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ABSTRACT

This research studied differential reflectivity (Z_{DR}) in pre- and non-tornadic supercells to determine if a regional bias occurred in the previously found suggested signal in the hook echo region. The previous study focused on the central plains and, with a 95% confidence level, found that the mean Z_{DR} values in pre-tornadic supercells was lower than that of non-tornadic. A new region of study was selected and statistical analysis was performed on pre- and non-tornadic supercells in this new region. The same relationship for Z_{DR} between pre- and non-tornadic supercells was observed in the new region with pre-torndic mean was lower than non-tornadic in the hook echo region. However: due to the small number of cases between both regions and the presence of other regions that tornadic supercells occur, a lack of regional bias in the Z_{DR} relationship can be suggested but not proven. A regional bias in the average Z_{DR} for the cases may have been found but further testing is required. A confirmation of the relationship between Z_{DR} and tornadogenisis also cannot be proven but can be suggested in two regions.

1. Introduction and Background

False alarm tornado warnings on supercell thunderstorms have resulted in a general lack of trust by the public in these warnings issued by the National Weather Service (NWS). These false warnings create a negative perception of the NWS forecasts and potentially lead to more severe injuries and deaths due to people disregarding these warnings. A more accurate way of predicting which supercells will produce tornadoes verses storms that do not could significantly benefit the public and NWS forecasters. If tornadoes can be better predicted and warned, this could help to offset the lack of trust in tornado warnings and could potentially result in more people taking shelter when warnings are issued. It could also lower the false alarm rate and increase the accuracy rate due to this potentially more accurate forecasting method. The NWS completed the installation of the first dual-pol research radar in 1983 and the first set of polarimetric data became available in 1992. It was not until spring of 2013 that the dual-pol upgrade to the NWS Weather Surveillance Radar-1988 Doppler (WSR-88D) network was completed.

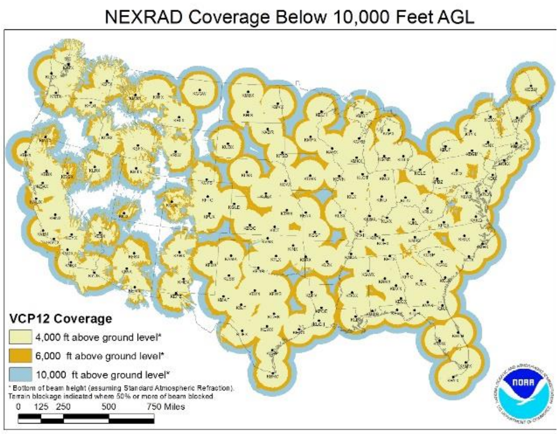

Fig. 1. NWS WSR-88D dual-pol network coverage of the continental United States.

The NWS WSR-88D does not have complete coverage of the entire CONUS due to the interference of the radar beam caused by the Rocky Mountains blocking the beam (Fig. 1). With the completion of the dual-pol upgrade to the radar network polarimetric radar products have become available across the United States. As this upgrade is relatively new, the full extent of these polarimetric products is not fully know.

A study done by Ryznkov et al. (2005) analyzed Reflectivity (Z_{HH}), radial velocity, differential reflectivity (Z_{DR}), correlation coefficient (ρ_{hv}), and specific differential phase (K_{DP}), as well as non-polarimetric products, to determine if these products could be used in early detection of tornadic cells. The study found that these products could be useful and found some anomalous polarimetric signals aloft. These signals could be related to the tornadogenesis process.

A study done by Cai (2005) used pseudovorticity to determine if a difference existed between tornadic and non-tornadic mesocyclones. The study used the following equation to calculate pseudovorticity values.

$$\zeta_{pv} = \Delta V / L \qquad (1)$$

The study defined pseudovorticity as the difference between the maximum inbound and maximum outbound velocities in a velocity couplet divided by the distance between the gates where the maximum values occur along the radial of the radar beam. Since the calculation only considers the vorticity along the radial instead of the full velocity the prefix "pseudo" is added to vorticity. The results from the study indicate that tornadic mesocyclones should have a steeper slope to the pseudovorticity lines than non-tornadic mesocyclones.

A signature that potentially identified tornadogenesis was found in Tuftedal and Aanstoos (2016). This study suggested, to a 95% confidence level using a pooled t-test, that a signature in mean Z_{DR} in the hook echo region was identified that appeared to distinguish between non-tornadic and pre-tornadic supercells. However, due to the small sample of supercells, this signature requires more study before any relationship between tornadogenesis and this signature can be proven. The study looked at Reflectivity (Z_{HH}), spectrum width (σ_v), differential reflectivity (Z_{DR}), correlation coefficient (ρ_{hv}), and specific differential phase (K_{DP}) to evaluate any differences between non-tornadic and pre-tornadic supercells. Gibson Ridge (GR2Analyst) was used to visually analyze the radar products to determine the possible signature. In the study, a pseudovorticity range was set as a proxy for tornadic/mesocyclone strength to determine whether the cases studied were statistically similar enough in rotational strength to be compared.

The goal of this research is to determine whether the signature found by Tuftedal and Aanstoos (2016) can be further supported with more cases in a new region or if a regional bias in the signature related to Z_{DR} between pre- and non-tornadic cells may occur. If a regional bias occurs, then an attempt to understand why the bias occurs will be made by looking at environmental factors as well as radar factors that could cause the bias to occur.

2. Data and Methods

a. Region of Study

In the study done by Tuftedal and Aanstoos (2016), a region containing portions of Iowa, Nebraska, Kansas, and Missouri (Central Midwest) was selected. To check for biases between multiple regions, a second region was selected for this research. The region, as seen in Figure 2; containing Colorado, New Mexico, Oklahoma, and northern Texas (Southwest), is located south and west of the region in Tuftedal and Aanstoos (2016). This region, with the exception of New Mexico and western Colorado, is still located in what is known as "Tornado Alley". This region was chosen because of the high number of tornadoes that occur in the region on a yearly basis, as well as, it did not overlap with the original region.

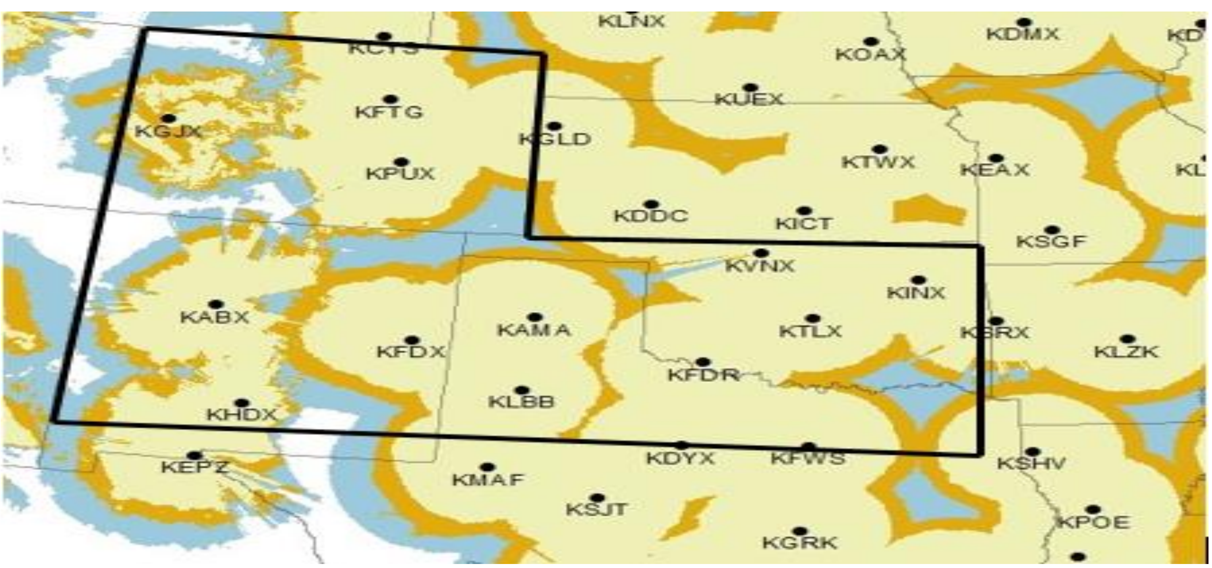

Fig. 2. Modified NWS WSR-88D coverage map. Region of study outlined by black lines. Radar sites located inside the region were used for data collection.

b. Data Description

Dual-pol, Next Generation Radar, (NEXRAD) level 2 data was obtained from radar sites of interest in the target region. This data was downloaded via the National Center for Environmental Information's (NCEI) Archive Information Request System (AIRS). Radar data was downloaded from the first appearance of the storms of interest until the storms moved out of radar range or dissipation of the storms occurred. Radar scans during thunderstorms update more often than in clear air mode providing more scans to analyze.

c. Selection Criteria

For this study, the Storm Prediction Center (SPC) event archive was used to identify events of study between the time interval of May 2013 and May 2016. As the NWS WSR-88D dual-pol upgrade was not completed until May 2013. Polarimetric product data required for this study was not available in the entire region of study until the upgrade was complete. This made May 2013 the lower limit for acquiring data. 160 cases were selected across the region during this time scale. A case was selected if the SPC event archive listed a tornado on the report in the region or severe storms occurred. These 160 cases were then sorted between tornadic and non-tornadic events.

For pre-tornadic storms, any radar site that did not provide polarimetric data for any reason on a storm was discarded as polarimetric data was necessary for analysis of the storms. Cases where radar data was affected by ground clutter or other anomalies were also discarded as they contained error sources. The final refinement of the pre-tornadic data was done using Gibson Ridge (GR2Analyst) radar software. Any storm producing a tornado that had the lowest elevation level scan at 1.6 km or higher were discarded. These storms were discard due to the radar not collecting data in the lower part of the storms. To determine if the elevation of the radar beam was above this threshold at a storm of interest, the data files were loaded into GR. GR gives a height estimation for the radar beam at any given point from the radar. The location of the storms was selected on the lowest elevation angle available and the height was given by GR. In total Seven pre-tornadic cases were selected for analysis (Table 1).

An archive for non-tornadic supercells is currently unavailable. To determine whether a supercell case was valid or not, the rotation of the storm had to be analyzed. The storm had to be rotationally capable of producing a tornado to eliminate weakly rotating cells. This was done to ensure that rotational strength was not the mechanism limiting the production of a tornado. Tornado Vortex Signature (TVS), defined as a gate-to-gate velocity difference of 36.0 ms^{-1} over a gate-to-gate distance of 1 km for velocity couplets over 56 km away from the radar or a gate-to-gate velocity difference of 46.3 ms^{-1} or greater over a gate-to-gate distance of 1 km for velocity couplets within 56 km of the radar (NWS 2009). Using equation 1 and the definition of TVS, the pseudovorticity thresholds of 0.036 s^{-1} and 0.0463 s^{-1} were set. Supercells that were tornado warned with the "radar indicated rotation" no tornado reports, and no Tornado

Debris Signature (TDS) were selected. The pseudovorticities were calculated and then evaluated to see if the cases fell within the threshold or exceeded it. Cases that did not meet the minimum threshold by the definition of TVS were not used in analysis. Seven non-tornadic cases were selected for study (Table 1).

a. Pre-Tornadic Cases				
Radar	Date and Time (UTC)	Pseudovorticity (s^{-1})	Range (km)	Azimuth (^{o})
KFTG	August 03, 2013 19:56	0.0368	83.41	48.4
KPUB	May 09, 2015 21:36	0.0419	25.85	327.3
KDYX	May 19, 2015 23:00	0.0323	113.13	37.4
KTLX	May 23, 2015 22:00	0.0556	71.97	254.4
KFTG	August 17, 2015 21:20	0.0405	82.48	229.5
KFDR	April 29. 2016 20:40	0.0378	70.75	47.0
KAMA	May 24, 2016 23:46	0.0991	71.97	26.6
b. Non-Tornadic Cases				
Radar	Date and Time (UTC)	Pseudovorticity (s^{-1})	Range (km)	Azimuth (^{o})
KAMA	September 19, 2013 22:59	0.0361	26.26	301.7
KDFX	June 06, 2014 23:31	0.0389	29.37	122.8
KPUB	May 23, 2015 18:16	0.0318	81.15	195.2
KAMA	June 12, 2015	0.0657	94.39	216.2
KTLX	November 05, 2015 20:19	0.07922	101.97	158.5
KPUB	April 04, 2016 19:00	0.0285	98.8	343.3
KFTG	May 07, 2016 20:22	0.0743	53.35	121.8

Table 1. Pre- and non- tornadic cases used for study. Radar site four-character station identifier. Date and time of scan which was closest to tornadogenesis for pre-tornadic cases or maximum pseudovorticity occurred for non-tornadic cases. Range and azimuth are measured from centroid of the velocity couplet to the radar site.

d. Statistical Analysis Procedure

For pseudovorticity a pooled t-test at the 95% confidence level was performed. This was done for both pre- and non-tornadic values at the maximum pseudovorticity values (non-tornadic) and prior to tornadogenesis. The test was run to determine if there was a statistically significant difference in the pseudovorticity means for the two sets of cases.

In the study done by Tuftedal and Aanstoos (2016), a potential signature indicating tornadogenesis was found in the Z_{dr} values in the hook echoes of supercells. For the cases in the current study, the Z_{dr} values were recorded 15 minutes prior to tornadogenesis and prior to the pseudovorticity maximum. Standard deviation and mean for each time stamp in each case, as well as the case average and standard deviation were calculated to determine if the signature was numerically present in the Southwest region. The standard deviation and averages were then compared to the Central Midwest region to see if there was a statistical difference between the two regions.

3. Results

a. Analysis of Pseudovorticity

As mentioned in the selection of cases criteria, there are not databases that archive non-tornadic supercells. These events are relative only for research, not the general public, leading to the lack of an archive. Once the non-tornadic supercells were selected following the method mentioned in the previous section, the pseudovorticity values for both non- and pre-tornadic cases were calculated using equation (1). Any supercells that did not meet the thresholds previously mentioned were discarded. A pooled t-test at a 95% confidence level was performed for the cases that meet or exceeded the thresholds. The t-test showed that there was not a significant statistical difference between the non- and pre-tornadic supercells. This demonstrates that the selection criteria and process was able to produce a set of cases that were similar in rotational strength, suggesting that in this region rotation was not limiting tornadogenesis.

b. Analysis of Z_{dr}

For each case, the Z_{DR} values in the hook echo region of pre- and non-tornadic supercells was recorded. The means and standard deviations for each case were calculated. The values in table 2 show a general trend that would support that signature previously found. The averages of each case were then averaged to find the supercell type average, i.e. the average Z_{DR} value for all pre- and non-tornadic supercells in the region. These values were then compared to the values found in Tuftedal and Aanstoos (2016) to determine if the region showed a difference in the signal. The pre-tornadic supercells had lower average Z_{DR} values than the non-tornadic cells. This shows the same relationship found in the Central Midwest region. In both regions the average Z_{DR} values in pre-tornadic supercells were lower than those in the non-tornadic cases. Another pooled t-test was run at the 95% level on the Z_{DR} values to determine if there was a significant statistical difference between the two types of supercells (Appendix A). A significant statistical difference was found between the two types of supercells. Pre-tornadic supercells have a lower average Z_{DR} in the hook echo region than the non-tornadic supercells. This again supports the previous study's signature.

A discovery made during the analysis of Z_{DR} was seen in the values of the averages between the previous and current region. As seen in table 3, the average Z_{DR} for both types of supercells in the Southwest region were higher than those in the Central Midwest region. The pre-tornadic average Z_{DR} in the

Southwest region was 0.30 dbz below the average Z_{DR} for non-tornadic supercells in the Central Midwest region. This could suggest that while the relationship from the previous study is supported the baseline Z_{DR} threshold for the signature may be different.

a. Pre-Tornadic Average Z_{DR}			
Radar	Date and Time (UTC)	Case Average Z_{DR} (dbz)	Case Standard Deviation Z_{DR} (dbz)
KFTG	August 03, 2013 19:56	2.38	0.33
KPUB	May 09, 2015 21:36	1.44	0.54
KDYX	May 19, 2015 23:00	2.38	0.45
KTLX	May 23, 2015 22:00	1.42	0.84
KFTG	August 17, 2015 21:20	1.58	0.47
KFDR	April 29. 2016 20:40	1.60	0.95
KAMA	May 24, 2016 23:46	1.78	0.90
b. Non-tornadic Average Z_{DR}			
Radar	Date and Time (UTC)	Case Average Z_{DR} (dbz)	Case Standard Deviation Z_{DR} (dbz)
KAMA	September 19, 2013 22:59	3.52	0.16
KDFX	June 06, 2014 23:31	4.69	1.13
KPUB	May 23, 2015 18:16	4.36	1.35
KAMA	June 12, 2015	3.82	0.32
KTLX	November 05, 2015 20:19	3.56	0.82
KPUB	April 15, 2016 19:00	1.89	0.76
KFTG	May 07, 2016 20:22	3.73	0.91

Table 2. The mean and standard deviation of Z_{DR} values for pre-tornadic and non-tornadic supercell cases used in this study. The averages were calculated for all time stamps 15 minutes before the maximum pseudovorticity value occurred until the respective times.

Region of Study	Supercell Type	Average Z_{DR} (dbz)
Central Midwest	Non-tornadic	2.23
Southwest	Non-Tornadic	3.65
Central Midwest	Pre-tornadic	1.79
Central Midwest without outlier	Pre-tornadic	1.49
Southwest	Pre-tornadic	1.93

Table 3. The mean of all Z_{DR} values for each supercell type in both the regions of study. Tuftedal and Aanstoos [(2016) Central Midwest] had a case considered as an outlier due to low pseudovorticity value but production of a large, long tracking tornado.

4. Conclusion and Discussion

With the comparison of the fourteen cases for pre- and non-tornadic supercells in the Southwest region with the ten cases from the region in Tuftedal and Aanstoos (2016), it can be suggested, at a 95% confidence level, that there is no a regional bias in the relationship between pre- and non-tornadic supercells in mean Z_{DR} values in the hook echo region indicating tornadogenesis. In the Southwest region, the mean values for both supercell types were higher than the Central Midwest region but both regions demonstrated that the mean Z_{DR} values in pre-tornadic supercells were significantly lower than those of non-tornadic supercells. This result verifies that the signature in the mean Z_{DR} found in the Central Midwest supercell hook echo region of thunderstorms holds true in another region. With the relationship holding true in two different regions it can be suggested as a possible forecasting tool for predicting which supercell thunderstorms may produce a tornado.

A regional bias was found to be present in the magnitude of the mean Z_{DR} between the Central Midwest and Southern regions. As previously noted in table 3, the average Z_{DR} in the hook echo regions in the Southwest were higher than those of the Central Midwest for both types of thunderstorms. This suggests that thunderstorms with near similar mean Z_{DR} between two regions may not produce the same results. For example, a supercell with a mean Z_{DR} of 2.08 dbz in the Central Midwest region would more likely be classified as non-tornadic as it is closer to the non-tornadic average than the pre-tornadic for the region. If the same supercell were to occur in the Southwest region it could be classified as a pre-tornadic as it is closer to the pre-tornadic average than the non-tornadic for the region.

The results of this research could suggest that another region such as Arkansas, Louisiana, Mississippi, and other southeastern states, northern central plains (North Dakota, South Dakota, Minnesota), or east central plains (Wisconsin, Illinois, Indiana, Ohio, Michigan) would have the same relationship in mean Z_{DR}. The non-tornadic supercells in these regions would have a higher average differential reflectivity than the pre-tornadic supercells. If this holds true in these additional regions then a potential signature will have been identified indicative of tornadogenesis. The threshold of the mean Z_{DR} signature in each of the different regions maybe different based on the fact that the Southwestern region was higher than the Central Midwest region. Further research into the Z_{DR} signature is needed for a more definitive confirmation of the signal.

A study in other regions will need to be done in order to further support the signal and determine threshold mean Z_{DR} values in each of the regions. Further research into potential causes for these different average values is also needed to further understand the potential signature and the differences in the supercells in each region. More research must also be done in the Central Midwest and Southwest regions due to the low number of cases across both regions, as well as the WSR-88D polarimetric radar upgrade only being fully active for four years in the regions. Understanding the potential causes, and the different thresholds in each region will provide useful information in predicting tornadic storms.

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Appendix

Appendix A. This table shows the mean value of all of the Z_{DR} for each case type and the lower and upper bounds of the 95% confidence interval.

Results of the Pooled t-test			
Case Type	Avg Z_{DR}	Lower 95% CI	Upper 95% CI
All Non-Tornadic	3.65	3.58	3.71
All Pre-Tornadic	1.93	1.88	1.98