



Tornado seasonality in the southeastern United States

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ABSTRACT

Tornadoes are among the most destructive natural events and occur most frequently in the United States. It is difficult to ascertain if the frequency of tornadoes in the U.S. is increasing because our ability to observe and report tornado occurrence has increased over time. Previous studies have demonstrated that tornado likelihood has shifted toward earlier dates across the south-central United States over the past seven decades, the region sometimes called “Tornado Alley”, if it can be assumed that seasonal observation effort has not shifted over time. It is unclear if such shifts in tornado seasonality have also occurred elsewhere, including the region of the southeastern United States where tornado likelihood has a bimodal annual distribution. We use circular methods to demonstrate that the date of observed peak tornado occurrence during the early tornado season has not changed in the past seven decades. However, the date of peak tornado occurrence during the later tornado season has shifted toward earlier dates by more than a week. The influence of tropical storms had no effect on changes in late-season tornado seasonality. The conclusions are robust with respect to whether tornado counts or tornado days are used as the response variable. Results demonstrate the ongoing need to encourage tornado preparedness in the southeastern U.S., where tornadoes tend to have a higher impact on humans, and to understand the mechanisms that underlie trends in tornado seasonality.

1. Introduction

Tornadoes are among the most extreme weather events on Earth, often striking with devastating consequences. The United States experiences more tornadoes per year than any other country (Grazulis, 1990; Henson, 2003) because large portions of the central and eastern United States experience conditions favorable to tornadogenesis (Brooks et al., 2003; Mercer et al., 2009; Shafer et al., 2009; Sherburn et al., 2016). Seasonal tornado activity in the region of the U.S. where tornadoes occur most frequently - the Great Plains - is well-defined and most occur during spring (e.g., Brooks et al., 2003; Long and Stoy, 2014). Maximum, or peak, tornado activity occurs at progressively later dates for locations farther north and range from early May for Oklahoma and southeastern Texas to early July for North Dakota (Brooks et al., 2003). There is little variability in the length of this seasonal cycle, which lasts approximately 3.5 months. Recent work has determined that peak, or maximum, tornado activity in the Great Plains has shifted earlier in the year by an average of 7 days (Long and Stoy, 2014) and 12–13 days (Lu et al., 2015) relative to the 1950s. Observed shifts in the seasonality in the Great Plains are accompanied by corresponding trends in convective available

potential energy (CAPE) and the fourth power of storm relative helicity (SRH⁴), as well as their interaction, CAPE × SRH⁴ (Lu et al., 2015).

Whereas the Great Plains have the most tornado occurrences, a region in the southeastern United States encompassing Arkansas, the northern and central portions of Louisiana, Mississippi, and Alabama, as well as portions of western Tennessee has the highest tornado risk (Coleman and Dixon, 2014) and the greatest concentration of tornado fatalities (Ashley, 2007). The delineation of this region, sometimes called “Dixie Alley” after the “Tornado Alley” of the central and southern Great Plains, varies slightly depending on the study (e.g., Ashley, 2007; Coleman and Dixon, 2014; Dixon et al., 2014; Deng et al., 2016). The seasonality of tornado activity in the southeastern United States is also more variable than the unimodal seasonality in the Great Plains. Namely, the southeastern states experience tornado activity throughout a substantially larger portion of the year with two periods of increased activity, one in spring and a second in autumn. The variation in the timing of these seasons is large, causing density plots of tornado activity in the southeastern United States to have broad peaks, which makes it difficult to assess where the maximum is located. Few studies to date have delineated tornado seasonality in the southeastern United

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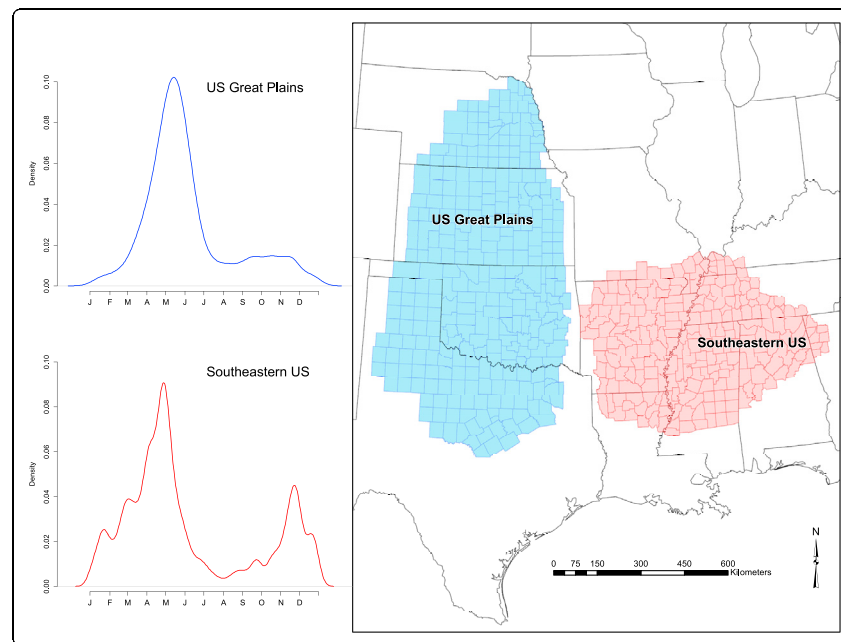


Fig. 1. Tornado activity in the Great Plains (blue) consists of a unimodal period of elevated activity during meteorological spring, whereas tornado activity in the southeastern United States (red) is bimodal with elevated periods of activity during spring and late autumn. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

States. Dixon et al. (2014) used K-means clustering to identify four seasons: winter (26 January–13 March), spring (14 March–7 May), summer (8 May–15 October) and fall (16 October–25 January), but this is for the tornado-prone regions of the entire United States. Tornado activity across the entire United States has a maximum in mid-June and a minimum in late December (Brooks et al., 2003), and the geographic region of maximum tornado activity in the United States changes throughout the year (Brooks et al., 2003; Tippett et al., 2014); thus, tornado seasonality is location-dependent. Brooks et al. (2003) examined the probability that a tornado day occurs at various locations in the contiguous United States, including several locations in the southeastern states and determined that the southeastern states face their biggest tornado risk in April. No studies to our knowledge have sought to identify any changes to tornado seasonality in the southeastern United States since the onset of systematic data collection.

The number of reported tornadoes in the southeastern United States has increased from an annual mean of 44 in the 1950s (1954–1959) to an annual mean of 97 during 2010–2015. Approximately 43% of the increase can be attributed to 2011, which had an unusually high number of tornadoes. It has also been widely reported that these increases are likely not “true” increases due to meteorological conditions, but instead reflect a variety of demographic factors such as better public awareness and reporting and increasing population trends, as well as technological improvements such as improved detection, better spotting techniques and the widespread implementation of Doppler radar (e.g., Verbout et al., 2006). We study trends in tornado seasonality rather than likelihood given known trends in reporting effort following Long and Stoy (2014). Furthermore, the increase in the number of reported tornadoes is primarily due to the increased reporting of weak tornadoes, (E)F0 and (E)F1 (e.g., Kunkel et al., 2013; Coleman and Dixon, 2014). Verbout et al. (2006) tested the stationarity of tornado frequency over a 50-year period and found that the number of annually reported tornadoes rated (E)F1 and greater was relatively constant over time, but the inclusion of (E)F0 tornadoes resulted in a non-stationary dataset. Consequently, researchers are divided with respect to whether or not (E)F0 events should be included in analyses, particularly those studies that look at trends over time. Others have reported a decrease in the number of days with at least one tornado (a tornado

day), and a simultaneous increase in the number of days with many tornadoes (tornado outbreaks) (e.g., Brooks et al., 2014a; Elsner et al., 2015; Tippett et al., 2016). The use of tornado days as the response variable, rather than tornado frequency, is increasingly seen as a means to minimize the effect of tornado outbreaks on tornado accounting (e.g., Elsner et al., 2015).

The use of tornado days is of particular interest to the southeastern U.S. in part because tornadogenesis includes contributions from extreme weather events like landfalling tropical cyclones, which result in multiple tornado events. The majority of cyclones spawn tornadoes, typically weak, that tend to form in the outer rainbands and occur in outbreaks that may have wide spatial distribution (Gentry, 1983; Belanger et al., 2009).

The purpose of this study is to characterize the seasonality of tornadoes in the southeastern United States. Specifically we seek to: (1) delineate tornado seasonality in the southeastern United States to more accurately account for the bimodal nature of the observations; (2) determine whether the dates corresponding to peak tornado activity have changed since the 1950s using both tornado counts and tornado days; (3) assess whether including (E)F0 events in the analysis alters the results; and (4) assess the impact of tropical cyclones on tornado seasonality in the southeastern US.

2. Data and methodology

Tornado intensity varies greatly across events and is described using a classification scheme based on damaging effects from which wind speed is inferred. The original scale, the Fujita scale, was developed in 1971 and classified tornadoes on a scale from F0 to F5, in which F0 denotes tornadoes with the lightest winds that tend to cause the least amount of damage (Fujita, 1971). Well-known limitations with the Fujita scale led to the adoption of the enhanced Fujita scale (EF) (Potter, 2007). As in the original scale, the EF scale is graduated, with EF0 denoting the category with the lightest winds and damage, and EF5 denoting tornadoes with the strongest winds and the most extensive damage. To account for changes in tornado reporting over time, we use the abbreviation (E)Fx to denote a combined Fujita and enhanced Fujita scale where x varies from 0 to 5.

2.1. Data

The area of interest within the region that is most prone to tornadoes in the southeastern United States (Fig. 1) follows other studies and includes portions of eight states: Arkansas, Louisiana, Mississippi, Alabama, Georgia, Tennessee, Kentucky, and Missouri. This tornado-prone area, “Dixie Alley”, is geographically ill-defined and our results reflect a composite of regions defined by others. We will refer to the area as the southeastern United States and leave it to others to more clearly delineate and label it.

The Storm Prediction Center's (SPC) severe weather database (SPC, 2017) contains records for all reported tornadoes in the United States since 1 January 1950. The SPC database is widely considered to be the most reliable data archive for tornadoes (e.g., Elsner et al., 2013); however, changes in counting and reporting efforts have been problematic. The US Weather Bureau (now the National Weather Service) began efforts to count all tornadoes in the United States in 1950; however, it was not until 1953 that the process was formally implemented (Ashley, 2007). For this reason, many researchers consider 1954 as the first full year of reliable data in the SPC dataset (e.g., Grazulis, 1990; Verbout et al., 2006; Kunkel et al., 2013). There are well-known issues with respect to biases and trends, as discussed in the introduction (see Verbout et al., 2006 for a detailed discussion). If one can assume that the seasonality of tornado observation efforts has not shifted over time, studies of changing tornado seasonality from the SPC dataset should reflect any

actual changes in tornado seasonality (Long and Stoy, 2014).

Temporal and spatial data were extracted from the SPC database for 1954–2015. Temporal data consisted of the day, month, and year of tornado events; spatial data consisted of county and state and was confined to the region of interest. Day and month were converted to Julian dates, which we refer to as day of year (DOY). An artificial 29 February was added to non-leap years, which has been shown to be a robust procedure for studies of tornado seasonality (e.g., Brooks et al., 2003; Long and Stoy, 2014). We created two versions of the dataset for analysis; (E)F1+, which was restricted to (E)F1 or stronger events, and (E)F0+, which included the (E)F0 tornadoes.

The World Meteorological Organization (WMO) International Best Track Archive for Climate Stewardship (IBTrACS, Knapp et al., 2010) was used to identify tropical storm tracks in the North Atlantic basin and to investigate the potential impact of tropical cyclone landfalls on tornado genesis. The IBTrACS dataset (Version 3r10) records the latitude and longitude of tropical cyclones, including hurricanes, every six hours throughout their lifecycle.

2.2. Methodology

The southeastern United States experiences tornadoes throughout the majority of the year with periods of elevated activity in the spring and in late fall/early winter. The data are, therefore, bimodal (Figs. 1 and 2) and our first task was to divide the year into two seasons. DOY data wrap back



Fig. 2. Histograms of tornado activity in the southeastern United States for 1954–2015 as annual observed tornado occurrences or tornado days: (a) (E)F1+ tornado occurrences ($n = 5458$); (b) (E)F0+ tornado occurrences ($n = 3918$); (c) (E)F1+ tornado days ($n = 1472$); and (d) (E)F0+ tornado days ($n = 1171$). The corresponding density curve has been superimposed on the histograms, which clearly show the bimodality of tornado activity in the data. Note that the density at the wrap-around point, the 31 December to 1 January transition, is not zero, which necessitates circular methods. The plot uses a bin width of 5 days.

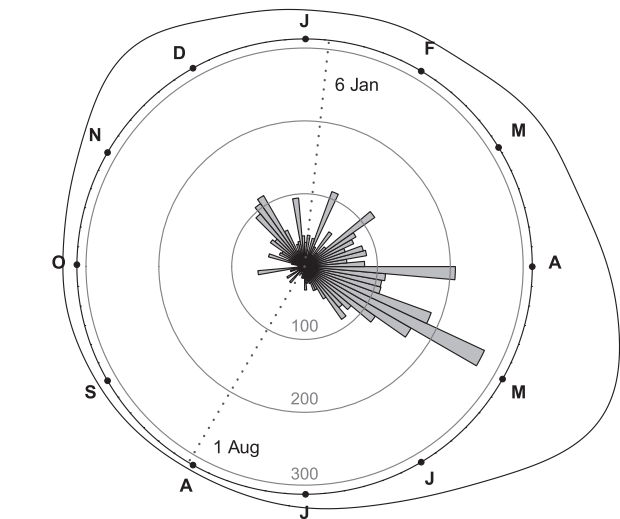


Fig. 3. Rose plot (circular histogram) with superimposed circular density plot for tornado activity in the southeastern United States. The plot uses a bin width of 5 days, the same as in Fig. 2, and is averaged over 1954–2015. Minimum density occurred on 6 January and 1 August, which divided the year into an early season (6 January to 31 July) and a late season (1 August to 5 January). January is at the top of the circle and the months proceed clockwise around the circle. The dotted lines identify the date corresponding to minimum circular density, which is also indicated by the dates in the plot. The concentric rings are labeled according to frequency and are equivalent to the y-axis in a traditional histogram.

on themselves such that the end series (31 December) is followed by the beginning of series (1 January); therefore, treating DOY as a linear variable is problematic, particularly if tornadoes occur during the annual transition, as is the case in the southeastern United States. Consequently, we treated DOY as a circular variable throughout this study following Long and Stoy (2014). We used density-based methods for circular variables to identify the dates corresponding to the local minima density of tornado occurrences, which we considered to represent the seasonal boundaries. Results from density-based methods are dependent on the choice of bandwidth. We used a selection algorithm that implements a cross validation scheme to select the optimal bandwidth based on minimizing squared-error loss, as implemented in the “circular” package (Agostinelli and Lund, 2013) of the statistical program R (R Core Team, 2015), which we used for all analyses.

Treating variables as circular produces results that are nearly identical to those obtained from treating the variable as linear if there are no observations near the wrap-around point. Circular methods have been shown to be more conservative than linear methods when estimating density on annual basis (Long and Stoy, 2014). Directional data, such as orientation, are inherently circular since they are measured in terms of compass direction. Similarly, temporal variables, e.g., time of day or DOY, are circular

Table 1
Delineation of the early and late seasons (1954–2015) as a function of the various datasets.

Basis	Dataset	Observations ^a	Early Minima	Late Minima
Tornado Frequency	(E)F0+	5458	4 January	1 August
	(E)F1+	3918	6 January	31 July
	(E)F1+ minus TC ^b	3777	6 January	31 July
Tornado Days	(E)F0+	1472	17 January	9 August
	(E)F1+	812	15 January	7 August

^a The number of events in the dataset.
^b The (E)F1+ minus the tornadoes likely associated with tropical cyclones (TC).

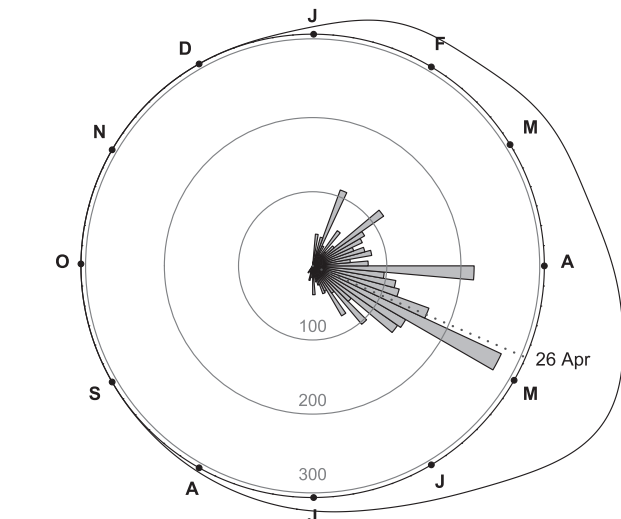


Fig. 4. Rose plot (circular histogram) with superimposed circular density plot for (E)F1+ activity, based on tornado occurrences, in the early season (6 January to 31 July) in the southeastern United States. The plot uses a bin width of 5 days and is averaged over 1954–2015. Peak, or maximum, tornado activity occurred on 26 April. January is at the top of the circle and the months proceed clockwise around the circle. The dotted line identifies the date corresponding to maximum circular density, which is also indicated by the date in the plot. The concentric rings are labeled according to frequency and are equivalent to the y-axis in a traditional histogram.

if the temporal units are converted to angles that are subsequently superimposed on a circle. There are three basic characteristics that distinguish circular variables from linear ones: (1) the beginning and end of the cycle are coincident at the wrap-around point, (2) angular measurements depend on the choice of origin, and (3) on the direction of rotation (e.g., Batschelet, 1981; Marchetti and Scapini, 2003). In most usages, the origin is considered to be the top of the circle – i.e., north on a compass rose or 12:00 on an analog clock, and with a clockwise rotation. This contrasts with mathematical tradition in which the origin is taken to be the x-axis with a counter-clockwise rotation. We followed the compass tradition and represented the beginning of the year, 1 January, as the top of a circle with the remaining days following in a clockwise rotation. Readers interested in the details of circular variables from a mathematical perspective are encouraged to review Batschelet (1981).

We considered the DOY for tornado activity based on a 10-year moving window beginning in 1954 and ending in 2015 (e.g., 1954–1963, 1955–1964, ..., 2006–2015) to minimize the effects of year-to-year variability. Our previous work (Long and Stoy, 2014), as well as initial work on this paper, suggest that a 10-year moving window – a decadal moving average – better captures long-term trends and minimizes the effect of single years with unusually high or unusually low tornado activity. We defined peak tornado activity within each season as the date of maximum circular density following Long and Stoy (2014). Using these approaches we divided tornado activity throughout the course of a year into an “early” season and a “late” season that follow the known bimodal seasonal distribution of tornado activity in the southeastern United

Table 2
Day of Year (DOY) corresponding to maximum (peak) tornado activity.

	Early Season (6 Jan–31 Jul)	Late Season (1 Aug–5 Jan)
Tornado Occurrences: (E) F1+	26 April	24 November
Tornado Occurrences: (E) F0+	26 April	24 November
Tornado Days: (E)F1+	25 April	20 November
Tornado Days: (E)F0+	27 April	21 November

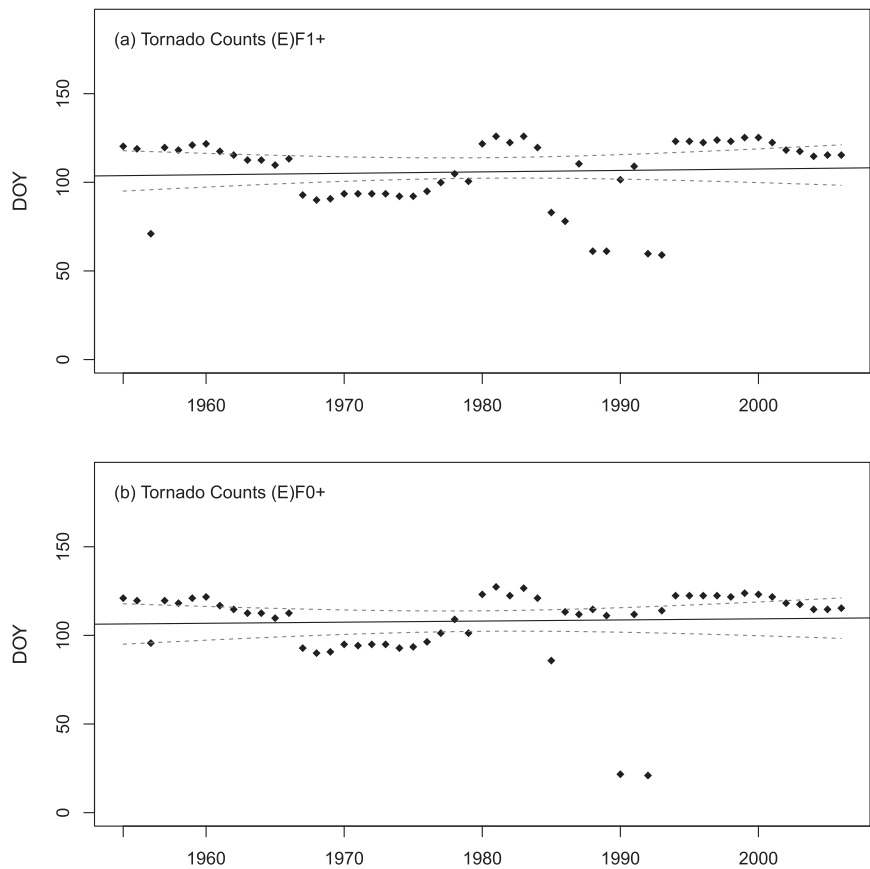


Fig. 5. Regression modeling of the day of year (DOY) corresponding to peak tornado activity, based on tornado occurrences, in the early season using a 10-year moving window for: (a) the (E)F1+ dataset and, (b) the (E)F0+ dataset. The horizontal axis (Year) is based on the first year of each decadal window (e.g., 1954 corresponds to the 1954–1963 window). The regression line and 95% confidence bands (dotted) are shown.

Table 3
Changes in the day of year for peak tornado activity during 1954–2015 using a 10-year moving average window as determined by linear regression with tornado frequency as the response variable.

	Slope ^a (days/time unit)	Standard Error (days/time unit)	p-value	Change (days) ^b
Early Season				
(E)F1+	0.0815	0.1724	0.638	+4.3
(E)F0+	0.0630	0.1883	0.739	+3.3
Late Season				
(E)F1+	−0.2126	0.0625	0.001	−11.3
(E)F0+	−0.5669	0.1239	<0.001	−30.0
(E)F1+ (2000, 2007, 2011 removed)	−0.2123	0.0671	<0.001	−11.3
(E)F0+ (2000, 2007, 2011 removed)	−0.5552	0.1133	<0.001	−29.4

^a Positive slopes indicates a shift to later in the year and negative slopes indicate a shift to earlier in the year. The number of days shifted is found by multiplying the slope coefficient by the number of time units (53 for the moving window approach).

^b Negative values represent shifts earlier in the year, while positive values indicate shifts later in the year.

States, and discuss results in this context.

Due to the large number of tornadoes (>5000) considered in this work it is not feasible to use high resolution meteorological data to directly diagnose tornadogenesis associated with the landfall of tropical cyclones. To address whether tropical cyclones affected the seasonality of

tornadoes in the study area, we took the conservative approach and assumed that tornadoes originating within a threshold distance of IBTrACS tropical cyclone tracks were caused by cyclone passage. Distances between tropical cyclones and tornado locations were determined based on the position of closest recorded tropical cyclone location at the time of tornadogenesis to the county's geographic centroid. Threshold distances of 500, 750, and 1000 km produced tropical cyclone related tornado counts of 126, 141, and 146 respectively. Since tropical storm winds can extend approximately 500 km from the center of a hurricane (UCAR, 2010) and because of the plateau in tornado occurrences between 750 and 1000 km, we used 750 km as a conservative threshold. Note that the actual strength or size of the tropical storm, which is not uniformly reported in IBTrACS, is not considered separately as we assumed all tornadoes within the threshold distance were caused by the tropical storm for the purposes of this analysis.

We used regression models to determine if the DOY corresponding to maximum tornado had changed over time by using tornado occurrences as the dependent variable and the 10-year moving window as the independent variable; we did this for the (E)F1+ dataset, the (E)F0+ dataset, and one in which hurricane-spawned tornadoes were eliminated. We repeated the regression analysis with tornado days as the dependent variable.

3. Results

3.1. Delineation of the early and the late season

The southeastern United States experiences tornado activity

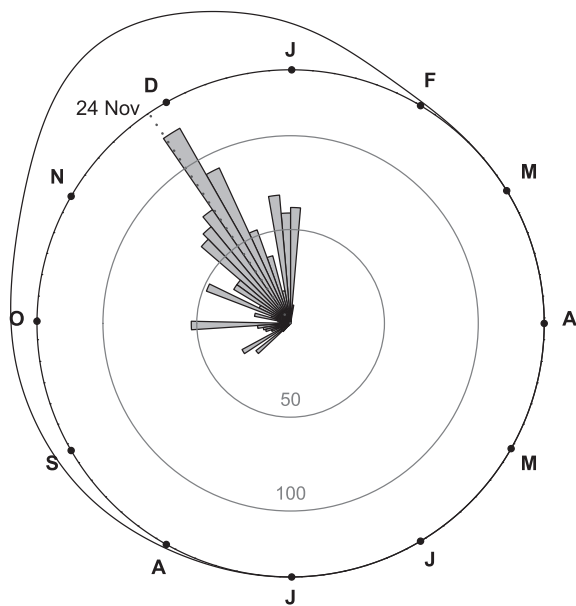


Fig. 6. Rose plot (circular histogram) with superimposed circular density plot for tornado activity, based on tornado occurrences, in the late season (1 August to 5 January) in the southeastern United States. Peak, or maximum, tornado activity occurred on 24 November. The plot uses a bin width of 5 days and is averaged over 1954–2015. January is at the top of the circle and the months proceed clockwise around the circle. The dotted line identifies the date corresponding to maximum circular density, which is also indicated by the date in the plot. The concentric rings are labeled according to frequency and are equivalent to the y-axis in a traditional histogram.

throughout much of the year, but there are two periods in the year in which tornadoes are more prevalent (Fig. 2). Tornado activity is minimal in the summer and in the early winter, but these minima are not equal in activity or duration. This timing contrasts sharply with the single well-defined season found in the Great Plains (Fig. 1). Circular density-based analysis of the (E)F1+ dataset identified minimal tornado activity in terms of tornado frequency in the southeastern United States as occurring on 6 January and 1 August (Fig. 3). The inclusion of (E)F0 events did not appreciably alter the delineation of seasonality as there was less than a two-day difference. Eliminating the hurricane-spawned tornadoes likewise produced no difference in seasonality as determined by tornado frequency. The use of tornado days instead of tornado counts suggested slightly different minima, approximately one week later in the year (Table 1). Given that these small differences occur during periods of minimal tornado activity, either in frequency or tornado days, we defined the “early” season as 6 January through 31 July and the “late” season as 1 August through 5 January of the following year. The inclusion of the entire year in the definitions of the “early” and “late” seasons was to acknowledge that tornadoes are possible at any time in the year in the southeastern US, and provided a convenient temporal framework for partitioning the bimodal data into separate unimodal datasets.

3.2. Seasonality based on Tornado occurrence

There were a total of 5458 observed and reported tornadoes in the study region during the 1954–2015 time frame; 3918 of these were (E)F1 or stronger events. Approximately 72% of the tornadoes were in the early season, regardless of whether we consider the (E)F1+ dataset (2815 of 3918 tornadoes) or the (E)F0+ datasets (3917 of 5458 tornadoes). Peak tornado activity, based on density estimates of early season tornado occurrences for the (E)F1+ dataset was on 26 April (Table 2). This peak is relatively broad and the maximum is not easily defined (Fig. 4). For example, density estimates for dates within a week of 26 April are within

3% of the estimate for 26 April. Inclusion of the (E)F0 tornadoes did not appreciably alter the results – peak tornado activity based on occurrences remained at 26 April.

Regression models using tornado occurrences indicated that the DOY corresponding to peak tornado activity in the early season has not changed since the 1950s (Fig. 5). There is a slight tendency toward peak activity occurring later in the year for the 2010s compared to the 1950s; however, this change in seasonality is not statistically significant at the 95% confidence level ($p = 0.638$). The regression results remained non-significant when we included the (E)F0 tornadoes ($p = 0.739$). Table 3 summarizes the regression modeling results using tornado frequency as the response variable.

There were substantially fewer observed and reported tornadoes in the study region during the late season: 1103 and 1541 in the (E)F1+ and the (E)F0+ datasets respectively. The years 1956, 1963, and 1975 were excluded from analysis because they had fewer than two late season tornadoes, and were incapable of providing meaningful annual estimates. Peak activity for tornado occurrences in the late season, based on the (E)F1+ dataset, was on 24 November (Table 2). As in the early season, the late-season peak was broad and the maximum difficult to define (Fig. 6). Inclusion of the (E)F0 tornado events did not alter the results – peak tornado activity based on occurrences remained at 24 November.

Regression analysis for the late season using the (E)F1+ dataset suggested that the date of peak tornado activity has shifted approximately 11 days *earlier* in the year since the 1950s – a statistically significant change ($p = 0.001$). The regression remained significant when we included the (E)F0 tornadoes ($p < 0.001$); however, the magnitude of the shift was larger – 30 days earlier (Fig. 7). The years 2000, 2007 and 2011 exerted influence due to very high standard deviations. Removing these years did not alter the conclusions regardless of dataset (Table 3), suggesting that the moving window approach is robust to outliers.

3.3. Seasonality based on Tornado days

There were 1472 days with at least one (E)F0 or stronger tornado during 1954–2015 in the study area, which is approximately 6% of all possible days. There were 812 tornado days for the (E)F1 and stronger tornadoes. Regardless of dataset, (E)F0+ or (E)F1+, the early season encompassed approximately 73% of the days, 1078 of 1472 and 596 of 812 respectively, similar to the 72% of total tornado occurrences during the early season. Peak tornado activity for the early season, based on density estimates of tornado days with the (E)F1+ dataset, was 25 April (Table 2). As we found with tornado occurrences, this peak was broad and difficult to precisely define the maximum (Fig. 8). The inclusion of (E)F0 tornadoes in the analysis indicated that the DOY corresponding to maximum tornado activity for the early season was 27 April, a two-day difference.

Regression models with tornado days indicated that changes in the DOY corresponding to peak tornado activity in the early season is dependent on the dataset. Using the (E)F1+ dataset, we find that peak tornado activity has shifted approximately 11 days earlier in the year for the 2010s compared to the 1950s (Fig. 9); however, this is not a statistically significant change ($p = 0.612$). The inclusion of the (E)F0 tornadoes also resulted in a non-significant shift ($p = 0.702$). Table 4 summarizes these results.

Peak tornado activity, based on density estimates of tornado days with the (E)F1+ dataset was 20 November for the late season (Fig. 10). This peak was typical of the others found in this study; broad and ill-defined. The inclusion of (E)F0 tornadoes in the analysis indicated that peak tornado activity for the early season was on 21 November.

Regression models for the late season using tornado days with the (E)F1+ dataset indicated a 10-day shift later in the year (Fig. 11), but this was not statistically significant ($p = 0.17$). Conversely, the (E)F0+ dataset indicated a 15-day shift *earlier* in the year (Table 4), which was statistically significant ($p < 0.01$).

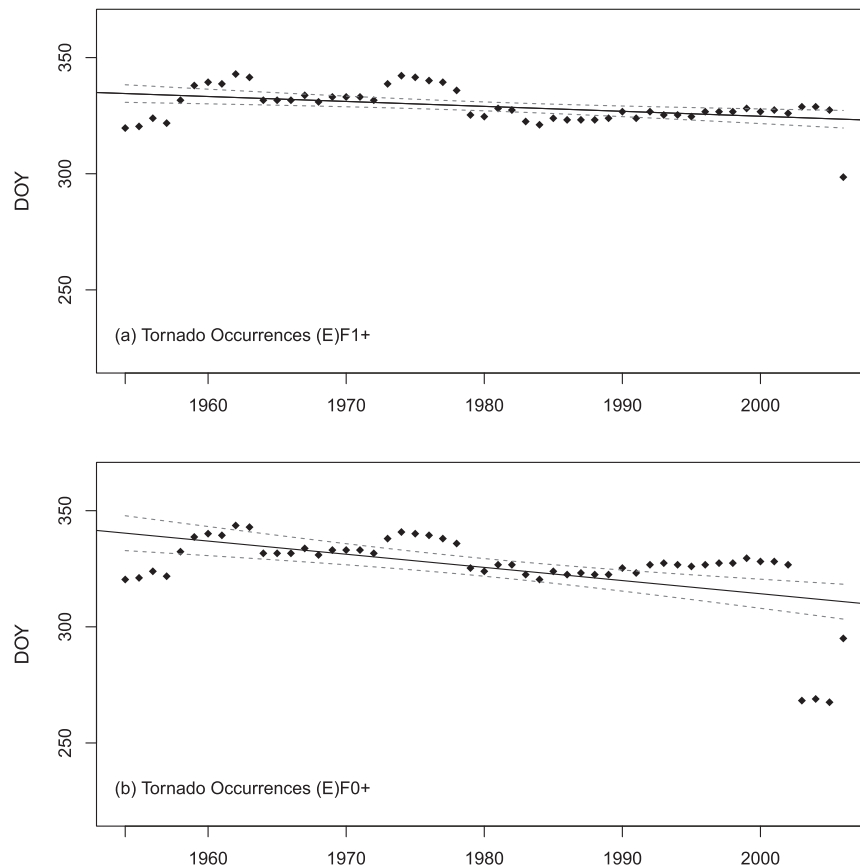


Fig. 7. Regression modeling of the day of year (DOY) corresponding to peak tornado activity, based on tornado occurrences, in the late season using a 10-year moving window for: (a) the (E)F1+ dataset and, (b) the (E)F0+ dataset. The horizontal axis (Year) is based on the first year of each decadal window (e.g., 1954 corresponds to the 1954–1963 window). The regression line and 95% confidence bands (dotted) are shown.

3.4. The impact of tropical cyclones on tornadogenesis

A total of 50 tropical cyclones passed through the study region (Fig. 12) between 1954 and 2015. The majority of these storms made landfall on the US Gulf Coast during August or September, which aligns closely with the North Atlantic hurricane season. These cyclones were likely associated with 141 tornadoes based on a 750 km distance buffer. Results showed that during August and September, the months of minimal tornado activity, tornadogenesis from tropical cyclones was likely the dominant factor in tornado occurrences in the southeastern United States. Tornado activity associated with tropical cyclones showed substantial variation on a decadal basis with clear maxima during 1976–1985 and 1996–2005, while other decades exhibited fewer tornadoes in August and September (Fig. 13). Eliminating tornadoes associated with tropical cyclone activity from the analysis had no effect on the DOY for peak tornado activity, nor indicated any changes in seasonality, for either the early or the late season.

4. Discussion and conclusion

Tornado seasonality in the southeastern United States is bimodal with two periods of elevated tornado occurrences, one in the spring and one in the fall/early winter. Tornado activity is more pronounced in the spring, which has approximately 72% of total activity, regardless of whether we consider tornado frequency or tornado days. This relationship between spring (early-season) and fall (late-season) tornado activity is robust with respect to tornado intensity as the inclusion of the weak (E)F0 events had no effect on the proportions. The density plots suggest that tornadoes are

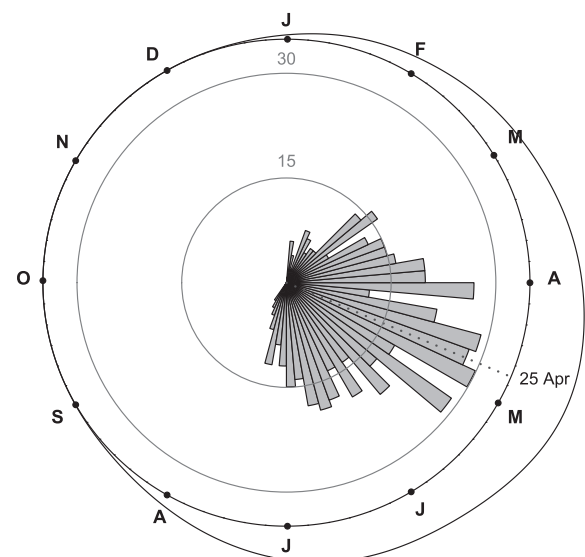


Fig. 8. Rose plot (circular histogram) with superimposed circular density plot for (E)F1+ activity, based on tornado days, in the early season (6 January to 31 July) in the southeastern United States. The plot uses a bin width of 5 days and is averaged over 1954–2015. Peak, or maximum, tornado activity occurred on 25 April. January is at the top of the circle and the months proceed clockwise around the circle. The dotted line identifies the date corresponding to maximum circular density, which is also indicated by the date in the plot. The concentric rings are labeled according to frequency and are equivalent to the y-axis in a traditional histogram.

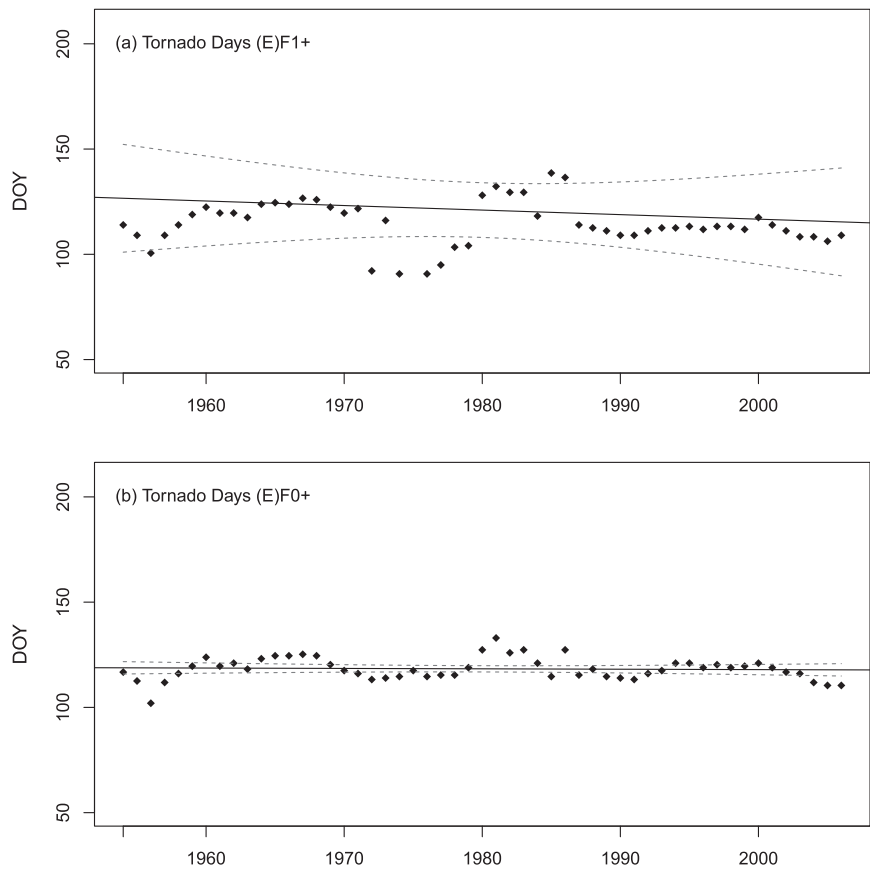


Fig. 9. Regression modeling of the day of year (DOY) corresponding to peak tornado activity, based on tornado days, in the early season using a 10-year moving window for: (a) the (E)F1+ dataset and, (b) the (E)F0+ dataset. The horizontal axis (Year) is based on the first year of each decadal window (e.g., 1954 corresponds to the 1954–1963 window). The regression line and 95% confidence bands (dotted) are shown.

possible throughout most of the year; however, summer (July through September) is the only time of the year in which tornadoes in the southeastern United States are infrequent (Fig. 3). Early August represents the center of the low-frequency period. The winter minimum is slightly more difficult to identify since it represents a *relative* minimum characterized by a broad trough.

The presence of two periods of elevated tornado activity would suggest that there are two times of the year in which the conditions are more conducive to tornadogenesis. Our results for peak activity closely mirror those of Smith et al. (2012), who found that the total number of tornado

Table 4

Changes in the day of year for peak tornado activity during 1954–2015 using a 10-year moving average window as determined by linear regression with tornado days as the response variable.

	Slope ^a (days/time unit)	Standard Error (days/time unit)	p-value	Change (days) ^b
Early Season				
(E)F1+	−0.216	0.423	0.612	−11.4
(E)F0+	−0.019	0.048	0.702	−1.0
Late Season				
(E)F1+	0.186	0.133	0.17	+9.9
(E)F0+	−0.291	0.101	<0.01	−15

^a Positive slopes indicates a shift to later in the year and negative slopes indicate a shift to earlier in the year. The number of days shifted is found by multiplying the slope coefficient by the number of time units (53 for the moving window approach).

^b Negative values represent shifts earlier in the year, while positive values indicate shifts later in the year.

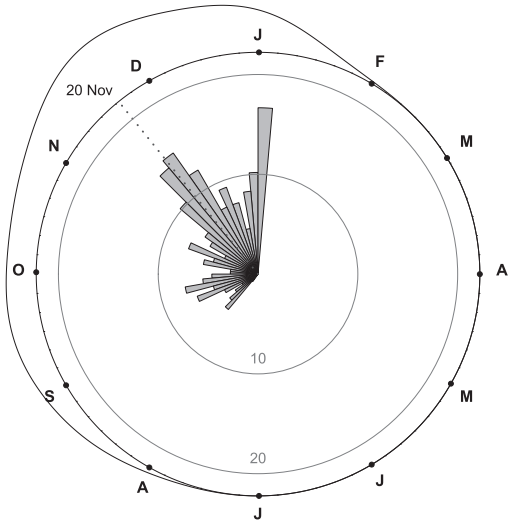


Fig. 10. Rose plot (circular histogram) with superimposed circular density plot for tornado activity, based on tornado days, in the late season (1 August to 5 January) in the southeastern United States. Peak, or maximum, tornado activity occurred on 20 November. The plot uses a bin width of 5 days and is averaged over 1954–2015. January is at the top of the circle and the months proceed clockwise around the circle. The dotted line identifies the date corresponding to maximum circular density, which is also indicated by the date in the plot. The concentric rings are labeled according to frequency and are equivalent to the y-axis in a traditional histogram.

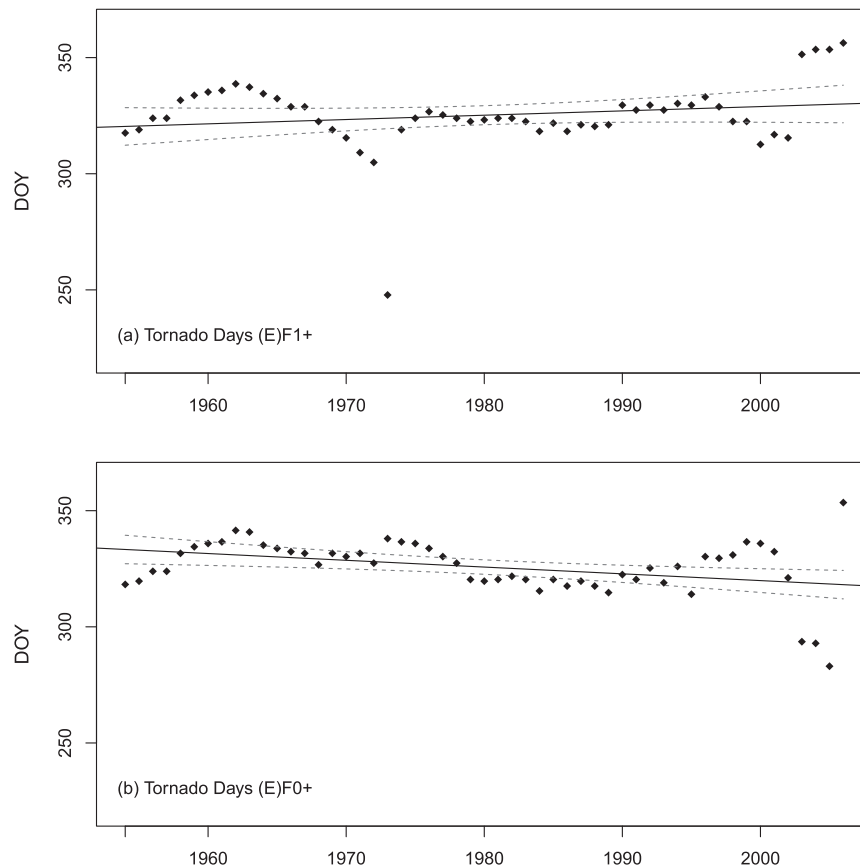


Fig. 11. Regression modeling of the day of year (DOY) corresponding to peak tornado activity, based on tornado days, in the late season using a 10-year moving window for: (a) the (E)F1+ dataset and, (b) the (E)F0+ dataset. The horizontal axis (Year) is based on the first year of each decadal window (e.g., 1954 corresponds to the 1954–1963 window). The regression line and 95% confidence bands (dotted) are shown.

events throughout the year varied by convective mode. They indicated that cyclonic supercells, whether discrete, cells in a cluster, or cells in a line, were by far the dominant convective mode for producing tornadoes, and in the spring, approximately 70% of all tornado activity occurs during cluster or discrete supercell convective modes with peak activity in May – we found that 72% of tornado activity was in the spring with peak activity on 26 April. Their early winter peak was in November and was dominated by a line supercell convective mode; we calculated 24 November as the peak of late-season tornado observations. Tornadoes generated by quasi-linear convective systems or disorganized systems were not particularly prevalent during either season (Smith et al., 2012).

The number of tornadoes spawned by tropical storms was low relative to all tornadoes and occurred primarily in August and September, when tornado activity in the region is at the annual minimum. The contribution of tropical storms to peak tornado activity was, therefore, minimal and had no effect on the conclusions regarding changes in seasonality.

The early season (6 January–31 July) is somewhat left skewed and has a two to three month build-up period prior to the peak, but then falls off more abruptly (Fig. 2). The DOY corresponding to maximum tornado activity in the early season (26 April) was largely immune to: (1) whether or not (E)F0 tornadoes are included in the analysis, or (2) whether we consider tornado activity in terms of tornado occurrences or tornado days; as there was only a two-day difference among these options (Table 2). The late season is shorter and more symmetric than the early season. The DOY corresponding to maximum activity in the late season (24 November) was also robust to the inclusion of the (E)F0 tornado events, and to whether we looked at tornado occurrences or tornado days; there was a four-day difference among the options (Table 2). These

findings suggest that peak tornado activity for each season is stable and not appreciably affected by the inclusion/exclusion of the weak (E)F0 tornadoes; therefore, the non-stationarity noted with weak tornado events does not affect the timing of maximum tornado activity. These findings also suggest that there is no discernable difference in the use of tornado frequency or tornado days, which indicates that the timing of maximum tornado activity is not appreciably affected by tornado outbreaks.

Regression modeling indicated slight differences in the DOY corresponding to maximum tornado activity in the early season from the 1950s to the 2010s. Using tornado frequency as the response variable, the modeling indicated a 3–4 day shift later in the year depending on whether (E)F0 events were or were not included (Table 3). On the other hand, the use of tornado days as the response variable showed an 11-day shift earlier in the year for the (E)F1+ dataset, but only a one-day shift earlier for the (E)F0+ dataset. The 13-day difference between the (E)F1+ and the (E)F0+ datasets using tornado days is likely reflecting the influence of spring tornado outbreaks. None of the shifts for the early season represented statistically significant changes (Tables 3 and 4); therefore, we conclude that there has been no discernable change in tornado seasonality for the early season.

The late season is more complicated. Regression modeling using tornado frequency suggests an 11-day or 30-day shift earlier in the year from the 1950s to the 2010s for the (E)F1+ and (E)F0+ datasets respectively (Table 3), both statistically significant changes. Clearly, the inclusion of the (E)F0 events has an effect on the timing of maximum tornado activity for the late season as determined by tornado frequency. The reported shift is based on the full time frame; however, there are

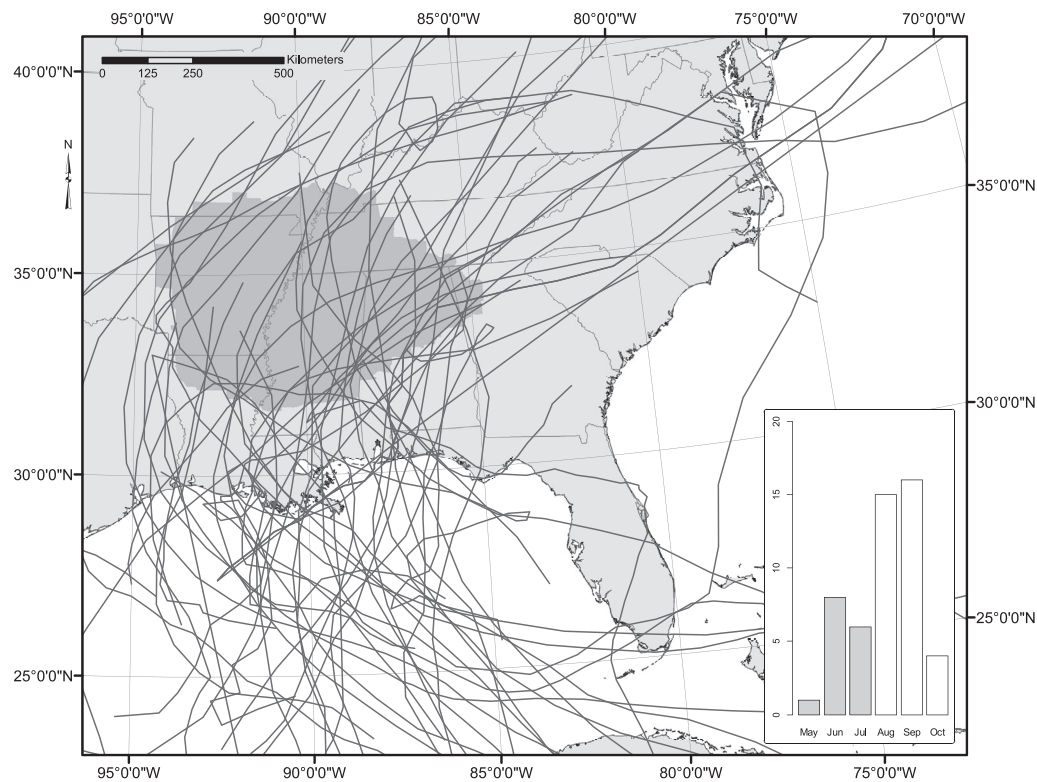


Fig. 12. Tropical cyclone paths intersecting the study area between 1954 and 2015 (IBTrACS data). The bar plot indicates the number of tropical cyclones by month.

three important sub-patterns within the late-season regression that merit consideration. Firstly, there are two periods of late-year activity in the mid-1960s and the mid-1970s, which seem to initiate the trend toward earlier in the year. Secondly, the data suggest that since the early 1980s, the trend is neutral or perhaps towards slightly *later* in the year. Finally, there are outbreaks of (E)F0 tornadoes early in the late-season for the

later part of the time series – note the low outliers in Fig. 7b. Consequently, we urge caution here because it is possible that these changes result from a few years with a comparatively large number of tornadoes late in the season during the early 1960s and mid 1970s coupled with an unusually large number of weak tornadoes in the early part of the season since 2003.

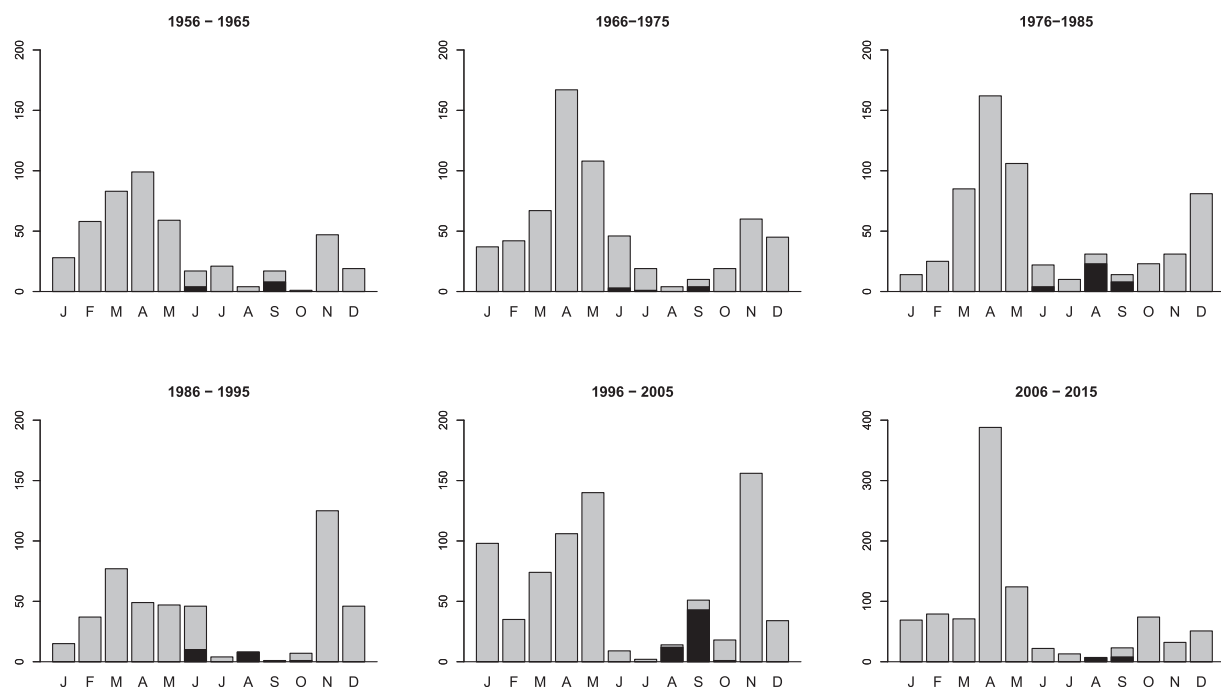


Fig. 13. Superimposed bar plots of tornado counts for representative decades (a) 1956–1965; (b) 1966–1975; (c) 1976–1985; (d) 1986–1995; (e) 1996–2005; and (f) 2006–2015. All tornadoes are in gray, whereas tornadoes generated near tropical cyclone paths are in the foreground and are black. Note that there is a change of scale for the 2006–2015 data.

Regression modeling using tornado days for the late-season gives contradictory trends. The (E)F1+ dataset indicated a 10-day shift later in the year, which was not statistically significant; however, the (E)F0+ dataset indicated a statistically significant, 15-day shift *earlier* in the year. As seen with tornado frequency, sub-patterns are apparent, particularly a change in slope around the early 1980s to a more shallow one, which would suggest little change in seasonality since the 1980s. These contradictory conclusions make it difficult to claim that an actual shift exists for the late season. The cause of any shifts in seasonality for the late season peak is unclear. If shifts in seasonality were related to a warming climate, we would expect the late-season shift to be in the direction of later in the year, as we see with the (E)F1+ dataset. Shifts earlier in the year, as suggested by the (E)F0+ dataset, might reflect mean annual temperature fluctuations, i.e., years with warmer than normal summer months and colder than average winters, since it has suggested that tornadoes are more likely in colder than average winters and less likely in warmer than average summers (Brooks et al., 2014b).

The observations make for an interesting contrast against those from the south-central Great Plains, where peak tornado likelihood has progressed earlier in the year over the same time frame by 1–2 weeks depending on location and methodology (Long and Stoy, 2014; Lu et al., 2015). Interpreting the meteorological conditions that led to the formation of 5458 tornado events (Table 1) exceeds the scope of this study, but an implication of our findings is that the mechanisms that cause tornado formation are occurring at an early time in the calendar year in the Great Plains but not the southeastern U.S. Data scarcity in the earlier years of the observation period makes the causes of these trends (and lack of trends) difficult to attribute, and future research should investigate potential trends or lack thereof in the environmental variables that are related to tornado formation to better understand patterns in tornado occurrence in both the Great Plains and the southeastern United States in order to understand why shifts in peak tornado density are apparent in some regions but not others.

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