# A Climatology of Severe Convective Events as a Function of Storm Morphology


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**ABSTRACT**

This study is an expansion of Gallus et al. (2008) (hereafter, G08), in which all convective systems that occurred within a ten-state region that covers parts of the Midwest and great plains between 1 Apr 2002 and 31 Aug 2002 were classified according to their dominant morphology. Severe weather produced by each system was associated with each morphology. Archived radar imagery was used to classify systems, which had to meet specific criteria to be classified. This study uses data in the same region as in G08, but the time period is 1 Apr 2007 to 19 Jul 2007. The same nine morphologies that were used in G08 are used in this study, which includes non-linear convective events, isolated cells, clusters of cells, broken lines of cells, squall lines with no stratiform precipitation, trailing stratiform precipitation, parallel stratiform precipitation, and leading stratiform precipitation, and bow echoes. Cellular systems that contained supercells were added as morphologies to incorporate the effects that supercells have on the type of severe weather produced.

The results of this study indicate that the trends exhibited by the systems in G08 also are exhibited by the systems in this study to an extent. It is also confirmed that supercellular systems produce severe weather more frequently, and also produce more intense severe weather.


## 1. Introduction

Radar is regarded as a critical tool for identifying severe thunderstorms (Burgess 1991). Therefore, being able to determine what type of severe weather may be produced by a given convective system by visual inspection of the radar is helpful for operational meteorologists in protecting life and property.

Many studies have attempted to classify mesoscale convective systems by organizational mode. Jirak et al. (2003) used satellite and radar data to separate mesoscale convective systems into four categories: mesoscale convective complexes, persistent elongated convective systems, meso-β circular convective systems, and meso-β elongated convective systems. The same study also classified systems by development on radar in terms of the presence of stratiform precipitation, whether the initial convection was linear or areal in coverage (or a combination), and whether systems merged with others. Baldwin et al. (2005) used one hour rainfall amounts to develop an automated classification procedure that separated rainfall events into stratiform nonconvective, convective linear, and convective cellular. Bluestein and Jain (1985) classified squall lines in terms of their development as broken line, back-building, broken areal, and embedded areal. Parker and Johnson (2000) considered squall lines with trailing stratiform precipitation, parallel stratiform precipitation, and leading stratiform precipitation. Other studies used isolated cells as an organizational mode (Grams et al. 2006), and Baldwin et al. (2005) alluded to classifying systems by both isolated cells and clusters of multicells. Gallus et al. (2008) (hereafter, G08) used several of these morphologies in a study relating severe weather reports to morphology type and added clusters of cells, squall lines with no stratiform precipitation, and non-linear convective systems. Bow echoes were studied by Fujita (1978).

Many studies have associated severe weather reports with the morphologies of convective systems. However, there are some difficulties in doing so. Many of the difficulties are related to the methods used to report storms and how they appear in the National Climatic Data Center's *StormData* publications and database. Such issues include the overreporting or underreporting of severe wind and hail events (Trapp et al. 2006), the affects of population density on the reporting of severe wind events (Weiss et al. 2002), the methods by which tornadoes are reported (Doswell and Burgess 1988; Trapp et al. 2005; Verbout et al. 2006), and the fact that most wind and hail reports are given as point measurements rather than as swaths, as tornado reports are. There are also difficulties in merely classifying some convective systems as one type of morphology or another. There is subjectivity in classifying them since many are hybrids of different morphologies and the amount of mixing of morphologies varies from system to system (G08). For example, Parker and Johnson (2000), Parker (2007), and Storm et al. (2007) noticed that the LS and PS systems in their respective studies had a mild tendency to transform to TS systems gradually. Despite these issues, certain morphologies have been shown to favor producing one or more types of severe weather. Parker (2007), among others, have shown that parallel-stratiform and leading-stratiform lines tend to produce more flooding than other systems. G08 also noted the tendency for trailing stratiform lines and non-linear convective events to produce more flooding reports. They also showed that cellular systems tended to produce more hail and tornado reports. Bow echoes and trailing stratiform events have been shown to produce a greater percentage of all severe wind reports and tend to have a large wind-to-hail report ratio (Klimowski et al. 2003; G08). One shortcoming of those studies, however, is the exclusion of supercells as a morphology or storm type. Additional data and more careful analysis are needed to identify supercells.

Supercells are known for their tendency to produce the most intense severe weather (Doswell and Burgess 1993; Moller et al. 1994). Thus it is significant for operational meteorologists to be able to recognize a supercell when it appears on radar or satellite. Several papers have been written on the subject of how to use radar to recognize supercells and other thunderstorms capable of producing severe weather (Forbes 1981; Johns and Doswell 1981; Burgess 1991; Moller et al. 1994). However, the methods described in some of those papers have been superseded by new methods introduced by improvements in technology, mainly via improvements in the WSR-88D radar network and in the capabilities of the radar programs in build 9.0 and after. For example, within the last 10 years, teams from the National Severe Storms Laboratory have written two algorithms which aid in the identification of supercells and tornado vortex signatures on radar: the Mesocyclone Detection Algorithm (MDA) (Stumpf et al. 1998) and the Tornado Detection Algorithm (Mitchell et al. 1998). Also to aid in storm tracking and position forecasting for cells, the Storm Cell Identification and Tracking (SCIT) Algorithm was written (Johnson et al. 1998). Both of the NSSL algorithms have been shown through testing of verification datasets to be better identifiers and predictors of supercells and tornadoes than past algorithms. One way in which the MDA is so useful is due to the defining characteristic of a supercell being the presence of a deep, persistent mesocyclone (Doswell and Burgess 1993). The MDA enables meteorologists to detect rapid rotation in all kinds of storms including ones in which the rotation may be difficult to see due to cluttering of reflectivity, distance from radar, or any other lack of obvious visual rotation. Then the SCIT algorithm aids meteorologists in following the storms as they evolve.

The present study is more or less an expansion of G08, using a new dataset, the 2007 season, and including the supercellular versions of the cellular morphologies as three additonal morphologies. Two hypotheses will be tested: (1) – that the trends in severe weather reports associated with each morphology found for the 2002 dataset in G08 remain true for the 2007 dataset; and, more importantly, (2) – that supercell morphologies will produce more severe weather more frequently and produce more intense severe weather than will non-supercellular morphologies. Section 2 outlines the data sources and methodology for the study, while section 3 provides the results and analysis of the study. Conclusions and discussion follow in section 4.

## 2. Data Sources and Methodology

To preserve continuity between the present study and G08, as many aspects of the data collection and methodology as possible were matched. Radar data used in this study came from the UCAR MMM image archive for warm season precipitation episodes found at http://locust.mmm.ucar.edu/case-selection/. The images are mosaics from various sources, but most are composite reflectivity. The spatial and temporal resolutions are 2 X 2 km and 30 minutes, respectively. For the few periods in which data from this archive were unavailable (the longest such period being 24 hours), the interactive radar feature on the Iowa Environmental Mesonet website was used instead. Settings on the interactive radar feature were matched as closely as posible to those of the UCAR image archive. The only difference that couldn't be matched was spatial resolution, which was higher for the interactive radar. This difference in spatial resolution did not adversely affect the data collection. Data used for finding supercells included storm attribute data from Level 3 radar data products, especially the Mesoscale Detection Algorithm (MDA) from the National Severe Storms Laboratory, and the Level III NEXRAD mesocyclone product from the National Climatic Data Center. While the storm attribute data was text output, NCDC's NEXRAD mesocyclone product required the Java NEXRAD Data Viewer to visualize data. Severe storm reports were collected using NCDC's *StormData* publication.

The period of study was 0000 UTC 1 April 2007 through 0000 UTC 19 July 2007. The time for the end of the period of study was chosen due to lack of data for detecting mesocyclones after that date. The domain of the study consisted of a ten-state region from the southern great plains through the upper Midwest (Fig. 1): Illinois, Iowa, Kansas, Minnesota, Missouri, Nebraska, North Dakota, Oklahoma, South Dakota, and Wisconsin. All convective events that formed within this domain and time period were included in the study as long as

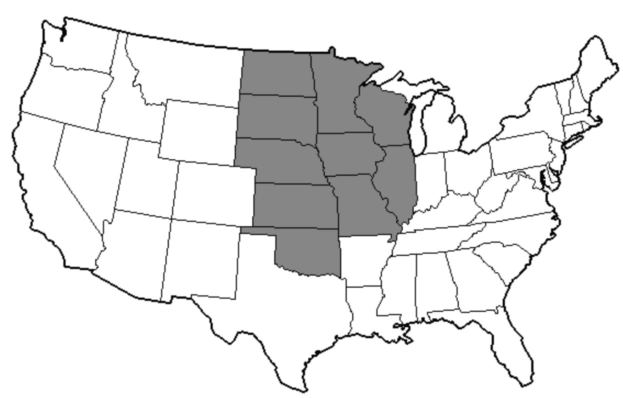

Figure 1. The ten-state domain used in the study. (Same as Fig. 1 from G08)

they met the following radar characteristics (the same as those in G08):

1) Minimum areal coverage of 6 km X 6 km of greather than 10 dBZ reflectivity

2) Maximum reflectivity in at least one pixel of data of at least 30 dBZ

3) Minimum temporal duration of one hour (at least two frames)

Any convective systems that met these criteria were then classified according to their dominant morphology as it appeared on radar. Nine reflectivities were named: three were cellular, consisting of isolated cells (IC), clusters of cells (CC), and broken lines (BL); five were linear, consisting of no stratiform precipiation squall lines (NS), trailing stratiform squall lines (TS), parallel stratiform squall lines (PS), leading stratiform squall lines (LS), and bow echoes (BE); the final one was the non-linear convective morphology (NL) (Fig. 2). To be classified as one of the linear morphologies, a system had to be at least 75 km in length, have an eccentricity (ratio of major axis to minor axis) of at least 3:1, and persist for at least 2 hours. Cellular systems had to contain identifiable cellular elements. If the elements were connected by relatively weaker reflectivities (around 30 dBZ), the systems were classified as CC. If no, or very weak reflectivities (less than 10 dBZ) connected individual cellular elements, the systems were classified as IC. If the cellular elements were

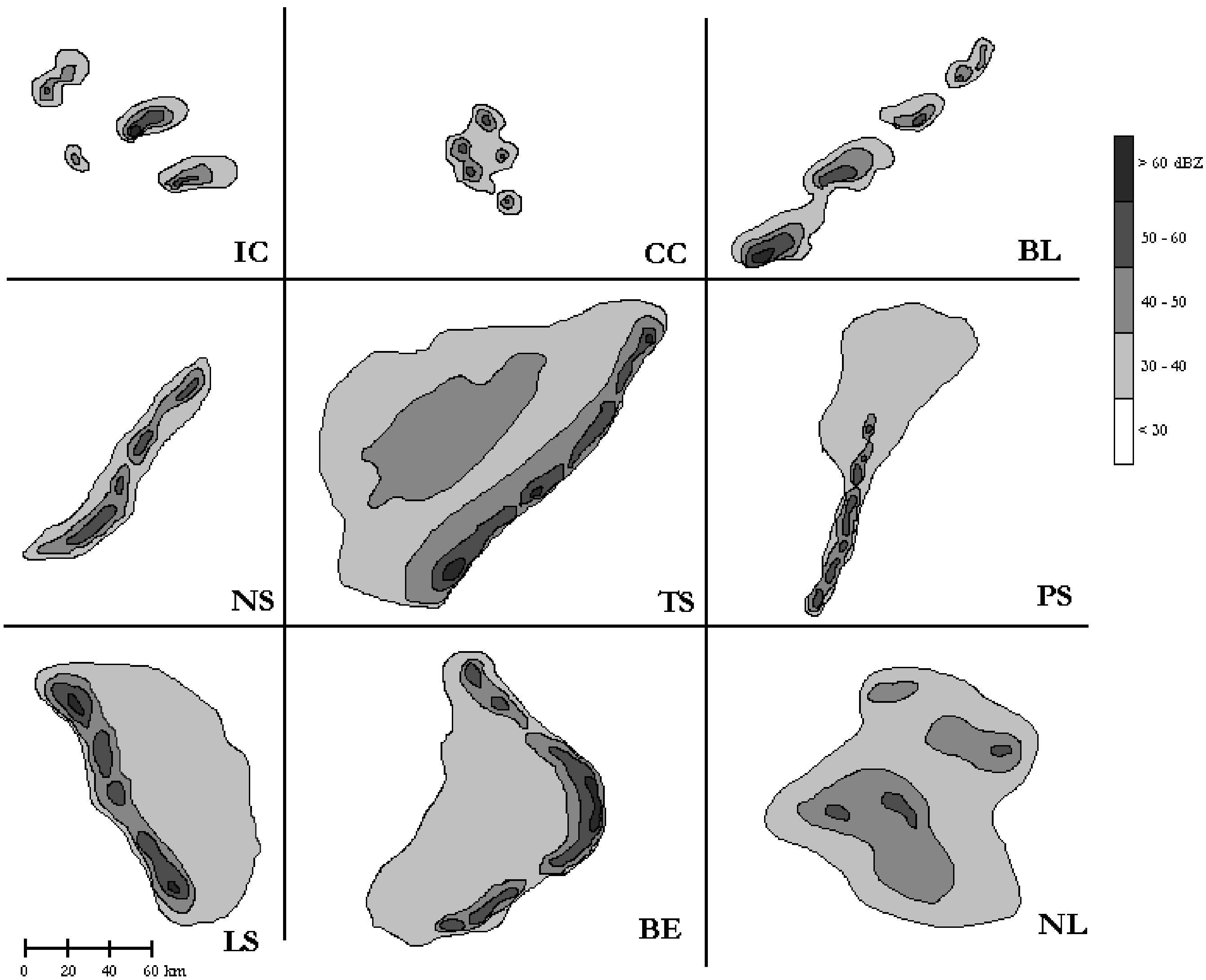


Figure 2. Schematic drawings of the nine morphologies. Abbreviations are as follows: IC, isolated cell; CC, cluster of cells; BL, broken line; NS, no stratiform precipitation squall line; TS, trailing stratiform precipitation; PS, parallel stratiform precipitation; LS, leading stratiform precipitation; BE, bow echo; NL, nonlinear. (Same as Fig. 2 from G08)

organized in a discontinuous line, the systems were classified as BL. Linear systems were classified according to their pattern of stratiform precipitation. Lines with no stratiform precipitation, or in which the stratiform precipitation was narrower than the convective part of the line, were classified as NS. Bow echoes were not required to possess stratiform precipitation. They only needed to consist of a line in which part of the line bowed out and clearly outran the rest of the line. If a system met the radar criteria but did not fit into one of the linear or cellular morphologies, it was classified as NL.

In classifying systems, only the dominant morphology was considered to preclude chaotic, short-lived morphological developments from altering the assigned morphology. All severe reports that occurred with that system were marked as an event for that morphology. However, if a system displayed properties of a different morphology for more than one hour during any time other than the initial and decaying stages of its life, then severe reports that occurred during that time were attributed to the other morphology. Some systems in this study did change their morphologies. In fact, some changed several times. In a very small number of cases, severe reports from the *StormData* publications did not occur near any reflectivity. Those reports were not counted. Effort was taken to prevent duplicated reports, especially hail and tornado reports (several of which were found), from being overcounted. It is recognized that some biases may arise as a result of not counting reports that occur with any system that is only partially inside the domain, and some systems may not produce severe weather until after they leave the domain, or before they enter the domain. However, counting the reports for those systems may introduce other biases. It is also recognized that classifying convective systems by mere visual inspection of radar is very subjective. The quantitative guidelines used for classification should reduce the subjectivity. The author of this paper maintained close contact with the authors of G08 to assure the process was being carried out in the same way as in their study. Nonetheless, systems exhibit a spectrum of morphologies, and a given system may exhibit characteristics of multiple morphologies both between successive scans and within one scan. This does cause some difficulty in distinguishing between some morphologies. The two cases of greatest difficulty in distinguishing between morphologies were between CC and IC, and between TS and BE. In the former case, how much weaker reflectivity connected cells was difficult to quantify, and in the latter case, the amount of bowing of the line was the only difference between several cases, as nearly all BE cases in this study did contain trailing stratiform precipitation.

The severe reports were divided into the following categories:

-Severe hail less than 1” in diameter (hail must be greater than or equal to 0.75” in diameter to be considered severe)

-Hail greater than 1” but less than 2” in diameter

-Hail greater than or equal to 2” in diameter

-Severe wind gusts less than 65 kts (wind gusts must have been listed as “thunderstorm wind” in *StormData* and be greater than or equal to 50 knots to be considered severe)

-Wind gusts greater than or equal to 65 knots

-Tornadoes

-Floods

-Flash Floods

In G08, the report of urban/small stream flooding was used. However, changes in the way *StormData* classified flooding reports caused the elimination of the term “urban/small stream flooding,” and consolidated it with other low impact flooding events that no longer appear in *StormData* (NWS 2007). Other changes to flooding reports listed in *StormData* include continuing a flash flood report as a flood report if the definition of a flood event is met from an ongoing flash flood report. This occurred rarely in the study, and was ignored. If a system met the radar requirements but was not associated with any reports of severe weather, the system was classified as a null case with its morphology preserved.

An additional morphology was included in this study: supercells. One of the goals of this study is to determine whether or not systems that contain supercells produce more violent severe weather or more severe weather in general. In order to be classified as the supercell morphology, a system must have been one of the cellular systems and must have contained at least one supercell. (Although it has been shown that non-cellular systems do contain embedded supercells, those will not be considered in this study to keep the focus of the study on the morphologies and not individual convective elements. Since supercells already resemble the elements that characterize cellular systems (i.e., they are cells), then they are easy to include with the cellular morphologies. It would take a much longer amount of time to separate embedded supercells from linear or non-linear systems.) If at least one supercell was found within a system, all reports for that system were attributed to the supercell morphology. The definition of supercell used in this study is as follows: since supercells are generally defined as storms that possess a mesocyclone for at least 15 minutes (Robert Lee, NOAA, 2008, personal communication), any identifiable cellular element from a cellular system that was flagged by the MDA consistently for a period of at least 15 minutes was considered to be a supercell. While in precipitation mode, radar scans generally come at a rate of one scan every four to six minutes. Therefore, the number of scans in which a cellular element was flagged as a mesocyclone was chosen to be four. Several levels of rotation are marked by the MDA, including “UNCO,” “3DCO,” and “MESO.” The “UNCO” and “3DCO” levels correspond to uncorrelated rotation at one isolated elevation angle and rotation at two adjacent elevation angles of the radar, respectively. Only the “MESO” level was used to mark a cell as possessing a mesocyclone. A cell must, therefore, have been flagged with “MESO” for at least four scans consecutively. Granting that supercells fluctuate in strength over time, a one-scan break in a sequence of four consecutive scans flagging a cell with “MESO” was allowed. Therefore, as long as a cell contained a sequence of four consecutive scans flagged as “MESO” with at most a one-scan break somewhere within that sequence, the cell was considered a supercell. No particular emphasis was placed on how many supercells a supercell system contained. Systems that were only partially inside the domain were only classified as a supercell system if any supercells that occurred within the system occurred within the domain. This process was used for both severe systems and those that did not produce severe weather.

Table 1. Overall results from the current study and from G08. The G08 study is that which used the 2002 data set, while the current study used the 2007 data set. In future tables, this is how the two studies will be labeled.

| Data set | Number of systems classified | Number (and %) that produced severe weather | Number (and %) that produced non-flooding severe weather | Number of severe reports | Number of non-flooding severe reports |
|---|---|---|---|---|---|
| 2002 | 711 | 433 (61%) | 402 (57%) | 7662 | 6735 |
| 2007 | 553 | 373 (67%) | 340 (61%) | 6484 | 5362 |

### 3. Results and Analysis

The results of this study are compared to those of G08 by reanalyzing the data from that study using the 1 April to 19 July time period used in the current study. Some overall results are shown in Table 1. The systems that produced severe weather produced an average of 17.4 reports (17.7 from G08) of severe weather per system (not shown; no figures from the reanalyzed data from G08 are shown), with BL supercell systems producing the largest average of nearly 37 reports per system (not shown).

120 (22% of all systems) supercell systems were classified, all but three of which produced at least one report of severe weather (therefore, 117 (31%) of the systems that produced at least one severe weather report contained supercells). Of the 120 supercell systems, the majority were CC systems, numbering 66 (55%), while IC events comprised 32 (27%) of the supercell cases, and BL events produced the remaining 22 (18%). For three systems, insufficient data was available to determine if any supercells were present in the systems, and thus they were

exluded from counting when it came to comparing supercell vs. non-supercell systems. The only one of them to produce severe weather was a CC system that produced three reports of severe weather. Thus, data will not be affected much by excluding those reports. It should be noted that approximately 5% of the systems proved very difficult to classify, either because they evolved rapidly (i.e., did not resemble a particular morphology for at least an hour), or because they exhibited characteristics of disparate morphologies simultaneously. In fact, an additonal morphology was suggested in Schumacher and Johnson (2005), called the training line/adjoining stratiform (TL/AS) morphology. A few of the systems in this study resembled TL/AS characteristics and would have been labeled as such had that morphology been included. However, since the TL/AS morphology was not included in G08, it was not included in this study.

*a. Morphological breakdown*

The breakdown of how much each morphology contributed to the total number of events is shown in Fig. 3. The largest single contributor was IC – non-supercell systems, whose 91 systems contributed 17% to the total. Note that LS systems contributed very little to this study. The definition of leading stratiform precipitation as a morphology, as defined in Parker and Johnson (2000), indicated that leading stratiform lines could also possess trailing or parallel stratiform precipitation. This definition caused difficulty in classifying LS

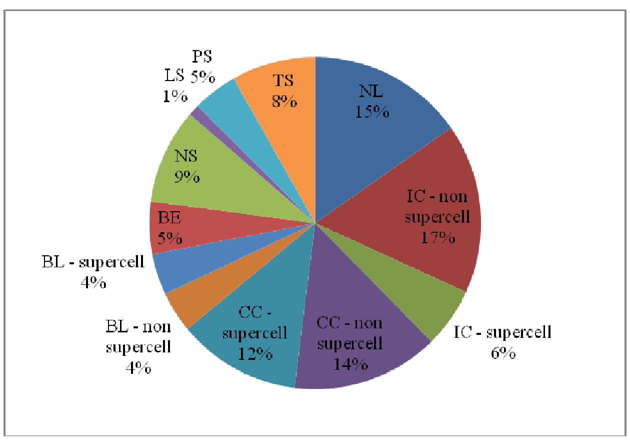


Figure 3. Percentage breakdown by morphology of the contribution to the total number of cases.

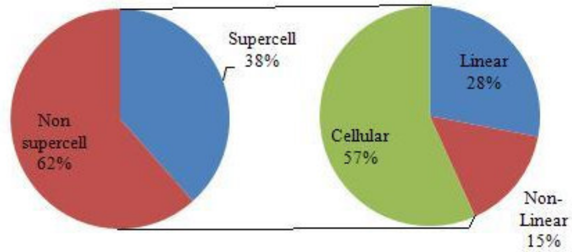


Figure 4. Breakdown by general morphological type. The pie on the left indicates the percentage of cellular systems that were supercellular.

systems since they resemble TS and PS systems. Therefore, some systems may have been classified TS or PS instead of LS even if some contained leading stratiform precipitation. NL systems were the most prevalent in G08, with 28% of all systems being NL in that study. However, IC events in G08 consisted of 26% of all systems, and CC events consisted of 22% of the total. If the supercellular and non-supercellular versions of the CC and IC morphologies in this study were combined, the percentages would be 26% and 25%, respectively. NL systems would still compose the third greatest percentage, however. Therefore, between the two studies, the same three morphologies (IC, CC, NL) occurred most frequently.

More generally, the breakdown by overall type is depticted in Fig. 4. It shows that cellular systems dominated, consisting of 57% of all systems. Of the cellular systems, 38% contained a supercell. The data from G08 behaved similarly, as cellular systems consisted of 51% of the total, while linear and non-linear systems contributed 28% and 21%, respectively, to the total.

If only those systems that produced severe weather were considered, the results changed. Fig. 5 shows that more of the severe events were CC – supercell (17%) than any other morphology. NL events consisted of slightly more than 12% of all severe producing systems, and CC – non-supercell systems composed just under 12% of all severe reports. There is very little difference in the general breakdown between all systems and only severe systems (Fig. 6, compared to Fig. 4). However, a much greater percentage of cellular systems were supercellular when only severe events were considered. 56% of all cellular events that produced severe weather were supercellular. The morphological breakdown in G08 also did not change much by considering only those events that produced severe weather. The same three morphologies composed the three greatest percentages of all severe producing systems, and in the same rank. The percentages became 26%, 23%, and 21% for NL, IC, and CC systems, respectively. The general breakdown also did not change much, as the percentages for each type of system (cellular, linear, non-linear), did not change by more than 6% for any type. The two data sets, therefore, differed in the most frequent morphology and the percentages each morphology contributed to the total, but NL and CC systems were two of the most common morphologies to occur in both studies.

Fig. 7 shows the percentage of systems that produced at least one report of severe weather by morphology. The major point that can be deduced from the figure is that nearly every supercell system produced severe weather, as opposed to the non-supercellular systems, only 59% of which produced severe weather. Also, in general, the NL morphology contained the smallest percentage of events that produced severe weather, 55%. However, if only non-flooding severe reports were considered, then only 36% of NL systems produced severe weather. In G08, NL systems also produced severe weather least frequently. Since

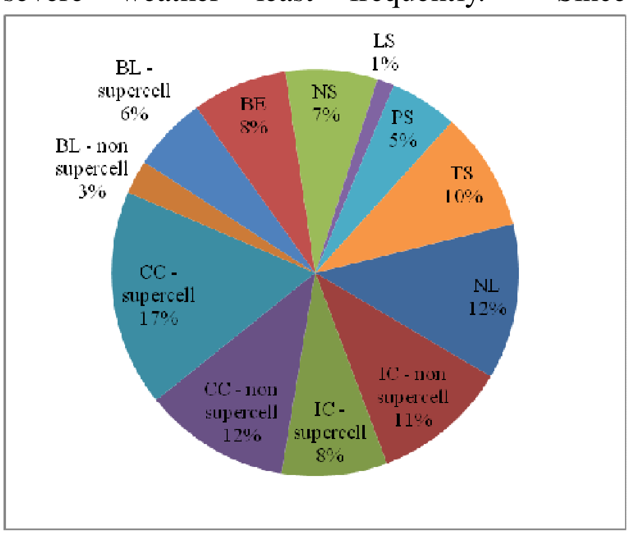


Figure 5. Same as Fig. 3, except for only those systems that produced severe weather.

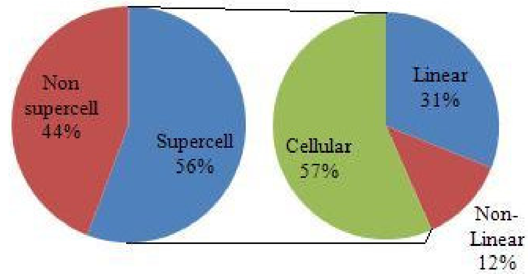


Figure 6. Same as Fig. 4, except for only those systems that produced severe weather.

supercells were not used in G08, it is difficult to directly compare the frequency of severe weather for the cellular morphologies. Therefore, the non-supercellular and supercellular cellular morphologies from this study were combined to give a better comparison to the data from G08 (Table 2). The table shows that the cellular systems produced severe weather more frequently in this study than they did in G08. However, it is noted that, in both studies, linear systems produced severe weather more often than did other types of systems.

Table 2. Percentage of systems from each morphology that produced weather with the supercellular and non-supercellular versions of the cellular morphologies from this study combined.

| Data set | IC | CC | BL |
|---|---|---|---|
| 2002 | 54% | 58% | 67% |
| 2007 | 57% | 74% | 73% |

A breakdown of the number of systems of each type of morphology that occurred in each month is found in Fig. 8. It supports the breakdown shown in Fig. 3, especially that IC – non-supercell events composed the largest chunk of all systems. The most numerous April morphology was the NL morphology, which also occurred most frequently in May. This is no surprise since NL made the second greatest contribution to the total count of systems. IC – non-supercells were the most frequent morphology to occur in June and July. With the exception of BL – non-supercell, NS, and LS cases, all morphologies grew in frequency of occurrence from April to May. In general, the linear systems peaked earlier in the season (in

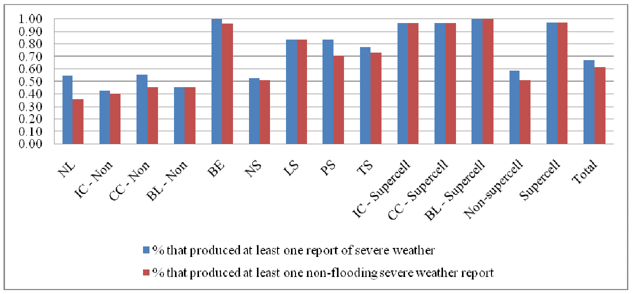


Figure 7. Percent of systems from each morphology that produced at least one report of severe weather and at least one non-flooding report of severe weather.

April or May), while the cellular systems peaked in the mid summer months of June and July.

The situation was similar for G08. NL systems were not the most frequent April or May morphology, but were a close second and third in those months, respectively. The NL morphology was the most frequent in June and July, however. While CC systems were the most frequent in April and May, they were only the third most frequent in June and July. IC systems had the second most occurrances in June and July, but only by a small number compared to NL events. The results of the reanalysis of G08 are summarized by saying that IC, CC, and NL systems were the top three in numbers of events in all months of the study. However, while the most common three morphologies match between the two studies, times at which each morhpology peaked in occurrence do not match. For the G08 data set, the times at which each morphology occurred the most frequently was more chaotic compared to that of the current study.

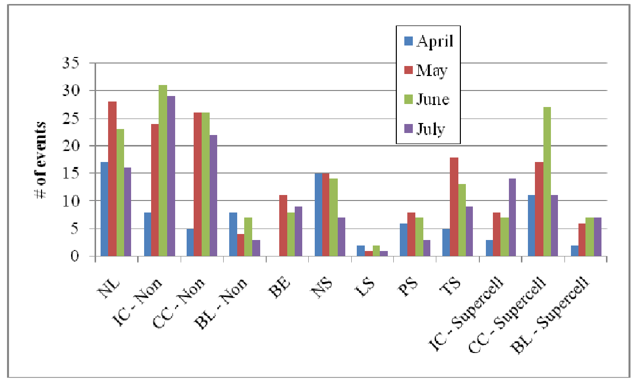


Figure 8. Breakdown by month of the number of systems that occurred by morphology.

*3b. Results by total number of reports*

Figs. 9a-d show the breakdown for the total number of tornado, hail, wind, and flooding reports for each morphology and for each month. The results by total number of reports is best summarized in Table 3. From the table, it is clear that CC – supercell systems produced the most severe weather in all categories except for flooding, in which NL systems produced the most reports. In terms of the most productive morphology, the results from G08 agree with those of the current study for most categories except for wind reports. It is also clear that LS systems produced the fewest reports in all categories in this study, and NS systems were generally the least productive in G08 with the exception of flooding reports (although NS systems only had one more flooding report than IC systems in G08). Although consistent within each individual study, the least productive morphology obviously is not the same between the two studies. The same goes for the second most productive morphology.

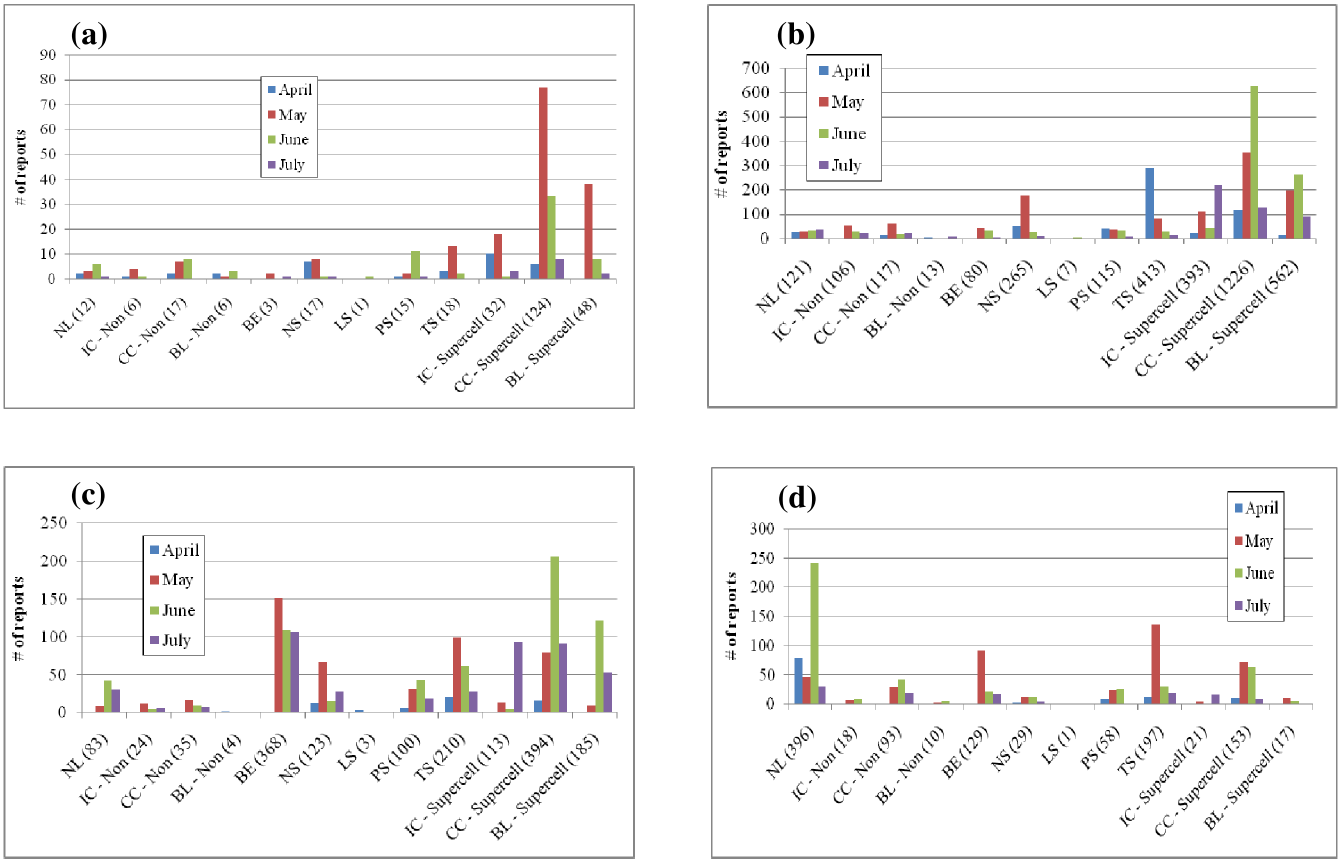


Figure 9. (Clockwise from top left) Total number of reports produced by all systems from each morphology and by month for (a) tornadoes, (b) hail, (c) wind, and (d) flooding.

Table. 3 Top two and least productive morphologies for the various categories of severe weather according to total number of reports from each category. The results from G08 are shown in parentheses.

| Severe weather category | Most productive | Second most productive | Least productive |
|---|---|---|---|
| Total reports | CC – supercell (CC) | BL – supercell (IC) | LS (NS) |
| Tornadoes | CC – supercell (CC) | BL – supercell (IC) | LS (NS) |
| Hail | CC – supercell (CC) | BL – supercell (IC) | LS (NS) |
| Wind | CC – supercell (TS) | BE (CC) | LS (LS) |
| Flooding | NL (NL) | TS (TS) | LS (IC) |

### *3c. Results by average number of reports*

A discussion of the total number of reports of severe weather produced by each morphology must come with the disclaimer that the number of systems affects the number of reports produced. Those systems that were more numerous overall (CC – supercell and NL systems, for example) had more opportunities to produce severe weather. To better understand the ability of each morphology to produce severe weather, reports were normalized to determine the average number of reports produced per event for each morphology. The results are displayed in Figs. 10a-d and Tables 4-7 and are discussed below.

Not only did supercell systems produce the most tornadoes overall, but also produced the greatest average number of tornadoes per event. BL – supercell systems were the most productive on average (Fig. 10a, Table 4). For the reanalyzed G08 data, it was the PS systems

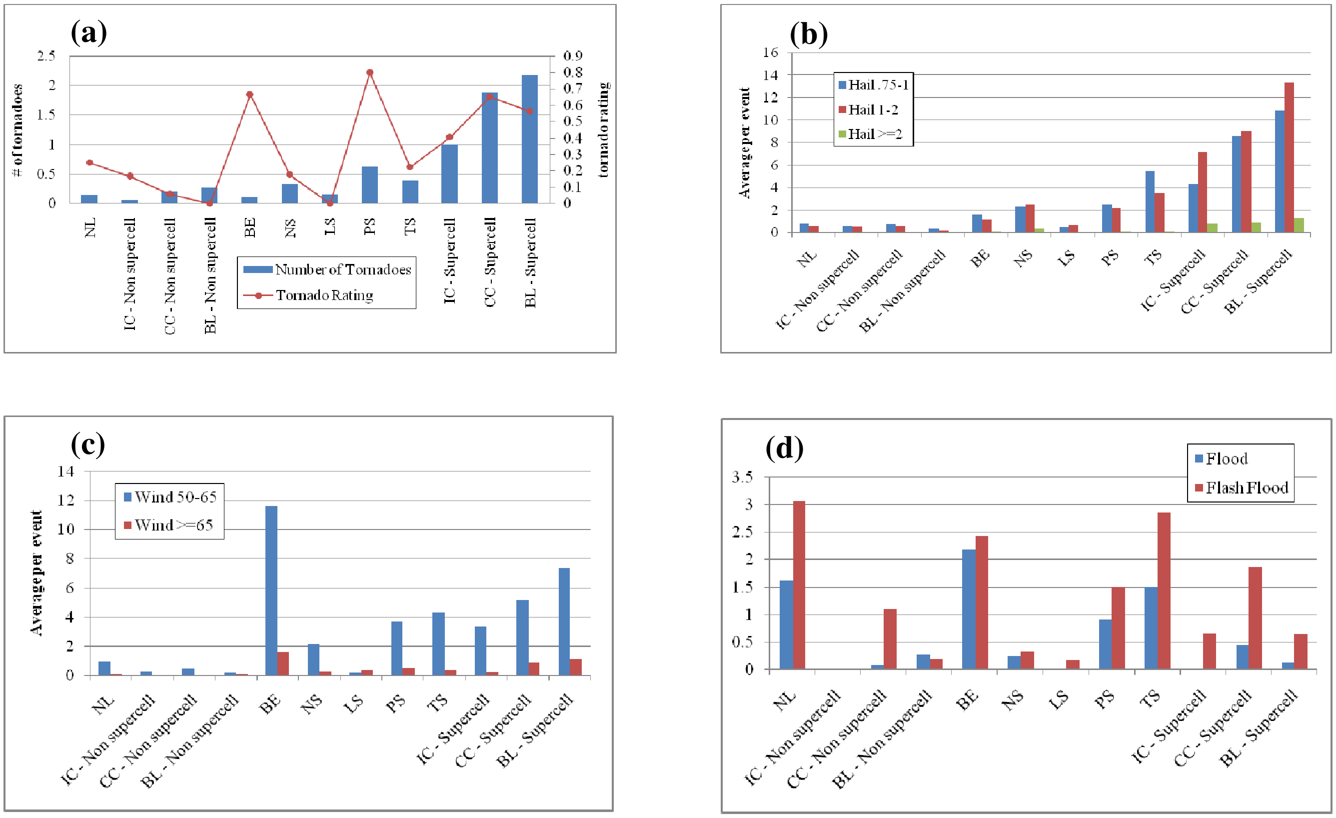


Figure 10. (clockwise from top left) Same as Fig. 9 except average numbers of reports per system for (a) tornadoes and tornado rating, (b) hail, (c) wind, and (d) flooding.

that produced the greatest average number of tornadoes. It is also interesting to determine which morphologies produced the most intense tornadoes. A weighted average of the EF-Scale rating (F-scale rating for the G08 data set) was computed for the tornadoes produced by the systems in each morphology to determine the average strength of the tornadoes produced. Due to the large number of EF0 tornadoes produced by many morphologies, the average ratings are all very low. In fact, none exceed a 1.0 rating (Fig. 10a). PS systems produced the largest average rating for tornadoes (Table 4). Interestingly, the average rating of tornadoes produced by CC – supercell systems was only 0.65. This result is suprising and unexpected since CC – supercell systems produced the most tornadoes and produced the strongest one (the Greensburg, KS EF5), and six EF3s (the largest number of EF3s produced by any morphology). However, PS systems produced only 15 tornadoes, so a few higher ranked (or fewer lesser ranked) tornadoes likely caused the higher averages. IC

Table 4. Morphologies that produced the largest and smallest average number of tornadoes per system and tornado rating for each study. The average per system is given in parentheses.

| | Highest | | Lowest | |
|---|---|---|---|---|
| Data set | Number of tornadoes | Tornado rating | Number of tornadoes | Tornado rating |
| 2002 | PS (1.81) | IC (0.59) | NS (0.10) | NS (0.00) |
| 2007 | BL – supercell (2.18) | PS (0.80) | IC – non-supercell (0.07) | BL – non-supercell & LS (0.00) |

systems produced the highest average rated tornadoes in G08 (Table 4). Between the two studies, there was not much agreement in which systems produce more or stronger tornadoes, other than that the cellular systems in G08 (supercellular systems for the current study) produce the strongest tornadoes.

Supercell systems produced the most reports, on average, of all three size ranges of hail. Specifically, BL – supercell systems produced the greatest average number of all three size ranges of hail per system, and for all hail reports (Fig. 10b, Table 5). The results for G08 were similar. Although BE systems produced the greatest average number of hail between 0.75" and 1" in diameter, BL systems produced the greatest average number of hail reports in the range of 1" to 2" in diameter and were second only to PS systems for the average number of reports per system for the largest hail size range (Table 5). BL systems produced the most reports of all sizes of hail on average, though.

Table 5. Morphologies that produced the largest average number of hail reports per system in each size range and for all hail reports. Numbers in parentheses indicate the average number of reports per event.

| Data set | Hail 0.75" – 1" | Hail 1" – 2" | Hail ≥ 2" | All hail |
|---|---|---|---|---|
| 2002 | BE (9.58) | BL (8.90) | PS (0.82) | BL (17.95) |
| 2007 | BL – supercell (10.91) | BL – supercell (13.36) | BL – supercell (1.27) | BL – supercell (25.55) |

While CC – supercell systems produced more severe wind reports than BE systems (albeit by a small margin), the fewer number of BE systems resulted in a much greater average number of reports of severe wind for these systems (Table 6, Fig. 10c). Note that TS systems had the third highest average, likely due to the resemblance of TS systems to BE systems. BE systems produced the greatest average number of wind reports in both categories also in G08. Table 6 shows clear agreement between the studies that BE systems were the leading producers of wind.

Table 6. Same as Table 5 except for average number of reports of wind per system for each range.

| Data set | Wind 50 - 65 knots | Wind ≥ 65 knots | All wind |
|---|---|---|---|
| 2002 | BE (18.08) | BE (1.42) | BE (19.50) |
| 2007 | BE (11.57) | BE (1.57) | BE (13.14) |

The highest average number of flooding reports per system was produced by BE systems, while NL systems produced the most flash flooding reports per system (Fig. 10d, Table 7). TS systems produced the second and third highest average numbers of reports of flash flooding and flooding per system, respectively, again likely due to their resemblance to BE systems. The stratiform precipitation associated with NL, BE, and TS systems is likely the cause of such a large average number of flooding reports. One surprising result from this study is the fact that PS systems did not produce as many flooding reports on average as NL and BE systems, which disagrees with Parker (2007). However, PS systems did average the most reports of flooding per system in G08 and for all flooding reports, which differs from the results of this study.

Table 7. Same as Table 5 except for average number of flooding reports per system for each type of flooding.

| Data set | Flood | Flash flood | All flood |
|---|---|---|---|
| 2002 | PS (0.68) | TS (3.25) | PS (3.86)* |
| 2007 | BE (2.18) | NL (3.08) | NL (4.71) |

*The average of all flooding reports from G08 includes urban/small stream flooding reports (not shown). Urban/small stream flooding reports were not included in this study.

Table 8. Percentage of the total amount of reports or systems contributed by each type of morphology. The * denotes that the two percentages do not add to 100% because 3 hail reports occurred with a CC system that did not have enough data to be considered a supercell or non-supercell system.

| | | Percent that produced severe weather | Percent of all severe weather reports | Percent of all tornado reports | Percent of all hail reports | Percent of all wind reports | Percent of all flooding reports | Percent of all systems | Percent of severe systems |
|---|---|---|---|---|---|---|---|---|---|
| All morphologies | Supercell | 97.5% | 50.4% | 68.2% | 63.6%* | 44.8% | 17.0% | 21.7%* | 31.4%* |
| | Non-supercell | 59.1% | 49.6% | 31.8% | 36.2%* | 55.2% | 83.0% | 77.8%* | 68.1%* |
| Cellular morphologies only | Non-supercell | 48.4% | 6.9% | 9.7% | 6.9% | 3.8% | 10.8% | 34.7% | 24.9% |

*d. Supercellular vs. non-supercellular systems*

A deeper look at the supercellular and non-supercellular systems will now be taken to compare how much, and how intense, severe weather each type of system produced. Another look at Figs. 7, 9, and 10, and a look at Tables 8 and 9 reveals many differences between supercell systems and non-supercell systems and between the supercellular and non-supercellular versions of the cellular morphologies.

Supercellular systems produced severe weather more frequently (almost every single supercellular system produced severe weather) than did any other type of system, produced over half of all severe weather reports, more than two-thirds of all tornadoes, and a significant number of hail reports compared to the non-supercellular systems, yet they only composed 21.7% of all systems and 31.4% of all severe systems.

The total number of reports produced by non-supercellular cellular systems was tiny compared to that of the supercellular systems. The 29 tornadoes produced by the IC – non-supercell, CC – non-supercell, and BL – non-supercell systems is a mere 14% of the 204 tornadoes produced by the supercellular systems. This trend holds for hail and wind reports, too. The non-supercellular cellular systems produced about 9.2 times fewer hail reports and nearly 11.0 times fewer wind reports as the cellular systems. In fact, the non-supercellular cellular systems produced only six reports of hail greater than or equal to 2” in diameter and three reports of wind greater than or equal to 65 knots. Those numbers compare to 116 and 89 reports of hail at least 2” in diameter and wind gusts at least 65 knots, respectively. There was a much closer comparison for flooding: 121 reports of flooding for the non-supercellular cellular systems against 191 for the supercellular systems.

In terms of average number of reports per event, supercellular systems far exceeded their non-supercellular counterparts and all other systems as well. This is obvious by observation of Table 9, which shows that the average number of reports per system for the supercellular systems was greater (in some cases far greater) than it was for the non-supercellular systems for every category of severe weather

Table 9. Same as Table 8 except for average numbers of reports per system for the various types of severe weather and for each type of morphology.

| | | Tornado number (rating) | Hail | Wind | Flooding | All reports |
|---|---|---|---|---|---|---|
| All morphologies | Supercell | 1.70 (0.59) | 18.18 | 5.99 | 1.59 | 27.23 |
| | Non-supercell | 0.22 (0.27) | 2.88 | 2.15 | 2.17 | 7.48 |
| Cellular morphologies only | Non-supercell | 0.15 (0.07) | 1.23 | 0.33 | 0.63 | 2.34 |

except for flooding, in which the all other morphologies averaged 2.17 flooding reports per event over the supercellular systems' average of 1.59. The higher average for the non-supercellular systems is likely due to the presence of the top flood producing systems, BE and NL, as non-supercellular systems. One major point to be made is that the average tornado rating of all supercellular systems was 0.59, compared to 0.27 for all other systems and 0.07 for the non-supercellular cellular sytems. So, it is clear that the supercellular systems were clearly more "dangerous" than their non-supercellular counterparts for all types of severe weather, and more "dangerous" than all other non-supercellular systems (including the supercellular ones) for all types of severe weather except for flooding.

## 4. Discussion and Conclusions

This study expanded the work done by Gallus et al. (2008), in which all convective events that occurred within a ten-state domain that included the midwest and great plains between April and August were classified according to their dominant morphology. The time period of this study was shortened to April through mid July. Systems had to meet specific radar criteria to be classified. Nine morphologies were used. All severe reports, which were obtained from NCDCs *StormData*, were attributed to the dominant morphology that characterized each system during its lifetime. Then, using storm attribute data and the Level III NEXRAD mesocyclone product from NCDC, supercell systems were separated from their non-supercellular counterparts according to the existence of a mesocyclone in a recognizable cellular element from one of the cellular morphologies (IC, CC, and BL). Data from G08 was also reanalyzed to match the 1 April through 19 July time period used in the present study to allow comparisons to be made.

The overall results are summarized in Table 10. They indicate that, although CC systems were more numerous and thus produced more total severe weather, BE and BL – supercell systems are the most violent overall between the two studies since each is the top producer, by average, of at least two individual types of severe weather and by all severe weather combined. BL – supercell systems were second behind CC – supercell systems in total tornado and hail production, but led CC – supercell systems in average hail, wind, and tornado reports per system. It should be noted that 100% of all BL – supercell systems produced severe weather, as did 97.5% of all CC – supercell systems, and 83.3% of BE systems in G08 produced severe weather.

On the other hand, the "weakest" morphology was LS. LS systems produced the fewest number of reports and had some of the lowest average number of reports per system for all categories of severe weather. Additionally, very few LS systems were classified. Two candidates, NS and NL systems, qualify as the "weakest" morphologies in G08 since NS systems produced the least amount of severe

Table 10. Overall leaders by morphology in terms of total number of reports and average number of reports per system for the various categories of severe weather and for all reports combined. Numbers in parentheses indicate the value for the total number of reports or the average number of reports per system for each leading morphology.

| | Data set | Tornadoes | Hail | Wind | Flooding | Total |
|---|---|---|---|---|---|---|
| Total | 2002 | CC (83) | CC (1358) | TS (476) | NL (330) | CC (1876) |
| | 2007 | CC – supercell (124) | CC – supercell (1226) | CC – supercell (394) | NL (396) | CC – supercell (1897) |
| Average | 2002 | PS (1.81) Rating: IC (0.59) | BL (17.95) | BE (19.50) | PS (3.86) | BE (36.58) |
| | 2007 | BL – supercell (2.18) Rating: PS (0.8) | BL – supercell (25.55) | BE (13.14) | NL (4.71) | BL – supercell (36.91) |

weather and NL systems had the lowest average number of reports per system.

Supercell systems were dominantly violent in this study. As was shown in Tables 8 and 9, the supercell systems produced a greater proportion of all severe reports and of many individual categories of reports, including: all hail sizes and tornado number. Therefore, the hypothesis that supercellular systems produce more severe weather and more violent severe weather is true in most ways that this study measured. They clearly did not produce a significant number of flooding reports. Due to the areal coverage of an individual cell being very small compared to that of linear and non-linear systems, it seems reasonable that this is the case. The morphologies that produced more flooding (NL, BE, TS) had larger areal coverage and thus could dump more rain over a larger region than could cells.

The comparison between this study and G08 revealed some similarities and some differences, which shows that the hypothesis that the trends displayed by the systems in G08 will also be displayed by those in the current study is partially true. There was a disparity between the number of systems classified and the number of reports of severe weather produced. This is likely the result of a difference in convective activity for the years used between the two studies. Despite that, NL, CC, and IC systems constituted the greatest proportion of all systems in both studies, and cellular systems were generally the most prominent in both studies. BL – supercell systems produced the most severe weather overall in this study, but BE systems produced the most in G08. While LS, PS, and BE systems most frequently produced at least one report of severe weather in G08 (around 85% of the systems from each morphology produced at least one report of severe weather), it was BE and supercell systems that most frequently produced severe weather in the current study (nearly 98% for each of those morphologies). Although several morphologies competed for top production of severe weather in G08, BE systems are considered the "most dangerous" morphology since they produced the most severe weather on average. Additionally, one must realize that the supplementation of 24 additional systems from Parker and Johnson (2000), and the fact that no systems were supplemented in the current study could alter the comparison between those systems in both studies. Thus the fact that LS systems were the "least dangerous" in this study does not correlate with that of G08.

An overall analysis of both studies reveals that BE, CC, and BL systems are generally the most productive severe weather systems, especially in terms of hail and tornadoes for CC and BL systems, but NL, TS, and BE systems produce the most flooding of all the morphologies, and BE systems conclusively produce the most severe wind.

Future work includes expanding the areal coverage of the study to that of the entire continental U.S. to develop a climatology of severe weather and convective events for all portions of the country, expanding the time domain to include all portions of the year, adding additional morphologies (such as TL/AS from Schumacher and Johnson 2005), and allowing systems from all morphologies (not just cellular ones) to be eligible to contain supercells. However, if the latter were used in the methodology of any follow up studies, the author of this study suggests that severe reports be associated only with individual convective elements and not general morphologies.

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