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A Statistical Evaluation of Tornado-Production Tendencies of Southernmost Supercells Compared to Adjacent Supercells in a North–South-Oriented Line

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ABSTRACT

Supercell events in which adjacent storms were oriented in a north–south, linear manner, with at least one storm producing a tornado, were identified to determine if southern-end supercells were favored for tornado production over other cells in the line. Data included the official Storm Prediction Center severe-weather database and Level II WSR-88D data for the full 2016 and 2013 calendar years, with select cases from 2011. A total of 568 supercells, 243 tornadic, were sampled in association with 193 north–south-oriented lines. The χ^2 statistic was used to test for independence between storm location and tornado production and to analyze other possible sources of dependency, including number of supercells in the line, month of occurrence, geographic region, type of surface boundary initiating the storms, and tornado destruction potential index. There was no statistically significant evidence to indicate that southernmost supercells are more prolific tornado producers than other supercells in the line, although certain subgroupings had larger observed frequencies of occurrence than expected. Among the other, more conclusive results were: 1) in March, April and October, fewer southernmost supercells produced tornadoes than expected; 2) more north–south-oriented lines occurred in the Southern Plains than any other U.S. geographic region, and these lines were commonly initiated by the dryline; 3) there was no dependency between southern-end storm tornado production and geographic location; and 4) warm fronts resulted in more southernmost tornadoes than expected values, but not at statistically significant levels.

1. Introduction

Studies have found that supercell thunderstorms often initiate in line segments along or near surface boundaries such as thermal fronts, the dryline, and outflow boundaries from prior or ongoing convection (e.g., Maddox et al. 1980; Bluestein and Parker 1993; Ziegler et al. 1997; Bluestein and MacGorman 1998; Markowski et al. 1998; Hane et al. 2002). These convective line segments sometimes evolve into a series of multiple supercells, frequently with nonsupercellular convection interspersed, that retain a linear-like configuration (e.g., Burgess and Curran 1985; Bluestein et al. 1988; Bluestein and Woodall 1990; Bluestein and Hutchinson 1996; Bluestein and Weisman 2000).

The southern-end storm in such a configuration of storms—whether it be a line of supercells or an isolated storm on the southern end of a squall line, is colloquially referred to as the "tail-end Charlie" storm (Branick 1996). (In the context of this paper, only lines of supercells will be discussed). There is a general consensus among many individuals seeking to observe or collect data on tornadoes to target southern-end supercells when events with multiple north–south-oriented supercells occur, albeit with little or no formal documentation in peer-reviewed literature about their decision-making process. This decision is based off the belief that southern-end storms are more likely to produce tornadoes over other cells under such a storm

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configuration (H. B. Bluestein 2018, personal communication; R. Edwards 2018, personal communication). Some scientific evidence supports this idea as well (e.g., Limpert et al. 2006; Sobash and Stensrud 2015). Bluestein and Weisman (2000) determined that end cells (both on the northern and southern flank of linearly oriented discrete storms) behave most like isolated cells under certain shear conditions, because they only have one neighbor with which to interact, suggesting the isolation of these storms might favor tornadoes.

Kuster et al. (2015) describe the only peer-reviewed reference to chasing the southern-end storm that the authors could find, stating about their chase: "The most obvious candidate for potential formation (of tornadoes) was the 'tail-end Charlie' storm to the west of Union City, Oklahoma, since it had unimpeded access to warm moist air residing south of the thunderstorm complex." However, many cases can be found from non-peer-reviewed sources, such as internet blogs, that document storm chasers who have used the tactic of targeting the southern-end storm. Wilhelm (2012) stated that during a chase, he waited for the southern storm to initiate explicitly due to the belief that the southernmost supercell often becomes the dominant storm. This proved to be a successful decision because the southern storm he later targeted produced multiple tornadoes, including twin tornadoes.

Another example where the southern-end storm successfully produced a tornado was documented by Robinson (2004). Livingston (2013) observed an event with convection initiating along a dryline/warm front triple point where multiple supercells produced tornadoes, including the southern-end storm. Bluestein and Parker (1993) also observed a case where a squall line broke into distinct segments and the southern-end storm produced a tornado.

Alternatively, there are documented instances where this tactic failed. Lucio (2016) targeted a southern-end storm that initiated along a dryline in the Texas Panhandle. In his case, the southern storm failed to produce a tornado; however, there were multiple tornadoes associated with other cells further north in the line. Carlsen (2017) targeted storms initiating along a warm front near Norfolk, NE. The mesocyclone on the cell they were targeting was slow to organize, and when a new cell initiated to its south, they chose to target that one. As the original cells merged into a line, the chasers continually refocused on the southern-end storm that became supercellular. Despite several periods of intensification, the southern-end storm never produced a tornado; however, one of the cells further north did. Thus, the main question is: Does this tactic actually work? Will storm chasers be more likely to observe a tornado by targeting the southern-end storm?

Numerous observational (e.g., Bluestein and Jain 1985; Bluestein and Parker 1993; Lee et al. 2006; Bluestein 2009; Smith et al. 2012) and numerical studies (e.g., Rotunno et al. 1988; Bluestein and Weisman 2000; Kirkpatrick et al. 2007) have examined how supercell thunderstorms initiate and what environmental conditions are conducive to general supercell development (e.g., Rotunno et al. 1988; Brooks et al. 1994; James et al. 2005; Kirkpatrick et al. 2007; Thompson et al. 2007; Houston et al. 2008; Thompson et al. 2012); however, considerably fewer studies have specifically analyzed cases with multiple supercells oriented linearly. James et al. (2005) found that the time of day affects the mode of convection such that lines of isolated cells occur more frequently in the evening and continuous lines of convection are more likely to occur in the morning. Bluestein and Parker (1993) proposed that the type of surface boundary and the magnitude of convergence along the boundary might influence whether convection grows linearly or remains discrete. Prefrontal troughs and drylines have been documented to produce discrete supercells more often than cold fronts (Dial et al. 2010), and Bluestein and Parker (1993) determined that over half of the convective storms forming near a dryline in the southern Plains began as isolated cells. Therefore, the success or failure of a southern-end storm to produce a tornado feasibly may be associated with the type of surface boundary that leads to the line.

Despite the above studies, and others that have looked at various aspects of supercells oriented in a line, no known studies provide systematic evidence that southern-end storms are favored for tornado production over others in a line. Thus, the purpose of this study is to statistically determine whether or not the southern-end supercell is favored for tornado production over the other supercells when there are multiple cells aligned in a north–south manner. The surface boundary-forcing mechanisms also are investigated for such cases, to identify trends between the success or failure of southernmost supercell tornado production and surface boundary type, as well as relationships with the month of occurrence, destruction potential index (DPI) (Thompson and Vescio 1998) and geographical location (Fig.1)

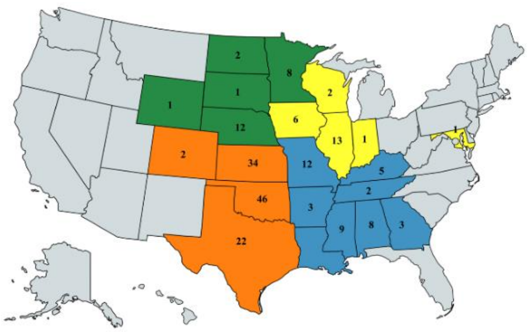

Figure 1: Representation of the geographic regions (Northern Plains = green; Southern Plains = orange; Southeast = blue; Midwest = yellow), as well as the number of north–south-oriented lines that occurred in each state. *Click image to enlarge.*

Determining if southern-end storms are statistically favored for tornado production is not only valuable information for storm chasers when deciding which storm to target, but also for forecasters when predicting primary severe weather hazards associated with an ongoing storm (James et al. 2005). The data and methodology used herein are discussed in section 2, while section 3 presents the results and discussion of the statistical analyses. The summary of results and future work are given subsequently in section 4.

2. Data and methodology

a. Case selection

Storm Prediction Center (SPC) storm report archives from the national severe-weather database (SPC 2018) were used as a first-order magnitude investigation to produce a list of potential cases for inclusion in this study (Fig. 2). The traditional NCEI Storm Events Database was not used because that database records tornadoes on a county-to-county basis, rather than by whole path, which caused confusion in determining which reports were associated with new tornado events versus events continuing from a previous county. Cases were selected from the full 2016 and 2013 calendar years, which were known to have several events where multiple supercells were aligned in a north–south configuration. Several more high-profile cases were included from 2011 (14 April, 27 April, 21 May, 22 May, and 24 May) to bolster the number of events with >3 consecutive supercells within the line, and to add to the geographic diversity of the sample. These cases were selected because they were unusually extreme outbreaks with a large number of tornadoes, many of which occurred with linearly oriented supercells. No data from the years 2015, 2014 or 2012 were included because a large sample size was already obtained. Although the years selected for samples are out of chronological order, this does not affect the end result of this study, because the case studies are not sensitive to time. Rather, the cases were selected based on a physical requirement—linearly oriented supercells—regardless of when they occurred.

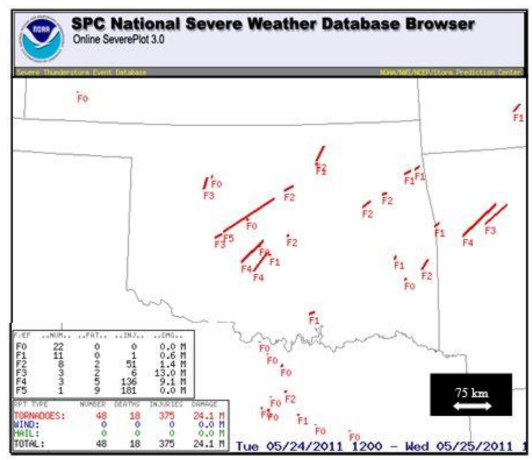

Figure 2: Example SPC severe-weather database browser graphical output for 24 May 2011, illustrating tornado reports including linear paths (start to end point path) and EF scale rating. *Click image to enlarge.*

After dates that produced tornadoes were determined, the next step was to confirm that the tornadoes were indeed produced by a supercell. Radar data from each of the potential dates were examined first using the NCEI interactive radar tool (https://gis.ncdc.noaa.gov/maps/ncei/radar, NCEI 2018). The reflectivity structure of the radar echoes was examined to identify the storm mode of the parent storms that produced the tornado associated with the report in question. The difference in reflectivity structure between squall lines and supercells is illustrated in Fig. 3. If the radar reflectivity field was not

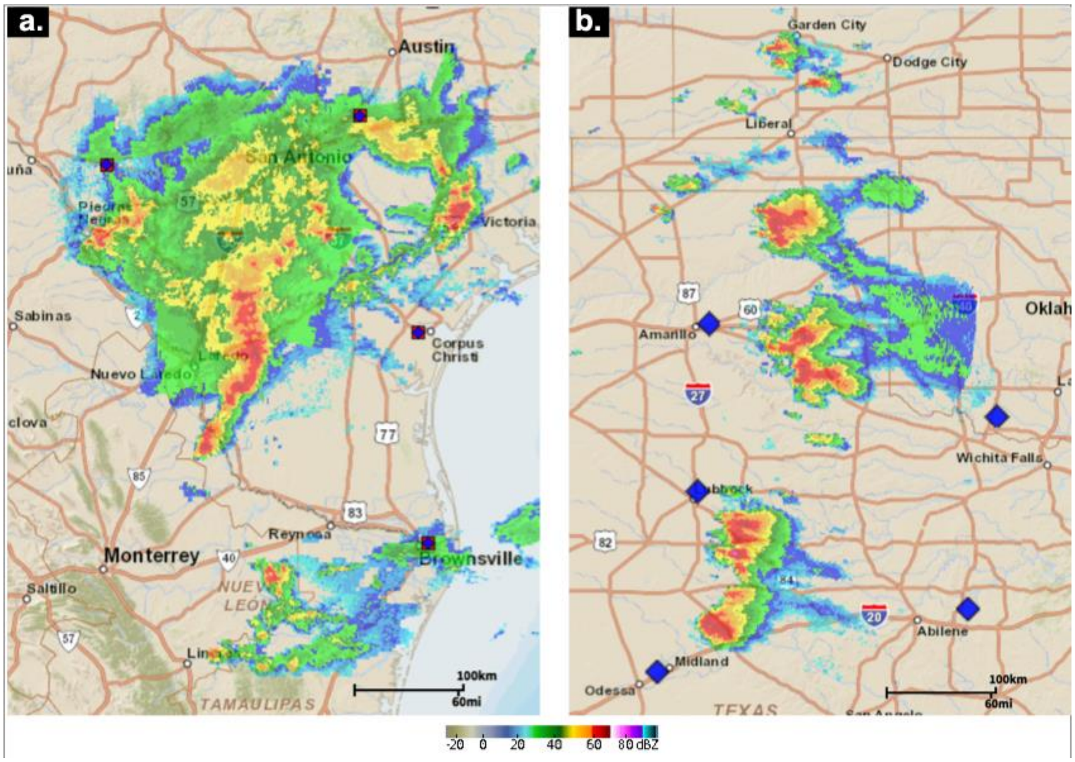

Figure 3: NCEI interactive radar image of the regional reflectivity (dB*Z*) composite for: a) an example of a squall line at 0355 UTC 19 March 2016; and b) an example of north–south linearly oriented supercells at 2255 UTC 22 May 2016. *Click image to enlarge.*

clearly a squall line or an isolated cell, the approximate timing of the event and the radars in closest proximity were documented for further analysis.

At this point, if a tornado report met the above qualitative requirements, Level II WSR-88D data were analyzed further using Gibson Ridge Level-II Analyst software (GR2 Analyst®) to determine if it met a series of additional requirements. In order to be included in the study, the following criteria had to be met:

1. There must be at least 2 supercells, as identified by the same criteria as Smith et al. (2012): the presence of a mesocyclone having $\Delta V > 10$ m s^{-1} for at least 3 radar scans embodying the time of the tornado report in the radial velocity field.
2. The axes of supercell groupings had to be oriented within 45° of north–south. Lines of cells that were more dominated by east–west orientation were not included.
3. The cores of adjacent cells had to be discrete (areas ≥40 dB*Z*[1] had to be separated by areas of reflectivity <40 dB*Z*).
4. The line of storms could not have a trailing precipitation region that was wider than the the supercells (in order to minimize dynamical differences between relatively isolated storms and those transitioning to the MCS mode).
5. Adjacent mesocyclones had to be <75 km from each other[2] in order to ensure that the adjacent cells within the line were close enough potentially to impact each other through processes such as precipitation fallout, outflow boundaries, etc.

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[1] The reflectivity threshold >40 dB*Z* was somewhat arbitrary, but represented an obvious visual change from yellow to green on the color scale used to view the data. Therefore, it was easy to discern visually if this condition was met.

[2] This distance is also somewhat arbitrary, but was chosen because cells separated by >75 km tended to be completely discrete and therefore the presence of other cells was likely not influencing any individual cell.

Table 1: All observed events included in this study, including the date, geographic region, total number of cells, total number of tornadoes, and the total number of tornadoes produced by the southernmost supercell.

Date	Region	Number of Cells	Number of Tornadoes	Number of Southern Tornadoes
14 April 2011	Southern Plains	40	15	4
27 April 2011	Southeast	28	13	4
	Midwest	3	1	0
21 May 2011	Southern Plains	26	9	2
	Southeast	2	1	1
22 May 2011	Midwest	25	6	5
	Northern Plains	6	3	0
	Southeast	32	15	5
24 May 2011	Southern Plains	45	20	8
18 February 2013	Southern Plains	16	8	4
18 March 2013	Southeast	4	1	0
30 March 2013	Southern Plains	5	2	2
7 April 2013	Southern Plains	2	1	1
8 April 2013	Southern Plains	2	2	1
	Northern Plains	3	1	1
11 April 2013	Southeast	5	2	1
17 April 2013	Southeast	6	2	0
	Southern Plains	2	1	1
18 April 2013	Southeast	3	1	0
8 May 2013	Southern Plains	5	1	0
15 May 2013	Southern Plains	14	9	2
18 May 2013	Southern Plains	6	4	2
19 May 2013	Southern Plains	14	7	2
	Northern Plains	2	1	0
20 May 2013	Southern Plains	11	5	3
27 May 2013	Southern Plains	2	1	1
	Northern Plains	2	1	0
28 May 2013	Northern Plains	3	1	1
29 May 2013	Northern Plains	5	3	1
30 May 2013	Southern Plains	2	1	0
31 May 2013	Southern Plains	5	2	2
11 June 2013	Northern Plains	2	2	1
12 June 2013	Midwest	3	1	1
21 June 2013	Northern Plains	4	3	1
22 June 2013	Northern Plains	4	2	1
22 July 2013	Northern Plains	2	2	1
	Midwest	6	2	0
3 August 2013	Southern Plains	3	1	0
14 August 2013	Southern Plains	2	1	1
17 November 2013	Midwest	17	7	3
	Southeast	10	5	2
13 March 2016	Southeast	6	2	0

Table 1 continued.

Date	Region	Number of Cells	Number of Tornadoes	Number of Southern Tornadoes
15 March 2016	Midwest	7	3	0
30 March 2016	Southern Plains	10	4	2
15 April 2016	Southern Plains	3	1	0
16 April 2016	Southern Plains	3	1	0
24 April 2016	Northern Plains	2	1	0
	Southern Plains	2	1	1
26 April 2016	Southern Plains	7	2	0
	Southeast	4	1	0
29 April 2016	Southern Plains	4	2	0
2 May 2016	Midwest	2	1	0
8 May 2016	Southern Plains	4	2	1
9 May 2016	Southern Plains	32	7	1
	Northern Plains	2	1	1
10 May 2016	Southeast	11	3	1
	Midwest	6	3	1
22 May 2016	Southern Plains	7	3	1
23 May 2016	Southern Plains	4	2	2
24 May 2016	Southern Plains	17	10	3
26 May 2016	Southeast	2	1	0
19 June 2016	Northern Plains	15	6	1
6 July 2016	Northern Plains	2	1	1
27 August 2016	Northern Plains	4	2	1
6 October 2016	Southern Plains	7	5	1
29 November 2016	Southeast	26	12	5
	Total	**568**	**243**	**88**

6. The supercell had to be cyclonic. Left-split cells (or those with mesoanticyclones) were not included.

The reflectivity, radial velocity and co-polar cross correlation coefficient parameters (when available) were used to check the tornado report (location and time) by confirming the presence of a tornadic vortex signature (TVS, Brown et al. 1978) and checking for a tornadic debris signature (TDS, Ryzhkov et al. 2005; Kumjian and Ryzhkov 2008) near the specified start latitude and longitude. Evidence of cyclonic rotation was required, but the presence of a TDS was only used to bolster confidence in the report; tornadoes having a TVS but not a TDS still were included. Based on these requirements, 66 cases having north–south-oriented supercells from 2016 and 64 cases from 2013 were included, each with a varying number of linearly oriented discrete supercells. Sixty-three additional cases from 2011, most having 3 or more supercells in a line, were also included since many of the 2013 cases had only 2 supercells in the line. The dataset is listed in Table 1.

b. Statistical analysis

Once a tornado report was associated with a line of supercells from Level II radar data, the storm data were reviewed further to determine which cell in the line produced the tornado, and to confirm whether or not the tornado was in the southernmost storm. At this point, southern-end storms were put in their own category. The number of additional supercells to the north was also counted and categorized. Whether or not the tornadic storm was on the southern-end was determined. Counts were made for both tornadic southernmost storms and tornadic non-southernmost storms. Figure 3 provides examples of multiple supercell aligned in a north–south manner.

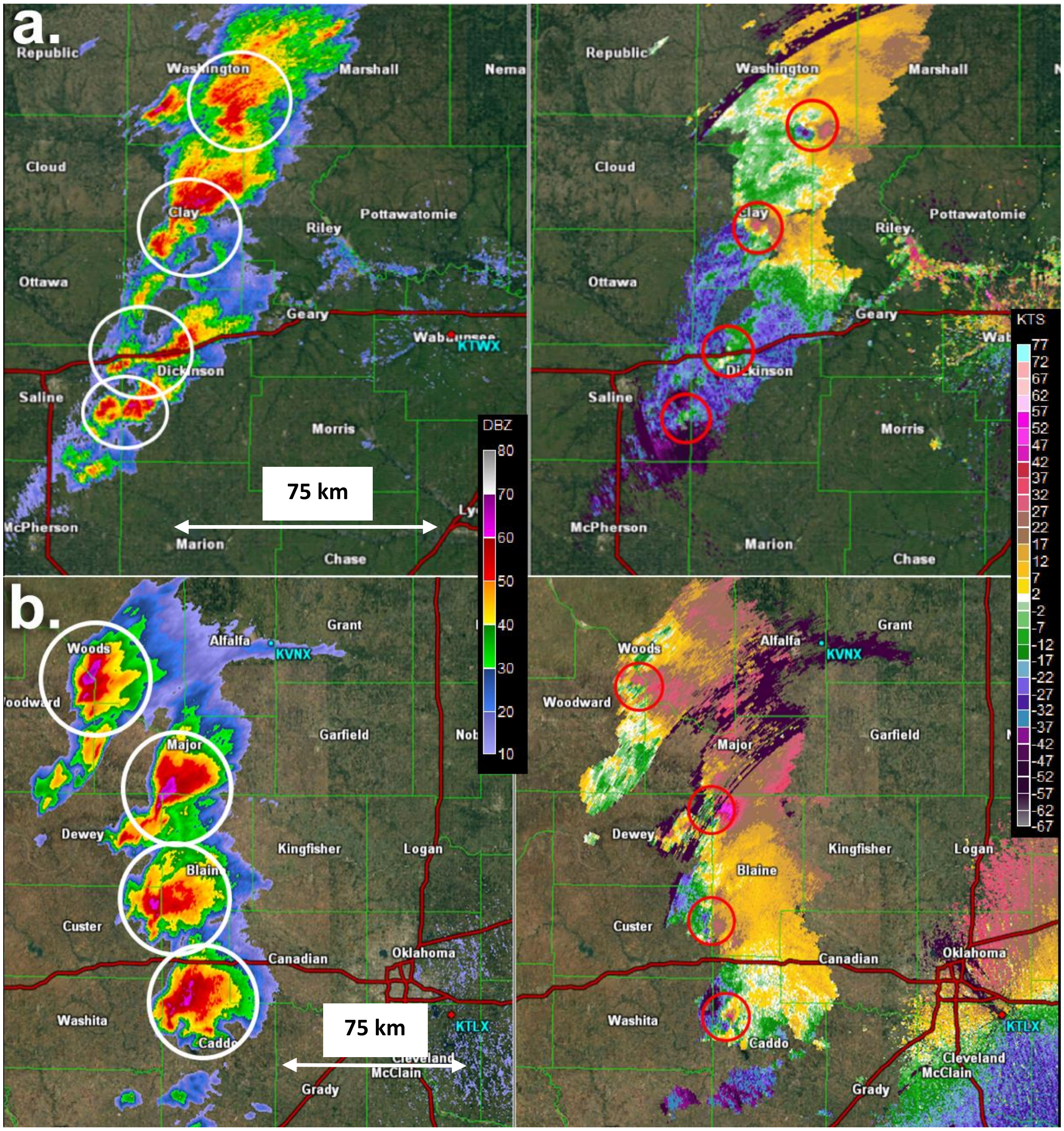

Figure 3: WSR-88D radar reflectivity (dB*Z*) (left) and radial velocity (kt) (right) providing an example of a north–south-oriented line of supercells from: a) 2136 UTC, 6 October 2016; and b) 2019 UTC, 24 May 2011. Circles denote individual supercells (white, left) and mesocyclones (red, right). *Click image to enlarge.*

Table 2: Example contingency table, with conceptual description of box contents used to evaluate statistical dependence between the relative location of a supercell and whether or not it produced a tornado.

Description	Tornadic Storm	Nontornadic Storm	Total
Southernmost Storm	The number of tornadic southernmost supercells.	The number of nontornadic southernmost supercells.	The number of southernmost supercells.
Not Southernmost Storm	The number of tornadic non-southernmost supercells.	The number of nontornadic non-southernmost supercells.	The number of non-southernmost supercells.
Total	The total number of tornadic supercells.	The total number of noontornadic supercells.	The total number of supercells.
			The χ^2 value.

In order to address the evolution of the line with time, particularly for lines that produced multiple tornadoes over several hours, some temporal threshold was needed in which the number of storms within the line would be re-evaluated. A duration of 20 min was deemed an appropriate threshold for this constraint, as storm numbers tended to not change at timeframes <20 min, but some lines sometimes evolved considerably with storms merging, new cells developing, old storms becoming nonsupercellular, etc., when >20 min passed. Therefore, if tornadoes were produced by the line of supercells for >20 consecutive min, the number of supercells in the line was recounted every 20 min after the first tornado was reported. If a single cell produced multiple tornadoes within the same 20 min, only the tornado with the highest enhanced Fujita (EF)-scale rating (WSEC 2006) was counted. If a specific tornado was long-lived, lasting for >20 min, the storm-tornado configuration still was reevaluated every 20 min.

Also, if multiple supercells produced tornadoes within the same 20-min period, or the number of supercells changed within the 20-min increment (which did not happen frequently), the numbers of tornadic supercells and total supercells was a cumulative sum of the total number of storms and tornadoes within that 20-min period. For example, if there were four supercells at 2300 UTC, and cell 2 produced a tornado at 2301 UTC; then at 2319 UTC a new supercell formed to the south of the original line and cell 5 produced a tornado, two tornadoes would have been added to the database, associated with five supercells. However, if a line included three cells, and cell 1 produced a tornado at 2000 UTC, then cell 2 produced a tornado a 2021 UTC, but the same three supercells were still present, there would be two tornado reports and six supercell reports.

Following this methodology, with recounts every 20 min to account for changes in the number of cells within the line as it evolved, *the total tally for the number of supercells included in this study is larger than the actual number of individual supercells that occurred.* This methodology was chosen because in many cases, the number of supercells changed between tornado report times.

In summary, the final form of the data included four categories: 1) the total number of southern-end supercells, 2) the total number of additional supercells present to the north of the southern-end supercell, 3) the total number of tornadic southern-end supercells, and 4) the total number of other tornadic supercells. Additionally, for each tornado that was confirmed to be supercellular, the EF rating, tornado path length and path width were acquired from the storm report to enable DPI calculation.

Because the data of interest are categorical (did the supercell produce a tornado—yes or no?) the χ^2 test for independence was used for statistical analysis to evaluate (in)dependence between southernmost and non-southernmost supercell tornado production. Prior to calculating χ^2, contingency tables were created to determine the expected frequency of events (E) compared to the observed number of occurrences. E was calculated for each of the cells within the tables.

$$E = \frac{\text{(column total) x (row total)}}{\text{total sample size}} \qquad (1)$$

For 2×2 contingency tables, Yates's correction was applied (Walpole et al. 2002). Table 2 includes a descriptive example of what the categorical values in the contingency table represent.

After the contingency tables were produced and the expected values calculated, the χ^2 statistic was calculated according to the following equation:

$$\chi^2 = \sum \frac{(observed_{cell\ i} - expected_{cell\ i})^2}{expected_{cell\ i}} \quad (2)$$

The data were evaluated using the 0.05 α level. For data with one degree of freedom to be considered statistically significant, $\chi^2 \geq 3.84$ was required; data with two degrees of freedom required $\chi^2 \geq 5.99$; data with three degrees of freedom required $\chi^2 \geq 7.82$; and data with five degrees of freedom required $\chi^2 \geq 11.07$ (Walpole et al. 2002, p. 675). Contingency tables were produced to examine the following relationships:

1. The propensity for southern-end storms versus other storms in the line to be tornadic for all cases;
2. The dependence of geographic region on southern-end tornado production;
3. The dependence of southern-end tornado production with calendar month;
4. The likelihood that tornadoes produced by southern-end storms will be more severe than other tornadoes according to the destruction potential index (DPI = EF scale × path length (km) × path width (km)).
5. The dependence of surface boundary-forcing mechanisms (as determined by surface analysis archives from the Weather Prediction Center)[3] on southern-end tornado production.

c. Case study

In order to examine the storm evolution and environment present on days when multiple discrete north–south-oriented supercells can occur, an example case study event that occurred on 9 May 2016 is discussed and examined in further detail. This case was selected because it produced a large number of discrete cells (10 at one point in time), and yet the southernmost storm never produced a tornado.

As part of the analysis, the distance between adjacent supercells was calculated to determine if this parameter impacted the ability of any given storm to produce a tornado, with the idea that storms closer to each other might be less likely to become tornadic. Radar data again were examined using GR2 Analyst®, and the distance between adjacent mesocyclones at the time nearest to tornadogenesis was determined. An estimated error of about ±1.50 km was associated with the given distances due to human error in identifying the center of the mesocyclone. Additionally, the synoptic-scale environment was analyzed to provide atmospheric context. Values for surface-based (SB)CAPE, SB convective inhibition (CINH), level of free convection (LFC), lifted condensation level (LCL), storm-relative helicity (SRH), and 0–6-km AGL shear were obtained from the SPC mesoanalysis (Bothwell et al. 2002; Bothwell et al. 2014), which are generated from RAP model analyses (Benjamin et al. 2016). Plymouth State Weather Center (https://vortex.plymouth.edu/myo/) values also were used when SPC mesoanalysis data were not available.

3. Results and discussion of statistical analyses

a. Results from statistical analyses

The contingency table for all events contained in the total sample is given in Table 3. When all tornado reports were included, the χ^2 value was 1.25, corresponding to α = 0.26. These values indicate that the likelihood of dependence between southern-end storm tornado production and supercell location for all events is 74%. Although this is not statistically significant using the 95% threshold imposed in this study, there is a slight tendency for southern-end storms to produce more tornadoes than expected, when comparing the observed versus expected values. Based upon the supercell location in the line for all tornado reports, no statistically significant link was established between southern-end cells and tornado production. In other words, statistically speaking, southern-end supercells are not more likely to produce tornadoes than others.

[3] To get more precise observations on the nature of the boundary, surface observations displayed graphically from the Mesoscale and Microscale Meteorology Laboratory webpage from the National Center for Atmospheric Research also were used (http://www2.mmm.ucar.edu/imagearchive/).

Table 3: Contingency table for all observed (left values) and expected (underlined values) tornadic and nontornadic supercells with respect to whether or not the supercell was the southernmost. The χ^2 value is bolded in the bottom right cell. Statistical significance requires a $\chi^2 \geq 3.84$.

All Events	Tornadic Storm	Nontornadic Storm	Total
Southernmost Storm	88, 81.3	102, 108.7	190
Not Southernmost Storm	155, 161.7	232, 216.3	378
Total	243	325	568
			χ^2 = 1.25

Table 4: Contingency table for all observed (left values) and expected (underlined values) tornado and non-tornado events with N = 2, 3, or 4+ supercells in the line. Statistical significance requires $\chi^2 \geq 3.84$.

# of Supercells in the Line	N = 2	N = 3	N = 4	Total
Tornadoes produced by the southernmost storm	43, 35.5	25, 22.1	20, 30.4	88
Tornadoes not produced by the southernmost storm	55, 62.5	36, 38.9	64, 53.6	155
Total	98	61	84	243
				χ^2 = 1.08

To analyze further if tornado production and/or rating in the southernmost storm was statistically favored over other storms in other specific scenarios, the data were grouped in various ways to create different contingency tables based upon what factor was being tested to have an influence on the tornado production.

In order to determine whether or not the total number of supercells present in the line might affect whether or not the southernmost storm was more likely to produce a tornado, the dataset was stratified into groups based upon the total number of supercells in the line: 2, 3, or 4+. The few cases with ≥5 cells were grouped with the lines of 4, to avoid misinterpretation of the statistics due to poor sample size (Table 4). The χ^2 value for this grouping was examined and found to be 1.08, corresponding to α = 0.58, meaning the likelihood of dependence between southern-end storm tornado production and the total number of supercells in the line is 42%. Interestingly, lines with two or three supercells were associated with *more*-frequent tornado production by the southernmost storm than expected, from comparing the observed and expected values in the contingency table: the observed value is more than the expected value. In lines with ≥4 supercells, southern-end storms produced fewer tornadoes than expected, although the difference was not statistically significant at the 95% confidence interval. In summary, some evidence suggests that with a small number of supercells (<4) in a line, the southernmost one may produce a tornado more readily than others.

More parameters were investigated for other possible correlations between southern-end storms and tornado development. Events from 2013 and 2016 were separated by month (Table 5). The 2011 cases were not included because they were only from April and May. Other months were not analyzed. No month had a χ^2 value that met the required criteria for significance; however, χ^2 was highest in February at 3.00, associated with α = 0.08. That implies a 92% probability that tornado production *is* a function of whether or not the supercell is the southernmost one for February cases. This value is almost statistically significant at the 95% confidence interval. In March, the χ^2 value was 0.00. This is associated with α = 1.00, meaning there is a 0% probability of dependency, implying essentially no correlation between the location of the supercell and its tornado production. This trend continued over the calendar year. No other months came close to having a statistically significant dependence with southern-end tornado production, although a few months did have slightly higher observed values than expected.

Table 5: Contingency table for all observed (left values) and expected (underlined values) tornado and non-tornado events for 2013 and 2016, separated by month. Statistical significance requires $\chi^2 \geq 3.84$.

February	Tornadic Storm	Nontornadic Storm	Total
Southernmost Storm	4, 2.0	0, 2.0	4
Not Southernmost Storm	4, 6.0	8, 6.0	12
Total	8	8	16
			χ^2 = 3.00

March	*Tornadic Storm*	*Nontornadic Storm*	*Total*
Southernmost Storm	4, 4.5	8, 7.5	12
Not Southernmost Storm	8, 7.5	12, 12.5	20
Total	12	20	32
			χ^2 = 0.00

April	Tornadic Storm	Nontornadic Storm	Total
Southernmost Storm	6, 7.1	12, 10.9	18
Not Southernmost Storm	13, 11.9	17, 18.1	30
Total	19	29	48
			χ^2 = 0.15

May	Tornadic Storm	Nontornadic Storm	Total
Southernmost Storm	25, 24.5	31, 31.5	56
Not Southernmost Storm	44, 44.5	58, 57.5	102
Total	69	89	158
			χ^2 = 0.00

June	Tornadic Storm	Nontornadic Storm	Total
Southernmost Storm	5, 5.0	5, 5.0	10
Not Southernmost Storm	9, 9.0	9, 9.0	18
Total	14	14	28
			χ^2 = 0.16

July	Tornadic Storm	Nontornadic Storm	Total
Southernmost Storm	2, 2.0	2, 2.0	4
Not Southernmost Storm	3, 3.0	3, 3.0	6
Total	5	5	10
			χ^2 = 0.42

August	Tornadic Storm	Nontornadic Storm	Total
Southernmost Storm	2, 1.8	2, 2.2	4
Not Southernmost Storm	2, 2.2	3, 2.8	5
Total	4	5	9
			χ^2 = 0.14

October	Tornadic Storm	Nontornadic Storm	Total
Southernmost Storm	1, 1.4	1, 0.6	2
Not Southernmost Storm	4, 3.6	1, 1.4	5
Total	5	2	7
			χ^2 = 0.02

November	Tornadic Storm	Nontornadic Storm	Total
Southernmost Storm	10, 8.2	8, 9.8	18
Not Southernmost Storm	14, 15.8	21, 19.2	35
Total	24	29	53
			χ^2 = 0.62

Table 6: Contingency table for all observed (left values) and expected (underlined values) tornado and non-tornado events for all data, separated by region. Statistical significance requires $\chi^2 \geq 3.84$.

Northern Plains	Tornadic Storm	Nontornadic Storm	Total
Southernmost Storm	11, 12.4	13, 11.6	24
Not Southernmost Storm	19, 17.6	15, 16.4	34
Total	30	28	58
			χ^2 = 0.24

Southern Plains	Tornadic Storm	Nontornadic Storm	Total
Southernmost Storm	53, 46.9	55, 61.1	108
Not Southernmost Storm	92, 98.1	134, 127.9	226
Total	145	189	334
			χ^2 = 1.76

Southeast	Tornadic Storm	Nontornadic Storm	Total
Southernmost Storm	13, 14.1	22, 20.9	35
Not Southernmost Storm	28, 26.9	39, 40.1	67
Total	41	61	102
			χ^2 = 0.06

Midwest	Tornadic Storm	Nontornadic Storm	Total
Southernmost Storm	11, 8.4	12, 14.6	23
Not Southernmost Storm	15, 18.6	35, 32.4	51
Total	27	47	74
			χ^2 = 1.21

Table 7 : Contingency table for observed (left values) and expected (underlined values) tornado DPI ratings for all tornado events, classified by whether or not the tornado was produced by the southernmost supercell. Statistical significance requires $\chi^2 \geq 11.07$.

DPI	0–50	50–100	100–150	150–200	200–250	250+	Total
Southernmost Storm	79, 81.5	3, 1.4	3, 2.5	1, 0.7	0, 0	2, 1.8	88
Not Southernmost Storm	146, 143.5	1, 2.6	4, 4.5	1, 1.3	0, 0	3, 3.2	155
Total	225	4	7	2	0	5	243
							χ^2 = 2.78

Table 8: Contingency table for observed (left values) and expected (underlined values) tornadic and nontornadic lines, classified by the type of frontal boundary. Statistical significance requires $\chi^2 \geq 7.82$.

Frontal Boundary	Warm Front	Cold Front	Dryline	Other	Total
Line Produced a Southernmost Tornado	9, 8.7	27, 27.4	31, 31.5	21, 20.5	88
Line Did Not Produce a Southernmost Tornado	10, 10.3	33, 32.6	38, 37.5	24, 24.5	105
Total	19	60	69	45	193
					χ^2 = 0.17

Events were also separated by region to determine if geographic area influenced tornado production in southernmost storms (Table 6), with the hypothesis that these events were more probable in the southern Plains states than in other regions. Southernmost supercells did produce tornadoes more frequently than expected in the Southern Plains and Midwest, but the results were not significant at the 95% confidence interval. No geographic region had statistically significant χ^2 values. From these results, geographic region appears not to influence tornado production tendencies in the southernmost supercell.

Tornado path characteristics also were tallied to evaluate if southern-end storms are more likely to produce larger DPI (Table 7). The χ^2 value for the DPI of all events was 2.78, corresponding to an α = 0.73. Thus, there is a 27% chance of dependency between southern-end storm tornado production and DPI, implying no correlation between DPI and the location of the supercell within the line. Southernmost supercells did produce tornadoes more frequently than expected with DPI >50. However, this result again is not significant. Similarly, given low sample size of EF4+ tornadoes, no general assumptions can be made.

Lastly, the nearby surface boundaries present for each event were analyzed to determine if any specific boundary type preferentially favored linear supercell configurations. Because multiple lines of supercells often were associated with different boundaries occurring on a given day, the events were separated according to the boundary most likely associated with storm initiation. Out of the 193 total lines that were evaluated, drylines produced the most lines of north–south-oriented cells, with 69, 19 were associated with warm fronts, 60 with cold fronts, and 45 lines in an "other" category with no identifiable surface boundary, or the boundary was not among those listed above. Perhaps drylines are the most prolific producers of linear events due to the inherent north-south orientation of the dryline itself, as well as its propensity to be associated with synoptic-scale conditions that favor severe weather in the southern Plains. The contingency table evaluating fronts is provided in (Table 8). The χ^2 value evaluating surface boundaries was 0.17, corresponding to α = 0.98 and a 2% probability of dependency between southern-end-storm tornado production and the surface boundary on which the storms that formed the line initiated. Warm fronts and "other" produced more southernmost tornadoes than expected, but the difference is not statistically significant.

Ultimately, under no circumstances were southern-end storms more likely to produce tornadoes than others, nor were tornadoes produced by southern-end storms higher-rated than others in the line

b. 9 May 2016 case study

In order to put the evolution and tornado production of discrete supercells that are oriented in a linear manner into the full event context, a case study from 9 May 2016 was selected. On this day, a series of discrete, linearly oriented supercells formed across the eastern half of Oklahoma, producing 7 tornadoes, including the "Katie" and "Sulphur" tornadoes. At one time, 10 supercells were <75 km from each other, meridionally across nearly the whole state. Despite the obviously favorable synoptic environment, the large number of supercells, and multiple tornadoes, the southernmost storm was nontornadic.

That afternoon, a surface low was located in north-central Kansas, associated with an upper-level trough moving eastward from the Rocky Mountains into the western Plains. A dryline extended from central Kansas southward through central Texas (Fig. 4). The 2100 UTC SPC mesoanalysis, showed 2500 J kg^{-1} to 3000 J kg^{-1} SBCAPE and SBCINH was <25 J kg^{-1} in central Oklahoma, the region of intensifying supercells. The LCL heights in the environments where supercells formed ranged from 750–1250 m AGL and the LFC height ranged from 1200–2000 m AGL. The 0–1-km SRH ranged from 100 m^2 s^{-2} in north-central Oklahoma to 200 m^2 s^{-2} in south-central Oklahoma, and the 0–3-km SRH ranged from 100 m^2 s^{-2} in north-central Oklahoma to 350 m^2 s^{-2} in south-central Oklahoma. The 0–6-km shear vectors were westerly between 15.4–25.7 m s^{-1} (30–50 kt), increasing equatorward. The 1200 UTC sounding from the nearest rawinsonde location (OUN) for 9 May 2016 and 0000 UTC sounding for 10 May 2016 were not representative of the storm environment. and therefore, were not included in the environmental analysis.

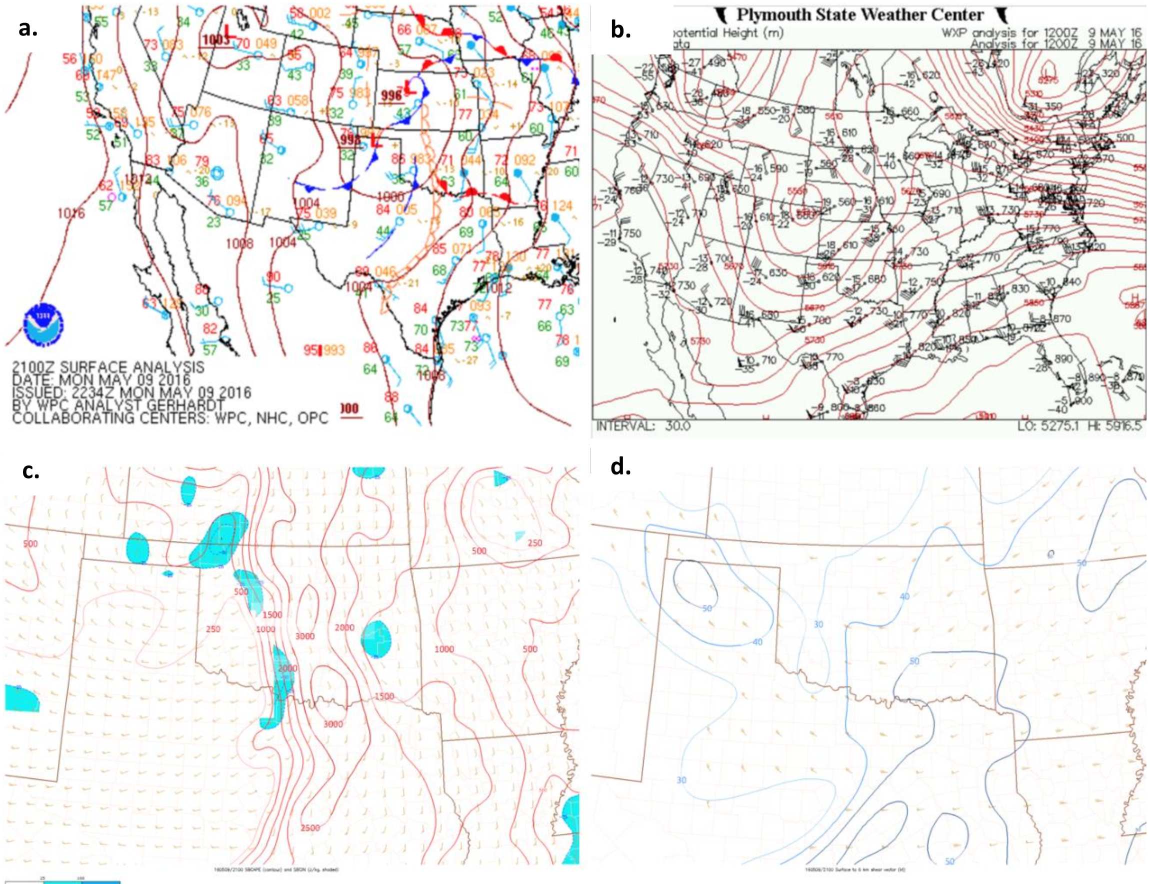

Figure 4: Analyses for 9 May 2016: a) surface analysis from WPC, b) 500 hPa wind and isohypses (wind barbs in kt) from Plymouth State, c) surface-based CAPE (J kg^{-1}) from SPC mesoanalysis (contours are given every 500 J kg^{-1} except for the first contour on 250 J kg^{-1}), and d) 0–6-km AGL shear vectors represented as barbs (short = 2.5 m s^{-1} (5 kt), long = 5 m s^{-1} (10 kt)) and isotachs for 15, 20, and 25 m s^{-1} (30, 40, and 50 kt) from SPC. All times are valid at 2100 except (b) which is from 1200 UTC. *Click image to enlarge.*

An hourly account of the evolution of the storms associated with this event is given in Fig. 5. Storms initiated[4] about 1903 UTC (Figure 5a) in Barber County, KS, just north of the Oklahoma border, along a dryline. Along the Kansas/Oklahoma border, convective precipitation strengthened into a line of discrete cells. Given the favorable synoptic environment, most of these storms quickly became supercellular. However, they did not produce tornadoes until about 4.5 h later.

Around 2015 UTC, convection began initiating separately, in south-central Oklahoma. By 2100 UTC, a strong supercell was ongoing and would produce the Katie, OK tornado. At this time, more cells were developing linearly, both to the north and south. (Note: the Katie supercell was still considered discrete, but had a distance >75 km from the next closest supercell to the northwest. It therefore did not contribute to the counts in this study.) By 2120 UTC, this second line included three supercells (Fig. 5c). At 2134 UTC, a second tornado ("Sulphur") was reported in Murray County, OK. Its parent storm also had produced the Katie tornado. It was the middle storm in a line of 3, and by far the most organized, with the most classic supercellular structure. The Sulphur tornado was long-lived, lasting 43 min (Fig. 6). When the configuration of storms was reanalyzed 20 min later at 2157 UTC; two more cells had developed and

[4] Initiation was defined when the 0.5° elevation radar reflectivity scan indicated a core value ≥35 dB*Z*.

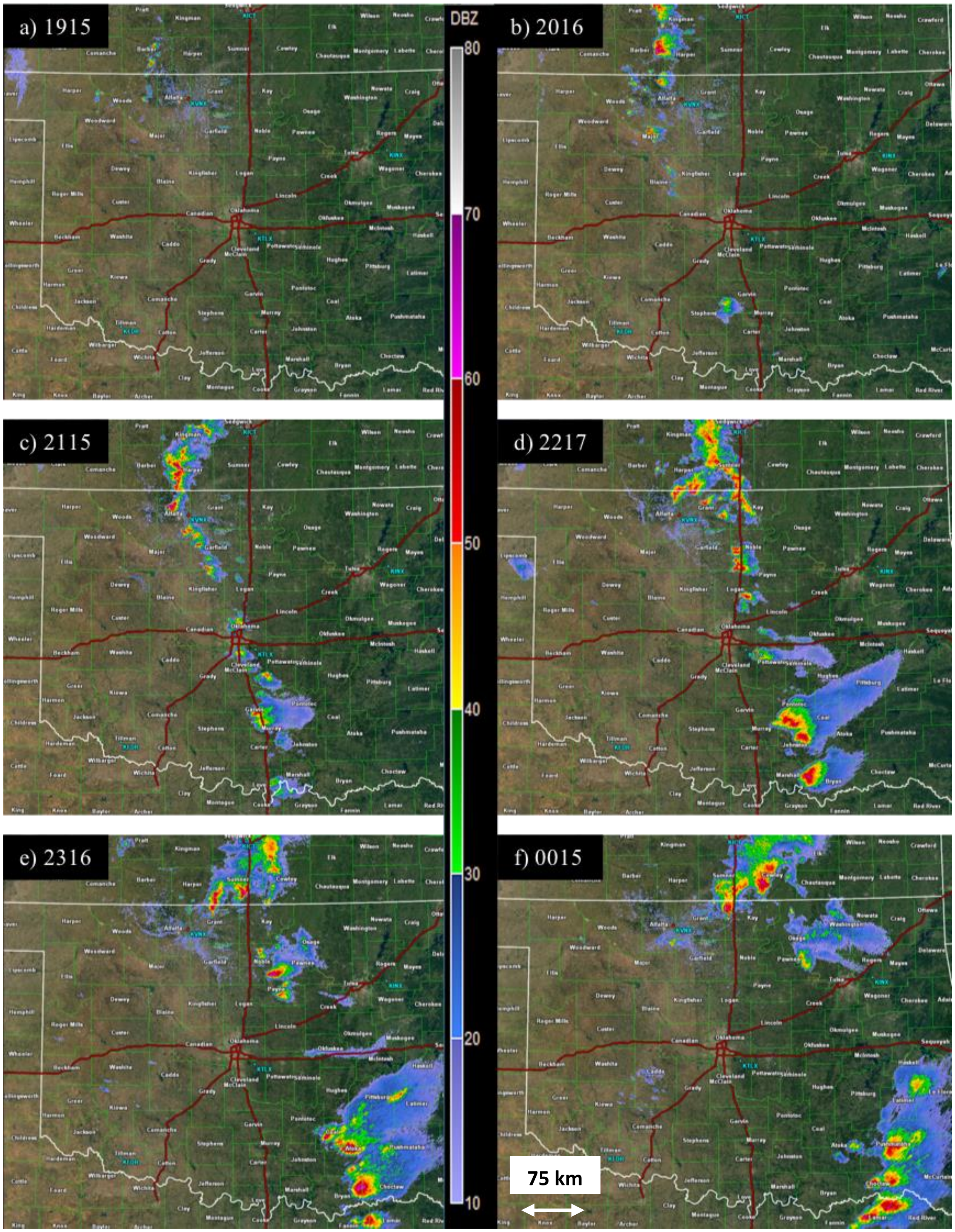

Figure 5: KVNX reflectivity (dBZ) from 9 May 2016 at approximately 1-h intervals (UTC). *Click image to enlarge.*

Figure 6: The Sulphur, OK EF3 tornado in Murray County, OK on 9 May 2016, © Ben Holcomb, used by permission.

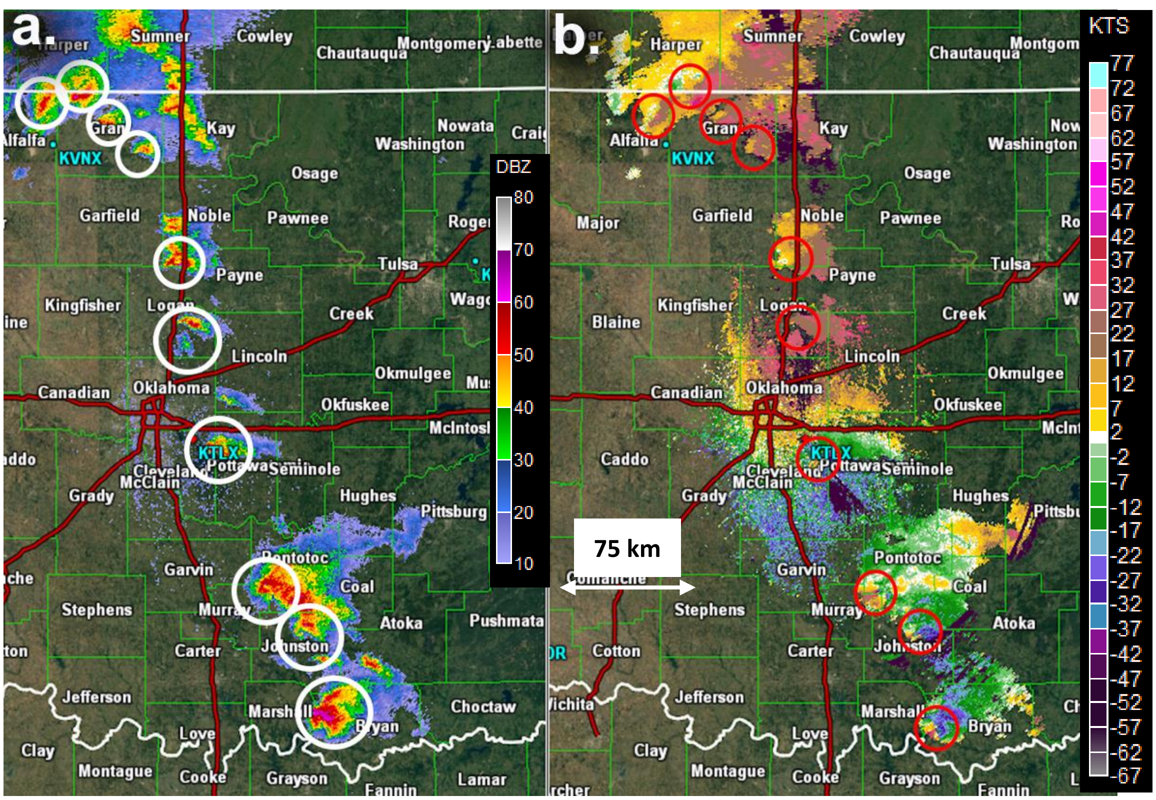

Figure 7: Reflectivity (dBZ) (left) and radial velocity (kt) (right) imagery from the KTLX WSR-88D radar from 2216 UTC 9 May 2016. There were a total of 10 supercells across central Oklahoma. Circles denote individual supercells (white, left) and mesocyclones (red, right). *Click image to enlarge.*

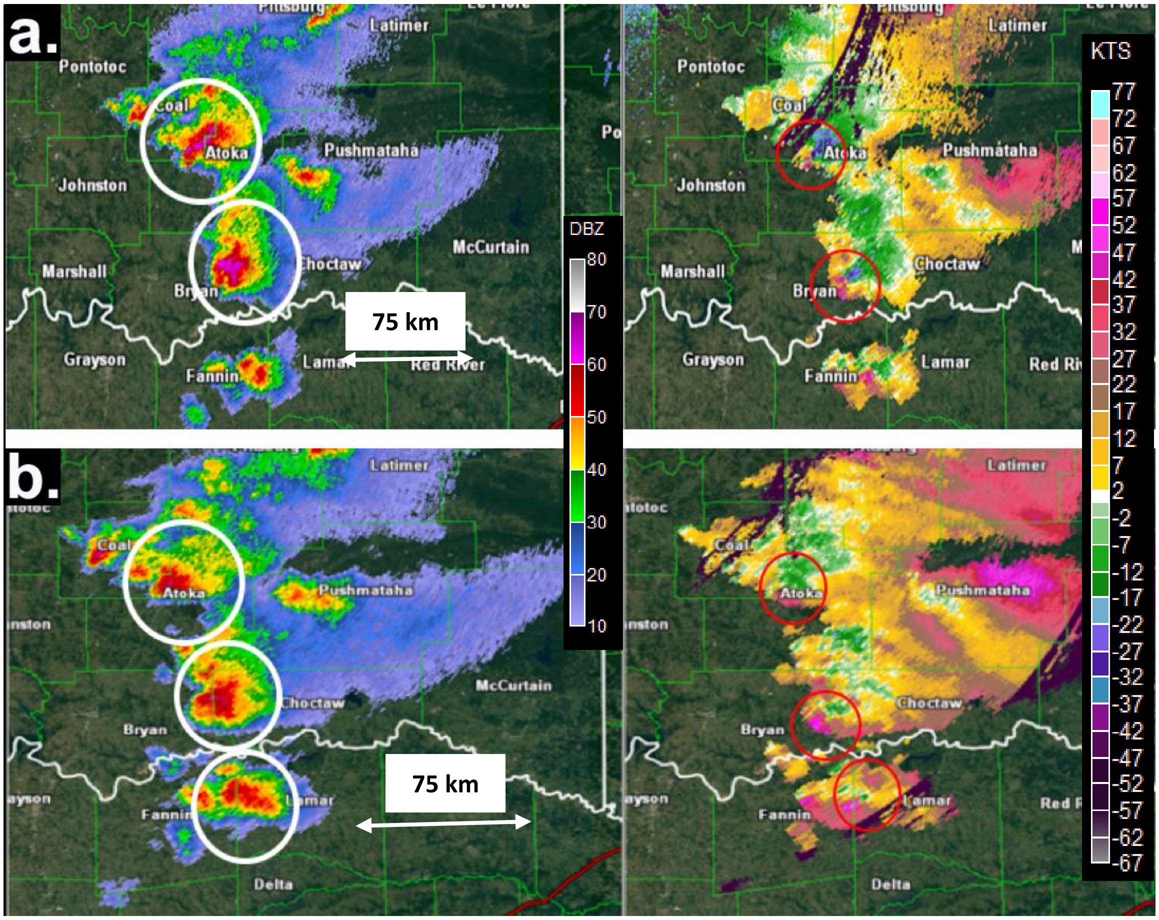

Figure 8: Reflectivity (dB*Z*, left) and radial velocity (kt, right) imagery from the KTLX WSR-88D radar from 9 May 2016: a) 2308 UTC, b) 2319 UTC. *Click image to enlarge.*

intensified to the north of the original cells so there was now a total of five cells in the line. This configuration persisted until the Sulphur tornado dissipated at 2217 UTC (Fig 5d).

With the development of new cells in central Oklahoma, the first line of cells in north-central Oklahoma linked to the line in south-central Oklahoma, resulting in a north-south line of ten supercells across the entire state by 2215 UTC (Fig. 7). At 2218 UTC, two tornadoes formed, this time in Johnston County, OK. One of them, the “Mill Creek” tornado, was not included in the statistical analysis because it was produced by a developing supercell that never matured, and typical supercellular tornado properties were not observed from the nearest WSR-88D (Burgess et al. 2016). This storm also did not have a discrete core. The second tornado was associated with a new cell that was now the next storm to the north of the southernmost storm. This tornado lasted 16 min and dissipated at 2234 UTC. As the line of cells continued to evolve, it again split into two separate entities with a distance between the two lines >75 km. This occurred as the cells in north-central Oklahoma translated northeastward and weakened, while the line of storms in the southern part of the state continued on an eastward path.

The cell that produced the Johnston County tornado also went on to produce the next tornado in Atoka County, OK at 2246 UTC. At this time, only two supercells in the southern portion of the line still met the ≤75 km distance requirement between cells. The parent cell of the tornado remained the northern of the two supercells. During that tornado, a third cell developed to the south of the original southernmost cell around 2255 UTC (Fig 5e). From the Oklahoma City radar scans in Fig. 9, the supercell count evolved considerably during the tornado. Another tornado at 2322 UTC in Bryan County, OK, passed near Boswell before dissipating at 2342 UTC. Its parent storm was the middle cell. The northernmost cell became nonsupercellular around 2327 UTC, but additional supercells formed to the north and south of the line by 2353 UTC. The result was four supercells at the time of the next tornado in Choctaw County at 0002 UTC, by the storm north of the southernmost one. That tornado dissipated at 0010 UTC. By about 0032 UTC, the cells lost their supercellular characteristics and merged to form two lines of precipitation.

For these events in Oklahoma on 9 May 2016, a total of 28 cells with six tornadoes were analyzed. None of the tornadoes were produced by the southernmost storm. Supercells developed along the northern part of the dryline first, and new cells formed to the south with time. Despite multiple lines of supercells, the best-organized storms for this case were not the southernmost ones, nor were the latter generally tornadic. Storms formed in an environment that supported supercells and tornadoes over a relatively large area. Regardless of this fact, the southern storms never produced tornadoes.

To see if the distance between adjacent storms may have contributed to the success or failure of some storms to produce a tornado, the distances between supercells at tornado times were calculated (Table 9). The distances between tornadic and neighboring supercells did not seem to affect whether or not the southern-end storm produced a tornado. Distances between all tornadic cells and the cells adjacent to them ranged from about 17–75 km, indicating distance may not impact tornado development substantially. However, the mean distance between tornadic supercells was around 45 km, compared to 32 km between nontornadic supercells. Figure 9 demonstrates the approximate distances between supercells when tornadoes were being produced.

4. Summary, discussion and future work

Cases of multiple north-south, linearly oriented supercells with at least one storm producing a tornado were acquired from the Storm Prediction Center's severe-weather database for the 2016 and 2013 calendar years, with several select events from 2011, in order to determine whether or not southernmost supercells are statistically more likely to produce a tornado than other storms in the line. The full dataset was stratified to examine if southernmost supercells are favored under specific circumstances. Relationships between tornadic supercells and the number of supercells in the line, month of event, geographic

Table 9 : The distances between adjacent supercells, categorized by whether or not they produced a tornado for the 9 May 2016 case study only. Distances were calculated over the duration of the event, so supercell counts and distances were recalculated periodically according to the methodology specified in section 2.

9 May 2016	Distance (km) between tornadic supercell and nearest adjacent supercell	Distance (km) between nontornadic supercell and nearest adjacent supercell
	20.8	53.6
	75.9	17.1
	17.2	10.6
	51.5	54.3
	31.8	32.4
	75	60.0
	72.8	26.9
	50.6	17.5
	51.7	21.5
	46.6	39.3
	36.5	17.8
	26.3	
	27.8	
Range (km)	**17.2–75.9**	**10.6–60.0**
Mean (km)	**45**	**32.1**
Std. Dev. (km)	**20.4**	**17.4**

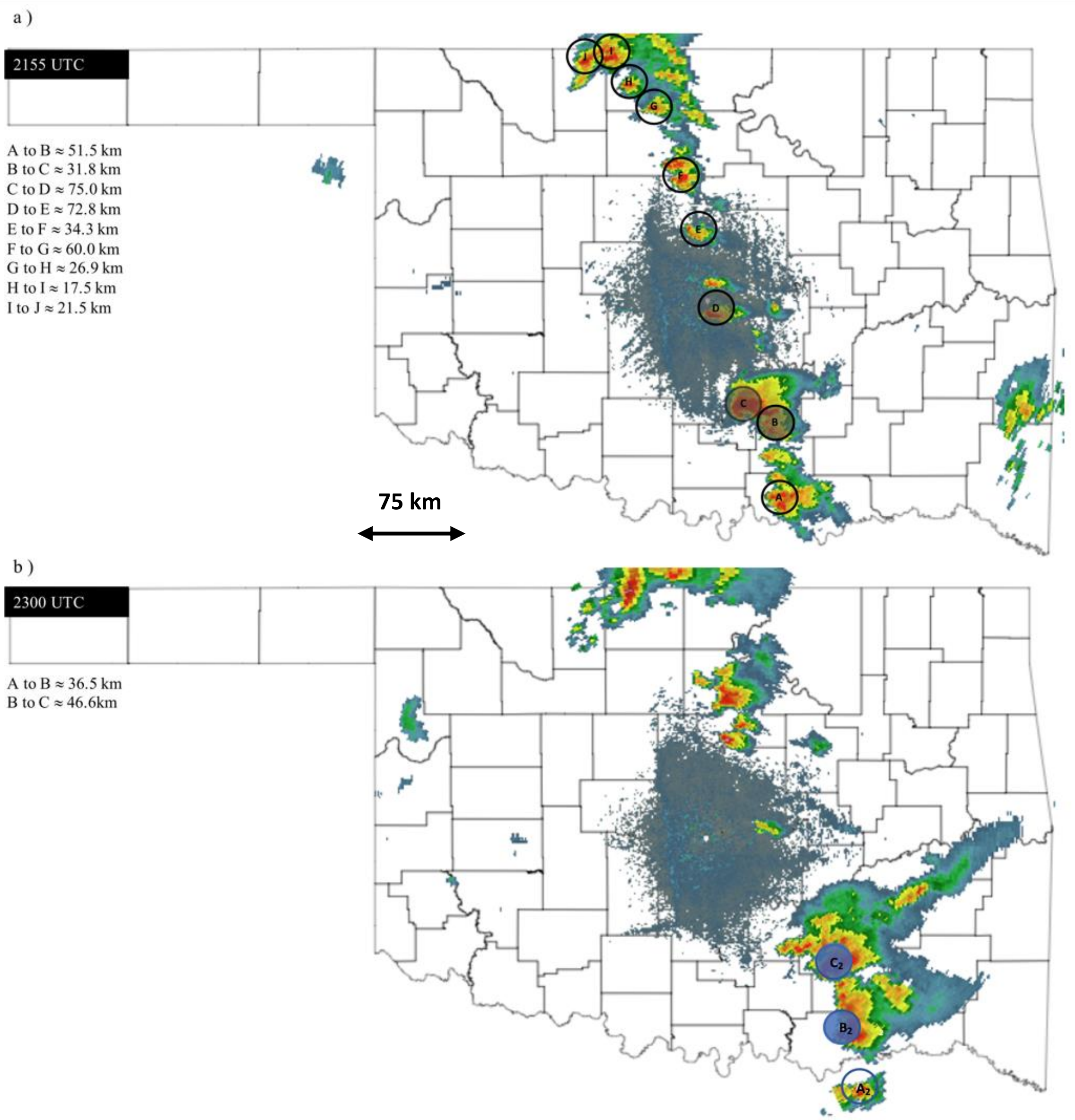

Figure 9: a) Representation of which cells on 9 May 2016 produced tornadoes and the distance between the cells. Absolute distances changed with cell evolution; however, relative distances between storms remained similar. Cells B and C and D produced tornadoes. b) Evolution of the convective line 65 minutes later. Cell A_2 is a new cell, cell B_2 was the previous storm A, and cell C_2 was the previous storm B. Cells B_2 and C_2 both went on to produce tornadoes between 2300 and 2330 UTC. *Click image to enlarge.*

location, destruction potential index, and associated surface boundary were investigated. Results indicate that tornado production is independent of where a supercell is located within the north–south-oriented line; southern-end storms are no more likely to produce a tornado than any other storm in the line.

For several subsets, including events with two or three supercells in the line, events that occurred in February, May, August, and November, events that occurred in the Southern Plains and Midwest, and tornadoes with a DPI >50, observed values of southern-end tornado production were slightly higher than expected, signaling a slight tendency for southernmost supercells to produce tornadoes more frequently than expected, but the dependency was not significant. Under other circumstances, southern-end supercells appear less likely to produce tornadoes than other cells.

Tendencies for storms to produce tornadoes in the month of February were calculated to be almost statistically significant, although the sample size was somewhat small (16) and therefore confidence of this conclusion is somewhat low. When observing geographic regions, the Southern Plains and Midwest were found to favor southernmost supercell tornado production more frequently than expected, but not at a statistically significant level. More north–south-oriented lines of supercells occurred in the Southern Plains than any other geographic region, but there was no statistical dependency between southern-end storm tornado production and geographic location. Thus, geographic region does not appear to influence whether or not a southern-end supercell produces a tornado. This result again is not surprising if one assumes that the underlying physical processes associated with these events remains the same, regardless of where the event is occurring.

The DPI was not statistically dependent upon the supercell location, refuting the idea that southernmost supercells produce higher-rated tornadoes; however, southernmost supercells did produce evidently stronger tornadoes more frequently than expected. Drylines produced the most lines of north–south-oriented cells compared to other surface boundaries, presumably due to the common north-south orientation of the dryline. Warm fronts and "other" did produce more southernmost tornadoes than expected, but again, the result is not statistically significant.

When cases were divided according to the number of supercells in the line, again no statistically significant results were found, but events with only two or three supercells in the line yielded more tornadoes produced by the southernmost storm than expected, while events with four or more supercells in the line produced fewer southern-end tornadoes than expected. When a larger number of supercells were present, more interaction was apparent among storms. However, this did not appear to impact their ability to produce tornadoes.

For the specific case of a linearly oriented supercell event from 9 May 2016, the environment was conducive for supercells and tornadoes over a relatively large area, but only a few supercells produced tornadoes. In this case, the southernmost storm *never* produced a tornado. The distance between adjacent supercells within the lines for those cases varied from 17–75 km, but the mean distance was larger between tornadic supercells compared to nontornadic supercells. This result supports the idea that tornadic supercells may be favored in an environment that is less convectively contaminated, with storms that are farther apart.

The primary conclusions that can be drawn from this study are summarized as follows:

1. Southernmost supercells are not more likely to produce tornadoes than other storms in a north–south-oriented line of storms.
2. There was no statistical dependency between southern-end storm tornado production and geographic region.
3. Warm fronts and "other" surface boundaries produced more southernmost tornadoes than statistically expected values, but the result was not significant.
4. Southernmost supercells produced tornadoes more frequently than expected when there were <4 supercells in the line compared to events with ≥ 4 cells.
5. The mean distance between tornadic supercells was greater than that of nontornadic supercells for one of the cases that produced a large number of supercells.

Future work includes investigating the environmental parameters and distance between supercells, as well as the azimuthal orientation between the supercells, for all cases. Additionally, the cells that produced tornadoes will be further stratified according to the location of the cell with respect to the southernmost storm. Furthermore, an examination of the overall frequency of linearly oriented supercell events in comparison to other supercell events will be conducted.

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REVIEWER COMMENTS

[Authors' responses in *blue italics.*]

REVIEWER A (Shawn M. Milrad):

Initial Review:

Recommendation: Accept with major revisions.

General comments: The authors present an analysis of a key piece of storm chasing/tornadic supercell lore, investigating whether "tail-end Charlie" is more statistically likely to produce tornadoes than other cells. This is a difficult topic, but I find the study concept and analysis methods to be interesting and the manuscript to be well written. However, some of the thresholds used in the analysis appear to be completely arbitrary and lacking appropriate references/justification. In addition, a few figures are missing color bars and/or are very difficult to read.

Substantive comments: Squall lines vs. "lines" of supercells: As a regular storm chaser and storm-chase course instructor, it was always my impression that the idea of the southernmost cell having the greatest chance of producing a tornado was in reference to severe squall lines, not a column of supercells if you will. It is entirely possible that this has just been my mistaken impression, but I think regardless it is worth specifying early in the manuscript that this analysis only considers lines of individual supercells, not squall lines or linear convection. The forecast implications are quite different between those phenomena.

The second author has 14 years of storm chasing experience and has heard this philosophy repeatedly over the years. In consultation with other experts in the field and in response to another reviewer's suggestions, we have now expanded the discussion on the "tail-end Charlie" philosophy and have added several relevant references. Unfortunately, there is very little documentation of chase tactics found in the formal literature, but we included personal communications and what little formal references we could.

Set of cases: I am honestly not sure that using one season of supercells is enough to conduct a statistical study like this. I realize that identifying events is time consuming and difficult, but I suspect that some of the lack of statistically significant relationships has to do with the small number of cases, especially in many of the sub-categories (e.g., Midwest). To their credit, the authors acknowledge this repeatedly throughout the manuscript. I just wonder if the conclusions would be more robust with multiple full years in the climatology. Along the same lines, it is unclear why only a few cases were chosen from 2011 and 2013, while all of 2016 was examined. If the authors are going to use cases from more than one year, they should use all cases in the additional years.

2016 was examined originally because it was the most recent year for official data when we began conducting this study. We did follow this suggestion and have now added the entire season's worth of data from 2013 and several additional high-profile cases from 2011 (the latter was done mainly to increase the number of cases with >3 supercells in the line). 2013 was selected because we already started analyzing the data from several cases performed earlier. As such, our sample size has increased from 123 tornadoes, 39 of which were the southernmost, and 324 supercells to 243 tornadoes, 88 of which are the southernmost, and 568 supercells. We have added additional discussion regarding the selection process of these cases in the "Case study selection" section.

Arbitrary thresholds:

- Case identification: There should be justification for why the authors chose five tornado and ten hail reports as the minimum required for a case in the study. In addition, the latitudinal requirements should be specified. I realize that with any manual analysis there will be some degree of arbitrariness, but it would be beneficial if a short justification and/or reference(s) were always included. Another possibility is to examine multiple thresholds and demonstrate that there was not much difference in the number of cases identified.

Upon further review to ensure we did not miss any cases, cases were chosen if they had multiple severe reports in a close geographic area, including at least one tornado report. There were no latitudinal requirements, we were considering all cases that occurred in the United States.

- Radar reflectivity values: Starting in section 2a, the authors state that "discrete cores of high reflectivity values" were identified. What specific value(s) does high refer to? Again, this can be somewhat arbitrary (e.g., 50 dBz), but it should at least be specified.

  Corrected… [Reproduced text omitted…]

- 75 km separation between cells: Are there any other studies that have defined a criterion like this for lines of supercells? Did the authors try other thresholds such as 50 or 100 km?
  Based upon manual investigation of the data, distances less than 75 km were too small to be set as the threshold and distances greater than 75 were too large because we wanted similar synoptic conditions.

- Velocity couplet of 10 m s^{-1}: Same general comment as the previous bullets. Why was this threshold chosen?

  This was arbitrarily selected based off of the idea that a velocity couplet of $\nabla V \geq 10$ m s^{-1} would indicate the presence of a mesocyclone. A study by Smith et al. 2012 (cited in this manuscript) also defined supercells as having a velocity difference of 10 m s^{-1}.

- Three consecutive radar scans: Again, why three? Also, does this include the MESO-SAILS upgrade implemented in the WSR-88Ds the past few years? If so, does it include it in all cases or just some?

  (Three) scans are representative of 12–15 min of a persistent mesocyclone, which equates to a mesocyclone that isn't transient. Similarly, Smith et al. 2012 also defined supercells as having a velocity difference of 10 m s^{-1} persisting for at least 10–15 min. We have now added this reference to the text.

- 20-min periods for tornadoes: Did the authors try other thresholds such as 15 or 30 min? Would there be a difference?

  20 min appeared to be the threshold that evolution was occurring in the lines. We have added text to the methodology section to better explain this choice.

Use of radial velocity: When identifying couplets, did the authors use base or storm-relative radial velocity? If base velocity was used, how were fast-moving cases handled? In other words, some cases may have been missed by using base velocity, although the increased time resolution in the base velocity field with the MESO-SAILS upgrade is certainly desirable for a study like this.

The base vs. SRV data are essentially the same except for a storm motion vector being subtracted for the SRV. The ΔV value will not change between these parameters as it is just a difference between max and min velocities, and since this was the threshold we used, it really didn't matter which field was used. We therefore chose to use base velocity because often the storm motion vector appeared to be improperly identified by the GR algorithm, and the SRV field was actually more challenging to interpret. The color bar for the velocity field was modified from the default GR2 Analyst (refer to Fig. 3 for an example), including a much wider range of colors. Therefore, shear areas that met the 10 m s^{-1} ΔV criteria were *obvious. Additionally, since the storm reports were all associated with times and lat/lon points, we could find the location of the report to confirm or refute the presence of a TVS nearby. We are confident that we did not miss any cases owing to storm-motion factors.*

Number of supercells in the two stratified groups: Again, this number will almost certainly be arbitrary. But why was 4 chosen? Also, perhaps adding some separation between groups (i.e., <4 vs. >5) would be useful.

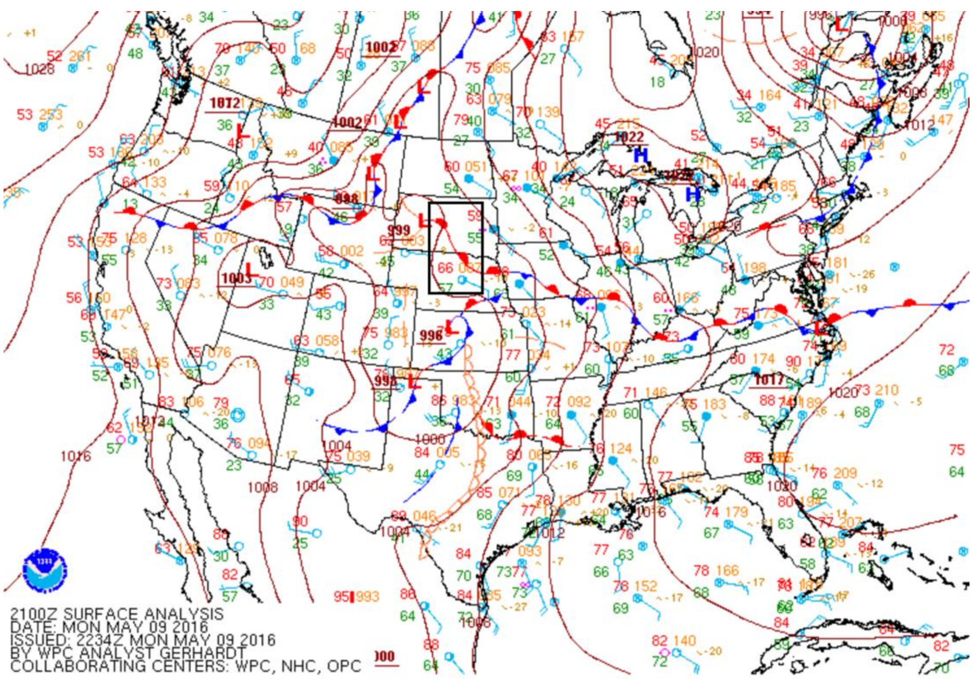
We decided to redo the contingency tables and look only at counts of tornado producing storms over the whole spectrum of numbers. There are now columns to investigate the dependency of tornado production on storm location for N=2, 3, and 4+ cells in the line. There were only a handful of cases (<10) for which there were 5 or more cells, so we lumped these with the 4's because it essentially conveys the same message as was our original intent.

Front(s):

- Do warm fronts really produce many north-south lines of supercells? I suppose they can, but the number of cases in one year seems large. Perhaps more importantly, what was the authors' definition of "north-south"? Was there an angle of orientation threshold imposed?

  An angle of approximately 45º from the vertical constituted as north–south-oriented for this study. This has now been specified in the text.

  Below is an example for one of our cases where north-south oriented cells were initiated by a warm front in Nebraska (marked by a black rectangle):



- I am not sure occluded fronts should be separated from cold fronts. Assuming that all cases in the study regions are cold occluded fronts, their general characteristics are very similar to those of cold fronts.

Because the vertical profile of temperature and wind could be different when an occlusion occurs compared to the pre-occlusion cold frontal profile, we chose to retain a distinct category for occlusions.

[Minor comments omitted…]

Second Review:

Recommendation: Accept with minor revisions.

General Comments: The authors have largely done a great job revising the manuscript into a much stronger and well-cited paper. I believe the conclusions are much more substantiated now and that the manuscript will make a nice addition to EJSSM. I do have a few minor edits listed below that should be addressed prior to publication. My primary comment is on the readability of Fig. 5, but I am willing to leave it up to the discretion of the editor as to whether (and how) it is addressed.

[Minor comments omitted…]

REVIEWER B (Roger Edwards):

Initial Review:

Recommendation: Accept with major revisions.

The modified "Rasmussen table" below summarizes my evaluation of this manuscript. Related general and specific comments follow the table.

Criterion	**Satisfied**	**Deficient, but can be remedied**	**Deficient; *cannot* be remedied by modifying the paper**	**Deficient, *not known* if it can be remedied by modifying the paper**
1. Does the paper fit within the stated scope of the journal?	X			
2. Does the paper 1) identify a gap in scientific knowledge that requires further examination; 2) repeat another study to verify its findings; or 3) add new knowledge to the overall body of scientific understanding?	X			
3. Is the paper free of errors in logic?		X		
4. Do the conclusions follow from the evidence?		X		
5. How reproducible are the findings given the information presented?		X		
6. Are alternative explanations explored as appropriate?		X		
7. Is uncertainty quantified?		X		

8. Is previous work and current understanding represented correctly?		X		
9. Is information conveyed clearly enough to be understood by the typical reader?		X		

Overview: The manuscript consists of an evaluation of tornadic supercell cases involving quasi-linear arrangements of discrete or semi-discrete supercells, assessing their tornado production by spacing, southern-end positioning, and springtime month.

My recommendation is "accept with major revision". The main value in this work is in using scientific and statistical methods for dispelling a longstanding myth that "Tail-end Charlie" storms (as southernmost supercells colloquially are known amongst storm observers and many meteorologists) are more-prolific tornado producers. The work is valuable in a niche way and should be a worthy addition to the body of literature related to supercellular environments and behaviors. The research serves a good purpose in debunking a pervasive myth that has infiltrated storm spotting and chasing, and perhaps even forecasting, as alluded at the end of section 1.

Some non-fatal concerns came up that need to be addressed (substantive comments below). The paper is worth publishing, pending what appear to add up to "major" revisions, when accounting in aggregate for major comments below and numerous minor technical and scientific comments that I've noted in the manuscript's Word file.

The paper mostly is well-organized, but wording can be tightened up in many places and made more specific in others, with more active verbs. I point out several examples in the minor comments, but please do comb the paper thoroughly for other opportunities to be more concise. This paper probably could contain at least 10% less text with no loss of meaning at all. I see no show-stoppers or onerously burdensome reconstructions that preclude proceeding with revision and eventual acceptance, if all the major and minor comments are addressed satisfactorily. Of course, suggestions of other reviewers also will need to be addressed.

I do wish to read the next draft and accompanying point-by-point responses.

We greatly appreciate the care, attention, and detail that you put into this manuscript. It will certainly be a much better product with the help of your comments! Thank you!

Substantive (major) comments: Stating the problem (and its importance): Let me preface the comment by stating flatly that the myth of southern-end tornado favorability indeed exists, and that I have heard about the legend of "Tail-end Charlie" for the entirety of the 3+ decades I have been storm observing. Although it probably started in reference to squall lines or QLCSs, I've heard of it in reference to broken to discrete lines or arcs of supercells as well. Working as an NSSL student research aide and storm-intercept archivist in the mid–late 1980s, I recall reading the term in a few long-lost field-project logs from the 1970s. The idea probably has been around as long as organized storm chasing by teams (at least from the early 1970s). However, in the Introduction, which ideally lays out the background of and case for the research performed, I'd like to see a more-robust statement and documentation of the problem, and justification from literature for attacking it (and you've attacked it quite successfully).

We have adjusted a good deal of the text in the introduction accordingly and have tried to streamline the discussion and more clearly present the background material in a manner that sets the stage for the primary scientific question investigated in this study.

Chase blogs constitute gray literature (Schultz 2009) of a rather murky shade. While not completely invalid, they exist only since the early 2000s and act to impart undue recency bias when standing alone. Instead they should take a back seat and supplement more longstanding references. What formal articles or books based on storm chasing discuss it? Is the idea noted in Howie Bluestein's book or its references, or in any of several pop-literature books on chasing made in the last 25 years, or in any formal references based on chasing that the authors can seek as good candidates to contain it? Is it mentioned in published case studies of tornadic southern-end supercells? A more-thorough literature review targeting this concept, including combing through potentially relevant printed material and (for digital archives) keywords such as "southern-end storm", "southernmost supercell" and "tail-end Charlie", may help.

Despite an extensive search online and in hard-cover books, we could not find any very strong arguments supporting this sentiment. We included the one reference we did come across and added it accordingly. We also added personal communications with both yourself (from your statement in this review) as well as Howie, who supported the idea that chasers often make decisions to target the southern-end storm.

**Side note, author Houser contacted Dr. Bluestein directly asking if he wrote or was aware of any books or manuscripts that documented chasers choosing to target the tail end storm, and he said he was not aware of any and he never wrote about it himself, to his recollection. We hope that including the correspondence with two highly reputable storm chasers/professionals will be sufficient to quell any hesitation or doubts that the readers/reviewers may have about this practice. With that said, we did choose to include the blog citations as they provide a strong source to reference decisions that chasers have made. Since there is really no scientific content to be cited from the blogs and they are being used to justify human behavior, the authors believe the inclusion of these references is appropriate. Professionals in human-based sciences and those studying communication use these sources very extensively.*

Preliminary storm reports (e.g., Fig. 1 and related text) should not be used in formal scientific studies when final reports are readily available for these years. Tornado reports quite often evolve between compilation of the local storm reports and the NCEI storm-events database (a.k.a. *Storm Data*). Furthermore, *Storm Data* itself is faulty for tornadoes, in that it offers county segments instead of whole tornado paths; therefore, the NCEI data also should not be used here. Fortunately, the fix here is straightforward: *Use the final SPC tornado-report database instead, from the beginning; these data are whole-path and not segmented.* The data are readily available either as online graphical plots through the SVRPLOT3 web program, as CSV files, or in GIS-compatible format, whichever suits your analytic needs best. This may not change your results much, and almost certainly not your conclusions. Still, while "final" tornado data have plenty of their own problems (e.g., Schaefer and Edwards 1999; Verbout et al. 2006; Doswell 2007; Smith et al. 2012), they will serve the authors' purposes in a far more defensible and reproducible way than the fluid and preliminary "rough logs" or county-segmented *Storm Data*.

I also wonder if the interspersion of sources (rough log, *Storm Data*) has caused the authors to get some tornado events incorrect in documentation. For example, the Katie (preceding Sulphur) and Hickory/Connerville (intervening mini-supercell) tornadoes on 9 May 2016 each appear to have been ignored or blended with another in the subsection dealing with that case. Please double-check that day and others to ensure precise and accurate documentation, via the final SPC ONETOR dataset.

Thank you for this suggestion. We went back through our 2016 data using the SVRPLOT3 database, and we added all of our additional cases from this source as well. Having the reports on an event by event listing rather than county by county was a huge help! We hope that we have remedied these concerns. Additionally, the Katie, OK tornado was examined, but not included because at the time, it exceeded the 75 km distance threshold (this was added to the text).

Sampling time period: I see no explanation on why the years selected were used, but not the intervening 2012–2015. Please solidly justify the omission in the text, or better yet, for sample-size considerations (Doswell 2007), examine and include all pertinent cases in those years as well. Doing so should make your analysis more robust via increasing sample size, and should fortify your points, based on what I fuzzily recall operationally about a few events in those years. The illustrative examples you used are nice and appropriate, so no substantial change is needed to those. Instead my suggestion gains you more background bulk data to analyze, without any disadvantage that I can see.

2016 was examined originally because it was the most recent year for official data when we began conducting this study.

We did follow this suggestion and have now added the entire season's worth of data from 2013 and several additional high-profile cases from 2011 (the latter was done mainly to increase the number of cases with >3 supercells in the line). 2013 was selected because we already started analyzing the data from several cases performed earlier. We limited our addition of data to that due to time constraints. It took 7 months to complete data collection for 2016 alone originally. With the more streamlined process suggested by using SVRPLOT, we got this down to a month and a half for 2013. However, to add all the additional years would have required more time than what could be dedicated given the deadline for revisions. As such, our sample size has increased from 123 tornadoes, 39 of which were the southernmost, and 324 supercells to 243 tornadoes, 88 of which are the southernmost, and 568 supercells.

Finally, we have added additional discussion regarding the selection process of these cases in the "Case study selection" section in order to better convey the selection process to the reader.

Assessment of supercell spacing by other tornadic measures? EF rating (not the same as "intensity"…see minor scientific comments embedded in the document) is one valid way to evaluate tornadoes produced by supercells in various spatial orders in a line. However, it is not the only one. Others include the related variables of path length and destruction potential index (DPI) (Thompson and Vescio 1998). Those are easy measures to obtain or compute, and may enrich your analyses in that damage rating can underrepresent tornadoes in remote areas (e.g., Doswell and Burgess 1988; Edwards et al. 2013). As it stands, your analysis would treat a small, narrow path with one EF3 damage indicator the same as a mile-wide EF3-rated (and likely underrated) wedge traveling many path miles, the Sulphur tornado in your study being a brutally apparent example of the latter.

We appreciate this suggestion. We computed the DPI for each individual tornado based upon the EF scale value and the damage path/width reports in an effort to better represent the "severity", so to speak, of the tornadoes.

Geographic domain: A "marginal minor/major" question—why not include Alabama also? This seems like a rather glaring omission since a lot of tornadic supercells occurred in that state from 2011–2016, and any that were in quasilinear geometric configurations would fortify your sample size. Also, see minor comments for possible reworking suggestions and need for an illustrative figure.

Alabama was included in our study with a case on 29 November 2016. However, we forgot to list in in the South-central geographic region. Sorry! This omission was not deliberate but was merely the result of the cases that met the criteria discussed in the case selection section. We chose to add the 27 April 2011 super outbreak to the events from 2011 in order to better represent tornadic supercell events in the (Southeast). Interestingly, despite the proclivity to produce tornadoes during that event, there were only a few instances where the selection criteria were met. Most of the time, supercells were either not oriented in a north-south manner, or the distance between consecutive supercells exceeded the 75-km threshold.

[Minor comments omitted…]

REVIEWER REFERENCES (from *major and minor* comments, not already cited by authors):

Bothwell, P. D., J. A. Hart, and R. L. Thompson, 2002: An integrated three-dimensional objective analysis scheme in use at the Storm Prediction Center. Preprints, *21st Conf. on Severe Local Storms*, San Antonio, TX, Amer. Meteor. Soc., JP3.1.

——, B. T. Smith, R. L. Thompson, A. R. Dean, and J. S. Kain, 2014: Severe weather parameter reanalysis project at the Storm Prediction Center. Preprints, *27th Conf. on Severe Local Storms*, Madison, WI, Amer. Meteor. Soc., 18.2.

Burgess, D. W., B. R. Smith, H. B. Bluestein, Z. B. Weinhoff, D. W. Reif, R. Smith, and D. Speheger, 2016: A mini-supercell observed during an outbreak of classic supercells on 9 May 2013. Proc., *28th Conf. on Severe Local Storms*, Portland, OR, Amer. Meteor. Soc., 12A.1.

Doswell, C. A. III, 2007: Small sample size and data quality issues illustrated using tornado occurrence data. *Electronic J. Severe Storms Meteor*., **2** (5), 1–16.

——, and D. W. Burgess, 1988: On some issues of United States tornado climatology. *Mon. Wea. Rev.*, **116**, 495–501.

——, S. J. Weiss, and R. H. Johns, 1993: Tornado forecasting—a review. *The Tornado: Its Structure, Dynamics, Prediction, and Hazards*, Geophys. Mongr., No. 79, Amer. Geophys. Union, 557–571.

Edwards, R., and J. C. Picca, 2016: Tornadic debris signatures in tropical cyclones. Preprints, *28th Conf. on Severe Local Storms*, Portland, OR, Amer. Meteor. Soc., 162.

——, J. G. LaDue, J. T. Ferree, K. Scharfenberg, C. Maier, and W. L. Coulbourne, 2013: Tornado intensity estimation: Past, present, and future. *Bull. Amer. Meteor. Soc.*, **94**, 641–653.

Schaefer, J. T., and R. Edwards, 1999: The SPC tornado/severe thunderstorm database. Preprints, 11th Conf. on Applied Climatology, Dallas, TX, Amer. Meteor. Soc., 215–220.

Schultz, D. M., 2009: *Eloquent Science.* Amer. Meteor. Soc., 412 pp.

Smith, B. T., R. L. Thompson, J. S. Grams, C. Broyles, and H. E. Brooks, 2012: Convective modes for significant severe thunderstorms in the contiguous United States. Part I: Storm classification and climatology. *Wea. Forecasting*, **27**, 1114–1135.

Thompson, R. L., and M. D. Vescio, 1998: The destructive potential index—A method for comparing tornado days. Preprints, *19th Conf. on Severe and Local Storms*, Minneapolis, MN, Amer. Meteor. Soc., 280–282.

Verbout, S. M., H. E. Brooks, L. M. Leslie, and D. M. Schultz, 2006: Evolution of the U.S. tornado database: 1954–2003. *Wea. Forecasting*, **21**, 86–93.

Second Review:

Recommendation: Accept with minor revisions.

The modified "Rasmussen table" below summarizes my evaluation of this manuscript. Related general and specific comments follow the table.

Criterion	Satisfied	Deficient, but can be remedied	Deficient; *cannot* be remedied by modifying the paper	Deficient, *not known* if it can be remedied by modifying the paper
1. Does the paper fit within the stated scope of the journal?	X			
2. Does the paper 1) identify a gap in scientific knowledge that requires further examination; 2) repeat another study to verify its findings; or 3) add new knowledge to the overall body of scientific understanding?	X			
3. Is the paper free of errors in logic?		X		
4. Do the conclusions follow from the evidence?	X			
5. How reproducible are the findings given the information presented?		X		
6. Are alternative explanations explored as appropriate?		X		
7. Is uncertainty quantified?	X			
8. Is previous work and current understanding represented correctly?		X		
9. Is information conveyed clearly enough to be understood by the typical reader?		X		

Overview: This manuscript is well on its way to acceptance. The authors mostly have done a reasonable job in revision, either following the recommendations of the reviewers or justifying why not. One example of the latter is in a sincere, if mostly unsuccessful, effort to find alternatives to "gray-literature" references such as chase blogs, where no more formal or scientifically robust sources otherwise exist for the necessary information. If it's not there, it's not there, but at least the authors satisfactorily did more to make sure of that. Such is all I can ask reasonably.

Major concerns from my first review (e.g., report sourcing, spatiotemporal sampling domain, original use of EF scale alone to "measure" tornadoes) otherwise were addressed satisfactorily, and the revision process introduced no additional major concerns. A couple of somewhat lesser (but still substantive) issues remain, in addition to numerous technical comments, but none are major in terms of large revisions needed. Therefore, my recommendation is "accept with minor revision". I do wish to read the next draft and accompanying point-by-point responses.

Substantive comments come first. I'll list minor comments in this review instead of marking up the manuscript, since the revision was submitted as a PDF. A considerable amount of technical cleanup still is needed.

Substantive comments: Why were tornado reports lacking proximal hail necessarily assumed to be "landspouts" (more properly, non-supercell or non-mesocyclonic tornadoes) in all cases? Some nontropical, midlatitude, tornadic supercells fail to produce severe hail, especially in the cool season in the Southeast. This isn't a show-stopper in the big picture, but deserves more explanation and better justification (preferably with supporting citation) in the text. On the other hand, the justification for disuse of NCEI tornado segments, per my first review, was well-stated. Thank you.

We actually ended up removing the hail requirement altogether when we re-evaluated the dataset prior to the previous submission. This criterion was a legacy of the original manuscript that we had failed to revise. We have now omitted this criterion altogether in this version of the manuscript.

For this otherwise exemplary case study, I'm still unsure if, or how, you counted the intermediary tornadic mini-supercell between the major "Sulphur" and "Atoka" supercells, in northwestern Johnston County. Maybe I'm missing something in the explanations that's there, but only inferential? Here is a photo and description of that tornado: http://skypix.photography/connerville-tornados-ragged-updraft/. Having observed both the huge Sulphur tornado and this one, I can attest first-hand that the latter was from a distinct (if shockingly small, ragged, otherwise unimpressive) storm, and not part of either the formerly tornadic Sulphur storm or the strengthening Atoka supercell to the south and southeast. [I decided not to intercept the "Atoka" storm due to an awkward and dangerous northwesterly approach angle with limited roads, into a likely significantly tornadic supercell (as it turned out to be).] Burgess et al. (2016) analyzed the tornadic mini-supercell. Since this was a well-known, albeit minor, tornadic storm in the outbreak, it deserves at least passing yet specific attention.

We have identified the supercell you are talking about and the storm report from the original NCEI data. However, in the NCEI data, the tornado is listed as an EFU and therefore, does not transfer over to the SPC severe weather database we later used with the EFU rating. This study is also using the WSR-88D radar network, and as stated by Burgess et al. 2016, KTLX was unable to observe the tornadic supercell characteristics. Furthermore, at the time of the tornado report in the NCEI, it did not have a discrete core, which would imply it would not be included for statistical purposes.

That being said, we have revised the text to mention that this tornado occurred, but was not included in the statistical analysis because it did not meet the requirements for a discrete core (Burgess et al. 2016).

[Minor comments omitted…]

REVIEWER C (Harold E. Brooks):

Initial Review:

Recommendation: Revisions required.

Overall Comments: The paper is a good effort to debunk or, at least, evaluate a persistent "myth" about storm behavior. The approach is sound, although it probably wasn't necessary to break things down as much as has been done. The horse died early in the analysis and the continued beating approached abuse.

We apologize if we bored you with the lengths to which we went in order to try to extrapolate some sort of dependency! Our goal was to extract something meaningful from the data and to attempt to approach the *question from a variety of different angles that storm chasers might use in their philosophy of targeting the southernmost storm. We did shorten the manuscript by removing the discussion on one of the two case studies. We decided that information was ancillary and not really needed.*

Why were 2011 and 2013 chosen to increase the sample size?

Supplemental cases from 2011 and 2013 were chosen because there were multiple cases with known linearly oriented supercells and there were a multitude of cases these years and less in the intervening years. In this version of the paper, we have included data from the entire 2013 data and several additional high-profile cases from 2011 (the latter was done mainly to increase the number of cases with >3 supercells in the line) to further increase our sample size at the request the reviewers. 2013 was selected because we already started analyzing the data from several cases performed earlier. This explanation has been made clearer. As such, our sample size has increased from 123 tornadoes, 39 of which were the southernmost, and 324 supercells to 243 tornadoes, 88 of which are the southernmost, and 568 supercells.

How many cases were removed?

There were only a handful (<10) of cases for which this occurred. [This is in reference to removing cases for which there was a report that was not substantiated by the radar, correct?]

The phrase "statistical significance" is associated with an arbitrary value. You can search for many of the papers that are collected in this book "What if there were no significance tests?": http://www.gbv.de/dms/ilmenau/toc/640188494.PDF. I particularly recommend the papers on "The earth is round" by Cohen and "Good science…" by Rozeboom.

We believe that the reviewer was suggesting that you cannot say something is statistically significant without specifying the level of significance. We have included this reference now.

[You make an] excellent point on sample size. Many of the subsamples here are small enough that, if even if a value met some arbitrary value for statistical significance, it wouldn't be meaningful in a practical sense.

We have increased the sample size dramatically in this version of the paper and have used a different index (the DPI) instead of the EF-scale in an attempt to better represent the data in terms of actual severity of the tornado as well as the number of samples. Therefore, we are more confident in the new data analysis and interpretation.

Second Review:

Recommendation: Accept.