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POLARIMETRIC TORNADO DEBRIS SIGNATURE SPATIAL AND TEMPORAL CHARACTERISTICS

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ABSTRACT

Debris lofted by tornadoes may be detected in polarimetric radar data, now available nation-wide. For the seventeen months from January 2012 – May 2013, data was examined for each tornado which occurred in the domain of an operational polarimetric WSR-88D. Presence or absence of a debris signature was recorded, as well as characteristics of the signature when present. Approximately 20% of all Storm Data tornado reports were associated with a debris signature, though this proportion varied widely by region. Signatures were more frequently seen with tornadoes rated higher on the Enhanced Fujita (EF) scale, associated with higher reported total property damage, when intercepted by the radar beam at lower elevation, and in tornadoes with longer single-county path length. Percent of tornadoes with a debris signature showed two peaks in occurrence. The first, in spring, was associated with a higher proportion of strong tornadoes, and the other, in fall, may be associated with higher natural debris availability. Areal extent of the debris signature generally increases with total reported property damage and, to a lesser extent, with EF-scale rating. This and future related work will provide operational meteorologists with a preliminary quantified look at typical characteristics of the polarimetric debris signature associated with tornadoes of varying characteristics.

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1. Introduction

Polarimetric weather radar can be used to distinguish meteorological from non-meteorological scatterers. Tornadoes often loft non-meteorological material, and if this debris reaches the elevation of the radar beam, it can be detected using its unique polarimetric signatures. The polarimetric tornado debris signature (TDS) published in a prior study (Ryzhkov et al. 2005) consists of several criteria being met:

1) Correlation coefficient (ρ_{hv}) values < 0.8;
2) Differential reflectivity (Z_{DR}) values < 0.5 dB;
3) Reflectivity factor (Z_{hh}) > 45 dBZ;
4) Collocation with a hook echo; and
5) Collocation with a pronounced vortex diagnosed using radial velocity (V_r).

Debris signatures have been observed in different types of tornado events, including supercell tornadoes, tornadoes from linear convective systems, and isolated convective cells (Schultz et al. 2012a). Cautions have also been presented about use of this signature in operational settings (Schultz et al. 2012b). No studies to our knowledge have systematically examined a large dataset of tornado events with large geographic and temporal variability to determine how the frequency of appearance of this signature relates to tornado or other characteristics. It is the goal of this study to provide an initial quantification of some associations between the TDS and tornado characteristics. Specifically, we will quantify:

1) Frequency of TDS occurrence as a function of geographic region, tornado intensity rating, total reported property damage, and altitude of the radar beam;
2) Seasonal variation in frequency of TDS occurrence; and
3) Signature areal extent associations with property damage and radar beam altitude.

2. Methods and Data

The Storm Events Database from the National Climatic Data Center (NCDC) was used to identify all tornado reports from the beginning of January 2012 through the end of May 2013. The database of events was further restricted to those occurring in the domain of an operational polarimetric Weather Surveillance Radar-1988 Doppler (WSR-88D) radar. Level II radar data was obtained for this set of cases (n = 1284) from the NCDC archive for the nearest polarimetric WSR-88D radar. For this database of events, information was recorded for each case starting with whether or not a debris signature was present for any portion of the reported life of the tornado. Analysis started a minimum of one sample volume prior to the reported tornadogenesis time, and ended at least one sample volume after the reported tornado demise time. For cases in which a signature was visible, prior and later scans were examined until a signature was no longer visible. For the work reported here, only data at the 0.5-degree elevation angle was examined.

For each tornado event in the database, a number of variables were recorded from the NCDC database, including tornado beginning and ending time, beginning and ending location (latitude/longitude), EF-scale rating, maximum width, path length (which is reported on a county-by-county basis in Storm Data), associated deaths and injuries, and reported property/crop damage.

Radar data were visualized using the Integrated Data Viewer (IDV), NCDC's Weather and Climate Toolkit, and in some cases, GR2Analyst. Some tornado events were eliminated from the dataset due to several possible reasons:

1) A polarimetric radar was not available as originally thought;
2) Distance was too great between the tornado and the nearest polarimetric radar;
3) Data quality was poor;
4) The tornado was occurring too close to a stronger vortex to be resolved;
5) There was no storm at the location of the tornado report;
6) Sufficient data was missing during the reported tornado time so that details of the event were uncertain;
7) Temporal resolution of radar scans was not sufficient to assess the tornado; or
8) No latitude/longitude was given in the tornado report, so a vortex location was not identifiable.

For each remaining tornado event (n = 821) associated with a debris signature, several pieces of information were recorded including mode of the associated convection, distance to the radar, elevation of the radar beam assuming a 4/3 Earth-radius model, the time of signature appearance and disappearance, time of maximum signature areal extent, and several characteristics of the associated polarimetric fields. Maximum areal extent of each signature was estimated by conforming it to a partial annulus and calculating the associated area. Once characteristics were recorded from all events, cases were stratified in various ways and statistics were calculated using Excel.

3. Results

a. Geographic TDS distribution

TDS were observed in many geographic locations, including most regions where tornadoes were reported (Fig. 1). Nationally, 19.4% of reported tornadoes were associated with a TDS (159 of 821 cases).

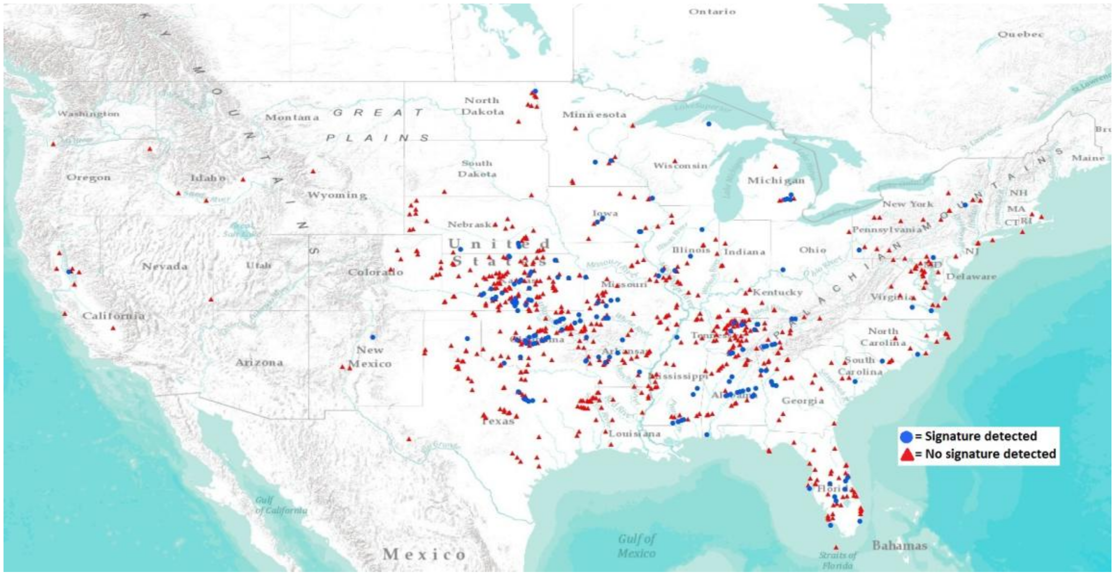

Figure 1: Tornado events with a TDS detected (blue circles) and without a detected TDS (red triangles).

Geographic variability of signature detection rate was high. Regions were chosen to roughly reflect types of tornado events in each region. For instance, California was separated because of its relatively unique tornado outbreaks in the Central Valley, and Florida was separated because of the prevalence of convection along sea breeze boundaries. TDS were detected relatively rarely in western and northern regions, including California, the West, the Northern Plains, and New England (Fig. 2). Detections occurred in a relatively high proportion of cases in the Southern and Central Plains, and in the Southeast. Detections may be higher in those regions partially because of the greater prevalence of strong (EF-2+) tornadoes, and partially because of a landcover condition more favorable for lofting of debris. These possibilities will be examined in future research.

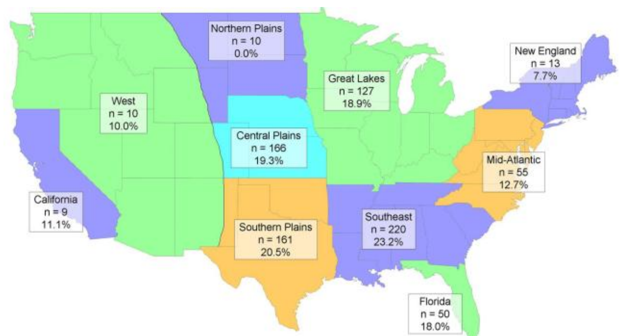

Figure 2: Number of tornado events in the database, and proportion of TDS detections, by region.

b. Seasonal dependence of the TDS distribution

The proportion of tornado events with a TDS varied remarkably through the year. All cases retained in the analysis were stratified by month. In cases when a tornado began in one month and ended in the next month, it was counted in the earlier month (e.g. a May-June tornado would be grouped with May tornadoes). Statistics were computed indicating the percentage of tornado reports in each month associated with a TDS, and percentage of tornadoes in each month meeting or exceeding an EF-2 intensity rating (Fig. 3).

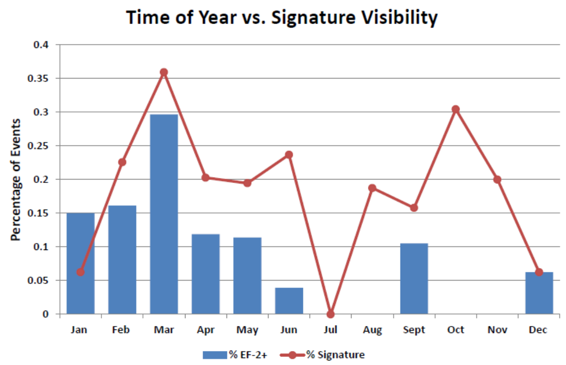

Figure 3: Percentage of tornadoes with a debris signature in each month (red line), and percentage of tornado events rated EF-2+ (blue bars). Spring maximum likely corresponds to more strong tornadoes; fall maximum may correspond to greater natural debris availability.

Two marked maxima in TDS detection frequency were noted. The first was in spring, with a sharp March peak when >35% of tornado events were associated with a TDS. This maximum corresponds to a significant maximum in the number of strong (EF-2+) tornadoes, which was nearly 30% of reported tornado events in March. Thus, the heightened detection level of springtime tornadoes is likely because tornadoes are typically stronger during that time of year. The second peak in TDS detection frequency was in the fall, and a maximum in October, when ~30% of reported tornado events were associated with a TDS. This peak was present despite the relative lack of strong autumn tornadoes. A hypothesis for this second peak is that a greater availability of natural debris (leaves, etc.) means that a tornado is more likely to loft debris that will create a radar signature, especially in open areas with little anthropogenic debris availability. An investigation of how detection varies regionally by time of year, planned for future research, will shed light on the validity of this hypothesis.

Time of TDS appearance from reported tornadogenesis was also examined by time of year. This time could be negative (e.g. a TDS could appear prior to the reported tornadogenesis time). Tornado events with a TDS were divided into winter (December-February), spring (March-May), summer (June-August), and fall (September-November). Large seasonal differences were seen (Tab. 1).

Season	n	Avg. Appearance After First Report (min)
Dec – Feb	13	6.3
Mar – May	77	**4.2**
Jun – Aug	18	5.2
Sept - Nov	11	2.0

Table 1: Time (min) to debris signature first appearance after reported tornadogenesis.

TDS were detected relatively late after reported tornadogenesis in winter and summer. Spring TDS appeared relatively quickly (average value was 4.2 min post-tornadogenesis), possibly reflecting the typically-stronger tornadoes during that time of year. A stronger tornado, all else equal, should loft debris to higher elevation more quickly. Autumn signatures were associated with the shortest time between reported tornadogenesis and appearance of a TDS (Tab. 1), with an average value of only 2.0 min. This may reflect the relative ease of lofting the type of debris available during that time of year (e.g. dry leaves). Also, a weaker vortex would be able to loft light debris to higher elevations.

c. Frequency of TDS appearance compared with tornado and radar characteristics

Stronger tornadoes would be expected to loft more debris, and to loft debris to higher elevations, and thus we would expect that a TDS should be visible more often with stronger tornadoes. This was the case (Tab. 2).

Classification	n	Percent with Signature
EF-0	460	7.8%
EF-1	263	24.3%
EF-2	67	**56.7%**
EF-3	24	83.3%
EF-4	6	100%
EF-5	1	100%

Table 2: Percentage of tornadoes in each EF-scale classification with a TDS.

The percentage of tornadoes exhibiting a TDS increased consistently with EF-scale rating. Though EF-4 and EF-5 tornadoes were very few in our dataset, all these events were associated with a TDS. A very large percentage of EF-3 tornadoes, of which a large number were available, had a TDS. Prior literature has indicated that a TDS may not be seen often if a tornado is rated below an EF-3 (e.g. Ryzhkov et al. 2005), but prior work has demonstrated that signatures may be seen with weaker tornadoes (Schultz et al. 2012a). Surprisingly, more than half of reported EF-2 tornadoes exhibited a TDS (Tab. 2). Percentage of weaker tornadoes with a signature dropped quickly, with only a quarter of EF-1 tornadoes and less than 10% of EF-0 tornadoes associated with a TDS. Nevertheless, it is a significant finding that such a high percentage of EF-1 and EF-2 tornadoes are associated with TDS in polarimetric radar data.

Another metric of tornado significance is reported damage. This is a flawed metric, since a strong tornado can hit little of importance and a weak tornado might do significant damage in an urban area. But, we investigated whether there was a relationship between reported property damage and percentage of cases with a TDS, since higher values of reported property damage likely indicate larger quantities of debris being lofted. Tornado events were stratified by amount of reported damage into seven categories of damage ranging from $0 to $10 million-$2 billion (Tab. 3).

Property Damage	n	Percent with Signature
$0	393	16.3%
$1 – 10,000	83	12.0%
$10,001 – 100,000	205	12.7%
$100,001 – 500,000	92	39.1%
$500,001 - $1M	17	64.7%
$1M - $10M	20	55.0%
$10M - $2B	11	81.8%

Table 3: Percentage of tornado events in varying categories of reported property damage which displayed a TDS.

A general increase in TDS prevalence was seen with increasing reported damage. In particular, less than 20% of events with a reported damage amount of $100,000 or less had a TDS. Reported damage in the range of $100,000-$500,000 was associated with a noticeably higher proportion of cases with a TDS, but tornado events with >$500,000 damage reported were associated a majority of the time with a TDS. Notably, tornado events placed into the highest damage category were not always associated with a TDS (9 of 11 cases; Tab. 3).

Reported path length of a tornado was hypothesized to be related to the likelihood of seeing a debris signature, since tornadoes with a longer path length would have longer to loft debris, and thus debris should be more likely to reach the radar beam. Storm Data reports single-county path length only (e.g. a tornado that tracked across two counties would have separate path lengths associated with each county). For the purpose of the research reported here, only this single-county path length was used. In future research, the total path length of each tornado will be accounted for. Few tornadoes, however, were observed to have path segments in multiple counties.

Likelihood of a tornado event displaying a TDS increased sharply with single-county path length (Fig. 4).

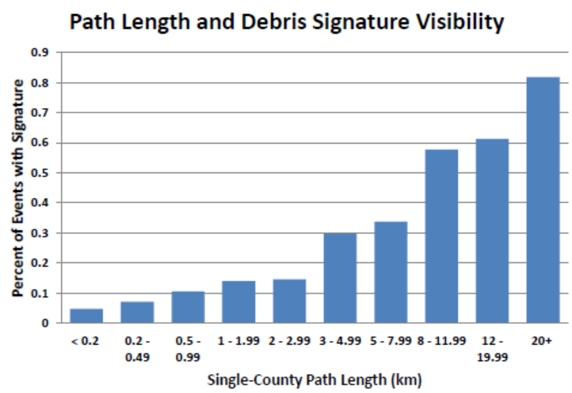

Figure 4: Percentage of tornadoes in multiple categories of single-county path length with a TDS.

As expected, tornadoes not on the ground very long (< 1 mile) were not associated with a TDS very often (~10% of cases or less). A sharp jump was observed as tornadoes crossed over the 3-mi path length threshold, and another sharp jump was evident as single-county path length exceeded 8 mi. A majority of events with single-county path length exceeding 8 mi were associated with a TDS. In future research, we also plan to investigate the association between path length and EF-scale rating.

Altitude of the radar beam should be a significant factor determining if a TDS will be seen from a given tornado. If the radar beam intersects the tornado vortex at high elevation, it is possible that debris has not been lofted that high, even if debris would be visible at lower elevation.

In future analysis, we plan to utilize distance from the radar instead of beam elevation, for a few reasons:

1) Distance from the radar also accounts for the effects of beam spreading (horizontal and vertical) with distance; and
2) In an operational setting, distance from the radar is a more intuitive variable than elevation of the radar beam.

These two fields are closely related. While recording data about each case, both distance to the sample volume of interest (the approximate center of the tornado vortex) and its elevation were recorded. Fig. 5 shows a scatterplot of these two variables for all tornado events, and indicates a nearly-linear relationship. This indicates that the use of elevation instead of distance will not introduce substantial error other than the beam spreading effect (which will lower correlation values).

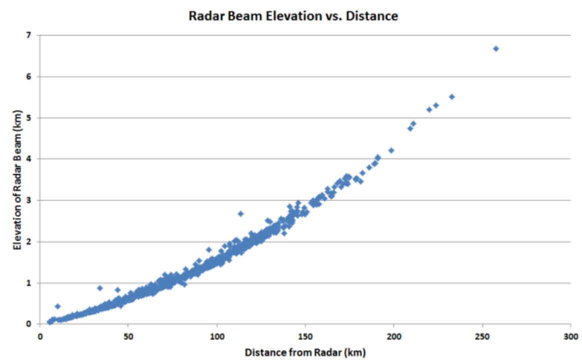

Figure 5: Radar beam elevation vs. distance, showing a nearly-linear relationship.

Several well-defined bins of signature appearance frequency were observed (Tab. 4).

Altitude of 0.5° Beam (km)	n	Percent with Signature
0.05 – 0.199	32	25.0%
0.2 – 0.399	84	27.4%
0.4 – 0.749	132	26.5%
0.75 – 0.99	89	12.4%
1 – 1.49	157	12.1%
1.5 – 1.99	112	11.6%
2 – 2.99	131	8.4%
3 – 3.99	34	2.9%
4+	9	0.0%

Table 4: Percentage of tornadoes with a TDS intersected at several altitude bins by the 0.5-degree beam.

If the radar beam intersected the tornado below 0.75 km, a signature was much more likely to be visible (>25% of all such cases). Tornadoes intersected at altitude between 0.75 and 2 km were less than half as likely to exhibit a TDS (average value of ~12% for all such cases), and tornadoes intersected above 2 km (and especially above 3 km) were unlikely to have an associated TDS (Tab. 4).

4. Example of a TDS Cross-section

A strong tornado (the Moore, Oklahoma, EF-5 tornado of 20 May 2013) was chosen as a well-defined example of a TDS (Fig. 6).

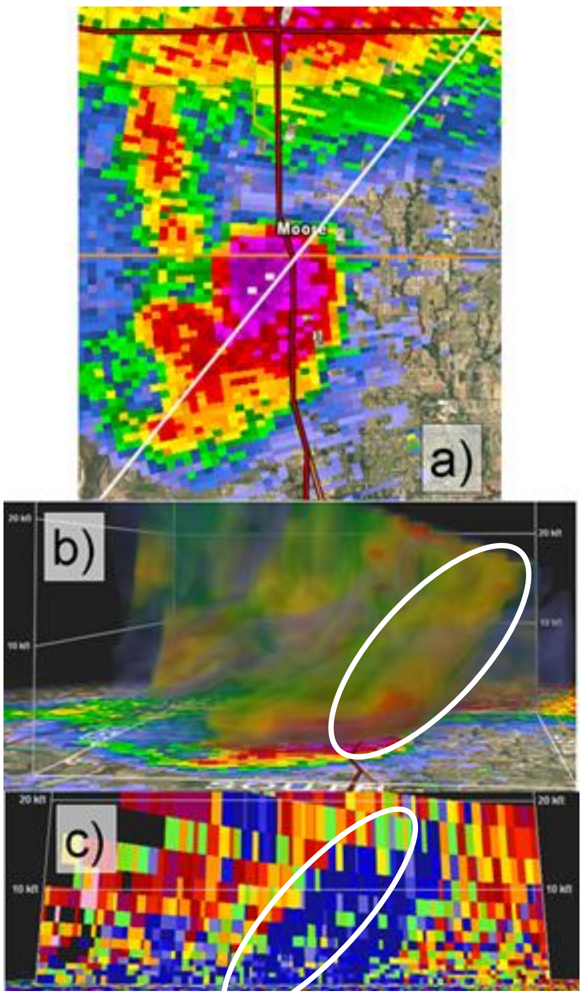

Figure 6: Debris from the 20 May, 2013, tornado in Moore, Oklahoma; a) Reflectivity (Z_{hh}) maximum in the echo appendage. White line indicates location of cross-section in panel (c). b) Z_{hh} isosurfaces seen from the south. High reflectivity values indicate debris being lofted toward the main storm body. c) Correlation coefficient (ρ_{hv}) cross-section indicating very low correlation values within the debris plume. White ovals in panels (b) and (c) indicate debris location.

The echo appendage at this time was dominated by very high reflectivity values, with maximum values of 70 dBZ (white pixels in Fig. 6a). A cross-section through this reflectivity maximum shows correlation values under 0.4, indicating non-meteorological scatterers extending upward to nearly 20,000 feet (Fig. 6c). Isosurfaces of reflectivity show reflectivity values exceeding 35-40 dBZ extending upwards in a plume from the surface debris region. The debris was being lofted upward and toward the main body of the supercell.

5. Example of the Value of Polarimetric Analysis

Some tornadoes are manifest as a local maximum in the reflectivity field (e.g. Fig. 6a). This feature, sometimes colloquially called a 'debris ball', is often used as an informal indicator that a tornado may be ongoing. This is not always the case, however—potential indications of tornado debris in the reflectivity field should always be checked against the polarimetric radar variables.

While analyzing the cases, several examples were found of 'debris balls' which were not actually associated with tornado debris. Fig. 7 is an especially difficult case for the operational nowcaster. This supercell, in Michigan's upper peninsula, had been producing a tornado for some time prior to the analysis time on 9 May 2012 (Fig. 7). For part of the tornado's early life, a TDS was present in association with the tornado. By the analysis time pictured in Fig. 7, a tornado was still ongoing within the echo appendage. A large region of high reflectivity values (Fig. 7a), collocated with a velocity couplet, would easily be assumed to be associated with this ongoing tornado. Looking at the polarimetric variables, however, it is evident that this is not actually tornado debris. Correlation coefficient values are generally 0.95 or higher, indicating meteorological scatterers (Fig. 7b), and differential reflectivity values are generally greater than 2 dB in the area (Fig. 7c), an indication of meteorological scatterers oriented with some component of their major axis parallel to the ground. Even though a tornado may be ongoing in this area, the large region of high reflectivity does not in this case indicate the presence of non-meteorological scatterers associated with a tornado.

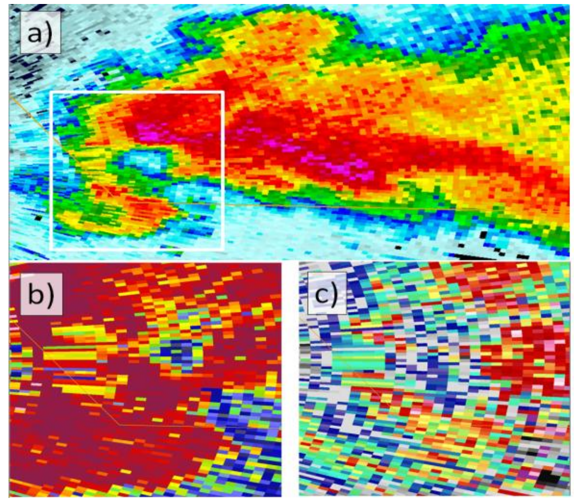

Figure 7: Polarimetric radar observations from the Marquette, Michigan, WSR-88D (KMQT) during a long-lived tornado on 9 June 2012. a) is reflectivity at a time when the tornado was ongoing, with large area of high values in the echo appendage. White box indicates location of panels (b) and (c). b) is correlation coefficient at the same time, showing high values in the echo appendage consistent with meteorological scatterers. c) is differential reflectivity, showing that values are high within the echo appendage, which would not be the case if a TDS was present.

6. Unusual TDS Situations

In the course of examining radar data from over 800 tornado events, a few unusual cases were noticed. Examples included several vortices at the trailing edge of a convective line which gradually became incorporated into storm cores, intense anticyclonic vortices, debris which infiltrated the entire mesocyclone (this may not be an unusual occurrence at high elevation angles, something we plan to investigate more in future research), and two cases which exhibited a well-defined TDS after storm reports indicated the tornadoes had been predominantly over water. One of these over-water cases is included here as an example of an unusual occurrence.

On 30 May 2012, a weak tropical system was coming onshore in the Carolinas. One cell, while apparently crossing a bay, produced a tornado which was only indicated in Storm Data to have been touched down for a total of 2 min. The tornado was within a local reflectivity maximum at the edge of a large convective cell (Fig. 8a), and collocated with a well-defined cyclonic vortex in the radial velocity field (Fig. 8b). A well-defined local minimum in the correlation coefficient field indicated non-meteorological scatter (Fig. 8c). This was a case in which using Storm Data and the radar data together would lead one to believe the tornado was over the water for its entire lifetime. From reports, though, we know this tornado did substantial house and tree damage on the east side of the bay prior to moving over water. The tornado time(s) reported in Storm Data were likely off by a minute or two. In reality, the tornado appears to have picked up a debris plume from the east shore of the bay and carried it out over the water. A nowcaster could have seen this signature and been confident that a tornado was in progress and lofting debris.

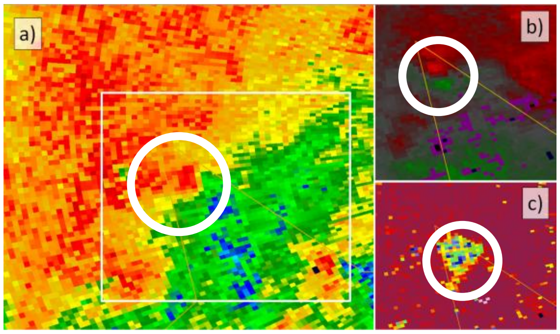

Figure 8: Radar observations from the Morehead City, North Carolina, WSR-88D radar (KMHX) during a short-lived tornado on 20 May 2012. a) is reflectivity, with white box indicating the location of panels (b) and (c). b) shows radial velocity and an intense cyclonic circulation. (c) shows lowered correlation coefficient values associated with the tornado. White circle in all panels indicates the tornado location.

7. Conclusions and Future Work

TDS were observed with just under 20% of tornado reports in Storm Data. The percentage of events with a signature varied regionally, with highest values in the Southern Plains and Southeast regions. Signatures were most frequent as a percentage of all tornado events in the spring (likely associated with a higher proportion of strong tornadoes) and autumn (possibly associated with an abundance of natural debris). As hypothesized, TDS were more common with higher-rated tornadoes on the EF scale, with increasing reported property damage, with increasing single-county path length, and with decreasing radar beam altitude at the radar beam-tornado intersection. Signatures were seen much less commonly when a tornado was observed at an elevation greater than 0.75 km.

Future work will focus on learning more about the relationship between signature occurrence and the underlying landcover. A closer examination of the temporal characteristics of the signature relative to reported tornado life cycles will also be undertaken. Signature vertical characteristic s will be examined. Typical evolution of polarimetric variable values through the tornado life cycle will be generalized.

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