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Z_{DR} Column Behavior in Real and Simulated X-band Radar Observations of Potentially Tornadic Storms

JAIME L. HERRIOTT*

Department of Earth, Atmospheric, and Planetary Sciences, Purdue University, West Lafayette, Indiana

**Current affiliation: School of Meteorology, University of Oklahoma, Norman, Oklahoma*

ROBIN L. TANAMACHI

Department of Earth, Atmospheric, and Planetary Sciences, Purdue University, West Lafayette, Indiana

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ABSTRACT

The primary objective of this research is to characterize distinct differential reflectivity (Z_{DR}) column behavior with respect to height, intensity, and aerial coverage before tornadogenesis (failure) in X-band radar observations of supercells. Z_{DR} observations of three supercells observed at high spatiotemporal resolution with X-band polarimetric radar, two tornadic and one nontornadic, are examined. Similar Z_{DR} column behavior is found in all three, despite differing outcomes with respect to tornadogenesis. Z_{DR} columns are also generated from a 30-member ensemble of simulated supercells. Height, intensity and areal extent of the simulated Z_{DR} columns are investigated just above the 0°C level. Simulated Z_{DR} column area and height both increase and Z_{DR} intensity inside the column was higher, on average, in the 5 min before tornadogenesis, whereas there was no appreciable change in these metrics for tornadogenesis failure. This result contrasts with our observational analysis, where there were no consistent, distinguishable changes in Z_{DR} column metrics before tornadogenesis versus failure. This research pinpoints Z_{DR} column metrics that can be foci of future study, both through field observations and numerical simulations.

1. Introduction

Polarimetric weather radar allows forecasters and researchers to observe detailed microphysical processes inside of thunderstorms in near-real time (e.g., Bringi and Chandrasekar 2001, Kumjian and Ryzhkov 2008). Dual polarized radar uses the reflectivity (Z) in both the horizontal (H) and vertical (V) polarizations to calculate reflectivity values Z_H and Z_V . The difference between these two quantities ($Z_H - Z_V$) is defined as the differential reflectivity (Z_{DR}), a variable that provides information on the aspect ratio and shape of hydrometeors in the sampled volume (Seliga and Bringi 1976).

The updraft of a convective storm can loft liquid water drops above the 0°C level, where

they become supercooled. These lofted raindrops are oblate in shape due to aerodynamic drag, and have typical Z_{DR} values of 1–6 dB. In contrast, frozen hydrometeors above the 0°C level have typical Z_{DR} values of 1 to –2 dB, as they tend to be more randomly oriented or spherical ($Z_{DR} \sim 0$ dB). The contrast between relatively high- Z_{DR} oblate liquid drops extending vertically into relatively low- Z_{DR} frozen hydrometeors above the 0°C level creates a Z_{DR} column (Illingworth et al. 1987, Kumjian and Ryzhkov 2008, Romine et al. 2008).

Z_{DR} columns can be considered a proxy for updrafts (Kumjian et al. 2014). Z_{DR} columns can be used to detect the initiation of new convective storms and characterizing the evolution of convective storm updrafts (Snyder et al. 2015). For example, vertical growth (to 1–4 km above the 0°C level) and narrowing of the Z_{DR} column signals a rapidly intensifying updraft (Kumjian et

Corresponding author address: Jaime L. Herriott, E-mail: Jaime.L.Herriott-1@ou.edu

al. 2014). As mature Z_{DR} columns indicate strong updrafts (Kumjian et al. 2014, Snyder et al. 2015), they can suggest conditions conducive to large- and damaging-hail production.

Z_{DR} columns arise from microphysical processes such as the lofting of supercooled liquid water and recycled hydrometeors within strong updrafts, and thus indicate updraft intensity rather than direct drivers of tornadogenesis. Prior work has shown that Z_{DR} columns are closely tied to enhanced updraft strength (Kumjian et al. 2014, Snyder et al. 2015), which can contribute to vortex intensification through stretching. In convective storms, vertical vorticity is generated primarily through the tilting of horizontal vorticity associated with the environmental wind shear, followed by stretching within the updraft (Markowski and Richardson 2009; Rotunno and Klemp 1985). Low-level updraft strengthening enhances this stretching, leading to an increase in vertical vorticity near the updraft core and at the surface. Additionally, the development of a pressure deficit within the rotating updraft promotes upward acceleration via the vertical pressure gradient force, further amplifying the vertical vorticity (Fischer et al. 2024). Because Z_{DR} columns reflect the presence of strong, sustained updrafts aloft, they indicate dynamical processes, particularly vertical acceleration and vorticity stretching, that are favorable for tornadogenesis.

There remains a gap in the understanding of changes and characteristics within Z_{DR} columns in relation to tornadogenesis. While previous research has established the importance of Z_{DR} columns in understanding storm and updraft evolution (French and Kingfield 2021, Healey and Van Den Broeke 2023, Kumjian et al. 2014, Picca et al. 2015, Van Den Broeke et al. 2020), it has been unable to conclusively link Z_{DR} column behavior and tornadogenesis. Picca et al. (2015) were the first to hypothesize that Z_{DR} columns would extend upward above the 0°C level before tornadogenesis, reflecting the positive relationship between Z_{DR} column height and updraft strength. Using WSR-88D observations of 45 tornadic supercells, they found a strong correlation between Z_{DR} column height and changes in updraft characteristics, but only a weak correlation between Z_{DR} column height and tornadogenesis. Kuster et al. (2019) looked at whether Z_{DR} column depth could be a useful metric in tornado-warning decision making for

forecasters. They found this an unlikely tool to improve tornado warnings, as Z_{DR} column depth was similar in their sample of 42 tornadic and nontornadic storms observed by the KOUN polarimetric WSR-88D. Van Den Broeke (2020) studied 32 tornadic and 31 nontornadic supercells observed by operational WSR-88Ds, and found that while Z_{DR} columns are larger, deeper, and less varied in tornadic storms, the small polarimetric differences due to Z_{DR} calibration drift issues (Ryzhkov et al. 2005) would make measuring Z_{DR} column changes difficult in an operational setting (Radar Observations Center DOC/NOAA 2015).

French and Kingfield (2021) examined Z_{DR} column area before and during tornadogenesis in 154 supercells observed by operational WSR-88Ds, finding that Z_{DR} column area was larger in supercells that produced tornadoes rated EF3+ than in those that produced EF1 and EF2 tornadoes. They also found larger variability in Z_{DR} column area in their tornadic supercells versus 44 nontornadic supercells. However, these observations were more broadly focused on tornado size and strength rather than tornadogenesis itself. Healey and Van Den Broeke (2023), using tornadic-nontornadic supercell pairs in similar environments, found that pre-tornadic storms had a larger Z_{DR} column area before their maximum low-level rotation than nontornadic storms, and concluded that supercells with larger Z_{DR} columns are more likely to become tornadic in the immediate future.

These studies used observational data from S-band radars, mainly the WSR-88D. Estimating Z_{DR} column metrics with WSR-88D can be difficult, due to beam spreading with height and loss of spatial resolution with increasing range from the radar (Snyder et al. 2015, Van Den Broeke 2017). The WSR-88D has relatively sparse vertical coverage above the 0°C level, due to the set of discrete elevation angles in its volume coverage patterns, wherein vertical distance between successive elevation sweeps increases at longer ranges. These radars also have relatively poor temporal sampling due to volume-update times of 5–6 min (Brown et al. 2005, Chrisman 2012). Supplemental Adaptive Intra-Volume Low-Level Scans (SAILS; Chrisman 2012) samples low elevation angles more rapidly, at the expense of longer revisit times at higher elevation angles, where Z_{DR} columns are generally found.

In this study, we use X-band radar observations and simulations to characterize the behavior of Z_{DR} columns before tornadogenesis (failure) in several tornadic and nontornadic supercells. We focus on X-band radar observations, as they generally provide higher spatiotemporal resolution than those of S-band radars (Rauber and Nesbitt 2018). By discerning distinct changes in Z_{DR} columns preceding tornadogenesis using both observations and model simulations, we hope to pinpoint Z_{DR} column features that will be the focus of future studies. We hypothesize that X-band radar observations and simulated radar data of Z_{DR} columns will show measurable changes in height, intensity, and areal coverage in the 5 min before tornadogenesis that are distinct from those observed during tornadogenesis failure. The 5-min time interval is similar to the typical WSR-88D volume update time (5–6 min).

2. X-band radar observations

Due to the transitory nature of severe convective storms, fixed-site S-band radars like those in the NEXRAD WSR-88D network may not have sufficiently high spatial and temporal sampling to resolve rapidly moving or changing storms (Bluestein and Wakimoto 2003). Ground-based mobile radars allow for the collection of data close to severe convective storms, even in remote locations. In addition to their proximity advantages, mobile radars tend to scan more rapidly (1–2-min volume-update times), which allows the observation of rapidly changing weather phenomena and small-scale features within them. Tornadogenesis can occur on time scales of a minute or less (Bluestein and Wakimoto 2003; Pazmany et al. 2013), shorter than the typical volume update time for most operational radars.

Despite the proliferation of X-band mobile radars for severe storms research, we found that rapidly scanned (i.e., volume-update times of ≤ 2 min) X-band radar observations of Z_{DR} columns through their full depth are relatively rare. Z_{DR} columns reside above the freezing level (~ 3 – 4 km AGL in the midlatitudes). Most mobile radars use scanning strategies that focus on low altitudes (< 1 km AGL) where high-impact weather like microbursts, strong straight-line winds, hail, or a tornado are observed (Brown et al. 2005; Radar Operations Center and DOC/NOAA 2015; Snyder et al. 2015). Dalman et al. (2018) were able to find three robust

datasets that met our criteria (i.e., volume coverage patterns that captured the full vertical extent of Z_{DR} columns above the 0°C level with temporal resolution ≤ 2 min).

The following subsections will describe the three cases, each of which was observed by a different X-band mobile radar, whose data were used in the observational portion of this study.

a. Case 1: Greensburg, KS tornadic supercell of 4 May 2007 observed by UMass X-Pol

The first EF5-rated tornado struck Greensburg, KS, at 0245 UTC 4 May 2007, leaving near-complete destruction and taking the lives of 11 people (Lemon and Umscheid 2008; Marshall et al. 2008; Tanamachi et al. 2012). The tornado (hereafter, “the Greensburg tornado”) had a maximum damage-path width of 2.74 km and a damage-path length of 46.7 km (Lemon and Umscheid 2008; Marshall et al. 2008).

Dr. Howard Bluestein’s research group from the University of Oklahoma used the University of Massachusetts Amherst (UMass) X-band polarimetric radar (UMass X-Pol; Bluestein et al. 2007) mobile radar to collect volume scans between 0132 UTC and 0234 UTC (Tanamachi et al. 2012). UMass X-Pol scanned at least 10 tornadoes, including the Greensburg tornado and multiple cyclonic and anticyclonic satellite tornadoes during this timeframe (Lemon and Umscheid 2008). Bluestein et al. (2007) provide a detailed description of the radar (main characteristics are given in Table 1), and Tanamachi et al. (2012) describe the mobile-radar observations of the Greensburg tornado’s parent storm and its tornadoes (Lemon and Umscheid 2008).

Table 1: UMass X-Pol 2007 configuration (Tanamachi et al. 2012).

UMass X-Pol Characteristics	
Wavelength	3 cm
Half-Power Beam Width	1.2°
Peak Power	25 kW
Pulse Repetition Frequency	Staggered, 1.6 – 2.4 kHz
Max. Unambiguous Range	60 km
Max. Unambiguous Velocity	19.2 ms^{-1}
Range Gate Spacing	150 m
Max. Azimuthal Scan Rate	24° s^{-1}

UMass X-Pol’s volume coverage pattern during genesis of the EF5 tornado was too shallow to capture the Z_{DR} column above the 0°C level. However, the radar operator deepened the volume later in the deployment, from 0207–0234 UTC, allowing UMass X-Pol to capture Z_{DR} column behavior during the mature phase of the EF5 tornado and genesis of both cyclonic and anticyclonic satellite tornadoes (Tanamachi et al. 2012).

b. Case 2: Luther–Carney, OK tornadic supercell of 19 May 2013 observed by RaXPol

During a tornado outbreak across central Oklahoma on 19 May 2013, one supercell spawned what started as an EF1-rated tornado in Fallis, OK at 2153 UTC. This tornado strengthened to an EF3 rating just south of Carney, OK at 2213 UTC. The tornado had a damage path length of 33.8 km, a maximum width of 0.8 km, and lasted 43 min (National Weather Service 2013). Sharma et al. (2021) provided in-depth analysis of this storm and tornado.

Dr. Howard Bluestein’s research group from the University of Oklahoma captured volumetric scans of this EF3 rated tornado near Luther and Carney, OK (hereafter, “the Luther–Carney tornado”), this time using the Rapid-Scanning X-Band Polarimetric Radar (RaXPol) mobile radar (Wienhoff et al. 2018). The RaXPol is a mobile X-band polarimetric, Doppler radar system developed for severe-weather research by ProSensing, Inc. in 2010 (Pazmany et al. 2013), with its main characteristics given in Table 2. RaXPol is equipped with a high-speed elevation over azimuth pedestal, and a low-sidelobe, dual-linear, polarized, parabolic dish antenna mounted on a Ford F550 truck. It can complete a 10-elevation-step volume scan in roughly 20 s with a 180° s^{-1} scan rate. RaXPol uses frequency-hopping waveforms, which allows for faster collection of independent samples than when a single frequency is used (Pazmany et al. 2013). RaXPol, which is operated by the University of Oklahoma Advanced Radar Research Center (OU ARRC), has been used to collect high spatial and temporal resolution data in severe storms since 2011 across the central U.S. plains (Bluestein et al. 2015, Bluestein et al. 2025, Wakimoto et al. 2015).

In the present study, the data analyzed from RaXPol include the reflectivity and differential

reflectivity fields collected by Dr. Bluestein’s research group. The RaXPol observed Z_{DR} column behavior before tornadogenesis near Fallis, OK with observations continuing for an additional 10 min after tornadogenesis.

Table 2: RaXPol configuration (Pazmany et al. 2013; https://arrrc.ou.edu/radar_raxpol.html)

RaXPol Characteristics	
Wavelength	3 cm
Half-Power Beamwidth	1.2 °
Peak Power	20 kW
Pulse Repetition Frequency	1 – 8 kHz
Max. Unambiguous Range	30 to 40 km
Max. Unambiguous Velocity	30 to 38 ms^{-1}
Range Gate Spacing	7.5 m to 75 m
Max. Azimuthal Scan Rate	180° s^{-1}

c. Case 3: Greenville, TX nontornadic supercell of 19 June 2019 observed by UMass Skyler

Our final observational case occurred on 19 June 2019 near Greenville, TX. A non-tornadic supercell (hereafter, “the Greenville storm”, not to be confused with the Greensburg storm of 2007) was observed by Dr. Robin Tanamachi’s research group from Purdue University, using the UMass Skyler mobile phased array radar (Heberling and Frasier 2021).

UMass Skyler is a Raytheon dual polarization X-Band phased-array radar (PAR) used by UMass MIRSLL for precipitation and severe-weather research (main characteristics are given in Table 3). PARs use an array of transmitting elements which phase together to create a desired radiation pattern as a single antenna (Kollias et al. 2018, 2022). PAR systems, which use an active electronically scanned array for beamforming and direction, are a candidate technology to replace the WSR-88D (Weber et al. 2021). UMass Skyler’s antenna array consists of 2560 transmitting/receiving elements that are steered and configured electronically. The radiating elements are direction-dependent in both phase and gain (Knappik and Frasier 2022).

For this study, the data analyzed from UMass Skyler consist of the reflectivity and differential reflectivity fields observed in the Greenville, TX storm (Tanamachi et al. 2020). The team observed a vigorously rotating updraft during

deployment (Tanamachi et al. 2020) from 2225–2235 UTC. The storm split around 2231 UTC, and no tornado formed. UMass Skyler observed the Z_{DR} column behavior for ≈ 8 min, encompassing this storm split.

3. Z_{DR} column detection

Building on the objective framework developed by Sharma et al. (2021) to identify and characterize Z_{DR} columns in X-band radar observations of supercells, the present study employs a closely related Z_{DR} column identification approach. Summarizing the procedure, Z_{DR} fields were first objectively analyzed to a uniform, 250-m, 3D Cartesian grid using a two-pass Barnes scheme (Majcen et al. 2008). Grid sizes for each case are shown in Table 4. Additional quality-control criteria were used to censor gates unlikely to contain meteorological observations. For the Greensburg, KS observations, gate filters were applied to exclude those with $Z_H < -10$ dBZ, velocity texture (Hong and Gourley 2015) $> 9 \text{ m s}^{-1}$ (as this value was found to eliminate most second-trip echoes), and correlation coefficient (ρ_{HV}) < 0.7 , indicating tree blockage or non-meteorological scatterers. Little to no overlap was seen between the tornado debris signature and the primary Z_{DR} column therefore interference between the two signatures is negligible. Owing to a data-quality issue with the UMass X-Pol Greensburg cross-correlation coefficient (ρ_{HV}) data specifically (detailed by Tanamachi et al. 2013), the ρ_{HV} threshold of 0.7 is relaxed relative to higher values (0.8 or 0.9) that are usually used in polarimetric radar data analysis. Lastly, the reflectivity fields were despeckled to remove noise.

Table 3: UMass Skyler 2017 configuration (Heberling et al. 2017).

UMass Skyler Characteristics	
Wavelength	3 cm
Half-Power Beam Width	1.9° Az, 2.1° El
Peak Power	125.4W
Pulse Repetition Frequency	flexible
Max. Unambiguous Range	40 km
Max. Unambiguous Velocity	18.8 ms^{-1}
Range Gate Spacing	25 m
Max. Azimuthal Scan Rate	N/A

Table 4: Grid dimensions for each observational case used in this study.

Case	Radar	Grid Size
Greensburg, KS	UMass X-Pol	60 km $\times$ 60 km $\times$ 10 km
Luther-Carney, OK	RaXPol	45 km $\times$ 45 km $\times$ 10 km
Greenville, TX	UMass Skyler	30 km $\times$ 30 km $\times$ 10 km

Contiguous volumes in the grid with Z_{DR} values > 1 dB were identified as Z_{DR} columns (Sharma et al. 2021). The Z_{DR} columns were then isolated using a convex hull implemented in the Python SciPy package (<https://scipy.org/citing-scipy/>, version 1.12), allowing for measurement of the columns' dimensions. Figures 1–3 show select results of the isolation procedure for the three observed cases. Where multiple Z_{DR} columns were identified, a primary column closest to the hook echo was manually selected for study.

4. Observational analysis results

We evaluated three metrics of the Z_{DR} columns: height, intensity and areal coverage. These metrics were chosen as some of the most promising ones identified by other researchers for their potential prognostic utility (Snyder et al. 2015, Van Den Broeke 2020, Wilson and Van Den Broeke 2021). A comprehensive summary of the Z_{DR} column metric behavior for each observational case is provided in Table 5.

a. Case 1: Greensburg, KS tornadic supercell of 4 May 2007 observed by UMass X-Pol

UMass X-Pol data in the Greensburg storm that spanned the full depth of the primary Z_{DR} column consisted of approximately 15 volume scans (Fig. 4). The Greensburg (EF5) tornado was ongoing throughout this period, accompanied by occasional satellite tornadoes. The Z_{DR} column area and height exhibited lagged increases occurring shortly after the formation of each satellite tornado (Figs 4, 5). Z_{DR} column height and area both increase in Fig. 5 at 0213:17 UTC, at 0221:01 UTC, and again at 0228:20 UTC (although it was less pronounced; Fig. 5).

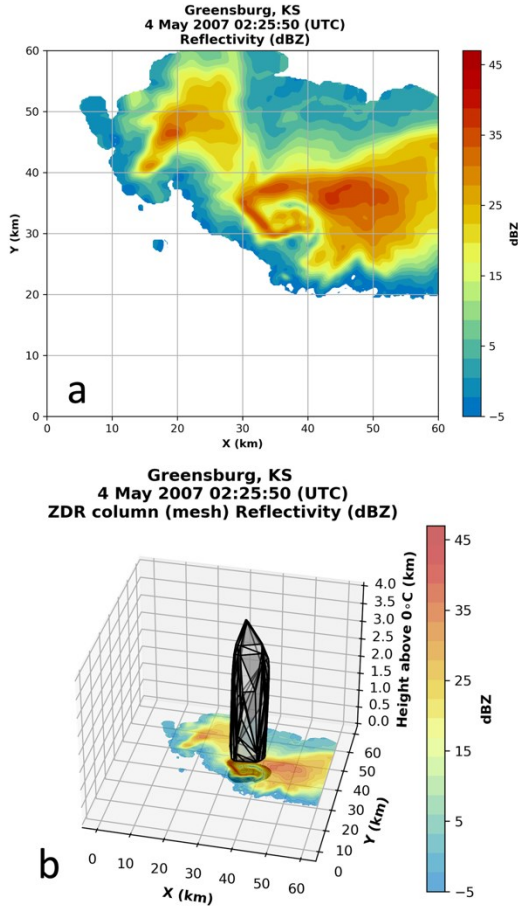


Figure 1: a) Objectively analyzed Z_H (in dBZ) at 3.75 km ARL in the 4 May 2007 Greensburg, KS supercell, observed by UMass X-Pol at 0225 UTC on 5 May 2007 (Tanamachi et al. 2012). b) Same as (a), but with the view expanded into 3D space and showing the Z_{DR} column in mesh with the ‘shadow’ (vertical projection) of the Z_{DR} column overlaid on the low-altitude reflectivity.

The height increase at 0213 UTC is certainly artificial as this is when the radar volume coverage pattern deepened from scanning 3° to 10° to 3° to 15° and, finally, 3° to 20° (Tanamachi et al. 2012; their Table 3). The Z_{DR} column intensity (i.e., maximum Z_{DR} inside the column; Fig. 5) increased slightly before the genesis of each satellite tornado.

These metrics are consistent with periodic fluctuations in updraft intensity (i.e., a pulsing updraft), although the signal is subtle and difficult to isolate given the presence of the long-lived EF5 primary tornado. Thus, although Z_{DR} column changes occur near the times of satellite-tornado formation and may be related to updraft

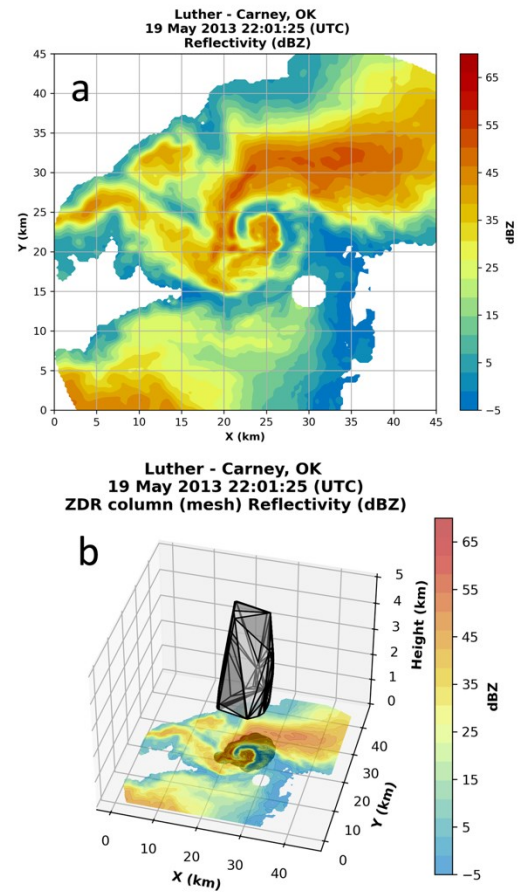


Figure 2: As in Fig. 1, but for (a) Z_H (dBZ) at 1.75 km ARL in the mature Luther–Carney, OK tornadic supercell of 19 May 2013 at 2201 UTC, derived from RaXPOL radar observations (Wienhoff et al. 2018). The circular ‘hole’ in the reflectivity field at (30 km, 15 km) marks RaXPOL’s cone of silence at this altitude.

and low-level vortex behavior, they do not provide enough evidence on their own to confirm a pulsing updraft.

Z_{DR} column area and height decreased slightly within the primary column before tornadogenesis. However, the pattern in these metrics is less distinct before genesis of each satellite tornado than it is for Z_{DR} column intensity. This result is consistent with Picca et al. (2015)’s hypothesis that the Z_{DR} column height may decrease before tornadogenesis in supercells due to an increase in downward pressure gradient force, as the low-level mesocyclone intensifies. The increase in Z_{DR} column height and area after genesis suggest intensification of the updraft after each satellite tornado appeared.

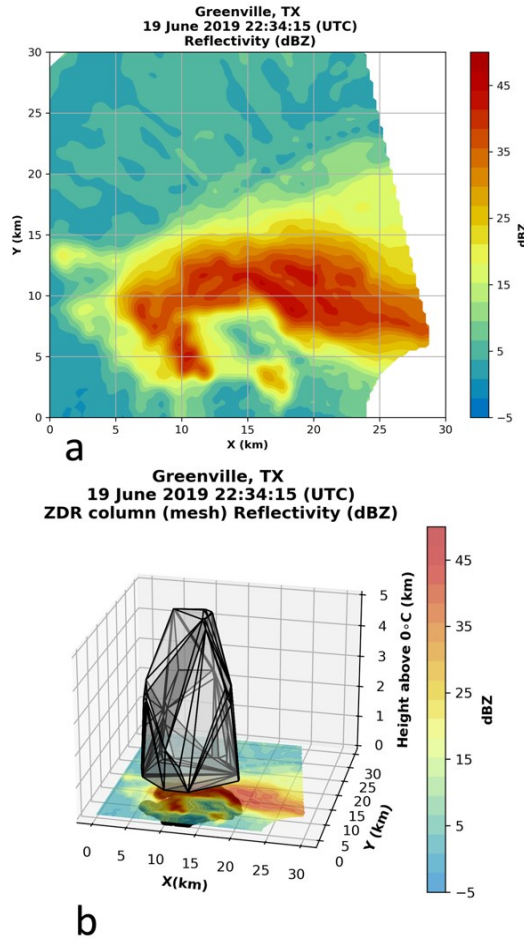


Figure 3: As in Fig. 1, but for a) Z_H (in dBZ) at 3.75 km ARL in the Greenville, TX nontornadic supercell of 2234 UTC 19 June 2019, derived from UMass Skyler radar observations (Tanamachi et al. 2020).

b. Case 2: Luther–Carney, OK tornadic supercell of 19 May 2013 observed by RaXPoL

The primary Z_{DR} column height (Figs. 6, 7) increased significantly, by about 1.5 km, in the 3 min before genesis of the Luther–Carney tornado (i.e., from 2151:01 UTC to 2153:37 UTC). This height change suggests the updraft was experiencing rapid growth just before tornadogenesis (Kumjian et al. 2014). This growth would not have been well resolved by a WSR-88D radar operating with a 5–6-min update time. Subsequently, the Z_{DR} column height oscillated around 3.75 km above the 0°C level in the post-tornadogenesis period.

The Z_{DR} column area substantially increased during and after tornadogenesis, from ≈ 60 – 80 km², as the tornado increased from an EF1 rating to an EF3 rating (Fig. 7). This expansion is consistent with findings from French and Kingfield (2021). Z_{DR} column intensity generally increased in the 10-min interval encompassing tornadogenesis, further signifying updraft intensification and growth throughout the tornadogenesis process (Fig. 7). In contrast to Case 1, where Z_{DR} column trends were difficult to distinguish owing to the presence of a long-lived parent tornado, Case 2 exhibits a more coherent increase across all Z_{DR} column metrics through tornadogenesis. This difference suggests that the relationship between Z_{DR} column behavior and tornadogenesis may be more clearly resolved in some cases than others, particularly when the signal is not obscured by confounding processes.

c. Case 3: Greenville, TX nontornadic supercell of 19 June 2019 observed by UMass Skyler

In the Greenville, TX nontornadic supercell, the Z_{DR} column increased in height, intensity, and area in the 1–5-min period preceding tornadogenesis failure (Figs. 8, 9a). Here, tornadogenesis failure refers to a supercell that exhibited characteristics typically associated with tornadogenesis (e.g. a rotating updraft and hook echo) but did not produce a tornado despite a favorable dynamic and kinematic environment. The Z_{DR} intensity inside the column exhibited a significant increase just before the updraft enhancement. At 2231:22 UTC, a Z_{DR} column split was observed (Tanamachi et al., 2020) during the process of updraft intensification.

The convex hull mesh (Fig. 8 at 2231:22 UTC) does not show the dual peaks of the Z_{DR} columns, whereas an isosurface representation (Fig. 9b) does. Z_{DR} intensity and Z_{DR} column area decreased in the 1 min before the Z_{DR} column split. However, area, height, and intensity all increase after the Z_{DR} column split. There is rapid increase in area and height after the Z_{DR} column splits, in the Z_{DR} column evolution (Fig. 8 from 2231:22 UTC to 2232:48 UTC). The areal increase can be attributed to the Z_{DR} column split as the two separating columns envelop more area than the single ancestral column. As a result, the post-split increase in area likely reflects a geometric effect of the column splitting rather than a direct indication of updraft strengthening, suggesting the Z_{DR} column

area may not serve as a reliable indicator of updraft evolution in this case. Furthermore, the column split indicates decreased organization of the updraft that could be the cause of tornadogenesis failure. In contrast, the Z_{DR} column height rapidly increased, suggesting

updraft intensification as seen in the tornadic cases (Fig. 5 and Fig. 7). This result argues against our hypothesis that the Z_{DR} columns would exhibit distinct changes before tornadogenesis that were not present before tornadogenesis failure.

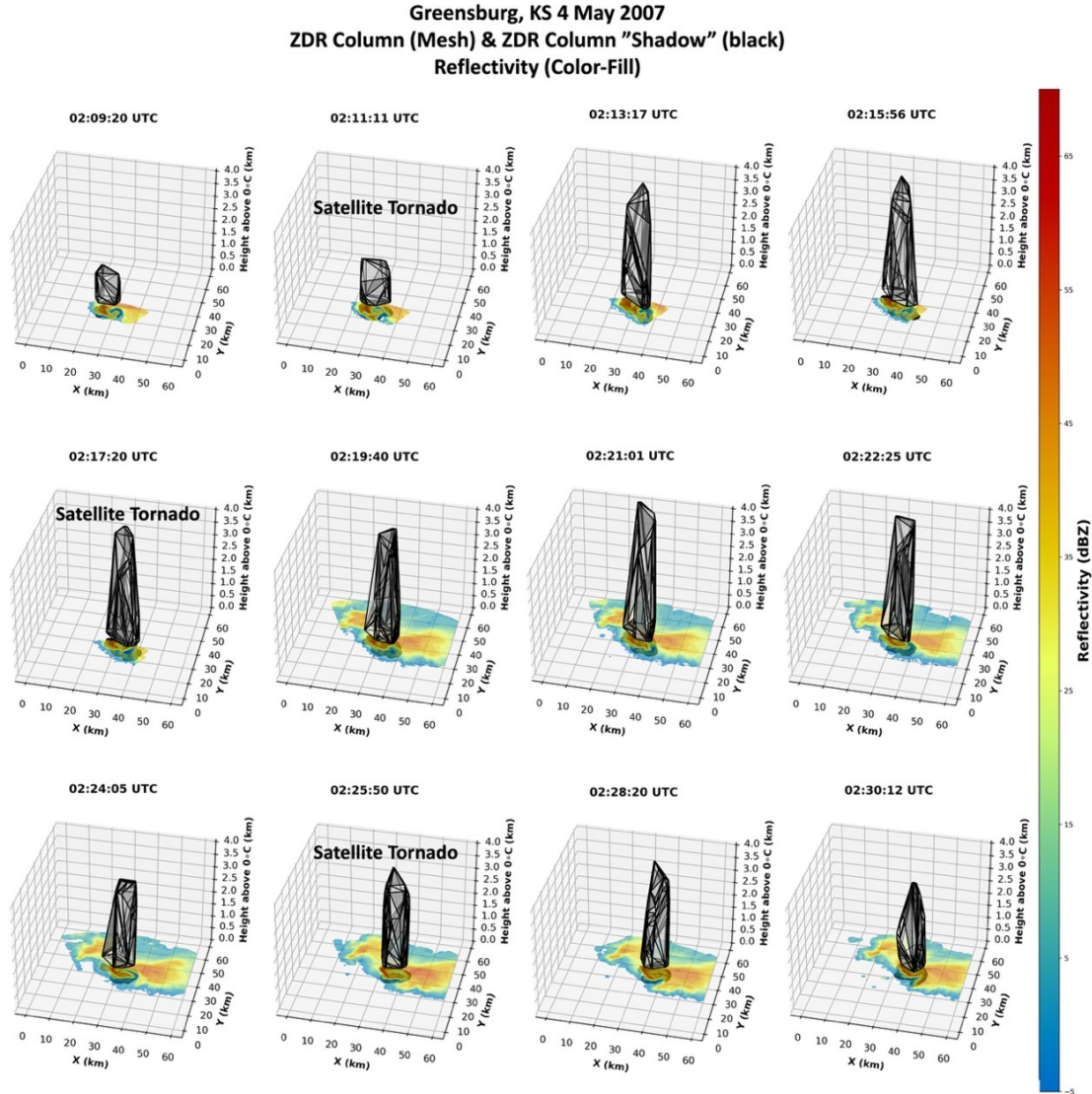


Figure 4: Reflectivity (color fill, in dBZ), the objectively identified Z_{DR} column (mesh), and the 'shadow' of the Z_{DR} column (black) overlaid on the reflectivity for each UMass X-Pol volume scan collected from 0207:50 UTC to 0230:12 UTC 5 May 2007. Images show the evolution of the Z_{DR} column height above 0°C and areal coverage over time of the Greensburg, KS tornadic storm. The Greensburg EF5 tornado was ongoing throughout this period; the genesis times of several satellite tornadoes are annotated.

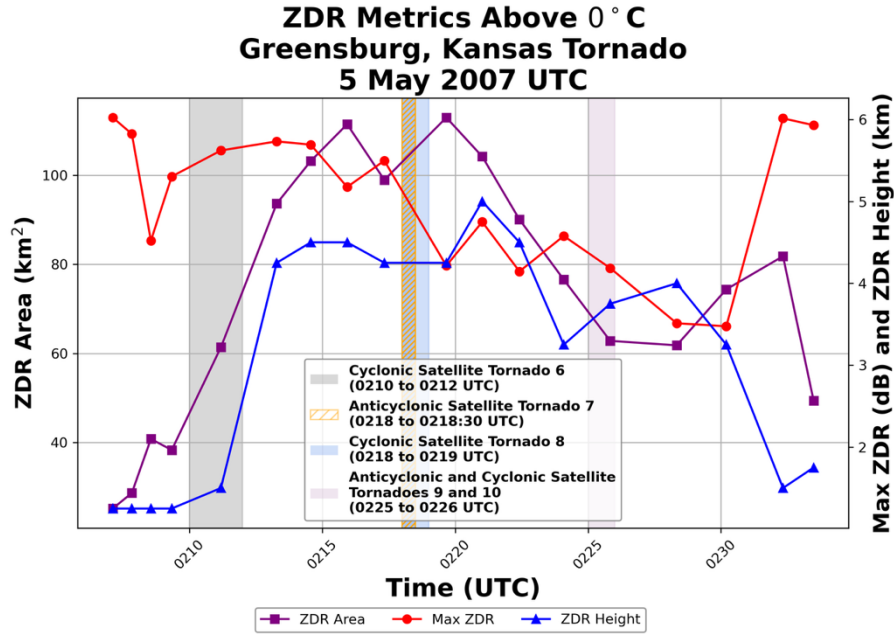


Figure 5: Time series, from 0207–0233 UTC, of characteristics of the primary Z_{DR} column of the Greensburg, KS tornadic supercell, above the 0°C level. The EF5 rated Greensburg tornado (tornado 5 per Lemon and Umscheid, 2008; Tanamachi et al., 2012) was ongoing throughout this time frame; the times of several of its satellite tornadoes, including tornadoes 6–10 (Tanamachi et al., 2012), are indicated by colored shading and hatching.

5. Simulated Z_{DR} columns

The above three cases comprise the total relatively small number (to the best of the authors’ knowledge) of supercellular, X-band radar data sets with high spatiotemporal resolution (~ 100 m, ~ 1 – 2 min), above the 0°C level. Clearly, three cases are too few from which to draw general inferences about the behavior of Z_{DR} columns in potentially tornadic supercells. To make up for this scarcity of usable data, we generated synthetic Z_{DR} columns from high-resolution numerical simulations of supercells. We coupled the model output with a polarimetric emulator (Oue et al. 2020) at X-band wavelengths to simulate radar variables. In addition to making up for the scarcity of real data cases, a simulation-based study also provides more control of the storm environment and eliminates noise and clutter that can often be present in observational X-band data.

Supercell simulations were generated using Cloud Model 1 (CM1), a cloud-resolving numerical weather forecast model (Bryan and Fritsch 2002, Bryan 2024). Our experiment

setup is based on that of Coffey et al. (2017), whose ensemble samples plausible parameter spaces for tornadic and nontornadic supercells. They used CM1 Release 17 with the NSSL two-moment microphysics scheme (Mansell 2010; Ziegler 1985) to simulate storms for 2 h on a $200\text{-km} \times 200\text{-km} \times 18\text{-km}$, initially horizontally homogeneous domain. A 30-member ensemble of supercells was populated by adding small perturbations to the wind profiles of composite tornadic (15 members, denoted tor00–tor14) and nontornadic (15 members, denoted nt00–nt14) soundings created by Parker (2014) from VORTEX2 radiosonde data. Their 120-min simulations produced a wide variety of outcomes in production of tornado-like vortices (TLVs), including “nontornadic” ensemble members that produced TLVs and “tornadic” members that did not. Moreover, a similar variety of behaviors were found related to mesocyclones, including single steady mesocyclones, multiple simultaneous mesocyclones, and shorter-lived, cyclic mesocyclones. The stochastic formulation of this experiment drew us to use it for simulation of a plausible variety of Z_{DR} column behavior.

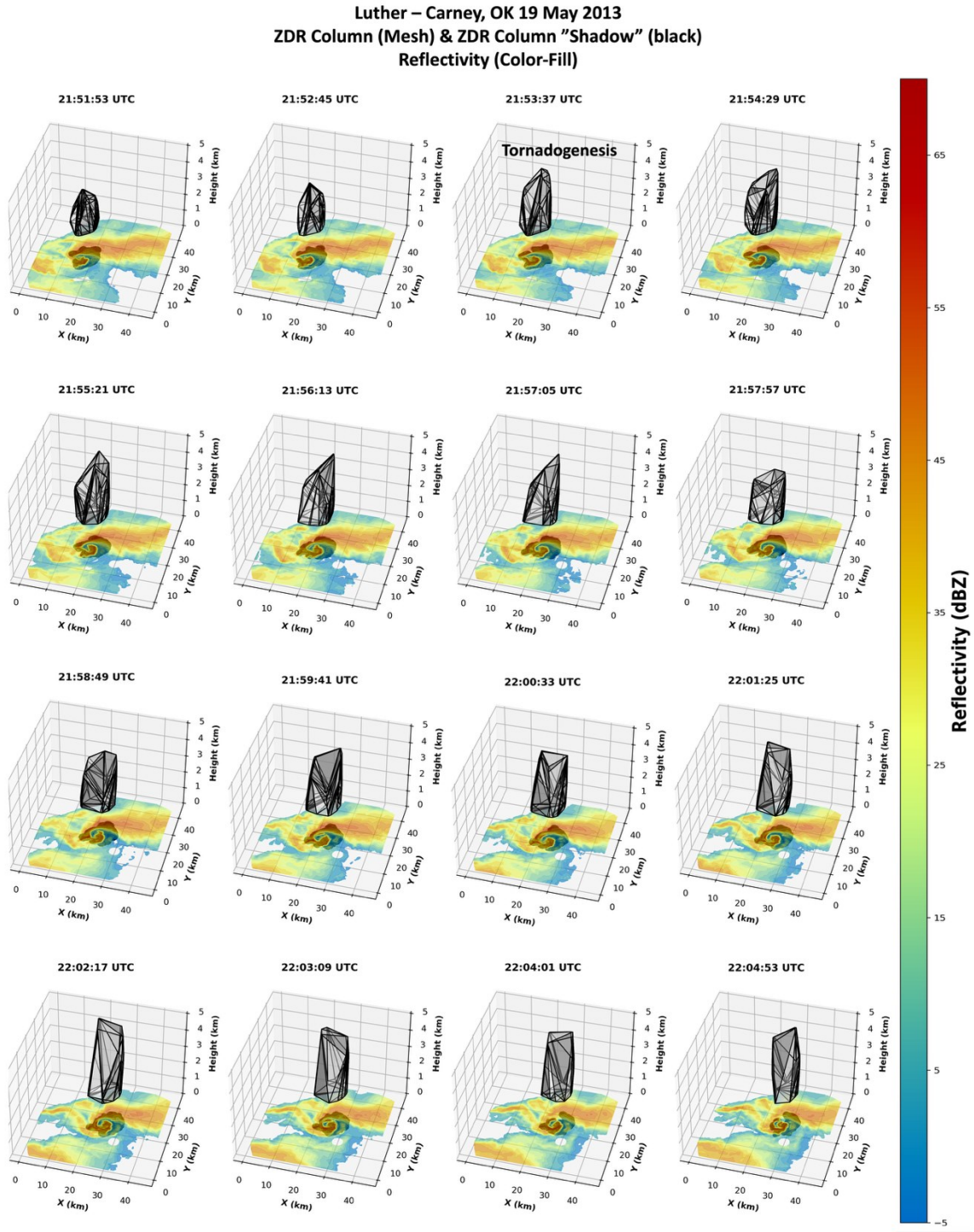


Figure 6: As in Fig. 4, but for RaXPoI volume scans collected in the Luther–Carney, OK EF-3 tornado of 19 May 2013, from 2147:32 UTC to 2204:53 UTC.

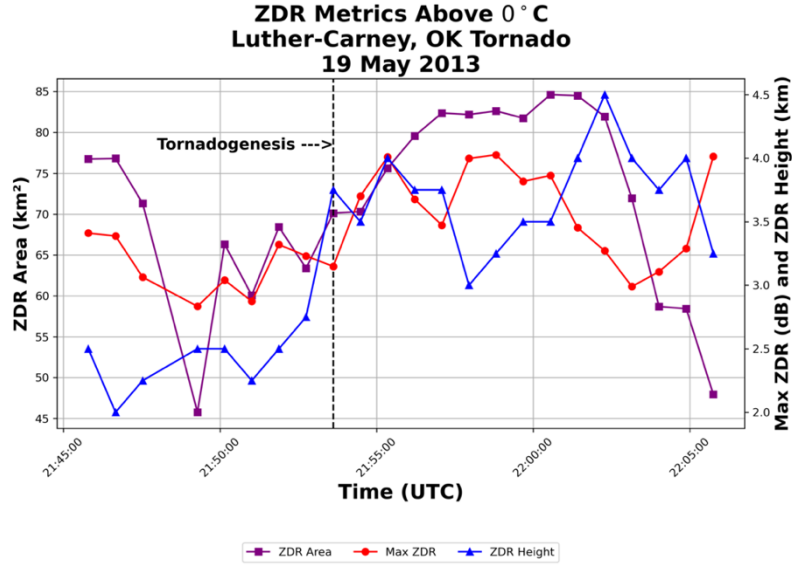


Figure 7: As in Fig. 5, but for the primary Z_{DR} column of the Luther–Carney, OK tornadic supercell. The genesis of the Luther–Carney tornado, near Fallis, OK at 2153 UTC (Sharma et al. 2021), is indicated by a dashed vertical line.

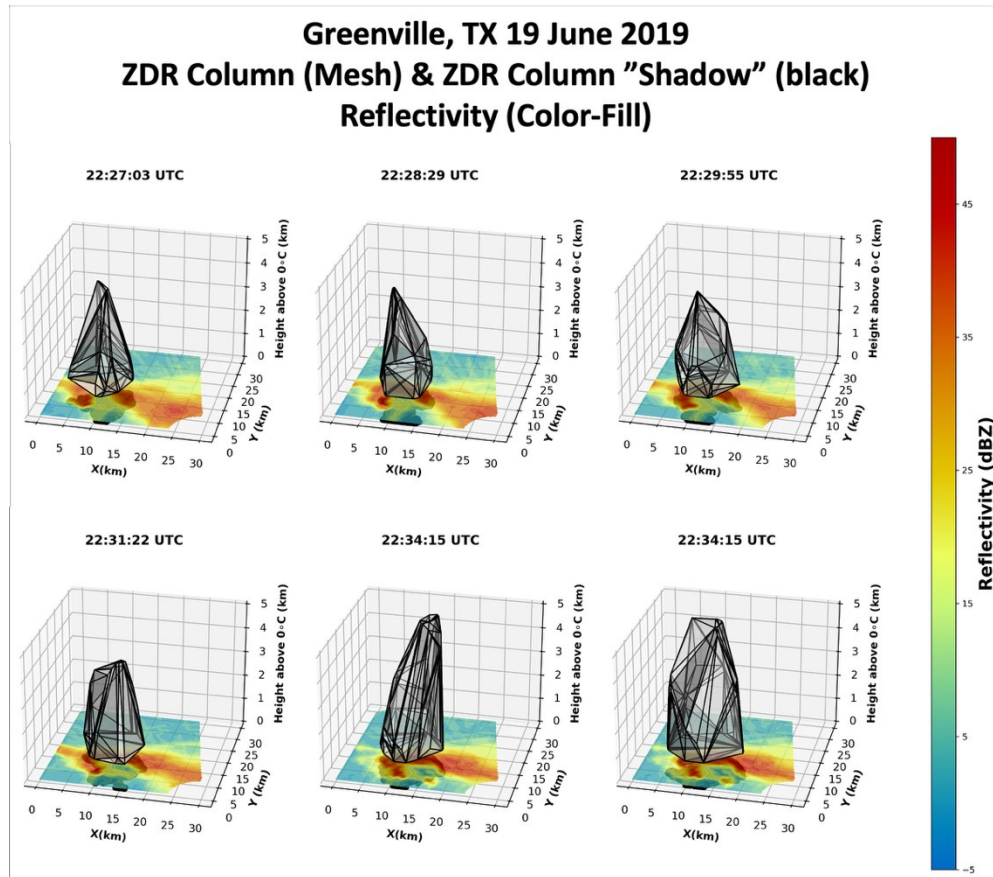


Figure 8: As in Fig. 4, but for UMass Skyler volume scans collected in the Greenville, TX nontornadic supercell of 19 June 2019, from 2227:03 UTC to 2234:15 UTC. Note that the Z_{DR} column split is obscured by the geometry of the convex hull.

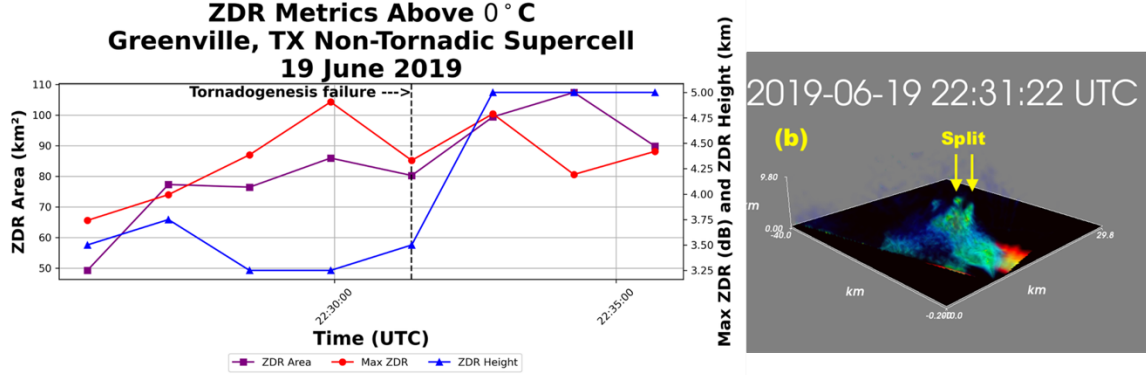


Figure 9: a) As in Fig. 5, but for the primary Z_{DR} column of the Greenville, TX nontornadic supercell. The time of an apparent tornadogenesis failure and attendant Z_{DR} column split is indicated by a dashed vertical black line. b) Volume rendering (blue) of $Z_{DR} > 1$ dB, overlaid on near-surface reflectivity, from Tanamachi et al. (2020), with the apparent supercell split annotated.

Table 5: Z_{DR} column metric performance for each observational case study 5 to 0 min before tornadogenesis or failure. The three entries for the Greensburg, KS row correspond to satellite tornadoes 6, 7 and 8 (paired), and 9 and 10 (paired) respectively (Lemon and Umscheid 2008).

Case	Height	Intensity	Area
Greensburg, KS	↔ (0.0 km/3 min)	(+1 dB/1 min)	(+15 km ² /4 min)
	↓ (1.0 (−0.3 km/3 min)	↓ (−0.3 dB/3 min)	↑ (−10 km ² /1 min)
	↓ (−1.8 km/3 min)	↓ (−0.2 dB/3 min)	↓ (−40 km ² /4 min)
Luther-Carney, OK	↑ (+1.5 km/4 min)	↑ (+0.6 dB/4 min)	↑ (+24 km ² /6 min)
Greenville, TX	↑ (+0.25 km/1 min)	↑ (+0.65 dB/5 min)	↑ (+30 km ² /5 min)

Our experimental setup (Table 6) differed from that of Coffey et al. (2017) in that we used Release 21 of CM1 and the Morrison two-moment bulk microphysics scheme (Morrison and Milbrandt 2011) for compatibility with the polarimetric emulator (to be discussed later). A known limitation of the default CM1 namelist settings for the Morrison two-moment microphysics scheme is that resulting simulations exhibit stronger cold pools and higher surface precipitation rates than are generally observed in real supercells (Morrison and Milbrandt 2011). We performed a sensitivity experiment (not shown) on the tornadic control ensemble member (tor00) based on recommendations from H. Morrison (2025, personal communication), in which we modified the drop breakup parameter from 300 μm to 500 μm . Larger mean drop size implies drops have a smaller evaporation rate, which decreases the cold-pool strength. The increase in the drop breakup threshold diameter helped to weaken the cold pool, creating a more favorable scenario for supercell longevity, structure and tornadic

potential (Dawson et al. 2013). All 30 ensemble members were run using this modification to the Morrison and Milbrandt (2011) microphysical parameterization scheme.

The full simulation domain, $200 \times 200 \times 18$ km, contained a subdomain of $50 \times 50 \times 18$ km to center on the supercell using an inner mesh (Table 6). We use the same metrics for simulated tornadogenesis (i.e. TLV production) defined by Coffey et al. (2017): 1) the surface vertical vorticity exceeds 0.3 s^{-1} ; 2) the pressure deficit (relative to the base-state environmental sounding) within the vortex exceeds 10 hPa (or 8 hPa in the case of the nontornadic ensemble members) over a depth of at least 1 km; and 3) the instantaneous ground-relative windspeed in the vortex is $>35 \text{ m s}^{-1}$. All of these criteria needed to be concurrent for at least 2 min for a vortex to be considered a TLV. If tornadogenesis criteria were not met, then the time of tornadogenesis failure was denoted as the time of maximum surface vertical vorticity.

Table 6: CM1 configuration used for this study.

CM 1 Configuration	
Domain Extent	200 km $\times$ 200 km $\times$ 18 km
Inner Mesh	50 km $\times$ 50 km $\times$ 18 km
Inner Mesh grid spacing	$\Delta x = \Delta y = 100$ m, $\Delta z \geq 20$ m
Outer Mesh	Stretching to $\Delta x = \Delta y = 3.5$ km
Horizontal Grid Size	1056 $\times$ 1056 $\times$ 115
Vertical Grid	115 levels starting at $\Delta z = 20$ m stretching to $\Delta z = 280$ m at 18 km
Pressure Solver	Klemp and Wilhelmson, 1978 time splitting, vertically implicit
Microphysics	Morrison two-moment (Morrison and Milbrandt 2011)
Subgrid Turbulence	TKE scheme (Deardorff 1980)
Bottom Boundary Condition	Semislip
3D initialization	Updraft nudging (Naylor and Gilmore 2012)

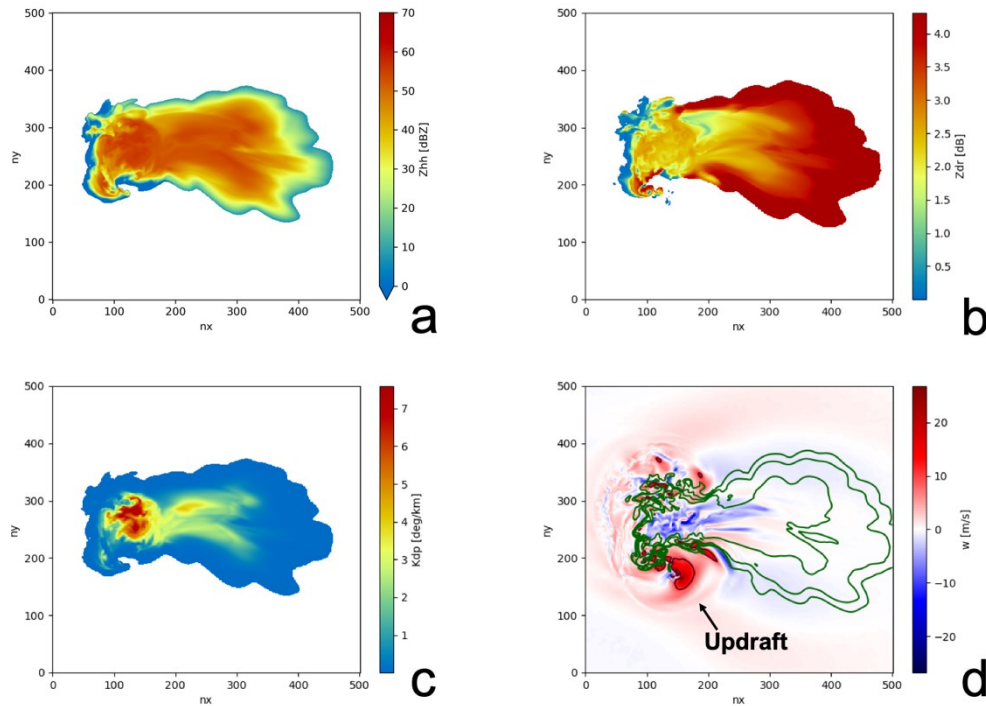


Figure 10: CR-SIM output at the lowest model level ($z = 0.01$ km AGL) for a) horizontally polarized reflectivity (in dBZ), b) Z_{DR} (in dB) showing indication of high values throughout the forward flank edges consistent with size sorting issues noted in two-moment microphysics schemes (Morrison and Milbrandt 2011), c) specific differential phase (K_{DP}), and d) vertical wind speed (w) inherited from the CM1 output from minute 28 of control sounding tor00. Horizontal axes are indicial.

CM1 does not simulate electromagnetic scattering and therefore does not produce estimates of radar variables apart from a simplified estimate of logarithmic radar reflectivity factor (the “dBZ” field). We applied the Cloud-resolving model Radar Simulator (CR-SIM; Oue et al. 2020) v4.0, to the CM1

simulation output to produce simulated polarimetric radar observations. CR-SIM emulates radar observables using a forward-modeling approach that transforms precipitation microphysical quantities (mixing ratio, number concentration, and shape parameter for each hydrometeor species) in CM1 output into

idealized radar variables (Oue et al. 2020). The output from CR-SIM consists of radar variables such as horizontally and vertically polarized reflectivity (Z_h and Z_v , respectively), Doppler velocity, Z_{DR} , specific differential phase, and numerous others, at each model grid point. For all 30 CM1 ensemble members (15 tornadic and 15 nontornadic) we used CR-SIM v4.0 to emulate dual polarized variables like Z_{DR} on a 501×501 grid point subdomain centered on the supercell. Figure 10 shows examples of CR-SIM outputs before being merged into CM1 output.

An example of the resulting Z_h and Z_{DR} fields at low levels is shown in Fig. 11. Panel (b) shows abnormally high values throughout the forward flank edges consistent with inadequate representation of size sorting noted in two-moment microphysics schemes (Morrison and Milbrandt 2011). However, the representation of the Z_{DR} column appears robust and realistic. Figure 12 shows a cross section of a Z_{DR} column coinciding with the edge of an updraft.

X-band Z_{DR} fields were generated using the Cloud Resolving Radar Simulator (CR-SIM; Oue et al., 2020), a state-of-the-art polarimetric emulator on a $500 \times 500 \times 115$ grid-point subdomain focused on the primary updraft region of the supercell. The position of the simulated radar was near the center of the simulation domain, near and south of the simulated storm's hook echo. CR-SIM output was generated for the (−5 min, +5 min) interval relative to tornadogenesis time as defined by Coffey et al. (2017)'s criteria (vorticity, pressure deficit, vortex depth). Before contiguous Z_{DR} regions were identified, Z_{DR} was masked below the 0°C level and above the -40°C level (Fig. 12b) to restrict Z_{DR} column identification to mixed-phase regions. The 0°C height is where liquid water begins to freeze, and constitutes the lowest possible altitude where a Z_{DR} column can exist. Conversely, above the -40°C level, all hydrometeors are assumed to be completely frozen. With this layer defined, our identification methodology for simulated Z_{DR} columns is consistent with that used for the real Z_{DR} columns.

As with the real Z_{DR} observations, the simulated Z_{DR} columns were isolated using the convex hull method in the Python Scipy package (v1.12, Virtanen et al. 2020). Figure 13 illustrates an example of the low-level reflectivity and the isolated Z_{DR} column (mesh) above the 0°C level, and shadow of the Z_{DR}

column overlaid on the low-level reflectivity for a tornadic ensemble member.

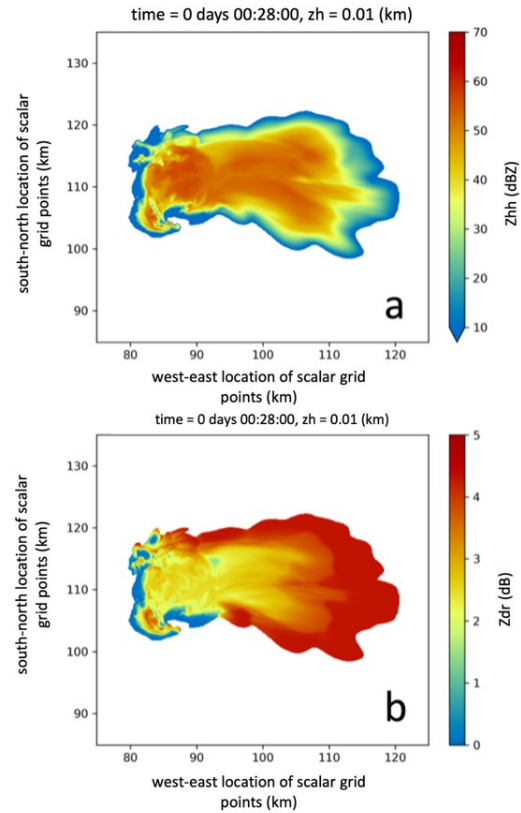


Figure 11: Combined CM1 and CR-SIM output: a) horizontally polarized reflectivity at $z = 0.01$ km AGL (dBZ), b) Z_{DR} (dB) from minute 28 of control sounding tor00.

6. Simulation results

For the purposes of this study, tornado-like vortex (TLV) genesis in the simulations is treated as equivalent to tornadogenesis in the observations, and hence, we use the term “tornadogenesis” for both processes. To assess potential relationships between tornadogenesis and Z_{DR} column behavior in the simulated ensemble of supercells, we applied the criteria of Coffey et al. (2017), which include thresholds for vertical vorticity, pressure deficit, and vortex depth. If these three criteria occurred simultaneously for a period >2 min, tornadogenesis was said to have occurred. TLVs identified during the first 30 min of the simulation were excluded from further analysis, as this period was considered model spin-up, during which the model adjusted from its initial conditions and the simulated convective dynamics were not yet fully developed.

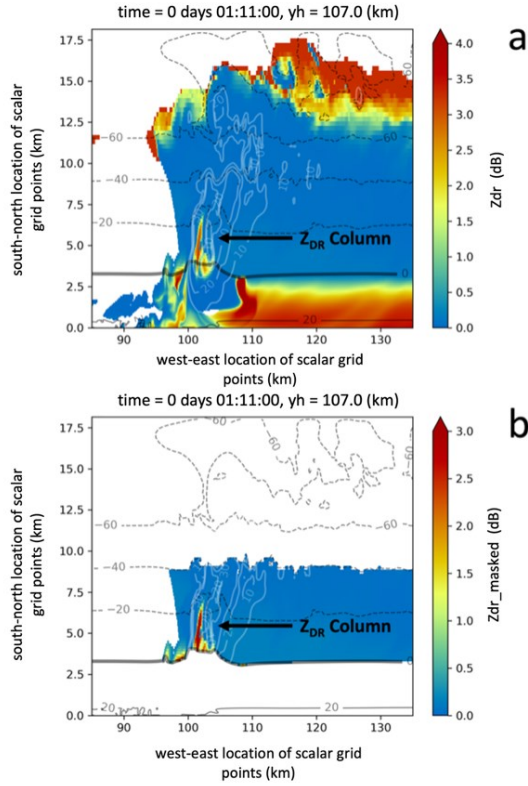


Figure 12: x–z cross section of Z_{DR} (color fill) showing the a) unmasked and b) temperature-masked regions in a tornadic ensemble member. The semitransparent gray contours show the temperature in $^{\circ}\text{C}$, with the thicker, solid gray contour showing the location of the 0°C level. The semitransparent white contours mark 10, 20, and 30 m s^{-1} vertical velocity (w) contours. The spurious high Z_{DR} values at the top of the unmasked cross section are likely due to low signal levels, where very small Z_H and Z_V values introduce numerical noise and produce artificially large, noisy Z_{DR} .

If a simulation produced vortices that approached but did not meet the tornadogenesis thresholds (section 5), tornadogenesis failure was said to have occurred. In these cases, the time of tornadogenesis failure was taken as the time of maximum surface vertical vorticity (Coffer et al. 2017). Thus, tornadogenesis (TLV) failure represents a near-miss scenario rather than a complete absence of vortex development. Because no TLVs were detected in any of the nontornadic members that met Criterion 2, the required pressure-deficit threshold was relaxed to 8 hPa for all nontornadic members.

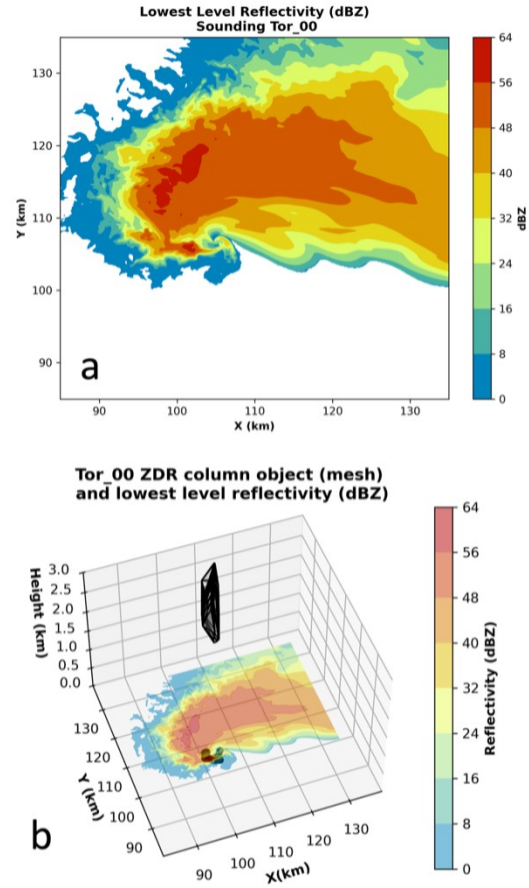


Figure 13: a) CR-SIM simulated horizontally polarized reflectivity (dBZ) at the lowest available model level ($z = 0.01 \text{ km}$) from the control member (tor00) sounding at minute 81. This was the time of maximum surface vorticity for this ensemble member. b) Same as panel (a), but showing the Z_{DR} column in mesh with the 'shadow' of the Z_{DR} column overlaid on the reflectivity. Only a $50 \text{ km} \times 50 \text{ km}$ subdomain of the full simulation domain is shown.

Similar to the findings of Coffer et al. (2017), the “tornadic” and “nontornadic” classifications of the initial soundings did not necessarily correspond to the simulated outcomes with respect to TLV production. In other words, some ensemble members initialized with “nontornadic” soundings produced one or more TLVs, while some initialized with “tornadic” soundings did not. Moreover, some ensemble members produced multiple tornadogenesis (failure) events.

Following the spin-up period, each ensemble member was categorized according to TLV behavior (Fig. 14) as:

1. **No TLV:** No TLV detected during the entire 90-min simulation.
2. **TLV during spin-up:** TLV detected during simulation minutes 0–30.
3. **TLV failure:** TLV genesis failure during simulation minutes 30–90.
4. **Single TLV producing:** One TLV detected during simulation minutes 30–90.
5. **Long-lived TLV producing:** One TLV lasting >10 min during simulation minutes 30–90.
6. **Multiple TLV producing:** Multiple TLVs produced during simulation minutes 30–90.

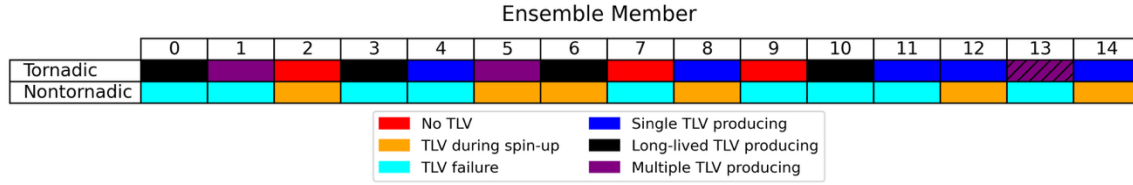


Figure 14: Outcomes of each tornadic and nontornadic ensemble member.

We included only ensemble members that produced either (a) at least one TLV after the 30-min spin-up period, or (b) a TLV failure event during the same period. Ensemble members that produced TLVs only during the spin-up period, or that did not exhibit TLV development, were excluded. After applying these criteria, the analysis included 10 tornadic ensemble members (0, 1, 3, 4, 5, 6, 10, 11, 12, 13) and 9 nontornadic ensemble members (0, 1, 3, 4, 7, 9, 10, 11, 13). Here, the included nontornadic members correspond to cases exhibiting TLV failure, rather than absence of vortex development.

a. Simulated Z_{DR} column analysis

We used CR-SIM to produce synthetic Z_{DR} fields for the 19 ensemble members selected for the next stage of study.

In the three observational case studies (section 4), Z_{DR} columns encompassed the primary updrafts of their respective storms (Figs. 4, 6, and 8). We identified many more candidate Z_{DR} objects above the freezing level in our simulations than were found in the observed supercell cases. On occasion, multiple candidate Z_{DR} objects were detected within the updraft region of the simulated supercell. When this occurred, the Z_{DR} column of interest was taken to be that with highest mean internal vertical velocity (i.e., collocated with the updraft).

Once our Z_{DR} object within the region of interest was identified, the following Z_{DR} column

metrics were calculated for an 11-min window centered on each tornadogenesis (failure) event:

1. **Height:** The vertical extent of the convex hull enclosing the identified Z_{DR} column.
2. **Intensity:** The maximum value of Z_{DR} within the column.
3. **Areal Coverage:** The projected area of the 3D convex hull on the x-y plane.

Figure 15 is an example of the simulated Z_{DR} column evolution over time taken from tornadic ensemble member 04 (tor04). Overall, the simulated Z_{DR} columns were smaller compared to the observed Z_{DR} columns (Section 4). We attribute this difference to an apparent artificial upper limit on mean drop size within the two-moment Morrison microphysics scheme. The default two-moment Morrison scheme uses a ~2.8-mm mean diameter for the drop distribution, corresponds to ~4.5 dB according to Beard and Chuang (1987). Additionally, the Morrison and Milbrandt (2011) two-moment scheme incorporates a drop-breakup parameterization. As previously mentioned, we adjusted the drop-breakup parameter from the default 300 μm to 500 μm based on advice (H. Morrison 2024, personal communication). This adjustment allows larger mean drop sizes to persist before breakup, which helps constrain cold-pool production. However, even with this adjustment, the synthetic Z_{DR} column intensity never seemed able to exceed 4.5 dB. In contrast, the observed Z_{DR} columns exhibited maximum

Z_{DR} as high as 6.0 dB in UMass X-Pol observations of the Greensburg, KS storm (Fig. 5) and as high as 4.9 dB in UMass Skyler observations of the Greenville, TX storm (Fig. 9). Clearly, the precipitation microphysics scheme still struggled to replicate real-world complexities of drop size distributions within storms. This issue will need to be addressed in future studies. We proceed nonetheless, focusing on the *trends* in Z_{DR} intensity, rather than the specific values.

Overall Z_{DR} column behavior is exemplified by ensemble member tor04 (Fig. 15). Ensemble member tor04 produced a TLV that began at $t = 74$ min and lasted roughly five min. Its primary Z_{DR} column increased in height and areal coverage before TLV genesis and continued to do so after TLV genesis. The Z_{DR} column decreased in height and areal coverage around the 79-min mark, indicating the updraft had also begun to weaken just before the TLV dissipation.

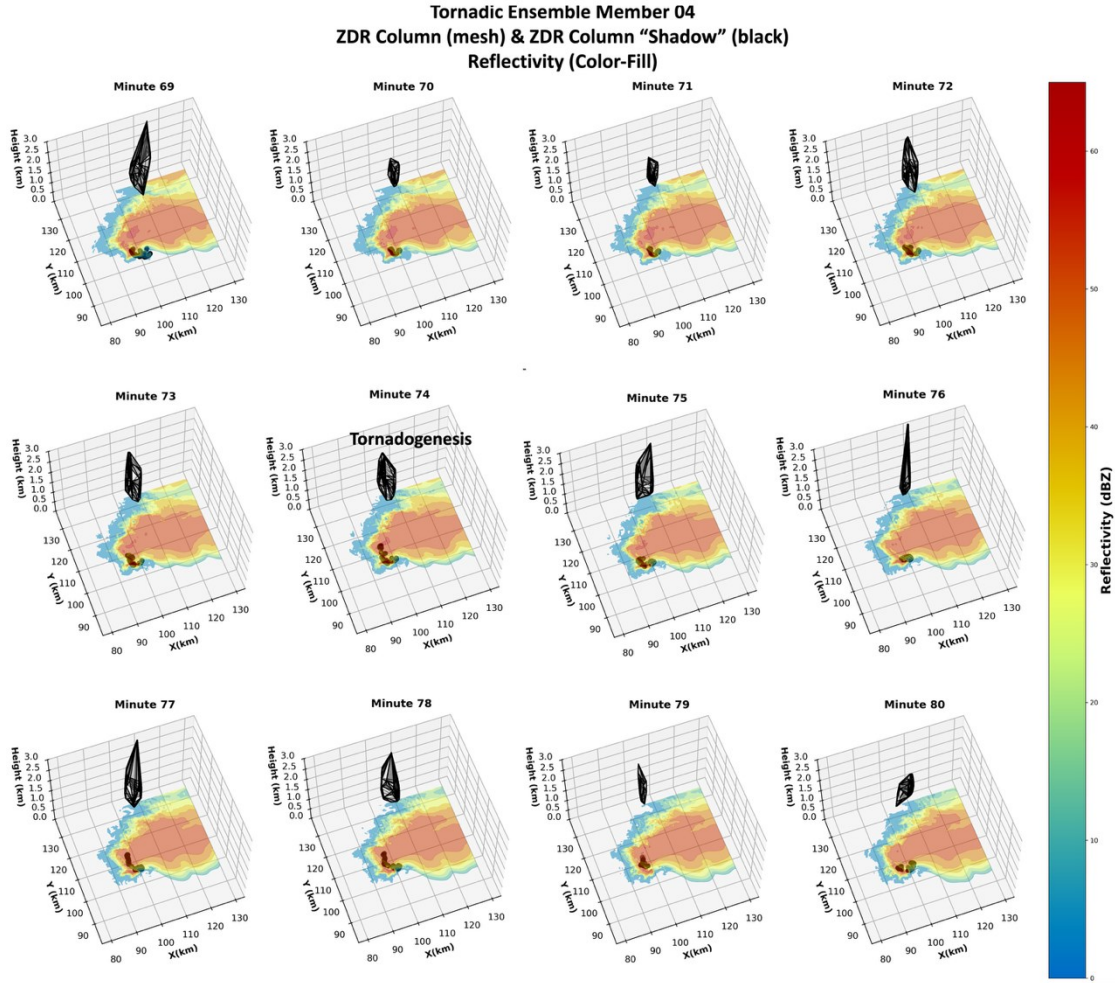


Figure 15: Simulated reflectivity (color fill), the Z_{DR} column (mesh), and the 'shadow' of the Z_{DR} column (black) overlaid on the reflectivity from minutes 69–80 of the tornadic ensemble member 04. Images show the evolution of the Z_{DR} column height above 0°C and areal coverage over time.

However, similar behavior was also observed in the nine nontornadic ensemble members examined. Figure 16 shows typical Z_{DR} column evolution from a nontornadic ensemble member (nt03). This case behaved like the tornadic cases, with the Z_{DR} column height and area

increasing before TLV genesis failure. However, the column shrank at the tornadogenesis failure timestep and quickly became smaller in area, becoming unidentifiable 5 min after TLV genesis failure. This behavior was consistent with the tornadic members in that

their Z_{DR} column metrics increased (on average) before tornadogenesis, but those metrics quickly diminished at or shortly after TLV genesis failure. This result indicates weaker updrafts overall in the nontornadic members, as Z_{DR} column height correlates with vertical velocity (Kumjian et al. 2014). This result is perhaps unsurprising, as Parker (2014)'s nontornadic composite sounding had slightly less surface-based CAPE (2377 J kg^{-1}) than the tornadic composite sounding (2755 J kg^{-1}) (Coffer and Parker 2018).

Figure 17 shows the height and areal coverage of the Z_{DR} column for each TLV-producing tornadic ensemble member at the time of tornadogenesis. Figure 18 shows the height and areal coverage of the Z_{DR} column for each nontornadic ensemble member at the time of tornadogenesis failure. Z_{DR} columns associated with tornadogenesis failure are, overall, smaller and less developed than the Z_{DR} columns associated with tornadogenesis.

To quantify the relationship between height and area of the Z_{DR} columns observed in tornadic and nontornadic ensemble members at tornadogenesis (failure), we calculated the aspect ratio. Using the height and area metrics obtained from the convex hull, aspect ratio was calculated as:

$$\text{Aspect Ratio} = \frac{H^2}{A}$$

Apart from one outlier amongst the nontornadic Z_{DR} columns, the tornadic Z_{DR} columns all had higher aspect ratios than the nontornadic Z_{DR} columns (Fig. 19), indicating that all of the tornadic Z_{DR} columns were relatively tall compared to the nontornadic Z_{DR} columns at tornadogenesis (failure), as can be seen in Fig. 17. The tornadic Z_{DR} columns also had a wider range of aspect ratios compared to the nontornadic Z_{DR} columns (Fig. 19).

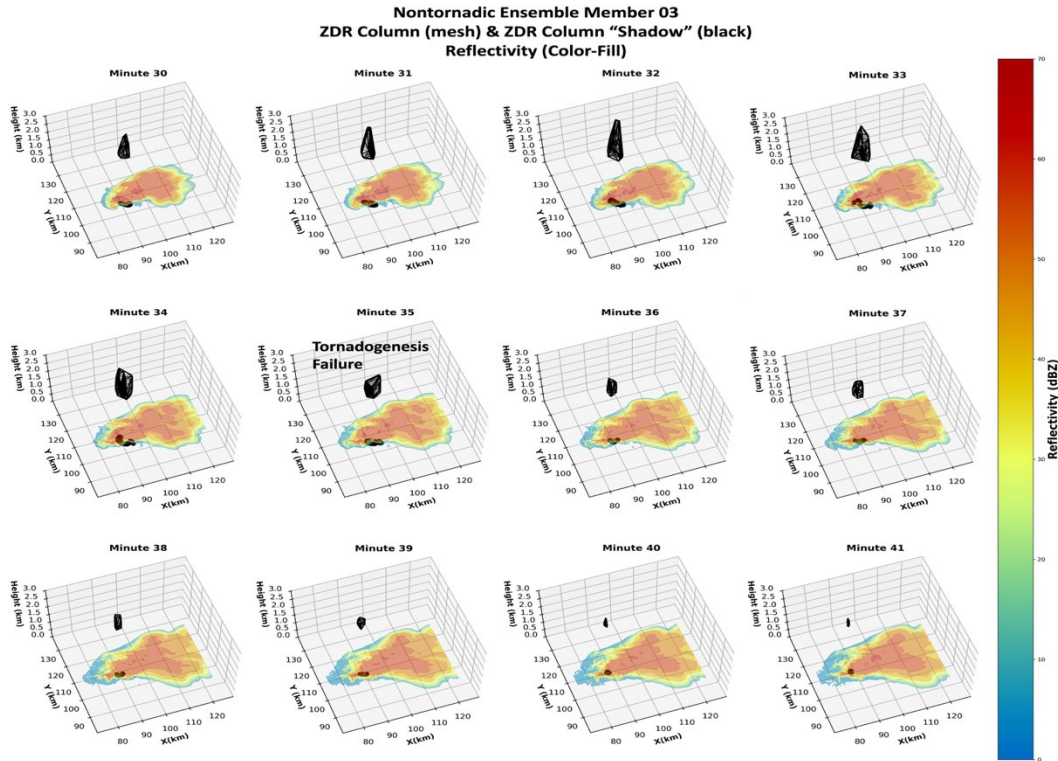


Figure 16: As in Fig. 15, but for minutes 30–41 of the nontornadic ensemble member 03.

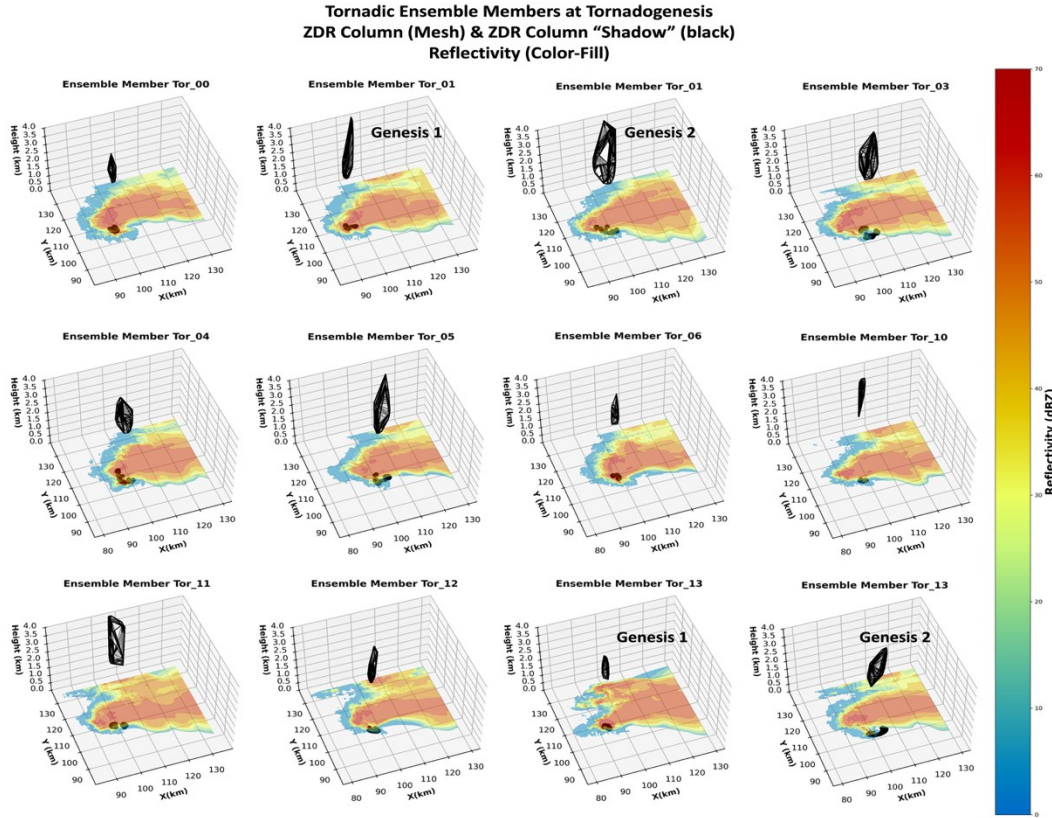


Figure 17: As in Fig. 15, but for all 12 TLV-producing tornadic ensemble members at their respective tornadogenesis times.

Because the vertical velocity (w) field is available from these simulations, it is possible to characterize the updraft strength inside each Z_{DR} column object. The higher aspect ratios for tornadogenesis-associated Z_{DR} columns are consistent with their enhanced vertical velocity (Fig. 20), potentially causing vertical vortex stretching. This result is consistent with RaXPol observations of Z_{DR} column behavior during tornadogenesis in the Luther–Carney, OK case (Section 4b), where tornadogenesis was preceded by rapid intensification of the updraft. Conversely, shorter and squatter Z_{DR} columns at tornadogenesis failure (Fig. 18, 19) contained relatively low vertical velocities (Fig. 20) which would not allow for as much vortex stretching and intensifying rotation needed for tornadogenesis.

b. Simulated Z_{DR} column trends

We also examined simulated Z_{DR} column metric behavior from the 5 min before and after 5 min following tornadogenesis or tornado-

genesis failure, for the tornadic and nontornadic ensemble members. The tornadic subset included 10 members, three of which produced two tornadogenesis events, yielding 13 total tornadogenesis events. The nontornadic subset included nine members, each with one tornadogenesis failure time.

First, we examined the magnitudes of Z_{DR} column intensity, area, and height relative to tornadogenesis (failure) using Figs. 21 and 22. Overall, the tornadic members tended to produce stronger, wider, and taller Z_{DR} columns than the nontornadic members. Those differences were most apparent in Z_{DR} column area and height, which were consistently larger near tornadogenesis than near tornadogenesis failure. Together with the higher Z_{DR} column aspect ratios and stronger interior vertical velocities shown previously (Figs. 19 and 20), these results indicate that tornadic members generally contained more vertically developed and intense updraft structures than nontornadic members.

Z_{DR} column intensity was also generally larger in the tornadic members, especially during the minutes leading up to tornadogenesis (Fig. 21a). Tornadic Z_{DR} column intensities were commonly between 3.5 and 4.5 dB, whereas the nontornadic member exhibited a broader range of values, from roughly 2.0 to 4.3 dB (Fig. 22a). However, interpretation of the intensity trends is complicated by an apparent artificial upper bound near 4.5 dB in the simulated Z_{DR} fields. This upper limit is lower than the Z_{DR} values observed in the Greensburg, KS, and Greenville, TX cases discussed in section 4, where observed Z_{DR} column intensity often exceeded 4.5 dB (Figs. 5 and 9). The default Morrison and

Milbrandt (2011) microphysical parameterization in CM1 imposes an upper limit of 2.8 mm on the mean drop size (H. Morrison, 2025 personal communication). Since a mean drop size of 2.8 mm corresponds to a Z_{DR} of roughly 4.0 dB (Beard and Chung 1987), this imposed limit may explain the apparent cap in simulated Z_{DR} intensity. Because the drop-size distribution tails off exponentially at these large drop sizes, Z_{DR} values may still extend somewhat above 4.0 dB, approaching the apparent 4.5-dB limit. Future work could adjust this mean drop-size constraint to allow larger simulated drops, and therefore, potentially larger synthetic Z_{DR} values.

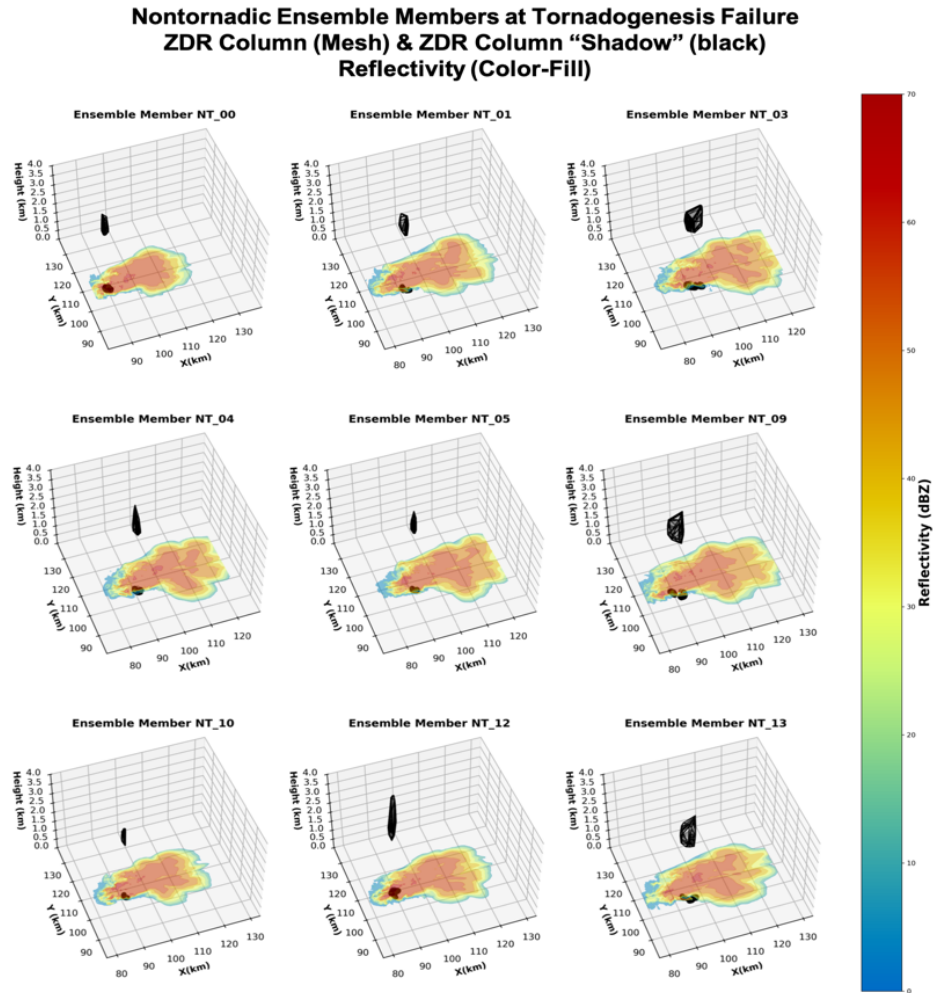


Figure 18: As in Fig. 17, but for all nine nontornadic ensemble members at their respective tornadogenesis failure times.

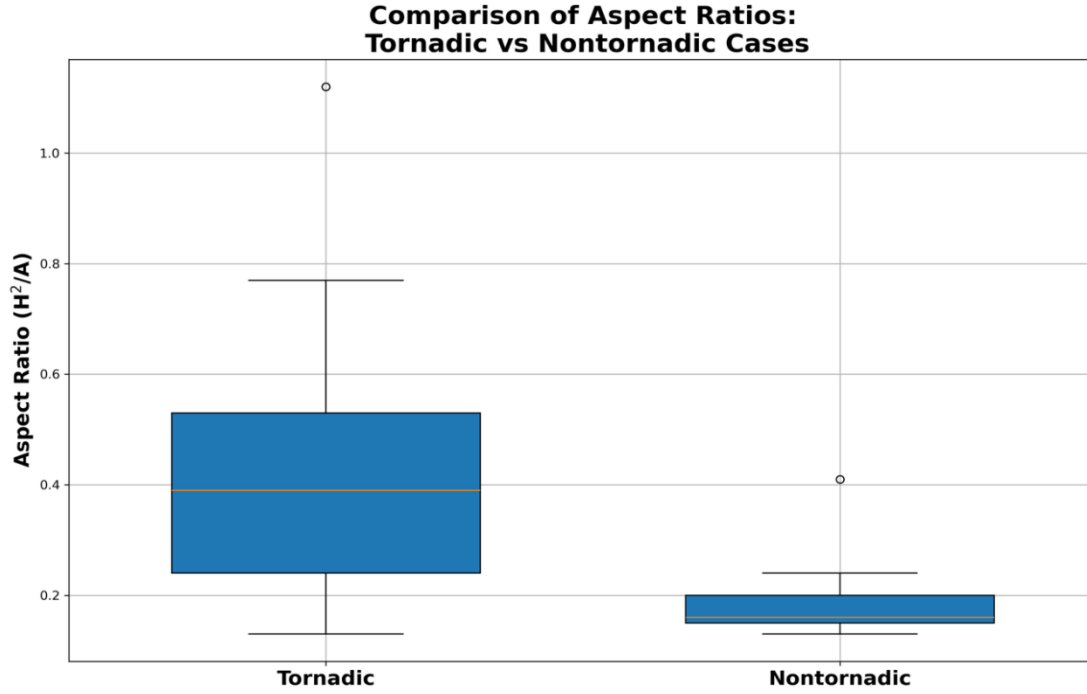


Figure 19: Box and whisker plots of the aspect ratio (H^2/A) of the Z_{DR} column of tornadic and nontornadic members at tornadogenesis and tornadogenesis failure, respectively. The shaded region represents the center quartile range and the lower and upper whiskers extent to the 25th and 75th percent respectively. Higher aspect ratios indicate relatively tall, narrow Z_{DR} columns.

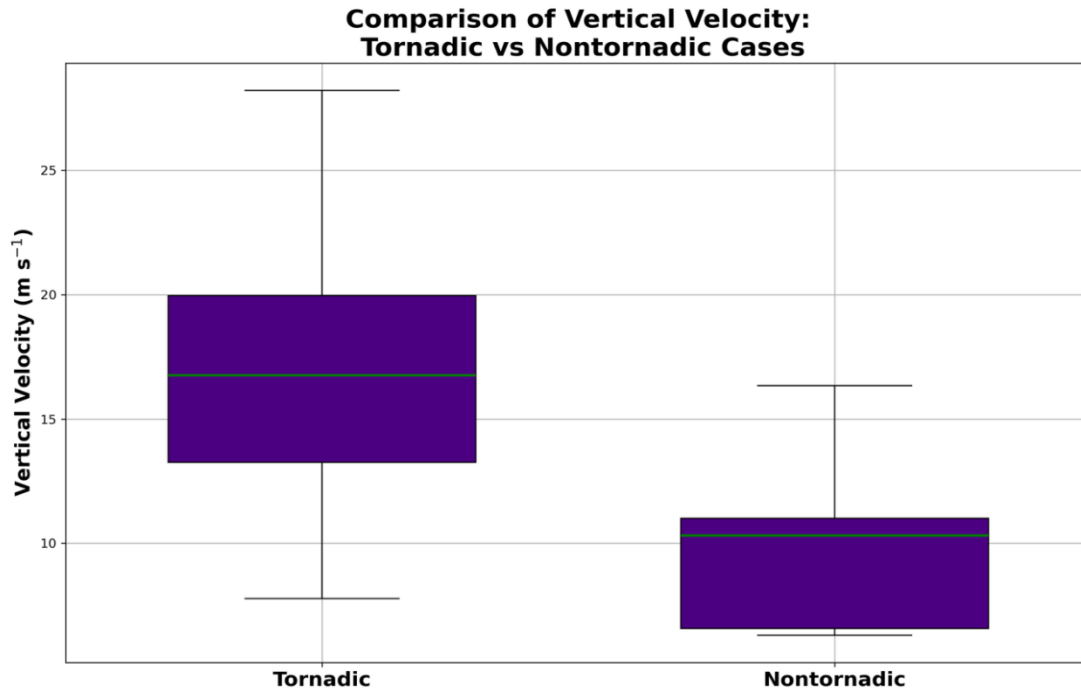


Figure 20: As in Fig. 19 but for the vertical velocity inside the Z_{DR} columns of tornadic ensemble members and nontornadic members at tornadogenesis and tornadogenesis failure, respectively.

Despite this caveat, tornadic Z_{DR} columns were generally more intense than their nontornadic counterparts. The tornadic ensemble mean remained relatively high (3.5 dB to 4.5 dB) throughout the analysis window, with several members reaching the apparent upper bound before tornadogenesis (Fig. 21a). In contrast, the nontornadic ensemble mean increased from the 3 min before tornadogenesis failure through ≈ 1 min after failure, but then decreased during the later post-failure period (Fig. 22a). Because the tornadic intensity values frequently approached the apparent model-imposed upper limit, Z_{DR} column intensity alone provides a less clear separation between tornadic and nontornadic members than the area and height metrics.

Clearer magnitude differences were evident in Z_{DR} column area. Tornadic Z_{DR} columns encompassed substantially greater area than nontornadic Z_{DR} columns. Ensemble-mean areas were roughly twice as large near tornadogenesis as near tornadogenesis failure (Figs. 21b and 22b). The nontornadic ensemble-mean area remained comparatively small (4 km²), and varied only slightly during the 11-min window centered on tornadogenesis failure (Fig. 22b). In contrast, the tornadic ensemble-mean Z_{DR} column area increased by ≈ 5 –7 km² within 2 min before tornadogenesis, reaching values near 20–21 km² (Fig. 21b). This larger Z_{DR} column area suggests a broader updraft in the tornadic members, consistent with studies linking larger Z_{DR} columns to broader updrafts (French and Kingfield 2021; Trapp et al. 2017). The tornadic events also showed more spread in Z_{DR} column area than the nontornadic events, suggesting variability in the size and organization of the updrafts among tornadic storms.

Z_{DR} column height also differed between the tornadic and nontornadic members. On average, Z_{DR} columns associated with tornadogenesis were taller than those associated with tornadogenesis failure (Figs. 21c and 22c). In the tornadic members, mean Z_{DR} column height increased by about 1 km during the 3 min before tornadogenesis and reached approximately 2.5 km above the 0°C level approaching tornadogenesis (Fig. 21c). The increase indicates greater vertical development and intensification of the updraft in the lead up to tornadogenesis (Kumjian et al. 2014). Z_{DR} columns associated with tornadogenesis have

higher aspect ratios (Fig. 19) and interior vertical velocities (Fig. 20) than do the tornadogenesis-failure counterparts. The nontornadic members showed only minor variations in Z_{DR} column height (~ 0.5 km), with the ensemble mean remaining lower and increasing only slightly before tornadogenesis failure (Fig. 22c). These lower heights are consistent with weaker or less vertically organized updrafts, and lower aspect ratios analyzed at tornadogenesis failure (Figs. 19 and 20).

The mean rates of change for each Z_{DR} column metric (intensity, area, and height) then were computed for tornadogenesis (failure) events (Figs. 23 and 24). In the following discussion, intensification rates in the range ± 0.2 dB min⁻¹ are regarded as “stagnant.” Such small changes in Z_{DR} column intensity are unlikely to be operationally detectable, as they fall below calibration limits for most weather radars (Ryzhkov et al. 2005). The second tornadogenesis event in ensemble member tor01 produced a TLV late in the model (at $t = 86$ min), so the 11-min time series was padded with NaNs, which were then excluded from the rate-of-change calculations.

For Z_{DR} column intensity, both the tornadic and nontornadic ensembles exhibited a period of intensifying several minutes before tornadogenesis or tornadogenesis failure, with mean rates reaching approximately 0.4–0.5 dB min⁻¹ about 3 min before the event (Figs. 23a and 24a). In the tornadic members, Z_{DR} column intensity weakened at tornadogenesis, with the mean rate decreasing to ≈ -0.4 dB min⁻¹ at the time of tornadogenesis (Fig. 23a). The tornadic Z_{DR} columns began intensifying again during the 2–3 min following tornadogenesis, suggesting some post-genesis reinforcement of the updraft. The nontornadic members showed weakening for the 2 min before tornadogenesis failure, with rates remaining near stagnant values (Fig. 24a). The strongest weakening in the nontornadic ensemble occurred 1 min after tornadogenesis failure, when the mean intensity decreased at a rate near -0.4 dB min⁻¹. Thus, although both ensembles showed intensifying before the event, the tornadic members were distinguished by more pronounced weakening during tornadogenesis, whereas the nontornadic members remained comparatively stagnant during tornadogenesis failure.

The rate of change of ZDR column area showed a clearer distinction between tornadic and nontornadic members (Figs. 23b and 24b). In the tornadic ensemble, ZDR columns were generally expanding during the 5 to 2 min before tornadogenesis, with expansion rates reaching approximately $5 \text{ km}^2 \text{ min}^{-1}$ (Fig. 23b). This pre-genesis expanding period indicates increasing areal coverage of the ZDR column before tornadogenesis. Near tornadogenesis, however, the mean area tendency reversed, and the ZDR columns began contracting. The strongest contracting occurred ≈ 1 min after tornadogenesis, with a mean rate near $-5 \text{ km}^2 \text{ min}^{-1}$. The

tornadic Z_{DR} columns then transitioned back to expanding 2–3 min after tornadogenesis, suggesting renewed broadening of the updraft following the initial genesis period. In contrast, the nontornadic ensemble exhibited mostly stagnant expansion or contraction rates throughout the analysis window (Fig. 24b). Mean area tendencies generally remained near $0 \text{ km}^2 \text{ min}^{-1}$, with only brief and relatively small departures from stagnant values. This indicates that nontornadic Z_{DR} columns did not undergo the same organized pre-event expanding or near-event contracting seen in the tornadic members.

Simulated ZDR Column Metrics Trends Tornadic

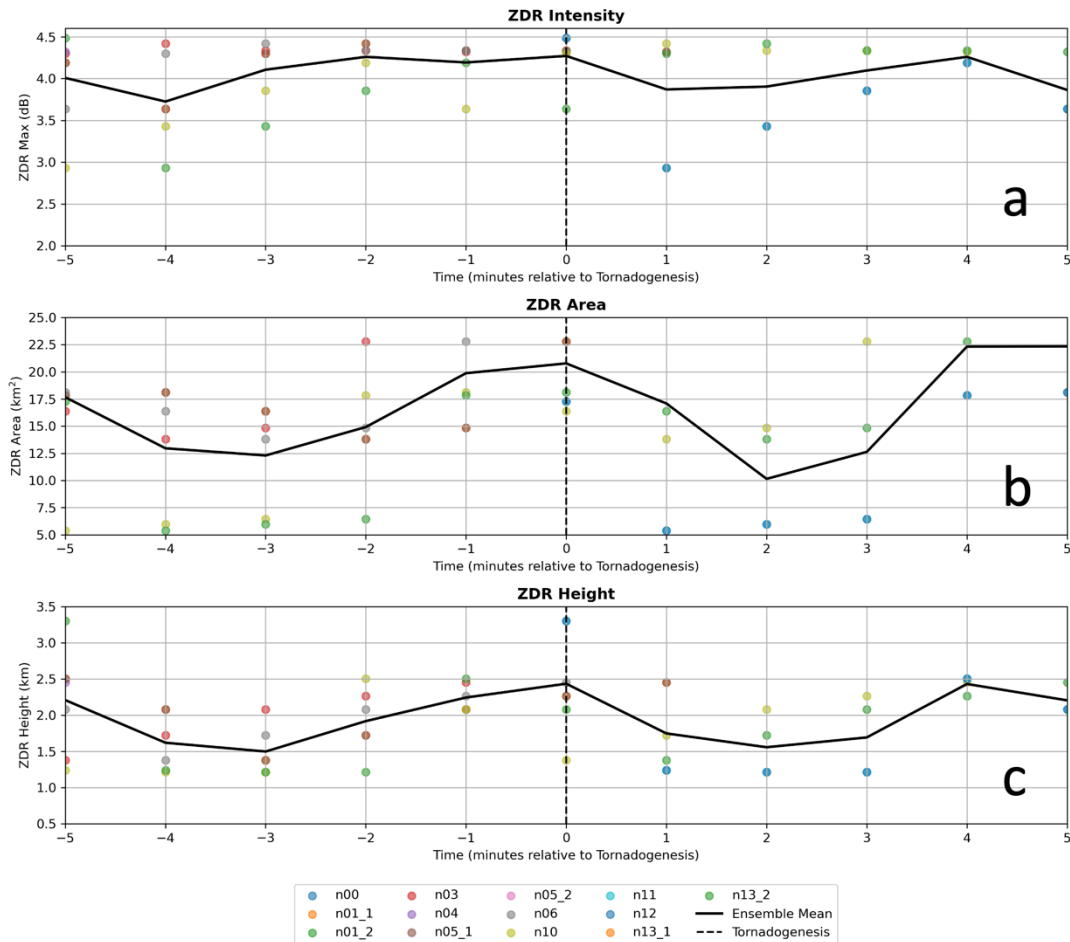


Figure 21: Z_{DR} column a) intensity, b) area and c) height for tornadic ensemble members (colored dots) and their mean (solid black line). Times are given in minutes relative to tornadogenesis.

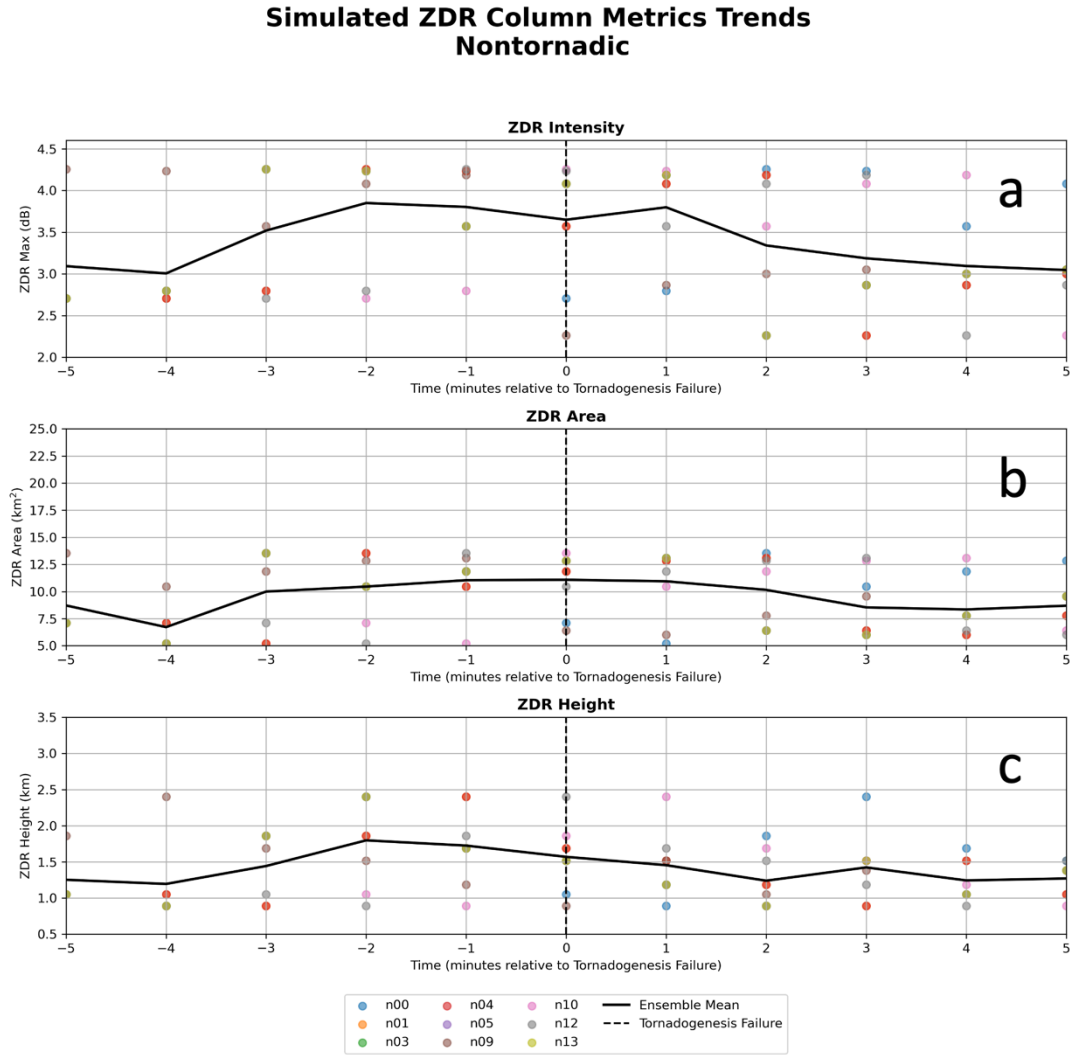


Figure 22: As in Fig. 21, but for nontornadic ensemble members and for times relative to tornadogenesis failure.

by weakening, contracting, and shrinking near tornadogenesis, and then renewed intensifying, expanding, or growing after tornadogenesis. Nontornadic members, in contrast, generally exhibited smaller and less systematic changes, especially in Z_{DR} column area and height. These differences suggest that tornadogenesis was associated with more dynamic changes in column structure near the time of vortex development.

6. Conclusions

In this study, we examined X-band Z_{DR} column metrics (intensity, area, and height) for three observed cases and an ensemble of 30 simulated supercells (half nominally tornadic, and half nominally nontornadic). This study was

undertaken to assess whether polarimetric radar observations might be used as a short-fuse predictor of tornadogenesis in supercells. Owing to a paucity of real datasets meeting our selection criteria (rapid volume scans during tornadogenesis and/or tornadogenesis failure), supplementation via simulation was justified.

Finally, Z_{DR} column height tendencies also differed between tornadic and nontornadic members (Figs. 23c and 24c). In the tornadic ensemble, Z_{DR} columns were generally growing during the 3 min before tornadogenesis, with mean growth rates reaching approximately 0.4 km min^{-1} (Fig. 23c). This pre-genesis growing period suggests an intensifying and vertically developing updraft. At tornadogenesis, however, the mean Z_{DR} column height decreased abruptly, indicating

that the column was shrinking at a rate near -0.6 km min^{-1} . This shrinking is consistent with the hypothesis of Picca et al. (2015), in which the Z_{DR} column may shrink near tornadogenesis in response to the development of a downward-directed perturbation pressure gradient force associated with an intensifying vortex. Following tornadogenesis, the Z_{DR} column resumed growing after approximately 2 min, again suggesting post-genesis updraft reintensification. In contrast, the nontornadic ensemble showed weaker and less organized growing and shrinking tendencies, with mean rates generally remaining near stagnant values throughout the 11-min window (Fig. 24c). Although brief periods of growing and shrinking occurred, these changes were smaller and less coherent than in the tornadic ensemble.

Overall, the rate-of-change analysis indicates that tornadic Z_{DR} columns underwent more organized and pronounced temporal changes than nontornadic Z_{DR} columns. Tornadic members tended to exhibit pre-genesis intensifying, expanding, and growing, followed

Our observational data set consisted of only three cases: Two tornadic storm cases, and one apparent tornadogenesis failure case. All of these storms were observed by different X-band radars, possibly having slight differences in calibration. Based on the overall case study results (also summarized visually in Table 4) we conclude:

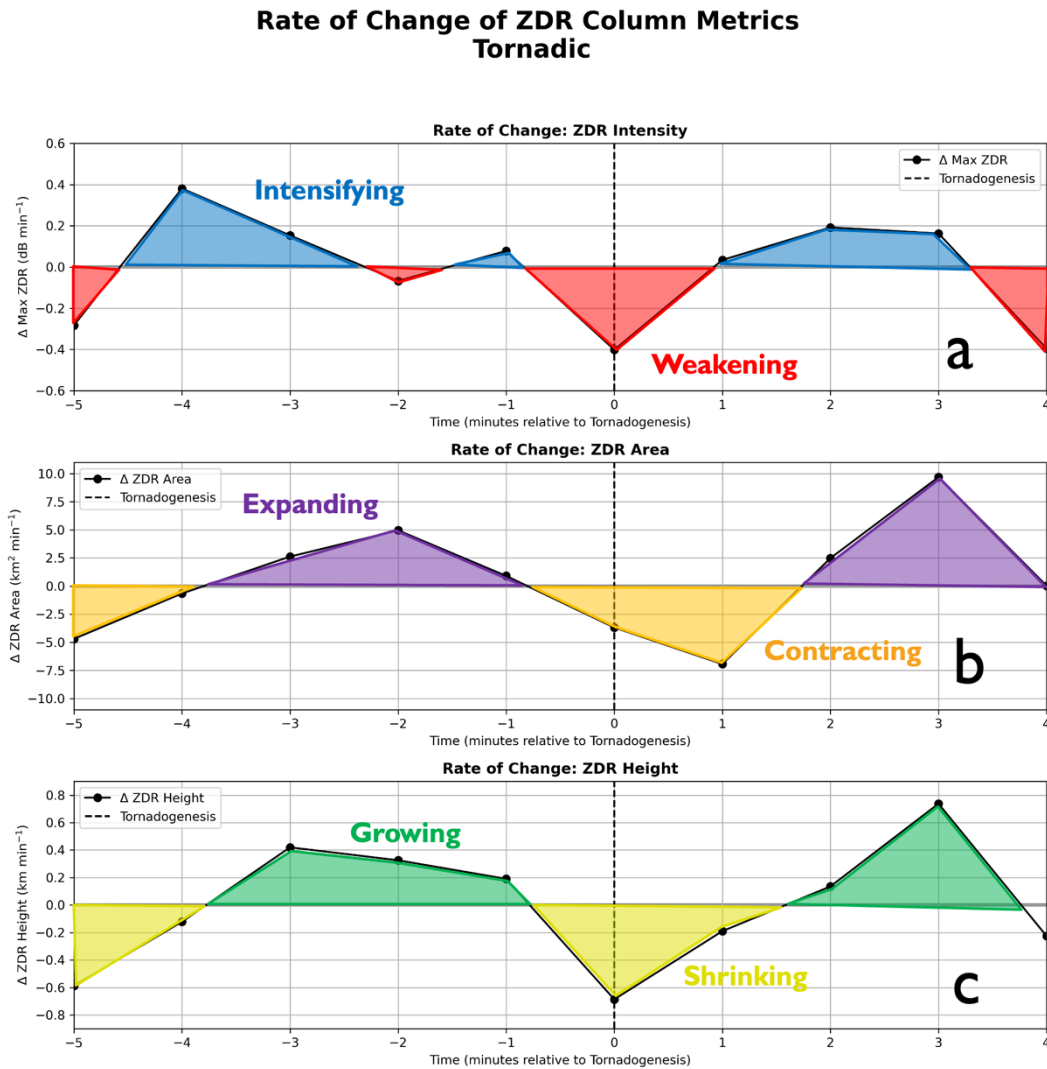


Figure 23: Rate of change of Z_{DR} column a) intensity, b) area and c) height for tornadic ensemble members.

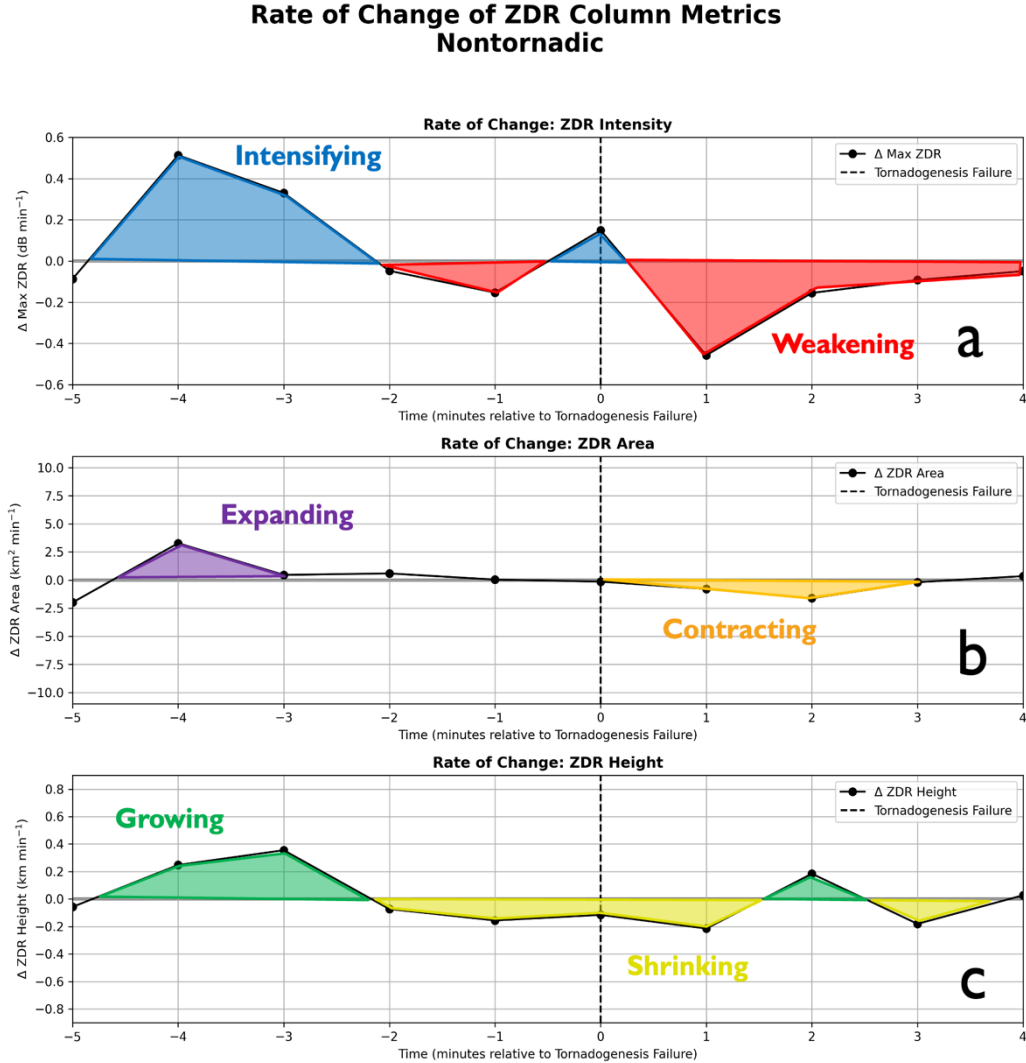


Figure 24: As in Fig. 23, but for nontornadic ensemble members.

1. In the Greensburg, KS tornadic supercell, an ongoing EF5 tornado was present through the entire analysis period. Z_{DR} columns exhibited periodic growth (in height) and decay cycles that appeared to lag in at least two satellite tornadogenesis events (Figs. 4, 5), suggesting multiple updraft pulses. However, Z_{DR} column area and intensity did not exhibit consistent behavior with respect to satellite tornadogenesis.
2. In the Luther–Carney tornadic supercell, Z_{DR} column height, area, and intensity all increased rapidly in the 4–5 min before tornadogenesis (Figs. 6, 7). This behavior suggests rapid growth (and intensification) of the storm’s primary updraft before tornadogenesis, potentially aiding vortex intensification via stretching, consistent with our hypothesis.
3. In the Greenville, TX nontornadic supercell, Z_{DR} column height and area also increased before tornadogenesis failure, while intensity stayed relatively steady (Figs. 8, 9). Unlike the preceding two cases, the Greenville storm exhibited a Z_{DR} column split immediately before tornadogenesis failure (a time defined as when low-level azimuthal shear, a proxy for vorticity, reached a maximum in the hook echo region). This Z_{DR} column split suggests some disorganization within the updraft which could be the cause of tornadogenesis failure. In the classic

conceptual model of a splitting supercell (Klemp 1987), the storm's primary updraft is split by a competing central downdraft, reducing each surviving updraft's capacity to stretch the vortex.

Overall, similar Z_{DR} column height and area trends were found in these three diverse supercells (multiple tornadic, tornadic, nontornadic) (Table 5). Z_{DR} column height tended to increase in advance of both tornadogenesis (Greensburg KS satellite tornadoes 7 through 10, Luther–Carney, OK tornado) and tornadogenesis failure (Greenville, TX storm) cases, but also decreased before Greensburg, KS satellite tornado 6. Similar results were found for Z_{DR} column areal coverage above the 0°C level (Table 7). In contrast, Z_{DR} column intensity increased in both tornadogenesis (Greensburg, KS satellite tornado 6, Luther–Carney, OK tornado) and tornadogenesis failure (Greenville, TX storm) cases, but also decreased in others (Greensburg, KS satellite tornadoes 7 through 10). **Based on this very small sample, we therefore propose that the X-band Z_{DR} column height, area, and intensity are of limited use for prognosing tornadogenesis on time scales of 5 to 0 min.** Repeating this analysis on a larger set of well-sampled Z_{DR} columns will clarify whether these results apply more generally.

Our simulation results offer a modest glimmer of hope for Z_{DR} column prognostic utility, however. Overall, the analyzed 13 tornadogenesis (i.e. TLV genesis) events had higher intensity, broader area, and taller height in the 5 to 0 min before tornadogenesis than did the nine instances of tornadogenesis failure. The Z_{DR} column intensity peaked, on average, 2 min before tornadogenesis, weakened at genesis, and then intensified again after genesis (Fig. 21). In the tornadic ensemble mean, the Z_{DR} column area expanded more quickly just before and just after tornadogenesis, indicating a well-organized, rapidly growing updraft. The nontornadic cases showed more stagnant metrics and rate of change in both Z_{DR} column area and height, with decreasing area and height trends before tornadogenesis failure (Figs. 22 and 24).

The presentation of the Z_{DR} column is affected by the chosen volume coverage pattern (Snyder et al. 2015) and volume update time, during which the storm may translate several km. If the entire radar volume is treated as though all of the data were collected instantaneously,

translational distortion may manifest as an artificial enhancement of Z_{DR} column height and area due to tilting. This factor was considered in our case selection criteria (volume update times of two min or less). Because RaXPol and UMass Skyler are capable of exceptionally rapid volume scans (~ 1 min or less), this effect is probably not measurable for the Luther–Carney, OK and Greenville, TX cases. Tanamachi et al. (2012) found that UMass X-Pol observations of the Greensburg, KS tornado did exhibit artificial tilt with height due to storm translation away from the radar. However, this distortion was corrected in the version of the data set used in that and our research.

Our present research has provided a path toward improved understanding of tornadic and nontornadic storms and their Z_{DR} column behavior. Future research directions include gathering more high spatiotemporal radar data collection above the 0°C level inside the updrafts of potentially tornadic storms. The In-situ Collaborative Experiment for the Collection of Hail In the Plains (ICECHIP; <https://icechip.niu.edu/>) field campaign, which concluded in July 2025, collected C-band and X-band radar observations above the 0°C level in multiple tornadic and nontornadic storms. Owing to ICECHIP's focus on hail, with more scans concentrated aloft, ICECHIP radar data are well suited to expand the present study.

We anticipate further results from future studies incorporating more high spatiotemporal resolution observations of Z_{DR} columns, and synthetic Z_{DR} observations using more advanced microphysics schemes. We look forward to future analyses devoted to Z_{DR} columns and other polarimetric signatures that may be useful for predicting tornadogenesis on short time scales.

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UMass Skyler under NSF grants ATM-0641201 and AGS-1741088, respectively, and Dr. Hugh Morrison of NCAR for his guidance on his two-moment microphysics scheme used for this research. Simulations were performed on Purdue supercomputing resources under NSF grant AGS-2146262 to Dr. Daniel Dawson. Thanks are due to Dr. Daniel Dawson and Dr. Scott Landolt for their guidance and assistance in completing this work as part of the first author's thesis committee.

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REVIEWER COMMENTS

[Authors' responses in *blue italics*.]

REVIEWER A (Joseph C. Picca):

Initial Review:

Recommendation: Accept with major revisions.

Summary: The authors present a combined observational and modeling study that analyzes potential relationships between Z_{DR} column metrics and tornadogenesis/failure. The observational aspect of the study examines data from three mobile X-band radar cases (two tornadic, one non-tornadic), while the modeling aspect examines ensemble output from the CM1 model (paired with a polarimetric emulator), driven by observed tornadic and non-tornadic soundings. Understandably, they found little signal within the observational dataset, limited especially by the small sample size. The modeling results found slightly more utility in Z_{DR} column metrics, with the tornadic samples generally presenting greater magnitudes of intensity, area, and height prior to tornadogenesis (relative to moments just before genesis failure in nontornadic cases).

The authors have performed an analysis that could advance the literature in understanding how the Z_{DR} column signature may relate to tornadogenesis/failure. Before the manuscript is ready for publication, however, they must resolve several significant issues with ambiguous/contradictory statements (especially regarding tornadogenesis/TLV-genesis and non-TLV vs. TLV failure, etc), figure clarity, and general lack of clarity in the writing. See the following notes for specific issues (both major and minor):

Major/Significant Issues: The [Introduction] paragraph that starts with “ Z_{DR} columns, which arise from microphysical processes...” needs significant updating. I understand you’re trying to detail the process of tilting of horizontal vorticity into the vertical, with subsequent stretching of that now-vertical vorticity. Across several sentences you repeat the description of this tilting and stretching process described in the literature, without any real synthesis. It seems like you’re attempting to describe the processes at both mid and low levels, but it’s quite confusing. This paragraph could likely be shortened considerably with a much clearer synthesis of what the literature has found up to now.

We thank the reviewer for identifying the lack of clarity and repetition in this paragraph. In response, we have substantially revised the text to provide a more concise and coherent synthesis of the relevant processes. The revised paragraph more clearly connects Z_{DR} columns to updraft intensity and emphasizes their role as indicators of dynamical processes, particularly tilting and stretching of vorticity that are associated with tornadogenesis.

[EDITOR’S NOTE: Original and revised text blocks omitted for brevity.]

Radar Specs Tables: I assume you have different data available for the different platforms, but I think you should make the tables consistent. In some instances, the metrics have different names (e.g., Table 1 shows ‘Maximum Azimuthal Scan Rate’ while Table 2 shows ‘Max Azimuthal Rotation Rate’). In other instances, what may be available in one table (e.g., Table 2: Dynamic Range) is not available in the others (Tables 1 and 3). These tables should be consistent in which radar metrics are presented, how they’re named, and the order in which the specs are presented. If you have data for one radar, but not another, then I’d suggest you either try to find that information or simply indicate ‘N/A’ for that radar field.

All tables have been updated to reflect the same parameters (wavelength, half-power beamwidth, peak power, PRF, max unambiguous range and velocity, range gate spacing, and max. azimuthal scan rate).

Analyses of Cases 1 and 2: Are we able to definitively state, from these data alone, that these metrics indicate a pulsing updraft? When we remove the spurious/artificial trend due to changing the VCP, it's tough to see much consistent trend with the remaining two satellite tornadoes. Additionally, how much can we infer regarding the times of two satellite tornadoes, with the primary tornado ongoing the entire time? Can we use the development of two satellites as definitive markers for potential changes in the updraft (and resultant signatures in the Z_{DR} column)? I'm not sure we can, as I'd expect the signal to be drowned out by the primary tornado. Perhaps the development of satellite tornadoes is consistent with a strengthening low-level vortex and thus you can make some of these connections between satellite tornadogenesis and Z_{DR} column trends, but if so, you fail to state that clearly. I think this needs to be described in more detail for there to be much worthwhile conclusion from this case.

We thank the reviewer for highlighting this important point. We have rewritten the statement to clarify the uncertainty.

I think this is further highlighted by your data from Case 2, which show all metrics increasing considerably through tornadogenesis. These are somewhat at odds with the results from Case 1, although as stated before, I'm not sure there is much signal from Case 1 anyway, given the dataset. I think this difference needs to be stated and resolved in the paper.

We thank the reviewer for the suggestion to compare Case 1 and Case 2. A comparison of the cases was added after discussion of the Case 2 metric performance.

Analysis of Case 3: At the beginning of the analysis, you state "...the Z_{DR} column increased in height, intensity, and area just prior to tornadogenesis failure (Figs. 8, 9)." Then later in the paragraph you state " Z_{DR} intensity and Z_{DR} column area decreased just prior to the Z_{DR} column split." According to Fig 9, tornadogenesis failure and the column split are at the same time, so these statements seem contradictory.

We added clarity to this perceived contradiction by adding the "column increased in height, intensity, and area in the 1 to 5 min period preceding tornadogenesis failure" and " Z_{DR} intensity and Z_{DR} column area decreased in the 1 min prior" to the column split.

Also, while you do define tornadogenesis failure later in the manuscript for the simulation cases, how is it defined here? Is it from the Tanamachi paper? Either way, it needs to be clarified.

We add an explanation for failure: "Here, tornadogenesis refers to a supercell that exhibited characteristics typically associated with tornadogenesis (e.g. a rotating updraft and hook echo) but did not produce a tornado despite a favorable dynamic and kinematic environment."

Lastly, you mention that the increase in the area is associated with the updraft split. If so, can we definitively say that the increase in area is counter to your hypothesis that we'd see notable differences between tornadogenesis and failure cases? Perhaps the trend in this case is just an artifact of the split and cannot be used as a marker here for updraft trends as they relate to tornadogenesis?

We thank the reviewer for pointing out this distinction. We have added the following regarding the column split: "As a result, the post-split increase in area likely reflects a geometric effect of the column splitting rather than a direct indication of updraft strengthening, suggesting the Z_{DR} column area may not serve as a reliable indicator of updraft evolution in this case."

The first sentence in section 5 seems to be missing some words...? Or at least it doesn't make sense as currently constructed. The next sentence then mentions the criteria for achieving tornadogenesis/TLV-genesis. I'll note that throughout the rest of section 5, you frequently refer to either tornadogenesis or TLV-genesis. I strongly suggest you stick to one or the other. You can define that TLV-genesis in the simulation counts as tornadogenesis for your study, but from there on, for clarity, you should then just use tornadogenesis.

This opening sentences were changed to, “For the purposes of this study, tornado-like vortex (TLV) genesis in the simulations is treated as equivalent to tornadogenesis in the observations, and hence, we use the term “tornadogenesis” for both processes. To assess potential relationships between tornadogenesis and Z_{DR} column behavior in the simulated ensemble of supercells, we applied the criteria of Coffey et al. (2017)” and a statement was added to clarify TLV-genesis is treated as the equivalent of tornadogenesis for our study.

Additionally, you state: “If a member produced vortices that approached, but did not meet, at least one of the tornadogenesis criteria, tornadogenesis failure was determined at the time of...”. What qualifies as ‘approached’? Any increase in the criteria? Presumably not. Was this a manual process that was performed? That’s fine, but you need to define the subjective process in the text.

We have changed the text to define “approached” where the thresholds mentioned are the Coffey et al. (2017) criteria.

On page 18, this really gets at the heart of the lack of clarity in your text regarding TLVs/tornadogenesis. I’m really confused by your description of which ensemble members were included. You state that all nontornadic members that produced TLVs after the 30-min threshold were included in your analysis. Yet your Fig 14 only shows nontornadic members with either ‘TLV failure’ or ‘TLV during spin-up.’ According to the figure then, there are no nontornadic members that should be included in your analysis. That said, the nontornadic members you say are included are clearly the ‘TLV failure’ members shown in the figure. But if there was TLV failure, how was there a TLV in the first place? Additionally, your Table 7 says those included nontornadic members were ‘Non-TLV producing.’ How were they included if they didn’t produce a TLV, though? And if they did produce TLVs, how are they considered tornadogenesis failure, since you’re using TLVs as proxies for tornadoes? In summary, there needs to be a significant overhaul of the definitions, descriptions, and terminology in the text before this is ready for publication. Otherwise, it really is unclear what your methodology is, as there are numerous contradictions. Given the confusion, it’s quite difficult to put much stock in / review section 5 as it currently stands.

We thank the reviewer for this important comment and agree that the original text lacked clarity and contained inconsistent terminology regarding TLVs and tornadogenesis. In response, we have substantially revised this section to clearly define TLV genesis as equivalent to tornadogenesis, distinguish TLV failure as a near-miss vortex that does not meet all tornadogenesis criteria, and explicitly state the inclusion and exclusion criteria for ensemble members.

[EDITOR’S NOTE: Most original and revised text blocks omitted for brevity.]

[Minor comments omitted.]

Second Review:

Recommendation: Revisions required.

Summary: The authors present a combined observational and modeling study that analyzes potential relationships between Z_{DR} column metrics and tornadogenesis/failure. The observational aspect of the study examines data from three mobile X-band radar cases (two tornadic, one non-tornadic), while the modeling aspect examines ensemble output from the CM1 model (paired with a polarimetric emulator), driven by observed tornadic and non-tornadic soundings. Understandably, they found little signal within the observational dataset, limited especially by the small sample size. The modeling results found slightly more utility in Z_{DR} column metrics, with the tornadic samples generally presenting greater magnitudes of intensity, area, and height prior to tornadogenesis (relative to moments just before genesis failure in nontornadic cases).

I appreciate that the authors have made significant improvements to the manuscript. They removed the confusion I had regarding tornadic/nontornadic/TLV-genesis/tornadogenesis and rendered the analysis and conclusions much more intelligible. I think the manuscript is close to being ready for publication, but there are still some organizational issues and other oversights that need to be addressed before publication.

Moderate Issues [substantive]:

Figure 5: The figure and caption do not mention the metric that each color corresponds to, leaving the reader having to guess. This is pretty important, as I couldn't easily connect your text commentary to trends in the time series. These legends are in Figs. 7 and 9, so eventually I was able to piece it together, but you need a similar legend in Fig. 5.

We thank the reviewer [for] noticing this. The metrics legend was cut off in Fig. 5 by the graphic sizing in Python. This has been fixed and the legend is now visible on the graphic.

Figure 5 and Table 5: Looking at Tanamachi et al 2012 and based on your Fig. 5, it looks like you paired Tornado 6 with 8, and 9 with 10, with 7 being left independent. Your Table 5 indicates (seemingly correctly) that 6 is independent (which makes more sense given the timing), while 7 is paired with 8, and 9 with 10. I'm guessing the issue is with your Fig. 5. Regardless, it's inconsistent with Table 5 (Tanamachi et al 2012). Perhaps you don't mean to communicate any pairings in your Fig. 5, but the way it's displayed, it seems to imply you're pairing them in a different manner than Table 5 states so this needs to be clarified.

We thank the reviewer for pointing out the lack of clarity here. Figure 5 has been updated to show that Tornado 6 happened independently, Tornado 7 and 8 occurred simultaneously with Tornado 7 having a shorter duration. I have used new colored shading for Tornado 8 and used a hatched outline for the duration of Tornado 7 to overlay on the Tornado 8 shading so this is clearer. As Tornado 9 and 10 occurred simultaneously and for the same durations, their shading has been left as is. Figure 5 was not meant to communicate pairings, simply the time and duration for which each satellite tornado occurred. The satellite legend has also been updated to reflect these changes.

I would also recommend appending numeric values (or at least a note for why there isn't a value) for Tornado 6's height trend in Table 5. It took me a second to understand what the sideways arrows meant.

(0.0 km/3 min) has been added next to the horizontal arrow for Greensburg Tornado 6 in Table 5 to help convey that there was no change in height prior to genesis.

With the discussion involving Figs. 21–24, I think the organization of your text could be improved. For most of p. 21, you discuss trends in the Z_{DR} column metrics for tornadogenesis / failure, and you reference Figs. 21–22 (which are time series of the magnitudes and admittedly you can infer trends from them). But then in the last paragraph, you state, “The mean rates of change for each Z_{DR} column metric (intensity, area, and height) were then computed for...” and you go into analysis of the trends on p. 22, but it seems like you're repeating what you've already stated? For example, you mention Z_{DR} column intensity trends of tornadogenesis failure cases, but then again [on the next page] you mention Z_{DR} column intensity trends of tornadogenesis failure events (as well as tornadogenesis events). There are the same redundancies with column area and height as well.

Overall, I think the analysis is a little redundant. Figures 21–22 use ‘Trends’ in their titles, but Figs. 23–24 are the actual derivatives, rates of change, so your text ends up discussing the same trends twice. I think you could either eliminate Figs 23–24 and related text (and just infer trends based on your time series in Figs 21–22) or utilize Figs. 21–22 purely for analysis of magnitudes relative to tornadogenesis/failure time and Figs 23–24 purely for trend analysis.

We thank the reviewer for noting the overlap between the mean ensemble trends and rate-of-change analyses. We agree that the distinction between these analyses needed to be clarified. We retained both

analyses because they highlight complementary aspects of the Z_{DR} column behavior: the mean ensemble trends emphasize differences in the magnitudes of the Z_{DR} column metrics between tornadic and nontornadic cases, whereas the rate-of-change analysis emphasizes how those metrics evolve with time relative to tornadogenesis or tornadogenesis failure.

To make this distinction clearer, we revised the rate-of-change figures by adding color coding to emphasize periods of intensifying and weakening, expanding and contracting, and growing and shrinking. We also rewrote the rate-of-change discussion using this terminology. In addition, we revised the mean ensemble trend discussion to focus more explicitly on differences in Z_{DR} column metric magnitudes relative to tornadogenesis or tornadogenesis failure.

[Minor comments omitted...]

REVIEWER B (David Moran):

Initial Review:

Recommendation: Accept with minor revisions.

Overview: Overall, I thought this was a well written paper. I really don't have any criticisms, but there was one thing that piqued my curiosity.

Substantive comment: What was the reasoning to use 0.7 as the lower limit on correlation coefficient when the data was filtered? A lot of the papers I've read use 0.8 and I was just curious why the difference.

We have added the following text in the revised submission: "Owing to a data quality issue with the UMass X-Pol Greensburg ρ_{HV} data specifically (detailed by Tanamachi et al. 2013), the ρ_{HV} threshold of 0.7 is relaxed relative to higher values (0.8 or 0.9) that are usually used in polarimetric radar data analysis.."

Second Review:

Recommendation: Accept with minor revisions.

Overview: With the comments from the other reviewer, the manuscript is much improved.

[Minor comment omitted...]