14.2 POLARIMETRIC ANALYSIS OF A 3 MAY 1999 TORNADO

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1. INTRODUCTION

Dual-polarization radar has been recognized as an efficient tool for classification of different types of hydrometeors and for discrimination between meteorological and non-meteorological scatterers (Zrnic and Ryzhkov 1999, Vivekanandan et al 1999). It is reasonable to expect that tornadic debris associated with a tornado touchdown would produce polarimetric signatures that are different from the signatures of hydrometeors.

In this study, we examine evolution of a three-dimensional pattern of radar polarimetric variables for one of the tornadic storms that constitute the 3 May 1999 tornado outbreak in central Oklahoma. To our knowledge, this is the first attempt to localize tornadic touchdown using dual-polarization weather radar. The data have been collected with the NSSL's Cimarron polarimetric radar.

2. DESCRIPTION OF DATASET

Multiple tornadoes occurred in a close proximity of the Oklahoma City metropolitan area during the event of 3 May 1999. Approximate damage paths and highest Fujita scale ratings for multiple storms within the Cimarron radar coverage area SW of Oklahoma City are shown in Fig. 1. Polarimetric data from the Cimarron radar are available for the period from 21:45 UTC to 23:22 UTC when the radar went down after being hit by a storm B (Fig. 1). Thus, the radar missed the most violent stage of the storm A that eventually struck the Oklahoma City metropolitan area. However, we have 15 volume scans of polarimetric data that include developing stages of the storms A and B and a less destructive tornado rated as F3 in the Fujita scale (west of Chickasha in Fig. 1). This tornado produced about 900 m – wide damage swath and lasted from 22:46 until 23:10 UTC. Tornado track was at the ranges 45 – 60 km from the radar.

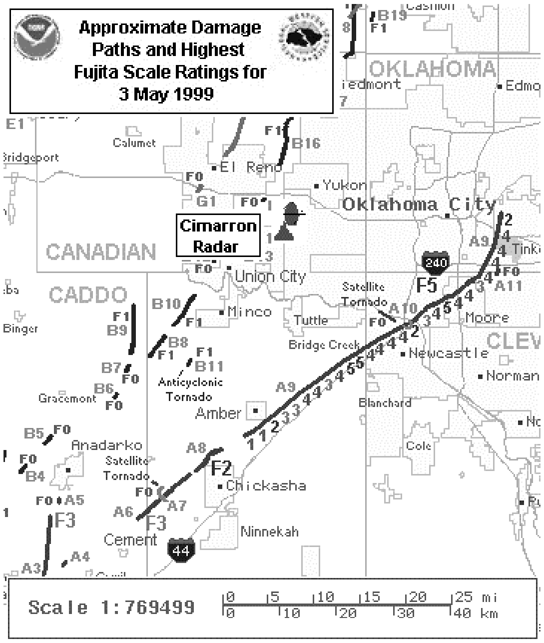

Fig. 1 Approximate damage paths and highest Fujita scale ratings for the 3 May 1999 tornado outbreak

The Cimarron radar measured radar reflectivity factor Z at horizontal polarization, differential reflectivity Z_{DR}, differential phase Φ_{DP}, and cross-correlation coefficient ρ_{hv} between radar returns at two orthogonal polarizations. The data were collected at the elevations of 0.0°, 0.5°, 1.5°, 2.5°, 4.0°, and 6.0° with update time of approximately 6 min. All radar variables were measured with radial resolution 0.24 km and azimuthal resolution of about 1.9° (although radar beam has 0.9° width). In order to reduce statistical measurement errors, we average Z_{DR} and ρ_{hv} over 1 km in range. Larger averaging window of about 3.8 km is applied for differential phase. This precludes the use of Φ_{DP} and specific differential phase K_{DP} for detection of such small-scale phenomenon as tornado unless special oversampling processing technique is implemented in order to reduce Φ_{DP} measurement errors (Torres and Zrnic 2001).

Because tornado touchdown occurs at the surface, it is important that we utilize the radar data collected at 0.0° elevation for which a center

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of the radar beam is as close to the ground as possible. At such low elevation, radar beam is inevitably partially blocked and the power-related radar variables such as Z and Z_{DR} are biased. Partial blockage, however, does not affect phase-related variables - Doppler velocity and differential phase. Moreover, it is possible to restore correct values of Z and Z_{DR} using K_{DP} and the idea of self-consistency between Z, Z_{DR}, and K_{DP} even in the presence of severe beam blockage. Such technique was recently developed at NSSL (Ryzhkov et al 2002) and is currently used to adjust the Cimarron data collected at 0.0° and 0.5° elevations. This method allows us to restore Z and Z_{DR} with the accuracy of 2 dB and 0.2 dB respectively. Fig.2 gives an idea about the estimated Z biases that the Cimarron radar experiences at the elevations of 0.0° and 0.5° within the azimuthal sector of 90° where the tornadic storm was observed. Part of the negative biases (about 5 dB) is attributed to radar system problems. Another component of the bias varies with azimuth and relates to partial beam blockage.

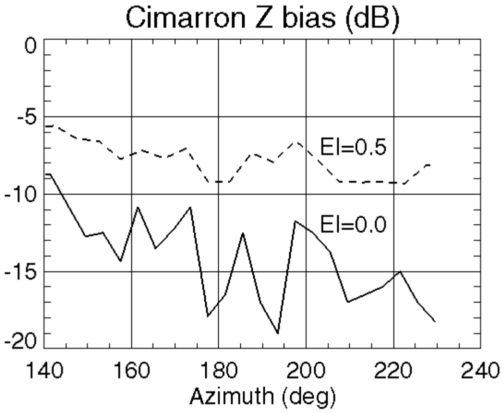

Fig. 2 Retrieved biases of Z measured by the Cimarron radar at the elevations of 0.0° and 0.5° in the storm sector.

3. POLARIMETRIC SIGNATURES OF TORNADO

After analysis of all 15 volume scans of data, we have selected the one that started at about 23:05 UTC to illustrate tornadic polarimetric signatures. At that time, the F3 tornado was still observed on the ground and the storm was relatively close to the radar (within 55 km), therefore, small-scale features can be more easily resolved. Combined plot of Z, Z_{DR}, and ρ_{hv} at the lowest CAPPI level (approximately 200 m above ground at the range of 50 km) is shown in Fig. 3.

At that moment, a hook echo was well developed and the area of intense hail mixed with rain is recognized in the forward-flank downdraft (FFD) region. The latter is marked with Z exceeding 60 dBZ near ground and 65 dBZ aloft. Radar reflectivity within the hook is between 40 and 45 dBZ.

Differential reflectivity is high (more than 2 – 3 dB) in the extended area including rear-flank downdraft (RFD) region, northern part of a major reflectivity core and to the east of it. Analysis of the vertical structure of Z_{DR} shows that the region of high Z_{DR} stretches above freezing level in the RFD region (the "Z_{DR} column") and is very shallow (confined to a 1-km-depth layer) elsewhere. Z_{DR} is close to 0 dB in the hook and in the southern part of the high reflectivity core, both adjacent to the main updraft weak echo region.

Cross-correlation coefficient is low in the high reflectivity region where hail is mixed with rain and it is anomalously low (less than 0.4!) at the inner side of the hook in the vicinity of a tornado track depicted by a dashed line.

Vertical cross-section of the three radar variables along the azimuth 203° (marked by a straight solid line in Fig. 3) is even more revealing (see Fig. 4). Radar reflectivity maximum centered at 1.5 km height is accompanied by low Z_{DR} and high ρ_{hv}. Those might indicate pure hail. In the area underneath, Z_{DR} sharply increases but ρ_{hv} decreases which likely point to a mixture of hail and big raindrops with ice cores inside.

Within a hook, a tiny, shallow signature centered at 49.5 km from the radar and extended less than 1 km above ground is visible. This signature is characterized by Z_{DR} close to 0 dB and ρ_{hv} less than 0.4. Very close proximity to the tornado track on the ground suggests that this signature is very likely associated with tornadic debris. Indeed, this is exactly what is expected for randomly oriented non-meteorological scatterers with irregular shape and high refractive index.

Another notable signature can be seen higher up in the hook where the remnant of the "Z_{DR} column" with high values of Z_{DR} is associated with very low ρ_{hv}. Low values of the cross-correlation coefficient in this area are more likely caused by low signal-to-noise ratio than the presence of non-meteorological scatterers.

4. DISCUSSION AND SUMMARY

Although it would be premature to make far-reaching conclusions based on the analysis of only one (although well-documented) tornado case, this study shows great potential of a dual-polarization radar for possible tornado detection and warning. Further investigation is needed to understand what kind of a 3D polarimetric pattern

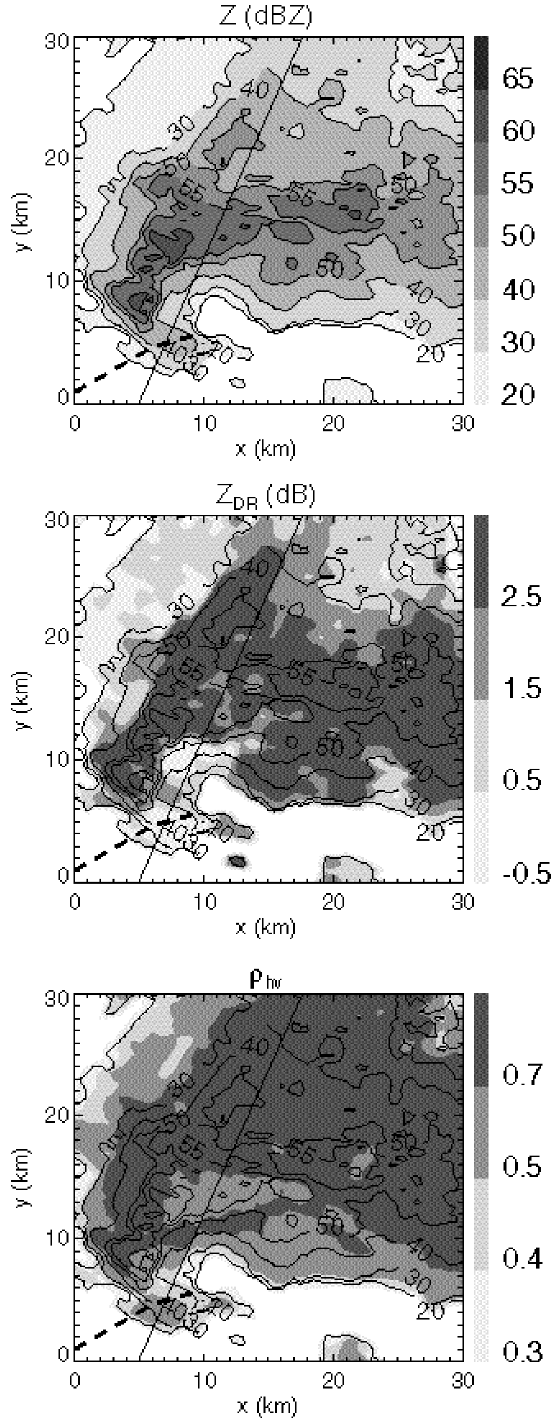

Fig. 3 Fields of Z, Z_{DR}, and ρ_{hv} at the lowest CAPPI level (~200 m) at 23:04 UTC. Solid line indicates azimuthal direction 203°, dashed line depicts tornado track on the ground.

near the ground and aloft precedes tornado touchdown.

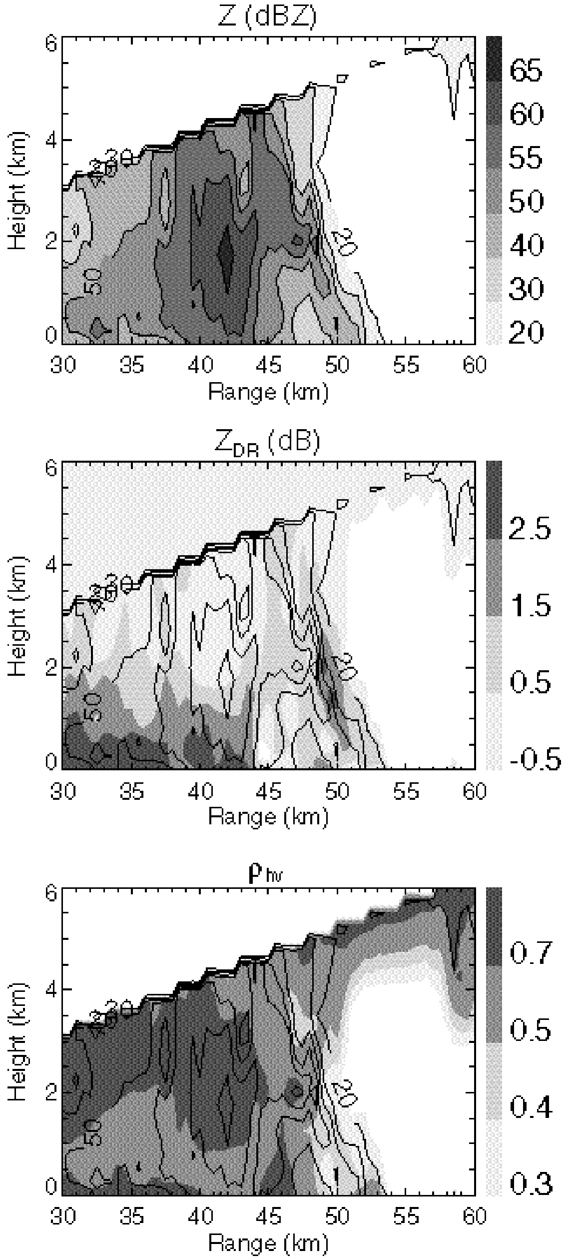

Fig. 4. Vertical cross-section of Z, Z_{DR}, and ρ_{hv} corresponding to azimuthal direction 203°

Nevertheless, it is clear that at least two polarimetric variables, Z_{DR} and ρ_{hv}, provide very useful information that is relevant to tornado detection and prediction. Anomalously low values of ρ_{hv} combined with Z_{DR} close to zero observed in the hook echo might indicate the presence of tornado. Cross-correlation coefficient is the most attractive variable because, unlike Z_{DR}, it is not affected by radar miscalibration, attenuation in precipitation, and partial radar beam blockage. Linear depolarization ratio LDR that can be considered as a proxy for ρ_{hv} is vulnerable to all these conditions.

A capability to correctly estimate radar variables very close to the ground at the elevation less than 0.5° is another important advantage of a dual-polarization radar.

Polarization measurements will complement Doppler variables that are traditionally used for mesocyclone and tornado detection. Doppler measurements require good spatial resolution in order to resolve small tornado vortex, whereas identification of polarimetric signatures can be accomplished with coarser resolution. Moreover, these signatures are "isotropic" in their nature, i.e., as opposed to Doppler velocities, they do not depend on a viewing angle. Heavy debris as well as large hailstones are not perfect tracers of air motions. Polarimetric identification of those scatterers will help in a quality control and better interpretation of Doppler measurements.

Although tornado detection is important, its prediction and early warning are even more important. Cursory look into evolution of the 3D pattern of polarimetric variables prior to tornado touchdown reveals quite unusual and intriguing polarimetric signatures aloft that might be related to subsequent tornado. Understanding and interpretation of these signatures could provide insight into microphysical aspects of tornadogenesis.

References

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