On the Climatological Distribution of Tornadoes Within Quasi-Linear Convective Systems

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ABSTRACT

Tornadoes threaten our communities every year. They can occur throughout the U.S. in any season, and at any time of day. Currently an area of concern is the type of storms from which tornadoes form. “Supercell” thunderstorms are thought to be the most common tornado producers. Yet, recent studies have brought forth the question of how many tornadoes form within other storm types, such as squall lines or hurricane rainbands. A related question regards possible relationships between parent storm type and tornado intensity. In this study, Doppler radar reflectivity images were analyzed for each tornado case between March 1998 and February 1999 to determine whether the parent storm type was a quasi-linear convective system (QLCS), cell, or hurricane rainband. 1,660 total tornadoes were analyzed for the 12-month study, and cells produced the majority (76%). QLCSs accounted for 19%, and hurricane rainbands were responsible for 5%. Seasonal, diurnal, and geographical distributions will be presented to show any patterns in frequency on such scales. A distribution by damage intensity will also be provided to illustrate the level of danger each classification of tornadoes can pose. In addition, two case studies are presented to describe the meteorological environments of a non-tornadic and a tornadic QLCS from this study.
1. INTRODUCTION

Approximately 1,000 tornadoes occur within the contiguous U.S. on average each year. The parent storm type that produces these tornadoes varies from supercell (and non-supercell) thunderstorms, to quasi-linear convective systems (QLCSs) such as squall lines and bow echoes, to hurricane rainbands. The percentage of tornadoes produced by each parent storm type is unknown.

We are particularly interested in QLCS tornadoes since their attributes, especially their climatological distribution, have yet to be studied in depth. Moreover, the work of Trapp et al. (1999) suggests that traditional radar-based indicators of impending tornadogenesis may, in the case of QLCS tornadoes, offer very little operational tornado-warning guidance. Thus, it may be argued that operational meteorologists are generally unable to assess the potential risk of tornadic winds in QLCSs, given the lack of fundamental knowledge of QLCS tornadogenesis/tornado climatology.

The purpose of this research is to estimate the percentage, relative to all tornadoes, of QLCS tornadoes reported for a twelve-month period. Previous research in this field is reviewed in section 2. Radar reflectivity images are used to classify the parent storm type of each tornado event as described in section 3. The QLCS tornadoes then are distributed according to geographical region, season, local standard time, and damage intensity (section 4). Studies of two QLCS cases (one non-tornadic and one tornadic) are presented in section 5. Conclusions are made in section 6.
2. BACKGROUND

One of the first studies documenting tornadoes within quasi-linear convective systems was published by Nolen (1959). He coined the term “line echo wave pattern” (LEWP), and defined it as a “…configuration of radar echoes in which a line of echoes has been subjected to an acceleration along one portion and/or a deceleration along that portion of the line immediately adjacent, with a resulting sinusoidal mesoscale wave pattern in the line.” Hamilton (1970) elaborated on Nolen’s work by noticing a “bulge,” or concave-shaped echo, within the LEWP, and associating it with severe straight-line winds and tornadoes. Later, Fujita (1979) documented the evolution of the “bow echo,” in which the curvature of the line echo was caused by downburst winds.

The complete evolution of the bow echo was categorized by Fujita (1979) into three stages: tall echo, bow echo, and comma echo (Fig. 1). He described the initial stage as a tall thunderstorm with a gust front that begins to bulge outward as the thunderstorm collapses. The next stage takes place when the downburst is most intense, and the bowing line echo begins to look like a “spearhead.” This is the stage that Fujita claims is most likely to produce tornadoes. The comma echo stage includes the development of cyclonic and anticyclonic rotation at the ends of the bow (also referred to as “bookend vortices” by Weisman 1993). As the system progresses with time, the cyclonic rotation at the northern end of the bow (in the Northern Hemisphere) intensifies due to the Coriolis force, while the anticyclonic rotation at the southern end of the echo becomes less pronounced. After this stage the system gradually falls apart.

Further studies of bow echoes by Przybylinski (1995) and Weisman and Davis (1998) have investigated the formation of mesoscale and storm-scale vortices within
Figure 1. Evolution of the bow echo. Conceptualized by Fujita (1979).
QLCSs. Weisman and Davis used idealized simulations of QLCSs to show that mesoscale vortices are generated by the vertical tilting of horizontal barotropic and baroclinic vorticity. Przybylinski noted that there are intense regions of shear along outflow boundaries that appeared to be associated with brief tornadoes. Little else about the formation of tornadoes within QLCSs has been discussed in the literature.

Trapp and Davies-Jones (1997) distinguished two modes of tornadogenesis: mode I and mode II. Mode I tornadogenesis occurs when the vortex forms aloft, and by means of the “dynamic pipe effect” it descends toward the ground. Mode II tornadogenesis is characterized by a vortex that forms at low levels or that develops nearly simultaneously within a several-kilometer depth and ascends upward. A study by Trapp et al. (1999) looked at 52 tornado cases and classified them as “descending” or “non-descending.” There is a direct correlation between mode I (mode II) and the classification of descending (non-descending). Trapp et al.’s approach was to examine the tornadic vortex signature (TVS) of each tornado on radar and determine if it was first detected aloft (descending; see Fig. 2) or at lower levels (non-descending; see Fig. 3). The results of the study showed that 48% of the tornadoes were first detected at lower levels and then grew upward.

Seven of the 52 tornadoes from the Trapp et al. study formed within a QLCS, and all but one of those tornadoes were classified as non-descending. In addition, the mean lead time between initial TVS detection and tornadogenesis was only 5 minutes for these non-descending QLCS tornadoes; the mean lead time was much greater for tornadoes with descending characteristics. This rapid development of non-descending tornadoes (and possible correlation with QLCSs) can make it difficult for forecasters to
Figure 2. Time-height diagram of the maximum gate-to-gate velocity from the June 22, 1995 tornadic supercell near Falcon, CO. The bold-faced "T" indicates the time of the tornado. This pattern is typical of descending tornadoes. (Trapp et al. 1999)

Figure 3. Time-height diagram of the maximum gate-to-gate velocity from the November 11, 1995 tornadic squall line near Jackson, MS. The bold-faced "T" indicates the time of the tornado. This pattern is typical of non-descending tornadoes. (Trapp et al. 1999)
issue a warning prior to the tornado. This provides the motivation for our study of QLCS
tornadoes.

3. DATA AND ANALYSIS

Tornado-damage verification information and radar reflectivity images comprise
the data used for this project. Both were obtained through the National Climatic Data
Center website (NCDC, http://www.ncdc.noaa.gov/) which offers a database with
records of every severe weather event during the time period of this study. The Storm
Data database was searched for individual months of tornado reports between March
1998 and February 1999 for all intensity categories (F0 through F5 on the Fujita scale).
Once the query was complete, the individual records were downloaded and modified by
including the parent storm type. Reports of funnel clouds and waterspouts were not
considered. However, waterspouts that moved onshore were included because they
were listed in the database as a tornado case. In addition, events in Alaska, Hawaii,
and Puerto Rico were excluded in order to focus the study on the contiguous U.S. only.

The parent storm type of each case was determined by examining radar images
taken nearest the time of reported tornadogenesis. National composites of radar
reflectivity were obtained from the NCDC website. When the spatial (8 km) and
temporal (hourly) resolution of these composites were insufficient to discern parent
storm type, or when necessary composites were missing from the NCDC archive, we
obtained higher-resolution images from archives maintained by the Research
Applications Program (RAP) at the National Center for Atmospheric Research (NCAR)
and by the University of Utah.
Parent storm type was classified as “cell”, “line” (QLCS), “hurricane rainband”, or “unknown”. Because this type of classification has at least some level of subjectivity, we established classification criteria for the sake of reproducibility. Hence, a “cell” was an effectively isolated, roughly elliptically shaped region of radar reflectivity with maximum values greater than or equal to 50 dBZ. We arbitrarily defined a “line” as a quasi-linear region of radar reflectivity greater than or equal to 40 dBZ, continuously distributed over a horizontal distance greater than 100 km. A “hurricane rainband” may be similarly defined, except that it spirals in toward the hurricane center. The “unknown” category was available for instances in which the parent storm type could not be readily classified.

We recognize there are problems with the verification of tornadoes. For example, tornado reports are much more accurate with respect to location than to the time of the tornado because a tornado’s location can be deduced from the damage path, whereas the time of the tornado is based upon spotter observation (Witt et al. 1998). Hence, we made every attempt to reconcile the radar data with the verification data, but if there were no radar echoes for the location and time of the report within a ± 1-h time window, we omitted the report from our database. We also made the important assumption that erroneous reports are not biased toward a particular parent storm type.

After the parent storm type was determined, the data files were sorted to determine the percentage of each storm type out of all the events throughout the time period of the study. The files were also sorted by damage intensity, state, month, and local standard time, in order to get a geographical, seasonal, and diurnal distribution of occurrence.
4. RESULTS

According to our modified database, there were 1,660 tornado events between March 1998 and February 1999. Out of these events, 76% were produced by cells (Table 1). Quasi-linear convective systems accounted for 19% of the tornadoes, and hurricane rainbands for the remaining 5%. There was only one event classified as unknown, and consequently it was dropped from further analysis.

These results were stratified by state and geographical region. The state with the highest number of QLCS tornadoes (36) was Louisiana; Iowa had 32 QLCS tornadoes during our study period (Fig. 4). The midwestern region¹ (see Fig. 5) had a high percentage (27%) of QLCS-produced tornadoes as did the northeast and southern regions (Fig. 6). It should be noted that for this sample, there were no QLCS tornadoes west of the Rocky Mountains.

The files were then sorted by month to determine the seasonality, if any, of tornadoes associated with each parent storm type. The seasonal distribution of tornado events show that cells are most predominant in the spring and summer months (Fig. 7). Hurricane rainbands generated the majority (89%) of its tornadoes in September; most of the hurricane rainband cases in September were a result of Hurricane Georges, a landfallen Category 2 hurricane. The percentage of QLCS tornadoes remained fairly consistent throughout spring, summer, and winter.

¹ The regions used in this distribution are those as defined by the National Climate Center regions.
Table 1. Distribution of tornadoes by parent storm type.

<table>
<thead>
<tr>
<th>Cell</th>
<th>QLCS</th>
<th>Hurricane Rainband</th>
</tr>
</thead>
<tbody>
<tr>
<td>1263</td>
<td>311</td>
<td>85</td>
</tr>
<tr>
<td>76.13%</td>
<td>18.75%</td>
<td>5.12%</td>
</tr>
</tbody>
</table>

Figure 4. Distribution of QLCS tornadoes across the contiguous U.S. between March 1998 and February 1999.
The distribution by local standard time (LST) was computed to look for diurnal patterns in each of the parent storm types (Fig. 8). Consistent with previous studies (e.g. Kelly et al. 1978), the number of tornadoes produced by cells peaked during the 18:00 LST hour; more than 66% of these tornadoes were reported during the 15:00-19:00 LST time frame. Tornadoes spawned by QLCSs had a less evident temporal pattern (Fig. 8). Indeed, QLCS tornadoes do not appear to be as strongly coupled to the diurnal cycle of solar heating as do cell- and also hurricane rainband- produced tornadoes.

In order to assess any relations between parent storm type and tornado intensity, a distribution by Fujita (F) scale was constructed. The damage intensities for all of the cases varied between F0 and F5 (Fig. 9). The majority of the 311 QLCS events fell into the F0 and F1 categories (83%), which reflected the overall tendency for all of the tornadoes to be weak (F0 or F1), regardless of parent storm type. Hurricane rainbands did not produce any tornadoes with a ranking higher than F2 (Fig. 9). There were only three tornado cases that fell into the F5 category; all were spawned by cells. However, two of the thirteen F4 tornadoes were produced by QLCSs, indicating that QLCSs do have the potential to produce violent tornadoes.

5. CASE STUDIES

In order to provide examples of the larger-scale meteorological conditions associated with QLCSs, two cases studies are presented. Level III radar reflectivity data (2 km horizontal resolution, 5 min temporal resolution), 00 UTC and 12 UTC sounding data, and archived 00 UTC and 12 UTC surface and upper air charts were
Figure 5. National Climate Center regional map.

Figure 6. Distribution of tornadoes by parent storm type and National Climate Center region, normalized by the total tornadoes per region.
Figure 7. Distribution of tornadoes by parent storm type and season, normalized by the total tornadoes per parent storm type.

Figure 8. Distribution of tornadoes by parent storm type and local standard time (LST), normalized by the total tornadoes per parent storm type (note y axis maximum of .18).
Figure 9. Distribution of tornadoes by parent storm type and damage intensity (on the Fujita scale), normalized by the total tornadoes per parent storm type (note y axis maximum of .70).
analyzed to understand the general evolution of these storms, and the synoptic environments that produced them. The soundings used were from stations ahead of the systems, in order to get a sample of the pre-storm environment.

It is necessary to keep in mind that these two cases are for illustrative purposes only, and may not represent an average non-tornadic/tornadic QLCS event. Any significant differences between the two cases will be of interest, although no universal conclusions can be made.

The two events can be introduced as follows. A north-south oriented non-tornadic squall line developed in western Texas by 06 UTC on 15 May 1998 (Fig. 10). As it moved northeastward through Oklahoma it exhibited some concavity, like a bow echo. It later moved into Kansas before it began to disorganize shortly after 10 UTC. Severe winds of up to 75 kts were reported across the three states causing widespread tree damage, power outages, and roof damage. The system later moved into Iowa and Minnesota and re-organized around 16 UTC into a tornadic QLCS.

An extensive, yet narrow, squall line tracked across the central U.S. on 10 November 1998 (Fig. 11). It developed by 00 UTC and quickly became tornadic. Between 01 and 19 UTC, 18 tornadoes were reported throughout seven states, with intensities ranging from F0-F3. There were numerous reports of high winds between 50-60 kts, with a few up to 70 kts. Though it was very extensive, it exhibited some smaller bowing segments along the line at various times throughout its duration. It disorganized shortly after producing its last tornado (~ 19 UTC).
Figure 10. Radar reflectivity mosaic on 15 May 1998 at 07 UTC of a non-tornadic QLCS over Texas.
Figure 11. Radar reflectivity mosaic on 10 November 1998 at 08 UTC of a tornadic QLCS over Missouri, Arkansas, and Texas.
a. 15 May 1998: Non-tornadic quasi-linear convective system

At 00 UTC on 15 May 1998 (hereafter, 00/15), a shortwave trough was positioned to the west of the Texas panhandle (Fig. 12a). The 00/15 surface analysis indicated a dry line in western Texas and a surface cyclone (998 hPa) centered over Nebraska; the squall line appeared to develop along the dry line boundary (Fig. 13a). The wind profiles in Texas and Oklahoma denoted prevailing southwesterly flow at all levels. At Norman, OK for 00/15 the speed shear was 20 m/s in the lowest 3 km AGL (above ground level) (Fig. 14a). The surface-based Convective Available Potential Energy (CAPE) in front of the system was ~2600 J/kg.

The 300 hPa shortwave was negatively tilted and appeared to be near-cutoff by 12 UTC on 15 May 1998 (hereafter, 12/15) (Fig. 12b). The surface analysis for 12/15 (2 hours after the QLCS disorganized) showed the surface cyclone now centered over the Kansas-Nebraska border, with a cold front extending to the south (Fig. 13b). The central pressure (997 hPa) of the system did not change much from the 00/15 observations. Unidirectional wind profiles from the southwest were evident ahead of the system. Low level speed shear (0-3 km) was 30 m/s at Omaha, NE (Fig. 14b). Surface-based CAPEs preceding the squall line ranged from 1000-2000 J/kg.

This case is consistent with the “dynamic pattern” in which the squall line develops ahead of a cold front that is associated with a migrating low pressure system (Johns 1993). If the speed shear is assumed to be constant at all levels, then this case is coherent with simulations yielding bow echoes, in which the 2.5 km AGL shear values were at least 20 m/s (Weisman 1993).
Figure 12. 300 hPa heights and windspeed analysis on 15 May 1998 for a) 00 UTC b) 12 UTC (images from Unisys).
Figure 13. Surface analysis on 15 May 1998 for a) 00 UTC b) 12 UTC (images from Unisys).
Figure 14. Skew T diagrams on 15 May 1998 for a) 00 UTC at Norman, OK b) 12 UTC at Omaha, NE (courtesy of the University of Wyoming).
b. 10 November, 1998: Tornadic quasi-linear convective system

The 300 hPa analysis for 00 UTC on 10 November, 1998 (hereafter, 00/10) indicated a deep longwave trough over Colorado (Fig. 15a). The right exit region of the jet max at 300 hPa (150 kts) was over the initiation area. The 00/10 surface analysis illustrated a surface cyclone (992 hPa) over Kansas with an associated cold front extending southward into western Texas (Fig. 16a). The QLCS appeared to develop along this cold front. Southwesterly flow was evident at all levels preceding the front with low level (0-3 km) speed shear values around 25 m/s at Norman, OK (Fig. 17a). Surface-based CAPE values ahead of the squall line were ~900 J/kg.

The 500 hPa trough had become very negatively tilted and cutoff by 12 UTC on 10 November, 1998 (hereafter, 12/10) (Fig. 15b). The 300 hPa jet max over the region was 160 kts. The 12/10 surface map indicated that the surface cyclone (972 hPa) had tracked northeast and was positioned over the Iowa-Minnesota border (Fig. 16b). It had deepened 20 hPa in the previous 12-h period. The surface cold front extended from the surface low southeastward to Tennessee and then back southwestward into Louisiana. There was unidirectional southwesterly flow at all levels. At Davenport, IA for 12/10, the low level (0-3 km) speed shear was 35 m/s (Fig. 17b). Surface-based CAPEs were very low at this time (~40 J/kg), possibly due to diurnal cooling near the surface.

This case also correlated with the dynamic pattern for the development of bow echoes (Johns 1993). It also exhibited the strong low level speed shear that Weisman (1993) indicated to be necessary for long-lived bow echo formation. There was much less instability in this example than with the ideal cases described by Weisman (1993),
Figure 15. 300 hPa heights and windspeed analysis on 10 November 1998 for a) 00 UTC b) 12 UTC (images from Unisys).
Figure 16. Surface analysis on 10 November 1998 for a) 00 UTC b) 12 UTC (images from Unisys).
Figure 17. Skew T diagrams on 10 November 1998 for a) 00 UTC at Norman, OK b) 12 UTC at Davenport, IA (courtesy of the University of Wyoming).
yet marginal instability is more common in dynamic pattern situations (Johns 1993). Consistent with operational experience, this dynamic pattern QLCS occurred in the fall with little diurnal dependence, and tracked across the Mississippi river valley area (Johns and Doswell 1992).

6. CONCLUSIONS

The objective of this project was to estimate the number of tornadoes that form within quasi-linear convective systems compared to cells and hurricane rainbands. The parent storm classification was based on the analysis of national composite radar reflectivity images for every tornado event recorded during a one year period in the National Climatic Data Center storm events database (minus the events in Alaska, Hawaii, and Puerto Rico). The percentages of the 1,660 tornado events between March 1998 and February 1999 that were produced within cells(QLCSs)/hurricane rainbands were 76%/19%/5%.

Most tornadoes were weak (F0-F1 on the Fujita scale) including those produced by cells, QLCSs, and hurricane rainbands. There were only three F5 cases, and cells produced all three. There were thirteen F4 tornadoes, two of which were produced by QLCSs. Therefore, quasi-linear convective systems, in addition to cells, are capable of producing violent tornadoes. Geographically, the south central and Midwestern U.S. had the highest frequency of QLCS tornado occurrence. QLCS tornadoes were most common in spring, summer, and winter. Finally QLCS tornadoes tended not to form in the mid-late morning, but otherwise did not exhibit a strong tendency to form during other specific times of the day.
Two case studies were presented to illustrate the general synoptic environments of a non-tornadic and a tornadic QLCS from within this study. The synoptic patterns were very similar for both cases. The squall lines developed ahead of a surface cold front that was associated with a migrating low pressure system. Environments for both QLCSs exhibited unidirectional wind profiles, with strong low level speed shear. The upper level troughs associated with these systems both became negatively tilted toward the end of the storms' duration. In general, both cases fit the dynamic pattern for the development of bow echoes. The similarities between these two cases may indicate that the difference lies within the mesoscale.

There are some important considerations to make when reviewing the results of this study. First, the sample period may not represent a typical season or year. Additional sample periods will have to be analyzed in order to resolve this issue. Secondly, classifications of each parent storm type may vary between analysts. We will continue to enhance our objective criteria to reduce future classification ambiguities. Finally, the accuracy of the data used in this project is subject to the accuracy of tornado reports in general. Owing to the fact that the most difficult aspect of tornado reporting is the time and not the location (the damage path easily verifies its location and thus its existence), it is acceptable to assume that this database suited the needs of this study sufficiently.

Ultimately, these results will be used in a larger project to determine and understand the mechanisms for tornadogenesis within quasi-linear convective systems (see Trapp and Weisman 2000). This work will not only benefit meteorologists
forecasting these events, but it will in turn affect the people in our communities relying on the forecasters for accurate and prompt warnings.

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REFERENCES


