Quantifying the Separation of Enhanced Z_{DR} and K_{DP} Regions in Nonsupercell Tornadoic Storms

SCOTT D. LOEFFLER AND MATTHEW R. KUMJIAN

Department of Meteorology and Atmospheric Science, The Pennsylvania State University, University Park, Pennsylvania

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ABSTRACT

Tornadoes associated with nonsupercell storms present unique challenges for forecasters. These tornadoic storms, although often not as violent or deadly as supercells, occur disproportionately during the overnight hours and the cool season—times when the public is more vulnerable. Additionally, there is significantly lower warning skill for these nonsupercell tornadoes compared to supercell tornadoes. This study utilizes dual-polarization Weather Surveillance Radar-1988 Doppler (WSR-88D) data to analyze nonsupercell tornadoic storms over a three-and-a-half-year period focused on the mid-Atlantic and southeastern United States. A signature found in a large number of cases is the separation of low-level specific differential phase K_{DP} and differential reflectivity Z_{DR} enhancement regions, thought to arise owing to size sorting. This study employs a new method to define the “separation vector,” which comprises the distance separating the enhancement regions and the direction from the K_{DP} enhancement region to the Z_{DR} enhancement region, measured relative to storm motion. While there is some variation between cases, preliminary results show that the distribution of separation distance between the enhancement regions is centered around 3–4 km and tends to maximize around the time of tornadogenesis. A preferred quadrant for separation direction is found between parallel and 90° to the right of storm motion and is most orthogonal near the time of tornadogenesis. Further, it is shown that, for a given separation distance, separation direction increasing from 0° toward 90° is associated with increased storm-relative helicity.

1. Introduction

Severe convective storms capable of producing damaging winds, hail, and tornadoes can manifest in several different regimes or “convective modes.” These convective modes include supercells, multicells, mesoscale convective systems (MCSs), quasi-linear convective systems (QLCSs), and isolated nonsupercell storms. Over the past several decades, a large emphasis has been placed on furthering the understanding of supercells using theoretical (e.g., Rotunno 1981; Davies-Jones 1984), modeling (e.g., Weisman and Klemp 1982; Rotunno and Klemp 1982, 1985), and observational (e.g., Lemon and Doswell 1979; Markowski et al. 2012a,b) approaches. Supercells are the most prolific producers of large hail and tornadoes, accounting for nearly all (97%) tornadoes rated EF3 or greater on the Enhanced Fujita scale (Smith et al. 2012). Relative to tornadoes produced by supercells, tornadoes from nonsupercells are associated with decreased warning performance.

Brotzge et al. (2013) showed that although the probability of detection (POD; percent of tornado reports with a warning) for supercell tornadoes was ~85% with an average lead time of about 17 min, the POD for nonsupercell tornadoes was only 45% with an average lead time of only about 12 min. The results from a more comprehensive 13-yr climatology by Anderson-Frey et al. (2016) calculated a POD for tornadoes from right-moving supercells of 79% but a POD for QLCS tornadoes of only 49%.

Clearly, there is a significant gap in tornado warning performance when comparing supercell and nonsupercell tornadoes, warranting further attention to nonsupercell tornadoes and their environments. Although there is overlap between the environments in which supercells and nonsupercells occur, QLCS environments in particular are shifted toward smaller CAPE and larger vertical wind shear values (e.g., Thompson et al. 2012; Anderson-Frey et al. 2016). This region of the shear–CAPE parameter space is associated with higher false alarm ratios (FARs; percent of tornado warnings without a verified tornado report) and lower POD

Corresponding author: Scott D. Loeffler, swl5295@psu.edu

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(Anderson-Frey et al. 2016). The use of parameters such as CAPE and the significant tornado parameter (STP; Thompson et al. 2003), popular choices in classic supercell environments, tends to underestimate the risk of tornadoes associated with these high-shear, low-CAPE environments (Sherburn and Parker 2014). Other difficulties with nonsupercell tornadoes include their seasonal and diurnal distributions. Compared to supercells, QLCS tornadoes occur more frequently in the cool season and overnight (Trapp et al. 2005; Anderson-Frey et al. 2016). Ashley et al. (2008) demonstrated the increased risk associated with these cool-season, nocturnal tornadoes by showing that nocturnal tornadoes are almost twice as likely to cause fatalities as those during the day. This stems from decreased visibility for storm spotters as well as the general public being asleep and less likely to receive and act on warnings.

This study aims to utilize dual-polarization (or polarimetric) radar data to reveal any characteristics or trends leading up to, during, and after nonsupercell tornadic storms. The WSR-88D network was fully upgraded to dual-polarization capabilities in the summer of 2013 (having started in 2011), giving operational forecasters a wealth of new information by transmitting and receiving horizontally and vertically polarized waves simultaneously. In addition to the traditional radar moments, dual-polarization capabilities provide the variables of differential reflectivity Z_{DR} , differential propagation phase shift Φ_{DP} and half its range derivative (specific differential phase K_{DP}), and the copolar correlation coefficient (ρ_{HV} in the research community, CC in the operational community). For a comprehensive review of the polarimetric variables and their applications, see Kumjian (2013a,b) and Doviak and Zrnić (1993).

Differential reflectivity was introduced for precipitation measurements by Seliga and Bringi (1976, 1978). The Z_{DR} is the difference between the logarithmic radar reflectivity factors at horizontal and vertical polarizations. For hydrometeors that are small compared to the wavelength with their major axis oriented horizontally (e.g., oblate raindrops), Z_{DR} is positive. Because drops become more oblate as they grow larger, Z_{DR} can also be used to assess the median drop size: large Z_{DR} values can indicate the presence of large raindrops. Unlike Z_{DR} , a polarimetric variable that is sensitive to number concentration is specific differential phase K_{DP} . The K_{DP} was first used by Seliga and Bringi (1978) and Sachidananda and Zrnić (1986, 1987) for rainfall rate estimates. The K_{DP} has been shown to be nearly linearly related to the rainfall rate (Sachidananda and Zrnić 1986); therefore, large K_{DP} values are usually located in regions of heavy precipitation and large liquid water content. The K_{DP} is also insensitive to

quasi-spherical hydrometeors (i.e., tumbling or dry hail). These properties of K_{DP} have been exploited by Balakrishnan and Zrnić (1990) and Aydin et al. (1995) for radar measurements of mixed-phase precipitation. Note that K_{DP} is very sensitive to small melting hail, where meltwater accumulates on the hailstone, both stabilizing the hailstone and increasing its dielectric constant. Although K_{DP} is strongly affected by drop size, it is less affected compared to reflectivity [e.g., Sachidananda and Zrnić (1986) calculated a dependence of $D^{4.24}$]. Drops still need to be large enough to have some measure of “oblateness” in order for there to be a differential phase shift; K_{DP} will be unaffected by the presence of small spherical drops.

Research radar data have allowed for numerous polarimetric studies of convective storms. Many of these primarily focused on supercells (e.g., Loney et al. 2002; Ryzhkov et al. 2005; Bluestein et al. 2007; Kumjian and Ryzhkov 2008; Romine et al. 2008; Van Den Broeke et al. 2008; Frame et al. 2009; Kumjian et al. 2010; Palmer et al. 2011; Tanamachi et al. 2012; Snyder et al. 2013; Houser et al. 2015). The polarimetric analysis of supercells by Kumjian and Ryzhkov (2008) found several characteristic signatures, including a region of enhanced Z_{DR} along the inflow side of the forward flank, referred to as the “ Z_{DR} arc.” The authors attributed this signature to hydrometeor size sorting, where smaller drops are preferentially “sorted out” of this region, leaving behind a sparse population of large drops. As hydrometeors descend, smaller drops take longer to reach the surface than larger drops because the terminal velocity of raindrops increases with size (e.g., Gunn and Kinzer 1949; Foote and du Toit 1969; Beard 1976; Brandes et al. 2002). Initially, this leads to a sorting of drops based on size, with larger drops below the smaller drops (assuming steady-state conditions aloft). In the absence of storm-relative winds, the smaller drops reach the surface at the same location and the drops are no longer sorted by size. This is the transient size sorting mechanism described by Kumjian and Ryzhkov (2012).

However, there are mechanisms that can maintain this process, as discussed in detail by Kumjian and Ryzhkov (2012). One such mechanism is the presence of nonzero storm-relative winds in the sorting layer. Dawson et al. (2015) showed that these storm-relative winds are fundamental to size sorting, not storm-relative helicity (SRH; Davies-Jones 1984) that earlier works had linked to the magnitude of the Z_{DR} arc (e.g., Kumjian and Ryzhkov 2009). Because of their slower fall speeds, smaller drops spend more time in the sorting layer. This allows the smaller drops to be advected farther from the updraft by the storm-relative winds, compared to larger drops which fall rapidly through the layer and are

therefore advected a shorter distance downwind. This leads to a horizontal separation of the smaller and larger drops, with the direction of the mean storm-relative wind in the sorting layer pointing from larger drops to smaller drops. The region of larger drops is then depleted of relatively smaller drops due to this size sorting, which decreases reflectivity (Z_H) owing to the partial removal of the drop spectrum. However, the median drop size of this region increases and therefore causes an increase in Z_{DR} . Palmer et al. (2011) observed a Z_{DR} arc with Z_{DR} values > 8 dB at C band, where Z_H values were < 25 dBZ. The region with smaller drops would have smaller Z_{DR} due to a smaller median drop size, but the large number concentration results in large K_{DP} . This results in a horizontal separation between regions of enhanced K_{DP} and Z_{DR} .

Though the Z_{DR} enhancement region, or Z_{DR} arc, is fairly well represented in the literature (Ryzhkov et al. 2005; Kumjian and Ryzhkov 2008, 2009; Dawson et al. 2014, 2015), comparatively few studies have analyzed both K_{DP} and Z_{DR} enhancement regions and the separation between the two. Crowe et al. (2012) utilized a C-band radar to assess the offset in enhancement regions and showed that the offset was larger in tornadic storms, but they did so qualitatively with a very small sample size. More recent work by Martinaitis (2017) qualitatively assessed the separation of K_{DP} and Z_{DR} enhancement regions in tropical cyclone convection and found no distinction between tornadic and nontornadic cases. Both studies observed the separation of K_{DP} and Z_{DR} enhancement regions in both supercell and nonsupercell storm modes. Additionally, Mahale et al. (2012) analyzed vortices within a QLCS storm. Those authors noted the presence of Z_{DR} arcs proximate to areas of increased rotation, furthering the notion that signatures originally found in supercells may be found in nonsupercell storms as well.

Although both Crowe et al. (2012) and Martinaitis (2017) assessed the separation qualitatively, Jurewicz and Gitro (2014) attempted to quantify this separation in supercells. However, their use of point maximum values to define K_{DP} and Z_{DR} maxima made their measurements sensitive to radar noise. In contrast, we develop and employ a new method to quantify the separation between low-level K_{DP} and Z_{DR} enhancement regions that is more robust against noise. The goal of this study is to quantify the separation between K_{DP} and Z_{DR} enhancement regions leading up to, during, and after a nonsupercell tornadic event in order to reveal any characteristic features or trends. As such, this study does not assess differences between tornadic and nontornadic nonsupercell storms. Section 2 will describe the data and methodology used in this study. Section 3

will detail the results from both qualitative and quantitative analyses of a large population of nonsupercell tornadic storms. Section 4 will provide some concluding remarks as well as some thoughts for the future extension of this work.

2. Data and methods

In this study, the separation between K_{DP} and Z_{DR} enhancement regions was analyzed in nonsupercell tornadic storms. Cases were selected from a dataset of Storm Prediction Center (SPC) tornado reports from states comprising the National Weather Service (NWS) Eastern Region and southeastern United States, so the results presented here may be biased by the environments frequently seen in these regions. This dataset was quality checked by filtering erroneous storm reports, which include duplicate reports, report locations far removed from a radar echo, or report times off by tens of minutes to an hour. This filtering process is similar to that used in Smith et al. (2012, 2015). This dataset spans the period from July 2013 to December 2016 to only include storms for which polarimetric radar data are available.

To ensure adequate data quality and resolution, the storm must be sufficiently close to the radar to mitigate issues associated with nonuniform beam filling (NBF; Ryzhkov 2007) and ensure adequate low-level coverage. Only storms that were within 60 km of a radar site were considered further, a similar range to that used in Davis and Parker (2014) based on where they retrieved their best results. These storms were then manually classified using a simplified version (fewer categories and subcategories) of the system used in Smith et al. (2012). Storms were classified as supercell, linear, MCS (convective system that does not display linear characteristics), or weak/marginal discrete cell (a single cell that does not display supercell characteristics). The simplifications compared to Smith et al. (2012) included the MCS category containing convective storms with widespread precipitation that did not have linear characteristics such as the 3 to 1 aspect ratio from Smith et al. (2012). However, these storms still had localized enhanced reflectivity, just not in a linear fashion. For linear storms, we still used the aspect ratio criterion but relaxed the criterion stating a contiguous line of at least 100 km of at least 35 dBZ. This allowed for linear segments that fell short of 100 km due to breaks in the line. Embedded or lines of supercells were classified as “supercells” and were excluded from the MCS and linear categories. Because the focus of this study was on nonsupercell storms, only storms classified into one of the latter three categories were considered (examples

FIG. 1. Examples of the three nonsupercell storm types. (a) Z_H and (b) velocity for a linear case on a $100 \text{ km} \times 100 \text{ km}$ grid. Data are from the Maxwell Air Force Base radar in Alabama (KMXX) at 0050 UTC 16 Feb 2016. (c),(d) As in (a) and (b), but for an MCS case on a $90 \text{ km} \times 90 \text{ km}$ grid. Data are from the Wilmington, NC, radar (KLTX) at 1530 UTC 24 Dec 2014. (e),(f) As in (a) and (b), but for a single cell case on an $80 \text{ km} \times 80 \text{ km}$ grid. Data are from the Boston, MA, radar (KBOX) at 2108 UTC 23 Jun 2015. All scans are at 0.5° elevation, and all figures have up, down, right, and left corresponding to north, south, east, and west.

shown in Fig. 1). Level-III WSR-88D radar data were used to analyze these storms in order to use K_{DP} data that are operationally available (i.e., not deriving our own). However, this limits the coverage to the lowest few tilts.

From all the cases ($n = 201$) that met the criteria previously mentioned, 70 cases were chosen for an initial qualitative assessment to observe any low-level signatures, mainly the separation between low-level K_{DP} and Z_{DR} enhancement regions, leading up to, during, and

after a tornadic event. These 70 cases were chosen based on the availability of “good” radar data (e.g., low amounts of K_{DP} or Z_{DR} noise) and to select cases far enough removed from each other in either space or time to gather a diverse group of cases. After the separation signature was observed in the initial qualitative assessment, a method to quantify the separation between low-level K_{DP} and Z_{DR} enhancement regions was developed and applied to each case in which it was

FIG. 2. Depiction of the process used to define enhancement regions and centroids. Scans are 0.5° elevation from 1711 UTC 21 Jun 2016 at the Sterling, VA, radar (KLWX) on a $50 \text{ km} \times 50 \text{ km}$ grid. Analysis box is $25 \text{ km} \times 25 \text{ km}$. Thresholds used are $\text{CC} = 0.93$, $K_{\text{DP}} = 3^\circ \text{ km}^{-1}$, and $Z_{\text{DR}} = 3 \text{ dB}$. (a) The K_{DP} ($^\circ \text{ km}^{-1}$) scan showing the analysis box (yellow) and (b) K_{DP} enhancement region and centroid (red). (c) As in (a), but for Z_{DR} (dB) with the analysis box in red, and (d) as in (b), but for Z_{DR} with centroid in blue. Storm motion is from the west-southwest, and the separation vector is 60° to the right of storm motion.

observed ($n = 30$). For a given volume scan, the lowest elevation angle (0.5°) was chosen. Plan position indicators (PPIs) of the radar variables were then converted from polar coordinates and plotted on a Cartesian grid with the radar at the origin. Once the variables were plotted, a region of interest called the “analysis box” was chosen (Figs. 2a,c) to avoid analyzing the entire domain of the PPI, which could sample multiple storms. The placement of the analysis box introduces some subjectivity, but for consistency the standard analysis box used in this study was $20 \text{ km} \times 20 \text{ km}$, associated with a region of rotation if one was readily apparent. The dimensions of the analysis box were altered to capture the relevant features when enhancement regions were elongated in the zonal or meridional directions or when the size of the box needed to be further constrained to avoid sampling nearby storms.

After an analysis box was determined, the enhancement regions were then determined by defining the requirements a radar gate must meet to be included.

First, the gate must be located within the analysis box. Next, the gate must have a K_{DP} (Z_{DR}) value that exceeds a predefined minimum K_{DP} (Z_{DR}) value, referred to as the “threshold value.” This requirement isolates the enhanced values of K_{DP} (Z_{DR}). Last, these gates with enhanced K_{DP} and Z_{DR} values must have a CC value exceeding a minimum threshold value to ensure that nonhydrometeorological returns are excluded from consideration. All of the gates that meet these requirements define the K_{DP} (Z_{DR}) enhancement region. The median x and y coordinates of each enhancement region were calculated from all radar gates in each region in order to determine the centroid of each enhancement region (Figs. 2b,d).

The distance and orientation are the two components of what we call the “separation vector.” Because each enhancement region centroid has an x and y coordinate, it is straightforward to calculate Δx and Δy between the two centroids: $\Delta x = x_{Z_{\text{DR}}} - x_{K_{\text{DP}}}$ and $\Delta y = y_{Z_{\text{DR}}} - y_{K_{\text{DP}}}$. The Δx and Δy were then used to calculate the distance

FIG. 3. The K_{DP} and Z_{DR} centroids (markers) from 1901 to 1945 UTC 24 Feb 2016 near Sussex, VA. Lines show linear fit to the centroids in order to calculate storm motion. Domain size is $110 \text{ km} \times 110 \text{ km}$.

between the two centroids: $\sqrt{(\Delta x)^2 + (\Delta y)^2}$. The orientation of the separation was calculated as degrees clockwise from the storm motion. Storm motion was determined by calculating a least squares line to both the K_{DP} and Z_{DR} centroids throughout the analysis period. The average slope of these two lines was used to define storm motion direction, and the start and end points of these lines and the time between the first and last volume scan were used to calculate the average speed. This process is similar to that used by Aydin et al. (1995), who tracked the K_{DP} maxima to define storm motion. A depiction of this process is shown in Fig. 3. The separation vector at a particular time points from the K_{DP} centroid to the Z_{DR} centroid. Then, the separation vector (Fig. 4) points from smaller drops to larger drops, presumably antiparallel to the mean storm-relative wind over the sorting layer following arguments by Kumjian and Ryzhkov (2008), Kumjian and Ryzhkov (2009), Dawson et al. (2014), and Dawson et al. (2015). This method was employed for every volume scan during the analysis period to assess trends in the separation vector leading up to tornadogenesis.

To test the variability of the results to small changes in the threshold values, sensitivity tests were run by varying one threshold while holding the other two constant. A tornadic nonsupercell storm from 21 June 2016 near Baltimore, Maryland, was used to test these sensitivities. Figure 5 shows the results from varying the CC threshold while holding the K_{DP} threshold at 3° km^{-1} and the Z_{DR} threshold at 3 dB. The CC thresholds were varied between 0.88 and 0.94, and the resulting trends show little variability. A CC threshold of 0.93 was chosen for analyzing further cases. This CC threshold is smaller

FIG. 4. Schematic depicting the separation vector. The separation vector points from the K_{DP} centroid (red marker) to the Z_{DR} centroid (blue marker). The vector is defined by the distance between the two centroids and the angle clockwise from the storm motion to the vector.

than the 0.95 used (for X band) in French et al. (2015) and the 0.98 used in Kumjian (2011). However, those studies focused on retrievals from rain-only processes, whereas this study focuses on enhancements of K_{DP} and Z_{DR} where small melting hail and graupel can contribute to these enhancements (Kumjian and Ryzhkov 2012; Ryzhkov et al. 2013; Dawson et al. 2014), warranting a slight reduction.

Although keeping a CC threshold constant throughout an analysis period is appropriate, keeping K_{DP} and Z_{DR} thresholds constant may not be. The magnitude of an enhancement region may, and in our experience quite often does, increase and/or decrease throughout the life cycle of the storm. As such, keeping a constant threshold may not accurately capture the evolution of a given enhancement region. The characteristics of these enhancement regions are also likely regime dependent (e.g., Kumjian and Ryzhkov 2009; Dawson et al. 2015), and broadly applied constant thresholds may not adequately capture these different regimes and may also be affected by Z_{DR} bias. On the other hand, selecting a threshold for every volume scan introduces subjectivity and would be time consuming and detrimental to warning issuance in an operational setting. To resolve these issues, this study utilizes an “adaptive threshold” to objectively select the K_{DP} and Z_{DR} thresholds. Rather than selecting a threshold for each variable, the adaptive threshold only uses a gate threshold. This gate threshold indicates the minimum number of radar gates N_G in the horizontal plane that can define an enhancement region. It then finds the largest K_{DP} or Z_{DR} threshold (incrementing by $0.5^\circ \text{ km}^{-1}$ or dB, respectively) that gives an enhancement region of at least that specified number of gates. In this way, the adaptive threshold can respond to changes in the magnitude of the enhancement region. This helps resolve some of the issues Martinaitis (2017) encountered in

FIG. 5. Time series of (a) separation distance and (b) separation orientation for a variety of CC thresholds. Measurements taken from the KLWX radar on 21 Jun 2016.

their effort to quantify the separation, stating that “the large range of K_{DP} and Z_{DR} values suggests that no minimum threshold value could be established for either product.”

An additional benefit of the adaptive threshold is that it reduces the number of input thresholds from three (CC , K_{DP} , and Z_{DR}) to two (CC and N_G). The adaptive threshold is also insensitive to Z_{DR} bias. The N_G threshold makes Z_{DR} insensitive and adaptable to offsets as long as the offset is not very large (~ 1 – 2 dB). Our qualitative assessment revealed none with such significant biases. As a result of ongoing efforts to correct for Z_{DR} biases, most radars have offsets much smaller in magnitude (Cunningham et al. 2013; Zittel et al. 2014). Thus, it is extremely unlikely that

Z_{DR} bias will negatively affect our results. The sensitivities to varying the gate threshold are shown in Fig. 6 and show little variability in the trends of both separation distance and orientation. The choice of the gate threshold introduces some subjectivity, as a smaller threshold identifies smaller, stronger enhancement regions, whereas a larger threshold identifies broader, weaker enhancement regions. A gate threshold of $N_G = 10$ was used for further analyses in this study.

The separation vector method was applied to non-supercell tornadic cases to assess the characteristics and evolution of the separation vector around the time of tornadogenesis. The separation distance is related to the magnitude of the storm-relative flow, and the

FIG. 6. As in Fig. 5, but for varying gate thresholds.

TABLE 1. List of 30 cases that exhibited K_{DP} – Z_{DR} separation and were quantitatively analyzed. The LSR is used as the estimated time of the tornado.

Date	Radar ID	LSR (UTC)	Storm type
27 Nov 2013	KMHX	0315	MCS
21 Feb 2014	KRAX	1825	Linear
29 Apr 2014	KMHX	1825	Single
14 May 2014	KILN	2153	MCS
15 May 2014	KRAX	2210	MCS
15 Oct 2014	KLWX	1623	Single
24 Dec 2014	KLTX	1530	MCS
4 Jan 2015	KEOX	1227	Linear
3 Apr 2015	KOHX	2222	Single
4 Apr 2015	KHTX	0210	Linear
19 Apr 2015	KJGX	1723	MCS
20 Jun 2015	KLWX	2339	Single
23 Jun 2015	KBOX	2139	Single
26 Jun 2015	KRLX	2328	MCS
27 Jun 2015	KPBZ	2106	Single
18 Nov 2015	KGWX	0953	Linear
18 Nov 2015	KFFC	2148	Linear
24 Dec 2015	KOHX	0412	Linear
24 Dec 2015	KEOX	1029	Linear
3 Feb 2016	KGWX	0502	Linear
16 Feb 2016	KMXX	0057	Linear
16 Feb 2016	KAMX	1250	Linear
24 Feb 2016	KAKQ	1935	MCS
24 Feb 2016	KRAX	2105	Single
1 Mar 2016	KBMX	2312	Linear
2 Mar 2016	KMXX	0230	Linear
21 Jun 2016	KLWX	1729	Linear
23 Jun 2016	KILN	0703	Linear
22 Aug 2016	KBOX	0720	MCS
30 Nov 2016	KGSP	2152	Linear

orientation angle is hypothesized to be related to the turning of the winds in the near-storm environment. Because of these characteristics, it is desirable to determine correlations between these separation vector measurements and the near-storm environment. Separation vector measurements for a particular case were matched with corresponding environmental parameters from 0-h analyses from the Rapid Refresh model (RAP; Benjamin et al. 2016) at the nearest grid point and closest preceding time. For calculating SRH, vertical wind profiles from the RAP were combined with the radar-derived storm motion to compute SRH using the summation given in Markowski and Richardson (2010),

$$\text{SRH} = \sum_{n=1}^{N-1} [(u_{n+1} - c_x)(v_n - c_y) - (u_n - c_x)(v_{n+1} - c_y)], \quad (1)$$

where N is the number of wind observations, u and v are the x and y components of the wind, and c_x and c_y are the x and y components of the storm motion.

FIG. 7. Locations (red triangles) of the 30 nonsupercell tornadic events for which the K_{DP} – Z_{DR} separation was analyzed.

3. Results and discussion

The qualitative assessment of 70 nonsupercell tornadic storms revealed the signature of the separation of low-level K_{DP} and Z_{DR} enhancement regions in a large number of cases. The separation of low-level K_{DP} and Z_{DR} enhancement regions was observed in 30 cases (Table 1; Fig. 7). In cases where this signature was not observed, localized enhancements of K_{DP} and Z_{DR} were not readily discernible mainly due to either noisy data or very homogenous K_{DP} and Z_{DR} fields with low values. Five of these 30 tornadic cases were not warned. Of the remaining 25 cases with an associated warning, only 14 had positive lead times (i.e., a warning that was issued before the tornado occurred). These warning statistics are comparable to the 40 cases that did not exhibit separation, as shown in Table 2, indicating that cases showing separation are not more or less likely to be warned.

For the 30 cases in which low-level separation was observed, we computed the separation vector at every volume scan during the analysis period. An example of this analysis is shown from 1 March 2016 near the KBMX radar (Figs. 8, 9). The temporal trends of the separation vector were assessed using PPIs and measurements of the separation distance and orientation. The local storm report (LSR) for this storm indicated that a tornado occurred at 2312 UTC and storm motion was from west-northwest to east-southeast. The separation orientation 5 min prior to (Fig. 8g) and at the time of the LSR (Fig. 8h) is nearly orthogonal to storm

TABLE 2. Warning statistics for 30 cases that showed K_{DP} – Z_{DR} separation and 40 others that did not show separation.

	Separation	No separation
Positive lead time	14 (46.67%)	18 (45%)
Nonpositive lead time	11 (36.67%)	13 (32.5%)
Unwarned	5 (16.67%)	9 (22.5%)
Total	30	40

motion. This is also seen in several volume scans prior to the LSR in the time series of separation orientation (Fig. 9b). The average separation distance was around 5 km but had some considerable changes between volume scans with the peak separation distance around 10 km occurring around 12 min before the LSR (Fig. 9a). We assessed the evolution of the magnitude of the K_{DP} and Z_{DR} enhancement regions by analyzing the

time series of the K_{DP} and Z_{DR} thresholds that were chosen by the adaptive threshold at every volume scan (Fig. 10). In this particular case, there is an increase in Z_{DR} magnitude leading up to tornadogenesis and a decrease in K_{DP} magnitude after tornadogenesis. However, these temporal trends of K_{DP} and Z_{DR} magnitude varied from case to case, and therefore no repeatable signatures were found.

This type of analysis was done for all 30 cases to obtain a large number of separation vector measurements in an effort to determine characteristics of the separation vector in nonsupercell tornadic storms. Although a time series from one case can be quite noisy (see Fig. 9), taking information across all 30 cases can better reveal trends and characteristics. Kernel density estimation (KDE; e.g., Peel and Wilson 2008) of the distance-orientation parameter space is shown in Fig. 11.

FIG. 8. PPIs of K_{DP} ($^{\circ} \text{ km}^{-1}$) at 0.5° near the Birmingham, AL (KBMX) radar at (a) 2307, (b) 2312, and (c) 2317 UTC 1 Mar 2016. Red circles indicate the location of the K_{DP} centroid. (d)–(f) As in (a)–(c), but for Z_{DR} (dB). Blue circles indicate the location of the Z_{DR} centroid. (g)–(i) As in (a)–(c), but for Z_H (dBZ). Black (blue) circles indicate the location of the K_{DP} (Z_{DR}) centroid. Magenta triangles show the location of the LSR at 2312 UTC. Scans are on a $50 \text{ km} \times 50 \text{ km}$ grid. Storm motion is from the west.

FIG. 9. Time series of (a) separation distance and (b) separation orientation from 1 Mar 2016 near the KBMX radar. The vertical dashed line represents the time of the LSR at 2312 UTC.

Data within 10 min of the LSR are shown in blue and data within 5 min are shown in red. Both datasets show distributions centered close to 3–4 km and in a preferred quadrant of 0° – 90° to the right of storm motion compared to any other quadrant. The center of the distribution (distance, orientation) for data within 10 min is (2.9 km, 70°) while the center for data narrowed to within 5 min is (3.4 km, 76°).

While there is certainly plenty of overlap in the two distributions, the distribution focused closer to the LSR shows a slight increase in separation distance. From this, we can hypothesize that a given storm might experience its maximum separation distance closer to the time of the LSR, possibly from a strengthening updraft near tornado time which can increase low-level storm-relative winds due to mass continuity. To test this hypothesis, the time of the peak separation distance relative to the LSR for each storm is documented. The distribution of these “peak separation times” is shown in Fig. 12a. If the peak separation distance is not related to the formation of the tornado, the peak separation times would be random from storm to storm, resulting in a uniform distribution of the peak separation times relative to the LSR. However, the distribution of peak separation times shows a maximum in the time interval from the LSR time to ~ 5 min after it. This suggests that the time of the peak separation distance is not random and is related to processes associated with the tornado itself. This could simply be related to a strengthening updraft because stronger vertical motions would suspend the drops for a longer period of time in the sorting layer. Given the short lifetime of these nonsupercell storms, the storms generally weaken shortly after tornadogenesis, making it less likely for a storm to experience its peak separation distance at times after the LSR. This is reflected in

Fig. 12a, as the KDE values decrease with increasing time after the LSR.

A similar analysis is done for the other component of the separation vector: the orientation. We hypothesize that a given storm might experience its most orthogonal orientation, angle closest to 90° to the right of storm motion, closer to the time of the tornado. We make this hypothesis based off of the slight shift toward 90° in Fig. 11 when the data are focused closer to the tornado time. Physically, a mean storm-relative wind oriented more orthogonal to storm motion implies greater veering of the storm-relative winds in the sorting layer compared to a more parallel orientation. Furthermore, simulations from Kumjian and Ryzhkov (2009) showed that more orthogonal orientations were associated with increases in SRH, an important parameter for tornado

FIG. 10. Time series of K_{DP} (red) and Z_{DR} (blue) thresholds chosen by the adaptive threshold from 1 Mar 2016 near KBMX.

FIG. 11. Contours of 2D KDE distributions of the distance–orientation parameter space for data points within 10 min of the LSR (blue) and within 5 min of the LSR (red). Median points for each distribution are marked with asterisks. Contours enclose 25%, 50%, and 75% of the data points.

production. The time relative to the LSR corresponding to the orientation closest to orthogonal for each case is documented and the distribution of these times is shown in Fig. 12b. Once again, if the orientation was chaotic and completely random, we would expect a uniform distribution. However, the distribution of “most orthogonal” times shows a clear peak at the time of the LSR, suggesting that, on average, the orientation becomes most orthogonal close to and at the time of the LSR.

SRH, defined previously, is often used for assessing a storm’s tornadic potential. While SRH is generally used in relation to mesocyclone intensity in supercells, Anderson-Frey et al. (2016) showed that QLCS tornadic events had substantial SRH in the near-storm environment. A nonsupercell storm in an environment with

increased SRH may be able to take on “supercell-like” traits, such as increased rotation, more well-defined notches in a linear system, or more pronounced Z_{DR} arcs like those in Mahale et al. (2012). Although Dawson et al. (2015) showed through some “pathological cases” that SRH is not fundamental to size sorting, there is a general correlation between SRH and the storm-relative winds (e.g., Kerr and Darkow 1996), allowing for a possible connection between SRH and the separation vector. For making comparisons to SRH, both the separation distance and orientation play an important role. Recall that the separation orientation is thought to be antiparallel to the mean storm-relative wind and that the separation distance is thought to be proportional to the magnitude of the mean storm-relative wind, both of which are important for the accumulation of SRH in a layer. (Of course, heterogeneities in the environment could lead to significant changes in SRH around the storm.) However, separation distance and orientation show essentially no correlation with 0–1 km SRH ($r^2 = 0.003$ and 0.01, respectively). The fact that neither distance nor orientation display a strong correlation with 0–1 km (or 0–3 km SRH, similar trends) suggests that it is the combination of distance and orientation that is, perhaps, related to SRH.

In order for SRH to be present, nonzero storm-relative winds need to be present. The area under the hodograph (i.e., SRH) will increase with increasing storm-relative winds (Dawson et al. 2015, their Fig. 7). For a given mean storm-relative wind magnitude, the area under the hodograph will increase as the orientation of the mean storm-relative wind becomes more orthogonal. Therefore, more orthogonal orientations for a given separation distance are related to increased SRH values. To incorporate both separation distance and orientation to determine any correlation between

FIG. 12. KDE distribution of times relative to the LSR for (a) peak separation distance and (b) most orthogonal orientation. Red markers indicate the 25th, 50th, and 75th percentiles from left to right.

the separation vector and SRH, a size sorting parameter (SSP) was developed and utilized here:

$$SSP = D|\sin A|, \quad (2)$$

where D is the median separation distance within 10 min of the LSR, and A is the median separation orientation within 10 min of the LSR. Based on the previous discussion of how increased separation distance and more orthogonal orientations may be associated with increased SRH, this size sorting parameter increases with increasing separation distance and separation orientations deviating from parallel to storm motion and approaching orthogonal to storm motion. A value of SSP is assigned to each case to compare with the corresponding SRH value. When all cases are considered, SSP shows essentially no correlation ($r^2 = 0.02$) with 0–1 km SRH.

However, we hypothesize that, for a given separation distance, separation orientations approaching orthogonal to storm motion are associated with increased SRH. To test this hypothesis, the SSP values are subdivided by the median separation distance (Fig. 13). This separates the SSP data into groups of similar separation distance to assess the correlation between varying separation orientation and SRH. The 3.5–7 km (red) grouping shows suggestive results, with a positive correlation ($r^2 = 0.543$) between SSP and 0–1 km SRH significant at the 95% confidence level. The correlation values and trends are comparable when analyzing the correlations between SSP and 0–3 km SRH (not shown). Because data points within a group have similar values for the D term of SSP, the increasing SSP values largely come from an increasing $\sin A$ term (separation orientation angles approaching orthogonal). The increasing SSP values from more orthogonal separation orientations corresponding to increased 0–1 km SRH values provide some support for the earlier hypothesis that, for a given magnitude of the mean storm-relative wind (separation distance), more orthogonal separation orientations are associated with higher SRH. However, more cases would certainly strengthen this claim. Although only from a limited number of cases, this suggests that forecasters could possibly use polarimetric radar data in real time to qualitatively assess SRH in the near-storm environment, as suggested by Kumjian and Ryzhkov (2009).

4. Conclusions and future work

This study analyzed the separation of enhanced low-level K_{DP} and Z_{DR} regions associated with tornadoes within 60 km of a radar from nonsupercellular storm modes, such as weak single cells, MCSs, and QLCs.

FIG. 13. 0–1-km SRH compared to SSP filtered by median separation distance.

Although a large majority of intense tornadoes (EF3+) are associated with supercells, nonsupercell tornadoes pose a societal threat owing to a more frequent occurrence in the cold season and at night when the public is generally more vulnerable and less aware. These nonsupercell tornadoes present a challenge to forecasters, given their occurrence in less “textbook” environments and their relatively brief lifetimes. Previous studies have shown that these challenges manifest themselves in significantly lower POD values for tornadoes from nonsupercells than those from supercells. A warning difficulty for forecasters is that these nonsupercell storms quite often do not display well-documented radar signatures such as a strong, persistent mesocyclone and hook echo that are seen with supercell tornadoes. Furthermore, some storms may exhibit these features, but they are not resolved by the radar owing to distance from the radar or small scales of these features.

We developed, tested, and employed a new technique to calculate the separation distance and orientation between the K_{DP} and Z_{DR} enhancement regions. This technique utilizes a CC and gate threshold to objectively define enhancement regions of K_{DP} and Z_{DR} , from which the centroids of these regions are calculated. The distance and orientation of separation between the two centroids are the two components of the separation vector. This technique was applied to 30 nonsupercell tornadic storms. Statistics of typical separation distance and orientation for these nonsupercell tornadic storms were compiled. The results show that the separation distance for these storms peaks most frequently around the time of tornado report. The separation orientation also tends to become more orthogonal to storm motion

around the time of the tornado report. The results also show a preferred quadrant for the separation vector, directed between parallel and orthogonal to the right of storm motion (0° – 90° to the right of storm motion). The distribution of separation distance was centered around 3–4 km. However, we did not assess nontornadic nonsupercell storms and, therefore, cannot assess the discriminatory power of these signatures. Rather, these findings provide typical characteristics of some non-supercell tornadic storms.

The separation vector for the 30 cases was also related to SRH values calculated from RAP proximity soundings and radar-derived storm motion. The results show that, for a given separation distance, SRH increases with separation orientations approaching orthogonal to storm motion (90° to the right). This result could allow forecasters to use polarimetric radar measurements to assess the degree of SRH in the near-storm environment. Future work should include a similar analysis for nonsupercell storms exhibiting low-level rotation that failed to produce a tornado, which will elucidate any differences in this separation feature between tornadic and nontornadic nonsupercell storms. Any distinctions between the two could aid in the warning decision process for such storms.

Nonsupercellular tornadic storms are still a significant forecasting challenge. To gain a better understanding of these storm types to aid forecasters, more analysis and cases need to be added to the work already presented in this study. However, these results are encouraging. Future studies should analyze any differences in either microphysical or environmental aspects between storms that displayed this separation signature and those that did not. Another goal of future analysis is to elucidate differences between populations of tornadic and nontornadic storms to provide forecasters additional insights from dual-polarization radar with discriminatory power to aid in the warning process.

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