Kinematic and Polarimetric Radar Observations of the 10 May 2010, Moore–Choctaw, Oklahoma, Tornadic Debris Signature

CASEY B. GRIFFIN
School of Meteorology and Advanced Radar Research Center, University of Oklahoma, Norman, Oklahoma

DAVID J. BODINE
Advanced Radar Research Center, University of Oklahoma, Norman, Oklahoma, and Advanced Study Program, National Center for Atmospheric Research, Boulder, Colorado

ROBERT D. PALMER
School of Meteorology and Advanced Radar Research Center, University of Oklahoma, Norman, Oklahoma

(Manuscript received 2 September 2016, in final form 17 March 2017)

ABSTRACT

Tornadoes are capable of lofting large pieces of debris that present irregular shapes, near-random orientations, and a wide range of dielectric constants to polarimetric radars. The unique polarimetric signature associated with lofted debris is called the tornadic debris signature (TDS). While ties between TDS characteristics and tornado- and storm-scale kinematic processes have been speculated upon or investigated using photogrammetry and single-Doppler analyses, little work has been done to document the three-dimensional wind field associated with the TDS.

Data collected by the Oklahoma City, Oklahoma (KTLX), and Norman, Oklahoma (KOUN), WSR-88D S-band radars as well as the University of Oklahoma’s (OU) Advanced Radar Research Center’s Polarimetric Radar for Innovations in Meteorology and Engineering (OU-PRIME) C-band radar are used to construct single- and dual-Doppler analyses of a tornadic supercell that produced an EF4 tornado near the towns of Moore and Choctaw, Oklahoma, on 10 May 2010. This study documents the spatial distribution of polarimetric radar variables and how each variable relates to kinematic fields such as vertical velocity and vertical vorticity. Special consideration is given to polarimetric signatures associated with subvortices within the tornado. An observation of negative differential reflectivity ($Z_{DR}$) at the periphery of tornado subvortices is presented and discussed. Finally, dual-Doppler wind retrievals are compared to single-Doppler axisymmetric wind fields to illustrate the merits of each method.

1. Introduction

The advent and operational implementation of dual-polarization radar has led to vast improvements in hydrometeor classification (e.g., Vivekanandan et al. 1999; Bringi and Chandrasekar 2001; Ryzhkov et al. 2005a; Park et al. 2009; Kumjian 2013a,b), as well as improvements in the ability to differentiate between meteorological and nonmeteorological scatterers (e.g., Zrnić and Ryzhkov 1999). Tornadoes can loft substantial amounts of non-meteorological scatterers, which exhibit unique polarimetric attributes. The tornadic debris signature (TDS) is characterized by low values of copolar cross-correlation coefficient at lag 0 $\rho_{hv}$, and is often accompanied by a local maximum in the reflectivity factor at horizontal polarization $Z_{HH}$ and low values in differential reflectivity $Z_{DR}$ (Ryzhkov et al. 2002, 2005b). The polarimetric signature is often, but not always, collocated with a tornadic vortex signature (e.g., Van Den Broeke and Jauernic 2014).

Attempts to algorithmically detect tornadic debris have been made, with future work expected to optimize and improve the application to operations (Snyder and Ryzhkov 2015; Wang and Yu 2015). However, there are
many caveats to polarimetric tornadic debris detection (Schultz et al. 2012b). Attenuation and differential attenuation may lead to erroneous values of $Z_{hh}$ and $Z_{dr}$. However, $\rho_h$, is still a reliable indicator of tornadic debris provided that there is uniform beam filling up radial and in the target volume (Bluestein et al. 2007). Additionally, tornados must be strong enough to loft debris to a height where it can be sampled by a radar, and the debris field must be large enough to be spatially resolved (Kumjian and Ryzhkov 2008). Both of these conditions are modulated by the range that a tornado is from the radar and the scanning strategy chosen. Finally, the presence of a TDS does not necessarily mean that a tornado is ongoing. TDSs sometimes precede tornadogenesis (e.g., Saari et al. 2014; Van Den Broeke 2015) and persist after a tornado’s demise (e.g., Van Den Broeke 2015; Houser et al. 2016). Accounting for these considerations, the TDS can be used, with caution, to operationally confirm the presence of ongoing tornadoes (Schultz et al. 2012a,b).

An understanding of how the TDS relates to tornado characteristics can expand the utility of polarimetric radars. If relationships between the distribution of polarimetric radar variables and tornado structure can be documented, more accurate inferences can be made about tornados in real time. Previous studies have found a correlation between the areal extent and height of the TDS and tornado intensity and pathlength (Bodine et al. 2013; Van Den Broeke and Jauernic 2014; Van Den Broeke 2015). Additionally, studies have shown that seasonal and regional differences in land type and usage modify some of the characteristics of a TDS, including the height to which debris is lofted and the likelihood that a tornado of a given intensity will exhibit a TDS (Van Den Broeke and Jauernic 2014; Van Den Broeke 2015). The life cycle stage of a tornado may also influence whether a tornado exhibits a TDS, with the probability of a TDS increasing during the first 5 min following tornadogenesis and decreasing between the 5 min preceding and 5 min following the dissipation of a tornado (Van Den Broeke 2015). Recently, Wakimoto et al. (2015) used rapid-scan polarimetric radar data in conjunction with photogrammetric data to document the evolution of the spatial distribution of debris in the 31 May 2013, El Reno, Oklahoma, tornado, noting many features, such as the weak echo hole (WEH), “debris overhang,” and “pockets” of low-level debris associated with the rear-flank gust front (RFGF). Similarly, Kurzdo et al. (2015) noted instances during the 20 May 2013 Moore, Oklahoma, tornado where debris was ejected from the tornado along bands coinciding with RFGFs. Finally, Houser et al. (2016) investigated the three-dimensional structure of the TDS and how it evolved with changing tornado structure using high spatial- and temporal-resolution data.

The 10 May 2010 Oklahoma tornado outbreak produced 55 tornadoes, including two tornadoes rated as category 4 on the enhanced Fujita (EF) scale in central Oklahoma. This case provides a rare opportunity to perform dual-Doppler polarimetric radar analyses on a large, debris-lofting tornado and compare the results of dual-Doppler analyses to those performed by single-Doppler methods. The serendipitous collection of data at relatively close range by the Oklahoma City, Oklahoma (KOUN), WSR-88D S-band radars, and the University of Oklahoma’s Polarimetric Radar for Innovations in Meteorology and Engineering (OU-PRIME) C-band radar operated by the Advanced Radar Research Center (ARRC), briefly provide a favorable dual-Doppler lobe for the interrogation of the Moore–Choctaw, Oklahoma, tornado, which will be the focus of this study. While previous studies have focused primarily on single radar representations of the TDS, little work has been done to document the two- and three-dimensional wind field associated with a large, heterogeneous TDS using two radars. The use of dual-Doppler-derived data may provide insight into some of the kinematic processes that have been hypothesized in prior literature that utilized single-Doppler radar data. Further details regarding the 10 May 2010 outbreak can be found in Palmer et al. (2011).

2. Methods

a. Radar data

The polarimetric radar data used in this project were collected by OU-PRIME, which is located near the National Weather Center, and by KOUN, which is located at University of Oklahoma Westheimer Airport in Norman. Supplementary velocity data for dual-Doppler analyses were provided by KTLX, which is a WSR-88D radar. Selected specifications for each radar appear in Table 1. For a full system overview of OU-PRIME and details regarding system performance during the event, please refer to Palmer et al. (2011). At its closest range, the Moore–Choctaw tornado was sampled as low as ~100 m above radar level (ARL) by OU-PRIME. Later in the period, the lowest OU-PRIME scan available (1.0°) sampled the Moore–Choctaw tornado at an altitude of ~400 m. KTLX sampled the Moore–Choctaw tornado as close as ~5 km, with a beam height as low as ~75 m at the range of the center of the tornado.

Radar data editing for this project was completed using the National Center for Atmospheric Research
Earth Observing Laboratory’s Solo3 editing software (Oye et al. 1995), which is available online (https://www.eol.ucar.edu/software/solo3). Clutter, identified by regions of stationary high-power returns with near-zero radial velocity, and erroneous data, most often in the form of azimuths affected by partial beam blockage or multiple-trip contamination, were subjectively removed. Low values of signal-to-noise ratio (SNR) were objectively thresholded below 0 dB. No $\rho_{hv}$ thresholding was performed, which potentially introduces error into the analyses as a result of variance in the radar measurements increasing as $\rho_{hv}$ decreases (Bringi and Chandrasekar 2001). However, a $\rho_{hv}$ threshold would eliminate many desirable volumes containing debris and bias the distribution of polarimetric variables in the TDS. Solo3 was also used to subjectively dealias the radial velocity prior to performing the dual-Doppler and axisymmetric analyses. Values of the differential phase in the vicinity of the TDS ranged between $-20^\circ$ and $0^\circ$ and a simple differential attenuation correction calculation (not shown) created no appreciable changes in the polarimetric fields near the tornado. Thus, no differential attenuation correction was applied to the data presented.

b. TDS criteria

The original criteria for a TDS at S band proposed by Ryzhkov et al. (2005b) were values of $\rho_{hv} < 0.8$, $Z_{DR} < 0.5 \text{ dB}$, and $Z_{HH} > 45 \text{ dBZ}$ collocated with a vortex signature in radial velocity $V_r$. The criteria for $Z_{HH}$ were relaxed by Schultz et al. (2012a) to 30 dBZ and were further relaxed by Van Den Broeke and Jauernic (2014) to 20 dBZ given the Warning Decision Training Division recommendation (WDTB 2013) based on numerous tornadic events exhibiting $Z_{HH} < 30 \text{ dBZ}$. To include the WEH, the $Z_{HH}$ threshold for tornadic debris in this study is 10 dBZ. Radar volumes with $Z_{HH}$ in the 10–20 dBZ range were screened to ensure that they were representative of tornadic debris. This project uses the original $\rho_{hv} < 0.8$ and $Z_{DR} < 0.5 \text{ dB}$ thresholds as additional constraints. Finally, pixels also had to be within 5 km of the tornado center to be included. These constraints perform well in spatially identifying tornadic debris in the Moore–Choctaw tornado (not shown); however, for many TDSs, an upper $\rho_{hv}$ threshold of 0.8 may be too restrictive. Additionally, a $Z_{DR}$ threshold may perform poorly if too much precipitation is present from entrainment (Bodine et al. 2014). Therefore, the authors do not recommend these thresholds for TDS identification in all circumstances. Other TDS identification methods have been implemented with success in the past, including using percentile-based polarimetric thresholds as opposed to specific value thresholds (Bodine et al. 2014) and using an adaptive fuzzy logic system (Wang and Yu 2015).

c. Dual-Doppler analysis

Dual-Doppler and objective analyses are performed using the Observation Processing and Wind Synthesis (OPAWS) code developed by D. Dowell (NOAA/Earth System Research Laboratory) and L. Wicker (National Severe Storms Laboratory). Documentation and source code can be found online (http://code.google.com/p/opaws/). Radar data are first objectively analyzed on a 30 km × 30 km domain using a two-pass Barnes method (Barnes 1964) with a second-pass convergence parameter $\gamma$ of 0.3 used to further recover the amplitudes of smaller-scale spatial structures (Barnes 1973; Majcen et al. 2008). The limiting spatial resolution $\delta$ in the vicinity of the tornado was $\sim 350 \text{ m}$. A smoothing parameter $[\kappa = (1.336)^2]$ of 0.216 km$^{-2}$ (Pauley and Wu 1990) was chosen. A horizontal and vertical grid spacing of 250 m was chosen to accommodate coarser limiting spatial resolution in other parts of the analysis domain. Motion of the supercell between each radar sweep in a volume is linearly corrected within the objective analyses prior to performing the dual-Doppler synthesis.

\begin{table}
\centering
\begin{tabular}{|c|c|c|c|}
\hline
Radar characteristic & OU-PRIME & KOUN & KTLX \\
\hline
Operating frequency (MHz) & 5510 & 2705 & 2700–3000 \\
Peak power (kW) & 1000 & 760 & 750 \\
Beamwidth (°) & 0.45 & 0.93 & 0.93 \\
Gate length (m) & 125 & 250 & 250 \\
Nyquist velocity (m s$^{-1}$) & 16.06 & 26.92 & 26.92 \\
Volumetric update time & 2 min 50 s & 4 min 18 s & 4 min 18 s \\
Polarization & Simultaneous transmit simultaneous receive (STSR) & STSR & — \\
Scanning strategy & 1.0°, 2.0°, 3.0°, 4.0°, 5.0°, 6.5°, and 9.0° & VCP 12 & VCP 12 \\
\hline
\end{tabular}
\caption{A selection of radar characteristics for OU-PRIME, KTLX, and KOUN.}
\end{table}

\footnote{We used the formula for grid spacing ($\Delta = \delta/2.5$) based on Koch et al. (1983), where values of $\delta$ exceeded 600 m in parts of the analysis domain.}
using a translation velocity determined by a comparison between the mesocyclone location at the previous time and its location at the analysis time. While correcting for advection partially mitigates errors in the analyses caused by propagation between elevation scans and mismatched temporal sampling by the two radars, the mesocyclone motion may not be representative of tornado motion at all heights and can introduce errors in the analyzed location of the tornado at some levels. Dual-Doppler wind syntheses are performed in regions where the look-angle difference between OU-PRIME and KTLX is between 20° and 160°. Vertical velocities are calculated using upward integration of the mass continuity equation with the implementation of a \( w = 0 \) at \( z = 0 \) boundary condition. Density is assumed to decrease exponentially with height. Hydro-meteor fall speeds are corrected using the terminal fall velocity–reflectivity relationships obtained from Joss and Waldvogel (1970) and implemented by OPAWS (Potvin et al. 2012). It is noted that OU-PRIME did not sample the low-level mass flux below 400 m in the vicinity of the tornado, which may lead to large errors in the vertical velocity estimates; however, KTLX sampled the wind field below 75 m, which may partially mitigate this issue. A major crux of the dual-Doppler assumption is that the two radars are observing the same volume of space at nearly the same time. Because this study does not use coordinated radar scans, and OU-PRIME was running a different scanning strategy than the WSR-88Ds, only two analysis times approached synchronization. The first analysis time began at approximately 2223 UTC, about 3 min after tornadogenesis, when scan times between OU-PRIME and KTLX varied between 3 and 10 s. The 2223 UTC dual-Doppler analysis (Fig. 1) illustrates some interesting features, including a cyclonic–anticyclonic vortex pair and small raindrops in the rear-flank downdraft. However, these topics are beyond the scope of this paper, and the lack of a TDS in the early life cycle of the Moore–Choctaw tornado dictates that this time serve only to confirm the locations of the supercell structures, like the rear-flank gust front and a strong cyclonic vortex, consistent with theoretical models (e.g., Lemon and Doswell 1979; Bluestein 2013).

The other time that approximately fulfills the simultaneous observation requirement is the volume beginning at approximately 2231 UTC, when the difference between scan times is on the order of \(~30\) s. The Moore–Choctaw tornado exhibits a large, inhomogeneous TDS at 2231 UTC (Fig. 2), which will be the main focus of this study. Because of the main circulation pattern being near the edge of the dual-Doppler lobe, kinematic analyses only cover the lowest \(~1\) km of the tornado. The lowest scans of KTLX and OU-PRIME are also the most synchronized.

d. Axisymmetric wind retrieval

Using the assumption of axis symmetry, Lee et al. (1999) developed a method of diagnosing mean three-dimensional motion within tropical cyclones. This technique was called the ground-based velocity track display (GBVTD) method and has been successfully applied to tornado vortices (e.g., Bluestein et al. 2003; Lee and Wurman 2005; Tanamachi et al. 2007; Kosiba and Wurman 2010; Wakimoto et al. 2012). This paper uses the simplified single-Doppler wind retrieval approach similar to GBVTD defined by Dowell et al.’s (2005) Eqs. (25)–(27) that recovers only the azimuthally averaged (zero wavenumber) radial and tangential velocities, \( u \) and \( v \). This method has previously been used by Kosiba et al. (2008) to derive axisymmetric wind fields for a tornado near Harper, Kansas, and by Bodine et al. (2014) to interrogate the Moore–Choctaw tornado of interest to this study. For KOUN and OU-PRIME, \( u \) and \( v \) are calculated for 250-m-wide annuli, at 125-m intervals. Vertical velocities are computed by vertically integrating the radial mass flux using Eq. (2.2) from Nolan (2013). KOUN did not sample the lowest 150 m of the tornado, which as noted in Nolan (2013) could result in significant errors in the retrieved vertical velocities as a result of insufficient observations of the low-level mass flux. However, circumstantial evidence supporting the derived vertical velocities will be discussed in conjunction with the results in future sections.

Radar-derived wind fields are known to have a radially outward bias owing to objects within the tornado vortices undergoing centrifugal accelerations (Dowell et al. 2005; Bodine et al. 2016b). In the absence of

---

3 These relationships were derived for precipitation, and are likely to be underestimates of the fall speeds for debris. However, no alternative methods for debris exist.

4 For other potential dual-Doppler analyses, the scan times between KOUN and KTLX are on the order of \(~2\) min, which is well beyond the length of time where we can assume steady state for processes within supercells (Taylor 1938).
debris, centrifuging can be corrected using the terminal fall velocities of radar-derived drop size distributions (Wakimoto et al. 2012). However, since the radar volumes in this study are filled with debris, we use the method described by Nolan’s (2013) Eq. (3.1) that accounts for the velocity owing to the centrifugal force at each location as a component of the biased radial wind field $U_{\text{mod}}$:

$$U_{\text{mod}} = U + U_{\text{bias}} = U + C_{\text{max}} \frac{v^2/r}{\max(v^2/r)}$$

where $C_{\text{max}}$ is a specified maximum flow-relative radially outward velocity estimate, $v$ is the tangential velocity, and $r$ is the radius from the center of the vortex. For the purposes of this study, a conservative value of $C_{\text{max}} = 8.0 \text{ m s}^{-1}$ was chosen, similar to the maximum positive bias in radial velocity found by Wakimoto et al. (2012; see their Fig. 9) and similar to values for centrifuging tested by Kosbia and Wurman (2013). The correction for centrifuging recovered low-level inflow without dramatically changing the rest of the analysis.

The analyses were not qualitatively sensitive to values of $C_{\text{max}}$ between 4 and 12 m s$^{-1}$.

3. Results

a. Spatial distribution of polarimetric variables

At 2231 UTC, areas of high $Z_{\text{HH}}$ surround a region of strong azimuthal shear in $V_r$ associated with the Moore–Choctaw tornado (Figs. 2a,b). Large raindrops, with $\rho_{hv}$ values of $\sim 0.95$ and $Z_{\text{DR}}$ values in excess of 4 dB, enshroud the tornado (Figs. 2c,d). Small raindrops exhibiting $\rho_{hv} > 0.98$ and $Z_{\text{DR}}$ of approximately 0.5 dB are located farther to the south in the rear-flank downdraft, as noted by Kumjian (2011) and French et al. (2015). The tornado exhibits a TDS in excess of 2 km in diameter. While this TDS has been examined statistically by Bodine et al. (2014), the spatial distribution of polarimetric variables was not the focus. Thus, of particular interest to this study are the local minima in $Z_{\text{DR}}$ and $\rho_{hv}$, which are not located in the center of the TDS, but rather are concentrated...
in pockets near the periphery of the TDS (Figs. 2c,d). In contrast, values of $Z_{DR}$ and $\rho_{hv}$ are locally maximized near the center of the TDS.

Plots of both raw and two-pass Barnes-analyzed $Z_{DR}$ and $\rho_{hv}$ versus distance from the subjectively defined center of the TDS (Fig. 3) indicate that the lowest values of both polarimetric variables occur 500–1000 m from the center of the TDS. Data points flagged as part of the TDS are plotted in red. Within volumes containing considerable amounts of debris (red lines), there is a weak tendency for $Z_{DR}$ and $\rho_{hv}$ to decrease with distance from the center of the tornado. Some of the points in the outer half of the TDS exhibit values of $\rho_{hv}$ below 0.3 and values of $Z_{DR}$ less than $-2$ dB. As expected, the trend lines have a better fit to the objectively analyzed data (Figs. 3a,b) than the noisier raw data (Figs. 3c,d).

Axisymmetric cross sections are used to gain a better perspective on how mean radial profiles of polarimetric variables change with height (Fig. 4). The cross section of reflectivity (Fig. 4a) illustrates that the radius of the maximum in reflectivity within the TDS increases with height associated with the centrifuging of debris, similar to what has been noted previously within tornadoes (e.g., Wurman and Gill 2000; Dowell et al. 2005; Bodine et al. 2014). As seen in Fig. 3, the minimum in $\rho_{hv}$ occurs at approximately 750 m from the center of the TDS. The local minimum extends up from the lowest analysis level and is largely confined to below 1.0 km ARL (Fig. 4b), similar to what was seen in the photogrammetric analyses performed by Wakimoto et al. (2015; e.g., their Fig. 5d). Unlike the cross sections presented by Wakimoto et al. (2015), a secondary minimum in $\rho_{hv}$ is absent from the center of the TDS aloft. This may be because of greater

---

5 It is possible that some of the bins exhibiting low values of $\rho_{hv}$ at small radii in Fig. 3c also contain small concentrations of debris but did not meet the 10-dBZ reflectivity threshold.

6 All scatterplots in this study are fitted to second-order polynomials.
precipitation entrainment in the Moore–Choctaw tornado (Schwarz and Burgess 2011; Bodine et al. 2014), as suggested by the large raindrops surrounding the tornado in Fig. 2 or simply because of a higher SNR in the Moore–Choctaw tornado.

The minimum in $Z_{DR}$ below 0.8 km ARL occurs approximately 800 m from the center of the TDS. Above 0.8 km ARL, the minimum in $Z_{DR}$ is located closer to the center of the TDS (Fig. 4c). Axisymmetric $v$ is plotted in Fig. 4d and illustrates that the TDS, as approximately defined by the dashed 0.8-$p_{hv}$ contour, is largely constrained within the radius of maximum winds (RMW) similar to what was found in Houser et al. (2016). Heights where the TDS extends beyond the RMW exhibit $v$ in excess of 40 m s$^{-1}$. Strong $v$ are likely necessary in order for debris to be centrifuged to such a large radius. The radius of the TDS increases with height, which is likely the result of continued debris centrifuging in combination with a vertically increasing core diameter of the tornado and low-level mesocyclone (Fig. 4d). Because of the lack of low-level coverage provided by OU-PRIME, supplemental axisymmetric analyses from KOUN are used. These are interrogated in the next subsection. Included in these analyses is the secondary circulation, which is omitted from Fig. 4.

b. Tornado subvortices

The plan position indicator (PPI) of $V_r$ at 2231 UTC (Fig. 5a) indicates at least two regions of locally enhanced radial shear, likely associated with tornado subvortices (e.g., Wurman 2002; Wurman and Kosbia 2013). A dual-Doppler analysis with KTLX at this time (Fig. 5b) indicates two regions of locally enhanced vertical vorticity oriented in the same manner as the regions of enhanced shear in Fig. 5a. It is possible that the dual-Doppler analysis is only resolving the two largest subvortices and that more are present at the subgrid scale. Axisymmetric wind fields were retrieved from the Moore–Choctaw tornado using KOUN data beginning at 2229 UTC (Fig. 6). The analysis of the secondary circulation (arrows), comprised of radial and vertical velocities, provides evidence of a central downdraft, with upward vertical velocities displaced to $-1$ km in radius from the center of the tornado. This observed

---

**Fig. 3.** Scatterplots of objectively analyzed (a) correlation coefficient and (b) differential reflectivity (dB), and raw (c) correlation coefficient and (d) differential reflectivity (dB) vs radial distance (km) valid at 2231 UTC. Blue dots indicate non-TDS flagged points and red dots indicate TDS-flagged points. The black line is the second-order polynomial fit for all points and the red line is the second-order polynomial fit for TDS flagged points.
secondary circulation pattern closely resembles the model for moderate to high swirl: two-celled vortices seen in previous studies (e.g., Church et al. 1979; Davies-Jones 1986; Wakimoto and Liu 1998; Lewellen et al. 2004, 2008) and conceptually summarized by Bluestein (2013). It is possible that the low-level divergence field, which is poorly sampled at ~17 km in range, offsets or supersedes the divergence and convergence of $u$ at higher altitudes rendering the secondary circulation erroneous. However, the Moore–Choctaw tornado exhibited tornado subvortices and a RMW of ~1 km, which is consistent with a moderate-to-high swirl ratio vortex that should likely contain a central downdraft. Regardless, the authors caution that the magnitude of the downdraft may be exaggerated by the absence of boundary layer inflow, similar to what was noted by Kosiba and Wurman (2010) and shown by Nolan (2013).

The axisymmetric analyses capture the top of an inflow layer, which extends to at least 300 m in height. The low levels are characterized by radial inflow and a strong vertical gradient in angular momentum (Fig. 6b). Radial inflow also extends into the RMW at higher altitudes (Fig. 6a), similar to what was noted by Nolan (2013). The maximum in $v$ is observed at approximately 1100 m in radius at 500 m ARL, with values exceeding 45 m s$^{-1}$. A secondary maximum in $v$ exists at 250 m ARL at 800 m in radius. At this height, radial inflow extends into the RMW, impinging farther than inflow aloft. The 0.8- contours, which serve as a proxy for the TDS, is confined within the RMW at a given level for analyses above ~400 m ARL, but the 0.8- contour extends beyond the RMW at lower altitudes. This may be the result of enhanced debris lofting and loading at lower levels because of strong inflow (e.g., Lewellen et al. 2008; Bodine et al. 2016a), lofting of light debris from high near-surface inflow winds, or fallout of debris from aloft (e.g., Bodine et al. 2013; Kurdzo et al. 2015; Van Den Brocke 2015; Houser et al. 2016). However, the lowest values of $p_{hv}$ are confined within the RMW throughout the column.

As noted in the previous subsection, the lowest values of $p_{hv}$ in the TDS are displaced ~ 600 m from the center.
of the tornado (Fig. 6c). The 0.8-\(\rho_{hv}\) contour exists near the radius where vertical motion becomes directed upward because of radial convergence. This pocket of low \(\rho_{hv}\) does not extend as high as in Fig. 4; however, this may be due to the difference in transmit frequency between the radars or the difference in analysis times, which is approximately 1 min. The lowest values of \(Z_{DR}\) are located at 500 m in altitude and 600 m in radius in a region of downward vertical velocity (Fig. 6d). At this same altitude, there is a strong gradient in \(Z_{DR}\) between 700 and 1100 m in radius corresponding with a strong gradient in vertical velocity. This region has low values of \(\rho_{hv}\) throughout, which may mean that the gradient in \(Z_{DR}\) is due to differences in debris type/orientation between the updraft and downdraft. Locally reduced values of \(Z_{DR}\) also extend vertically above and below 500 m ARL and between 600 and 1000 m in radius.

c. Polarimetric versus kinematic variables

To gain a better understanding of what underlying processes may be responsible for the aforementioned distribution of polarimetric variables, scatterplots of \(Z_{HH}\), \(\rho_{hv}\), and \(Z_{DR}\) versus dual-Doppler kinematic variables are presented in this section. Spatial correlation between vertical vorticity \(\zeta\) and each of the polarimetric fields interrogated is observed. Additionally, there is an observed relationship between vertical velocity and \(\rho_{hv}\).

Prior to the Moore–Choctaw tornado exhibiting a TDS, there is no relationship between the radar variables and \(\zeta\) in the vicinity of the tornado (Fig. 7). At 2223 UTC, all values of \(Z_{HH}\), \(\rho_{hv}\), and \(Z_{DR}\) (not shown) are almost equally likely to be collocated with positive and negative values of \(\zeta\). By 2231 UTC, the Moore–Choctaw tornado has strengthened to the point where debris is lofted to altitudes where it can be sampled by the radars, and the distribution of \(\zeta\) versus \(Z_{HH}\) has been significantly modified from the earlier analysis (Fig. 8). At 250 m ARL, \(\zeta\) increases with increasing values of \(Z_{HH}\) for all points within 5 km of the TDS center (Fig. 8a). There is also a tendency within the TDS for higher \(Z_{HH}\) to be associated with greater cyclonic \(\zeta\). Recall that the greatest cyclonic \(\zeta\) at 250 m ARL is found within the tornado subvortices (Fig. 5b). Thus, this result can be interpreted as the tornado subvortices exhibiting the highest \(Z_{HH}\), likely because of locally enhanced debris lofting. It is possible that the subvortices exhibit a minimum in \(Z_{HH}\) at their centers because of centrifuging (Dowell et al. 2005), which causes the manifestation of the weak echo column...
(WEC) observed in this study and others (e.g., Tanamachi et al. 2012; Bodine et al. 2014).

A scatterplot of all points within 5 km of the TDS center indicates that the largest values of $z$ are associated with the lowest values of $r_{hv}$ at 250 m ARL, with a tendency for increasing $z$ to be associated with decreasing $r_{hv}$ within the bins flagged as tornadic debris (Fig. 9a). Similar to the pattern observed within the $Z_{HH}$ data, this result can be interpreted as the lowest $r_{hv}$ being associated with the tornado subvortices similar to what was observed by Wakimoto et al. (2016). Overlays of $z$ onto constant altitude PPIs (CAPPIs) of $r_{hv}$ support the collocation of locally reduced pockets of $r_{hv}$ with the tornado subvortices (Fig. 9c).

At 1000 m ARL, there is still an inverse relationship between $r_{hv}$ and $z$ among all points within 5 km of the TDS (Fig. 9b). However, there is no longer a relationship between $r_{hv}$ and $z$ among TDS flagged points. This is likely because tornado subvortices are confined to a relatively shallow layer near the surface (Wurman 2002), and thus the debris associated with the lowest values of $r_{hv}$ are no longer tied to its lofting mechanism. A CAPPI of $r_{hv}$ overlaid with $z$ indicates the presence of a dominant, central vortex, associated with the parent circulation (Fig. 9d).

Within the TDS, a direct relationship exists between $r_{hv}$ and vertical velocity at 1000 m ARL (Fig. 10a). The highest values of $r_{hv}$ are associated with downward vertical velocity with magnitudes from 0 to 40 m s$^{-1}$. Higher values of $r_{hv}$, but still sufficiently low to be classified as debris, are associated with upward motion in excess of 40 m s$^{-1}$. A downdraft is located in the southwest half of the TDS (Fig. 10b) collocated with a half annulus of low $r_{hv}$. It is possible that these bins of

---

8 A bias in the divergence field due to debris centrifuging may impact the magnitudes of the vertical velocity in the dual-Doppler analyses. Additionally, poor sampling of the lowest 100 m of the storm may also affect the magnitude of the retrieved vertical velocity. Finally, the analyses do not capture subgrid-scale features, like suction vortices, which may exhibit larger vertical velocity magnitudes.
low $\rho_{hv}$ represent a separate type of debris falling out from aloft (e.g., Houser et al. 2016) compared to the relatively higher $\rho_{hv}$ bins that are collocated with the updraft in the northeast half of the TDS. For example, the downdraft may aid the fallout of larger debris whereas smaller debris can be lofted into the storm-scale updraft on the northeast side. However, differential sedimentation of debris cannot be confirmed. The northeast-to-southwest decrease in $\rho_{hv}$ is also seen above 1000 m (not shown), but the lack of a sufficient

![Fig. 7. Scatterplots of vertical vorticity (s$^{-1}$) vs the OU-PRIME (a) reflectivity (dBZ) and (b) correlation coefficient valid at 2223 UTC. No significant relationship is observed between either radar variable and vertical vorticity.](http://journals.ametsoc.org/mwr/article-pdf/145/7/2723/4719017/mwr-d-16-0344_1.pdf)

![Fig. 8. Scatterplots of vertical vorticity (s$^{-1}$) vs OU-PRIME reflectivity (dBZ) at (a) 250 and (b) 1000 m ARL, and CAPPIs of OU-PRIME reflectivity (shaded, dBZ) overlaid with dual-Doppler winds (arrows) at (c) 250 and (d) 1000 m ARL valid at 2231 UTC. Blue dots in (a) and (b) represent non-TDS-flagged points and red dots indicate TDS-flagged points. The black lines in (a) and (b) represent the second-order polynomial fit for all points and the red lines are the second-order polynomial fits for TDS-flagged points.](http://journals.ametsoc.org/mwr/article-pdf/145/7/2723/4719017/mwr-d-16-0344_1.pdf)
look-angle difference for analysis aloft prevents the confirmation of a similar bifurcation in vertical velocity. In general, the lowest values of $Z_{DR}$ are associated with the largest values of $z$ at 250 m ARL (Fig. 11a). As previously noted in section 3a, precipitation exhibiting high values of $Z_{DR}$ surrounds the TDS at 2231 UTC (Fig. 11c). Thus, it is unsurprising that $Z_{DR}$ decreases when approaching the tornado. Many of the largest values of $\zeta$ in the tornado correspond to near-zero values of $Z_{DR}$. Figure 11c illustrates $Z_{DR}$ values near zero in the center of the tornado subvortices, with lower, negative values of $Z_{DR}$ located at the periphery of the vortices. The near-zero values of $Z_{DR}$ in the center of the subvortices are possibly due to nearly random particle
orientations. At 1000 m ARL, the relationship between $\zeta$ and $Z_{DR}$ is similar to what was observed at low levels (Fig. 11b). Unlike at 250 m ARL, however, the near-zero values of $Z_{DR}$ and surrounding annulus of negative $Z_{DR}$ are associated with the parent vortex at the center of the TDS (Fig. 11d) as opposed to with the tornado subvortices. The observation of negative values of $Z_{DR}$ at the periphery of the vortices will be a subject of discussion in the next section.

4. Discussion

a. Polarimetric observations

The previous section illustrates that the subvortices in the Moore–Choctaw tornado at 2231 UTC are associated with locally enhanced $Z_{HH}$, locally reduced $\rho_{hv}$, and near-zero $Z_{DR}$. The enhanced $Z_{HH}$ is likely due to locally enhanced concentrations of debris. It is speculated that subvortices are capable of lofting the largest debris, which could lead to lower $\rho_{hv}$ (e.g., through resonance-scattering effects). If the large debris were effectively random in orientation, $\rho_{hv}$ would be further reduced and backscattered power would be nearly equal in the horizontal and vertical polarizations, resulting in the near 0-dB $Z_{DR}$ that was observed.

Regions of negative $Z_{DR}$ within the TDS exist near the periphery of the tornado subvortices (Fig. 12). A region of negative $Z_{DR}$, with values below $-0.6$ dB, is located just to the east of the largest vortex (vortex 1), with another, larger area of negative $Z_{DR}$ with values below $-0.9$ dB located to the northwest of vortex 1. The third region of negative $Z_{DR}$ is located just to the east of the smaller subvortex (vortex 2) with values also below $-0.9$ dB. Since the subvortices rotate cyclonically around a common center, the second and third areas of negative $Z_{DR}$ are located in regions just vacated by the subvortices (vortex “wakes”). It is possible that the regions outside of the subvortices are associated with less turbulence and allow for recently ejected, trailing debris to become oriented in a less random manner. Alternatively, the vortex wakes could contain a different concentration of debris compared to the subvortices leading to differences in the relative contribution of debris to the returned signal, or vortex wakes could contain a different debris type than the subvortices as a result of size sorting. We speculate that the region of negative $Z_{DR}$ to
the east of vortex 1 may be associated with an unresolved subvortex, with debris fallout from aloft, or perhaps with an eastward debris ejection from vortex 1, similar to what was observed by Kurdzo et al. (2015).

The final topic of discussion regarding polarimetric variables is the WEC illustrated in Figs. 4 and 6. Similar to what was observed by Wakimoto et al. (2015) in the 2013 El Reno, Oklahoma, tornado, the region of low $Z_{HH}$ and $\rho_{hv}$ at the center of the 2010 Moore–Choctaw tornado is also characterized by $Z_{DR} < 0$ dB. As discussed by Wakimoto et al. (2015), this region is likely composed of low concentrations of small, randomly oriented debris. However, unlike what was observed in the El Reno tornado (which contained $\rho_{hv}$ as low as 0.1 in the WEC), values of $\rho_{hv}$ were greater than 0.5 in both the KOUN and OU-PRIME analyses. Part of the differences in $\rho_{hv}$ values may be due to differences in particle scattering between the X-band radar used by Wakimoto et al. (2015) and the S- and C-band radars used in this study. However, as noted by Bodine et al. (2014), the Moore–Choctaw tornado likely entrained considerable amounts of precipitation, whereas it was hypothesized by Wakimoto et al. (2015) that few hydrometeors were present in the El Reno WEC. It is possible that precipitation found in the Moore–Choctaw WEC was transported from aloft by the central downdraft illustrated in Fig. 6.

**b. Comparison of single- and dual-Doppler analyses**

It is important to recognize the trade-offs and differing degrees of utility of the single- and dual-Doppler techniques used in this study. To better understand some of the strengths of each method, a brief direct comparison of the analyses created by each technique was performed. By radially averaging the dual-Doppler analyses and vertically interpolating the data, a mean, axisymmetric wind profile is created that is similar to the one made by the single-Doppler technique. The magnitude of tangential velocities is greater in the single-Doppler analysis than the dual-Doppler analysis at almost every point with the greatest velocity difference ($V_{single} - V_{dual}$) occurring at the RMW (Fig. 13c). However, the two analyses are qualitatively similar with an RMW at approximately 1 km and the strongest winds occurring between 200 and 500 m ARL. It is likely that the difference in tangential velocity magnitude between the analyses is the result of the single-Doppler analysis having finer grid spacing (~100 m) compared to the dual-Doppler analysis (250-m grid spacing), which...

---

9 No correction for centrifuging was applied to either the single- or dual-Doppler analyses for the comparison in Figs. 13a and 13b.
allows the single-Doppler method to better sample the peak velocities.

In most places, the difference in radial velocity between the single- and dual-Doppler analyses is $<10$ m s$^{-1}$ (Fig. 13d). The largest difference is between 1 and 2 km in radius at the lowest two analysis levels where the single-Doppler method exhibits stronger negative radial velocity, which represents stronger low-level inflow into the tornado. It is likely that these differences are due to the better native resolution of the single-Doppler analysis in
addition to the dual-Doppler analysis being constrained by the data horizon of two radars, which may limit the sampling of the inflow layer. The other region of large radial velocity difference is between 150 and 1000 m in radius and between 300 and 800 m ARL, where the single-Doppler analysis has much higher outward radial velocities than the dual-Doppler analysis. The single-Doppler technique better samples the peak radial velocities, which may be most biased by the effects of debris centrifuging. The region of maximum velocity difference is similar to the region found to contain the largest difference in radial velocity between the air and debris by Dowell et al. (2005), which supports the hypothesis that centrifuging may account for some of the observed differences. However, it is also possible that the observed differences are the result of the single-Doppler technique better sampling the radial divergence associated with a stronger two-celled vortex.

Both Figs. 13a and 13b capture a downdraft near the center of the tornado with vertical velocity becoming directed upward near the RMW. Recall that both the dual-Doppler and axisymmetric analyses may have significant errors in vertical velocity because of the poor sampling of the low-level wind field. Thus, while they are qualitatively similar, it must be cautioned that their agreement cannot be used as validation for the derived secondary circulation. Similar to tangential and radial velocities, the single-Doppler technique exhibits larger-magnitude vertical velocity than the dual-Doppler method (Fig. 13e). The underestimate of vertical velocity in the dual-Doppler analysis is likely due to poor sampling of the low-level flow, as can be seen in Fig. 13d, where stronger radial inflow exists beneath the updraft and stronger radial outflow exists beneath the axial downdraft in the single-Doppler analysis. One more takeaway from the vertical velocity comparison is that the dual-Doppler solution is much more stable near the center of the vortex. This is likely due to errors in the single-Doppler technique that arise from using a small number of data points near the center of the vortex, which is less of an issue when subsetting and radially averaging dual-Doppler data from a larger domain.

While the single-Doppler technique has the advantage of better capturing the mass flux, the dual-Doppler technique is not constrained by an axisymmetric assumption and clearly illustrates an asymmetric vortex (e.g., Fig. 5b). Thus, the assumption of axisymmetry is violated in this case. However, the axisymmetric mean is still useful and can be used as a base state to linearize the dual-Doppler wind field in the vicinity of the tornado and provide a meaningful visualization of the asymmetries in the Moore–Choctaw tornado (Fig. 13e). The CAPPI of perturbation vertical velocity (Fig. 13f) illustrates that the Moore–Choctaw tornado may not be characterized simply by a downdraft at its center and an updraft at approximately 1 km in radius. Rather, the Moore–Choctaw tornado may be composed of at least two concentrated downdrafts: one near the center of the vortex and one in the southern portion of the tornado. Likewise, there may be at least two concentrated updrafts, with the strongest one in the northeast quadrant of the vortex. Thus, even though the dual-Doppler axisymmetric analysis undersamples the largest-magnitude vertical velocities, the dual-Doppler technique still captures one updraft and two downdrafts within the tornado.

5. Conclusions

The 10 May 2010 Moore–Choctaw tornado produced a large, heterogeneous TDS. Within the TDS, values of $Z_{\text{HH}}$, $Z_{\text{DR}}$, and $\rho_{\text{hv}}$ varied considerably. The highest values of $Z_{\text{HH}}$ and lowest values of $Z_{\text{DR}}$ and $\rho_{\text{hv}}$ were displaced 500–1000 m from the center of the TDS. Both axisymmetric and dual-Doppler analyses suggest the presence of an axial downdraft within the center of the TDS, characteristic of a two-celled vortex. Single-Doppler $V_r$ and dual-Doppler $\zeta$ provide evidence for the presence of two large tornado subvortices that were located at approximately the radius of maximum $Z_{\text{HH}}$ and minimum $Z_{\text{DR}}$ and $\rho_{\text{hv}}$.

The maxima in dual-Doppler $\zeta$ associated with the two large subvortices are collocated with two polarimetric variable extrema within the TDS (Fig. 14a). At low levels, the tornado subvortices are associated with the highest values of $Z_{\text{HH}}$ and the lowest values of $\rho_{\text{hv}}$, likely because of locally enhanced debris concentrations. While these relationships are likely representative of what is occurring in a mean sense, it is possible that finer-resolution observations may reveal more detail, especially near subvortex centers. The subvortices are also associated with near-zero values of $Z_{\text{DR}}$, likely because of near-random particle orientation. Negative regions of $Z_{\text{DR}}$ were constrained to the periphery and trailing regions of the subvortices. At 1000 m, a bifurcated distribution of $\rho_{\text{hv}}$ was observed, with higher values of $\rho_{\text{hv}}$ collocated with a strong updraft in the northeast part of the TDS and lower values of $\rho_{\text{hv}}$ collocated with a downdraft in the southwest portion of the TDS.

Axisymmetric cross sections of the Moore–Choctaw tornado (Fig. 14b) illustrate an annulus of $Z_{\text{HH}}$ caused by centrifuging and resulting in the WEC. Axisymmetric cross sections also capture the reduced $Z_{\text{DR}}$ and $\rho_{\text{hv}}$ in the tornado subvortices, which manifest as annuli near the RMW. A direct comparison of the single- and
dual-Doppler axisymmetric cross sections was made. When the additional axisymmetric constraint was applied to the dual-Doppler data, the two analyses were qualitatively similar. Both methods agreed on the placement of updrafts and downdrafts and had similar RMWs. The single-Doppler method better sampled the high-magnitude velocities and low-level mass flux than the dual-Doppler method and, thus, exhibited stronger radial and vertical velocities. But, the dual-Doppler method is not constrained by the axisymmetric assumption and was used to provide insight into asymmetries in the tornado by utilizing the axisymmetric mean to linearize the wind field in the vicinity of the tornado.

Additional dual-Doppler datasets of TDSs are needed, especially ones with the high spatial and temporal resolutions that are provided by mobile radars. Expansion on the findings of this paper will further our understanding of how debris is distributed by the three-dimensional winds in the vicinity of tornadoes, which, in turn, will facilitate more accurate inferences of tornado structure using polarimetric radars.

Acknowledgments. This study is supported by the National Science Foundation under Grant AGS-1303685. DJB is also supported by the National Center for Atmospheric Research (NCAR) Advanced Study Program. NCAR is sponsored by the National Science Foundation. Many thanks to Jim Kurdzo for his meticulous efforts to improve this paper. Finally, the authors thank the three anonymous reviewers who provided thorough comments that greatly improved the paper.

REFERENCES
——, R. D. Palmer, and G. Zhang, 2014: Dual-wavelength polarimetric radar analyses of tornadic debris signatures. FIG. 14. Conceptual diagrams of polarimetric signatures associated with large tornado subvortices displayed as (a) a PPI and (b) an axisymmetrically averaged vertical cross section. Axisymmetric averages are computed for each radius along line c–d in (a). In (a) the high $Z_{HH}$, low $\rho_{hv}$, and near-zero $Z_{DR}$ observed within the high-$z$ regions associated with the largest two subvortices in the 10 May 2010 Moore–Choctaw tornado are illustrated. Also illustrated is the trailing region of negative $Z_{DR}$. In (b) the annulus of $Z_{HH}$ associated with debris centrifuging and the annuli of low $\rho_{hv}$ and $Z_{DR}$ associated with the tornado subvortices and bound by the RMW (white dashed line) are illustrated.