2-2008

Spring and Summer Severe Weather Reports over the Midwest as a Function of Convective Mode: A Preliminary Study

William A. Gallus Jr.
Iowa State University, wgallus@iastate.edu

Nathan A. Snook
University of Oklahoma Norman Campus

Elise V. Johnson
University of Alabama - Huntsville

Follow this and additional works at: http://lib.dr.iastate.edu/ge_at_pubs

Part of the Atmospheric Sciences Commons, Geology Commons, and the Meteorology Commons

The complete bibliographic information for this item can be found at http://lib.dr.iastate.edu/ge_at_pubs/52. For information on how to cite this item, please visit http://lib.dr.iastate.edu/howtocite.html.
Spring and Summer Severe Weather Reports over the Midwest as a Function of Convective Mode: A Preliminary Study

Abstract
Radar data during the period 1 April-31 August 2002 were used to classify all convective storms occurring in a 10-state region of the central United States into nine predominant morphologies, and the severe weather reports associated with each morphology were then analyzed. The morphologies included three types of cellular convection (individual cells, clusters of cells, and broken squall lines), five types of linear systems (bow echoes, squall lines with trailing stratiform rain, lines with leading stratiform rain, lines with parallel stratiform rain, and lines with no stratiform rain), and nonlinear systems. Because linear systems with leading and line-parallel stratiform rainfall were relatively rare in the 2002 sample of 925 events, 24 additional cases of these morphologies from 1996 and 1997 identified by Parker and Johnson were included in the sample. All morphologies were found to pose some risk of severe weather, but substantial differences existed between the number and types of severe weather reports and the different morphologies. Normalizing results per event, nonlinear systems produced the fewest reports of hail, and were relatively inactive for all types of severe weather compared to the other morphologies. Linear systems generated large numbers of reports from all categories of severe weather. Among linear systems, the hail and tornado threat was particularly enhanced in systems having leading and line-parallel stratiform rain. Bow echoes were found to produce far more severe wind reports than any other morphology. The flooding threat was largest in broken lines and linear systems having trailing and line-parallel stratiform rain. Cellular storms, despite much smaller areal coverage, also were abundant producers of severe hail and tornadoes, particularly in broken squall lines.

Keywords
climate change, precipitation (meteorology), rain, storms, tornadoes, bow echoes, cellular convection, cellular storms, convective storms, weather forecasting, flooding, hail, radar, risk assessment, spring (season), stratiform cloud, summer

Disciplines
Atmospheric Sciences | Geology | Meteorology

Comments
This article is from Weather and Forecasting 23 (2008): 101, doi: 10.1175/2007WAF2006120.1. Posted with permission.

This article is available at Iowa State University Digital Repository: http://lib.dr.iastate.edu/ge_at_pubs/52
Spring and Summer Severe Weather Reports over the Midwest as a Function of Convective Mode: A Preliminary Study

WILLIAM A. GALLUS JR.
Department of Geological and Atmospheric Science, Iowa State University, Ames, Iowa

NATHAN A. SNOOK
School of Meteorology, University of Oklahoma, Norman, Oklahoma

ELISE V. JOHNSON
Department of Atmospheric Science, University of Alabama in Huntsville, Huntsville, Alabama

(Manuscript received 27 December 2006, in final form 19 July 2007)

ABSTRACT

Radar data during the period 1 April–31 August 2002 were used to classify all convective storms occurring in a 10-state region of the central United States into nine predominant morphologies, and the severe weather reports associated with each morphology were then analyzed. The morphologies included three types of cellular convection (individual cells, clusters of cells, and broken squall lines), five types of linear systems (bow echoes, squall lines with trailing stratiform rain, lines with leading stratiform rain, lines with parallel stratiform rain, and lines with no stratiform rain), and nonlinear systems. Because linear systems with leading and line-parallel stratiform rainfall were relatively rare in the 2002 sample of 925 events, 24 additional cases of these morphologies from 1996 and 1997 identified by Parker and Johnson were included in the sample.

All morphologies were found to pose some risk of severe weather, but substantial differences existed between the number and types of severe weather reports and the different morphologies. Normalizing results per event, nonlinear systems produced the fewest reports of hail, and were relatively inactive for all types of severe weather compared to the other morphologies. Linear systems generated large numbers of reports from all categories of severe weather. Among linear systems, the hail and tornado threat was particularly enhanced in systems having leading and line-parallel stratiform rain. Bow echoes were found to produce far more severe wind reports than any other morphology. The flooding threat was largest in broken lines and linear systems having trailing and line-parallel stratiform rain. Cellular storms, despite much smaller areal coverage, also were abundant producers of severe hail and tornadoes, particularly in broken squall lines.

1. Introduction

Many attempts have been made to classify the morphologies of midlatitude convective systems. Parker and Johnson (2000) devised three main morphologies for linear convective systems: those with trailing stratiform, those with leading stratiform, and those with parallel stratiform rain. In addition, Bluestein and Jain (1985) proposed four different organizational modes for the formation of squall lines: broken line, broken areal, embedded areal, and backbuilding. Grams et al. (2006) modified these morphologies in a study of the relationship between mesoscale model forecast errors and observed system type, using classifications of continuous linear, continuous bowing, continuous nonlinear, discontinuous areal, and isolated cells. Fowle and Roebber (2003) examined the ability of a near-cloud resolving resolution numerical model to depict storm morphology by focusing on three system types: linear, multicellular, and isolated. Classification of storm morphology is important because different modes may behave differently and be dominated by different dynamics.

Corresponding author address: William A. Gallus Jr., Iowa State University, 3025 Agronomy, Ames, IA 50011.
E-mail: wgallus@iastate.edu

DOI: 10.1175/2007WAF2006120.1

© 2008 American Meteorological Society
In addition, it has long been recognized that storms of different morphologies produce different types of severe weather events. As early as 1978, Fujita (1978) provided insights into the development of bow echoes, and recognized that this type of storm was associated with the production of severe wind events. In addition, Trapp et al. (2005) documented the occurrence of tornadoes in some bow echoes. Supercell storms have long been recognized in the meteorological community as the most common producers of tornadoes (Moller et al. 1994). Miller and Johns (2000) have shown that the most extreme wind events within derechos can be associated with embedded supercells. Although squall lines are not generally thought to produce the most violent types of severe weather, Trapp et al. (2005) noted the occurrence of tornadoes in some squall lines. Using Parker and Johnson’s classification scheme, Pettet and Johnson (2003) found that storms with leading stratiform and parallel stratiform morphologies played a role in flash flooding. A better understanding of the relationship between storm morphology and severe weather reports could allow for better specification of severe hazards during convective storms, and could lead to a better understanding of the behavior of convective storms.

The present study examines convective events over a 5-month period during the warm season of 2002 to determine whether or not particular types of severe weather are more or less likely to be associated with particular convective morphologies. Section 2 discusses the data and methodology. Results follow in section 3, with conclusions summarized in section 4.

2. Data and methodology

Using radar data from the University Corporation for Atmospheric Research (UCAR) warm season archive (information online at http://locust.mmm.ucar.edu/episodes/) all convective storms that occurred over 10 midwestern states (Fig. 1) during the period between 1 April and 31 August 2002 and met specific radar-based criteria were classified according to their predominant morphology. This region was chosen because it is convectively active with a substantial number of severe thunderstorm events producing all types of severe weather during both the spring and summer seasons. To be counted as a part of the dataset, a storm had to persist for at least 1 h, had to attain a peak radar echo intensity of at least 30 dBZ, and had to contain echo above the noise level of the data (10 dBZ) covering an area greater than approximately 6 km × 6 km. These criteria were selected due to the limitations on the spatial and temporal resolution of the radar data archive, and they were used for all of the morphologies described below. Radar images were available at most once every 30 min (more often every 60 min) and were limited to approximately 2 km × 2 km horizontal resolution.

Storms were classified as cellular, nonlinear, or linear. Cellular systems were those in which the strongest radar echoes were organized into discrete, individual cells. Cellular storms were subdivided into three morphologies: individual cells (IC; no weaker radar echoes connecting the cells), clusters of cells (CC; connected by weaker radar echoes), and broken squall lines (BL; individual cells arranged in a linear fashion). Although Bluestein and Jain (1985) considered broken lines to be one of the organizational modes for the formation of squall lines, the present study emphasizes severe weather reports that are localized and more dependent on storm-scale dynamics than on mesoscale organization, so we felt it more appropriate to consider them a type of cellular system. The individual cells producing the severe weather in broken lines usually have some separation between them, thus resembling the other cellular types more than the linear ones. Linear systems were those in which the strongest radar echoes were organized in a connected, linear fashion at least 75 km in length and at least three times as long as wide, with these criteria present on the available radar images for at least 2 h. Five morphologies fell into the linear category, including three morphologies proposed by Parker and Johnson (2000): squall lines with trailing (TS), leading (LS), or line-parallel stratiform rain (PS), as well as two other morphologies, squall lines without stratiform rain (NS), and bow echoes [BE, considered a type of quasi-linear convective system by Trapp et al. (2005)]. Nonlinear convective systems (NL) were those in which the strongest radar echoes were organized in a connected but nonlinear fashion. A schematic showing
the general organization of the nine morphologies is shown in Fig. 2.

It is recognized that any classification of dominant storm morphology is inherently subjective since storm structures cover a spectrum of types and often evolve over time. These challenges have been confronted in several recent papers (e.g., Parker and Johnson 2000; Done et al. 2004; Grams et al. 2006). In addition, in the present study, storms were classified according to the dominant morphology over time exhibited in the radar data, which had a rather coarse temporal resolution. The classification procedure first involved determining the lifetime of the storm with the start (end) time being the first (last) radar image where 10-dBZ echo coverage exceeded the 6 km × 6 km area with a maximum exceeding 30 dBZ. Next, each radar image was examined in chronological order to note the morphology and any changes in it over time. If the morphology remained the same throughout the life of the event, all storm reports were attributed to that mode. If the morphology changed during the life of the system, and each different mode was present for more than 1 h, storm reports during those time periods were attributed to the different modes present at the times of the reports. However, if one particular mode was present for 1 h or less (e.g., in only one hourly image), usually the case in newly formed or dying systems, that morphology was ignored and the storm reports were attributed to the morphology that dominated the majority of the system’s lifetime. It should be noted that the hourly resolution of the radar images introduces some uncertainty into monitoring individual cells, whose lifetimes may be

---

**Fig. 2:** Schematic demonstrating each of the nine storm morphologies used in the classification system. Morphologies are abbreviated as follows: IC, isolated cells; CC, clusters of cells; BL, broken line; NS, squall line with no stratiform rain; TS, squall line with trailing stratiform rain; PS, squall line with parallel stratiform rain; LS, squall line with leading stratiform rain; BE, bow echo; and NL, nonlinear system.
less than 1 h. This drawback is minimized by our emphasis on general storm type. If isolated cells are present in the general area over a period of more than 1 h, severe weather reports will be attributed to the isolated cell category, and it is not important to know if the cell present at a later time is the same cell seen at a slightly earlier time. If systems extended beyond the edge of the 10-state domain, they were included in the sample, but only storm reports from within the 10-state region were included. It is recognized that in some events, the storm reports may have not occurred until the system left the domain, and thus the inclusion of these events in the sample could introduce some bias into the results. However, the number of such events was small, and other biases would have been introduced by ignoring these events.

Because the number of linear systems having either line-parallel or leading stratiform rainfall was small over the 10 midwestern states during the 2002 period, this dataset was supplemented by including a total of 24 linear systems having line-parallel and leading stratiform rainfall during the spring and summer of 1996 and 1997, as identified by Parker and Johnson (2000) in the same 10-state region. Since there is no obvious reason to believe that the types of storm reports associated with a particular morphology would have changed between 1996 and 2002, and the two years are close enough in time to minimize differences in public reporting of storm reports, the addition of these 24 events into the sample should not introduce any bias into the statistics large enough to adversely affect results.

All severe weather reports that occurred over the same time period were recorded, cataloged, and associated with the storm systems that produced them using data from the National Climatic Data Center (NCDC) Storm Events Database. Categories of severe reports included hail 0.75 in. or larger but <1 in. in diameter, hail ≥1 but <2 in. in diameter, hail ≥2 in. in diameter, severe wind ≥50 but <65 kt, severe wind ≥65 kt, floods/flash floods, and tornadoes.

Numerous studies have pointed out bias and quality problems inherent in the Storm Events Database (e.g., Doswell and Burgess 1988; Weiss et al. 2002; Doswell et al. 2005; Verbout et al. 2006; Trapp et al. 2006; Smith et al. 2006). For instance, Doswell et al. (2005) note that although tornadoes are assigned a pathlength and width, hail and wind reports are treated as point events, despite the fact that hail and wind occur in swaths having diverse geometrical properties. Treating these events as point occurrences means that it is likely the largest hailstone and strongest wind gust do not get reported. Hail size is rarely measured, and at least half of the wind reports do not contain a measured wind value. In the present study, reports that only indicated wind damage and not a speed were included with the winds <65 kt. Trapp et al. (2006) suggest that in the future, damage surveys similar to those performed after tornadoes be done for wind-producing thunderstorms to reduce some of these problems. Among other problems, uncertainties exist in assignments of tornado intensity. Human bias and population biases also influence all types of severe weather reports and are largely responsible for substantial increases in the numbers of weaker tornadoes, hail, and wind reports appearing in the database over time (e.g., Billet et al. 1997; Weiss et al. 2002; Verbout et al. 2006). In sparsely populated regions, particularly before the growth in popularity of “storm chasing,” many severe weather events were likely unreported. The narrow temporal focus of the present study helps to minimize problems from the changing climatology, but the other deficiencies in reporting must be kept in mind when interpreting results.

A few additional limitations of the present study should be noted. First, only 10 midwestern states were examined, and primarily over a period of only 5 months. Despite these spatial and temporal limitations, 949 different systems were identified. Nonetheless, a larger sample size might be needed to generalize the results, particularly to other geographic regions and other seasons. Second, the partitioning of severe hail and wind reports into multiple categories enhances the sensitivity of some of the results in the present study to errors in severe storm reports. Finally, classification of morphology is somewhat subjective and difficult at times. Even with strict objective guidelines defining each morphology, there are still storms that may exhibit two or more morphologies, making classification difficult. Approximately 10% of the cases analyzed proved especially difficult to classify.

3. Results

The distribution of the nine morphologies associated with the 949 separate storm systems identified from the radar data examined across the 10-state region can be seen in Fig. 3. Note that the states vary in area from around 150 000 km² (Iowa) to 225 000 km² (Minnesota), so caution must be used in comparing state totals directly. Among those morphologies containing large numbers of events, nonlinear systems are a relatively larger fraction of the whole sample in northern areas. Isolated cells and clusters of cells are a larger fraction of the events in the Great Plains states from South Dakota south to Oklahoma than they are in areas farther east.
Distribution by month

The distribution of severe storm reports for each morphology as a function of month is shown in Fig. 4. Tornadoes (Fig. 4a) are most common in April or May for most morphologies except NS, TS, and NL systems, which have their peaks later in the summer. The distribution of hail reports (Fig. 4b) is similar to that of tornadoes, although the differences between the summer monthly totals and the peak spring totals are less than with tornadoes. Some tendency for wind reports to be more common later in the year than hail or tornado reports can be seen in Fig. 4c. For cellular systems, in particular, the distribution of wind reports is more uniform over all months than for hail or tornadoes. Flooding reports (Fig. 4d) dominate in May and June. Overall, severe reports for cellular systems are most common in April or May, despite the fact that the number of these cellular systems is greatest in July or August (Fig. 5), primarily due to an increased frequency of IC events in summer. The NL, NS, and TS systems show a peak in severe reports in summer (Fig. 4), matching the months when these types of systems are most common (Fig. 5). The BE, LS, and PS events have a May peak in severe reports. May is also the month of peak occurrence for LS and PS systems (Fig. 5), while the relatively rare BE events are fairly evenly distributed. The tendency for cellular events to be most common in summer and yet most associated with severe weather reports in spring implies that these cellular events may be more often supercells in the spring when vertical wind shear is more favorable for storm-scale rotation, and more often nonsupercellular in the summer. The larger number of PS and LS events early in the warm season compared to NS and TS events is consistent with Parker and Johnson’s (2004) and Parker’s (2007a,b) findings that LS and PS systems occur in more strongly sheared environments that may also favor supercells. Most morphologies showed a relative minimum in severe weather reports during July, likely reflecting the weather pattern during 2002 and not necessarily long-term climatology.

Distribution by convective node

The distribution of the 949 events among the nine morphologies is shown in Fig. 6. Cellular systems were most common, composing 48% of all storms. Nonlinear systems composed 29% of storm systems, and linear systems composed the remaining 23%. Fowle and Roebber (2003) stated that linear systems were the most organized of all convective events, and thus it may not be surprising that this type of system was less frequent. Nonlinear convective systems were the most common of the nine morphology categories given, possibly a result of the fact that this category was not subdivided, while bow echoes and squall lines with leading stratiform rain were the rarest, occurring only 16 and 18 times, respectively, in the dataset. It should be noted that most BE events could also be classified as TS systems, although we did not assign multiple morphologies in the present study.

Of the 949 systems classified, 671 (71%) were associated with at least one report of flooding or severe
report meeting Storm Prediction Center (SPC) criteria for hail size (≥3/4 in. diameter), wind speed (≥50 kt and/or convective wind damage), or tornado (Fig. 7). The relatively high frequencies of severe reports from all types of storms may reflect the minimum criteria used for evaluation, which ensured that a cell had to cover at least a 6 km × 6 km region over a period lasting for more than 1 h with a maximum intensity ≥30 dBZ. A higher reflectivity threshold would likely have led to even larger frequencies of severe reports since it would have excluded more moderate intensity storms less likely to produce severe weather. Linear systems were most likely to be associated with at least one severe report, with every linear type averaging higher than an 80% rate. Cellular and nonlinear systems had rates below 70%. The lower rates for cellular systems may reflect their smaller areal coverage. Small size would not explain the lower rates for NL events, and it is likely the lower rates reflect a tendency for many of these systems to be less organized and occur in an environment less conducive for severe weather. The 671 “severe” systems were associated with a total of 9678 severe reports meeting the SPC criteria and 1122 flooding reports. Cellular systems produced the most severe reports, accounting for 45% of severe weather reports (Fig. 8a). Linear systems, though they composed only 23% of observed storm systems, produced 34% of severe weather reports. The remaining 21% of severe reports were caused by nonlinear convective systems. Of the nine specific morphologies examined, clusters of cells produced the largest total of severe weather events, followed closely by nonlinear systems and isolated cells. Flooding events were dominated by nonlinear systems, with trailing stratiform linear systems next in importance (Fig. 8b).

c. Severe reports as a function of convective mode

When the results are broken down according to type of severe report, additional observations can be made.
First, however, a basis for comparison must be defined that accounts for the fact that the number of occurrences of different morphologies varied widely (Figs. 6 and 7). Because of this variation the number of severe reports associated with each morphology was normalized by the number of occurrences of that morphology to arrive at a number of severe reports per case. Although this normalization helps in some ways to better convey the risk of severe weather from a particular morphology, it must be noted that the great variations in areal coverage among the storm types also must be considered. Normalization by area would provide additional information to help convey the risk, but such normalization would require a huge amount of additional time and was beyond the scope of this study. One should keep in mind while interpreting the results that follow that cellular systems are much smaller in scale.
than linear and nonlinear systems, with potentially less than 10% of the areal coverage. It should also be noted that other factors influence the number of storm reports including longevity of systems, time of day, population and/or spotter density, and National Weather Service (NWS) office report collection procedures, among others. Thus, a wide range of parameters could be used for normalization.

Figure 9 shows that the most reports per case of severe hail less than 1 in. in diameter were observed in bow echoes and broken lines. Bow echoes averaged 9.88 reports per case, and broken lines 8.34. For the other linear types of systems, the largest hail frequency was in line-parallel stratiform cases, followed by leading stratiform, trailing stratiform, and finally no stratiform rain cases.

For severe hail ≥1 and <2 in. in diameter (Fig. 10), broken lines clearly dominated with the most events per case (8.3). The LS and PS storms had between five and six reports per case, while no other morphology had more than four.

Figure 11 shows the number of severe reports per case of significantly severe hail (≥2 in. in diameter) for each morphology. Squall lines with line-parallel stratiform rain had the greatest number of reports per case, 0.83, a result that may be surprising since hail of this size is often believed to require the intense updrafts only found in cellular convection. However, Parker (2007a,b) pointed out that these systems with line-parallel stratiform rain occur in environments similar to those favoring supercells, and quasi-supercellular elements were produced in simulations of these events. In
general, storms having all three cellular morphologies had relatively larger numbers of reports per case than all linear types except LS and PS, a result different from that of the smaller-hail categories. Although our database does not include supercells as a separate category, we speculate that the larger values of wind shear and instability often associated with supercell environments may allow updraft speeds to approach theoretical buoyancy-derived values (Bluestein et al. 1988), permitting exceptionally large hail to fall from supercells, which likely constitute a sizable portion of the events in our cellular classifications. Significant hail larger than 2 in. in diameter is very rare in all storms, regardless of morphology. We speculate that if supercells were a separate category in our analysis, very large hail might be most frequent for that type of storm.

Parker and Johnson (2004) noted that LS events tend to fall in environments in the spectrum between those favoring TS events and those with supercells. Thus, it may be reasonable to expect the LS and PS types of squall lines to be associated with more significant hail reports and tornadoes, the severe storm reports typically associated with cellular convection, than would be found with TS squall lines. The low number of significant hail reports associated with TS events may be consistent with the theory proposed in Rotunno et al. (1988) that implies TS events, typically having a strong cold pool, do not have an optimal balance between the cold pool–induced vorticity and that due to the ambient low-level shear, and are unable to generate long-lived updrafts strong enough to produce significant hail. The lack of significant hail despite an abundance of smaller hail is especially evident for bow echoes (BE), which had no reports of hail 2 in. or greater in diameter within the domain of this study, despite having the highest frequency of severe hail less than 1

![Fig. 10. As in Fig. 9 but for reports of severe hail 1–2-in. diameter per case.](image)

![Fig. 11. As in Fig. 9 but for reports of severe hail 2-in. or greater in diameter per case.](image)
in. in diameter. In general, a relative minimum in hail frequency was present for nonlinear systems, and linear systems with trailing stratiform rain, or no stratiform rain.

Reports of severe wind less than 65 kt (or wind damage not assigned a speed) are shown in Fig. 12. Bow echoes clearly dominate in this category, with 18.56 reports per case, nearly twice as many reports per case as the next most active morphology, squall lines with trailing stratiform rain (7.92). This result corresponds well with the longstanding traditional perception of bow echoes as prolific wind producers (Fujita 1978). A possible explanation for the large number of reports for the TS morphology is that trailing stratiform systems, just like bow echoes, often have well-developed rear-inflow jets that can transfer momentum toward the surface (e.g., Smull and Houze 1987; Duke and Rogash 1992). Most bow echoes do contain trailing stratiform rain, and the only difference between these two morphologies is in the shape of the leading convective line. If the bow echoes in this study were also classified as TS events, the wind reports for TS would increase substantially. The results for reports of severe wind 65 kt or greater in magnitude (Fig. 13) were very similar to those for severe wind less than 65 kt.

As shown in Fig. 14, two different linear morphologies had the greatest number of reports of flooding per case. These morphologies were squall lines with line-parallel stratiform rain (3.75 reports per case) and squall lines with trailing stratiform rain (3.04 reports per case). Flood frequency was much less for linear systems lacking stratiform rain. Broken lines were fairly substantial flood producers as well. As might be expected due to their small size, the other two cellular morphologies had the smallest frequency for flood reports.

The fact that there was such a marked difference between different linear morphologies for flood reports
suggests that the location of the stratiform rain in relation to the squall line is very important in predicting flooding potential. In cases of squall lines with line-parallel stratiform rain, winds aloft are generally rather strong and parallel to the line; this wind profile is necessary to cause stratiform rain to be blown in a direction parallel to the line. This also suggests that back-building (Parker and Johnson 2000; Parker 2007a) and training of cells, likely steered by these strong line parallel upper-level winds, may be a cause of flooding in these cases (Doswell et al. 1996; Schumacher and Johnson 2005, 2006). In cases of squall lines with trailing stratiform rain, the often very large area of stratiform rain behind the squall line can augment heavy rainfall totals and induce flooding. Leading stratiform rain cases likely occur with strong rear-to-front flow aloft that could increase the speed of movement of these systems, reducing the flood threat. It must be noted, however, that Pettet and Johnson (2003) found LS systems to possess a distinct flood threat, and Parker and Johnson (2000) found LS systems to often be slow moving. Further research is needed to explore the causes of the differences between that study and the present one. It is also unclear why linear systems lacking stratiform rain have the least likelihood of producing flooding, although the total rain volume produced by the systems may be less due to the absence of the stratiform rain.

The distribution of tornado reports (Fig. 15) shows that two morphologies have particularly high numbers of reports per case: squall lines with line-parallel stratiform rain (1.79) and broken squall lines (1.61). Another interesting result is the stark difference between clusters of cells and broken squall lines. Both of these morphologies generally consisted of multiple cells and had comparable areal coverage. When compared to clusters of cells, though, broken squall lines had nearly four times as many reports of tornadoes per case. Linear systems tend to occur near baroclinic boundaries, which would likely be regions of enhanced vertical wind shear, assuming thermal wind balance. Stronger deep-layer shear values typically favor supercell formation, but deep-layer shear does not appear to discriminate between tornadic and nontornadic supercells (e.g.,
Thompson et al. 2003). Additional work is needed to explore the differences in tornado frequency between CC and BL events. In addition, the shear vector would be oriented along the line, favoring PS systems for any convective events that grow upscale and develop stratiform rain areas (Parker 2007a,b) in these baroclinic regions.

One might expect that individual cells would have the most reports of tornadoes per case, but this morphology has relatively few. There are several possible causes for this. First, individual cells are often much smaller in areal coverage than other morphologies, sometimes involving only a single, short-lived cell. Also, as Fig. 5 implied with its midsummer maximum in IC events, many airmass thunderstorms, which typically occur in low-shear, weakly forced environments quite unlikely to produce tornadoes, fell into this morphology, likely decreasing the observed number of reports per case. Finally, it should be noted that individual cells did have the most total reports of tornadoes, but were so numerous that relatively few reports per case resulted. Future work should use higher-resolution radar data to differentiate between individual cells that are supercells and those that are not. As with the larger hail sizes, the NL, NS, and TS systems had the smallest frequency of tornadoes.

4. Conclusions

From the data presented in this study, it can be concluded that significant differences exist between the types and numbers of severe reports in convective storms of different morphologies that satisfied the minimum classification criteria. Also, no morphology of convective storm is without a severe threat; all morphologies (not necessarily all events) were observed to have at least some reports of severe weather.

In nonlinear storms the greatest threats appear to be marginally severe hail, flooding, and severe wind. Of the three broader types of storms (linear, nonlinear, and cellular), nonlinear tended to have fewer severe reports per case than any other category of storms.

For linear storms, all types of severe weather were a threat, but the frequencies depended greatly on the specific type of linear system. Overall, the single greatest threat appears to be severe wind, which was most likely in bow echoes and squall lines with trailing stratiform rain. Bow echoes produced especially high numbers of severe wind reports per case. Hail reports were common, especially marginally severe hail in bow echoes, and all sizes of hail in lines with line-parallel or leading stratiform rain. Flooding in linear storms was observed to be most likely to occur in squall lines with line-parallel or trailing stratiform rain. The presence and location of the stratiform rain appears to be important in predicting flooding potential, as squall lines with no stratiform rain or leading stratiform rain had noticeably less reports of flooding during the period of this study. Tornadoes are a greater threat in linear systems with line-parallel and leading stratiform rain than in other types of linear systems. The environments leading to this type of structure may contain greater wind shear, such that embedded supercells are more likely to occur.

Cellular storms appear to present two major threats: hail of all sizes and tornadoes. The most reports of tornadoes per case occurred when cells were organized in a broken squall line. The flood threat was surprisingly high for this type of cellular convection as well. Of the three cellular morphologies, broken squall lines tended to produce the most severe reports per case. This result is partly related to the larger areal coverage of this type of system compared to an individual cell. However, the clusters of cells generally had similar areal coverages and yet produced fewer severe reports for most categories. The linear organization of broken lines likely reflects their development in baroclinic zones, which would have enhanced vertical shear favorable for tornado development.

When interpreting the results, areal coverage of the storm system must also be taken into account. Cellular storms with relatively few severe reports per case should not be viewed as less dangerous than linear or nonlinear storms with more reports per case, because cellular storms often cover a small area compared to linear and nonlinear storm systems. Because the storm reports are concentrated in such a small area, any given point affected by a cellular storm may actually be more likely to receive severe weather than any given point affected by a linear or nonlinear system.

Several areas of additional research should be pursued to enhance the results of this study. First, additional years should be analyzed over a wider geographical area to expand the sample size and determine the generality of the results. Second, further work could determine whether or not certain morphologies of storms are more likely in some geographical regions than in others. In addition, results could be normalized by area covered by each morphology instead of by number of events. Finally, higher-resolution radar reflectivity data and/or velocity data could be used to isolate supercells from nonsupercell events within the cellular morphology.

Acknowledgments. This research was funded in part by National Science Foundation Grants ATM-0226059, ATM-0226059/REU, and ATM-0537043. The paper
was improved by the helpful suggestions of Dr. Matthew Parker and two anonymous reviewers.

REFERENCES


