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Spatial and Temporal Characteristics of Polarimetric Tornadic Debris Signatures

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ABSTRACT

Nonmeteorological scatter, including debris lofted by tornadoes, may be detected using the polarimetric radar variables. For the 17 months from January 2012 to May 2013, radar data were examined for each tornado reported in the domain of an operational polarimetric Weather Surveillance Radar-1988 Doppler (WSR-88D). Characteristics of the tornadic debris signature (TDS) were recorded when a signature was present. Approximately 16% of all tornadoes reported in *Storm Data* were associated with a debris signature, and this proportion is shown to vary regionally. Signatures were more frequently seen with tornadoes that were rated higher on the enhanced Fujita (EF) scale, with tornadoes causing higher reported total property damage, with tornadoes that were closer to the radar and thus intercepted by the beam at lower altitude, and associated with tornadoes with greater total pathlength. Tornadic debris signatures were most common in spring, when more strong tornadoes occur, and in autumn, when natural debris is more available. Debris-signature areal extent is shown to increase consistently with EF-scale rating and tornado longevity. Vertical extent of a TDS is shown to be greatest for strong, long-lived tornadoes with large radii of damaging wind. Land cover is also shown to exhibit some control over TDS characteristics—in particular, a large percentage of tornadoes with substantial track over urban land cover exhibited a TDS and do so very quickly after reported tornadogenesis, as compared with tornadoes over other land-cover classifications. TDS characteristics over grassland and cropland tended to be similar.

1. Introduction

Meteorological and nonmeteorological scatterers have differentiable polarimetric radar signatures. Tornadoes often loft nonmeteorological debris, and, if carried to the altitude of the radar beam, this debris can be inferred by its unique combination of polarimetric characteristics. The polarimetric tornadic debris signature (TDS), as originally identified by Ryzhkov et al. (2002, 2005), was said to require several specific criteria: 1) reflectivity factor $Z_{HH} > 45$ dBZ, 2) copolar cross-correlation coefficient $\rho_{hv} < 0.8$, 3) differential reflectivity $Z_{DR} < 0.5$ dB, 4) collocation with a hook echo, and 5) collocation of a pronounced vortex diagnosed using radial velocity V_r (Ryzhkov et al. 2005). From this combination of characteristics, one can infer nonmeteorological scatter and, when present in a vortex, lofted debris.

The use of hard radar variable thresholds may present challenges. In a sample of seven TDS events, Bunkers and Baxter (2011) found Z_{HH} ranging from 51 to 72 dBZ, although much lower values may be observed. Differential reflectivity Z_{DR} may suffer from data-quality degradation if, for instance, differential attenuation is large (Bluestein et al. 2007; Schultz et al. 2012a); Z_{DR} values in tornadic debris may be significantly greater than 0 dB if precipitation is entrained into the tornadic circulation (Kumjian and Ryzhkov 2008; Bodine et al. 2011) or frequently may be less than zero, possibly because of Mie scatter from debris elements or debris with a common orientation (e.g., Bodine et al. 2014). The ρ_{hv} values may also increase above the typical TDS threshold if meteorological scatterers are entrained into the circulation (Bodine et al. 2011; Schwarz and Burgess 2011). In addition, meteorological scatter may occasionally exhibit ρ_{hv} values that are low enough to be confused with tornadic debris, as noted by Payne et al. (2011) for large hailstones.

Given these challenges, several new sets of criteria for identifying TDSs have been proposed. The Warning Decision Training Branch (WDTB) uses the same ρ_{hv}

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threshold but states that a *local minimum* associated with a strong vortex may be sufficient, even with ρ_{hv} values up to 0.95 (WDTB 2011). The WDTB also uses $Z_{\text{HH}} > 20$ dBZ to ensure a sufficiently high signal-to-noise ratio (SNR). If ρ_{hv} and Z_{HH} criteria are met in the vicinity of a rotational signature, collocated low Z_{DR} values may also be used for extra verification of debris presence. Given the ~ 14 – 20 -s temporal offset between the separate scans that produce the dual-polarization products and the V_r estimate, the rotational signature may be slightly offset, typically slightly downstream, from the polarimetric debris signature (WDTB 2011; Schultz et al. 2012b). A slightly different set of criteria was used by Schultz et al. (2012a). They defined a TDS as a rotational signature collocated with $Z_{\text{HH}} > 30$ dBZ and ρ_{hv} values ≤ 0.7 and used Z_{DR} for extra confidence, as long as differential propagation phase $\phi_{\text{dp}} < 15^\circ$. A percentile approach has also been used with some success (Bodine et al. 2013), eliminating the need for particular thresholds.

TDSs may be observed most commonly with supercell tornadoes, but consistent signatures have also been associated with tornadoes from broken convective lines and from a mesoscale convective vortex (Kumjian and Ryzhkov 2008; Schultz et al. 2012a), as well as with quasi-linear convective system (QLCS) tornadoes (Mahale et al. 2012; Schultz et al. 2012a). They are not considered to be common in association with tornadoes rated lower than 3 on the enhanced Fujita (EF) scale (EF-3) but have been observed with tornadoes down to EF-0 intensity (WDTB 2011; Schultz et al. 2012a). Schultz et al. (2012a) show that a TDS may rarely be observed 120 km from the radar where the signature elevation is approximately 3 km. Other observations indicate that a TDS associated with an EF-1 tornado may be observed out to 74 km, and one associated with an EF-3 or EF-4 tornado may be observed out to 111 km; observations beyond these ranges are said to be unlikely (WDTB 2011). The height at which debris is observed generally increases with stronger tornadoes and has been reported to an altitude of 12.5 km (Lemon et al. 2011; Stelten and Wolf 2014).

Significant limitations of using TDSs operationally have been noted in the literature. For instance, Schultz et al. (2012b) document a case in which no damage was found after a TDS was observed; the signature may be attributable to debris from a prior tornado, or to light lofted debris in a wind field that was not strong enough to produce tree or structural damage. The TDS does not typically precede tornadogenesis (although this was seen in a few cases) and therefore is not generally efficacious at increasing warning lead time (e.g., WDTB 2011). A TDS may, in fact, first be detected after tornado dissipation

(Schultz et al. 2012b) and typically first appears well after reported tornadogenesis. A tornado can occur in a region of relatively few scatterers, leading to low SNR values that complicate ρ_{hv} interpretation (Schultz et al. 2012b). TDSs can also be wider than the associated tornado because of debris centrifuging (e.g., Dowell et al. 2005). Last, a TDS often persists for a significant time after tornado demise, which makes sense given observations of long-range debris transport (e.g., Magsig and Snow 1998). Even with these limitations, the TDS remains a good indicator of lofted debris and is especially useful in the absence of a spotter network (e.g., Blair and Leighton 2014).

Given the recently completed upgrade of the Weather Surveillance Radar-1988 Doppler (WSR-88D) network to polarimetric capability, polarimetric radar data are now available for a much larger sample of tornado events across a much broader geographic area. Given the availability of these data, there is a need to quantify associations between tornado and TDS characteristics. Using a large sample of reported tornadoes ($n = 744$), this study provides preliminary answers to the following questions for the benefit of the operational and research communities:

- 1) How often is a TDS observed for tornadoes of varying intensity rating, total pathlength, and reported damage?
- 2) How does the spatial extent of TDSs vary by intensity rating and reported damage?
- 3) What is the effect of range on TDS occurrence?
- 4) How is TDS vertical extent related to reported tornado characteristics?
- 5) How does TDS occurrence vary by geographic region and by land-cover characteristics?
- 6) During what times of year are TDSs more likely to be visible, and why?

Answers to these questions, derived from a large operational dataset, will give forecasters and researchers quantification of TDS variability in numerous situations and may be helpful for understanding the debris distribution in tornadoes, which affects tornado airflow particularly near the surface (Lewellen et al. 2008).

2. Data and methods

The Storm Events Database from the National Climatic Data Center was used to identify all reported tornadoes from 1 January 2012 through 0400 UTC 1 June 2013. This database has known limitations (e.g., Doswell et al. 2005; Trapp et al. 2006). Weak tornadoes may be missed in the dataset, and there may be a temporal offset between genuine and reported tornado times.

TABLE 1. Land-cover categories in the USGS 200-m resolution land-cover dataset, broad code assigned to each, description of the dominant lofted material for each broad code, and number of events n included under each broad code.

Land-cover classification	Code	Predominant material lofted	n
Water	1	Water	21
Perennial ice and snow	X	—	—
Low-intensity residential	2	Anthropogenic materials	71
High-intensity residential	2	Anthropogenic materials	71
Commercial/industrial/transportation	2	Anthropogenic materials	71
Bare rock/sand/clay	7	Soil or rock	4
Quarries/strip mines/gravel pits	7	Soil or rock	4
Transitional	3	Broad vegetative elements	235
Deciduous forest	3	Broad vegetative elements	235
Evergreen forest	4	Coniferous vegetative elements	33
Mixed forest	3	Broad vegetative elements	235
Shrubland	3	Broad vegetative elements	235
Orchards and vineyards	3	Broad vegetative elements	235
Grasslands/herbaceous	5	Grasses	316
Pasture/hay	5	Grasses	316
Row crops	6	Crops and soil	213
Small grains	6	Crops and soil	213
Fallow	7	Soil or rock	4
Urban/recreational grasses	5	Grasses	316
Woody wetlands	3	Broad vegetative elements	235
Emergent herbaceous wetlands	5	Grasses	316

For instance, in a study of the Storm Prediction Center's database, tornado times were found to be biased late by approximately 8 min, although this bias may be less where the spotter network is more dense, such as in central Oklahoma (D. Burgess 2007, personal communication). Despite its limitations, the Storm Events Database contains the most rigorously verified tornado dataset that is regularly published, and therefore we believe its use is justified. Characteristics of each tornado during the time of interest were recorded, including state, county, and weather forecast office of occurrence, date, beginning and ending times, EF-scale rating, deaths and injuries, property and crop damage, pathlength and width, and beginning and ending latitude and longitude.

The nearest operational WSR-88D was ascertained for all tornadoes by comparing the tornado-track center point with the coordinates of nearby radars. Then, the list of all tornado events was reduced to include only those that occurred within the domain of an operational *polarimetric* radar. This was accomplished by comparing the date of tornado occurrence to a list of upgrade dates, available from the Radar Operations Center (ROC). Level-II radar data, collected at 100 individual WSR-88D sites, were obtained for the resulting 1284 tornado events.

Of interest in the current study is how TDS occurrence may be related to land cover. To assess this aspect, land-cover data mapped in the National Atlas of the United States from the U.S. Geological Survey (USGS) were utilized (USGS 2013). The land-cover data have

200-m resolution and are divided into 21 land-cover categories, which were then grouped into 7 general categories for the purpose of this research on the basis of the dominant expected type of lofted material (Table 1). Each tornado event was assigned to a dominant land-cover classification if at least 50% of the total track length was located over the same broad land-cover category or was assigned to two land-cover classifications if each dominated roughly one-half of the track. Otherwise, that particular tornado event was excluded from the analysis of land-cover effect. One limitation is that the land-cover dataset is derived from 1992 satellite imagery, and therefore a small percentage of land-cover classifications may have changed since then. To reduce the prominence of this effect, we compared the land-cover classification data with recent satellite imagery and recorded the satellite-derived classification when the two approaches differed. For instance, if a tornado track dominated by grassy fields in 1992 had since grown up into young deciduous forest, the land-cover classification would be recorded as deciduous vegetation rather than grass.

Some tornado events were eliminated from the dataset for data-quality or other issues. Weak tornadoes were *not* eliminated, because they are occasionally associated with debris signatures. The following were reasons to eliminate cases:

- 1) radar data were not polarimetric as originally expected,

- 2) no storm was present at the location of the tornado report,
- 3) distance to a polarimetric radar was too great, leading to problems such as a lack of velocity data or very low ρ_{hv} values around the expected vortex location,
- 4) data were at close range to a radar but of low quality (e.g., down radial of a hail core),
- 5) a nearby stronger vortex kept a weaker tornado from being well resolved,
- 6) volume scans were missing during part of the reported tornado time, making the details of the event uncertain,
- 7) temporal resolution of the radar data was not sufficient to assess the tornado (e.g., with a 1- or 2-min tornado event, a volume scan needed to be present during this time or within 1 min of reported tornado dissipation for the event to be retained), or
- 8) the initial tornado reported lacked a latitude and/or longitude so that no vortex location was identifiable.

In the Storm Events Database, a separate event entry is listed for each county/parish affected by a tornado. After eliminating cases from the database as described above, remaining events that represented the same tornado in different counties/parishes were combined. This process included assigning a final ending time, choosing the highest EF-scale rating reported, combining deaths, injuries, and crop/property damage, summing the total pathlength from all counties, and choosing the largest-reported path width. After these modifications, 744 individual tornado events remained to be analyzed.

TDSs were identified using a combination of criteria from the literature. We required collocation with a rotational signature in radial velocity but *not* with a hook echo, since nonsupercell tornadoes were common in our dataset. We did not require a particular Z_{DR} threshold to be met but used values ≤ 0.5 dB as extra verification of the presence of debris, following the original threshold in Ryzhkov et al. (2005) and the application of this variable in Schultz et al. (2012a). A Z_{HH} threshold of 20 dBZ was used, as recommended in the WDTB's (2013) training materials, since numerous events were noted in $Z_{\text{HH}} < 30$ dBZ [the threshold of Schultz et al. (2012a)] with strong rotational signatures. A ρ_{hv} threshold of 0.8 was used, following Ryzhkov et al. (2005). Collocation with a rotational signature and extra confidence from Z_{DR} were used to ensure that we were not looking at very low ρ_{hv} values in large hail. As noted by the WDTB (2013), ρ_{hv} values may be much higher than 0.8 in debris because of precipitation ingestion (Bodine et al. 2011). If a well-defined rotational signature was

present, Z_{DR} was near 0 dB, and Z_{HH} was at least 30 dBZ, we still classified pixels as tornadic debris as long as ρ_{hv} values were < 0.9 and these lowered ρ_{hv} values were at a local minimum relative to those in the surrounding region of high reflectivity in precipitation.

For each tornado event, presence or absence of a TDS was assessed. For all events, including those with no signature, land-cover type was recorded and average distance to the radar was approximated. Average distance was defined as the distance to the average of the beginning and ending points of the total track (e.g., distance to the track midpoint). Also recorded for all tornado events with a debris signature were maximum vertical extent of the debris, time between TDS appearance and reported tornadogenesis, time between TDS disappearance and reported tornado demise, time of the most prominent TDS, maximum Z_{HH} within the debris, typical Z_{DR} values in the debris, and the minimum debris-associated ρ_{hv} value. Maximum areal extent of the TDS was also calculated using the method described in Van Den Broeke (2013) for regions of biological scatter. In this method, the TDS is approximated as a partial annulus, the area of which is calculated given range from the radar and azimuthal angle subtended by the TDS. An estimate of maximum debris altitude assumes the standard $\frac{4}{3}$ Earth-radius model valid for beam centerline (Doviak and Zrnić 1993). The accuracy of this estimate relies on the assumption of a standard-atmosphere vertical temperature profile. Given the radar beam's conical shape, scatter could also come from a lower altitude than beam centerline.

3. Observations of polarimetric tornadic debris signatures

In this section, TDS prevalence, characteristics, and vertical extent are related to tornado characteristics and reported impacts and to range from the radar. Signature differences by geographic region, predominant land cover, and time of year are also examined. Over all reported tornado events, 16.0% ($n = 119$) were associated with a TDS.

a. Debris signatures and tornado intensity, path properties, and reported damage

Characteristics of fields of tornadic debris were examined by Dowell et al. (2005) in a modeling study. They concluded that the concentration of debris in a strong vortex is quickly reduced by centrifuging and that the centrifuging effect is more significant for larger debris elements. Tornadoes with higher EF-scale ratings generally contain stronger winds, provided that the tornado affects something by which its wind speed may

TABLE 2. Average longevity of tornadoes in each EF-scale classification, percentage of tornadoes in each rating classification exhibiting a TDS, and average TDS areal and vertical extents for all events with a signature.

Classification	<i>n</i>	Avg longevity (min)	% with signature	Avg areal extent (km ²)	Avg max vertical extent (km)
EF-0	437	3.2	6.2%	0.93	1.47
EF-1	227	7.1	18.9%	1.83	1.93
EF-2	57	10.2	49.1%	2.42	3.11
EF-3	17	31.1	88.2%	7.67	4.37
EF-4	6	32.2	100.0%	6.83	4.32
EF-5	1	31	100.0%	23.74	6.28+

be estimated. Tornadoes in this dataset with higher EF-scale ratings tended to have greater longevity (Table 2), particularly from EF-0 to EF-3 intensity. Thus, it might be expected that tornadoes with higher EF-scale rating may loft more debris in their stronger wind field and have more opportunity to loft debris to the height of the radar beam during a time when the radar is scanning a volume that is representative of the tornado. As expected, stronger-rated tornadoes were more likely to exhibit a TDS (Table 2). This increase in probability was consistent for all EF-scale classifications. *A majority of EF-3 and stronger tornadoes* exhibited TDSs, and approximately *one-half of EF-2 tornadoes* had a TDS; this signature was *relatively uncommon among EF-0 and EF-1 tornadoes*. Of note is that 27 EF-0 tornadoes had a TDS. These events were associated with well-developed supercell storms ($n = 15$), weak or embedded supercells ($n = 4$), linear convection ($n = 3$), multicell and QLCS modes ($n = 2$ for each), and one possible “landspout” case.

Tornadoes with large pathlength may have a greater opportunity to affect a land-cover type promoting the lofting of debris. Also, greater pathlength was associated with longer time reported on the ground (Pearson’s correlation = 0.911; not shown). This is limited by potential faulty reporting of the times at which a tornado is occurring and by the variable speed of motion exhibited by tornadoes under different synoptic and mesoscale regimes. Nonetheless, tornadoes with greater total pathlength should be more likely to loft debris to the radar beam, as was found (Fig. 1). TDS prevalence *generally increased with total pathlength*, with a cutoff apparent at a pathlength around 4.8 km. Tornadoes reported for at least 4.8 km were more than 2 times as likely to have a TDS as were tornadoes with shorter pathlengths. A reason for this cutoff may be the scan time of the WSR-88D. Tornadoes in this dataset had an average forward speed of 15.1 ms^{-1} (not shown), corresponding to a total time on the ground of approximately 5.3 min for a 4.8-km track. This value is close to the total volume scan update time of approximately 4.5 min for volume coverage pattern (VCP)-12, 5 min for VCP-11, and 5.75 min for VCP-121 (WDTB 2013), which are commonly

used in severe-weather operations. Tornadoes with pathlength $\geq 32.2 \text{ km}$ exhibited a TDS in most cases.

Greater path width is also hypothesized to be associated with increased TDS visibility, because wider tornadoes often have greater longevity and produce a larger, stronger wind field (Brooks 2004). The expected relationship was clearly seen (Fig. 1), with *greater than 25% of tornadoes with maximum path width of at least 182.9 m* exhibiting a TDS. Tornadoes in the uppermost category of maximum path width (at least 914.4 m) had a TDS in most cases.

It is possible that as more anthropogenic debris is lofted, characterized by large irregular elements, TDS visibility should be increased. This is a flawed metric, because a tornado can hit little of monetary value or, in a similar way, a weak tornado may do substantial damage in an urban area. Nevertheless, an increasing trend in TDS occurrence was observed with increasing property damage (Table 3). Of note is that TDS occurrence was *<15% among tornadoes doing \$100,000 reported damage or less* and was *50% or greater among tornadoes doing at least \$1 million in reported damage*.

b. Spatial extent of debris signatures

Maximum areal extent was estimated for each observed TDS to ascertain whether size of the signature could be meaningfully related to other parameters. The lowest elevation angle was used, since it is likely to yield the most important information about lofted debris (Bodine et al. 2013). TDS areal extent generally increased with damage, although total reported damage was *not well correlated* with maximum areal extent of a TDS when it occurred (Table 3). This was attributed to the limitations of damage reporting and importance of other factors such as radar–TDS distance. Pathlength was closely related to TDS occurrence—tornadoes with greater pathlength generally had a larger average TDS areal extent (Fig. 1). In a similar way, tornadoes with greater longevity were more likely to exhibit a TDS of larger areal extent (Fig. 2), with a cutoff observed around 10 min, or approximately the time of two full radar volume scans. Tornadoes reported for longer than

FIG. 1. Relationships for (a) average TDS areal extent (km^2 ; blue shading) and average TDS vertical extent (km; red line) vs tornado pathlength (km) and (b) average TDS vertical extent (km^2 ; blue line) vs maximum path width (m). Total number of events and percentage of events with a TDS are indicated next to the pathlength and width categories (x axis).

10 min had TDS areal extents that were 3 times those reported for less than 10 min, and long-lived tornadoes (>40 min) were associated with the largest TDS areal extent. As expected, EF-scale rating showed a clear relationship with TDS areal extent (Table 2)—areal extent increased consistently with EF-scale rating. This finding is consistent with Schultz et al. (2012a), who found slightly larger TDS diameter with stronger tornadoes.

c. Debris signatures and range from radar

A key limitation to TDS use is that, because debris is only lofted to a particular elevation and the radar beam

curves upward relative to Earth's surface as it travels outward, TDS detection is expected to decrease with distance from a radar. Thus, there is motivation to assess signature visibility with respect to distance from the radar. As expected, TDSs were visible much more often with tornadoes close to the radar (Table 4). Over one-third of reported tornadoes that were less than 25 km from the radar had a TDS; this prevalence was 2.2 times that over the entire dataset (16.0%). Events within 65 km of the radar were detected more often than the average of the entire dataset. Tornadoes between 65 and 125 km from the radar were detected with nearly equal

TABLE 3. Association between reported property damage, TDS occurrence, and average TDS areal and vertical extent for all events with a signature.

Property damage	<i>n</i>	% with signature	Avg areal extent (km ²)	Avg max vertical extent (km)
\$0	361	11.6%	2.84	2.79
\$1–\$10,000	47	4.3%	0.59	1.01
\$10,001–\$100,000	178	12.9%	0.93	2.11
\$100,001–\$500,000	104	22.1%	1.72	2.32
\$500,001–\$1 million	22	40.9%	6.03	2.61
\$1 million–\$10 million	24	50.0%	3.74	3.26
\$10 million–\$2 billion	9	100.0%	9.44	3.69

frequency, and tornadoes beyond 125 km were rarely associated with a TDS (Table 4). Although nowcasters should never use the TDS for warning issuance unless a warning is not already in place, these results suggest limited use of the TDS for increasing nowcaster confidence of an ongoing tornado beyond 65 km from the radar and virtually no use beyond 125 km.

d. Debris signature vertical extent

Schultz et al. (2012a) used the center of the TDS to identify its height. In this study, the farthest down-radial portion of the TDS, corresponding to the maximum height within the signature at a given elevation angle, was used to identify a value that is representative of maximum vertical extent. The discrete nature of elevation angles presents a significant limitation to our estimates, because a TDS was often well defined at one elevation angle and absent in the next highest. Our height estimates also assume TDS elevation at beam centerline, following the $\frac{4}{3}$ Earth-radius model (Doviak and Zrnić 1993). A caveat applicable to the operational

use of maximum TDS elevation is the dependence of this variable on surrounding vertical motion. For instance, a TDS surrounded by a downdraft may not be expected to reach as high (Bodine et al. 2013). In EF-3 and EF-4 tornadoes, Bodine et al. (2013) found maximum TDS elevation after 5–10 min of sustained EF-3/4 damage.

TDS vertical extents >3 km were typically associated with EF-2 or stronger events, and many EF-3 and EF-4 events had TDS vertical extent exceeding 4 km (Table 2). The lone EF-5 event was too close to the radar to ascertain a maximum vertical extent, but a TDS was clearly visible to the maximum observable elevation of 6.28 km. One EF-3 event was associated with maximum TDS vertical extent of 10.14 km, the highest seen in this dataset. The TDS can rarely be seen at much greater altitude—in one documented long-track EF-5 tornado, debris was documented to at least 12.5 km (Lemon et al. 2011; Stelten and Wolf 2014). Of note is that 63% of events with TDS vertical extent of at least 4.5 km were EF-3 or stronger. Reported property damage, while

FIG. 2. Tornado longevity (min) and number of TDSs in each longevity class (*x* axis) vs average TDS areal extent (km²; blue-shaded area) and average TDS vertical extent (km; red line).

TABLE 4. Percentage of reported tornado events with a TDS for several categories of distance between the radar and TDS, and ratio of signature prevalence in each distance category to prevalence over the entire dataset (16.0%).

Distance (km)	<i>n</i>	% with signature	Ratio to all tornadoes
5–24.99	54	35.2%	2.2
25–44.99	104	26.9%	1.68
45–64.99	115	21.7%	1.36
65–84.99	113	15.0%	0.94
85–104.99	126	10.3%	0.64
105–124.99	97	13.4%	0.84
125–149.99	84	4.8%	0.3
150–258	50	2.0%	0.13

generally increasing with maximum TDS vertical extent (Table 3), was not as strongly associated as EF-scale rating.

Maximum TDS vertical extent was a useful indicator of maximum tornado path width (Fig. 1b) but was not as strong of an indicator of total pathlength (Fig. 1a). A consistent increase in TDS maximum elevation was noted with increasing path width once tornadoes were at least 91.4 m wide, and 75% of tornadoes with maximum path width of at least 914.4 m had a TDS extending up to at least 3 km. A stronger association with maximum path width, rather than with pathlength, indicates the importance of a *large* radius of strong wind to loft debris to great altitude. This may be an artifact of the size of radar sample volumes rather than the true absence of debris at high elevation in some events. Maximum TDS vertical extent was also a good indicator of how long a tornado was reported (Fig. 2), with vertical TDS extent ≥ 3 km generally associated with tornadoes lasting for >15 min,

although there were exceptions. Overall, we can conclude that long-lived tornadoes with large radii of strong winds are *most likely to produce a TDS at 3–4-km elevation or higher*. These events are usually associated with high EF-scale ratings, as shown in Table 2.

e. Debris signature variability by geographic region and land cover

TDSs occurred with 16.0% of reported tornado events in our dataset, with the signatures observed in many geographic areas (Fig. 3). Occurrence varied within several defined regions, although a large sample of events was not available from all regions (Fig. 4). If a tornado started in one region and moved to another ($n = 4$), the state in which the tornado had the longest track segment was considered to be the tornado's region of occurrence. California was separated because of its tendency for tornado outbreaks in the Central Valley (e.g., Blier and Batten 1994), and Florida was separated because tornadoes are prevalent there along sea-breeze boundaries and their intersections with outflow boundaries (e.g., Hagemeyer and Schmocker 1991). Although land cover is similar across much of the Great Plains, it was separated into several regions to account for differing time of year and synoptic regimes associated with tornadoes from south to north.

In our dataset, TDSs were uncommon in the Northern Plains (0%), New England (9.1%), the West (10%), and California and the Mid-Atlantic region (11.1%) (TDS occurrence is indicated here as percentages of all reported tornado events in each respective region; Fig. 4). TDSs were most common in the Great Lakes region (18.8%), Florida (18%), and the Southeast (17.8%). To investigate

FIG. 3. Reported tornado events associated with a TDS (red triangles) and for which a TDS was not detected (blue circles).

FIG. 4. The 10 geographic regions defined, the number of tornado events in each region, and the percentage of tornado events in each region with a TDS.

how much regional variability was due to some regions receiving stronger tornadoes and to assess whether any of the regions were outliers with respect to TDS prevalence, percentage of tornadoes with a signature versus percentage of tornadoes rated EF-2 or stronger was plotted for all regions (Fig. 5). A rating threshold of EF-1 was also tested, and the same outlier regions were identified as are discussed below (not shown). Although most regions fell within a narrow regime of increasing TDS prevalence with increasing EF-2+ tornadoes, there were outliers. The Northern Plains was one such region, with no strong tornadoes and no TDSs. This is attributed to the sample period, in which few tornadoes affected

this region. New England had relatively few TDSs given the percentage of strong tornadoes, and Florida had a very high TDS proportion given the low percentage of strong tornadoes (Fig. 5). New England's outlier status may again result from the low number of tornado events during the study period. Adding one more New England event with a signature, for instance, would move this area into the typical regime, and therefore the outlier status of New England is doubtful. Florida, however, *truly appeared to be an outlier region*. Many weak, short-lived tornadoes in the Florida Peninsula were observed to produce large, well-defined TDSs; although only 2% of tornadoes in Florida were EF-2 or stronger, 18% of

FIG. 5. Percentage of tornadoes in a region with a TDS (x axis) vs percentage of tornadoes in a region rated EF-2 or higher (y axis). Regions inside the thick blue line are characterized by increasing percentage of EF-2+ tornadoes associated with increasing TDS prevalence.

FIG. 6. Radar signatures at the 0.5° elevation angle from the Tampa WSR-88D (KTBW) at 1935 UTC 24 Jun 2012: (a) Z_{HH} (dBZ), (b) V_r (m s^{-1}), (c) ρ_{hv} , and (d) Z_{DR} (dB). The upper oval in each panel shows a TDS associated with a reported tornado (beam height ≈ 1.6 km), and the lower oval shows a TDS that is not associated with a tornado report (beam height ≈ 1.8 km).

reported tornadoes in this region were associated with a TDS (Fig. 5). We speculate that this is the case because of the regional vegetation—tornadoes with TDSs were especially prevalent in the central Florida Peninsula and to the north through coastal South and North Carolina (Fig. 3), consistent with the Southern Coastal Plains and southern Middle Atlantic Coastal Plains ecoregions (EPA 2013a). Both ecoregions are dominated by large areas of wetland and forest with very wet soils (EPA 2013b). Although this sample of tornado events is too small to reach conclusions about TDS prevalence in particular ecoregions, the high TDS prevalence in peninsular Florida and north along the coastal plain invites study.

Polarimetric signatures consistent with debris were occasionally observed in the absence of a tornado report. No systematic search was made to estimate the prevalence of such signatures, but several well-defined

examples were noted over the Florida Peninsula. A striking example occurred on 24 June 2012 and was observed by the Tampa, Florida, WSR-88D (KTBW). A small storm with a strong gate-to-gate shear signature in the V_r field (Fig. 6) was associated with a large area of $\rho_{hv} < 0.7$ and a local minimum in Z_{DR} with values from 0.4 to -3.6 dB. No tornado was reported nearby, but one may have gone unreported. Another vortex with an associated tornado report and a well-defined TDS was located approximately 25 km north of the unreported vortex (Fig. 6). Such debris-consistent signatures may help to identify locations of unreported tornadoes after an event. Velocity signatures and ground surveys may be useful to distinguish tornadic winds from nontornadic winds lofting debris. Nonrotational winds in the vicinity of a vortex can still be tornado strength (e.g., Karstens et al. 2013) and could possibly loft scatterers visible as a debris signature.

TABLE 5. Number and *average characteristics* of tornadoes in each broad land-cover classification. Columns include percentage of tornadoes rated EF-2 or higher, reported property damage, total pathlength, maximum path width, reported tornado longevity, percentage of events with a TDS (%sign), maximum vertical extent of TDS, time between reported tornadogenesis and TDS appearance, and maximum areal extent of TDS. Land-cover classifications include deciduous vegetation (Decid) and coniferous vegetation (Conif).

Class	<i>n</i>	EF-2+	Property damage	Length (km)	Width (m)	Longevity (min)	%sign	Max vertical extent (km)	Appearance after (min)	Max areal extent (km ²)
1: Water	21	4.8%	\$39,190	3.64	58.7	4.62	19.0%	3.58	9.25	1.67
2: Urban	71	11.3%	\$32,327,239	3.91	205.5	4.55	25.4%	1.81	2.29	1.12
3: Decid	235	14.0%	\$761,214	6.73	196.5	6.47	17.4%	2.79	4.71	2.95
4: Conif	33	18.2%	\$288,742	6.39	191.2	6.79	21.2%	2.21	5.86	1.17
5: Grass	316	10.8%	\$7,220,228	5.42	155.5	5.98	13.9%	2.75	4.93	4.34
6: Crops	213	11.7%	\$104,594	5.79	155.2	6.44	15.5%	2.95	4.97	2.68
7: Soil	4	0.0%	\$25,000	5.68	69.8	6	0.0%	—	—	—

Dependence of TDS occurrence on broad land-cover classifications was investigated for the entire dataset. Changing land cover has been noted as one possible factor that may affect the maximum elevation to which a TDS is observed (Stelten and Wolf 2014); this is motivated by the lack of knowledge on the differences in TDSs occurring as a result of anthropogenic materials and vegetation (Bodine et al. 2013). Changing land cover may result in changing TDS characteristics, although debris characteristics can also change with tornado morphology (e.g., Davies-Jones et al. 1978). Seven land-cover classifications were defined as described above (Table 1), and cases were identified with the one or two most descriptive categorizations. A few events with roughly equal track length over three or more land cover classifications were excluded from the analysis. Classification 7 (bare soil or rock) was excluded because of the low number of cases ($n = 4$). Because tornadoes could be assigned to two dominant land-cover classifications, some tornado events were considered to be representative of multiple land-cover types. Because strong tornadoes occur in preferred regions and land cover is also regionally dependent, a control was needed to ensure that differences between land-cover classifications were not the result of differing percentages of strong tornadoes. Thus, percentage of EF-2+ tornadoes in each land-cover classification was plotted against the TDS variables of interest (Table 3). A rating threshold of EF-1 was also tested, with virtually identical results (not shown).

Fundamental tornado characteristics such as total pathlength, maximum path width, and longevity did not vary substantially among land-cover classifications (Table 5). This was the expected result, since tornado intensity is controlled more by atmospheric conditions than by land cover. The only exception was higher longevity, with tornadoes occurring partially over water relative to percentage of EF-2+ events, an expected result since the lack of rating over water may cause the percentage of strong tornadoes to be underestimated.

Confidence in our method was increased by the much higher average property damage reported with tornadoes in the urban land-cover classification (Table 5). Average maximum areal extent of TDSs varied considerably but did not appear to vary by land cover (Table 5). Time to appearance of a TDS after reported tornadogenesis averaged around 5 min, with tornadoes in most land-cover classifications being similar. One exception occurred if a tornado was over water for a significant portion of its track—in these events, a TDS showed up much later than the dataset mean (Table 5), consistent with little debris being ingested. Liquid drops would have higher ρ_{hv} values and would not appear as debris. The other exception was the urban classification, over which tornadoes exhibit TDSs much more quickly than the dataset average (Table 5). This also makes sense because of higher availability of anthropogenic debris, which greatly decreases ρ_{hv} values.

The percentage of reported tornado events with a TDS varied by land cover, but this appeared to be a function of percentage of tornado events rated EF-2 or higher (Fig. 7a). Although tornadoes over coniferous forest were often associated with TDSs, they were also often associated with strong tornadoes. *The only outlier was the urban classification*, in which tornadoes were often associated with a TDS (25.4% of events) despite a percentage of EF-2+ tornadoes that was equal to the dataset total (11.3%). Maximum vertical TDS extent appeared to *decrease* with higher percentages of strong tornadoes (Fig. 7b). Tornadoes over urban land cover *did not, on average, contain a TDS to as high of an altitude* as for other land-cover classifications. It is possible that anthropogenic debris elements are larger—if true, they should stay at lower elevation within the tornado vortex (Dowell et al. 2005). Relatively shallow urban debris columns have been documented in prior work (Stelten and Wolf 2014). Average Z_{HH} values were *not* higher for urban tornadoes; this may be a function of distance to a radar, however.

FIG. 7. For each land-cover class, the percentage of tornadoes rated EF-2 or higher vs (a) percentage of tornadoes with a TDS and (b) average maximum TDS vertical extent. Land-cover classifications include deciduous vegetation (Decid) and coniferous vegetation (Conif).

f. Debris signature variability by time of year

The database of events was sorted by season. Tornadoes beginning in one season and ending in the next were counted with the earlier season [e.g., a tornado that occurred partially on 31 May and partially on 1 June, which occurred several times, was counted with May (spring), not June (summer)].

TDS occurrence strongly preferred spring and autumn, with a peak centered on March and a second, larger peak centered on October (Fig. 8a). Percentage of tornadoes rated EF-2 and stronger, in our dataset, showed a strong preference for early spring (Fig. 8a). March was the month of highest occurrence of EF-2+ tornadoes by percentage (28.3% of events), with smallest percentage of strong tornadoes in the summer and autumn months. Approximately 21% of March tornadoes ($n = 46$) and 30% of October tornadoes ($n = 23$) exhibited a TDS. A large percentage of strong March tornadoes likely accounts for that peak, because higher-rated tornadoes were shown to be more frequently associated with a TDS (Table 2). Of note, the autumn peak does not occur when many EF-2+ tornadoes were recorded. We speculate that the autumn peak may be due to the prevalence of natural debris, such as dry and loose leaves. A tornado would more readily loft such light debris to the elevation of the radar beam. It is possible that weaker tornadoes, which would not typically produce a TDS, may have this signature in the autumn because abundant light natural debris is readily lofted. When a rating threshold of EF-1 was tested, results were not as strong but still indicated a peak in percentage of strong tornadoes in March (Fig. 8b). A maximum in percentage of EF-1+ tornadoes was also evident in October, but it

was not sufficient to explain the large maximum in percentage of tornadoes with a TDS in that month in comparison with many winter and spring months, which had higher percentages of EF-1+ tornadoes (Fig. 8b).

TDSs were also observed to appear quickly after the reported time of tornadogenesis during September–November (Table 6). A TDS was first observed, on average, *only 2 min after reported tornadogenesis during autumn*. During all other seasons, a TDS took more than 2 times as long to appear; it took an average of more than 6.5 min to appear during winter (December–February). This is consistent with an abundant natural supply of readily transportable debris during autumn and possibly with a lack of growing vegetation and a damp surface in winter. The relatively small autumn sample size may also contribute to this result. Maximum vertical extent of the average TDS was *highest in winter* (December–February; Table 6), although values were comparably high in spring when the largest percentage of strong tornadoes occurred.

4. Primary conclusions and future work

Many tornado characteristics influence the manifestation of an associated TDS. TDS prevalence was most common in strong tornadoes—in particular, in those rated EF-3 or higher, for which a majority of reported tornadoes contained a TDS. Although less common, even weak tornadoes were occasionally associated with a TDS. Thus, appearance of a TDS should not be taken as evidence that a strong tornado is ongoing. This was especially true in Florida, where weak tornadoes were often associated with well-defined TDSs. Tornadoes

FIG. 8. Percentage of tornadoes rated (a) EF-2+ and (b) EF-1+ by month (blue bars), and percentage of tornadoes with a TDS (red line).

with a TDS are more likely to have pathlength > 4.8 km and greater maximum path width, but there were exceptions. A TDS was more common among tornadoes doing significant reported damage. This result may have been because these events were strongly associated with urban land cover, over which many events exhibited a TDS. It was notable, though, that numerous tornadoes with no reported damage also exhibited a TDS, and the signature can be pronounced even if a tornado tracks over primarily forest, grassland, or cropland areas. Sometimes a TDS occurs without any tornado report; these events should be investigated further.

The areal and vertical extent of a TDS may contain information that is useful to nowcasters. These variables are related to total reported damage but are related

more strongly to EF-scale rating and total pathlength. In particular, tornadoes lasting for > 10 min showed significantly larger TDS areal extent when a TDS occurred, likely related to the persistence of the wind field and associated debris plume. Vertical TDS extent typically increased with final EF-scale rating and path width, in agreement with prior studies (e.g., Bodine et al. 2013). If a TDS is observed to high elevation, however, it should not be concluded that a large, strong tornado is in progress, because a few smaller, relatively weak tornadoes also had a TDS to 5 km or higher.

Nowcasters would benefit by knowing to what range a TDS may typically be observed. Tornadoes within 25 km of the radar site often exhibited a TDS ($\sim 35\%$ of reported events), and tornadoes within 65 km exhibited a TDS more often than the average of the full dataset. A TDS was rarely observed beyond 125 km, and the signature has little utility at such large range. Given these results, we suggest using the TDS to raise confidence of an ongoing tornado primarily within 65 km of the radar, although a TDS beyond 65 km and especially beyond 100 km may indicate a significant ongoing event [in general agreement with, e.g., WDTB (2011) and Schultz et al. (2012a)].

Reported tornadoes were scarce in some regions, limiting what could be said about geographic TDS occurrence. Over the entire dataset, 16% of reported tornadoes were associated with a TDS, and this value was exceeded by $\sim 2\%$ – 3% in the Great Lakes region, Florida, and the Southeast. Florida and the coastal plain to the north, dominated by wetland and wet forest, were unique in having a high TDS prevalence but few strong tornadoes. TDSs were most common as a percentage of all tornado events in spring and autumn, corresponding to many strong tornadoes in spring and to an abundance of readily loftable natural debris in autumn. The autumn peak also corresponded to TDSs appearing very quickly after reported tornadogenesis.

Land cover exhibited some control over TDS characteristics. In particular, tornadoes with significant track proportion over urban land cover were more likely to have a TDS, which appeared more quickly than over other land-cover types. Urban TDS vertical extent was lower, however, possibly because of the presence of

TABLE 6. Seasonal breakdown of average first TDS appearance after time of reported tornadogenesis and maximum TDS vertical extent.

Time of year	<i>n</i>	Avg TDS appearance after genesis (min)	Max vertical extent (km)
December–February	139	7	2.82
March–May	452	4.6	2.75
June–August	107	4.8	1.82
September–November	47	2	2.02

larger debris elements. These results suggest that nowcasters should be aware of land cover in their area of responsibility and should consider how land cover may affect anticipated and observed TDS characteristics.

Future investigations could be undertaken using a larger dataset of tornado events, particularly in underrepresented regions and over less well-represented land-cover types, to allow more to be definitively said about TDSs in those areas. Land-cover associations with TDS characteristics could still be better understood, especially how storm types that are predominant in different regions may affect perceived land-cover associations. Values of the polarimetric variables within TDSs, and how they change relative to TDS and tornado life cycles, would be useful to investigate. Temporal characteristics of TDSs relative to tornado life cycles would be valuable to operational meteorologists. Relationships between tornado warnings, unwarned tornadoes, and TDSs also should be examined.

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REFERENCES

- Blair, S. F., and J. W. Leighton, 2014: Assessing real-time tornado information disseminated through NWS products. *Wea. Forecasting*, **29**, 591–600, doi:[10.1175/WAF-D-13-00126.1](https://doi.org/10.1175/WAF-D-13-00126.1).
- Blier, W., and K. A. Batten, 1994: On the incidence of tornadoes in California. *Wea. Forecasting*, **9**, 301–315, doi:[10.1175/1520-0434\(1994\)009<0301:OTIOTI>2.0.CO;2](https://doi.org/10.1175/1520-0434(1994)009<0301:OTIOTI>2.0.CO;2).
- Bluestein, H. B., M. M. French, R. L. Tanamachi, S. Frasier, K. Hardwick, F. Junyent, and A. L. Pazmany, 2007: Close-range observations of tornadoes in supercells made with a dual-polarization, X-band, mobile Doppler radar. *Mon. Wea. Rev.*, **135**, 1522–1543, doi:[10.1175/MWR3349.1](https://doi.org/10.1175/MWR3349.1).
- Bodine, D., M. R. Kumjian, A. J. Smith, R. D. Palmer, A. V. Ryzhkov, and P. L. Heinselman, 2011: High-resolution polarimetric observations of an EF-4 tornado on 10 May 2010 from OU-PRIME. *35th Conf. on Radar Meteorology*, Pittsburgh, PA, Amer. Meteor. Soc., 4B.3. [Available online at https://ams.confex.com/ams/35Radar/webprogram/Manuscript/Paper191661/tds_paper_amsradar.pdf.]
- , —, R. D. Palmer, P. L. Heinselman, and A. V. Ryzhkov, 2013: Tornado damage estimation using polarimetric radar. *Wea. Forecasting*, **28**, 139–158, doi:[10.1175/WAF-D-11-00158.1](https://doi.org/10.1175/WAF-D-11-00158.1).
- Bodine, D. J., R. D. Palmer, and G. Zhang, 2014: Dual-wavelength polarimetric radar analyses of tornadic debris signatures. *J. Appl. Meteor. Climatol.*, **53**, 242–261, doi:[10.1175/JAMC-D-13-0189.1](https://doi.org/10.1175/JAMC-D-13-0189.1).
- Brooks, H. E., 2004: On the relationship of tornado path length and width to intensity. *Wea. Forecasting*, **19**, 310–319, doi:[10.1175/1520-0434\(2004\)019<0310:OTROTP>2.0.CO;2](https://doi.org/10.1175/1520-0434(2004)019<0310:OTROTP>2.0.CO;2).
- Bunkers, M. J., and M. A. Baxter, 2011: Radar tornadic debris signatures on 27 April 2011. *Electron. J. Oper. Meteor.*, **12** (7), 1–6. [Available online at <http://www.nwas.org/ej/pdf/2011-ION1.pdf>.]
- Davies-Jones, R. P., D. W. Burgess, L. R. Lemon, and D. Purcell, 1978: Interpretation of surface marks and debris patterns from the 24 May 1973 Union City, Oklahoma tornado. *Mon. Wea. Rev.*, **106**, 12–21, doi:[10.1175/1520-0493\(1978\)106<0012:IOSMAD>2.0.CO;2](https://doi.org/10.1175/1520-0493(1978)106<0012:IOSMAD>2.0.CO;2).
- Doswell, C. A., H. E. Brooks, and M. P. Kay, 2005: Climatological estimates of daily local nontornadic severe thunderstorm probability for the United States. *Wea. Forecasting*, **20**, 577–595, doi:[10.1175/WAF866.1](https://doi.org/10.1175/WAF866.1).
- Doviak, R. J., and D. S. Zrnić, 1993: *Doppler Radar and Weather Observations*. Academic Press, 562 pp.
- Dowell, D. C., C. R. Alexander, J. M. Wurman, and L. J. Wicker, 2005: Centrifuging of hydrometeors and debris in tornadoes: Radar-reflectivity patterns and wind-measurement errors. *Mon. Wea. Rev.*, **133**, 1501–1524, doi:[10.1175/MWR2934.1](https://doi.org/10.1175/MWR2934.1).
- EPA, cited 2013a: Level III ecoregions of the continental United States. U.S. Environmental Protection Agency National Health and Environmental Effects Research Laboratory. [Available online at ftp://ftp.epa.gov/wed/ecoregions/us/Eco_Level_III_US.pdf.]
- , cited 2013b: Level III and IV ecoregions of the continental United States. U.S. Environmental Protection Agency Western Ecology Division. [Available online at http://www.epa.gov/wed/pages/ecoregions/level_iii_iv.htm.]
- Hagemeyer, B. C., and G. K. Schmocker, 1991: Characteristics of east-central Florida tornado environments. *Wea. Forecasting*, **6**, 499–514, doi:[10.1175/1520-0434\(1991\)006<0499:COECFT>2.0.CO;2](https://doi.org/10.1175/1520-0434(1991)006<0499:COECFT>2.0.CO;2).
- Karstens, C. D., W. A. Gallus, B. D. Lee, and C. A. Finley, 2013: Analysis of tornado-induced tree fall using aerial photography from the Joplin, Missouri, and Tuscaloosa–Birmingham, Alabama, tornadoes of 2011. *J. Appl. Meteor. Climatol.*, **52**, 1049–1068, doi:[10.1175/JAMC-D-12-0206.1](https://doi.org/10.1175/JAMC-D-12-0206.1).
- Kumjian, M. R., and A. V. Ryzhkov, 2008: Polarimetric signatures in supercell thunderstorms. *J. Appl. Meteor. Climatol.*, **47**, 1940–1961, doi:[10.1175/2007JAMC1874.1](https://doi.org/10.1175/2007JAMC1874.1).
- Lemon, L. R., C. A. Van Den Broeke, C. Payne, and P. T. Schlatter, 2011: Dual-polarimetric Doppler radar debris signature characteristics of a long-track EF-5 tornado. *National Weather Association 36th Annual Meeting*, Birmingham, AL, National Weather Association, 1227. [Available online at <http://www.nwas.org/meetings/nwa2011/presentations/NWA2011-9.3.zip>.]
- Lewellen, D. C., B. Gong, and W. S. Lewellen, 2008: Effects of finescale debris on near-surface tornado dynamics. *J. Atmos. Sci.*, **65**, 3247–3262, doi:[10.1175/2008JAS2686.1](https://doi.org/10.1175/2008JAS2686.1).
- Magsig, M. A., and J. T. Snow, 1998: Long-distance debris transport by tornadic thunderstorms. Part I: The 7 May 1995 supercell thunderstorm. *Mon. Wea. Rev.*, **126**, 1430–1449, doi:[10.1175/1520-0493\(1998\)126<1430:LDDTBT>2.0.CO;2](https://doi.org/10.1175/1520-0493(1998)126<1430:LDDTBT>2.0.CO;2).
- Mahale, V. N., J. A. Brotzge, and H. B. Bluestein, 2012: An analysis of vortices embedded within a quasi-linear convective system using X-band polarimetric radar. *Wea. Forecasting*, **27**, 1520–1537, doi:[10.1175/WAF-D-11-00135.1](https://doi.org/10.1175/WAF-D-11-00135.1).
- Payne, C., L. R. Lemon, C. A. Van Den Broeke, and P. T. Schlatter, 2011: Identifying significant severe-size hail with S-band dual-polarization radar. *National Weather Association 36th Annual Meeting*, Birmingham, AL, National Weather Association, 1216. [Available online at <http://www.nwas.org/meetings/nwa2011/presentations/NWA2011-9.1.zip>.]

- Ryzhkov, A., D. Burgess, D. Zrnic, T. Smith, and S. Giangrande, 2002: Polarimetric analysis of a 3 May 1999 tornado. Preprints, *21st Conf. on Severe Local Storms*, San Antonio, TX, Amer. Meteor. Soc., 639–642. [Available online at <https://ams.confex.com/ams/pdfpapers/47348.pdf>.]
- , T. J. Schuur, D. W. Burgess, and D. S. Zrnić, 2005: Polarimetric tornado detection. *J. Appl. Meteor.*, **44**, 557–570, doi:10.1175/JAM2235.1.
- Schultz, C. J., and Coauthors, 2012a: Dual-polarization tornadic debris signatures part I: Examples and utility in an operational setting. *Electron. J. Oper. Meteor.*, **13**, 120–137. [Available online at <http://www.nwas.org/ej/pdf/2012-EJ9.pdf>.]
- , and Coauthors, 2012b: Dual-polarization tornadic debris signatures part II: Comparisons and caveats. *Electron. J. Oper. Meteor.*, **13**, 138–150. [Available online at <http://www.nwas.org/ej/pdf/2012-EJ10.pdf>.]
- Schwarz, C. M., and D. W. Burgess, 2011: Supercell polarimetric signatures at X-band: Data from VORTEX2. *35th Conf. on Radar Meteorology*, Pittsburgh, PA, Amer. Meteor. Soc., 7B.4. [Available online at https://ams.confex.com/ams/35Radar/webprogram/Manuscript/Paper191298/CS_AMS_Radar_Conf_Paper.pdf.]
- Stelten, S., and R. Wolf, 2014: Investigating the effect of land cover on the correlation between TDS heights and tornado strength and other TDS characteristics. Abstract, *18th Annual Severe Storms and Doppler Radar Conf.*, Ankeny, IA, National Weather Association Central Iowa Chapter. [Available online at http://www.iowa-nwa.com/conference/files/2014_Agenda_Lite.pdf.]
- Trapp, R. J., D. M. Wheatley, N. T. Atkins, R. W. Przybylinski, and R. Wolf, 2006: Buyer beware: Some words of caution on the use of severe wind reports in postevent assessment and research. *Wea. Forecasting*, **21**, 408–415, doi:10.1175/WAF925.1.
- USGS, cited 2013: Map layer info: Conterminous United States land cover 1992–200 meter resolution. U.S. Geological Survey National Center for Earth Resources Observation and Science. [Available online at <http://nationalatlas.gov/mld/lancovi.html>.]
- Van Den Broeke, M. S., 2013: Polarimetric radar observations of biological scatterers in Hurricanes Irene (2011) and Sandy (2012). *J. Atmos. Oceanic Technol.*, **30**, 2754–2767, doi:10.1175/JTECH-D-13-00056.1.
- WDTB, cited 2011: Dual-polarization radar training. National Weather Service Warning Decision Training Branch. [Available online at <http://www.wdtb.noaa.gov/courses/dualpol/index.html>.]
- , cited 2013: Distance learning operations course—Principles of meteorological Doppler radar: WSR-88D fundamentals. National Weather Service Warning Decision Training Branch. [Available online at <http://www.wdtb.noaa.gov/courses/dloc/topic3/lesson1/index.html>.]