A Geographic Information Systems–Based Analysis of Supercells across Oklahoma from 1994 to 2003

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ABSTRACT

Oklahoma is a region that is well known for its high frequency of severe thunderstorms, which vary in activity, mode, and coverage. In particular, this region experiences a significant number of highly organized supercell thunderstorms that pose hazards such as high winds, large hail, and tornadoes. This demonstration study focuses on the development and analysis of a 10-yr sample of supercell storms resulting from organized severe weather events in Oklahoma. Geographic information systems (GIS) were used as the primary tool to develop and analyze the 10-yr supercell dataset. The use of GIS technologies within the field of meteorology has increased dramatically in recent years and will likely continue as additional atmospheric science data formats become available in popular GIS software packages such as the Environmental Systems Research Institute’s ArcGIS series. For this specific study, GIS served as a critical component for developing individual georeferenced storm features and analyzing the life span and characteristics of 943 supercell thunderstorms. The results of a series of spatial storm frequency, initiation, termination, and direction analyses are presented. Results revealed that for the period spanning 1994–2003 supercell storms resulting from organized severe weather events were most frequent across several regions, including east-central Oklahoma, southwest Oklahoma, and west-central through northeast Oklahoma, with an overall mean track from the southwest to northeast. Supercell tracks were predominantly southwesterly during the first 5 months of the year, northwesterly from June through September, and once again southwesterly from October through the end of the year. A final set of analyses and examples illustrate the utility of storm feature–based climatologies.

1. Introduction

Severe local storms and their associated hazards of tornadoes, large hail, and strong winds are common features across Oklahoma. Studies of multiyear periods of tornado (Kelly et al. 1978; Brooks et al. 2003) and nontornadic (Kelly et al. 1985; Doswell et al. 2005) report data repeatedly illustrate the high frequency and probability of storm-related hazards across Oklahoma during the months of April through June. While the general seasonal characteristics of storm reports have been studied, less emphasis has been placed on the parent storm and mode responsible for producing the severe weather. Specific storm-mode climatologies are sparse and have been mainly confined to less numerous mesoscale systems, such as derechos and bow echoes (Johns 1982; Bentley and Mote 1998; Burke and Schultz 2004; Coniglio and Stensrud 2004). Very few climatologies have focused on supercell thunderstorms, and in most cases, supercell studies are limited to the identification of specific types, such as high-wind-producing supercells (Klimowski et al. 2003), the identification of mesocyclones via radar algorithms (Wood et al. 1996; McGrath 2003), or the identification of observational differences in supercell structures (Moller et al. 1994).

Much of the understanding of the spatial and temporal trends of severe storms across the United States has resulted from various analyses of the National Weather Service storm reports that are contained in the National Oceanic and Atmospheric Administration publication Storm Data. However, research focused on storm reports has revealed inconsistencies in storm-reporting policies (Galway 1989), significant increases in low-end
nontornadic reports (Weiss and Vescio 1998; Brooks 2000), and high biases in populated regions (King 1997). Even so, Storm Data remains one of the few severe storm databases available. To address such issues, recent spatial climatologies of storms such as Brooks et al. (2003) and Doswell et al. (2005) have applied new probabilistic and smoothing techniques to the severe storm report dataset. However, Brooks et al. (2003) and Doswell et al. (2005) note that certain inherent weaknesses in Storm Data prevent a more coherent depiction of severe storms over time. These shortcomings include the lack of all three report types during tornadic storms, missing reports at the peak of storm severity, or point features misrepresenting the geographic extent of different storm types. In addition, storm reports yield little information concerning critical storm characteristics, such as initiation, track, duration, termination, and type.

The application of geographic information systems (GIS) in meteorological studies has increased in recent years (Yuan and McIntosh 2003, 2004) and has established the technology as a viable means for analyzing large collections of archived weather events. As such, this study was conceived to combine the use of Next Generation Weather Radar (NEXRAD) radar data archives along with GIS technologies to visualize and analyze a decade of storm occurrences in a new and innovative way.

This study was designed as a demonstration project to quantify the spatial and temporal characteristics of supercells that occurred during organized severe weather events across Oklahoma from 1994 to 2003 using radar data and GIS technologies. The first objective focused on developing a GIS database of storms, which required a selection of events using several established criteria and the historical severe weather archives available from the Storm Prediction Center (SPC). This process yielded more than 330 separate severe storm event days over the 10-yr period. Level-II and level-III radar data were acquired for all event days and were analyzed using a simple set of storm classification criteria. Geocoded storm location data were imported into ArcGIS and converted into spatial features. The second objective was to quantify the spatial and temporal patterns of supercells during the 10-yr study over varying time periods. This was accomplished by utilizing GIS queries, spatial analysis tools, and spatial statistics tools. Varying temporal periods, including the total study duration, cumulative months, and specific years, were analyzed to determine the spatial and temporal characteristics of storms. Further, storm reports were imported into GIS for several spatial density comparison analyses.

2. Data and methodology

a. Event selection

While storm report data have served as the main source of analysis for many past storm climatologies (e.g., Kelly et al. 1978, 1985; Brooks et al. 2003; Doswell et al. 2005), it was only used as an initial step for event selection for this study. Using the latest version of SeverePlot (Hart and Janish 1999), two domains were defined across Oklahoma (Fig. 1), and a search was conducted for days with a significant number of storm reports. Organized severe weather event days were defined as any single convective day (1200–1159 UTC) when either (i) the total combined severe storm reports (hail and wind) was greater than or equal to 20 or (ii) any tornado was reported in Oklahoma. The first criterion was similar to a severe weather outbreak requirement used by Johns (1982), while the second criterion captured any event day when any tornado report existed across Oklahoma, irrespective of the number of hail or wind reports (i.e., 8 May 2003; 17 severe reports in Oklahoma). Used in conjunction, the criteria were intended to create a substantial candidate set of potential supercell days resulting primarily from organized yet significant severe weather activity. While several additional supercell days could have existed with fewer storm reports, the inclusion of a significant number of marginal storm event days discouraged the use of more conservative criteria.

b. Monthly and annual severe weather event distributions

The distribution of selected severe weather event days by month illustrates the seasonal variability of organized severe weather across Oklahoma. A total of 332 severe weather event days occurred across Oklahoma during 1994–2003, and all were analyzed for the occurrence of supercell storms. The distribution of events throughout each month is shown in Fig. 2a. The months of April through June mark the most active portion of the year, with a significant decrease in activity beginning in July. While not as evident in the all-event distribution, the tornado event distribution reveals a secondary, less significant maxima of events associated with tornado reports in the fall. On an annual basis, storm event occurrence was quite variable, and ranged from a minimum of 27 events in 1997 and 2000 to a maximum of 46 events in the exceptionally active year of 1999 (Fig. 2b). Further, an average of 33 event days occurred each year from 1994 to 2003, while 19 tornado event days occurred per year for the same period.
c. Data sources

Because of the objective of classifying supercell storm types, it was determined that the use of numerous individual radar site data was the most accurate method to accomplish this task. This differs from several studies that employ the use of composite, merged, or mosaic reflectivity for storm classification (e.g., Parker and Johnson 2000; Burke and Schultz 2004), which is more appropriate for large-scale event tracking, such as mesoscale convective systems, quasi-linear convective systems, or bow echoes.

For storm identification, Weather Surveillance Radar-1988 Doppler (WSR-88D) level-II data were obtained from all sites located near storm report activity for each individual event. Corresponding level-III data were substituted when level-II data were unavailable (approximately 15%–20% of the total storm-tracking points).

d. Supercell storm classification criteria and tracking methodology

The Gibson Ridge level-II radar software package (GRLLevel2) was used to analyze the level-II data ob-

![Figure 1](image1.png)

**Fig. 1.** The domain used to search through the severe storm database, and all WSR-88D radar sites used for storm identification (dark circles).

![Figure 2](image2.png)

**Fig. 2.** (a) Monthly and (b) annual distribution of event days analyzed across Oklahoma from 1994 to 2003 for all event days (white) and all event days associated with a tornado report (black).
tained for the project. The software enabled a very effi-
cient observation of radar reflectivity and velocity
data for all elevation levels for time sequences up to 3 h long. Two- and three-dimensional views of storms were also available for better observation of storm structure. Level-III data for the project were viewed using the National Climatic Data Center (NCDC) Java NEXRAD Viewer software, which contained several overlay features and looping capabilities, as well as a marker editor used for storm-tracking purposes.

The classification of severe convection is rather arbitrary because storms represent a continuous spectrum rather than discrete objects that fit into particular categories (Vasiloff et al. 1986). However, supercells contain a unique kinematic structure (i.e., correlation between updraft and vertical vorticity) that isolates such storms from other forms of convection and allows for distinct classification. While supercells also include a spectrum of storm types, ranging from low-precipitation to (Bluestein and Parks 1983) classic (Browning 1964), high-precipitation (Moller et al. 1990), anticyclonic (Fujita and Grandoso 1968), and miniature (Kennedy et al. 1993) supercells, the occurrence of a mesocyclone collectively places each type within one categorization (Moller et al. 1994).

To establish the necessary criteria for supercell identification, a series of severe weather events were viewed and analyzed using radar data. These benchmark events were comprised of a spectrum of storm event types that included marginal severe storm events, cold core miniature supercell events, classic supercell events, and widespread mixed-mode convective events. Based on the review of reflectivity and velocity data from these cases, the following criteria were designated to classify and track supercell storms in this study:

1) the storm contains a mesocyclone with an azimuthal velocity differential $\geq 7.7$ m s$^{-1}$ (15 kt) at base level,
2) the storm persists for 30 min or greater,
3) cell initiation is based on first occurrence of a 40-dBZ echo, and
4) termination is based on the loss of the mesocyclone.

The disparate variety of supercell storm types and structures posed a significant challenge to defining effective criteria. While classic supercells contain highly identifiable velocity couplets with relatively large mesocyclones, miniature supercells typically had weaker and more compact regions of rotation (Grant and Pren-tice 1996; Kennedy et al. 1993). Numerous studies have revealed significant variations in velocity differentials associated with supercells [e.g., a maximum of 40 m s$^{-1}$ in a classic, tornadic supercell identified in Wakimoto and Liu (1998); a peak of 80–110 m s$^{-1}$ in an F4 tornado–producing supercell in Wakimoto et al. (2003); and a maximum of 18 m s$^{-1}$ in a tornadic minisupercell in Outinen and Teitinen (2007)]. Thus, a relatively low velocity differential criteria value was required to capture all supercell types. Because of these considerations, as well as the thorough review and analysis of the Oklahoma benchmark events, an azimuthal velocity differential of 7.7 m s$^{-1}$ (15 kt) was utilized for the identification of mesocyclones in this study. In addition, a temporal requirement of 30 min or greater was applied to ensure that cells maintained a quasi-steady rotating updraft for at least five or six volume scans. Although supercells persist over different lengths of time, the 30-min requirement removed the identification of storms that only temporarily exhibited supercell characteristics. Some previous studies (e.g., Burke and Shultz 2004) have applied more stringent temporal requirements, such as 1 h or greater; however, the 30-min mark is consistent with the supercell definition established in studies such as Thompson et al. (2003) as well as Moller et al. (1994), which requires “lifetimes at least on the order of tens of minutes.”

The intent of the criteria was to capture the full spectrum of supercell types as opposed to capturing only the most severe, classic-type storms that are studied most frequently. Further, an explicit mesocyclone depth requirement was not established because of the observed variation in supercell depths (e.g., minisupercells versus classic supercells) as well as radar beam overshooting at long distances from radar sites. Characteristic reflectivity features noted in Moller et al. (1994), such as appendages, hook echoes, and bounded weak-echo regions (BWERs), as well as track characteristics such as deviant motion, were used in aiding identification. All storm analyses utilized the looping feature of the radar software extensively to best observe characteristic supercell storm development, morphology, and dissipation.

One particular goal of this study was not only to determine where and when supercells occurred during 1994–2003 across Oklahoma, but also to quantify storm initiation locations, tracks, and termination locations. Johnson and Mapes (2002) noted that, “Climatologies of triggering mechanisms for severe weather are virtually nonexistent as a result of inadequate measurements.” The authors also proposed that, “One approach would be to extend the climatologies of mature-phase severe storms back to the initial stages of development.” These statements provided motivation for not only tracking the supercell portion of the storm life cycle, but the formative stages as well. The following steps were followed in tracking supercell storms,
which included low-precipitation, classic, high-precipitation, miniature, and squall line-embedded storms (note that all storms were tracked at the lowest tilt level):

1) Cell initiation was determined from first evidence of a 40-dBZ echo.
2) Centroid coordinates were collected every 15 min or shorter, as needed, for cell morphology.
3) The cell was labeled as a supercell once a mesocyclone formed.
4) The supercell centroid was assigned to the high-reflectivity factor values just north of the inflow notch.
5) Coordinates of the supercell were cataloged every 15 min or shorter as long as the mesocyclone was evident.
6) Termination was defined as the last radar scan with an identifiable mesocyclone.

At each tracking point the pertinent position and other data were recorded. The closest radar within range of a storm was used for tracking and would be switched as needed. For example, several long-track storms required the use of three or four radar sites during the entire storm life cycle. If a storm lost supercell characteristics and later regained a mesocyclone, storm tracking continued with the appropriate storm classification denoted (e.g., cell 202, supercell 202, cell 202-2, and supercell 202-2).

The process for identifying and tracking anticyclonic supercells varied slightly from all other types because of the continuous spectrum of convective storms. To address this issue, the defined supercell criteria were followed as closely as possible during the identification of storms. However, the most difficult cells to classify were those that bordered the criteria (e.g., a storm with supercell characteristics for roughly 30 min). In such cases, a multitude of radar data, including multiple sites, radar reflectivity sequences, cross sections, and multiple scanning levels, were viewed to aid in the classification process.

2) HUMAN CLASSIFICATION OF STORMS

The determination of specific storm types posed several challenges because of the continuous spectrum of convective storms. To address this issue, the defined supercell criteria were followed as closely as possible during the identification of storms. However, the most difficult cells to classify were those that bordered the criteria (e.g., a storm with supercell characteristics for roughly 30 min). In such cases, a multitude of radar data, including multiple sites, radar reflectivity sequences, cross sections, and multiple scanning levels, were viewed to aid in the classification process.

3) STORM EVENT SELECTION AND DOMAIN ERRORS

A storm report query approach was utilized as a first step to determine organized storm event days with potential supercells. Thus, days consisting of fewer than 20 reports (and no tornado report) were not investigated in this study. While this intentional omission isolated organized severe weather events significantly weighted with supercell storms, some storms may have been unintentionally omitted due to a lack of accurate reporting. Furthermore, the geographic borders of Oklahoma were selected as the boundaries for storm identification in this study. Thus, events that straddled these boundaries may not have been selected if events numbered fewer than 20 reports within Oklahoma. However, during the analysis of the events, extreme care was given to the analysis of any supercell storm that entered or exited the state to limit such errors.

4) SMALL SAMPLE SIZE OF IDENTIFIED SUPERCELLS

Limitations in the longevity of radar archives restricted the findings to a 10-yr sample of supercells.
Thus, it is not possible to draw long-term conclusions regarding the spatial and temporal characteristics of these storms with a high level of confidence because of the relatively small size analyzed in this study. However, as data collection continues and increases, future research efforts will have a greater opportunity to build upon the concepts applied in this demonstration study to quantify the long-term tendencies of organized supercell activity throughout the world.

3. GIS components

a. Importing and representing supercell data in ArcGIS

Several spatial conversions were applied to the data to effectively represent supercell storms in GIS. Supercell data were collected as a series of points representing a storm from its initiation, to its period of supercell characteristics, through to its termination. All storm point locations were imported into Environmental Systems Research Institute’s (ESRI) ArcMap by adding the latitude and longitude columns as x–y data. Next, all series of points with identical storm identification numbers were converted to vector line features representing not only the track of the storm but its direction as well. Finally, the vector paths of the supercells were buffered at a distance of 5 km (i.e., 10-km-wide polygon) to develop an approximate swath of the most intense portion of the storm. Although arbitrary, 10 km was determined to be a conservative estimate considering the range of supercells observed. Figure 3 illustrates an example of supercell tracking performed during the 3 May 1999 supercell event. The black vectors in Fig. 3 indicate the supercell portion of the storm tracks, while the dashed lines show the track of each storm before it became a supercell. The blue swaths represent an approximation of the region impacted by the most intense portion of the supercell. Figure 4 illustrates the process for converting point features to lines and the subsequent polygon swaths for the entire dataset.

b. Storm reports in GIS format

To facilitate a comparison between storm occurrences determined by this study and storm report locations, all hail, wind, and tornado storm reports were imported into GIS. All storm reports between 1994 and 2003 in or within 20 km of Oklahoma were selected from the dataset. Wind and hail reports were imported as latitude and longitude x–y coordinate data in separate layers. Tornado reports were imported similarly and converted to vector line features by connecting identical report identification numbers in chronological order. Single tornado reports (not tracks) were assigned within a separate point feature layer.

c. GIS spatial analysis techniques

To determine the frequency of storm cells across Oklahoma, a grid spanning 0.1 decimal degrees (dd) latitude (approximately 11 km) by 0.1 decimal degrees longitude (approximately 9 km) was created. The size of the grid cells was chosen to be similar to the supercell
swaths and at a sufficient resolution to accurately determine local maxima and minima during the study period.

Using the high-resolution grid, GIS was used to perform a frequency analysis of storms across the grid domain. The total sum of unique storm identification numbers was tabulated for each grid cell during different time periods, including all months and all years. In addition, other analyses were overlaid on the frequency results to reveal further storm characteristics, such as the mean center of initiation points, mean storm track, and density of storm points and tracks. Because Oklahoma is the domain of the study, it should be noted that results involving mean initiation points or mean storm tracks represent geographic mean relative to Oklahoma.

4. Results

The results of the Oklahoma supercell study highlight several unique spatial and temporal characteristics found during the 10-yr period from 1994 to 2003. A significant emphasis was placed on illustrating the results of numerous GIS spatial analyses to illustrate the utility of GIS for climatological research based on the importance of location and data query. Storm Data was also used during various analyses as an additional comparison tool.

a. Temporal supercell distributions

The monthly and annual supercell occurrences that are shown (see Figs. 5 and 8) closely resembled the storm event distributions identified in Fig. 2. Figure 5a illustrates the monthly supercell frequency representing the 943 supercells observed during the 10-yr study. Supercell totals increased significantly from March (55) to April (194), followed by a strong peak in May (366) before decreasing dramatically in July (27). During the warm, late-summer months of August and September supercells occurred infrequently yet consistently with identical totals for each month of the study period (29). Supercell activity then briefly increased during the month of October (65) in association with Oklahoma’s secondary severe weather season during the fall. Storm activity decreased markedly during the remainder of the year. In terms of monthly percentages, the period from April through June represented approximately 75% of the total number of supercells throughout the year.

Several interesting features were revealed when comparing the number of supercells observed per month with the number of supercell days (any single day with at least one supercell storm in Oklahoma) per month (Fig. 5b). June had more supercell days during the study period than April (Fig. 5b), yet April had approximately 50 more supercells than June (Fig. 5a). This indicates that April was comprised of more supercell outbreak events during the 10-yr study than June. A similar occurrence also happened later in the year during the month of October. Nearly twice as many supercell days were observed during August and September than in October (Fig. 5b), yet October had more supercells than the previous 2 months combined. Thus, the October results were highly influenced by supercell outbreak days (e.g., 4 October 1998 and 9 October 2001), more so than August and September.

Daily supercell frequencies and supercell days were also overlaid with 2-week moving averages to quantify
the supercell storm seasons during the 10-yr observation period (Figs. 6a,b). In terms of supercell frequency, the peak in storms occurred during the first 10 days of May. This peak in total number of supercells is contrasted with the peak in supercell days, which was found to occur in late May. These results imply that for the period of study, supercell outbreaks were more common during late April through early May while super-

Fig. 5. (a) Monthly supercell totals and (b) monthly supercell days across Oklahoma during 1994–2003.

Fig. 6. (a) Daily number of Oklahoma supercells and (b) supercell days from 1994 to 2003 with 2-week moving averages overlaid.
cell days occurred most frequently 3–4 weeks later. The secondary supercell season can also be seen during October in the supercell frequency curve (Fig. 6a). However, in terms of supercell days, this season peaked a few weeks earlier in mid-September (Fig. 6b).

To further investigate several of the interesting springtime features noted in Figs. 6a,b, an analysis of tornado-track information from Storm Data was completed for the months of April, May, and June for Oklahoma (Figs. 7a,b). Tornado-track data from 1950 to 2005 were used independently of all other storm report types (hail, wind, or tornado point reports) to most effectively isolate the supercell signal inherent in the data without the use of radar data. The results revealed several remarkably similar characteristics between supercells during the 10-year analysis and tornado tracks from the 55-yr analysis for the period from April through June. Tornadoes were found to occur most frequently in early May, diminish slightly during mid-May, and reach a secondary maximum during the last 10 days of the month. For tornado days (any day with at least one tornado report), tornadoes increased during the end of April through early May, decreased briefly in mid-May, and peaked at the end of May. These results correspond very closely with three key results identified in the 10-yr supercell study for the April through June period: supercell outbreaks were most common in early May; the middle portion of May was relatively less active than the rest of the month; and the peak in supercell days occurred in late May.

On an annual basis, supercell frequencies were quite inconsistent (Fig. 8a); however, the variability of supercell days (Fig. 8b) appears to be strongly correlated with the number of storm events per year (Fig. 2b). The results show that 1994 was the most inactive year of the study (43 supercells), while 1999 included the greatest
number of supercells during the study period (152 supercells). Furthermore, the mean annual total of supercells observed across the state was 94. In terms of annual supercell days (Fig. 8b), yearly totals ranged from a low of 21 in 1998 to a high of 45 the following year. Overall, the 10-yr study period revealed an average of 28 supercell days per year.

b. Spatial frequency of supercells

The spatial frequency analysis determined that several local maxima existed across the state during the limited 10-yr study period. The main regions of activity included one that stretched from just west of the Oklahoma City metropolitan area northeastward into Kansas, a second region in east-central Oklahoma, and a third across southwestern Oklahoma (Fig. 9a). Additionally, the supercells studied had a mean initiation location west of the Oklahoma City metropolitan area, a mean storm track from southwest to northeast, and a mean path extending from west-central through north-central Oklahoma. To determine the magnitude of supercell tracks per unit area, a line density analysis of supercell tracks was calculated. Figure 9b shows the 0.01 dd × 0.01 dd raster analysis using a search radius of 0.2 dd. The results are consistent with Fig. 9a showing main activity regions across north-central and into northeastern Oklahoma, east-central Oklahoma, and southwestern Oklahoma.

1) General supercell characteristics

A series of probabilistic and histogram plots also display several key characteristics of supercells during the study period. The most frequent period for supercell initiation occurred from 2000 to 0000 UTC while termination was most common between 2300 and 0300 UTC (Fig. 10). For probabilistic storm durations, the analysis revealed that the probability of storms exceeding longer durations (supercells and cells that later became supercells) decreased along a log-linear curve (Fig. 11a). For example, supercells had a 25% probability of lasting 2 h or greater while a supercell that maintained itself for roughly 7 h or more occurred in approximately 1 out of 1000 supercells. Additionally, the time between initiation and the acquisition of supercell
characteristics most frequently spanned 30–60 min (Fig. 11b). Figure 11b also indicates that once supercell status was attained, most storms lasted between 30 min and 1 h, with a decrease in frequency for each 30-min increase in storm duration.

2) Spatial density of initiation and termination points

In addition to quantifying the most active regions of supercell coverage, initiation and termination densities
were also determined for the 10-yr supercell dataset. Figure 12 illustrates the results of several kernel point density analyses that determine the concentration of points within 0.5 dd of each initiation and termination point. Regions with the most extensive overlay of the kernel surfaces result in the highest density of initiation point features.

Supercell initiation (Fig. 12a) was the most concentrated across portions of southwest Oklahoma, east-central Oklahoma, as well as north-central Oklahoma. Many of these regions are located west of supercell frequency local maxima and several are situated relatively close to enhanced terrain features such as the Wichita Mountains in southwest Oklahoma and the Ouachita Mountains in southeast Oklahoma. Supercell termination density (Fig. 12b) was highest across north-central into northeastern Oklahoma, which is near and to the east of the northern Oklahoma supercell local maxima.

3) Cumulative Month Periods

Dividing the dataset into cumulative month periods provides increased insight for both the spatial distributions and monthly variability of supercell occurrence observed from 1994 to 2003. The first quarter of the year was relatively inactive, and supercells were mainly confined to the eastern and central portion of the state (not shown). Supercell occurrence and coverage increased significantly in April (Fig. 13a) with a pronounced southwest-to-northeast mean storm track (Fig. 14d). Two axes of increased activity prevailed during the study years and were located from south-central into eastern Oklahoma and from north-central into northeastern Oklahoma. Because of the well-dispersed coverage across the state, the mean initiation location was situated in central Oklahoma.

During May (Fig. 13b), supercell occurrence was pronounced statewide with a notable increase across the Oklahoma panhandle. Because of the greater occurrence of storms across the western portion of the state, the mean initiation location also moved farther west from its position in April. A more significant variation in storm-track vectors was observed during May (Fig. 14e) with a mean storm track from the southwest to northeast. June (Fig. 13c) saw a marked decrease in supercell occurrence, particularly across the eastern part of the state. As a result, the average supercell ini-
tiation point migrated northwestward. One other notable change during June was a shift in the mean storm track to a northwest-to-southeast orientation (Fig. 14f).

As spring transitioned to summer, supercell occurrences decreased significantly through July, August, and September (Figs. 15a,b; July is not shown). However, several characteristics, including mean storm track (Figs. 14g–i) and storm coverage, remained consistent. As such, supercells occurred primarily across the northern two-thirds of the state, thus transitioning the mean storm initiation values northwestward throughout this period.

Supercell occurrence increased quite significantly during October, which marked Oklahoma’s brief secondary severe weather season (Fig. 15c). Several major events occurred during the study, which resulted in an eastward progression of the mean storm initiation value from previous months. In addition, the mean storm track transitioned back to a southwest-to-northeast orientation (Fig. 14j). Further into November and Decem-
ber, storm occurrence decreased (not shown), the mean storm initiation moved eastward, and mean storm track was generally from the southwest to northeast (Figs. 14k,l).

Two overall trends were noted in the spatial analysis of supercells by cumulative month periods (Figs. 16a,b). First, Fig. 16a illustrates the movement of the monthly mean supercell initiation point as the year progresses. Initially, such locations were concentrated in the eastern part of the state. As the spring season arrived, more storms occurred statewide and the mean initiation point moved westward into the central part of the state. Through the summer, supercells became more confined to western Oklahoma, and the mean initiation point

![Fig. 14](image_url)
reached its westernmost location. Finally, during the final 3 months of the year, the mean storm initiation value moved eastward due to the concentration in the eastern portion of the state.

Figure 16b shows the corresponding mean storm tracks for each month showing the transition from mainly southwest-to-northeast storm tracks from January through May, to northwest-to-southeast tracks from June through September, and southwest-to-northeast tracks from October through the end of the calendar year. Although a number of factors contribute to supercell motion, including surface boundaries, storm dynamics, and storm interactions, the impact of the general synoptic pattern is a probable cause responsible for the change in mean storm-track vectors.

c. Spatial distribution of supercells and Storm Data

Point and line density analyses were applied to Storm Data during 1994–2003 and were compared with the cumulative supercell results shown in Fig. 9. The density of all storm reports points (hail, wind, and tornado) is shown in Fig. 17a (0.01-dd-sized raster cells with a 0.2-dd search radius). As noted in prior research, the density of all point storm reports is strongly correlated with population centers and does not resemble the observed supercell frequency for the same time period.
The density of tornado tracks is shown in Fig. 17b (0.01-dd-sized raster cells with a 0.2-dd search radius). The tornado-track density analysis reveals higher densities throughout much of east central, central, and north-central Oklahoma, with isolated higher values in southern and southeastern Oklahoma. Overall, numerous regions of Oklahoma do not exhibit well-defined spatial correlations between tornado-track density (Fig. 17b) and supercell density (Fig. 9), with the exception of portions of north-central Oklahoma. Because of factors such as nontornadic supercells, tornadoes produced by nonsupercellular convection, and incomplete supercell or tornado-track databases, the comparison between this type of supercell database and currently existing Storm Data information is imperfect.

5. Discussion

a. A new generation of storm climatologies

This study successfully employed the use of new techniques to analyze the spatial and temporal characteristics of a specific storm mode. Traditional storm climatologies have relied significantly on the severe storm report archive, which contains a collection of known inconsistencies including population biases, increases in reporting, and reporting discrepancies across National Weather Service Forecast Office borders. NEXRAD radar data analysis represents a modern approach to storm identification and tracking that removes the biases of human storm reporting while adding the ability to document entire life cycles of storms. Importing storm-tracking information into increasingly powerful GIS software packages enables the storage of information into a database structure within an environment that can spatially analyze vector and raster data types. Future storm climatologies must continue to incorporate evolving radar and spatial database technologies to further advance the knowledge of severe storms. Using the feature-based approach illustrated in this study as an initial example, it is proposed that future storm datasets further incorporate GIS-type technologies to greatly enhance data mining and exchange. Several brief examples using the developed Oklahoma storm dataset illustrate the utility of such GIS databases.

b. Example applications of GIS storm datasets

1) RANGE-BASED STORM SELECTION

For studies focused on specific spatial and temporal limits, GIS could be used to query the appropriate in-
formation by space and attribute. For example, specific radar sites could be buffered at differential ranges to select supercell occurrences (Fig. 18a) based on proximity to the radar. The selection could be further modified to specific months, a range of initiation times, or particular storm durations. Such storm event selection could prove highly useful in radar algorithm studies, case studies, and radar-based observational research.

2) **Specialized Storm Data Queries**

Potential operational uses of the supercell dataset could include advanced queries of past storm events to assist in current forecast preparation. One important component to forecasting severe local storms is pattern recognition. The GIS storm dataset can assist in this process by rapidly providing critical information for varying storm characteristics. For example, during an early June severe weather forecast situation, meteorologists could enter several basic pieces of information to search for previous storm events. Figure 18b illustrates a situation in which forecasters search for northwest-to-southeast-propagating storms lasting greater than 1 h during the first 15 days of June. With the resultant spatial and tabular (not shown) data, additional archived meteorological information such as surface maps, upper-air maps, mesonet observations, and radar data could then be viewed for the analog supercell events to assist in forecast preparation.

3) **Queries of Supporting Data Sources**

Other data sources can be queried in association with specific storm events across Oklahoma. With the availability of the Oklahoma Mesonet (McPherson et al. 2007) surface data throughout the duration of the supercell dataset, it is possible to query specific sites for additional meteorological analysis. Figure 18c shows the selection of all supercell storm swaths during the 3–4 May 1999 outbreak and all Oklahoma Mesonet sites within 25 km of each swath. In such an example, mesonet data could be analyzed to better understand near-storm conditions such as surface temperature, dewpoint, and wind speed and direction during all portions of the supercell life cycle. Such results could be further compared to other nontornadic supercell events by performing additional GIS queries.
c. Future meteorological applications in GIS

The latest version of the popular GIS software package ArcGIS (ESRI) has the additional capability to import atmospheric data types (including NetCDF format), which will allow for additional data interoperability. Further advancements are currently being made to enhance analysis involving multidimensional temporal data within GIS platforms. Such enhancements encourage further meteorological research using GIS technologies as a means for accomplishing a number of tasks, including multilayer spatial analyses, real-time data archive, and advanced data mining. The further application of meteorological research in geospatial database environments will inevitably lead to further collaboration and cooperation between various earth science disciplines.

d. Additional perspectives on GIS

While the future of atmospheric research and GIS appears to be promising, a number of challenges were identified during this study, which underscores the current limitations of meteorological research in GIS. Al-
though numerous meteorological data sources now inclu-
de GIS formats, a significant amount of observa-
tional meteorological data is not available in GIS. Fur-
thermore, some sources that could be incorporated 
into the software (i.e., radar data) were extremely cum-
bbersome and rendered relatively inefficient analyses. 
This issue led to the development of the supercell fea-
ture dataset in this study, which was based on geocoded 
storm locations derived from traditional radar software 
programs. Developing a dataset also required knowl-
dge of appropriate file formatting and subsequent im-
porting procedures as well as effective geometrical rep-
resentations of geocoded spatial features. Overall, the 
authors found GIS datasets to be extremely useful for 
climatological studies; however, such datasets should be 
developed using automated methods to ensure more 
efficient and robust contents. 

Although the creation of a GIS dataset proved chal-
lenging, the benefits are significant. The platform en-
abled a very powerful, yet simplistic method for data 
mapping, query, and overlay of various sources of informa-
tion. We believe that future database development 
projects need to be aimed toward creating automated, 
real-time methods of data archive in GIS. For example, 
anational center could be tasked with collecting all 
storm mesocyclone detections in real time, quality con-
trolling the data, and outputting the results into GIS 
datasets. Such datasets could provide new ways to 
quantify the spatial and temporal occurrence of super-
cells across the country and facilitate further research. 
Further, a focused effort in automated dataset devel-
oped will likely lead to new information discovery 
and encourage more interdisciplinary research. 

6. Conclusions 

This study was designed as a demonstration project 
to quantify the spatial and temporal characteristics of 
supercells across Oklahoma over a 10-yr period. A cri-
teria-based approach was applied to the identification 
and classification of storm types using level-II and 
level-III radar data. Furthermore, GIS was utilized in a 
new and innovative way to organize, visualize, and ana-
lyze the spatial aspects of storms various time 
scales. This methodology resulted in the identification 
While the observation of nearly 1000 supercells during 
a decade is quite significant, the sample size is too small 
to represent long-term spatial and temporal character-
ostics of supercell thunderstorms across Oklahoma. 

A number of key findings resulted from the spa-
tiotemporal analysis of supercells across Oklahoma 
during the limited 10-yr demonstration study period. 
Key results included the following: 

- The location of the maxima of supercell occurrences 
  was identified across three main regions: east-central 
  Oklahoma, southwest Oklahoma, and west-central 
  into northeast Oklahoma. 
- The mean supercell initiation location moved west 
  between January and September and moved east 
  from September through the end of the calendar 
  year. 
- Initiation was most frequent between 2000 and 0000 
  UTC. 
- Termination was most common between 2300 and 
  0300 UTC. 
- Supercell initiation density was the greatest across 
  portions of southwest, north-central, and east-central 
  Oklahoma. 
- Supercell termination density was most common 
  across northern and northeastern Oklahoma. 
- The month of May was composed of three important 
  climatological features: a supercell outbreak peak in 
  early May, a midmonth relative minimum of activity, 
  and a peak in supercell days at the end of May. 
- The secondary supercell season was identified during 
  late September to early October. 
- The monthly mean supercell tracks were oriented 
  from southwest to northeast from January through 
  May, from northwest to southeast from June through 
  September, and from southwest to northeast through 
  the end of the year. 

Storm report data were analyzed using several spatial 
density tools and revealed that the distribution of point 
reports (wind, hail, and tornadoes) was approximately 
correlated with population centers. The density of tor-
ado tracks did not exhibit the same population bias; 
however, only north-central Oklahoma was strongly 
correlated with supercell locations for the same period. 
Overall, the GIS-based supercell dataset was found to 
be a valuable, new form of storm archive that enabled 
the efficient query of past storms, powerful spatial 
analyses, and multiple data overlay. The combined use 
of radar storm classification and GIS as a database cre-
ation and analysis tool proved highly effective in quan-
ifying the spatial characteristics of past supercells 
across Oklahoma during a 10-yr period. If applied on a 
larger scale, utilizing a set of more automated methods 
such as storm algorithm identification combined with 
quality assurance measures, similar detailed analyses 
could be extended to larger regions of the United States 
over longer periods of time. 

It is the authors’ recommendation that a national 
center be given the task of creating an automated 
framework for developing GIS datasets consisting of 
critical storm information gathered in a real-time, qual-
ity-assured manner. While *Storm Data* will continue to serve as a useful storm reporting and National Weather Service verification tool, new approaches are needed to more effectively document and research storm occurrences. For example, with the availability of extensive WSR-88D coverage across the country, the potential exists for more effective use and storage of important radar-derived storm features such as hail detections, mesocyclone detections, or storm cell identification and tracking information. The storage of such data into GIS datasets would enable effective data mining of past storm days, facilitate incorporation with other datasets, and ultimately foster further meteorological research and data discovery. The resultant storm datasets would provide beneficial information to a range of sectors, including forecast operations, synoptic and mesoscale research, and economic interests. With continued increases in GIS-compatible meteorological datasets, such as the ones proposed herein, it appears likely that GIS will serve as an important tool for archiving, visualizing, and analyzing a vast array of meteorological data in the future.

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