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An 11-Year Radar-Based Study of Tornadic Thunderstorms over Central Oklahoma

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ABSTRACT

In an 11-y period (2000–2010) 126 tornadoes affected central Oklahoma within a 111-km (60-nm) radius of the Twin Lakes, Oklahoma (KTLX) WSR-88D. The tornadoes resulted in 265 injuries and 3 deaths. This study used archived WSR-88D data to obtain information about storm characteristics such as mode, width, height, and measures of the mesocyclone, at the time of initial tornado formation. The radar data provided information about the supercell spectrum and highlighted differences between tornado-producing supercells and tornado-producing quasi-linear convective systems (QLCSs), especially with respect to midlevel rotational velocity. Warning lead-time information also was obtained and compared with the radar characteristics. No specific radar attribute was strongly correlated with lead time, likely due to the multitude of variables involved in the tornado warning process. A strong correlation did exist between lead time and storm mode. Applying these findings in an operational environment similar to that found in central Oklahoma may enhance tornado warning performance.

1. Introduction

Every year about 1200 tornadoes move across the United States, killing 55 people on average (AMS Council 2000). A wide spectrum of storms, ranging from large isolated supercells to quasi-linear convective systems (QLCS), produces these tornadoes (Davies-Jones et al., 2001). The advancement of weather radar, especially the installation of the WSR-88D network, has led to a nationwide average tornado warning lead time of 13 minutes, as of 2004 (Erickson 2007). However, tornadoes with zero or negative lead time still pose a threat to life and property as they account for 8.5% of tornado-related deaths (Brotzge and Erickson 2009).

Classification of storm mode based on weather radar has received attention in previous research and plays a role in this study. Trapp et al. (2005) divided storms into three separate modes: cell, quasi-linear convective system (QLCS), or other. A storm received a classification of "cell" if it was isolated, had a circular or elliptical shape, and had a maximum reflectivity ≥50 dB*Z*. QLCSs consisted of a primarily linear region of reflectivity ≥40 dB*Z* that extended for at least 100 km in the horizontal. All other storm modes not meeting the above criteria were classified as "other".

Gallus et al. (2008) separated storm morphologies into nine distinct categories. Storms initially were classified as cellular, linear,

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or nonlinear. Cellular storms consisted of discrete cells while a linear classification was assigned to storms that were organized in a linear fashion ≥75 km long and at least three times longer than wide. From the initial classification, storms were divided further into more specific modes such as "isolated cell", "cluster of cells", and "squall line with parallel stratiform rain".

In building upon the research done by Trapp et al. (2005) and Gallus et al (2008), Smith et al. (2012) classified storms as QLCS, supercell, or disorganized with subcategories such as discrete cell, cell in line, and bow echo. In order for a cell to be defined as a supercell, a peak rotational velocity ≥10 m s^{-1} had to be present in addition to rotation extending throughout at least ¼ of the cell depth and persisting for at least 10–15 min. Range dependence was accounted for when classifying supercells and was consistent with the mesocyclone detection algorithm presented by Stumpf et al. (1998). Any cell falling below this threshold was classified as disorganized (Smith et al. 2012).

This study focuses on radar characteristics of tornadic thunderstorms in central Oklahoma over an 11-y period, and uses a simple storm classification system based on Trapp et al. (2005), Gallus et al. (2008), and Smith et al. (2012). Previous studies (e.g., Trapp and Weisman 2003) have examined the environmental conditions leading to QLCS tornadoes and their structural characteristics, but have not specifically quantified the radar signatures associated with QLCSs or the differences between the radar characteristics of each storm mode. Therefore, a long-term dataset of radar characteristics, in central Oklahoma, was gathered and then used to comment on the differences between tornadic supercells and QLCSs as well as tornado warning lead time. Since little research links radar characteristics and tornado warning lead time, radar imagery and observed storm mode were compared to lead time in order to ascertain any relationships between the two. Ultimately, the data collected and subsequent analysis of those data was intended to benefit operational meteorology.

2. Methodology

Storm data provided by the National Climatic Data Center's (NCDC) Storm Event Database (http://www.ncdc.noaa.gov/stormevents/) were used to find all reported tornadoes occurring within a 111-km (60-nm) radius of the Twin Lakes WSR-88D site in central Oklahoma (KTLX) during the period 2000–2010. This radius was selected in order to maintain a relatively large sample size (126 tornadoes) while ensuring a majority of the storms (81) could be sampled in the lowest kilometer above radar level (ARL). All duplicated reports arising from tornadoes crossing county lines were identified and reduced to one report per tornado.

Radar data provided by the NCDC WSR-88D archive (http://www.ncdc.noaa.gov/nexradinv/) were downloaded for each tornado and displayed using GR2Analyst^{TM} software (http://www.grlevelx.com/gr2analyst). Data came from KTLX except in situations where low-topped storms were located relatively far from KTLX or when storms passed close to that radar, leading to data loss in the "cone of silence". In all instances of data loss or corruption, the WSR-88D at Vance Air Force Base (KVNX), located in northern Oklahoma, was used to obtain the desired radar characteristics. In all instances of data loss, KVNX was the next nearest WSR-88D to the storm. This additional radar site proved especially useful when looking at storm height, mesocyclone height, and storm-top divergence.

Interrogation using GR2Analyst^{TM} allowed for the classification of storm mode associated with each tornado and calculation of several radar characteristics. All identified tornado-producing storms were classified as QLCS, supercell, or other. A QLCS consisted of a continuous quasi-linear area of radar reflectivity with reflectivity values ≥40 dB*Z* over a horizontal distance ≥100 km (Trapp et al. 2005). Supercells had to display rotational velocity ≥10 m s^{-1} (Smith et al. 2012; Stumpf et al. 1998) at low levels (≤1 km ARL) or at midlevels (defined below) if low-level data were unavailable. Storms not meeting the criteria for QLCS or supercell were classified as "other". All storm-mode classifications and radar characteristics were determined at tornadogenesis, a time that served as a proxy for the mature stage of each storm. Storm direction and speed were determined by finding the position of the midlevel radar echo centroid over a time period of four volume scans (approximately 20 min) and then using the "set storm motion from marker" feature in GR2Analyst^{TM}. This allowed for the use of storm-relative velocity, which aids the eye in interpreting velocity information while leaving measures of rotation and divergence unchanged.

Low-level rotational velocity was determined according to

$$\frac{V_{i,max} + V_{o,max}}{2} \qquad (1)$$

where $V_{i,max}$ and $V_{o,max}$ refer to the maximum inbound and outbound velocities, within a horizontal distance of 10 km, on any single elevation slice below 1 km ARL respectively. If the height of the lowest elevation scan was >1 km ARL, low-level rotational velocity was omitted for the given tornado. Midlevel rotational velocity was calculated in a similar manner using the elevation slice that displayed maximum rotational velocity *above* 1 km ARL.

Mesocyclone diameter was found by measuring the distance between the maximum inbound and outbound velocities at the height of maximum midlevel (3–7 km ARL) rotational velocity. Mesocyclone height was defined as the height (always within the upper region of the thunderstorm) at which velocity imagery revealed the mesocyclone to be more strongly divergent than rotational. Determining mesocyclone height required finding the level at which a line connecting the maximum inbound and outbound velocities was moved by divergence to an angle of ≥45º relative to a line perpendicular to the radar beam that bisected the mesocyclone. A protractor was placed on the computer screen to determine the angle described above. When the angle at a given radar elevation tilt was not precisely 45º, two different angles on separate elevation slices were found. An online linear interpolator (http://www.johndcook.com/interpolator.html) then provided the mean weighted height. These heights do not account for earth's curvature beneath a theoretical 0º beam height. This multi-step process made mesocyclone height the most uncertain, subjective, and potentially erroneous characteristic of all the measured radar variables.

Calculation of storm width consisted of measuring the length of a continuous string of gates with ≥45 dB*Z* reflectivity (Kennedy et al. 1993) oriented perpendicular to storm motion at the widest section of the storm. Storm height involved finding the highest occurrence of the 30-dB*Z* isosurface using the cross section feature in GR2Analyst^{TM}. While previous studies (e.g. McCarthy et al. 2006) used 15 dB*Z* to determine storm height, the 15-dBZ isosurface extended above the upper height limits of the GR2Analyst^{TM} cross section feature in several cases. Therefore, a reflectivity value of 30 dB*Z* provided a more accurate and reliable threshold for this study. All storm heights were rounded to the nearest 30.5 m (100 ft).

Due to the pixelated nature of the radar display, all measurements involving mesocyclone width and height were taken at the center of each pixel. Storm-top divergence was measured by summing the maximum inbound and maximum outbound velocities at a height where the given storm was purely divergent. In some cases, the max inbound and max outbound velocities occurred at two different elevation scans due to radar sampling limitations.

All tornado warning lead-time data came from the Iowa Environmental Mesonet at Iowa State University: (http://mesonet.agron.iastate.edu/cow/) or from NWS Performance Management (https://verification.nws.noaa.gov/). Tornadoes then were grouped into two categories, unwarned and warned. All tornadoes that were unwarned or had negative or zero lead times were classified as unwarned and lead time was set to 0 min. All tornadoes with positive lead time were classified as warned. These categories then were compared with the radar characteristics and storm mode.

Every effort was taken to minimize errors, but several sources of error still were noted. Radar sampling limitations, especially at far and close ranges, affected the data set. The "cone of silence", radar horizon, and aspect ratio all could have led to small errors in the data set (Doswell et al. 1993). Radar horizon issues with low-topped storms and range folding led to missing radar data in some cases. In addition, radar sampling issues become more substantial with smaller supercells observed within the dataset (Burgess et al. 1995). A relatively small sample size also may have affected some of the results.

3. Results

a. *Supercell and QLCS differences*

A total of 126 tornadoes were reported within 111 km of KTLX between 2000–2010, resulting in 265 injuries and 3 deaths. Of these tornadoes, 89 were produced by supercells, 19 were associated with QLCSs and 15 were classified as "other". Several substantial differences exist between the storm heights, midlevel rotational velocities, mesocyclone heights, and storm-top divergence values of tornadic supercells and tornadic QLCSs.

The most intriguing results (Table 1) lay in the large differences between the midlevel rotational velocities of each mode. Tornadic supercells have a mean midlevel rotational velocity of 22.9 m s^{-1} while tornado-producing QLCS events reach mean midlevel rotational velocity values of only 14.5 m s^{-1}. Confidence intervals also were calculated using 95% confidence levels. The 95% confidence intervals for midlevel rotational velocity show no overlap, with the upper end of the QLCS confidence interval falling 3.5 m s^{-1} below the lower end of the supercell confidence interval. Therefore, it can be said with 95% confidence that midlevel rotational velocity for the studied QLCSs will fall between 10.8–15.67 m s^{-1}, while midlevel rotational velocity of supercells will fall between 19.5–22.7 m s^{-1}.

Differences in the other radar characteristics also show that supercells extend higher into the atmosphere, have deeper mesocyclones, and have greater storm-top divergence values than QLCSs. Based on the data set, on average, tornadic supercells have stronger overall updrafts and storm-scale circulations than tornadic QLCS events, therefore posing a greater threat of destructive tornadoes across central Oklahoma. Supercell tornadoes caused 264 injuries and had a maximum F/EF (Fujita 1981; Doswell et al. 2009) rating of 4 while QLCS tornadoes were responsible for 1 injury and had a maximum F/EF rating of 1.

These results may prove useful for operational meteorologists, especially when issuing tornado warnings for a given storm mode. On average, QLCS tornado events in central Oklahoma exhibit less substantial radar characteristics (e.g., lower storm heights) and produce weaker tornadoes. Therefore, when the radar characteristics of a QLCS event become comparable to the mean values observed in the supercell radar characteristics, more substantial impacts could be expected by a forecaster. For example, based on results of this analysis, a QLCS event with a midlevel rotational velocity of 22.9 m s^{-1} (the mean value for supercell tornadoes) or greater could alert a forecaster to the potential for more substantial impacts from a tornado. Figure 1 uses box plots to illustrate the lower values of low-level and midlevel rotational velocity in tornadic QLCS events.

b. Tornado warning lead time

No strong correlations exist between individual radar characteristics and tornado warning lead time. The variable showing greatest linear correlation coefficient with respect to lead time (0.277) is mesocyclone height, the second greatest (0.167) being storm-top divergence. These weak correlations likely result from the multitude of variables present during the tornado warning process. If other information suggests or rebuts the issuance of a tornado warning, lead time may be affected by these environmental biases. For instance, if a forecaster notices very high lifting condensation levels, he or she may require seeing very strong evidence of a tornado in radar displays before issuing a tornado warning, since high LCLs do not favor significant tornadoes (e.g., Rasmussen 2003).

Anticipation also may play a role. If a forecaster is expecting tornadoes to occur, he or she may be more likely to issue a tornado warning sooner than on a day when little tornado activity is anticipated. Rapid storm-scale evolutions can also affect lead time as was the case on 14 May 2009 near Anadarko, OK. This storm exhibited the deepest mesocyclone and strongest midlevel rotational velocity of any supercell in the data set, yet the lead time was a mere 2 min. This short lead time arose from rapid changes in the storm's intensity. At 0216 UTC, 10 min before the tornado developed, the midlevel rotational velocity was 18 m s^{-1}, which falls below the mean value for supercells. Only 9 min later, at 0225 UTC, the midlevel rotational velocity had increased to 38 m s^{-1}, the maximum value observed in this data set. Other factors such as hardware or software changes, alterations to operational procedures, and personnel issues (Waldstreicher 2005) also can affect lead time. In addition, the fact that radar characteristics only were examined at a single point in time, without any information about storm trends, may also affect these results. Therefore, the low correlations between tornado warning lead time and the radar characteristics were expected.

Table 1: Measured radar characteristics common to tornadic supercells and QLCSs. RV stands for rotational velocity.

Supercell								
	Width (km)	**Height (km)**	**Low-level RV (m s^{-1})**	**Midlevel RV (m s^{-1})**	**Meso Dia. (km)**	**Meso Hgt. (km)**	**Storm-top Div. (m s^{-1})**	**Tornado Duration (min)**
Mean	17.8	13.8	19.4	22.9	3.1	6.8	62.4	8.4
Median	17.2	14.6	18.7	23.2	3.0	6.8	65.4	5.0
Max	34.4	19.4	35.2	38.0	7.1	14.1	115.3	54.0
Range	29.4	13.0	26.5	29.0	6.9	12.8	100.3	53.0
Sample Size	85	86	56	86	86	64	73	89
QLCS								
Mean	12.2	11.5	13.4	14.5	2.9	4.7	43.6	5.2
Median	10.9	11.3	13.5	14.0	3.1	4.6	42.7	4.0
Max	25.6	17.3	23.2	27.5	4.3	7.2	71.5	17.0
Range	21.9	11.2	17.2	20.0	3.1	4.4	52.0	16.0
Sample Size	19	18	14	18	18	8	16	19

Table 2: Mean values and confidence intervals (range shown by min and max in the table) for all radar characteristics between unwarned and warned supercell tornadoes.

	Unwarned			**Warned**		
Characteristic	**Min**	**Mean**	**Max**	**Min**	**Mean**	**Max**
Width (km)	12.4	15.3	18.2	17.1	18.8	20.6
Height (km)	10.7	12.1	13.5	13.7	14.5	15.3
Low-Level Rot. Vel. (m s^{-1})	16.0	18.4	20.8	17.8	20.0	22.1
Midlevel Rot. Vel. (m s^{-1})	18.7	21.3	23.8	21.7	23.6	25.5
Meso Diameter (km)	2.3	2.9	3.5	2.8	3.1	3.5
Meso Height (km)	4.1	5.1	6.0	6.7	7.6	8.5
Storm-top Divergence (m/s^{-1})	37.9	51.8	65.7	59.5	66.6	73.8
Tornado Speed (m s^{-1})	11.3	15.5	19.7	13.4	14.7	16.0

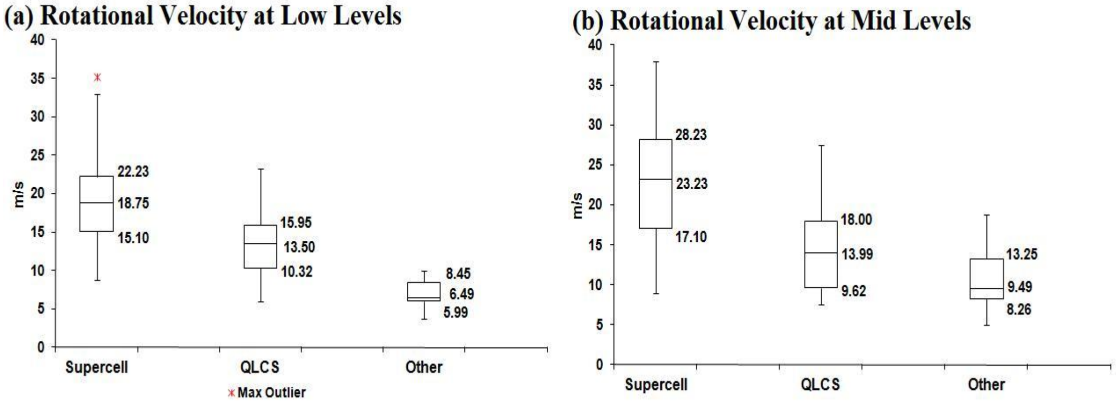

Figure 1: Box plots of rotational velocity at a) low levels and b) mid levels. Each box is bounded by the first and third quartiles. Whiskers are the highest or lowest data within 1.5 times the interquartile range below the first quartile and above the third quartile. Center line marks the median. Maximum and minimum outliers, if present, are marked in red if they fall beyond either whisker.

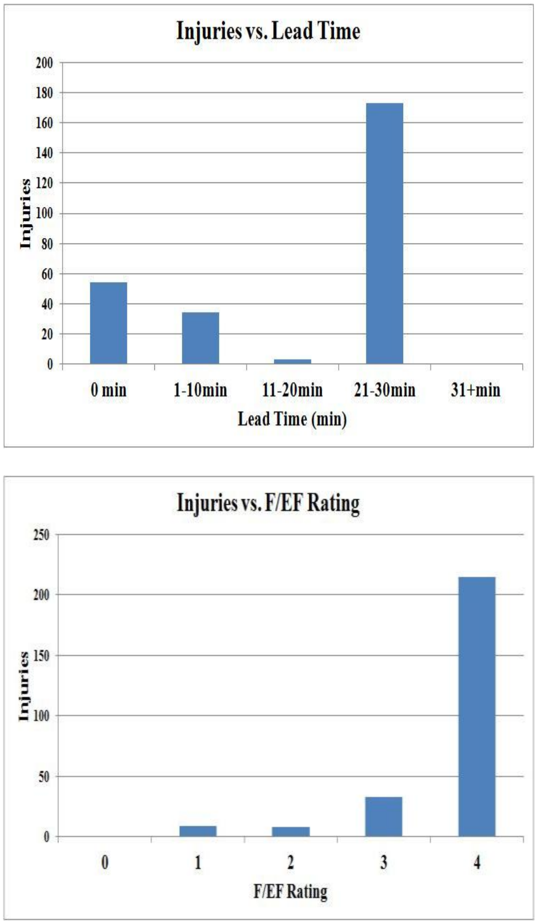

Figure 2: Bar charts of injuries compared to lead time and F/EF rating, as labeled.

Thunderstorm mode did appear to be associated with lead time. Of the 104 supercell tornadoes that occurred during the 11-y time span, only 19.2% went unwarned. At the same time, of the 19 QLCS tornadoes, 68.4% were unwarned. The average lead time for tornadoes associated with supercells was 13.4 min, while the average lead time was 2.0 min for tornadoes associated with QLCSs. The average lead time for all tornadoes in this data set was 11.7 min. The QLCS lead time was quite low due to the fact that a majority of these tornadoes were unwarned and the lead time therefore was set to 0 min. This result may arise from the fact that QLCS events in the Norman Forecast Office County Warning Area tend to exhibit much weaker radar characteristics than supercell tornadoes. Based on this data set, QLCS echo tops and storm-scale circulations are shallower and display weaker low and midlevel rotation than supercells.

In central Oklahoma, injuries associated with these weaker, short-lived QLCS tornadoes are also substantially fewer than injuries resulting from supercellular tornadoes. In the study period, only one person required medical attention as a result of a QLCS tornado, while the other 264 injuries stemmed from supercell tornadoes. While a relationship between storm mode and lead time does exist in central Oklahoma, this may not necessarily apply to the rest of the United States. A larger nationwide study conducted by Brotzge and Erickson (2009) found no relationship between storm type and lead time. This difference may be due to the large percentage of tornadoes with zero or negative lead time within their nationwide subset of data, as opposed to only central Oklahoma, or the storm mode classification scheme used.

There was very little correlation (0.03) between lead time and injuries. However, a much stronger correlation (0.56) appeared between F/EF rating and injuries, suggesting that injuries are more associated with tornado rating than with lead time (Fig. 2). Stronger tornadoes tend to produce more damage and as a result, more injuries, despite having the longest average lead time.

c. Supercell radar characteristics

Correlations between various radar characteristics of tornadic supercells also were examined. Storm-top divergence was best correlated to all other radar characteristics with midlevel rotational velocity following close behind (Table 3). This means, for example, that if storm-top divergence is large, so are mesocyclone height, storm width, low-level rotational velocity, etc. More importantly, of all the radar characteristics measured, midlevel rotational velocity showed the strongest correlation to F/EF rating and tornado duration (Fig 3). These correlations, 0.41 and 0.35 respectively, suggest that if midlevel rotational velocity is large, tornado rating and duration tend to be high and long respectively. Storm height and low-level rotational velocity had the next highest correlations with F/EF rating, also suggesting that if low-level rotational velocity is large or storm height is deep, tornado rating tends to be high. Midlevel rotational velocity and low-level rotational velocity were also most correlated to tornado duration. Therefore, when these two radar characteristics exhibit large values, tornado duration tends to be long.

Radar characteristics not well correlated with tornado rating and duration were mesocyclone height, mesocyclone diameter, and storm width (Table 3). The low correlation observed with mesocyclone height may result from the inherent challenges associated with this characteristic (see section 2). Otherwise, these three storm traits may not be as useful when diagnosing potential tornado rating and duration when using weather radar, at least according to findings of this study which focused on radar characteristics at a single point in time.

4. Summary and discussion

Radar data were compiled for tornadic thunderstorms occurring from 2000–2010 within 111 km of the KTLX radar in central Oklahoma. Several radar-based characteristics were measured and analyzed for each of the 126 tornado cases. An analysis of tornado warning lead time in relation to these radar characteristics, as well as to injuries, also was performed.

Significant differences were found between tornadic supercells and tornadic QLCSs. Supercells exhibited much greater midlevel rotational velocities and storm-top divergence values than QLCSs. In general, no strong correlations were found between tornado warning lead time and the radar characteristics. This result was expected due to the numerous variables involved in the tornado warning process. A relationship between storm mode and tornado warning lead time was found, at least partially due to the high number of unwarned QLCS events. This may be due to the fact that within this dataset, QLCSs produced weaker tornadoes with lower risk to life and property than supercell tornadoes. This observation is evidenced by substantially weaker midlevel rotational velocities observed with QLCS tornadoes than with supercell tornadoes, and the correlation between tornado rating and midlevel rotational velocity (Table 3).

Future research could include expanding the current dataset by adding earlier years, then performing the same analysis. A dataset including more regions of the nation could be useful, especially in fully defining a QLCS tornado spectrum and commenting upon tornado warnings associated with this storm mode. Data from the phased array radar located in Norman, OK could supplement and enhance the existing data set, especially in relation to lead time and the rapidly evolving storm-scale features often observed in this dataset (Heinselman et al. 2012). A comparison could be made between radar characteristics measured from the WSR-88D and the phased array radar to discover whether more frequent data would affect the results of this study. Radar characteristics also could be measured and analyzed in a 15–20 min time frame before and after tornadogenesis to capture changes within the supercell directly before a tornado and at the tornado's mature stage. This analysis could enhance knowledge about lead time and radar characteristics associated with most of the tornado's life cycle, and build upon this study's results which focused on single moments in time.

Despite its relatively small scope and sample size, the results of this study still can be considered qualitatively in an operational setting. Substantial differences exist between tornado-producing supercells and QLCSs in central Oklahoma. Additionally, lead time does not have a high correlation with injuries. Further research with larger sample sizes is needed, but

Table 3: Correlations between all supercell radar characteristics. Units as in Table 1.

	Width	Height	Low-Level Rot. Vel.	Midlevel Rot. Velocity	Meso Dia.	Meso Hgt.	Top Div.	Tor. Dur.	F/EF Rating
Storm Width		0.67	0.33	0.51	0.40	0.53	0.74	0.08	0.08
Storm Height	0.67		0.22	0.55	0.05	0.63	0.84	0.28	0.21
Low-level Rot. Vel.	0.33	0.22		0.59	0.02	0.07	0.36	0.31	0.35
Midlevel Rot. Vel.	0.51	0.55	0.59		0.03	0.46	0.52	0.35	0.41
Mesocyclone Diameter	0.40	0.05	-0.02	-0.03		0.09	0.21	-0.10	-0.18
Meso. Height	0.53	0.63	0.07	0.46	0.09		0.64	0.10	0.05
Storm-top Divergence	0.74	0.84	0.36	0.52	0.21	0.64		0.22	0.19
Tornado Duration	0.08	0.28	0.31	0.35	0.10	0.10	0.22		0.58
F/EF Rating	0.08	0.21	0.35	0.41	0.18	0.05	0.19	0.58	
Mean	0.42	0.43	0.28	0.42	0.05	0.32	0.47	0.23	0.21

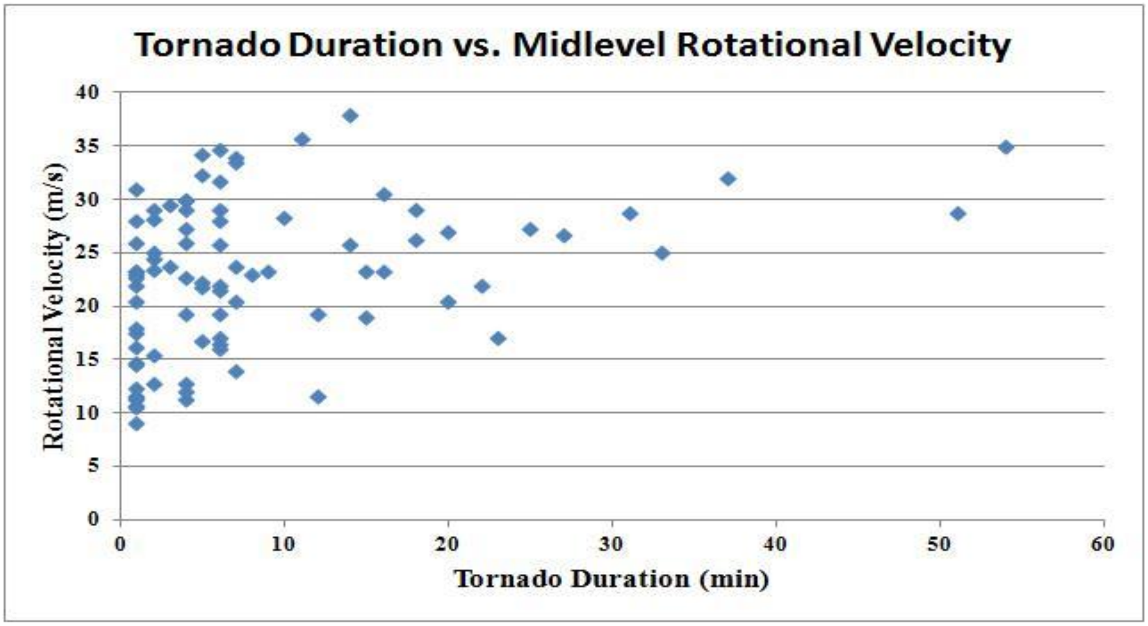

Figure 3: Scatter plot showing relationship between midlevel rotational velocity and tornado duration.

this study suggests that increasing lead time may not lessen the number of injuries resulting from strong tornadoes. In addition to lead time, those wishing to lower the tornado casualty numbers may need to pursue factors such as information dissemination, education, call-to-action statements within tornado warnings, and building-construction standards.

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REVIEWER COMMENTS

[Authors' responses in *blue italics.*]

REVIEWER A (Richard L. Thompson):

Initial Review:
Recommendation: Accept with minor revisions.

Substantive Comments:

Overview
The paper documents the WSR-88D characteristics of 126 tornado events in central Oklahoma during an 11-year period beginning in 2000. The overall findings are of interest to a broader audience, though the paper is relatively limited in scope since it does not consider any near-storm environmental information.

The authors should provide justification for the limitation to cases within 60 nm of the radar site. This may be as simple as stating that this distance was used ensure velocity data within 1 km of the ground.

Good point. An explanation has been added.

Supercells are not quantified in terms of rotational velocity, which is a significant limitation regarding reproducibility of this work. Figure 1 shows the maximum midlevel rotational velocity distributions, and I'm concerned that "supercell" events go as low as 5 m s^{-1}, which is well below any of the mesocyclone algorithm thresholds [see Stumpf et al. (1998), which should be considered as a reference in this work], and is not consistent with similar previous work (e.g., Thompson et al. 2003).

The reviewer is correct. Additional references have been considered and rotational velocity thresholds have been added to the storm classification scheme in order to make the work more consistent with Stumpf et al. (1998) and Smith et al. (2012).

Some related work should probably be considered, such as the **Convective Modes for Significant Severe Thunderstorms in the Contiguous United States. Part 1: Storm Classification and Climatology** by Smith et al. (2012; see early online releases for *Weather and Forecasting*—it should appear soon, and Part II of that paper series is already available and might also be relevant). Otherwise, I can provide a copy to the authors.

Extra references have been considered and added.

[Editor's comment: This paper became available in AMS early online releases during review and now is published.]

Specific Comments:

[Minor comments omitted...]

All "technical comments" are embedded in the Word document and not reproduced here.

Introduction - I assume this distance from the radar site was to ensure velocity data below 1 km AGL? Please explain this choice in the text.

Good point. An explanation has been added in the text.

Equation 1 - You haven't defined any rotational velocity thresholds for supercell identification. I read the paper and get the impression that the presence of a supercell was decided before velocity data were examined. As it stands, your results are not reproducible.

Very good point. Thresholds for rotational velocity have been included.

[Editor's comment: The threshold(s) for what was considered supercellular, and reasoning for them, need to be specified for the sake of analytic reproducibility.]

Top of 2nd column P. 2 - Were these storms supercells? Why remove them from your sample? You don't refer to storm environment anywhere else, so why resort to that arbitrary distinction here?

Good point. The three storms have been classified using the scheme presented in the methodology section and added to the dataset.

95% confidence intervals? You need to provide more background description.

Background has been added.

Somewhat speculative. A stronger updraft aloft may not have much to do with updraft strength in the lower parts of the storm, where tornado formation typically occurs. In other words, be careful with the implied "stretching" argument unless you're prepared to go into much more detail regarding the physical links between mid-upper level updraft velocities and low-level stretching potential.

This is a good point. Wording has been altered somewhat to make the sentence less speculative. This statement was intended to comment on the more robust radar signatures (related to storm scale circulation strength and overall updraft strength) associated with supercells over QLCSs.

Would help to provide a few references when you refer to "numerous authors".

This section has been removed since it distracts from other results presented in the text. In addition, the number of mini supercells (as defined by Kennedy et al. 1993; Burgess et al. 1995; and McCarthy et al. 2006) within the dataset represented a relatively small portion of the observed supercells.

Could the "large" size of the storms have something to do with radar sampling, and why the signatures are strongest?

This section has been removed from the text, but this is a very good question, though I am unsure of the answer. Radar sampling may have played a role in this, though many of these large storms were relatively close to KTLX. I do not think it is a coincidence that these strong signatures were associated with supercells occurring during outbreak days.

"may"? I understand your argument, but I've seen plenty of evidence to the contrary in warning operations, where environmental information appears to have little influence on warning decisions.

Good point. The text has been changed.

Significant at the 95% confidence level? Please specify this and the type of significance test used.

Specification has been added to the text.

I don't see any correlation coefficients calculated for lead time by mode, thus you would be more precise to say "associated".

This has been changed in the text.

What is the average lead time for OUN tornado warnings? You quoted 13 minutes as the national average. Is OUN below that average for whatever reason?

Average lead time for OUN has been added to the text. OUN is slightly below the national average for tornado warning lead time for tornadoes in this dataset, though it is out of the scope of this study to comment on the reasons for this difference in lead time.

Table 2: These tornado duration numbers seem awfully high. *All* unwarned tornadoes in the OUN area lasted more than 20 minutes?

Very good point. The table should have read tornado speed and has been changed in the text.

Second review:

Recommendation: Accept with minor revisions.

General Comments: The paper has improved from the original submission, though I still have a few questions and suggestions to consider before it is ready for publication. The scope of the paper is quite narrow and it is my impression that the findings are marginal for a formal publication, but it is close enough to give the authors the benefit of the doubt. My specific comments follow below.

Substantive Comments:

P. 3, 1st column: Why do what appears to be an intermediate step in the convective mode assignments, considering your following discussion of three categories?

Good point. The intermediate step was not needed to successfully classify the storms involved in the study and has been removed from the text.

P. 5, 2nd column: I think a bigger reason for the low correlations is using a single snap shot at the initial time of the tornado. As you mentioned, forecast expectations and storm environment can make a big difference in the willingness to warn, along with time trends in radar attributes.

Very good point. More emphasis has been added to the text that radar characteristics were only examined at a single point in time instead of over some duration of time.

P. 7, 1st column: Jerry's got some newer results that do show variations in tornado warning POD by storm mode and storm environment, but this information is not yet in publication. Recall that they only characterized the reflectivity into the simple bins of line, cell, tropical, and undefined. They did not consider velocity data and did not identify supercells.

Good point. One of the suggested reasons that a difference occurred in the respective results was the fact that a different storm classification scheme was used.

P. 7, 1st column, end of sub-section b: You may want to explain the apparently contradictory statement in the last sentence of the paragraph, compared to the second sentence of the paragraph. I'm guessing that the injuries are dominated by just a couple of tornadoes, and lead time statistics largely reflect the more common weak tornadoes.

More text was added to help clarify this paragraph.

P. 7, end of section 3: Be sure to emphasize that you're only considering radar data at a single time at the start of an event—time trends could suggest something entirely different!

Good point, an emphasis has been added.

Last paragraph of conclusions: I realize that the two co-authors have left OUN and additional work would be challenging. However, some of the suggested "future work" (such as peak values before or after the beginning of each tornado) would be nice to see with this paper because it is quite narrow in scope.

This additional information would be nice, though this will not be able to be added to the paper.

[Minor comments omitted...]

Third review:
Recommendation: Accept with minor revisions.

Specific Substantive Comments:

I don't see any mention of a distance requirement between the max inbound and outbound velocities. Smith et al. (2012) used ≤10 km for that distance.

Good point. In all instances, the maximum inbound and maximum outbound velocities were within 10 km of one another, so the distance requirement is consistent with Smith et al. 2012. This has also been clarified in the text in section 2.

Why 45 dB*Z* instead of 40 dB*Z* which is used to define QLCS? Some explanation for the difference is needed, like what you did below for the echo top heights (15 vs. 30 dB*Z* discussion).

A source has been added to help explain the choice for using 45 dBZ. This source was in the paper originally but must have been left out in one of the revisions. The choosing of the 45 dBZ contour for storm width was based upon this article and was also somewhat subjective as few sources could be found that specifically stated a reflectivity value to use when determining storm width.

If I understand this correctly, the whiskers should extend the same distance above and below the box, which is clearly not the case for QLCS mid levels. Instead, do your whiskers extend to the max or min value within 1.5 times the interquartile range?

You are correct. After some further research, I went back and looked at the program that created the box plots and its documentation, which contains some somewhat vague language, and determined that the whiskers lie at the maximum or minimum data point within 1.5 times the IQR. This has also been changed in the figure caption.

REVIEWER B (Albert E. Pietrycha):

Initial Review:
Reviewer recommendation: Decline.

General comments: The purpose of the manuscript is to demonstrate radar characteristics between supercell and QLCS tornadoes. Various radar-based measures are shown to illustrate the authors' points. However, the authors main point(s) is lost due to the numerous other threads introduced, none of which are rigorously explored (e.g., radar characteristics vs. tornado lead times, supercell spectrum and mini-supercells, lead time vs. injuries, forecaster cognitive issues, societal issues, etc.). The manuscript lacks clarity, direction, depth, original content, has far too few references which may have helped flush out original content (I cite more references in this review than what the authors used), lacks discussion of findings in light of other works, and is riddled with opinion and conjecture. The paper reads as though the authors pieced together what each contributed without proper editing in order to weave the ideas together. Should the paper make it for a second round of reviews, I expect what does come back will be a completely different paper. Hence, a new submission and review process may be in order. In its current form I cannot accept this paper for the EJSSM.

I highly encourage the authors to carefully re-approach and research their efforts by distilling the plethora of threads and select one main topic that is new or unique. The authors have several intriguing topics in front of them, several of which could become individual papers provided effort is put forth and a thorough internal review is done before formal submission.

More clarification has been added to the background, methodology, and motivation of the research in order to bring more clarity to the research and conclusions presented in the text.

Substantive comments: Within the manuscript I provide *forty seven* comments and suggestions, as well as numerous edits and several references. Many of the comments are minor. Instead of rehashing all of them here, I've selected what I believe are major comments and concerns.

Please increase font size on all the graphs for readability. The axis labels are very difficult to read. Also, with Fig. 1a where are the min/max outlier asterisks denoted in the figure? You mention them in the graphic, but do not show them.

Figures have been improved and outlier asterisks have been addressed.

[Editor's comment: EJSSM does provide a "click to enlarge" option for authors to link to larger, higher-resolution versions of figures. Whether or not an author takes advantage of this, every label and element of a figure still needs to be decipherable as-is, in the paper.]

Abstract:
I'm unclear to the meaning of 'listed'. Do the authors mean *cited* or *credited*? If so, how can you state 88D data were the basis for warnings in many (most) cases as opposed to spotter/chasers/EMs/media

reports, storm history, atmospheric environmental factors, that very likely also contributed to the warnings? Can the authors state how much weight these additional factors may have had on the issuance of warnings?

All good points and concerns with the wording of this sentence. Portions of the sentence have been removed for clarity.

I'm unclear to what the authors mean by "… not have a physical basis". There is no disagreement that I'm aware of in the scientific literature that mini-supercells have dynamic or kinematic differences compared to larger supercells. Physical differences do exist, however, as a function of atmospheric environmental conditions that foster and maintain the development of relatively shallow and/or narrow updrafts compared to larger supercells. From an operational warning prospective, the distinction is important insofar as a forecaster's situational awareness that he/she may need to interrogate shallower supercells in a different manner compared to larger supercells (e.g., using different 88D volume coverage patterns, "closer-in" storm integration, etc.). Please clarify this point later in the body of the paper.

The reviewer is correct and "physical basis" as well as the entire sentence has been removed from the text.

Introduction:
You cannot use the WDTB DLOC course as a reference. The course is a culmination of referenced material wrapped and presented for the purpose of targeted training. Please site specific relevant references to the topics discussed.

Specific sources have now been cited instead of DLOC.

[Editor's comment: DLOC courses can be used as references when no other literature exists on the specific topic, or when the subject matter specifically deals with training; however, I don't see that to be the case here. They are "gray literature" to be avoided when possible (see Schultz 2009, Eloquent Science, for a discussion on gray literature).]
Why did the authors select a 60 mile radius compared to something larger or smaller? The selection of this radius is never explained in the paper. Also, please change to SI units throughout the paper.

An explanation has been added and SI units are now used throughout the text.

[Editor's comment: SI units must be used throughout. English units are optional and can be provided. If you do the latter, however, be consistent with it.]

Methodology section:
Since GRAE was used as the radar integration software, I ask if your radar related heights are ARL, AGL, or MSL? Given you used GRAE units would be ARL. Please fix this and with all occurrences in the paper and figures.

All heights are in ARL and this has been included in the text.

Results "a" section:
8) The authors wrote, "Notable also is the absence of landspout tornadoes in this data set." This may be, in part, a function that non-supercell tornadoes often are NOT distinguished from supercell tornadoes in storm reports. That written, you cannot discount non-supercell tornadoes may be in your data base. A mention of these points should be included in the paper. Furthermore, avoid using the colloquialism "landspout". Instead use non-supercell tornadoes.

Very good point. This comment within the text has been removed since one cannot be certain that non-supercell tornadoes did not exist within the dataset.

The authors wrote, "The short-lived nature of the many landspout tornadoes may have made observation and reporting of these features difficult." Remove this sentence as it's based on opinion. To my knowledge, to date, there have been no formal studies documenting duration comparisons between 'landspouts' and supercell tornadoes.

This sentence has been removed.

The authors wrote, "Differences in the other radar characteristics also show that supercells extend higher into the atmosphere, have deeper mesocyclones, and greater storm top divergence values than QLCSs." It would be worthy to mention something about the environments that foster these differences and use several references to back your results that have already outlined conditions favorable for deeper supercells and shallower QLCSs mesocyclones.

Good point. This research focused on radar characteristics of tornado producing storms rather than environmental conditions. While it may be useful to include discussion about the environments supporting the tornadoes in the data set, discussion will not be added to remain consistent with the rest of the text.

The authors wrote, "This figure simply illustrates the lower values of mid level rotational velocity in tornadic QLCS events in this data set." Why not just use figure 1a to illustrate this finding? Also I'm unclear as to the relevance of 1b given the lack of its discussion and relevance in the study. More should be written to identify the significance as to why you compared warned supercells to unwarned QLCS tornadoes? Why didn't the authors do a comparison between unwarned supercells to unwarned QLCS tornadoes?

Good point. The figure has been changed. 1b was originally intended to show that unwarned supercells had more robust radar signatures than even the warned QLCSs in an attempt to further illustrate the differences in the radar signatures between supercells and QLCSs. This was, however, not the best method to illustrate this, so low-level rotational velocity has been used instead and is ultimately much clearer.

Results "b" section:
I have a difficult time with this entire first paragraph, especially with the last sentence. Based on the Kennedy et al. definition, what percentage of all supercells in your study met their criteria? Based on fig. 2a & b, it appears a small percentage. Therefore, is your populated size statistically large enough to make such a claim? Additionally, you never define in the paper what your supercell spectrum is comprised of. As an example, Moller et al. (1994) clearly defined their supercell spectrum as LP, Classic and HP supercells. Based on how your paper reads you have only two types, mini- and, for the lack of a better word, "normal" supercells. Your "normal" supercells are not defined in the paper as to what *they are*. Lastly, did the authors find any differences in warning lead times between mini-supercells and "normal" supercells? I highly recommend this entire topic be omitted from the paper given the lack of a rigor and also how it detracts from the other points discussing supercell tornadoes vs. QLCS tornadoes.

Good points. The section pertaining to mini supercells has been removed from the text. One goal of the research was to use the radar characteristics to develop a set definition of a mini supercell, at least over central Oklahoma. This could not be accomplished due to the continuous spectrum of radar characteristics shown in the data set, and it was difficult to determine the actual number of mini supercells captured in the data set due to the somewhat differing definitions of the phenomenon presented in other research (Kennedy *et al. 1993; Burgess et al. 1995; and McCarthy et al. 2006). The section has been removed because it does distract from the other results in the study.*

Results “c” section:
The authors wrote, “Other factors such as staff shortages, equipment problems, and number of tornadoes occurring (i.e., outbreak situation) will also affect lead time.” You need some references here. See Waldstreicher 2005 regarding task management issues. I also suggest you contact Liz Quoetone with the NWS WDTB for references regarding adult cognitive issues.

A reference has been added and the sentence has been changed to reflect this reference.

The authors wrote, “This result is not surprising, as a taller stronger storm is more likely to receive attention from a forecaster.” Be careful here with opinion. Can it be implied, conversely, that QLCS events or highly sheared storms **DON’T** receive the same amount of attention from a forecaster? Your statement also conflicts with what you wrote previously in this same section. “If a forecaster is expecting tornadoes to occur, he or she is more likely to issue a tornado warning sooner than on a day when little tornado activity is anticipated.” Based on this sentence can it be inferred it doesn’t matter how tall an updraft is as all the storms will have a forecaster’s attention if they are expecting tornadoes? Please clarify these points.

The reviewer brings up good points. The first sentence mentioned has been removed since it reflects more opinion than fact and is difficult to quantify. The other sentence has been modified to emphasize the plausibility of the statement. Several of the points in this section were presented in an effort to explain why there was little correlation between radar characteristics and tornado warning lead time.

The authors wrote, “These storms are shallower, have shorter mesocyclones, and weaker low and mid level rotation than supercells. Injuries associated with these weaker, short-lived QLCS tornadoes are also substantially fewer than injuries resulting from supercellular tornadoes.” Here again, some references would help back your findings. For example, Trapp et al. (1999) found tornadoes associated with QLCs were associated with shorter warning lead times, whereas Guillot et al. (2008) found greater tornado warning lead times for isolated supercells and strong convective lines.

This statement was based on the data from central Oklahoma and revisions have been made to the sentence to help clarify. If lead time affected the injury counts, QLCS tornadoes should account for more injuries as they have shorter lead times than tornadoes associated with supercells (Guillot et al. 2008). The data showed, however, that tornadoes associated with supercells resulted in many more injuries across central Oklahoma perhaps due to the fact that these tornadoes were stronger than those associated with QLCSs.

The authors wrote, “A larger nationwide study conducted by Brotzge and Erickson (2009) found no relationship between storm type and lead time.” Please comment as to why their findings are different than yours; larger sample size, different methodology, other?

Additional comments have been added.

The authors wrote, “In addition to lead time, those wishing to lower the tornado casualty numbers may need to pursue other factors.” These points should be placed in the summary section of the paper. Also, I encourage you to read the recent NWS Service Assessments from the Joplin and Tuscaloosa tornadoes as potential references behind the ideas offered here by the authors.

The points have been moved to the summary section.

Results “d” section:
The authors wrote, “These correlations, .44 and .39 respectively, suggest that if mid-level rotational velocity is large, a stronger tornado will result.” Correlation does not mean causation! You can not imply anything based on correlations. All you can state is when X is high Y is high. Additionally, a lot of correlation information is shown in Table 3, but there is little discussion to go along with it. I strongly suggest you pare down the information in the table to only what is discussed in the paper. Also, a figure would go a long way with this paragraph depicting rotational velocity vs. tornado rating and tornado duration.

Very good points. This has been corrected in the text. Extra discussion has been added regarding Table 3 as well. All of the correlations are still included in order for a potential reader to see how all characteristics correlated with one another if interested. A figure has also been added showing the relationship between midlevel rotational velocity and tornado duration.

Summary and Discussion:
The authors wrote, “A comparison could also be made between radar characteristics measured from the WSR-88D and the phased array radar (PAR) to discover whether more frequent data would affect the results of this study.” See Heinselman et al. (in press, WAF) as they conducted such a study with the PAR vs. the 88D concerning warning lead times.

This paper has been referenced within the text now.

Due the large number of minor comments I will not list them all here. Please see my comments and editorial suggestions embedded within the manuscript.
[Minor comments omitted…]

Second Review:
Reviewer recommendation: Accept with minor revisions.

General comments: The paper has much improved since its original submission in clarity, focus and presentation. The authors addressed all of my comments and concerns from the first round of reviews. At this time I have a handful of minor comments (12 comments) that deal mainly with editorial suggestions or grammatical issues. The comments are embedded within the manuscript and need to be addressed.

Since there were no major comments from the Pietrycha review and we agreed/understood all of the minor comments, there are no responses in that document.

[Minor comments omitted...]