cross-sections of radar reflectivity, differential reflectivity, and correlation coefficient over the KFFL observed with the KOUN polarimetric radar. Heights are given relative to MSL.

ing level. These sounding data were also used to adjust the calculated terminal fallspeeds of the raindrops with height.

Here we present representative height profiles of data retrieved using the KOUN and the OU profiler for different phases of the MCS as it passed over KFFL. For each of the selected cases, vertical profiles of Z_H, Z_{DR}, and ρ_{HV}, together with the Doppler spectra from the KOUN and the profiler are shown. Each spectrum has been normalized to its peak value. For the sake of comparison, the vertical spacing of the KOUN spectral data has been matched to the range resolution of the OU profiler (200 m). The four examples presented below were selected as characteristic of different stages of cloud and precipitation development within the MCS. A speculative account of the underlying storm processes contributing to the observations is provided for each of the four cases. Data from other available observations are still being studied in order to construct a more comprehensive analysis of the March 11 MCS. Although the explanations provided below remain to be verified, they are at least plausible and illustrate the utility of combined profiler and polarimetric weather radar observations to study precipitation.

Early development of precipitation aloft (heights exceeding 4 km) (11:22Z / Figure 6) The generation of large graupel is manifested by very large terminal velocities measured by the profiler and high radar reflectivity (well over 40 dBZ) at the altitudes above 4 km. The presence of strong downdrafts is not likely at such heights and substantial negative velocities above 4 km are associated with the fall of graupel / small hail. A sudden drop in the magnitude of Z_H and fall velocities below 4 km testifies that the hydrometeors in the lower portion of the cloud are very different than those aloft. Most likely, small-size dry and melting graupel is dominant within the height interval between 2.3 and 3.4 km. It seems that there is no connection between this small-size graupel and the large graupel / hail aloft. In other words, these two species of graupel might have been advected from different parts of the cloud. Raindrops with relatively small size below the melting layer result from melting graupel. The melting layer is marked by the decrease in ρ_{HV} and rapid change of Z_{DR} within the height interval between 2.5 and 3 km.

Strong updraft at lower levels (11:24Z / Figure 7) The updraft at lower levels (0.5 - 2.5 km) intensifies. This is revealed by the striking difference between the spectra of vertical velocities retrieved from KOUN and those

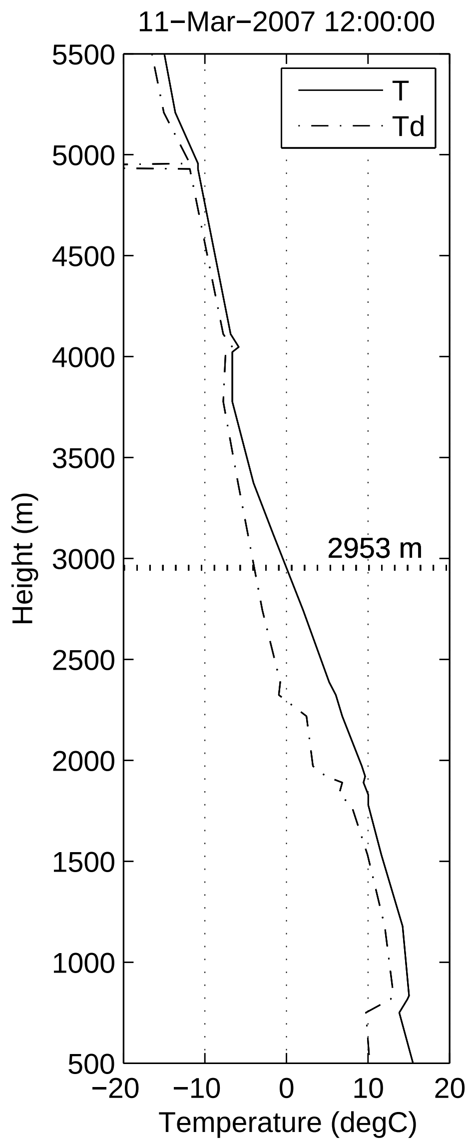

Figure 5: Vertical profile of temperature and dew point temperature at KOUN for 12Z on March 11, 2007. The freezing level is at 2953 m MSL.

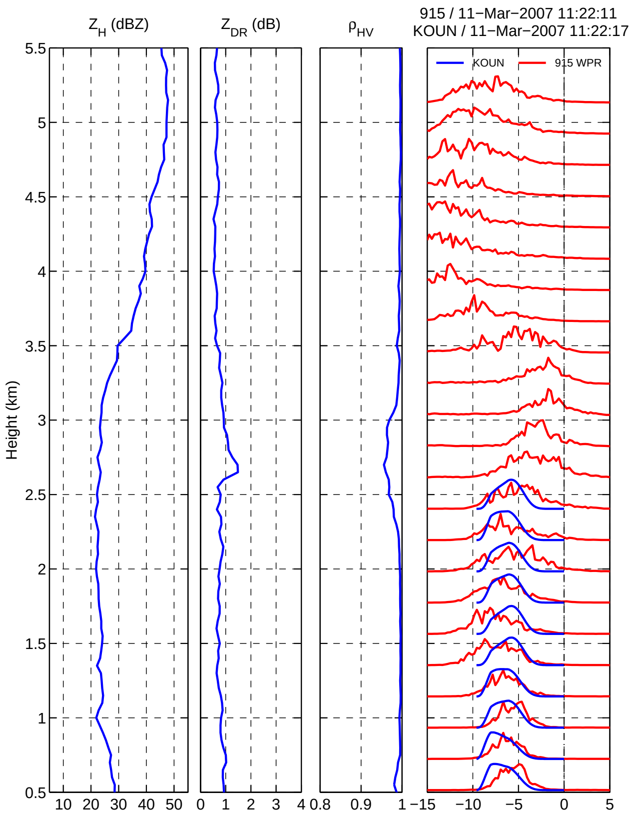

Figure 6: Vertical profiles of Z_H, Z_{DR}, ρ_{HV}, and spectra of the particle fall speeds and Doppler velocity at 11:22Z. The spectra of retrieved (KOUN) and measured (profiler) velocities are indicated in blue and red, respectively. The retrieved spectra are only shown for heights up to 2.5 km (well below the freezing level). Heights are given relative to MSL.

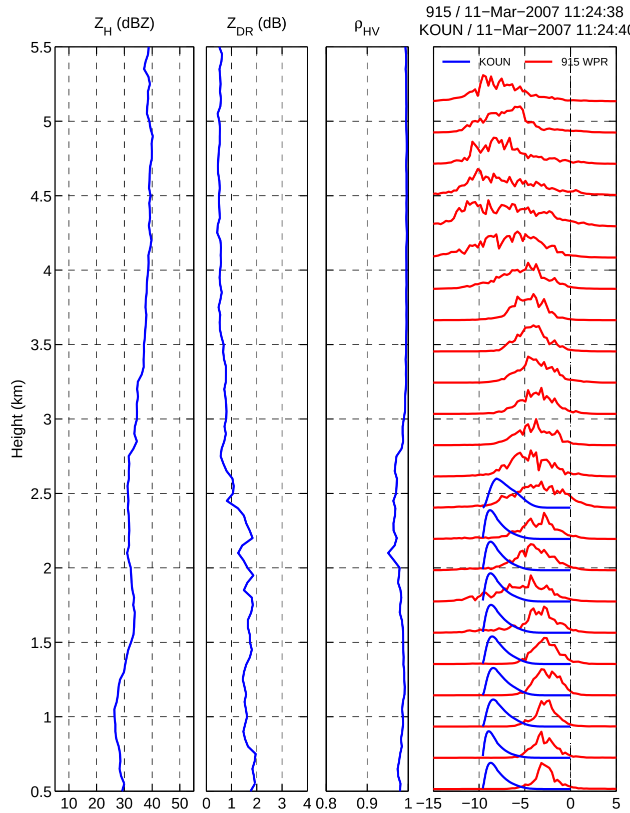

Figure 7: Same as Figure 6 but for 11:24Z.

measured by the profiler. The strength of the updraft is about 6 m s^{-1}. Another indication of the updraft below 2.5 km is the combination of low Z_H (of about 30 dBZ) and relatively high Z_{DR} (up to 2 dB at this time and above 4 dB one-two minutes later) which points to substantial size sorting of raindrops, i.e., raindrops with terminal velocities less than 6 m s^{-1} do not fall through the updraft. A low-level Z_{DR} column is apparent in the left side of the first convective cell in Figure 4. The corresponding time interval is from 11:24Z to 11:28Z. At higher levels, the situation is quite similar to the one previously discussed (11:22Z).

Convective downdraft (11:55Z / Figure 8) A classic signature of a convective downdraft within the main precipitation shaft is observed at this time. Convective rain below the melting layer originates from melting graupel / small hail, which has relatively high terminal velocities immediately above the melting layer. Near the ground, the difference between modal values of the KOUN and

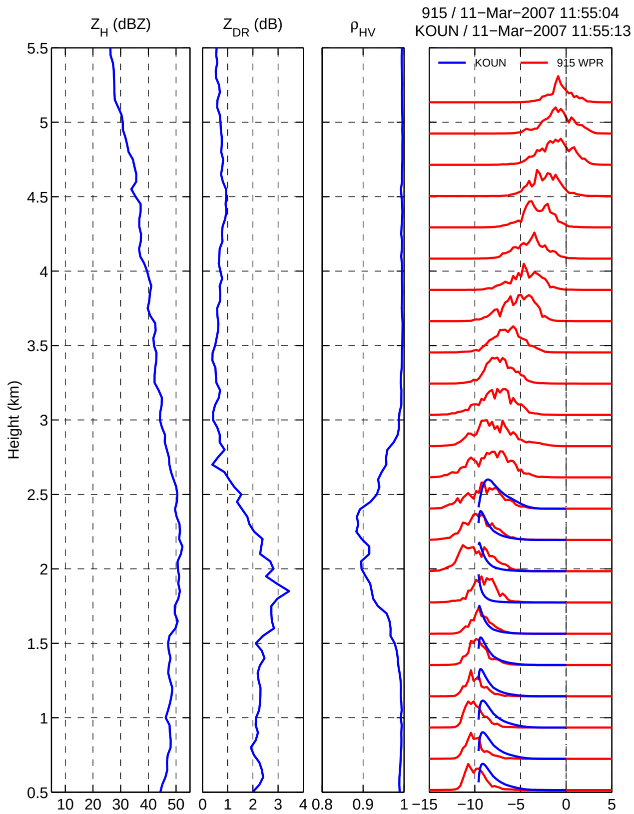

Figure 8: Same as Figure 6 but for 11:55Z.

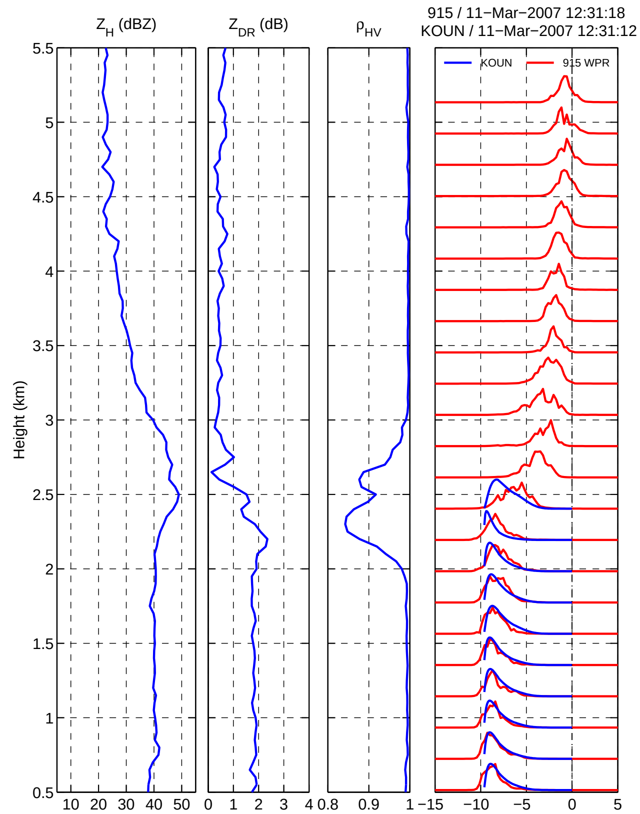

Figure 9: Same as Figure 6 but for 12:31Z.

profiler spectra corresponds to a downdraft of about 2 m s^{-1}, which is likely generated by melting graupel / hail. The downdraft combined with cooling due to melting pushes the melting layer down closer to the ground as indicated by the vertical profiles of Z_{DR} and ρ_{HV} (see Figure 4). As a result, complete melting of graupel / hail occurs at the height slightly above 1.5 km (with the freezing level at 3 km in the ambient air as Figure 5 indicates).

Stratiform rain - vertical motions are negligible (12:31Z / Figure 9) These data indicate a classic signature of the bright band generated by melting snowflakes. There is no graupel aloft and the difference between the terminal velocities of aggregated snowflakes above the freezing level and raindrops below is large. The minimum in the vertical profile of ρ_{HV} is deeper, narrower, and higher compared to the situation of convective downdraft. The agreement between the spectra of vertical velocities retrieved from the polarimetric radar and those measured with the wind profiler is amazingly good. This may serve as indirect evidence of high quality of polarimetric DSD retrieval used in this study.

4. SUMMARY / CONCLUSIONS

The study of precipitation can be greatly facilitated through the combined use of wind profiler and polarimetric weather radar data (May et al., 2001, 2002; May and Keenan, 2005). Here, we have described a method to examine the microphysical processes of rainfall formation, which takes advantage of such complementary observations. When oriented vertically, Doppler spectra from the wind profiler can be used to directly measure the vertical velocities of the sampled precipitation particles. These data are investigated together with the abundant information available through the polarimetric weather radar observations (such a Z_H, Z_{DR}, and ρ_{HV}), For example, these measurements facilitate a detailed study of precipitation processes in and around the melting layer. For the particular case of raindrops, the polarimetric observables Z_H and Z_{DR} are used estimate the underlying DSD based on a constrained gamma model. Using an assumed fallspeed relationship, the DSD can be mapped into an equivalent spectrum of reflectivity weighted vertical velocities. This can be directly compared to the observed spectrum of particle fall velocities measured with a profiling radar.

The method is being implemented in central Oklahoma using data from KOUN and KTLX in conjunction with measurements from the OU and NPN profilers (both located at KFFL). The separation between KOUN and the two profilers is only 30 km; therefore, the sampling volumes for KOUN and the OU profiler are very similar. In addition to these data sources, observations from additional instrumentation located at KFFL are available. These include the Oklahoma Mesonet, the DOE Atmospheric Radiation Measurement (ARM) program, a two-dimensional video disdrometer (2DVD), and a network of closely spaced tipping bucket rain gauges (PicoNet). These are described in Chilson et al. (2007).

An example of data collected for an MCS event have been presented. In particular, four instances representative of different stages of cloud and precipitation development within the MCS have been discussed in some detail. The analysis of these data is still on-going; however, it has been shown, for example, that

- Stacked profiles of the vertical velocity spectra retrieved from KOUN for raindrops show remarkable agreement with those directly measured with the OU profiler during stratiform precipitation
- In some cases, the spectra from KOUN and the OU profiler agreed well in shape, but were offset in velocity, which is attributed to vertical air motion
- Updrafts as large as 6 m s^{-1} were present near the leading edge of the MCS, which resulted in significant size sorting of the raindrops
- Melting graupel / hail below the melting level was likely responsible for an observed convective downdraft of 2 m s^{-1}.

Admittedly, the data presented here require further analysis in order to better understand the dynamic structure of the March 11 MCS. To this end, supporting data from the other available instrumentation will be used. Nevertheless, a plausible and self-consistent characterization of the storm event is already beginning to evolve based on the four cases that have been shown and discussed.

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