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A Dual-Wavelength Polarimetric Analysis of the 16 May 2010 Oklahoma City Extreme Hailstorm

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ABSTRACT

A comparative analysis of a supercell hailstorm using simultaneous observations with S-band and C-band polarimetric radars supported by abundant ground-truth reports is presented in this study. The storm occurred on 16 May 2010 and produced a swath of extremely damaging hail across a large portion of the Oklahoma City, Oklahoma, metro area. Hail sizes over 10 cm in diameter and hail drifts upward of 1.5 m in height were reported. Both S-band (KOUN) and C-band [University of Oklahoma Polarimetric Radar for Innovations in Meteorology and Engineering (OU-PRIME)] polarimetric radars in Norman, Oklahoma, sampled the storm at ranges less than 60 km, so that high-resolution dual-wavelength polarimetric data were obtained. At C band, this analysis mostly presents raw Z and Z_{DR} (due to problems with differential phase resulting from an incorrect censoring threshold in the examined case) while taking into account the possibility of attenuation in the interpretation of these data. Among the issues investigated in the study are the relation of hail size measured at the surface to the polarimetric signatures at both wavelengths, the difference between polarimetric signatures at the two wavelengths of hail aloft and near the surface (where melting hail is mixed with rain), and the three-body scatter spike (TBSS) signature associated with large hail.

1. Introduction

There is growing interest in hail studies, stimulated by the pending introduction of operational dual-polarization radars that measure differential reflectivity Z_{DR} , differential phase Φ_{DP} , and cross-correlation coefficient ρ_{hv} between the signals at orthogonal polarizations, in addition to the conventional radar reflectivity factor Z (Bringi and Chandrasekar 2001). The Z_{DR} of hailstones is lower than that of raindrops with similar reflectivity because of their tumbling during descent and their generally lower dielectric constant. The same factors are responsible for lower specific differential phase K_{DP} and ρ_{hv} in hail compared to values in rain.

Polarimetric algorithms for hydrometeor classification, which utilize a combination of Z , Z_{DR} , K_{DP} , and ρ_{hv} , demonstrate good skill for hail detection at S band as limited validation studies show (e.g., Heinselman and Ryzhkov 2006; Depue et al. 2007). Polarimetric hail detection algorithms originally developed for S band need

significant modification for applications at C band primarily because Z_{DR} of small- and medium-size melting hail at C band is greater than at S band (Ryzhkov et al. 2007; Tabary et al. 2010; Anderson et al. 2011). Typically, wet hail is mixed with rain, and anomalously high Z_{DR} due to resonance scattering associated with large raindrops and small melting hail at C band offsets the low intrinsic Z_{DR} of moderate-large hail.

The modeling studies of Ryzhkov et al. (2009, 2011) and Kumjian et al. (2010a) support this interpretation and show that Z_{DR} of melting hail is very sensitive to radar wavelength. The first direct comparisons of polarimetric hail signatures observed by closely located S- and C-band radars (Borowska et al. 2011; Gu et al. 2011) are generally consistent with results of these theoretical simulations.

Another important feature that must be considered for hail detection using shorter wavelengths is that the radar reflectivity of hail at these wavelengths may be significantly lower than at S band. The corresponding difference has been termed the “hail signal” in previous studies (Atlas and Ludlam 1961; Eccles and Atlas 1973; Bringi et al. 1986; Feral et al. 2003).

Determination of hail size remains challenging. The most recent version of the hydrometeor classification

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algorithm (HCA) developed at the National Severe Storms Laboratory for polarimetrically upgraded Weather Surveillance Radar-1988 Doppler (WSR-88D) radars detects “rain mixed with hail” (Park et al. 2009) and does not distinguish between large and small hail. The Colorado State University HCA distinguishes between “graupel–small hail” and “hail” without specifying the borderline size between small hail and hail (Lim et al. 2005). According to the criterion of the U.S. National Weather Service (NWS), hail is considered large and capable of inflicting substantial damage to property if its diameter exceeds 2.5 cm. Depue et al. (2007) recommended using the hail differential reflectivity parameter H_{DR} , defined as (Aydin et al. 1986)

$$H_{DR} = Z - g(Z_{DR}), \quad (1)$$

where

$$\begin{aligned} g(Z_{DR}) &= 27 \quad \text{if } Z_{DR} \leq 0 \text{ dB} \\ g(Z_{DR}) &= 19Z_{DR} + 27 \quad \text{if } 0 \leq Z_{DR} \leq 1.74 \text{ dB}, \\ g(Z_{DR}) &= 60 \quad \text{if } Z_{DR} > 1.74 \text{ dB} \end{aligned} \quad (2)$$

to identify large hail with a diameter exceeding 1.9 cm (considered large according to the past NWS definition) using an H_{DR} threshold of 21 dB.

The main limitation of the previous methods, including the approach by Depue et al. (2007), is that they do not account for the hail melting process, which has a very strong impact on the vertical profile of Z_{DR} . Indeed, if large melting hail is mixed with rain originating from the complete melting of smaller graupel–hail, the resulting Z_{DR} can easily exceed 1.74 dB and the condition $H_{DR} > 21$ dB suggested by Depue et al. (2007) is equivalent to $Z > 81$ dBZ, making little sense. Although the occurrence of high Z_{DR} with large hail is much more likely at C band, it can happen at S band as well, as shown in the in situ reports section below. Furthermore, whereas the cases of Depue et al. (2007) were located in the Colorado high plains, the 16 May 2010 case occurred in an environment characterized by relatively higher moisture, which enhances melting and in turn Z_{DR} . Therefore, methods for estimating hail size should be substantiated by retrievals from cloud models that explicitly treat the microphysics of melting hail, as regional climate variability can certainly affect polarimetric hail detection.

Such attempts have been performed recently by Ryzhkov et al. (2009, 2010) and Kumjian et al. (2010a), who formulated polarimetric criteria for discrimination between small (less than 2.5 cm) and large (more than 2.5 cm, according to the new NWS definition) hail using

model simulations of melting hail. They computed radar scattering characteristics of a rain–hail mixture for outputs of 1D and 2D cloud models with spectral (bin) microphysics. Indeed, these studies indicate that large-hail determination rules must account for the height of the radar resolution volume with respect to the storm freezing level.

Moreover, there are indications that very large dry hail or hail undergoing wet growth above the freezing level have anomalously low ρ_{hv} (Balakrishnan and Zrnić 1990; Rowe et al. 2007; Picca and Ryzhkov 2010) and a significantly high linear depolarization ratio (LDR) (Kennedy et al. 2001). Balakrishnan and Zrnić (1990) demonstrate that in the presence of large, resonance-size scatterers, whose backscatter differential phase δ is high, ρ_{hv} is significantly reduced. In addition, δ increases and ρ_{hv} decreases if hailstones acquire a water film, which occurs in the wet growth regime. The study of Rowe et al. (2007) demonstrates that ρ_{hv} proved even more important than Z_{DR} in discriminating between large and small hailstones. However, their study examined hailstorms much farther from the radar site (≥ 100 km versus approximately 50 km) and over more rural areas than the 16 May 2010 case, likely creating greater uncertainty in the hail reporting. Additionally, whereas Rowe et al. (2007) investigate S-band data only, this study takes advantage of both S- and C-band data for a comparative analysis. Thus, the potential of using the ρ_{hv} signature for identifying very large hail is further explored.

Another interesting radar signature associated with large hail is the “three-body scattering signature” (TBSS), which was studied by Zrnić (1987), Wilson and Reum (1988), Lemon (1998), Hubbert and Bringi (2000), Lindley and Lemon (2007), Zrnić et al. (2010), and Kumjian et al. (2010b). The TBSS is observed as a radial spike in Z . Moreover, Hubbert and Bringi (2000) noted the appearance of very high Z_{DR} and low ρ_{hv} in the TBSS observed with polarimetric radar. Therefore, potential links between the TBSS and hail size should be investigated.

Validation studies of polarimetric hail detection algorithms are rare. Notable exceptions include the works of Heinselman and Ryzhkov (2006) and Depue et al. (2007) at S band, and Boodoo et al. (2009) and Tabary et al. (2009a, 2010) at C band. To our knowledge, the study of Depue et al. (2007) is the only one where the correlation of the maximal size of ground-truth hail observations to polarimetric signatures has been examined systematically.

The purpose of this study is to take advantage of an opportunity to examine simultaneously obtained S-band and C-band polarimetric data from a unique hailstorm

FIG. 1. Surface conditions at 1800 UTC 16 May 2010. Wind data come from NWS surface stations and Oklahoma Mesonet stations; open circles, half barbs, and full barbs represent 0, 2.5, and 5 m s^{-1} , respectively. Surface temperatures are contoured every 2°C. The dashed line indicates the wind shift boundary associated with the weak surface warm front. The “X” enclosed within a circle indicates the location of the storm’s initial development over Major County. Other counties mentioned in the text are labeled. The locations of KOUN (S band) and OU-PRIME (C band) are indicated by arrows (Norman).

and explore practical implications for hail detection–sizing at each radar wavelength. On 16 May 2010, a supercell thunderstorm produced a swath of extremely damaging hail across a large portion of metropolitan Oklahoma City, Oklahoma. Hail sizes over 10 cm in diameter and hail drifts upward of 1.5 m in height were reported. Total damage costs from the storm are estimated to be hundreds of millions of dollars. The storm occurred in close proximity to the WSR-88D polarimetric prototype S-band radar (KOUN) and the C-band University of Oklahoma Polarimetric Radar for Innovations in Meteorology and Engineering (OU-PRIME; Palmer et al. 2011) such that high-resolution dual-polarization data were obtained. Finally, we utilize abundant ground truth for this event to evaluate methods for hail sizing and suggest areas of improvement for polarimetric hail detection.

2. Event description

a. Environment

At 1200 UTC 16 May 2010, a 500-hPa trough was present over the high plains of Nebraska and Colorado southward through the Texas Panhandle. This trough was the dominant upper-level feature, providing westerly flow over Oklahoma. At the surface, a weak warm front slowly progressed northward through central Oklahoma

(Fig. 1), supplying a focus for convective initiation, in conjunction with ascent from the upper-level trough. Afternoon surface conditions near and south of the front were characterized by temperatures above 21°C and dewpoints around 17°–19°C. With cooling at upper levels resulting from the approaching trough, CAPE values reached 2500 J kg^{-1} , creating favorable conditions for the development of severe thunderstorms capable of damaging hail.

b. Storm

At about 1800 UTC, among a cluster of small convective cells developing along the warm front, one particular cell over Major County rapidly gained supercellular characteristics. Giant hail reports (≥ 5 cm) followed with sizes of 7 and 10.8 cm in Major and Blaine Counties, respectively, between 1800 and 1900 UTC. Additionally, multiple funnel clouds were reported as the storm moved across Kingfisher and Canadian Counties. Over the next several hours, the supercell progressed southeast through central Oklahoma, where hail reports of at least golf-ball size (4.4 cm) were frequent, with several reports over 5 cm.

This hailstorm was one of the costliest in U.S. history with damage estimates in the hundreds of millions. Severe damage to automobiles, buildings, and vegetation was common along the storm’s path, especially in Oklahoma County. In some areas hail fell for over 10 min, which,

TABLE 1. Specifications and scanning details for KOUN and OU-PRIME on 16 May 2010.

Radar	KOUN	OU-PRIME
Wavelength (cm)	10.9	5.44
Antenna beamwidth (°)	0.9	0.45
Peak transmitter power (MW)	0.75	1
Radial resolution (m)	250	125
Update time (s)	261	145
Elevation angles (°)	0.5, 0.9, 1.4, 1.8, 2.4, 3.2, 4.0, 5.1, 6.4, 8.0, 10.0, 12.5, 15.6, 19.5 (14 total)	0.25, 1.0, 2.0, 3.0, 4.0, 5.0, 6.5, 9.0 (8 total)

for a given Z (Ryzhkov et al. 2005a). Both Z and Z_{DR} measured at C band can be significantly biased by attenuation/differential attenuation. The methods for attenuation correction in melting hail are not well established. In addition, the measured differential phase that is commonly utilized for the attenuation correction of Z and Z_{DR} was exceedingly censored out in the OU-PRIME data for this particular event because of inappropriate setting of the censoring threshold for Φ_{DP} . Therefore, we mostly present raw Z and Z_{DR} data and take into account the impact of attenuation in the interpretation of the data. At S band, the quality of the differential phase was not compromised and the specific differential phase K_{DP} was computed as prescribed by Ryzhkov and Zrnić (1996).

Observations from KOUN and OU-PRIME in this study cover a period of 66 min from 2028 to 2134 UTC. OU-PRIME C-band data are analyzed from 2028 to 2109 UTC, while KOUN S-band data are analyzed from 2055 to 2134 UTC. A unique dataset from about 2100 UTC contains both S- and C-band observations during one of the most intense periods of this hailstorm.

The location of the supercell to the northwest of the radar sites is suitable for accurate radial comparisons of the data, considering KOUN and OU-PRIME lie 6.9 km apart on a 157.3° – 337.3° axis. Subsequently, differences in the polarimetric variables between the two radars reveal quite significant information in terms of the bulk microphysics. Furthermore, the supercell was located at a range of approximately 40 km during the main analysis time. This close range ensures that the data are of fine spatial resolution while still remaining free of contamination from ground clutter.

3. Analysis and discussion

a. Low-level hail signature

As the supercell peaked in intensity around 2100 UTC, hailstones of baseball size and greater (>7 cm) fell across portions of northwest Oklahoma City, including

a large shopping mall, where numerous automobiles in parking lots were heavily damaged. Polarimetric data for this time display many particular features that are a result of the large size and number of falling hailstones (Fig. 3).

At S band, the powerful nature of the hail core is quite apparent, as 0.5° plan position indicator (PPI) Z values exceed 65 dBZ over a sizeable area (Fig. 3). Within the core, Z values reach a maximum of 72.5 dBZ, which almost certainly indicates the presence of large hail. Furthermore, this maximum is displaced well into the forward flank of the supercell. Typically, larger hailstones fall relatively close to the updraft–inflow region (e.g., Browning 1964). The location of these >70 dBZ values speaks to the extreme strength and organization of the cell updraft, which allowed very large hail to fall relatively far from the inflow region. Within the 60-dBZ contour, an extensive region of depressed Z_{DR} (≤ 0.5 dB) and low ρ_{hv} (generally ≤ 0.95) is observed. These values are a clear signature of large hailstones (>2.5 cm; Wakimoto and Bringi 1988) falling across an extremely wide swath within the supercell.

Two zones of negative Z_{DR} are also apparent (-1 dB $< Z_{DR} < 0$ dB). The first exists to the west and south-west of the inflow notch, and the second to the northeast well within the forward flank. In the first region, Z_{DR} drops as low as -0.6 dB, while the corresponding Z ranges between 62 and 66 dBZ. Figure 3 indicates that the Z_{DR} minimum is not associated with the highest Z in the rear flank of the cell, as a zone of $Z > 68$ dBZ is primarily located to the northwest of the range gates with negative Z_{DR} .

In the second region, Z_{DR} reaches a minimum of -0.75 dB, with the corresponding Z between 65 and 68 dBZ. Yet again, while near a zone of maximum Z (>72 dBZ, within 1.5–2-km range), the lowest Z_{DR} corresponds to Z approximately 4–6 dBZ less than the maximum.

In their calculation of Z_{DR} dependencies on hail size, Kumjian et al. (2010a) show that negative Z_{DR} is associated with hail of diameters greater than 4–5 cm at S band. Indeed, the presence of Z_{DR} from near -0.6 to -0.7 dB along with high Z could be indicative of hailstones at least 5 cm in diameter. Our C-band analysis to follow substantiates this conclusion. It should be cautioned, however, that positive Z_{DR} does not preclude the presence of very large hailstones, as few very large hailstones can be overwhelmed by many smaller, melting hailstones and large drops, which have high intrinsic Z_{DR} .

Figure 4 is a Z – Z_{DR} scatterplot displaying data from the intense precipitation core at 2059 UTC. Near-surface data within the core show most points with positive

FIG. 3. (left) KOUN (S band) and (right) OU-PRIME (C band) 2059 UTC 0.5° and 2100 UTC 0.25° PPIs, respectively, of (top) Z_H from 16 May 2010 and corresponding PPIs of (middle) Z_{DR} and (bottom) ρ_{hv} . Highlighted regions 1 and 2 represent areas in which giant hail is likely present, based on the polarimetric variables. Black lines display the radials from which the polarimetric values are displayed in Fig. 5. Contours of $Z = 50$ and 60 dBZ are overlaid. Effects of strong attenuation–differential attenuation are evident in the fields of C-band Z and Z_{DR} , which are not corrected for attenuation.

FIG. 4. The Z_H – Z_{DR} scatterplot from the KOUN 0.5° elevation scan of the supercell at 2059 UTC for gates with $Z_H > 55$ dBZ. The approximate beam height is 0.3 km above ground.

Z_{DR} . As Z increases, Z_{DR} trends toward 0 dB, which is expected with the presence of hailstones. At higher Z (generally >63 dBZ), there is a protrusion of negative Z_{DR} values, which are likely associated with very large hailstones. Finally, we observe a few points indicating negative Z_{DR} with $Z < 60$ dBZ. Kumjian et al. (2010a) discuss how the largest hailstones within a cell can fall at the periphery of the Z core in regions of relatively low Z . Because of size sorting within the updraft, these hailstones can fall in sparse concentration with relatively few raindrops present, producing lower Z . In their study of an Oklahoma supercell, Payne et al. (2010) present observations of a polarimetric signature of giant hail in regions of $Z < 60$ dBZ. Therefore, the possibility of very large hailstones should not be discounted if Z is not exceptionally high.

A major advantage of dual-wavelength data is the possibility of quantifying differences between S and C bands and potentially acquiring much better microphysical insight into the storm. At C band, Z is noticeably lower than at S band by nearly 10 dB throughout the hail core, which suggests that numerous hailstones of at least marginally large sizes (2–2.5 cm) are present (Feral et al. 2003; Snyder et al. 2010). This Z discrepancy is similar to the hail signal from past studies utilizing the ratio of S- and X-band reflectivities to identify regions of hail (Atlas and Ludlam 1961; Eccles and Atlas 1973; Snyder et al. 2010).

In areas of rain (outside the hail core), more expansive regions of $Z_{DR} > 5$ dB exist at C band than at S band. This difference is attributed to large drops (around 6 mm; Znić et al. 2000), which cause resonance scattering at C band and greatly increase Z_{DR} values. A maximum Z_{DR} of 7.5 dB is measured at the periphery of the forward-flank downdraft.

Even within the hail core, pockets of higher Z_{DR} (>2 dB) at C band are noted, similar to what has been observed in several C-band studies (Ryzhkov et al. 2007; Tabary et al. 2009a, 2010; Anderson et al. 2011). C-band Z_{DR} [$Z_{DR}(C)$] is 2–3 dB higher than S-band Z_{DR} [$Z_{DR}(S)$] between regions 1 and 2 of the hail core (overlaid circles in Fig. 3). In this area, large drops and small melting hailstones are the dominant scatterers within the C-band radar resolution volume, which enhances $Z_{DR}(C)$ (e.g., Borowska et al. 2011). Conversely, where the Z_{DR} difference falls below 1 dB and both radars show near-0 dB values (regions 1 and 2), we can be more confident that giant hail is falling. C-band data indicate here that hailstones are of a sufficiently large size and concentration to have a greater relative contribution to the signal, reducing Z_{DR} closer to that of S band. This analysis shows the additional value of the combined use of S- and C-band data in taking advantage of resonance scattering and its ability to highlight microphysical differences in various regions across the precipitation core.

Furthermore, observations of differences between the variables obtained at the two wavelengths are critical for adjusting any hail detection algorithm designed for S band in such a way that it can be used for C band. Figure 3 exhibits a ρ_{hv} difference [$\rho_{hv}(S) - \rho_{hv}(C)$] of 0.2–0.4 throughout the hail core, owing to enhanced effects of resonance scattering at the shorter wavelength. In areas where we identified a higher likelihood of giant hail, especially circle 1, the difference reaches a maximum near 0.4. Therefore, more extreme ρ_{hv} depressions at C band could be indicative of larger hail sizes. Indeed, it is quite clear that adaptation of hail detection algorithms from S band to C band must account for increased resonance scattering effects at C band.

b. Attenuation/differential attenuation at C band

To compare data from each wavelength in more detail, we match two sets of azimuths (shown in Fig. 3) for each radar and plot the radial profiles of Z , Z_{DR} , and ρ_{hv} (Fig. 5). These specific azimuths were selected because they provide the most direct radial comparisons. Although none of these radials pass through the highlighted regions in Fig. 3, they still carry significance for their location. The first pair (KOUN, S band: 348° , OU-PRIME, C band: 346°) passes through the inflow region where an abundance of large raindrops is not expected. Conversely, the second pair (KOUN: 353° , OU-PRIME: 351°) passes through a region producing extremely high attenuation–differential attenuation, likely characterized by a significant number of large raindrops and small hailstones.

At C band, both radials pass through areas of large hail with Z exceeding 60 dBZ, but only one (351°) exhibits anomalously high attenuation and differential attenuation

FIG. 5. Radial values of (top) Z , (middle) Z_{DR} , and (bottom) ρ_{hv} from KOUN at 2059 UTC (dashed curves) at (left) 348° and (right) 353° and from OU-PRIME at 2100 UTC (solid dark curves) at (left) 346° and (right) 351°. Values are taken from the lowest elevation angle for each radar (0.5° for KOUN; 0.25° for OU-PRIME). $Z(C)$ corrected for attenuation and Φ_{DP} are plotted in the top and middle rows, respectively (solid light curves). C-band curves are shifted to the left by 6 km to account for the distance between the two radar sites and to facilitate comparison.

(about 3 times larger than at 346°) as the comparison between Z and Z_{DR} at the two wavelengths indicates. If propagation were in pure rain without an excess of large drops, then attenuation-related biases ΔZ and ΔZ_{DR} are expected to be proportional to Φ_{DP} with coefficients of proportionality of about $0.06\text{--}0.08 \text{ dB } (^{\circ})^{-1}$ and $0.01\text{--}0.03 \text{ dB } (^{\circ})^{-1}$, respectively (e.g., Gu et al. 2011). The total spans of Φ_{DP} at 346° and 351° are 59° and 98°, respectively, and simple linear attenuation correction would yield much lower values of ΔZ and ΔZ_{DR} than the ones shown in Fig. 5. This certainly indicates that large raindrops originating from melting hail and water-coated

hailstones of smaller sizes are responsible for very high observed attenuation as hypothesized in Ryzhkov et al. (2009).

The areas contributing to anomalously high attenuation (i.e., “hotspots”) are usually quite small and a simple linear correction scheme does not work on them. One of the possible solutions is utilizing the so-called hotspot correction method described in Gu et al. (2011). This method restores reasonably well the radial profiles of attenuated Z at C band, $Z(C)$ (see reflectivity curves in Fig. 5), such that the corrected $Z(C)$ and $Z(S)$ are consistent behind the hotspots at both radials. Note that

despite generally corrupted measurements of differential phase at C band, it was possible to manually retrieve radial profiles of Φ_{DP} along selected radials. Tabary et al. (2009b) and Gu et al. (2011) demonstrate that differential attenuation increases dramatically in the presence of large raindrops manifesting themselves as very high Z_{DR} at the near side of the hotspot, as is the case for the radial at 351° . This explains extremely strong differential attenuation along the ray.

c. Hail growth region

In addition to the classic hail signature at low-elevation scans, the supercell's ability to produce a high number of large hailstones is evidenced by analysis of the mixed phase growth region in the minutes prior to 2100 UTC. Previous research has discovered that depressions in ρ_{hv} above the freezing level often indicate the presence of both liquid water and ice (Balakrishnan and Zrnić 1990; Ryzhkov et al. 2005b; Kumjian and Ryzhkov 2008). Large hail tends to grow in a wet growth regime, where an abundance of liquid water is present. A further reduction of ρ_{hv} is primarily due to strong variations of backscatter differential phase δ across the size spectrum of scatterers. The modeling studies of Balakrishnan and Zrnić (1990) at S band and Aydin and Giridhar (1991) at C band indicate that wild oscillations of δ start at hailstone sizes exceeding about 5 and 2.5 cm at S band and C band, respectively. These are the sizes at which Z_{DR} becomes negative as well (Kumjian et al. 2010a).

Viewing a pair of PPIs and RHIs from 2055 UTC (S band) and 2057 UTC (C band) clearly illustrates the efficient hail production of this storm (Fig. 6). RHIs from previous polarimetric analyses of powerful hailstorms show a tendency for the mixed phase growth region (indicated by low Z_{DR} and ρ_{hv} above the freezing level)—where hailstones can gain mass most efficiently—to be concentrated in a region above the primary updraft (Picca and Ryzhkov 2010). These observations are consistent with the hail trajectory schematic of Conway and Zrnić (1993). Even at an azimuth of 350° , S-band data from 2055 UTC indicate efficient growth of numerous hailstones, with negative Z_{DR} and $\rho_{hv} < 0.9$ extending over a significant volume from approximately 5 to 7 km AGL (Fig. 6), indicative of a very broad and organized updraft supporting large-hail growth. During the next several minutes, the descent of this hail core would result in excessive damage to buildings, automobiles, and vegetation across northwest portions of the Oklahoma City metropolitan area.

C-band data (Fig. 6) strikingly display the beginning of this descent from the hail growth region. At 2057 UTC, 2 min after the S-band RHI, a sizeable region (centered around 5 km AGL with an extension toward the surface)

of ρ_{hv} below 0.4 is present, which certainly indicates the likelihood of destructive hailstones, with sizes exceeding 2.5 cm.

These primarily qualitative glimpses at the mixed phase region provide a clear view of the storm's efficiency in generating destructive hailstones. However, a more quantitative analysis is performed to determine the ability of ρ_{hv} to signal changes in the size and intensity of developing hail. To do so, ρ_{hv} values for range gates with $Z \geq 50$ dBZ and above the environmental freezing level (EFL) for both C band (2028–2109 UTC) and S band (2055–2134 UTC) are analyzed and plotted versus height (Fig. 7). Though very large hailstones are possible in regions of relatively low Z , the lower bound of 50 dBZ is used to focus on zones where hail is most likely. The highlighted region indicates the approximate layer from -10° to -20°C temperatures for a parcel lifted from the surface. Past research has shown that this temperature region is the prime area for efficient wet hail growth (e.g., Dennis and Musil 1973). Therefore, ρ_{hv} reductions in the highlighted area could provide a key signal for the development of larger hail.

At 2055 UTC, both S- and C-band data show numerous points of low ρ_{hv} (Figs. 7a,c). For S band, the extension of reduced ρ_{hv} is located within the prime temperature range. Many values are below 0.9, indicating that the growth of giant hailstones is possibly occurring. The signature is even more striking at C band. Between 2.5 and 4 km above the EFL, numerous points have values below 0.4, which is remarkably low for C band, especially when considering the number of points in this range. The depression is deeper at C band because resonance scattering occurs for smaller hailstones and δ fluctuates over a wider range as compared to S band. Of note, however, the higher resolution of OU-PRIME relative to KOUN results in the increase of the number of C-band points, making the signature even more apparent. Additionally, the lack of points ≥ 5 km in height above the EFL is due to the relatively low-elevation scans (no higher than 9.0°).

The fallout of large hailstones is evident in the 2100 UTC data (Figs. 7b,d). At S band, a majority of the low ρ_{hv} points are now below the prime hail generation region, with few values less than 0.95 in this region. Indeed, it appears that the two scatterplots for KOUN indicate ongoing growth of very large hailstones at 2055 UTC, and then the decline of that growth along with the descent of this core during the next 5 min. This analysis agrees quite well with ground reports that indicated that hail intensity increased drastically at about 2100 UTC (reports of baseball size and higher) as the storm passed over the Penn Square Mall area. OU-PRIME C-band data at 2100 UTC support this conclusion, as the

FIG. 6. (left) KOUN 0.5° PPI from 2055 UTC and corresponding RHIs (350° , indicated on PPI) of Z , Z_{DR} , and ρ_{hv} below the PPI. (right) OU-PRIME 0.25° PPI from 2057 UTC (348.5°) and corresponding RHIs. Approximate environmental freezing level of 3.2 km AGL is indicated by horizontal lines on RHIs. Contours of $Z = 50$ and 60 dBZ are overlaid. C-band Z and Z_{DR} are not corrected for attenuation.

FIG. 7. Cross-correlation coefficient values above the EFL within the 50-dBZ contour for KOUN at (a) 2055 and (b) 2100 UTC, and OU-PRIME at (c) 2055 and (d) 2100 UTC. The highlighted region represents the approximate layer from -10° to -20°C using a surface-based parcel from the 17 May 2010 Norman sounding at 0000 UTC.

areas of lowest ρ_{hv} values descended below the optimal hail growth region, and indicate that the size of developing hailstones in this region has decreased. Whereas at 2055 UTC, ρ_{hv} points below 0.6 are quite common, there are none in the highlighted zone at 2100 UTC.

For each volume scan, the lowest 10th percentile of ρ_{hv} values between 2.5 and 4 km above the EFL was estimated. These are used to construct a series of scatterplots during 2028–2134 UTC to analyze temporal trends in ρ_{hv} within the highlighted zone. The results of this analysis are displayed in Fig. 8. Certainly, the most apparent feature is the great depression in ρ_{hv} values centered on 2055 UTC, which is evident in the scatterplots in Fig. 8a. Indeed, it seems clear from reports alone that the cell reached a maximum in intensity at about 2100 UTC, and ρ_{hv} data aloft appear to signal the development of giant hailstones during the minutes prior to this time. Furthermore, both scatterplots and the temporal trend in the 10th percentile data indicate that following 2055 UTC, hail growth in the mixed phase region decreased. Agreeing quite well with the ρ_{hv} data, following 2100 UTC, most reports show hail below 5 cm, indicating diminishing hail intensity. It is unlikely that larger sizes went unreported as the hail swath remained over a populated area for at least 20 min more. Therefore,

we can be confident in our estimates of the severity of the hail core around 2055–2120 UTC.

Figure 8b displays the maximum expected hail size (MEHS) computed from KOUN S-band data using the Enhanced Hail Detection Algorithm (EHDA; Witt et al. 1998), as well as the maximum reported hail size for each volume scan period. Although the MEHS shows good agreement with surface hail reports during the peak in hail size (2055–2100 UTC), the EHDA significantly overestimates maximum size starting around 2105 UTC. Most likely, high Z (>65 dBZ) at very cold temperatures ($<-25^{\circ}\text{C}$), which is not where the largest hailstones grow most efficiently, skewed the MEHS output toward larger sizes.

The Fig. 8a time series of C-band ρ_{hv} shows a pulsing nature of the hail growth, with a period of approximately 10–15 min. This implies that a sudden drop in ρ_{hv} values aloft could be followed by increasing hail sizes at the surface within the next 5 min. Although this does not provide extended lead time, forecasters and radar algorithms could still utilize these data to detect hail growth trends (especially one as poignant as at times leading up to 2055 UTC). In turn, the possibility exists for enhanced warnings that could include not only the current maximum expected hail size, but also forecasts for

FIG. 8. (a) Time series of the lowest 10th percentile for cross-correlation coefficient values within the 50-dBZ contour and the approximate layer for optimal hail growth (from -10° to -20°C ; 2.5–4 km above the EFL). Percentiles for C- and S-band data are shaded and solid lines, respectively. (b) Time series of MEHS predicted by the EHDA (Witt et al. 1998) using KOUN S-band data and the maximum reported hail size during each volume scan period.

potential changes in hail size and intensity in the short term.

d. Three-body scatter spike evolution

The three-body scatter spike (TBSS) signature can be attributed to the multiple reflection of electromagnetic waves by an atmospheric scatterer to the ground, back to the scatterer, and, finally to the radar, as illustrated in Fig. 9. With such multipath geometry of reflection, a false radar echo is produced well behind the scatterer.

Often observed in hail-bearing storms across a wide range of environments, TBSSs have rarely been analyzed in the literature (e.g., Zrnić 1987; Lemon 1998; Zrnić et al. 2010). With dual-polarized radar, the addition of Z_{DR} and ρ_{hv} data makes the TBSS even more apparent (Hubbert and Bringi 2000). The polarimetric TBSS manifests itself as a Z_{DR} enhancement and ρ_{hv} depression just behind the hail core. Of note, however, observations from the Alabama Microburst and Severe Thunderstorm (MIST) project show that the classic TBSS is not always associated with hail at the surface (Wilson and Reum 1988).

This TBSS echo has very distinctive polarimetric characteristics that can be explained in the framework of simple scattering theory. Differential reflectivity of the TBSS is a product of three factors:

$$Z_{dr} \sim \frac{I_h \sigma_h l_h}{I_v \sigma_v l_v}, \quad (3)$$

where the ratio I_h/I_v characterizes the difference between radiation patterns of the scatterer at orthogonal polarizations, σ_h/σ_v is the ratio between radar cross sections at the surface at horizontal and vertical polarizations, and l_h/l_v is the ratio of attenuation factors. All three factors are functions of the incidence angle θ .

In the Rayleigh approximation, a hailstone illuminated by microwave radiation can be modeled as a composition of horizontally and vertically oriented electric dipoles that are excited by an incident electromagnetic wave and emit secondary radiation. The radiation patterns of the horizontal and vertical dipoles excited by the horizontally and vertically polarized components of the incident wave are different (as shown in Fig. 9a). Namely, the vertical dipole does not radiate in the vertical direction down to the ground, but rather radiates at oblique incidence (i.e., $\theta \neq 0$). Therefore, the reflected signal from the surface just beneath the hailstone ($\theta = 0$) does not have a vertically polarized component. In reality, however, the TBSS is a result of downscatter paths over a conical region. Thus, the downscattered V-polarized component of radiation is nonzero but is still much smaller than the H-polarized component.

In the directions close to nadir ($\theta \approx 0$), the ratios σ_h/σ_v and l_h/l_v in Eq. (3) are close to one, and the resulting Z_{DR} is determined primarily by the factor I_h/I_v , which is very large. Hence, the TBSS Z_{DR} is expected to be high at relatively close distances to the hail shaft, causing three-body scattering. Extended TBSS spikes indicate that a significant part of the secondary radiation reflects from the ground at a relatively large θ so that the propagation path from the hailstone to ground and back is longer than in the case of nadir reflection (Fig. 9). At larger θ , the ratio I_h/I_v (known as bistatic Z_{DR} ; Aydin et al. 1998) decreases. Similarly, the ratio σ_h/σ_v and differential attenuation factor l_h/l_v also decrease with increasing θ (e.g., Ulaby et al. 1982).

Figure 10a exhibits a TBSS (originating around 40 km in range at a height of approximately 7 km AGL) that extends nearly 80 km from the hail core. Kumjian et al. (2010b) conclude that hailstones responsible for high Z_{DR} in the polarimetric TBSS (at S band) are of large, but not giant, sizes (approximately 2–4 cm in diameter). At closer ranges within this TBSS (<60 km), we find the highest Z_{DR} only reaching 1–2 dB. However, frozen

FIG. 9. Schematic illustrating the path of electromagnetic radiation that contributes to the TBSS pattern: from the radar to the hailstone, the hailstone to the ground, the ground back to the hailstone, and finally the hailstone back to the radar. Returns come from an oval projection underneath the hailstone, with θ_a representing the angle for a smaller conical region than with θ_b . Also presented are the schematics for the impact of the incidence angle on 1) the returned power ratio resulting from the radiation pattern, 2) the ground backscatter cross sections, and 3) losses from attenuation during scatter to and from ground.

hydrometeors at this height (with intrinsic Z_{DR} near 0 dB) may be masking the higher Z_{DR} of the TBSS, which has a very weak signal (usually 5–10 dBZ or less) compared to precipitation radar return, and reducing the usefulness of Z_{DR} values in this region to diagnose hail size accurately. Similarly, ρ_{hv} values are masked. At closer ranges, ρ_{hv} is quite reduced, but is not as low as is typically observed (<0.6) with a hail spike, owing to the dominance of very high ρ_{hv} from frozen hydrometeors located in the same region.

Negative Z_{DR} at more extreme ranges of the TBSS (>60 km) is also consistent with reports of an incredible number of very large hailstones around this time. Hypothetically, the tremendous radial extension of the TBSS is related to an increase of the conical area of returns beneath the hail region. Indeed, it is quite likely that only a hail core of this intensity could produce large enough θ necessary for such a TBSS range (Fig. 9b). As explained earlier, at sufficiently large θ (or longer ranges), the decrease of the ratios σ_h/σ_v and I_h/I_v may lead to negative Z_{DR} values associated with the TBSS, which were actually observed.

Figure 10b shows the rapid dissipation of the TBSS. Only 5 min later (at 2100 UTC), the length of the spike

becomes less than 30 km. Its presence is still quite apparent, as ρ_{hv} is reduced behind the core and a clear “flare” is observed behind this radial ρ_{hv} depression. However and perhaps more importantly, Z_{DR} is generally near 0 dB, indicative of the TBSS contributing little to the returned signal. As previously mentioned, hail production decreased in intensity following 2100 UTC, and the demise of a significant TBSS indicates the beginning of the decrease. The disappearance of the signature also coincides with a drastic increase in ρ_{hv} values (greater than 0.1) in the growth region between 2055 and 2100 UTC.

Over the next 30 min, the TBSS showed small changes in appearance and never approached the incredible size it displayed at 2055 UTC. Therefore, the temporal evolution of the TBSS appears to mimic the evolution of ρ_{hv} within the wet growth region, as there was a large depression at 2055 UTC that quickly diminished in magnitude at later times. Thus, it seems likely that the extreme size of the TBSS was a result of the great concentration of very large hailstones produced by the supercell.

e. Ground-truth hail reports

Perhaps the most important, yet unfortunate, aspect of this event is its path over a populated metropolitan

FIG. 10. KOUN 10.0° PPIs of (top) Z , (middle) Z_{DR} , and (bottom) ρ_{hv} for (a) 2055 and (b) 2100 UTC showing the TBSS.

FIG. 11. Scatterplot of (a) Z vs Z_{DR} , (b) Z_{DR} vs H_{DR} , (c) Z vs ρ_{hv} , (d) Z_{DR} vs ρ_{hv} , (e) Z vs K_{DP} , and (f) Z_{DR} vs K_{DP} measured at S band for 13 hail reports, segregated into three size categories ($D < 3$ cm; $3 \text{ cm} \leq D < 5$ cm; $D \geq 5$ cm), between 2058 and 2129 UTC across the Oklahoma City metro area. Solid black lines in (a) indicate threshold for large-hail detection for the beam height between 2 and 3 km below the freezing level according to Ryzhkov et al. (2010), while in (b) they indicate the thresholds for 1.9-cm hail (21-dB line; former NWS large-hail definition) and damaging hail (30-dB line) detection according to Depue et al. (2007).

area. Although damage costs are estimated to be hundreds of millions of dollars, the number of people in the storm's path allowed for numerous in situ hail reports. The high quality of radar data and specific location of many reports are sufficient to match individual hail reports with specific range locations. Consequently, we can establish a relation between KOUN S-band data from different regions of the supercell and ground reports of various hail sizes, ranging from 2.5 cm to upward of

8 cm. These sizes are taken from local storm reports (Storm Data) as well as media reports (distinguished in Fig. 2). This work leaves comparisons of low-level C-band data and hail reports to future studies.

Six scatterplots (Z – Z_{DR} , Z_{DR} – H_{DR} , Z – ρ_{hv} , Z_{DR} – ρ_{hv} , Z – K_{DP} , and Z_{DR} – K_{DP}) showing data from the 0.5° scans at locations of hail reports are presented in Fig. 11. Different symbols in the scatterplots indicate three categories of corresponding hail size from surface reports. For

every hail report, the radar data with $Z > 55$ dBZ within a spatial–temporal domain of $1 \text{ km} \times 1^\circ \times 6 \text{ min}$ centered on the report location have been selected. This creates 200+ data points for only 13 reports. Furthermore, as report time errors on the order of a few minutes could negatively impact the analysis, the 13 reports were segregated into three size categories ($D < 3 \text{ cm}$, $3 \text{ cm} \leq D < 5 \text{ cm}$, $D \geq 5 \text{ cm}$), instead of using specific hail sizes.

For the Z – Z_{DR} and Z – ρ_{hv} plots (Figs. 11a,c), there is a clear trend of larger hail sizes toward increasing Z and decreasing Z_{DR} or ρ_{hv} . Figure 11a reveals that when $Z > 65$ dBZ and $Z_{\text{DR}} < 1$ dB, all data points correspond to giant hail reports, exhibiting the general success of Z_{DR} at identifying regions of significant hail. However, where Z is 55–65 dBZ and Z_{DR} is 0–2 dB, there is a wide array of hail size data points, indicating the lack of accurate size discrimination necessary for improved hail sizing algorithms. Notably, high Z_{DR} exceeding 2 dB are found for hail sizes of 2.5 and 4.4 cm within the range of Z between 55 and 63 dBZ, showing that even large hail can be overwhelmed by the presence of smaller, melting hailstones and very large raindrops with high intrinsic Z_{DR} , which agrees with previous scattering model simulations (Ryzhkov et al. 2009, 2011).

Figure 11b clearly exhibits that the H_{DR} algorithm, under the criteria of Depue et al. (2007), would miss too much large and giant hail (blue squares and yellow triangles below the 30-dB line). Ryzhkov et al. (2010) created a set of rules that attempt to account for the height of the radar resolution volume with respect to the melting layer ΔH , and while it does result in significantly more correct detections of large hail for this case (Fig. 11a) with ΔH between 2 and 3 km, a noticeable number of large-hail occurrences are still missed (all points outside lower right box). Hence, it appears that further improvement is required through the refinement of a rule set such as the one proposed by Ryzhkov et al. (2010), which better represents the hail melting process.

The Z – ρ_{hv} scatterplot shows the benefit of using ρ_{hv} in combination with Z (Fig. 11c). When $Z > 65$ dBZ and $\rho_{\text{hv}} < 0.97$ or $Z > 55$ dBZ and $\rho_{\text{hv}} < 0.9$, all data points correspond to giant hail reports, exhibiting that ρ_{hv} also has success in identifying regions of significant hail. Yet again though, where Z is 55–65 dBZ and ρ_{hv} is 0.9–0.96, there is a wider distribution of hail sizes. Therefore, while also an improvement over the use of just Z , ρ_{hv} (in combination with Z) does not provide the size discrimination capabilities to offer a substantial upgrade over the classification algorithms described in the introduction.

Finally, the Z_{DR} – ρ_{hv} scatterplot suggests the utilization of both Z_{DR} and ρ_{hv} , along with Z , to estimate hail size most accurately (Fig. 11d). A clear trend of larger hail sizes toward lower Z_{DR} and ρ_{hv} values exists. This

trend is especially noticeable when considering the 2.5-cm data points against the larger sizes. None of these points are associated with Z_{DR} and ρ_{hv} values less than 1 dB and 0.95, respectively. Conversely, a large majority of the “giant” reports fall within values less than 1 dB and 0.96. This plot certainly bolsters the idea that ρ_{hv} can be combined with Z_{DR} to further improve estimates of hail size.

Figures 11e,f indicate that K_{DP} may have a general tendency to decrease with increasing hail size as all small-hail reports ($D < 3 \text{ cm}$) are associated with $K_{\text{DP}} > 3^\circ \text{ km}^{-1}$, while most giant reports with $Z > 65$ dBZ are characterized by $K_{\text{DP}} < 3^\circ \text{ km}^{-1}$. Nonetheless, according to theoretical simulations of polarimetric signatures of melting hail in Ryzhkov et al. (2009), K_{DP} is much more sensitive to the amount of liquid water than the presence of hail in the radar resolution volume. Smaller hailstones (red circles) likely fell in regions of higher liquid water content, which is consistent with the high K_{DP} ($> 3^\circ \text{ km}^{-1}$) and Z_{DR} (> 1.5 dB). Conversely, the two larger size categories show a wide distribution of K_{DP} , with some tendency for giant hailstones to be associated with relatively lower values ($\leq 3^\circ \text{ km}^{-1}$). While it is unlikely that K_{DP} can noticeably improve hail sizing capabilities, it can provide some clues on the relative amount of hail within a radar resolution volume.

4. Conclusions

The damage produced by the 16 May 2010 Oklahoma City hailstorm was extremely costly and imposed a heavy financial burden on residents and businesses affected by the storm. For this reason, the path of the supercell was quite unfortunate. At the same time, a hailstorm of this magnitude passing over a metropolitan area and being observed at relatively close range by two high-quality, nearly collocated polarimetric radars of different wavelengths has simply never occurred before. The dataset acquired is truly one of a kind, especially because of the high number of ground-truth hail reports.

Simultaneous observations with S- and C-band radars enable direct comparison of data at two wavelengths, which provides additional insight into the types and sizes of hydrometeors falling in the precipitation core. For example, only in regions of the largest hailstones did C-band Z_{DR} fall below 1 dB. Elsewhere, the magnified effect of resonance scattering boosted Z_{DR} at C band, while Z_{DR} remained relatively low at S band.

Anomalously high attenuation–differential attenuation revealed at C band via direct comparison of Z and Z_{DR} at the two wavelengths provides new insight into the microphysical properties of the precipitation core, emphasizing an abundance of very large raindrops originating

from melting hailstones in extensive parts of the storm. Therefore, it becomes apparent that our knowledge of the polarimetric signatures resulting from various hydrometeors at C band can be used to analyze more accurately the observed signatures at S band as well.

This case also bolsters previous findings that near the surface, the combination of $Z_{DR} < 1$ dB and $Z > 60$ dBZ indicates the presence of very large hail (>4 cm). Conversely, $Z_{DR} > 1$ dB and $\rho_{hv} > 0.95$ generally indicates smaller sizes, although the presence of melting hailstones and liquid water can produce these values even when hail diameters upward of 4 cm are present. Above the freezing level, $Z_{DR} \leq 0$ dB and $\rho_{hv} < 0.9$ are potential indicators of giant hail.

Ambiguities certainly remain in the polarimetric determination of hail size. There is a significant dependence on the height of the resolution volume relative to the wet-bulb zero temperature level, where hail melting starts, when estimating size via polarimetric variables. The tentative, model-based scheme for discriminating between small and large hail suggested by Ryzhkov et al. (2010) may need modification, as it does not imply Z_{DR} up to 4 dB for 4.4-cm hail. To further modify and solidify the rules in Ryzhkov et al. (2010) and Kumjian et al. (2010a) though, more cases must be analyzed along with the continued modeling of the scattering properties of hailstones and the resultant polarimetric values.

The combination of Z_{DR} and ρ_{hv} measured at S band provides the best discrimination between small and large hail for the examined storm, which suggests that ρ_{hv} has to be used more aggressively (along with Z and Z_{DR}) for the determination of hail size.

Although the TBSS does not appear to be the best indicator for maximum hail size (e.g., Zrnić et al. 2010; Kumjian et al. 2010b), the evolution of hail spikes has never been studied in depth. From this case it does appear that the length of the spike is correlated with the hail severity (concentration and perhaps size of hailstones). Nonetheless, the TBSS issue requires more scrutiny as it has the potential to be another polarimetric tool for size estimation and short-term prediction of hail trends.

Last, this case exhibits the significance of obtaining multiple in situ hail reports from one hailstorm. With numerous reports, hail sizes and types in different regions of the cell can be compared with polarimetric data to achieve a more comprehensive understanding of the microphysical processes within the hail growth zones and subsequently improve our ability to estimate hail size. Therefore, there should be a continued emphasis on collecting high-quality, accurate hail reports, especially from storms sampled by polarimetric radar.

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