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Expanding the historical "outbreak" climatology between 1880 and 1989

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Abstract

Tornado outbreak climatology is constantly evolving. Modern research highlights the current trends in tornado outbreak activity using the Storm Prediction Center's tornado database, which dates back to 1950. Here, digitized tornado records over the period of 1880–1989 are used to create a historical climatology of tornado outbreaks. Four hundred and sixty-two unique clusters are identified encompassing more than 4500 tornadoes. The spatial distribution of these clusters follows an L-shaped pattern, with tornadoes extending from Iowa to Oklahoma to Georgia consistent with modern tornado outbreak climatology. The historical tornado clusters show significant upward trends in the total number of clusters, tornadoes, and casualties by decade. Additionally, tornado clusters show similar upward trends seasonally and diurnally. Most clusters occur in March, April, and May and start in the early afternoon hours. The results within this manuscript are consistent with current trends detected in the modern tornado record. Future research will look to combine historical and modern tornado records to develop a more complete climatology of clusters since 1880.

Keywords Tornadoes · Clusters · Historical Outbreaks · Climatology

1 Introduction

A tornado is not a rare event in the USA. Over 100 days, each year will have at least one tornado although they often occur in clusters (Elsner et al. 2015). Many researchers evaluate clusters to identify climatological patterns that are occurring to better forecast the occurrence of these hazardous events. For example, the current research indicates that the number of days with a cluster of tornadoes is decreasing on average; however, the total number of tornadoes produced per cluster is increasing annually (Elsner et al. 2015; Tippett et al. 2016; Moore 2017a; Tippett and Cohen 2016; Moore 2017b; Moore and DeBoer 2019)). The greater frequency of favorable tornado environments and increasing accumulated tornado power (ATP) contribute to the greater intensity of tornado clusters over time

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(Schroder and Elsner 2021; Elsner et al. 2015; Tippett et al. 2016; Moore 2017a; Tippett and Cohen 2016; Moore 2018; Elsner et al. 2018b; Moore and DeBoer 2019; Schroder and Elsner 2019)). Tornado clusters are known to have a greater probability of producing casualties relative to individual tornadoes (Anderson-Frey et al. 2018; Fuhrmann et al. 2014). Fuhrmann et al. (2014) highlight the strong relationship between cluster strength and the total number of fatalities. Following this, Elsner et al. (2018a) suggest that increased energy dissipation results in increased casualties in densely populated areas. The threat for casualties varies based on a number of factors including demographic variables, time of day, geographic location, environmental factors, time of year, and convective mode of the storm (Kelly et al. 1978; Fricker et al. 2017; Fricker 2019).

The climatology of tornado clusters varies across space and time. Historical tornado clusters occur east of the Rocky Mountains. The greatest risk for tornado clusters is in the lower Mississippi River valley where they occur most frequently. The peak location for cluster activity is currently shifting eastward toward the area of maximum tornado activity (Moore 2021). Additionally, Galway (1977) found the peak tornado season to occur during March, April, and May in the late 1800s. The peak season for tornado occurrence is currently shifting to later in the year with the maximum number of tornadoes occurring in April, May, and June (Galway 1977; Kelly et al. 1978; Trapp 2014; Gensini and Ashley 2011; Moore 2021).

The current climatology of tornado clusters is centered on the use of the Storm Prediction Center's historical tornado database. This data set, however, only extends to 1950, which limits any deep understanding of tornado clusters occurring prior to this time. Recently, Fricker et al. (2022) provide additional data through the digitization of reports from John Park Finley (Finley 1882) and Thomas Grazulis (Grazulis 1990b, a) over the period of 1880–1989. Through the application of geocoding, they provide a spatial data set of all significant—F2 or greater—and killer—producing at least one fatality—tornadoes known as the Significant Tornado GIS data set (STORGIS).

In response, here, we develop a historical tornado cluster climatology using the STORGIS with the goal of creating a better understanding of tornado clusters dating back to the late nineteenth century. The objective is to identify patterns within the clusters that could enhance the current understanding of cluster climatology. The manuscript is outlined as follows. The data are outlined in Sect. 2. The methodology developed in Schroder and Elsner (2019) to cluster tornadoes based on space and time is outlined in Sect. 3. The climatology of the historical tornado clusters including spatial and temporal trends is outlined in Sect. 4. A case study of the most catastrophic cluster in the data is conducted in Sect. 5. The conclusions and future applications of this climatology are highlighted in Sect. 6.

2 Historical tornado reports

2.1 Digitization of the significant tornado record

The Significant Tornado GIS data set (STORGIS) was created through the digitization of state-level tables found in Grazulis (1990b) using ABBYYY FineReader PDF software. Each tornado track was then geocoded using the associated event narrative through the process described in Fricker et al. (2022). Attribute data from the STORGIS exists in a similar structure to the current Storm Prediction Center's Severe Weather GIS data set (SVRGIS) (https://www.spc.noaa.gov/gis/svrgis/) and includes information, if available, on the spatial path of the tornado (initiation point and end point), date, time, length and width of the damage path, maximum damage rating from 1 to 5—as determined by Grazulis (1990b)—injuries, fatalities, and impacted counties. Local times were converted to Central Standard Time (CST), and all spatial data are given in latitude and longitude coordinates. The data set covers all significant and killer tornadoes (F1 or greater) over the period of 1880–1989.

2.2 Data cleansing

Once digitized, tornado records were evaluated for alphanumeric errors and other tabulation issues. For example, if a tornado report had a path length of "f50", which stands for a *family* of tornadoes with a path length of 50 miles, we removed the "f" and tabulated a path length of 50 miles—before conversion to meters. Similarly, if a tornado report had a path length of "s25", which stands for a tornado that *skipped* with a path length of 25 miles, we removed the "s" and tabulated a path length of 25 miles—before conversion to meters. Of particular importance for this work is information on spatial location and time. Location is defined as the initial point of a tornado record, given in latitude and longitude coordinates, and time is defined in Central Standard Time. The geographic coordinates for each tornado were converted to Lambert conic conformal coordinates with the projection centered on 96° W longitude. All tornado reports without a time stamp were removed, and only those tornadoes considered significant were considered. In total, there were 12,010 significant—F2 or greater—and killer—producing at least one fatality—tornadoes in the STORGIS over the study period.

3 Historical tornado clusters

3.1 Large groups

To link the tornadoes into their respective groups, we calculate the space–time distance between each tornado pair. A space–time distance is the sum of the spatial distance (in meters) and the time distance (in seconds) between each of the genesis locations for each tornado in the data set. We divide the spatial distance by 15 m s^{-1} to account for the average speed of tornado-producing storms consistent with Schroder and Elsner (2019). We select 15 m s^{-1} because it is commensurate with the magnitude of the wind field at the steering level. We add the space and time distances together resulting in a single space–time distance for each unique tornado pair. Next, a tornado receives a group identification number (ID) based on the space–time distances. Two tornadoes receive the same ID if they occur close together in both space and time. The clustering ends for a unique ID once it surpasses 50,000 s (roughly 14 h) from any other tornado in the group. For example, three tornadoes each 50,000 s apart are considered a group. A fourth tornado is considered in the group if it is no more than 50,000 s from *any* one of the other three tornadoes. Additional detail on the clustering methodology is available in Schroder and Elsner (2019).

This algorithm results in 4,531 unique groups composed of F2 or higher-rated tornadoes. The duration of the groups ranges from 4,186 groups on a single day (12 AM to 12 AM) to three groups occurring over the course of 4 days (Table 1). The largest group, by number of tornadoes, occurred from April 3, 1974, to April 4, 1974. This group produced 94 tornadoes spanning much of the eastern US resulting in 5,694 casualties. The

Table 1 The total number of large groups and tornadoes by duration

Duration (days)	Number of groups	Number of tornadoes
1	4186	8998
2	324	2606
3	18	317
4	3	89

longest group in the data occurred between April 22, 1908, and April 25, 1908. This group produced 32 tornadoes spanning much of the south central US resulting in 2,520 casualties.

3.2 Clusters

For this work, the focus is on the most prolific clusters within the data set. Therefore, the data narrows to focus on clusters with at least 6 tornadoes occurring over the same convective day (24-h period beginning at 0600 AM). A selection of 6 or more tornadoes is consistent with Tippett et al. (2016) who define an outbreak as six or more EF1+ tornadoes. In total, there are 462 clusters in this data with 4,514 tornadoes, accounting for 38% of all tornadoes in the STORGIS. Interestingly, there are no days with more than a single cluster in this data set.

An example of a cluster as defined above can be seen in Fig. 1. On March 27, 1882, 14 tornadoes impacted Alabama and Georgia. These tornadoes included ten F2 and four F3 tornadoes. This cluster occurred over 15 h and resulted in 222 casualties. The top two clusters in the data are April 3, 1974, and April 11, 1965 (Fig. 2). The cluster responsible for the most loss of life occurred on April 3, 1974, and produced 5,694 casualties (305 were fatalities and 5,389 were injuries). This cluster produced 93 tornadoes extending over much of the eastern US (Fig. 2).

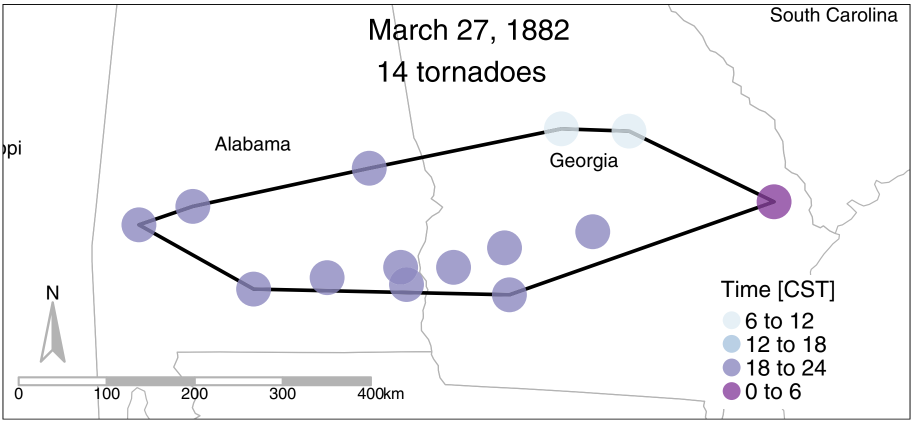

Fig. 1 March 27 is an example of a big day within the data. Each point represents a genesis location and is colored by the hour it occurred. The black line is the minimum convex polygon around the genesis locations (convex hull)

Table 2 Top ten clusters with at least 6 tornadoes rated F2 or higher

Clusters (6+ tornadoes)	Number of Tornadoes	Maximum Fujita Rating	Number of Casualties
April 3, 1974	93	F5	5694
April 11, 1965	37	F5	3698
February 19, 1884	37	F4	1221
March 21, 1932	35	F4	2477
June 5, 1916	34	F4	848
May 20, 1949	31	F4	69
March 28, 1920	30	F4	1056
March 30, 1938	26	F4	578
March 16, 1942	25	F5	1431
April 29, 1909	25	F4	757

4 Climatology of historical clusters

Historical clusters enhance the understanding of cluster variability across the USA over time. From 1880–1989, a total of 462 clusters with at least six tornadoes are identified within the data set. The average number of tornadoes per cluster is 9.8 with a median of 8 tornadoes. The values range from 128 clusters with 6 tornadoes to one cluster with 93 tornadoes. Over the same period, the average number of casualties per cluster is 218 with a median of 84 casualties. The values range from three clusters with no casualties to one cluster with 5,694 casualties.

4.1 Spatial variability

In the USA, tornado clusters occur east of the Rockies and west of the Appalachian mountains (Galway 1977; Dean 2010; Kelly et al. 1978). The historical clusters follow the same pattern with clusters spanning the middle South and extending northwestward toward the Central Great Plains. The location of the historical clusters follows the general L-shaped pattern of tornado activity from Iowa to Oklahoma to Georgia identified in the literature (Gagan et al. 2010; Concannon et al. 2000; Coleman and Dixon 2014). The densest areas of cluster activity are located in Oklahoma, Arkansas, Mississippi, and Alabama.

The historical cluster centroids highlight the tendency for larger and more deadly clusters to occur farther east than the traditional Great Plains (Fig. 2). Using the historical tornado clusters, we find that 51 clusters have at least 15 tornadoes and 50 clusters have more than 500 casualties. The majority of these devastating clusters occur east of the Great Plains region of the USA (Fig. 2). This finding is consistent with Anderson-Frey et al. (2018) who notes that the southeast receives more tornado clusters than the Great Plains, Midwest, or Northern Plains on average. Additionally, research shows that the southeast is more susceptible to highly rated (Fujita Scale), long-track, killer tornadoes that occur most frequently in tornado clusters (Fuhrmann et al. 2014).

The spatial distribution of historical tornado clusters shifts throughout the year (Fig. 3). The spatial shift in activity throughout the year follows the seasonal propagation of the jet stream (Cheng et al. 2015). This results in various peaks in cluster activity throughout the year. In the lower Great Plains, historical tornado clusters are most common in April, May,

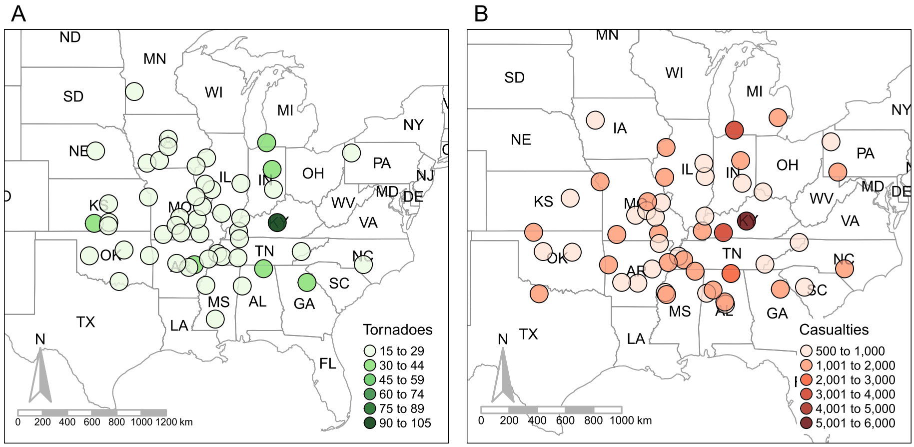

Fig. 2 Maps of the total clusters with more than 15 tornadoes (**A**) and 500 casualties (**B**). Each point is the centroid of the cluster. The colors denote increasing magnitude of the event with the darkest colors representing the most tornadoes (**A**) and casualties (**B**)

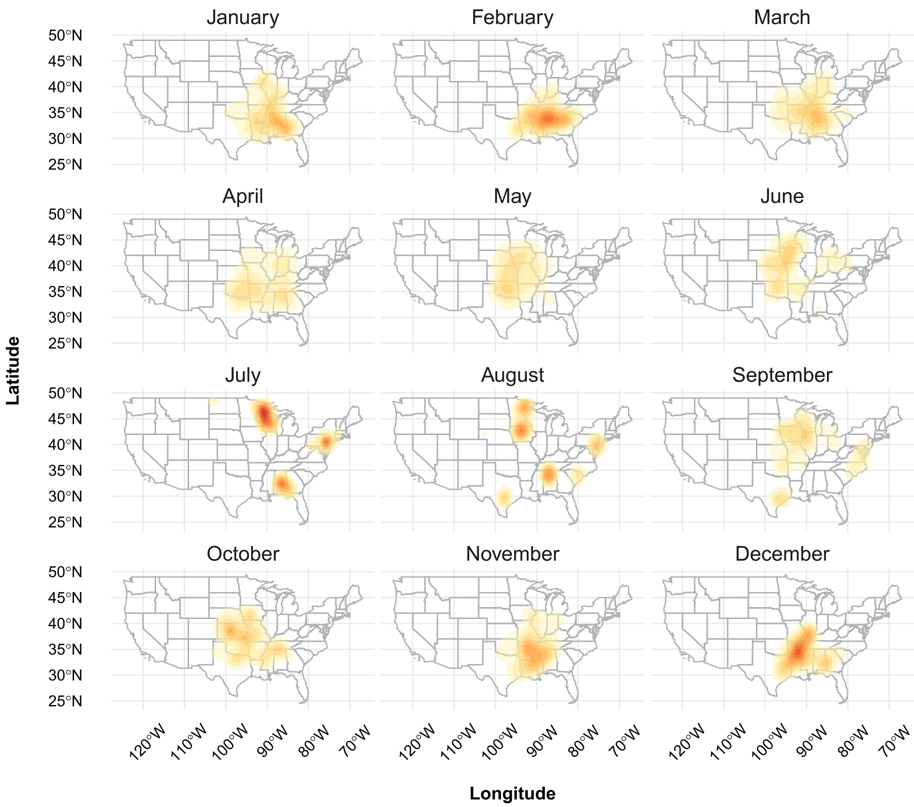

Fig. 3 The monthly distribution of tornado clusters in the contiguous United States. Red colors indicate a higher density of clusters in the area

and June when the jet stream does not extend much into the southern United States. In the Midwest, historical tornado clusters are most common in May, June, July, and August. In the southeast, historical tornado clusters are most common from October to May when the jet stream extends into the southern United States.

4.2 Temporal variability

Clusters have an extensive temporal variability. Clusters are known to vary on decadal, annual, seasonal, and daily time scales. We group the clusters by decade to detect trends in the total clusters and tornadoes. We conduct a Wilcoxon rank sum test on the nonparametric cluster data to test the significance of trends in tornado cluster characteristics over time. Table 3 shows a significant upward trend in the total number of clusters (p-value: < 0.001), the number of tornadoes (p-value: < 0.001), and total casualties (p-value: < 0.001). The decade with the most clusters is 1960 with 69 total clusters. Overall, there are a total of 677 tornadoes with 10, 438 casualties occurring between 1960 and 1969. The decade with the most casualties was 1920 with a total of 15,013 casualties resulting from 41 clusters that produced 438 tornadoes.

Tornado clusters are changing annually. On average, the frequency of historical clusters is not significantly changing, but the total number of tornadoes within the cluster is on the rise (Fig. 4). The average number of tornadoes per cluster annually is 44. Sixty years are below the annual average of tornadoes in a cluster. Forty years are above the annual average of tornadoes in a cluster. The majority of the above average years occur since 1950. This could be the result of undercounting of tornadoes in the early part of the historical record. Over time, technological and education advances led to higher reporting rates, which could be influencing this result. However, this result is consistent with research from the modern record that highlights the decline in total tornado days per year and an increase in the annual number of tornadoes per cluster (Elsner et al. 2015; Brooks et al. 2014; Tippett et al. 2016; Moore 2017a; Tippett and Cohen 2016; Moore 2017b; Moore and DeBoer 2019). More work is needed to understand the relationship between the impacts of climate change on tornado frequency.

Historical tornado clusters have unique seasonal and diurnal trends. Galway (1977) noted that the peak tornado season occurred during March, April, and May. The historical

Table 3 Clusters by decade

Decade	Number of clusters	Number of tornadoes	Number of casualties	Tornado density
1880	21	231	5415	4.55
1890	18	183	3387	3.90
1900	20	163	4002	4.33
1910	27	258	8133	5.84
1920	41	438	15,013	8.87
1930	48	475	11,427	10.4
1940	50	449	9719	10.8
1950	49	472	9731	10.6
1960	69	677	10,438	14.9
1970	38	433	13,588	8.23
1980	66	618	8748	14.3

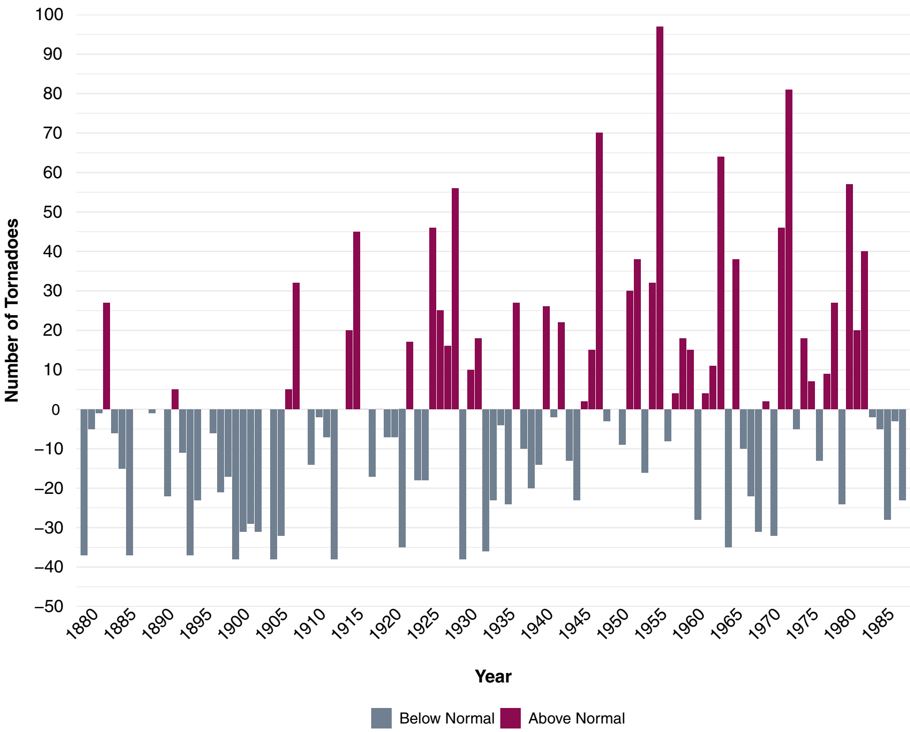

Fig. 4 Trends in the total number of tornadoes in clusters annually. The average number of tornadoes per cluster annually is 44 tornadoes. Gray bars indicate the number of tornadoes above the normalized average. Maroon bars indicate the number of tornadoes below the normalized average

tornado clusters in this analysis follow this pattern with the majority of cluster-producing tornadoes occurring in March, April, and May (Fig. 5). Historical tornado clusters are common in the southeast during the winter months and have more nocturnal tornadoes on average (Galway and Pearson 1981). The majority of historical clusters produce the most tornadoes between 12 PM and 4 PM (Fig. 5). The majority of historical clusters with a F5 tornado rating occur in the afternoon hours consistent with other work (Gagan et al. 2010).

5 Outbreak of the century

The "Outbreak of the Century" occurred on April 3, 1974, (Corfidi and Weiss 1974). In total, 94 tornadoes rated F2 or higher occurred within 15 h (Fig. 6). Twenty-eight tornadoes were rated F2 with winds estimated between 118 and 161 mph. Thirty-six tornadoes were rated F3 with winds estimated between 162 and 209 mph. Twenty-three tornadoes were rated F4 with winds estimated between 210 and 261 mph. Six tornadoes were rated F5 with winds estimated between 262 and 317 mph.

The cluster affected over 572,000 km^2 and caused more than 50 million dollars of damage across much of the eastern United States. Tornadoes were reported in 13 states extending from Mississippi to Wisconsin and Illinois to Virginia (Galway 1981). Overall, this day resulted in roughly 300 fatalities and over 5,694 casualties. The majority of fatalities

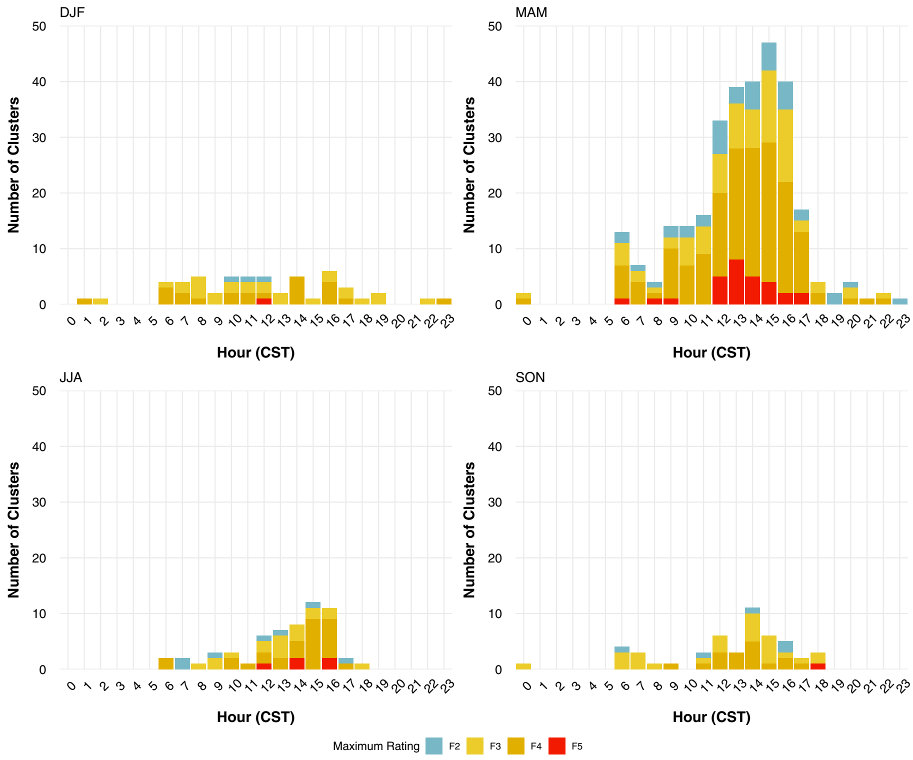

Fig. 5 The seasonal variation in initiation time for clusters

occurred in Alabama and Kentucky (Galway 1981). In total, ten states were declared federal disaster areas as a result (Corfidi and Weiss 1974).

6 Discussion and conclusions

Tornado outbreaks frequently occur throughout the USA. They are responsible for catastrophic damage and enhanced loss of life and property. April 3, 1974, was reasonably declared the Outbreak of the Century due to 94 tornadoes producing 50 million dollars in damage and over 5000 casualties.

Tornado outbreak climatology is well-developed for the modern record. Current climatologies are built on the use of the Storm Prediction Center's extensive tornado data set, which extends back to 1950. However, there is documentation of tornado reports prior to 1950 that are not included in the modern record. This research focuses on examining tornadoes that occurred between 1880 and 1989. Overall, 462 tornado clusters were identified over the 110-year period resulting in more than 4500 tornadoes.

The spatial variation of the historical clusters follows an L-shaped pattern with the majority of tornadoes occurring from Iowa to Oklahoma to Georgia. However, there is a tendency for larger more deadly clusters to occur farther east than the traditional Great Plains. This is consistent with the modern record and highlights that this pattern in tornado

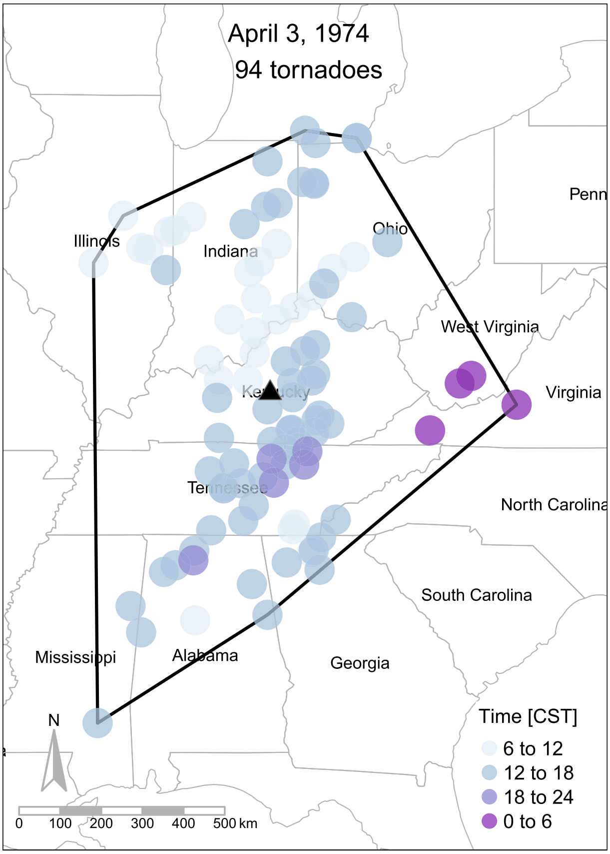

Fig. 6 The Outbreak of the Century. The cluster on April 3, 1974, resulted in 94 tornadoes produced over a 24-h convective day. Each dot is a tornado genesis location and colored by the local time in which it occurred

activity dates back to the 1800s. This work shows that clusters have likely always been more frequent east of the Great Plains. It is important to note that the eastward shift could be the result of the increased number of tornadoes and reports annually, which leads to an increase in the relative density of tornadoes in the area. Additionally, this could be a result of annual changes to the environmental conditions conducive to tornadogenesis, such as the significant tornado parameter, storm relative helicity, convective available potential energy, and wind shear (Gensini and Brooks 2018; Tippett et al. 2016; Lu et al. 2015; Elsner et al. 2018b; Moore et al. 2021; Schroder 2021; Taszarek et al. 2021). Additional research would need to identify the relationship between these trends and possible links to climate change.

The seasonal variation of the historical tornado clusters highlights the peak occurrence of clusters in March, April, and May relative to our current peak in April, May, and June for our modern record. Each season has a maximum area of tornado activity (Fig. 3). December, January, and February has peak activity in the southeast, while March, April, and May have a peak in the Great Plains, June, July, and August have a peak in the Midwest, and September, October, and November have a peak in the southeast. The seasonal spatial variations shown above are consistent with the current documented seasonal occurrence of tornado clusters in the USA (Moore 2017a, 2019; Elsner et al. 2018b; Schroder and Elsner 2019; Tippett et al. 2016; Gensini and Brooks 2018; Moore and Fricker 2020), often associated with the propagation of the jet stream (Cheng et al. 2015).

The temporal variation of these clusters follows similar patterns to the current record. Since 1880, clusters have significantly increased in frequency and size. Elsner et al. (2015) find an increase in the number of days with many tornadoes and increased tornado density. These trends are consistently attributed to changes in the local-scale thermodynamics (Elsner et al. 2015; DelGenio et al. 2007; Trapp et al. 2007; Diffenbaugh et al. 2013). While more research is needed on the local thermodynamics of the historical tornado clusters, our findings further support changing tornado behavior through an increased efficiency of the atmosphere with higher numbers of tornado clusters and tornado density over time.

Historical clusters provide important information about spatial and temporal variations over time. Currently, researchers are identifying trends in tornado climatology. This research supports the current understanding of tornado climatology as it indicates similar trends with historical clusters. Future research will combine the historical and modern records to develop a full view climatology of tornado clusters from 1880 to present. This will allow researchers to determine the significance of changes to tornado climatology dating back to the 1800s. Additionally, this would provide an extended data set that could be used to understand the role of climate change on tornado clusters.

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Code availability All code used in this research was developed using the open-sourced program, R. Graphics were made with the `ggplot2` (Wickham 2017) and `tmap` (Tennekes 2017) framework. The code for this research is available on GitHub (https://github.com/zschroder/HistoricalTornadoes) and the STORGIS data set is available from the second author, TF, upon reasonable request.

Declarations

Conflict of Interest There is no relevant financial or non-financial interests to disclose.

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