Reducing Tornado Warning False Alarm Rates across the National Weather Service Memphis County Warning Area

Preston Jewel Bradley

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REDUCING TORNADO WARNING FALSE ALARM RATES ACROSS THE NATIONAL WEATHER SERVICE MEMPHIS COUNTY WARNING AREA

by

Preston Bradley

A Thesis

Submitted in Partial Fulfillment of the Requirements for the Degree of

Master of Science

Major: Earth Sciences

The University of Memphis

December 2020
Abstract

Tornado detection has improved in recent years due, in part, to the deployment of dual-polarization radar technology. Despite these improvements, false alarm rates (FAR) for tornado warnings remain high over the Memphis, TN County Warning Area. The purpose of this research was to use a suite of radar products and storm environmental parameters in an effort to decrease tornado warning FAR over the Mid-South. The Memphis National Weather Forecast Office County Warning Area (CWA) serves as the study area for this research. Previous research has shown that storm mode and environment can impact FAR. Therefore, by combining radar products and storm environment, tornadic and non-tornadic events could be distinguished and the FAR could be reduced. Results suggest that some combination of rotational velocity and a modified energy-helicity index that places more emphasis on shear and is sensitive to low convectively available potential energy (CAPE) values might aid in reducing tornado warning FAR.
Acknowledgments

I want to thank my committee for their support and feedback throughout this process. If it was not for my advisor, Dr. Dorian Burnette, and my committee Dr. Arleen Hill and Dr. Mike Brown, I would not have been able to complete my thesis. Thank you, Dr. Burnette, for being patient with me, and helping me with my data analysis. I want to thank Dr. Hill for the moral support and for helping me improve as a writer. I want to thank Dr. Brown for helping me become the meteorologist I am today.

I want to also thank the National Weather Service in Memphis, TN for taking time out of their schedule to give feedback and giving feedback. I also want to thank them for giving me the opportunity and allowing me volunteer at the office. I want to thank Dr. Patrick Marsh from the Storm Prediction Center for his support and providing the data necessary for the thesis. Without them, this thesis would be what it is.

Lastly, I want to thank my mom and Alex Kent for their unconditional support through this process. I also want to thank my fellow graduate students from the Earth Sciences for their support and feedback along the way. I appreciate you listening to me and helping me through my master’s program. I want to thank them for answering my questions and being there for me.
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1. Introduction

Tornadoes happen throughout the year, day or night, and can have devasting impacts on human life and property. While tornado detection has improved with the advances of radar technology and increased storm reports, false alarm rates (FAR) for tornado warnings remain an issue. FAR is calculated by the ratio of tornado warnings with no confirmed tornadoes to the total number of tornado warnings (Brotzge et al. 2011). The Memphis National Weather Service (NWS) County Warning Area (CWA) had a FAR of 83% between the years of 2012-2018 (https://mesonet.agron.iastate.edu/cow/). Over the same period, the Little Rock and Nashville NWS had similar FAR percentages (https://mesonet.agron.iastate.edu/cow/). Brotzge et al. (2011) found that a combination of population density, distance to radar, time of day/year, county size and number of warned tornadoes contribute to the high FAR across the contiguous U.S.

This study focused on the County Warning Area (CWA) for the Memphis National Weather Service Forecast Office (NWSFO). This CWA is composed of counties in eastern Arkansas, northern Mississippi, western Tennessee, and portions of the Missouri Bootheel (Figure 1). FAR is a major concern for the Memphis NWSFO given that high FAR could lead to higher fatalities (Brotzge et al. 2013; Donovan 2014). The life-safety implications of FAR served as the primary motivation for this exploration of storm environments and tornado parameters. The objective of this work was to identify differences between tornadic and non-tornadic storms using radar products and storm environment data near tornadogenesis. Results are relevant to the goal of decreasing FAR and improving tornado detection, thereby increasing life-safety.
Literature Review

The methodology for this research was developed from and informed by multiple studies on both tornado detection and storm environment. Falk and Parker (1998) improved the rotational shear nomogram for tornadoes by including the diameter of the mesocyclone, which wasn’t part of the original nomogram developed by Andra (1997). The two formulas that were used in their study were rotational velocity

\[ V_{rot} = \frac{|V_{in} + V_{out}|}{2} \]  \hspace{1cm} (1)

and rotational shear

\[ S_r = \frac{2V_{r}}{D} \]  \hspace{1cm} (2)

(Falk and Parker 1998). In these equations, \( V_{in} \) is the inbound velocity value, \( V_{out} \) is the outbound velocity value, \( V_{r} \) is the \( V_{rot} \), and the \( D \) is the diameter from the maximum \( V_{in} \) to the maximum \( V_{out} \) (Falk and Parker 1998). The Falk and Parker (1998) study was done over a five-year period from 1994-1998 over the Shreveport, Louisiana CWA. Out of the 50 mesocyclones analyzed, 32 produced a tornado. Falk and Parker (1998) were also able to improve the tornado diagram and label the categories as minimal mesocyclone, tornado possible, tornado probable, and tornado likely. (Figure 2).

Considerable research has demonstrated that various measures of the storm environment can be used to assess the potential for thunderstorms to produce tornadoes (e.g., Rasmussen 2003, Craven and Brooks 2004). These measures of the storm environment have been combined with radar signatures to further aid in the discrimination between tornadic and non-tornadic thunderstorms. A recent study done by Davis and Parker (2014), investigated radar climatology
of tornadic and non-tornadic vortices in high-shear, low convectively available potential energy (CAPE) environments across the Mid-Atlantic and Southeastern United States. They used events where tornadoes occurred, the 0-6-km bulk wind shear difference was 35 knots or greater, and CAPE values were less than 500 J/kg. Davis and Parker (2014) manually identified the reflectivity signatures and azimuthal shear, which is the same as the rotational shear from Falk and Parker (1998), and reflectivity signatures. Reflectivity signatures were used to classify the storm as a supercell or non-supercell. Davis and Parker (2014) note that most non-supercells in their dataset were quasi-linear convective systems (QLCS). Davis and Parker (2014) looked for a hook echo, weak-echo region (WER), and bounded weak-echo region (BWER) to help identify supercells. For non-supercells, the researchers identified a rear-inflow notch, forward-inflow, gust-front cusp, and “broken S” signatures (Figure 3). A statistically significant difference in azimuthal shear between tornadic and non-tornadic vortices within 60 km of the radar was detected for non-supercells. Davis and Parker (2014) were not able to determine a statistically significant difference between tornadic and non-tornadic vortices for supercells. However, Smith et al. (2015), were able to establish a relationship between peak \( V_{\text{rot}} \) and the Enhanced Fujita Scale for all convective modes, where the significant tornado parameter and \( V_{\text{rot}} \) increase the probability for greater EF-scale damage increase.

Rogers et al. (2016) developed a mean rotational velocity for QLCS tornadoes through their research of QLCS tornadoes across the Lower Mississippi Valley. Rogers et al. (2016) calculated the \( V_{\text{rot}} \) of 138 QLCS tornadoes that occurred between 2009-2013, and found mean values ranges from 31-35 knots. They also note that QLCS tornadoes were more likely in low CAPE environments between October and May. Rogers et al. (2016) provide guidance for using
$V_{rot}$ to identify QLCS tornadoes and identify a possible relationship between the $V_{rot}$ and the distance between the radial velocities that needs further research.

**Purpose/Importance**

The importance of the study is to decrease the FAR and improve tornado detection. FAR is a major concern for the Memphis NWSFO. Brotzge et al. (2013) and Donavon (2014) suggest that high FAR could lead to higher fatalities. Thus, by decreasing FAR and improving tornado detection, a decrease the number of deaths may occur.

**Hypotheses**

Two hypotheses were examined in this research. First, radar and storm environment parameters can be identified in the dual-polarization era that could decrease the tornado warning FAR across the Mid-South. Second, the storm environment has an influence on $V_{rot}$ values. The Smith et al. (2015) study was completed over the contiguous United States. However, more QLCS tornadoes have been found to occur east of the Great Plains (Trapp et al. 2005), and these events seem to be associated with stronger shear and weaker buoyancy (i.e., high-shear, low CAPE; Thompson et al. 2012). Therefore, assessing the combined radar signatures from the dual-polarization era and storm environment data by region may yield important differences that impact tornado detection and the tornado warning FAR.
2. Methodology and Data

*Tornado Data*

A project dataset was created for the purpose of this study. All tornado events occurring in the Memphis CWA between 1950 and 2019 are included. Variables for each tornado event include: starting and endpoints, along with time and date of occurrence, track, length, max width, and a short summary of each tornado. The tornado data for this research were derived from the Memphis NWSFO Tornado Database. The database hosted by the Mississippi State University was used to access the tornado reports for the Memphis CWA (National Weather Service Tornado Database; http://www.midsouthtornadoes.msstate.edu).

Since dual-polarization was installed in late 2011 at the radar sites around the study area, analyses were restricted to the years 2012 to 2018, so the dual-polarization products could be included. This subset consisted of 99 tornadoes along with 50 tornado days. A tornado day was defined as a day where at least one tornado occurred (Elsner et al. 2015). Only tornadoes with a track length greater than or equal to a one mile were analyzed to limit the potential for a non-tornadic wind event. With these criteria applied, the total number of tornadoes available for analysis decreased to 65 and the number of tornado days decreased to 33 tornado days. This resulting subset of tornado events serves as the project dataset and is considered the confirmed cases. These data were subsequently considered with the radar and storm environment data (detailed below) to establish potential relationships between key variables and tornado ranking, which will then be used on a dataset of test cases.
Radar Data

The radar data were downloaded using the NOAA Weather and Climate Toolkit program (available at https://www.ncdc.noaa.gov/wct/), while the Gibson Ridge (GR2Analyst) program (available at http://www.grlevelx.com/) was used to analyze the radar products. The radar products analyzed included storm relative velocity, reflectivity (dBZ), differential reflectivity (ZDR), correlation coefficient (CC), and normalized rotation (NROT). Storm relative velocity is radar velocity data with storm motion removed in order to identify areas of possible rotation that could be hidden by the storm motion itself. Reflectivity is the energy reflected back to the radar. ZDR and CC are the two dual-polarization products that were used in this study. Dual-polarization allows the radar to send out two pulses of energy, one in the vertical direction and the second in the horizontal direction. ZDR is the logarithm ratio of the horizontally polarized reflectivity to the vertically polarized reflectivity. CC provides a measure of the consistency of the shapes and sizes of targets within the radar beam, where lower values signify varying shapes and sizes. NROT is calculated from normalizing the azimuthal shear by the area of the bins used in the computation of azimuthal shear (Lemon and Umscheid 2008). It is a radar product computed within the GR2Analyst program only and is not used by the Memphis National Weather Service forecasters regularly. With the exception of NROT, these are the primary radar products that are used to analyze the potential for tornado production within severe local storms.

Storm relative velocity was used to derive the values of $V_{rot}$. The GR2Analyst program computes the values for $V_{rot}$ and NROT of the mesocyclone and tornado vortex signature. For the $V_{rot}$, the maximum values for $V_{in}$ and $V_{out}$ had to be within four nautical miles of each other. For NROT, the maximum values that were co-located with the $V_{rot}$ values were selected. Reflectivity was used to help to define the storm mode, e.g., Figure 3, and locate any potential
tornadic debris ball signature. ZDR and CC values, were used to help in confirm any tornadic debris signature. The National Weather Service Warning Decision Training Branch Division (WDTD) suggests the following values on radar, co-located with the circulation on storm relative velocity, provides confirmation a damaging tornado is in progress (i.e., a tornadic debris signature): reflectivity values greater than or equal to 35 dBZ, ZDR values close to zero, and CC values of less than or equal to 0.90 (WDTD 2016). Figure 4 shows an example of a tornado debris signature on radar. Due to the different radar modes, only the 0.5° tilt was used to ensure consistency from volume scan to volume scan. Only tornadoes that were within 65 miles of the closest radar site were analyzed due to the 0.5° tilt of the radar beam and range folding, where low-level rotation on radar cannot be determined. Because of these limitations, the number of tornadoes that could be analyzed in this study dropped from 65 to 41. Finally, the tornadoes start, peak and end times were analyzed.

Storm Environment Data

The Storm Prediction Center’s mesoscale analysis products were used to collect data on the storm environment (Thompson 2019). These data were derived by merging surface data with the latest Rapid Update Cycle (RUC) model forecast before May 2012 and the latest Rapid Refresh (RAP) model forecast since May 2012. The parameters used in the analysis include Lifted Condensation Level (LCL) height, Level Free Convection (LFC) height, mixed layer-CAPE (MLCAPE), surface-based CAPE (SBCAPE), effective bulk shear, and the Energy Helicity Index (EHI) from 0-1 km and 0-3 km. LCL heights are when the air parcel becomes saturated and is used to estimate the cloud base. LFC height is when the lifted air parcel accelerates freely to the equilibrium level, and Davies (2004) found a decrease in tornado frequency when LFC heights were high. MLCAPE assumes the air parcel starts ascending
somewhere in the lowest 100 mb of the atmosphere, while SBCAPE assumes the air parcel starts ascending at the surface. Both MLCAPE and SBCAPE measure the instability over a region. Effective bulk shear is the difference in the wind vectors between the effective inflow base, defined as the level where CAPE ≥ 100 J/kg and CIN ≥ -250 J/kg, and the equilibrium level (Thompson et al. 2007). Thompson et al. (2004) note that the effective bulk shear along with radar signatures can help determine storm mode. EHI was originally developed by Hart and Korotky (1991) to identify the tornado potential within the lowest 3 km (i.e., 0-3 km) by combining a wind shear and CAPE, but Rassmussen (2003) added a different calculation of the same two parameters within the lowest 1 km only (i.e., 0-1 km) to improve the EHI’s ability to discriminate between tornadic and non-tornadic storms. Both computations were used in this study. Many of these parameters are involved in the computation of the significant tornado parameter (STP; Thompson et al. 2012). STP is a unitless value that measures the likelihood of seeing a significant tornado (EF-2 or greater; Thompson et al. 2012). All storm environment data were obtained from Dr. Partick Marsh at the Storm Prediction Center (SPC). Since the storm environment products from both the RUC and the RAP update hourly, data on the storm environment during specific hour of the tornado’s formation were analyzed. This method allows for consistency with a real-time operational storm warning mode. The tornado’s latitude, longitude, time and date of occurrence were used to extract the values for each of the storm environment parameters from the RAP and RUC.

Statistical Analysis of Confirmed Cases

Graphs between the maximum $V_{rot}$ and the diameter between $V_{in}$ and $V_{out}$ during each tornado’s start point and peak times were constructed to determine if any relationship between the two values existed. Box and whisker plots were then made for all radar products and storm
environment variables to determine the distribution of the values and compare those distributions with previous studies. Finally, forward and backward stepwise regression modeling was used to determine the radar products and storm environment data that were best at predicting the EF-rating of each tornado. The Akaike information criterion was used to select the best regression model using the fewest predictors possible (Akaike 1974; Wilks 2006).

**Test Cases**

A second dataset, purposely withheld from the analyses above, was collected and compared to the confirmed cases. This dataset was composed of all the tornado warnings in the Memphis NWSFO CWA during the year of 2019 and was compiled using Iowa State’s National Weather Service Storm Base Warning Verification database. (http://mesonet.agron.iastate.edu/cow/). Iowa State’s database has all the tornado warnings that were issued since June 8th, 2005. Tornadoes were confirmed by using the National Weather Service tornado database for the year 2019. As in the confirmed cases, only tornado warnings that fell within the 65 nautical miles of a radar site were analyzed. For tornado warnings that were extended, the extension was treated as a separate warning. The same storm environment parameters and the radar products were then used to analyze these tornado warnings. In total, 35 storms were analyzed in this test cases dataset. Combining the 41 confirmed and the 35 test cases, the total sample size for this study was 76.

**Statistical Analysis of Test Cases**

Box and whisker plots were constructed for all radar products and storm environment variables for two sub-samples—tornadic and non-tornadic storms. They were also compared against results from the confirmed cases and from the published literature. Forward and
backward stepwise regression modeling was also used to determine the radar products and storm environment data that predicted whether a tornado occurred. The data for the predictand was setup such that values of one and zero were used to denote whether a tornado did or did not occur, respectively. Once again, the Akaike information criterion was used to select the best regression model using the fewest predictors possible (Akaike 1974; Wilks 2006).

Statistical Analysis of Vrot and Storm Environments

A second hypothesis concerned whether the storm environment had an influence on \( V_{rot} \) values. In order to test this hypothesis, forward and backward stepwise regression modeling was run on both the starting point and peak intensity times for all tornadoes from both datasets. Storm environmental variables that were best at predicting \( V_{rot} \) were identified using the Akaike information criterion (Akaike 1974; Wilks 2006).

3. Results

Box and Whisker Plots

A box and whisker plot of surface-based CAPE (SBCAPE) for the confirmed tornadoes is presented in Figure 5. The median value is around 500 J/kg, while the mean value is closer to 1,000 J/kg. The mixed-layer CAPE (MLCAPE) has a similar median, but the mean has shifted closer to the median around 500 J/kg (Figure 7). In the MLCAPE, there is an outlier above 2,500 J/kg. Overall, SB and MLCAPE show that most tornadoes have occurred in low CAPE environments, which is defined where MLCAPE values are 1,000 J/kg or less (Anderson-Frey et al. 2019). When using the test cases, the data were separated into non-tornadic and tornadic storms. These two sub-samples are compared for both SB and MLCAPE in Figures 6 and 8, respectively. There is a slight shift downward in the median values for the tornadic storms for
SBCAPE, but the mean values were about the same. The median and mean values for the MLCAPE had a slight shift upward for the tornadic storms, but the distribution falls within the non-tornadic distribution.

LCL heights for the confirmed tornadoes had mean and median values of around 700 meters (Figure 9). Similar to the CAPE values, the distribution of LCL heights for tornadic storms fell into the same distribution as the non-tornadic storms for the test data (Figure 10). However, the box and whisker plot for the tornadic storms shows a more restricted range to the data than the non-tornadic storms. The maximum LCL for the tornadic storms, excluding the outliers, is at 800 meters, whereas the maximum for the non-tornadic storms is around 1,200 meters (Figure 10).

The median and mean values for LFC heights are around 2,000 meters for the confirmed cases (Figure 11). The LFC heights mean and the median values for the tornadic storms are around 1,500 meters. The median value for the non-tornadic storms is about the same as for the tornadic, but the mean for the non-tornadic storms is shifted upward to about 2,000 meters (Figure 12).

Effective bulk shear for the confirmed cases has a mean and median value of around 55 knots. However, there is an outlier of zero knots in the confirmed cases (Figure 13). In the test cases, the non-tornadic storms have a median value slightly above 50 knots and a mean value below 50 knots (Figure 14). Figure 14 shows that the tornadic storms have slightly higher values for both the mean and median of around 55 knots. Also, the 25th percentile is much higher in the tornadic storms than in the non-tornadic storms (Figure 14). However, the distribution for tornadic storms does fall into the same distribution as the non-tornadic storms.
In the effective layer STP, the median is below one, while the mean value is slightly above one for the confirmed cases (Figure 15). For the test data, the median value of the non-tornadic storms is below 0.5, while the mean is around 1.5 (Figure 16). For the tornadic storms, upward shifts in the mean the mean and median values is above two and around 2.5, respectively are noted. The distribution of the tornadic storms still falls into the same distribution as the non-tornadic storms, but the majority of the tornadic storms have a value of one or greater. The fixed-layer STP for the confirmed cases has median value of around 0.5 with a mean value of 1.5 (Figure 17). For the test cases, the non-tornadic storms have a median below 0.5 while the mean is around one (Figure 18). The tornadic storms have a median above one, while the mean is above 1.5. Just like in the effective layer STP above, most of the tornadic storms have a fixed layer STP of one or higher (Figure 18).

EHI from 0-1 km for the confirmed cases had a median value slightly below one and a mean value around 1.5 (Figure 19). Figure 20 shows the non-tornadic storms have a median value above 0.5, while the mean value is at one. The tornadic storms in the test data have a median value slightly above one with the mean value of 1.5 (Figure 20). Figure 20 also shows that majority of tornadic storms have 0-1 km EHI values of one or more. EHI values from 0-3 km for the confirmed cases have a median value above one and a mean close to two (Figure 21). Figure 22 shows the non-tornadic storms in the test cases have a median value slightly below one and a mean around 1.5. For the tornadic storms, the mean and the median are shifted up toward two and 1.5, respectively. Finally, note all that all the values of 0-3 km EHI were above one for the tornadic storms in the test dataset (Figure 22).

The starting $V_{rot}$ from the confirmed tornadoes has a median and mean value of around 38 knots (Figure 23). There is one outlier with a $V_{rot}$ of about 70 knots. The non-tornadic storms
from the test data have median and mean values of around 30 knots and a maximum value just under 40 knots (Figure 24). The tornadic storms have a much higher mean and median value of around 45 knots, with an outlier of near 80 knots. In fact, the whole box plot for the tornadic storms is shifted upward compared to the non-tornadic storms. The starting NROT values for the known cases have a median value slightly above one and the mean value of around 1.2 (Figure 25). For the test cases, the non-tornadic storms have a mean and median value below one, while the values for the tornadic storms were above one (Figure 26).

The peak $V_{rot}$ for the confirmed cases has a median and mean value of around 45 knots (Figure 27). The confirmed cases have two outliers with values at 85 knots and 100 knots. Figure 28 shows that the tornadic storms from the test cases have median and mean values at 50 knots with the two outliers around 85 knots. For the non-tornadic storms, the median and mean values are around 35 knots, which is much lower than the tornadic storms. As for the peak NROT values, the confirmed cases had median and mean values of around 1.25 (Figure 29). The non-tornadic storms from the test cases have a mean and median value of around one, while the tornadic storms have NROT mean and median values considerably higher (Figure 30).

The starting reflectivity values for the confirmed cases has a median value of about 45 dBZ and a mean value of about 43 dBZ (Figure 31). The starting reflectivity values for the test cases have the non-tornadic storms falling within the same distribution as the tornadic storms (Figure 32). Figure 32 shows tornadic storms having slightly higher median and mean reflectivity values than the non-tornadic storms. For the peak reflectivity values, the box plot for the confirmed cases has similar median and mean values as the starting reflectivity values (Figure 33). Similar to the test cases for the starting reflectivity values, the non-tornadic storms and the tornadic storms fell into the same distribution (Figure 34). The box and whisker plot for
peak reflectivity values are more restricted for the tornadic storms with all storms having a reflectivity value above 40 dBZ.

The confirmed cases have a median value of 0.97 and a mean value of about 0.92 for the CC for the starting point. Figure 35 shows the mean being well outside the box of the box and whisker plot. This suggests the CC values are skewed toward higher CC values in the confirmed cases. The box and whisker plot also shows multiple outliers for the starting CC with the lowest value being around 0.45. The test cases show a shift upwards for the non-tornadic storms for the CC at the starting point (Figure 36). The tornadic storms have a lower CC for both the mean and the median. The mean and median for tornadic storms are around 0.85. The non-tornadic storms have a mean value of about 0.90 and a median value of 0.95. The box and whisker plots for tornadic and non-tornadic storms were not as restricted as the confirmed cases (Figure 36 vs 35).

For peak intensity, the confirmed cases have a median of 0.95 and a mean about 0.85 for CC (Figure 37). The mean did not fall outside the box plot, but there is some skewness in the values toward higher values of CC. Figure 37 shows some outliers with the lowest being around 0.20. The test cases show the box plot being more restricted for the non-tornadic storms than the tornadic storms (Figure 38). The mean for the non-tornadic storms fell outside the box plot similar to that of the confirmed cases for the starting point again suggesting skewed data toward higher values of CC. The non-tornadic storms have a median value of about 0.95 and a mean value of about 0.90. Tornadic storms have a median value of 0.85 and a mean value about 0.75. The majority of the tornadic storms did not fall into the same distribution as the tornadic storms.

The starting ZDR has a median of 1.25, a mean of about 1.20, and an outlier at -1.5 for the confirmed cases (Figure 39). For the test cases, the non-tornadic storms have a median of about 1.5 and a mean of about 1.4 (Figure 40). The tornadic storms have a median of 1.25 and a
mean of about one. The non-tornadic storms have a more restricted box plot and an upward shift in the median and mean. The distribution of the tornadic storms and non-tornadic storms begins to overlap each other around 1.25.

The confirmed cases for peak ZDR have a median of one and a mean of about 0.90 (Figure 41). Comparing the confirmed cases, the peak ZDR values had a lower median and mean than the starting ZDR values (Figure 41 vs Figure 39). A downward shift in both the mean and median between the starting ZDR and peak ZDR values for the tornadic storms in the test cases dataset is also noted (Figure 40 vs Figure 42). The tornadic storms have a median of 0.69 and a mean of 0.90 (Figure 42). The non-tornadic storms show a negligible change in the median and mean values in the peak ZDR from the starting ZDR (Figure 42 vs Figure 40).

**Regression Model**

Stepwise regression modeling was used to identify the radar and storm environment variables that predicted tornado strength (EF-Scale). The first two regression models derived were from the starting point of the tornado. For the confirmed cases, the regression model is:

\[
EF = (0.0228) \cdot V_{rot} - (0.0134) \cdot CC + (0.5151) \cdot ZDR + (0.0004) \cdot M1CP + (0.0003) \cdot MLFC - 0.0158 \cdot DBZ + 0.565, \tag{3}
\]

where is the EF-Scale of the tornado, \( V_{rot} \) is the rotational velocity, CC is the correlation coefficient, ZDR is the differential reflectivity, M1CP is the mixed-layer CAPE, MLFC is the mixed layer LFC, and the DBZ is the base reflectivity. The equation has an adjusted \( R^2 \) value of 0.3852, and the most significant variables are \( V_{rot} \), ZDR and MLFC (Table 1). For the test cases the regression model is:
\[ \text{Tornado} = (0.0385)(V_{\text{rot}}) - (0.2402)(ZDR) + (0.0084)(CC) - (0.0004)(SBCP) + (0.0007)(M1CP) - (0.0006)(MMLH) - (1.9676)(EHI1) + (1.5675)(EHI3) - 1.3505, \] 

where tornado denotes whether or not a tornado occurred (value of zero or one). \( V_{\text{rot}} \) is the rotational velocity, ZDR is the differential reflectivity, CC is the correlation coefficient, SBCP is the surface-based CAPE, M1CP is the mixed-layer CAPE, MMLH is the mixed layer LCL height, EHI1 is the 0-1 km EHI, and the EHI3 is the 0-3km EHI. The equation has an adjusted \( R^2 \) value of 0.6015, and the most significant variables are \( V_{\text{rot}} \), ZDR, SBCP, EHI1, and EHI3 (Table 2).

The second two regression models derived were for the peak intensity of the tornado. For the confirmed cases, the regression model is

\[ \text{EF} = (-0.1903)(\text{Diameter}) + (0.0204)(V_{\text{rot}}) + (0.0549) + (0.0005)(SBCP) - (0.0006)(M1CP) - (0.0014)(MMLH) + (0.0199)(ESHR) - (0.8299)(SIGT) + (0.3448)(STPC) + (0.4643)(EHI3) - 2.4501, \] 

where EF is the EF-Scale of the tornado, Diameter is the diameter from the \( V_{\text{in}} \) and \( V_{\text{out}} \), \( V_{\text{rot}} \) is the rotational velocity, SBCP is the surface based CAPE, M1CP is the mixed-layer CAPE, MMLH is the mixed layer LCL height, ESHR is the effective bulk shear, SIGT is fixed layer STP, STPC is the effective layer STP and the EHI3 is the 0-3km EHI. This equation has an adjusted \( R^2 \) value of 0.4984, and the most significant variables are \( V_{\text{rot}} \), DBZ, MMLH, EHSR SIGT, STPC, and EHI3 (Table 3). For the test cases, the regression model is

\[ \text{Tornado} = (-0.1194)(\text{Diameter}) + (0.0254)(V_{\text{rot}}) - (0.0005)(SBCP) + (0.0005)(M1CP) - (0.8936)(SIGT) + (0.6746)(EHI3) - 0.4656, \]
where tornado denotes whether or not a tornado occurred (value of zero or one). Diameter is the
diameter from the \( V_{in} \) and \( V_{out} \), \( V_{rot} \) is the rotational velocity, SBCP is the surface based CAPE,
M1CP is the mixed-layer CAPE and the EHI3 is the 0-3km EHI. This equation has an adjusted
\( R^2 \) value of 0.3293, and the most significant variables are \( V_{rot} \), SIGT and EHI3 (Table 4).

Finally, all tornadoes in both confirmed cases and test cases were combined into single
datasets for start point and peak intensity in order to test the influence of storm environment
parameters on \( V_{rot} \). The regression equation for the starting point is

\[
V_{rot} = (-0.0071)(M1CP) + (3.2195)(EHI1) + 39.5244, \quad (7)
\]

where M1CP is the mixed-layer CAPE and EHI1 is the 0-1 km EHI. This equation has an
adjusted \( R^2 \) value of 0.0921, which is a rather poor value, but both variables were considered
significant (Table 5). For the peak intensity, the regression equation is

\[
V_{rot} = (-0.0107)(SBCP) + (7.7322)(EHI3) + 40.3329, \quad (8)
\]

where SBCP is the surface-based CAPE and EHI3 is the 0-3 km EHI. This equation has an
adjusted \( R^2 \) value of 0.2417 and both variables were identified as significant (Table 6).

4. Discussion

Radar Data

Previous studies identified differences between tornadic and non-tornadic storms at the
peak intensity only. This study, for the first time, also included the starting point in order to more
fully assess the radar products and the storm environmental data at a time closer to
tornadogenesis (i.e., a time more relevant to tornado warning issuance). Unfortunately, due to the
small sample size, results could not be subdivided into storm mode, distance to the radar, or EF
rating, $V_{rot}$ was the only variable selected as statistically significant in all four stepwise regression models. Considering that the majority of the tornadoes in the confirmed cases dataset were rated EF-0 or EF-1, the peak $V_{rot}$ values in this study were higher than the results from Smith et al. (2015). However, Smith et al. (2015) studied storms across the contiguous United States, and while most of those storms were east of the Rocky Mountains, the overall area was still larger than this study, which was focused over the Memphis NWSFO CWA. Figure 28 would suggest that a peak $V_{rot}$ around 40 knots may be a cutoff point between non-tornadic and tornadic storms, but a little more than half of the confirmed tornadoes had peak $V_{rot}$ values between 20 and 40 knots (Figure 27). An EF-3 and EF-4 tornado were the two outliers in the confirmed cases with peak $V_{rot}$ values of 86 and 100 knots, respectively (Figure 27). Also, of note was an EF-1 tornado that had a peak $V_{rot}$ of 71 knots, which was much higher than strongest EF-2 tornado in the dataset (47 knots). For the test cases, the two outliers were EF-2 tornadoes that impacted Monroe County, Mississippi. Note also that the highest non-tornadic peak $V_{rot}$ was 51 knots (Figure 28). Beginning $V_{rot}$ values reported in Figures 23 and 24 were lower than the peak $V_{rot}$ values. This is not surprising due to the tornado lifecycle. It is important to note though that no tornadoes were confirmed either at the beginning time or the peak time with $V_{rot}$ values of 20 knots or lower (Figures 23, 24, 27, 28), which is higher than the values associated with weaker tornadoes in the Smith et al (2015) study. Thus, once $V_{rot}$ values cross into the range of 20-50 knots, extra attention should be paid for potential tornadogenesis.

CC was only selected by the stepwise regression for the starting point data, but it was not statistically significant (Tables 1 and 2). This result is curious because the peak would seem to be a more logical time for CC to be selected. This could be a function of sample size, but it could also be a function of the multiple linear regression method and the lack of interaction terms. The
tornado debris signature is revealed through an analysis of $V_{rot}$, dBZ, ZDR, and CC (WDTD 2016). Thus, caution should be exercised in the interpretation of the selected variables in the model. Perhaps the addition of a binary term denoting whether a tornado debris signature is observed following WDTD (2016) guidelines is needed in future work. Figures 35 and 36 show there is some skewness in the data for the starting point for the confirmed cases and the test cases, however, the test cases showed a potential relationship between tornadic storms and non-tornadic storms. For the peak value, there was some skewness for the confirmed cases, but the mean remained inside the box plot (Figure 37). The test cases show the majority of tornadic storms had CC values of 0.90 or less.

Like CC, ZDR was only selected by the stepwise regression for the starting point data, but unlike CC, it was statistically significant (Tables 1 and 2). Similar caveats to the CC discussed above apply here though. Figures 40 and 42 show clear differences in ZDR values between tornadic storms and non-tornadic storms. When comparing the starting ZDR to the peak ZDR, the peak values of the confirmed cases and the tornadic storms had lower ZDR values. The non-tornadic storms had very similar ZDR values between the starting point and peak point. Note though that the tornadic storms had lower ZDR values than the non-tornadic storms (Figures 40 and 42). Moreover, the mean and median ZDR values from the starting point to the peak also declined (Figure 40 vs 42), which is consistent with debris signature expectations (WDTD 2016).

Two regression models selected dBZ for use in the modeling process—starting point confirmed cases and peak confirmed cases (Tables 1 and 3). However, only in the peak confirmed cases dataset was dBZ statistically significant. This would make sense, given the higher probability of a debris ball associated with a tornado in progress. The selection of dBZ
again suggests the need to explore interaction among the four variables used to identify a tornado debris signature. The box and whisker plots do show a shift upward in mean and median dBZ for the tornadic storms (Figures 32 and 34), which again is consistent with tornado debris expectations (WDTD 2016).

NROT was not selected in any of the four regression models. However, the box and whisker plots do show key values that may be helpful to forecasters. At the starting point, the confirmed cases show an average value around 1.25 (Figure 25). Using the 1.25 value as a potential critical value for the test data, the majority of the non-tornadic and tornadic storms begin to overlap each other at a value of 1.25. However, most of the tornadic storms had a value of about one or higher. NROT values of about one to 1.25 also appeared to be critical for the peak confirmed and test cases (Figures 29 and 30). This does suggest that storms with NROT values within the range of one to 1.25 need to watched for potential tornadogenesis.

Environmental Parameters

All four regression models selected environmental parameters but only one parameter was selected by all four models—MLCAPE (Tables 1-4). However, MLCAPE was not statistically significant in any of the models. Moreover, box plots clearly show very little separation between the non-tornadic and tornadic storms in the test dataset (Figure 8). It is also noted that the majority of the storms in this study developed in environments that would be classified as low CAPE scenarios (below 1000 J/kg; Anderson-Frey et al. 2019). A similar result was found for SBCAPE (i.e., most storms occurred in low CAPE environments). Regression modeling selected starting point SBCAPE in the test cases dataset and it was statistically significant (Table 2), but it was not selected in the confirmed cases (Table 1). Overall, these results do not yield any important clues for forecasters other than to stress the number of low
CAPE events that occur over the Mid-South and that very low MLCAPE or SBCAPE values (<250 J/kg) do not tend to work well for tornadoes.

No clear separation of the LCL height between the non-tornadic and tornadic storms was observed in the box plot diagrams (Figure 10). Two regression models picked LCL height as a variable—starting point test cases and confirmed peak cases (Tables 2 and 3). LCL height was statistically significant in the peak confirmed cases dataset (Table 3), but caution is advised given the results from Figure 10 noted above. There are not any important clues for forecasters here other than values higher than 1100 m do not tend to work well based on these analyses.

Davies (2004) noted that lower LFC heights seem to be more favorable for tornadogenesis, especially if the values were under 2000 m. LFC was selected in the stepwise regression model for the starting point in the confirmed cases dataset, and it was statistically significant (Table 1). However, despite the confirmed cases having an average value around 2000 m, one EF-2 tornado occurred with an LFC value of about 5300 m (Figure 11). Moreover, no good separation of the box plots was noted between the non-tornadic and tornadic storms in the test cases dataset (Figure 12). Thus, there doesn’t seem to be much useful information here for forecasters over the Mid-South. Davies (2004) paper also noted the importance of convective inhibition (CIN) along with the LFC, but CIN was not a variable analyzed by itself in this study.

Effective bulk shear was selected for the peak intensity in the confirmed cases regression model and was statistically significant (Table 3). Almost all tornadoes in the confirmed and test cases had effective bulk shear values of 30 knots or more (Figures 13 and 14). The exception was an EF-2 tornado that occurred in an environment with an effective shear of zero and a very high LFC (mentioned above; Figure 13). Figure 14 did not show much separation in the majority of the data between non-tornadic and tornadic storms though. The results do show that the majority
of the tornadic storms develop in high shear environments over the Memphis NWSFO CWA as defined by Davis and Parker (2014) and Anderson-Frey et al. (2019).

The two significant tornado (STP) variables, fixed-layer and effective-layer, were only selected by the regression models during the peak intensity cases (Tables 3 and 4). Fixed-layer STP was selected for both confirmed and test cases. The variable was also statistically significant in both models (Tables 3 and 4). Unfortunately, there is very little separation in the non-tornadic and tornadic box plots though there were differences in the mean and median (Figure 18). All tornadic storms in the test cases did have fixed-layer STP values of around 0.5 or higher and most tornadoes had a fixed-layer STP of one or more. However, the confirmed cases included an EF-2 tornado that occurred in an environment with the fixed-layer STP of zero (Figure 17). Effective-layer STP had a similar result where the box plot diagrams revealed little separation between the tornadic and non-tornadic storms, but, as in the case of the fixed-layer STP, there were differences in the mean and median and most tornadoes had effective-layer STP values of one or higher (Figure 16). However, there were 10 tornadoes in the confirmed cases dataset with effective-layer STP values of zero (Figure 15). Regression modeling only selected the effective-layer STP value in the peak confirmed cases dataset (Table 3). Given the calculation of either STP version includes variables like effective bulk shear and LCL heights (Thompson et al. 2012), interaction may have impacted variable selection. Regardless, the box plot diagrams do not demonstrate that either version of STP would be a useful tool to differentiate between tornadic and non-tornadic storms and improve FAR. This is not surprising given the number of QLCS tornadoes in this dataset and the STP was developed to differentiate between non-tornadic and significantly tornadic supercell environments (Thompson et al. 2012). A larger sample size
of tornadoes would be needed to better assess whether values of STP could be used to tweak the probabilities of EF-2 or stronger tornado noted in Smith et al. (2015) for the Mid-South.

EHI from 0-1 and from 0-3 km also include terms for CAPE and shear in their calculations (Rasmussen 2003). Thus, like STP above, interaction may be complicating the selection of these variables in the regression modeling phase. Regression modeling selected 0-1 km EHI in the test cases dataset for the starting point only (Table 2), while 0-3 km EHI was selected in each regression model except the starting point confirmed cases dataset (Tables 1-4). Box plot diagrams in Figures 20 and 22 revealed a little more separation between the non-tornadic and tornadic storms than the two STP variables with values of one or higher associated with the majority of the tornadoes. As with STP though, the confirmed cases dataset reveals complications where tornadoes did occur with 0-1 and 0-3 km EHI values less than one (Figures 19 and 21). In fact, an EF-2 tornado occurred in an environment with 0-1 and 0-3 km EHI values of zero. That said, even the box plot for the confirmed cases was shifted farther upward than either STP parameter, which might suggest some utility to differentiate tornadic and non-tornadic environments over the Mid-South. This could be due to the increased complexity of the two STP calculations, which include LCL, a value that does not seem to be as important given low LCLs are climatologically favored over the Mid-South and much of the Southeast. In other words, the two STP calculations may be adding unnecessary complexity. Given the number of high shear and low CAPE events over the Mid-South in this study and in other studies from the Southeast (Anderson-Frey et al. 2019), a tweak in the EHI calculation to increase the emphasis on shear and the sensitivity to smaller values of CAPE might be a better discriminator between non-tornadic and tornadic environments over the Mid-South and much of the Southeast. An experimental parameter, severe hazards in environments with reduced buoyancy (SHERB), has
been developed by Sherburn and Parker (2014) and modified in subsequent papers such as Sherburn et al. (2016) and King et al. (2017). SHERB was designed to include all significant severe weather, so its focus is on more than tornadoes. However, it does have some skill with high shear, low CAPE tornado events (Sherburn and Parker 2014), which suggest there might be some potential to lower tornado warning FAR in the Southeast with some sort of new parameter like SHERB or its modified versions.

The regression modeling of the storm environmental parameters to explain $V_{rot}$ resulted in models that poorly described $V_{rot}$ variability (Tables 5 and 6). The second equation utilizing environmental variables to describe peak $V_{rot}$ variability had the highest adjusted $R^2$ value (0.24). While that is still a weak value, it does select 0-3 km EHI as a significant variable in addition to surface-based CAPE (Table 6). Given CAPE is part of the EHI calculation, interaction could be involved, so interpretation should be done cautiously. Regardless, the fact that EHI is selected again suggests that something of additional value to Mid-South forecasters may be able to be extracted from EHI, especially if it is tweaked to identify high shear/low CAPE environments better. Additional data will be needed to explore this further.

**Warning and Behavior Implications**

This study focused on analyzing radar and environmental variables to improve FAR for the Memphis NWSFO CWA. Results suggest that some combination of $V_{rot}$ and a storm environment parameter that can improve the weighting of shear and CAPE to better discriminate between non-tornadic and tornadic environments during high shear/low CAPE events, might be able to improve the FAR. Completely regionalizing the Smith et al. (2015) study, which included probabilities of EF-2 tornadoes, would require a larger sample of tornadoes. Only six tornadoes in the confirmed dataset were rated EF-2 or higher. Perhaps expanding this local study to cover
much of the Southeast would be enough to derive a better high shear/low CAPE environmental parameter that could be used to improve the FAR. Then a larger database of significant tornadoes could also be utilized with the radar and environmental variables to suggest tweaks to the EF-2 tornado probabilities of Smith et al. (2015) and improve the impact base warnings (IBW) for the NWSFOs across the country.

This study did not investigate how the IBWs text could be improved or how the general public perceived tornado warnings and FAR associated tornado warnings across the Memphis NWSFO. Trainor et al. (2015) state that the higher the FAR, the less likely that the individual will take protective actions. Therefore, by reducing the FAR, perhaps more individuals will take shelter, which was the reason this research focused on identifying ways FAR could be reduced. Barnes et al. (2007) state that the FAR does not consider if the tornado warnings were justified. For example, if a funnel cloud was reported during the tornado warning, the warning would still be considered a false alarm (Simmons and Sutter 2009). For these reasons, there is an argument to make a revision to the FAR to account for warnings that were justified.

People come from different backgrounds of demographics and socioeconomics, experience, knowledge, fears, norms and other issues that are not listed here. Thus, some people may not take any precaution because of their background or exposure to storms. If a person has never been hit by a tornado when living in the same location for many years, their perception might be that either something is protecting them or that it will never happen to them and that might lead the person into inaction when warnings are issued. Another challenge is clear communication. From the National Weather Service assessment of the Joplin, MO 2011 tornado, one reason for large death count during the tornado was the mixed messages from the local emergency management (NOAA 2011). Another major conclusion was that people did not react
to the tornado warning immediately, but instead spent extra time assessing their personal risk (NOAA 2011). This is where lowering the FAR could, as Simmons and Sutter (2009) note, reduce the number of tornado facilities and injuries.

5. Conclusion

Between the years of 2012-2018, the NWSFO Memphis had a tornado warning FAR of 83% despite the advancement in dual-polarization radar. This research analyzed a suite of radar products and storm environment parameters via box and whisker plots and forward and backward regression modeling to highlight variables that may be able to lower the FAR over the Memphis NWSFO CWA. Moreover, insight has been gained on whether a regionalization of the Smith et al. (2015) values might be possible that could improve IBWs.

Two hypotheses were tested in this research. First, radar and storm environment parameters can be identified in the dual-polarization era that could decrease the tornado warning FAR across the Mid-South. The results suggest that this hypothesis is true. Some combination of $V_{rot}$ and a tweaked EHI that has an increased emphasis on shear and sensitivity to low CAPE values might aid in reducing tornado warning FAR. Given the differences noted in $V_{rot}$ between this study and Smith et al. (2015), it may also be possible to regionalize values from Smith et al. (2015) for use in IBWs.

The second hypothesis tested was whether the storm environment has an influence on $V_{rot}$ values. Overall, there is not much evidence of storm environment influence on $V_{rot}$, in these data with both regression models having weak adjusted $R^2$ values. A small signal may have been detected in the CAPE and EHI variables, but additional data and analysis that includes interaction terms will be needed to explore that hypothesis more fully.
Warning Decisions and Implications

This study showed $V_{rot}$ is a critical factor in diagnosing tornadic from non-tornadic storms. However, there is a grey area where the tornadic and non-tornadic storms overlap. This grey area was around $V_{rot}$ values of 20 knots. Most of the weaker tornadic storms developed in landfalling tropical storms or remnants of tropical systems. These tornadic storms had $V_{rot}$ values weaker than those from traditional supercells or QLCSs. For this reason, storms exceeding $V_{rot}$ values of 20 knots should required extra attention by forecasters. For supercell and QLCS environments, the recommended threshold is 30 to 35 knots. It also seems possible that other NWSFOs could be able to regionalize the Smith et al. (2015) study to their own CWAs, which could improve their FAR.

None of the environmental parameters alone, were able to determine a clear separation between tornadic and non-tornadic storms. However, there are a few parameters that can help forecasters better diagnose tornadic environments from non-tornadic environments. These include: SBCAPE, MLCAPE, MLLCL, 0-1 km EHI, 0-3 km EHI. These environmental parameters were significant in the regression model and had a small trend in the box and whisker plots. The issuance of tornado warnings should be discouraged when storm environments have SBCAPE and MLCAPE values less than 250 J/kg, MLLCL heights are below 400 meters and exceed 800 meters, and 0-1 km and 0-3 km EHI have values below one. Due to the poor performance of effective-layer and fixed-layer STP, it is recommended that STP should not be used in diagnose tornadic and non-tornadic storms. Both EHI calculations, 0-1 km and 0-3 km, performed better than either of the STP calculations. Thus, EHI should be relied on more than STP in diagnosing storm environment over the Mid-South. However, effective-layer and fixed-
layer STP should be used in combination with peak velocity values after the tornado has touched down for IBW messages.

Even with the recommendations for $V_{rot}$ and the environmental parameters, situational awareness is required for NWS forecasters. As mentioned before, the results from the regression model showed that the storm environment had little influence on velocity values at both the starting and peak values (Tables 5 and 6). With these results, it needs to be stressed that if the storm environment is favorable for tornadic storms based on the recommended thresholds, forecasters should be playing close attention to storms moving within those environments.

Future Work

Unfortunately, the short period of time dual-polarization radar has been available creates a challenge in using the best radar data available to identify key variables that could be used by forecasters to improve tornado warning FAR. Expanding this study to include a larger area of the Southeast with a similar climatology as the Mid-South will be needed to increase the sample size of tornadoes for analysis. A similar climatology is crucial because important criteria like low LCLs are more climatologically favored over the Southeast than in the Plains. Given experimental high shear/low CAPE storm environmental parameters have been developed (Sherburn and Parker 2014; Sherburn et al. 2016; King et al. 2017) and the number of these events over the Southeast (Anderson-Frey et al. 2019), future work should include these parameters in the analysis. Future research would also need to explore interaction terms more in depth in the regression modeling phase and a binary term for the tornadic debris signature following along the guidelines of WDTD (2016) is likely needed. Given the binary nature to some variables, different forms of regression may need to be explored (e.g., logistic regression).
References


Rasmussen, E.N., 2003: Refined supercell and tornado forecast parameters. Weather and Forecasting, 18, 530-535.


Figure 1. The map of the study area with the blue circles representing the radar sites and the red outlines representing the counties.
Figure 2. The rotational shear guidelines for tornadoes. The y-axis represents the rotational shear while the x-axis represents distance from the radar (Falk and Parker 1998).
Figure 3. The radar images showing an example of a time evolution of the “Broken S” signature in a QLCS (Davis and Parker 2014).
Figure 4. Top panel shows reflectivity (left) and storm relative velocity (right). The bottom panel shows CC (left) and ZDR (right). The circle in each panel is where the tornadic debris signature (TDS) is located within the storm.
Figure 5. A box and whisker plot of SBCAPE from the confirmed cases dataset, where the bar inside the box represents the median and the x represents the mean.
Figure 6. Same as Figure 5, but with SBCAPE from the test cases dataset.
Figure 7. Same as Figure 5, but for MLCAPE from the confirmed cases dataset.
Figure 8. Same as Figure 5, but for MLCAPE from the test cases dataset.
Figure 9. Same as Figure 5, but for MLLCL from the confirmed cases dataset.
Figure 10. Same as Figure 5, but for MLLCL from the test cases dataset.
Figure 11. Same as Figure 5, but for MLLFC heights from the confirmed cases dataset.
Figure 12. Same as Figure 5, but for MLLFC heights from the test cases dataset.
Figure 13. Same as Figure 5, but for effective shear from the confirmed cases dataset.
Figure 14. Same as Figure 5, but for effective shear from the test cases dataset.
Figure 15. Same as Figure 5, but for effective-layer STP from the confirmed cases dataset.
Figure 16. Same as Figure 5, but for effective-layer STP from the test cases dataset.
Figure 17. Same as Figure 5, but for fixed-layer STP from the confirmed cases dataset.
Figure 18. Same as Figure 5, but for fixed-layer STP from the test cases dataset.
Figure 19. Same as Figure 5, but for 0-1 km EHI from the confirmed cases dataset.
Figure 20. Same as Figure 5, but for 0-1 km EHI from the test cases dataset.
Figure 21. Same as Figure 5, but for 0-3 km EHI from the confirmed cases dataset.
Figure 22. Same as Figure 5, but for 0-3 km EHI from the test cases dataset.
Figure 23. Same as Figure 5, but for the starting $V_{rot}$ from the confirmed cases dataset.
Figure 24. Same as Figure 5, but for the starting $V_{rot}$ from the test cases dataset.
Figure 25. Same as Figure 5, but for starting NROT from the confirmed cases dataset.
Figure 26. Same as Figure 5, but for starting NROT from the test cases dataset.
Figure 27. Same as Figure 5, but for peak $V_{rot}$ from the confirmed cases dataset.
Figure 28. Same as Figure 5, but for peak $V_{rot}$ from the test cases dataset.
Figure 29. Same as Figure 5, but for peak NROT from the confirmed cases dataset.
Figure 30. Same as Figure, but for peak NROT from the test cases dataset.
Figure 31. Same as Figure 5, but for starting reflectivity from the confirmed cases dataset.
Figure 32. Same as Figure 5, but for starting reflectivity from the test cases dataset.
Figure 33. Same as Figure 5, but for peak reflectivity from the confirmed cases dataset.
Figure 34. Same as Figure 5, but for peak reflectivity from the test cases dataset.
Figure 35. Same as Figure 5, but for starting CC from the confirmed cases dataset.
Figure 36. Same as Figure 5, but for starting CC from the test cases dataset.
Figure 37. Same as Figure 5, but for peak CC from the confirmed cases dataset.
Figure 38. Same as Figure 5, but for peak CC from the test cases dataset.
Figure 39. Same as Figure 5, but for starting ZDR from the confirmed cases dataset.
Figure 40. Same as Figure 5, but for starting ZDR from the test cases dataset.
Figure 41. Same as Figure 5, but for peak ZDR from the confirmed cases dataset.
Figure 42. Same as Figure 5, but for peak ZDR from the test cases dataset.
Appendix B: Tables

Table 1. Stepwise regression model summary for tornado intensity at the starting point of the tornado. Rows in bold denote statistically significant variables (p<0.05).

<table>
<thead>
<tr>
<th>Variable</th>
<th>Estimate</th>
<th>Std. Error</th>
<th>T-value</th>
<th>P-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vrot</td>
<td>0.5650</td>
<td>0.0096</td>
<td>2.376</td>
<td>0.0233</td>
</tr>
<tr>
<td>CC</td>
<td>0.0228</td>
<td>0.0087</td>
<td>-1.547</td>
<td>0.1312</td>
</tr>
<tr>
<td>ZDR</td>
<td>-0.0134</td>
<td>0.1400</td>
<td>3.679</td>
<td>0.0008</td>
</tr>
<tr>
<td>M1CP</td>
<td>0.0040</td>
<td>0.0002</td>
<td>1.902</td>
<td>0.0656</td>
</tr>
<tr>
<td>MLFC</td>
<td>0.0003</td>
<td>0.0001</td>
<td>2.316</td>
<td>0.0267</td>
</tr>
<tr>
<td>dBZ</td>
<td>-0.0158</td>
<td>0.0118</td>
<td>-1.347</td>
<td>0.1869</td>
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</tbody>
</table>

Table 2. Stepwise regression model summary for tornado occurrence at the starting point of the tornado. Rows in bold denote statistically significant variables (p<0.05).

<table>
<thead>
<tr>
<th>Variable</th>
<th>Estimate</th>
<th>Std. Error</th>
<th>T-value</th>
<th>P-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vrot</td>
<td>0.0385</td>
<td>0.0071</td>
<td>5.45</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>ZDR</td>
<td>-0.0240</td>
<td>0.0882</td>
<td>-2.722</td>
<td>0.0119</td>
</tr>
<tr>
<td>CC</td>
<td>0.0084</td>
<td>0.0062</td>
<td>1.345</td>
<td>0.1913</td>
</tr>
<tr>
<td>SBCP</td>
<td>-0.0004</td>
<td>0.0002</td>
<td>-2.143</td>
<td>0.0424</td>
</tr>
<tr>
<td>M1CP</td>
<td>0.0007</td>
<td>0.0004</td>
<td>1.971</td>
<td>0.0604</td>
</tr>
<tr>
<td>MMLH</td>
<td>-0.0006</td>
<td>0.0004</td>
<td>-1.452</td>
<td>0.1594</td>
</tr>
<tr>
<td>EHI1</td>
<td>-1.9676</td>
<td>0.4648</td>
<td>-4.234</td>
<td>0.0003</td>
</tr>
<tr>
<td>EHI3</td>
<td>1.5675</td>
<td>0.3544</td>
<td>4.423</td>
<td>0.0002</td>
</tr>
</tbody>
</table>

Table 3. Same as Table 1 but for peak intensity.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Estimate</th>
<th>Std. Error</th>
<th>T-value</th>
<th>P-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter</td>
<td>-0.1903</td>
<td>0.1220</td>
<td>-1.561</td>
<td>0.1289</td>
</tr>
<tr>
<td>Vrot</td>
<td>0.0204</td>
<td>0.0076</td>
<td>2.679</td>
<td>0.0119</td>
</tr>
<tr>
<td>DBZ</td>
<td>0.0549</td>
<td>0.1780</td>
<td>3.086</td>
<td>0.0043</td>
</tr>
<tr>
<td>SBCP</td>
<td>0.0005</td>
<td>0.0004</td>
<td>1.314</td>
<td>0.1989</td>
</tr>
<tr>
<td>M1CP</td>
<td>-0.0006</td>
<td>0.0004</td>
<td>-1.321</td>
<td>0.1964</td>
</tr>
<tr>
<td>MMLH</td>
<td>-0.0014</td>
<td>0.0006</td>
<td>-2.468</td>
<td>0.0195</td>
</tr>
<tr>
<td>ESHR</td>
<td>0.0199</td>
<td>0.0079</td>
<td>2.509</td>
<td>0.0178</td>
</tr>
<tr>
<td>SIGT</td>
<td>-0.8230</td>
<td>0.2555</td>
<td>-3.248</td>
<td>0.0029</td>
</tr>
<tr>
<td>STPC</td>
<td>0.3448</td>
<td>0.1634</td>
<td>2.110</td>
<td>0.0433</td>
</tr>
<tr>
<td>EHI3</td>
<td>0.4643</td>
<td>0.2139</td>
<td>2.170</td>
<td>0.0381</td>
</tr>
</tbody>
</table>
Table 4. Same as Table 2 but for peak intensity.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Estimate</th>
<th>Std. Error</th>
<th>T-value</th>
<th>P-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter</td>
<td>-0.1193</td>
<td>0.0844</td>
<td>-1.414</td>
<td>0.1696</td>
</tr>
<tr>
<td>Vrot</td>
<td>0.0254</td>
<td>0.0084</td>
<td>3.019</td>
<td>0.0058</td>
</tr>
<tr>
<td>SBCP</td>
<td>-0.0005</td>
<td>0.0025</td>
<td>-2.012</td>
<td>0.0551</td>
</tr>
<tr>
<td>M1CP</td>
<td>0.0005</td>
<td>0.0032</td>
<td>1.436</td>
<td>0.1634</td>
</tr>
<tr>
<td>SIGT</td>
<td>-0.8936</td>
<td>0.3343</td>
<td>-2.673</td>
<td>0.0130</td>
</tr>
<tr>
<td>EHI3</td>
<td>0.6746</td>
<td>0.2871</td>
<td>2.350</td>
<td>0.0270</td>
</tr>
</tbody>
</table>

Table 5. Variables identified from stepwise regression modeling that could explain starting point Vrot. Rows in bold denote statistically significant variables (p<0.05).

<table>
<thead>
<tr>
<th>Variable</th>
<th>Estimate</th>
<th>Std. Error</th>
<th>T-value</th>
<th>P-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1CP</td>
<td>-0.0071</td>
<td>0.0030</td>
<td>-2.377</td>
<td>0.0212</td>
</tr>
<tr>
<td>EHI1</td>
<td>3.2195</td>
<td>1.3160</td>
<td>2.446</td>
<td>0.0178</td>
</tr>
</tbody>
</table>

Table 6. Same as Table 5 expect for peak intensity.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Estimate</th>
<th>Std. Error</th>
<th>T-value</th>
<th>P-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>SBCP</td>
<td>-0.0107</td>
<td>0.0035</td>
<td>-3.062</td>
<td>0.0035</td>
</tr>
<tr>
<td>EHI1</td>
<td>7.7322</td>
<td>1.7656</td>
<td>4.379</td>
<td>&lt;0.0001</td>
</tr>
</tbody>
</table>