Tornadoes from Squall Lines and Bow Echoes. Part I: Climatological Distribution

Robert J. Trapp

Purdue University, West Lafayette, Indiana

Sarah A. Tessendorf

Colorado State University, Fort Collins, Colorado

Elaine Savageau Godfrey

University of Oklahoma, Norman, Oklahoma

Harold E. Brooks

National Severe Storms Laboratory, Norman, Oklahoma

ABSTRACT

The primary objective of this study was to estimate the percentage of U.S. tornadoes that are spawned annually by squall lines and bow echoes, or quasi-linear convective systems (QLCSs). This was achieved by examining radar reflectivity images for every tornado event recorded during 1998–2000 in the contiguous United States. Based on these images, the type of storm associated with each tornado was classified as cell, QLCS, or other.

Of the 3828 tornadoes in the database, 79% were produced by cells, 18% were produced by QLCSs, and the remaining 3% were produced by other storm types, primarily rainbands of landfallen tropical cyclones. Geographically, these percentages as well as those based on tornado days exhibited wide variations. For example, 50% of the tornado days in Indiana were associated with QLCSs.

In an examination of other tornado attributes, statistically more weak (F1) and fewer strong (F2–F3) tornadoes were associated with QLCSs than with cells. QLCS tornadoes were more probable during the winter months than were cells. And finally, QLCS tornadoes displayed a comparatively higher and statistically significant tendency to occur during the late night/early morning hours. Further analysis revealed a disproportional decrease in F0–F1 events during this time of day, which led the authors to propose that many (perhaps as many as 12% of the total) weak QLCSs tornadoes were not reported.

1. Introduction

The understanding of tornadoes and their formation has grown dramatically over the past several decades, owing to the ever-increasing availability of visual and in situ observations, weather radar and satellite data, and sophisticated computer model simulations of severe convective storms (see the recent reviews by Davies-Jones et al. 2001 and Wilhelmson and Wicker 2001). Concomitant with this growth in knowledge has been an expansion of the accepted realm of the types of possible convective storms that produce tornadoes. Based on our current understanding, these range from supercell/mesocyclonic thunderstorms, complete with subtypes such as "low topped" or "mini" (e.g., Kennedy et al. 1993) and "high precipitating" (Moller et al. 1990); nonsupercell/nonmesocyclonic thunderstorms (Wakimoto and Wilson 1989; Brady and Szoke 1989); prefrontal rainbands (Carbone 1983); tropical cyclones (Spratt et al. 1997; McCaul 1987); and squall lines and bow echoes (e.g., Hamilton 1970; Forbes and Wakimoto 1983; Wakimoto 1983; and many others), which out of convenience we will refer to as either lines or quasi-linear convective systems (QLCSs).

Interestingly, prior to Browning's (1964) description of the supercell model—and in particular during the 1940s–50s (and perhaps earlier)—squall lines were considered by many to be the primary host of tornadoes (e.g., Lloyd 1942; Fulks and Smith 1950). Obviously this must be interpreted within the context of that era, during which "squall lines," "instability lines," and "upper-

Corresponding author address: Dr. Robert J. Trapp, Dept. of Earth and Atmospheric Sciences, Purdue University, 550 Stadium Mall Drive, West Lafayette, IN 47907.
E-mail: jtrapp@purdue.edu

level cold fronts" all were used somewhat interchangeably to describe lines of convective storms, be they continuous lines or broken lines or perhaps even lines of distinct supercells.

Brunk (1953) ostensibly had a dissenting opinion of the time, stating that tornadoes "usually [occur] before the formation of a squall line" and moreover that they "frequently occur when there is no identifiable squall line." In essence, this describes the current perception; based on a survey of contemporary tornado research activities (see, e.g., Davies-Jones et al. 2001), supercells appear to pose the most significant tornado threat, spawning a large percentage of the approximately 1200 tornadoes that occur within the contiguous United States on average each year.

As we show below, this focus on supercells is partly justified, especially since supercells are responsible for a large number of the strong-to-violent tornadoes (section 3). However this risk of strong and even violent tornadoes is not limited to supercells. Indeed, consider the tornadic squall line that occurred on 11 November 1995 near Flora, Mississippi (Fig. 1). At 0910 UTC (0310 LST), this ~300 km long squall line produced an F3 (Fujita 1981) tornado that persisted on the ground for 15 mi. Another F3 tornado formed at 1055 UTC (0455 LST), and had a 7-mi pathlength. Neither tornado was preceded by a user-defined tornadic vortex signature (TVS) by more than 10 min in radar scans collected by the Jackson, Mississippi (KJAN), Weather Surveillance Radar-1988 Doppler (WSR-88D; see Trapp et al. 1999). Hence, as in the other cases of QLCS tornadoes preliminarily investigated by Trapp et al.
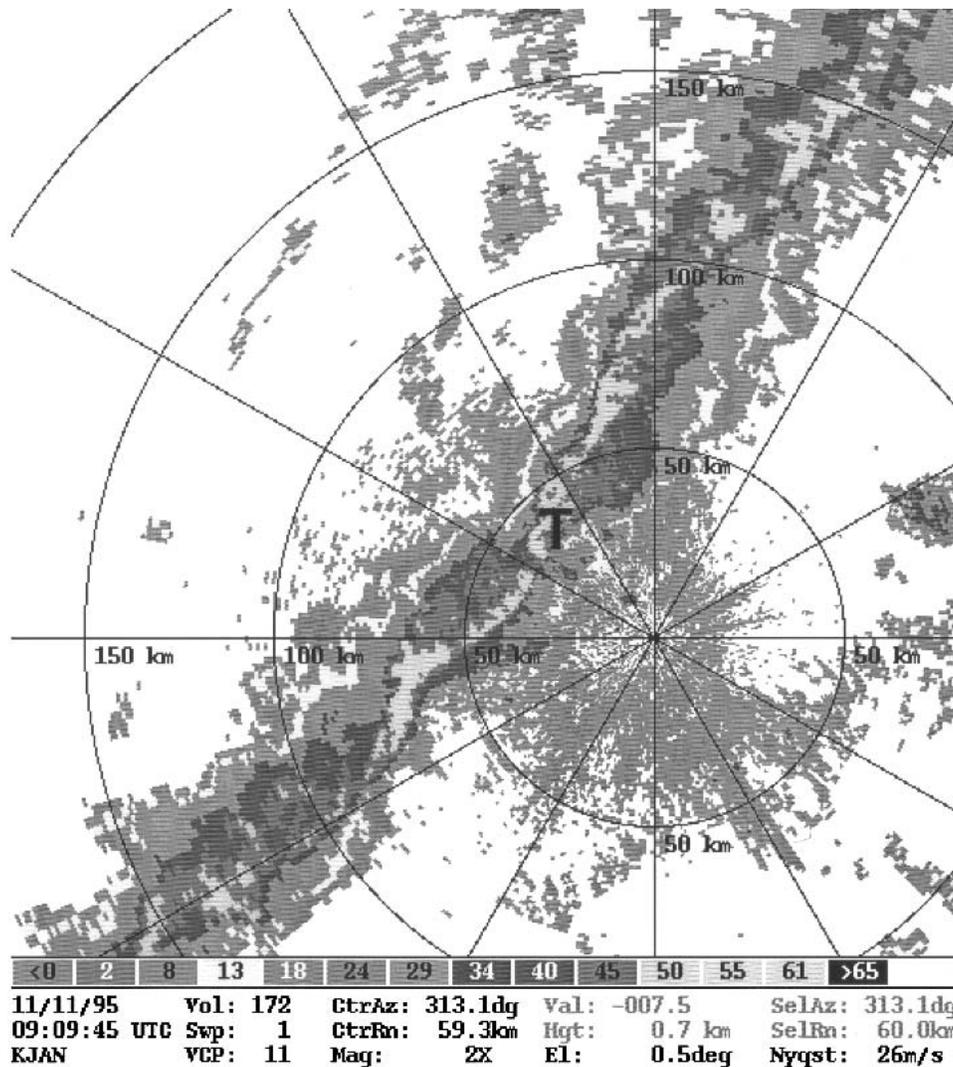

FIG. 1. Radar reflectivity factor (dBZ) from the KJAN WSR-88D, showing the tornadic squall line at 0909 UTC on 11 Nov 1995. Elevation angle is 0.5°, range rings are indicated at 50-km intervals, and the approximate location of tornado is indicated by a "**T**."

(1999), traditional radar-based indicators of impending tornadogenesis likely offered little operational tornado-warning guidance for this event. And since this example (which is one of several) of QLCS tornado occurrence happened during the overnight hours, guidance from storm spotters would have also been diminished, as would have the effectiveness of warning dissemination. Fortunately, no fatalities were associated with these tornadoes, although both resulted in two injuries and a total of $1 million in damage.

The Mississippi squall-line example, in addition to examples presented by Wakimoto (1983), Forbes and Wakimoto (1983), and others in the informal literature, illustrate that QLCS tornadoes can (i) be strong and (ii) have longer-than-average duration; in the absence of all but anecdotal evidence, we speculate that QLCS tornadoes are generally thought of as weak and short lived in the meteorological community, even though these qualifiers fit the majority of tornadoes in toto. The large horizontal length scale of the example case also draws attention to the considerable areal extent of possible tornado-breeding sites in QLCSs. Compounding this implied forecasting challenge is the apparent tendency for rapid QLCS tornado development, perhaps frequently during the overnight hours.

In future research, we will address this forecasting challenge explicitly by characterizing the environmental conditions under which tornadic QLCSs occur, and by determining their Doppler radar–derived attributes. Our objective here, however, is to define the scope of the problem by estimating the percentage, relative to all tornadoes, of QLCS tornadoes in the United States. This is accomplished by a classification of parent storm type using radar reflectivity images (section 2). The QLCS tornadoes are then distributed and analyzed statistically according to damage intensity, geographic region, and time and date of occurrence (section 3). Conclusions are made in section 4.

2. Parent storm classification

Tornado-damage assessment information and radar reflectivity images compose the data used for the parent storm classification and subsequent analysis. Both were obtained through the online database maintained by the National Climatic Data Center (NCDC, available online at http://www.ncdc.noaa.gov/). Individual records[1] of each tornado that occurred between January 1998 and December 2000 in the contiguous United States were downloaded and incorporated into our database. The records include information such as the

beginning and ending times/locations of the tornados, damage pathlengths and widths, numbers of fatalities and injuries, Fujita scale rating (Fujita 1981), and dollar amounts of property and crop damage. Note that although reports of funnel clouds and waterspouts were omitted from our database, waterspouts that moved onshore were included because they then have a definable damage track and an F-scale rating.

Parent storm type was determined by examining composites of (column maximum) radar reflectivity, valid nearest the time of reported tornadogenesis. We initially consulted the images from the NCDC archive, but obtained higher-resolution images from numerous other sources if the spatial (8 km) and/or temporal (hourly) resolution of the NCDC images were insufficient to discern parent storm type, or if necessary composites were missing. This procedure facilitated the labor-intensive categorization of a large number of events.

Each parent storm was classified simply as cell, QLCS, or other, guided by somewhat arbitrary radar reflectivity factor criteria: a cell was a relatively isolated, circular or elliptically shaped region of reflectivity with maximum values typically greater than or equal to 50 dBZ; a QLCS was a quasi-linear region of radar reflectivity greater than or equal to 40 dBZ, continuously distributed over a horizontal distance greater than 100 km; and the other category was populated primarily by tornadic outer rainbands of landfallen tropical cyclones. Despite the documentation of supercell-like features in small cells embedded in such bands (McCaul 1987; Spratt et al. 1997), and the suggestion by Robe and Emanuel (2001) that outer bands are tropical squall lines within the "kinematic environment of tropical cyclones," the possible implications that this unique kinematic environment may have on tornadic rainbands warranted, in our opinion, a separation of rainbands from cells and QLCSs. The other category was also used for storms that could not be readily classified, as well as for events for which radar data could not be obtained.

The distinction made herein between cells and QLCSs is based on dynamics unique to these phenomena. This dynamical distinction is explained as follows. First, we fully recognize that QLCSs are, by definition, convective systems built from short-lived, highly interacting cells. A product of such cells is a surface-based, system-scale pool of rain-cooled air that is fundamental to the dynamics of the QLCSs. Specifically, the cold pool helps govern the QLCS motion (see, e.g., Weisman and Trapp 2003), even though individual cells may have a motion different from that of the QLCS (Bluestein and Jain 1985). It also provides for a strong, leading-edge baroclinic zone, and hence for strong horizontal vorticity that may be tipped into the vertical to help form tornado-producing "mesovortices" at low levels (Trapp and Weisman 2003). In contrast, a convective entity that we have classified as a cell may have

---

[1] Essentially, the information found in these digital records is the same as that found in *Storm Data*, a National Oceanic and Atmospheric Administration (NOAA) publication based on NCDC records.

been a supercell whose dynamics and tornadogenesis are regulated largely by a mesocyclone (e.g., Rotunno and Klemp 1985). The other possible type of tornadic cell allowed by our classification scheme is a single cumulus congestus or growing cumulonimbus that produces a tornado by locally concentrating preexisting mesoscale vertical vorticity (Wakimoto and Wilson 1989; Brady and Szoke 1989). Formal subclassification of these two cell types fell outside the objective of this study, however.

Unavoidably subjective at times, our classification of convective lines should be consistent with that of other studies (e.g., Geerts 1998; Parker and Johnson 2000), although a duration criterion was not employed herein. Animation of reflectivity images aided us in our storm-type determination. We reiterate that the storm type at the reported time of tornado formation was what we recorded. Hence, a squall line (line of supercells) that some time after tornado occurrence fractured into distinct cells (coalesced into a continuous line) was still recorded as a QLCS (cell).

We acknowledge that there are problems with tornado reporting. For example, tornado reports are likely to be more accurate with respect to location than to time because a tornado's location can be deduced from the damage path, whereas the time of the tornado is based upon eyewitness account (Witt et al. 1998). Hence, when we could not initially reconcile the NCDC report with the corresponding radar data (e.g., no echoes at the reported time and location), we inspected other radar images within $\pm$ 1 h of the reported time and attempted to match a storm echo with the reported damage location. We omitted the report from our database if unambiguous reconciliation was not possible. Such erroneous reports are assumed herein to be unbiased toward a particular parent storm type. The possibility of storm-type biases from accurate reports is, however, acknowledged and discussed in section 3.

Besides these reporting errors, we also accounted for tornadoes that crossed geopolitical boundaries. In *Storm Data,* a tornado that affects more than one county and/or state is given a separate record per county/state that contains the tornado's attributes (F scale, damage path, etc.) in that county/state. This geopolitical segmentation of the tornado report was removed in our database. So, "property damage" is the total property damage due to the tornado, the "F scale" is the maximum F scale along the entire tornado track, etc.

3. Results

According to our database, 3828 tornadoes occurred in the contiguous United States during the 1998–2000 calendar years. Cells produced 79% of these tornadoes, and QLCSs produced another 18% (Table 1). Other

TABLE 1. The distribution of U.S. tornadoes by parent storm type during 1998–2000.

	Cumulative	1998	1999	2000
Cell	3013 (79%)	1092 (77%)	1070 (80%)	851 (80%)
QLCS	693 (18%)	244 (17%)	240 (18%)	208 (20%)
Other	123 (3%)	81 (6%)	31 (2%)	11 (<1%)
Total	3828	1417	1341	1070

storm types (mostly rainbands of tropical cyclones) were credited with only 3% of the tornadoes; although we regard these events as operationally important and interesting, we have chosen for the purposes of this paper to limit much of our subsequent discussion to cell and QLCS tornadoes.

Surprisingly good year-to-year consistency is shown in percentages of QLCS and cell tornadoes. Considering that the storm-type classification work was done sporadically over several years, this result gives us faith that our simple classification is robust and that our sample is reasonably representative. We can quantify this further by estimating confidence intervals about our sample percentages. As with most commonly used statistical analysis techniques, however, we must first make the implicit assumption that each tornado event in our dataset is independent. We view independence here in terms of individual parent storms. So, for example, independence is a good assumption when a given storm produced only one tornado. In instances of multiple tornadoes per parent storm, the assumption should still be fairly good provided that individual events had some time and/or space separation (e.g., $\sim$1 h, $\sim$100 km, respectively). The events that remain were usually associated with large outbreaks of tornadoes (e.g., 3 May 1999 in Oklahoma and Kansas), and these tended to be associated with cells.

Since the true distribution of tornadoes by parent storm type is unknown, and our sample is still relatively small, we obtained confidence intervals for the percentages of QLCS and cell tornadoes using the bootstrap technique (Wilks 1995). A nonparametric or distribution-free method like bootstrap requires no assumptions about whether the data fit a particular theoretical distribution such as the well-known normal distribution. To use the bootstrap here, we randomly resampled (with replacement) our dataset of storm-type classified tornadoes to create a very large number (10 000) of synthetic datasets. We then applied the percentile method to the replicated data. The resultant 95% confidence intervals for the percentages of QLCS and cell tornadoes are [16.9%, 19.3%] and [77.4%, 80.0%] respectively. Our estimates of U.S. tornadoes spawned annually by QLCSs and cells appear, therefore, to be statistically significant at this level.

The distribution of total tornado days (d_T; see Brooks et al. 2003 and references therein) by parent storm type during 1998–2000 suggests a slightly higher percentage of QLCS tornadoes (25%) over the 3-yr

period of study (Table 2). This alternative representation of the tornado distribution is not affected by large outbreaks over a single day that, by virtue of Table 2, appear to be associated mostly with cell tornadoes; it also tends to exhibit less temporal variability owing to lower sensitivity to the nonmeteorological factors that have inflated the tornado record over the past 50 yr (Brooks et al. 2003). We note that our counts of tornado days by parent storm type allowed for the joint occurrence of a cell-tornado day (d_c) and a QLCS tornado day (d_L; and/or "other" tornado day, d_o) on a given calendar day. Hence, the percentages in Table 2 were computed with respect to the sum of tornado days due to each storm type ($\Sigma\ d_c\ +\ d_L\ +\ d_o$), which may be larger than the total number of tornado days ($\Sigma\ d_T$).

a. Geographical distribution

The number of tornadoes and tornado days as a function of storm type varied widely across the United States. This is summarized in Fig. 2, which quantifies the cell and QLCS tornado days as a function of state. Consistent with the analysis of Brooks et al. (2003), particularly large numbers of tornado days occurred in the southern Great Plains and in Florida as well as in the plains of Colorado (Fig. 2a).

Throughout these specific areas, most of the tornado days (and tornadoes) were associated with cells (Fig. 2b). While such a strong statement cannot be made for QLCS tornadoes in other areas of the country, we can state that the percentages of QLCS tornado days (and tornadoes) exceeded 25% (the national average) in the states along a curved axis from Louisiana to Pennsylvania (Fig. 2c). Indeed, 50% of the tornado days in Indiana during the 3-yr study period were associated with QLCSs. We note that the large percentages in parts of New England must be viewed with caution since these are associated with very low numbers of total tornado days (Fig. 2a).

Limited previous results compare favorably with our analysis of the geographical distribution of QLCS tornadoes. Knupp et al. (1996) presented a preliminary classification of tornadic storms in northern Alabama that suggests at least the relatively frequent occurrence of tornadic QLCSs, as we also show in Fig. 2c.

TABLE 2. The distribution of total U.S. tornado days by parent storm type during 1998–2000. Percentages are computed using the boldfaced value in "total" row, which is sum of cell, QLCS, and other values ($\Sigma\ d_C\ +\ d_L\ +\ d_O$). This need not be equal to the total number of tornado days ($\Sigma\ d_T$), indicated in italics.

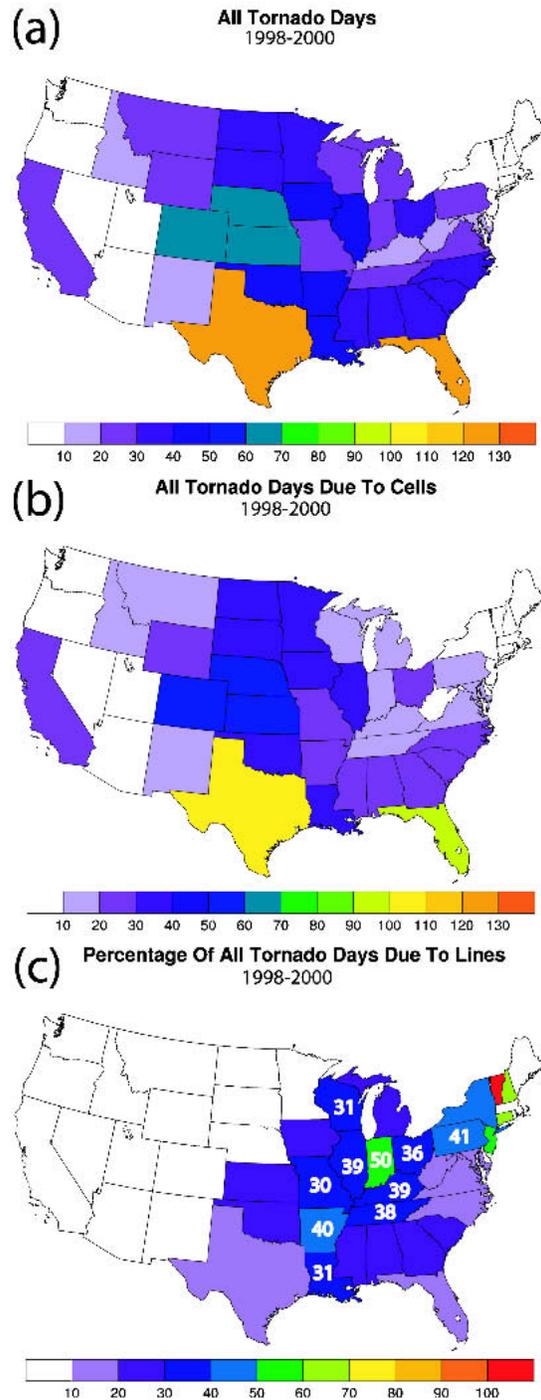|	Cumulative	1998	1999	2000
Cell	540 (72%)	185 (71%)	162 (70%)	193 (75%)
QLCS	185 (25%)	64 (24%)	60 (26%)	61 (24%)
Other	25 (3%)	13 (5%)	8 (3%)	4 (1%)
Total	**750** *587*	**262** *198*	**230** *181*	**258** *208*

FIG. 2. Geographical distribution of (a) all tornado days, (b) all tornado days due to cells, and (c) the percentage of all tornado days due to QLCSs, for 1998–2000.

Though confined to derecho- (and not necessarily tornado-) producing MCSs, the 10-yr study by Bentley and Mote (1998) shows maxima in occurrences that extend in part through Oklahoma–Texas and through Ohio–Pennsylvania.

b. Distribution by F scale

The 50-yr tornado record analyzed by Brooks and Doswell (2001) exhibits a log-linear distribution of tornado occurrence as a function of the Fujita (F) scale.

The set of all tornadoes in our smaller record also exhibits a log-linear F-scale distribution (Fig. 3a) and, not surprisingly, so do the cell tornadoes. In comparison, the QLCS tornadoes are distributed differently, as shown more clearly when the entire QLCS-tornado dis-
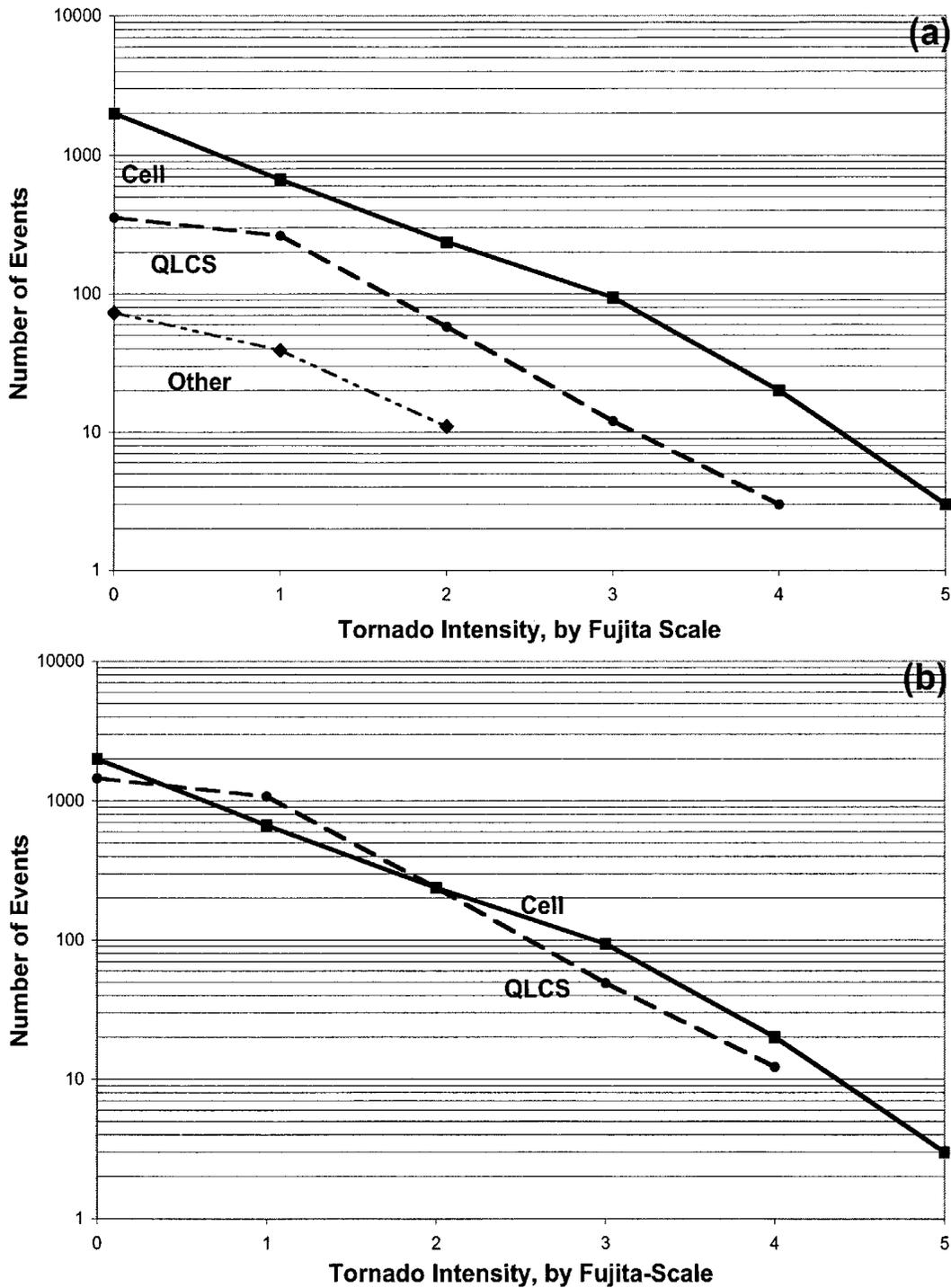

FIG. 3. 1998–2000 U.S. tornado distribution by F scale and parent storm type (cell, QLCS, other), presented (a) with all tornadoes and (b) with the distribution of QLCSs adjusted or normalized such that it has 237 F2 tornadoes.

tribution is artificially shifted so that the number of F2 QLCS tornadoes equals the number of F2 cell tornadoes (Fig. 3b). Indeed, there appear to be disproportionately more F1 tornadoes from QLCSs, and more F3–F4 tornadoes from cells. This is examined below. The disparity between F0 QLCS and cell tornadoes is likely due to the underreporting of QLCS events (see, also, Knupp 2000), which is addressed in section 3d. Finally, the absence of F5 QLCS tornadoes is consistent with the relative infrequency of F5 tornadoes, which comprise less than 0.2% of cell tornadoes in the dataset.

It is unclear whether these differences between the two F-scale distributions are due to the relatively small QLCS tornado sample size or if they occur naturally. We can test this using the Monte Carlo method, in which a statistical model is simulated—under the assumption that the null hypothesis (H_o) is true—using artificially generated data that are consistent with the observed data (von Storch and Zwiers 2002). Specifically, a large number of realizations of some test statistic are generated to construct an empirical estimate of the distribution of the test statistic under H_o. This distribution then provides the means for H_o rejection at some significance level.

One null hypothesis of particular interest is that the probability of a strong (F2–F3) tornado, given a QLCS, is the same as the probability of a strong tornado, given a cell. The Monte Carlo technique was used to test this hypothesis as follows (see Godfrey 2003 for more details). First, F0 tornadoes were disregarded (see below). This left a sample of 336 F1 and greater QLCS tornadoes, and also a sample of 1021 F1 and greater cell tornadoes that were used to compute the cumulative probabilities of cell F scales (Table 3); in other words, the observed F-scale distribution of cell tornadoes was assumed to represent the "truth." We then drew a sufficiently large number (10 000; von Storch and Zwiers 2002) of 336-member samples of random numbers between 0 and 1. Each random number in a 336-member sample was put into the appropriate F1–F5 bin according to the cumulative cell probability table. The result was an F-scale distribution for each of the 10 000 realizations or years of simulated tornadoes. Finally, these simulated F-scale distributions were compared to the observed QLCS F-scale distribution. The comparison was quantified as a percentage of realizations in which there were more observed QLCS tornadoes in an F-scale bin than there were simulated (cell) tornadoes.

From Fig. 4, we see that every one of the 10 000 simulated distributions had fewer than 263 F1 tornadoes (the portion of the 336 total observed QLCS tornadoes that were rated F1). In other words, at the 100% confidence level, there were significantly more F1 tornadoes from QLCSs than from cells. In contrast, at the 99% and 100% confidence levels, respectively, there were significantly fewer F2 and F3 tornadoes from QLCSs than from cells. There were also fewer F4 and F5 QLCS tornadoes (89% and 63% confidence levels, respectively), but no significant conclusions can be drawn about these tornadoes because the events are particularly rare, even in cells.

We conclude that, statistically, the F-scale distribution of QLCS tornadoes from the 3-yr dataset is significantly different than that of cell tornadoes. The probability that tornadoes from cells could have had the same distribution as tornadoes from QLCSs in the F1–F3 range is less than 1%. QLCSs produced many more F1 yet many fewer F2–F3 tornadoes than cells did. QLCSs were less likely to produce strong tornadoes than were cells, thus allowing us to reject our null hypothesis.

c. Distribution by monthly occurrence

Cell as well as QLCS tornadoes tended to be most frequent during the months of April through June (Fig. 5). Generally speaking, the occurrence of QLCS tornadoes in our 3-yr dataset was biased toward the first half of the calendar year, with a comparatively higher likelihood in January through March. Such early year QLCS tornadoes were found in greatest numbers in Florida (45), Louisiana (31), and Texas (31), consistent with (though not necessarily wholly explaining) the maxima in tornado day probabilities for 19 February shown by Brooks et al. (2003, their Fig. 7a). Interestingly, strong (F2–F3) QLCS tornadoes occurred with a

TABLE 3. Cumulative probabilities of cell tornadoes by F scale, based on 1998–2000 U.S. tornadoes. The probabilities exclude F0 tornadoes.

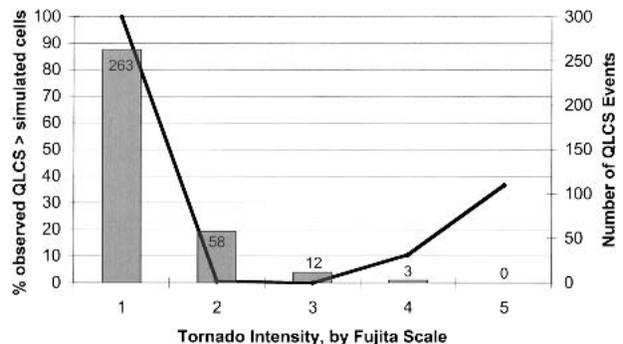| F scale	Cumulative cell-tornado probability
≥F1	1.000000
≥F2	0.346719
≥F3	0.114594
≥F4	0.022527
≥F5	0.002938

FIG. 4. Histogram of 1998–2000 U.S. QLCS tornado distribution by F scale, and percentage of the 10 000 Monte Carlo realizations in which there were more observed QLCS tornadoes in an F-scale bin than there were simulated (cell) tornadoes. Realizations are based on 336 cell tornadoes, which excludes F0 cell tornadoes.
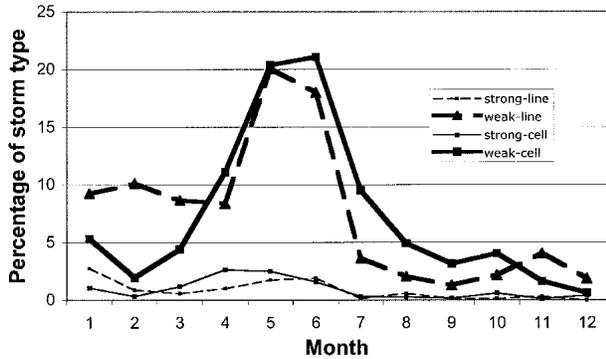
FIG. 5. 1998–2000 U.S. tornado distribution by month of occurrence and parent storm type (cell or QLCS). Percentage is based on total number of events per storm type. "Weak" denotes F0–F1 tornadoes, and "strong" denotes F2–F3 tornadoes.

slightly higher frequency during this time than in May and June (Fig. 5). Strong cell tornadoes, on the other hand, were most frequent during the months of April and May.

Cumulative probability distributions help us further quantify tornado as well as tornado day occurrence by month. As can be inferred from Fig. 6, 32% (29%) of the QLCS tornadoes (tornado days) occurred within the first three months of the year, compared to only 14% (16%) for cell tornadoes (tornado days). We use this to motivate another null hypothesis: the probability of a tornado during the months of January–March, given a QLCS, is the same as the probability of a tornado during the months of January–March, given a cell. The Monte Carlo technique was used again for the hypothesis testing. All tornadoes were considered. Hence, we drew 10 000 693-member samples (number of QLCS tornadoes) of random numbers between 0 and 1. Each random number in a sample was binned according to the cumulative probabilities of cell-tornado occurrence by month (see Fig. 6). The resultant monthly distributions for each of the 10 000 simulated years were compared to the monthly distribution of observed QLCS-

tornado occurrence, and then quantified as a percentage of realizations in which there were more observed QLCS tornadoes in a particular month bin than simulated (cell) tornadoes.

The Monte Carlo results show the occurrence of significantly fewer QLCS tornadoes during the summer and early fall months, at or above the 95% confidence level (Fig. 7). For example, 9646 (or ~96%) of the 10 000 simulated years had monthly distributions with fewer than 138 QLCS tornadoes in the month of June. However, significantly more QLCS tornadoes occurred from January to March, and then again from November to December, at or above the 95% confidence level. Thus, we again reject our null hypothesis with high confidence, and conclude that QLCS tornadoes appear more likely to occur during the "cool season" than do cell tornadoes.

d. Distribution by hourly occurrence

We next present 3-h running means of the hourly distributions of tornadoes by parent storm type (Fig. 8a). Cell tornadoes have a clear peak in occurrence near 1800 LST, which has been shown in previous studies for all tornadoes (e.g., Kelly et al. 1978). A similar daytime peak exists for QLCS tornadoes. But, these events additionally display a comparatively higher tendency to occur in the late night/early morning hours, which reflects the tendency of QLCSs in general to form in the late afternoon/early evening and then persist until morning (e.g., Bentley and Mote 1998). Cumulative probabilities of the 3-h running means of tornado occurrence (not shown) further quantify the differences with respect to storm type: 88% of cell tornadoes occurred between 1000 and 2000 LST, while 37% of QLCS tornadoes occurred between 2000 and 1000 LST.

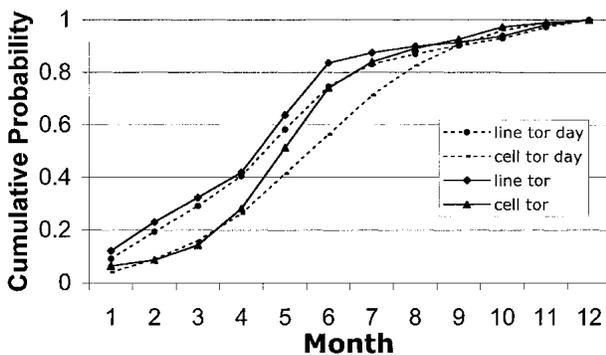We are particularly interested in the statistical sig-

FIG. 6. Cumulative probabilities of occurrence of QLCS and cell tornadoes, and of QLCS- and cell-tornado days, by month of year, based on 1998–2000 U.S. tornadoes.
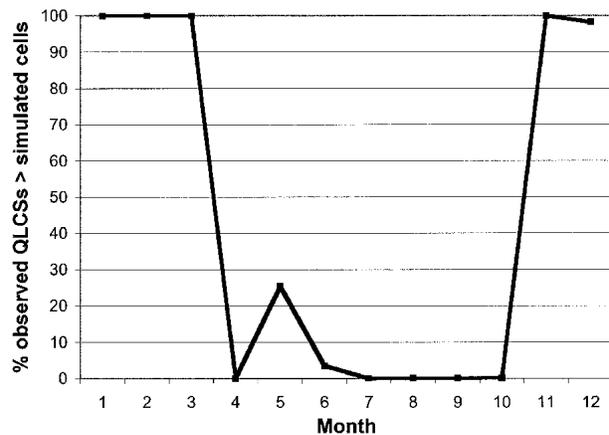

FIG. 7. Percentage of the 10 000 Monte Carlo realizations in which there were more observed QLCS tornadoes in a given month than simulated (cell) tornadoes. Realizations are based on all (682) cell tornadoes during 1998–2000 in the United States.
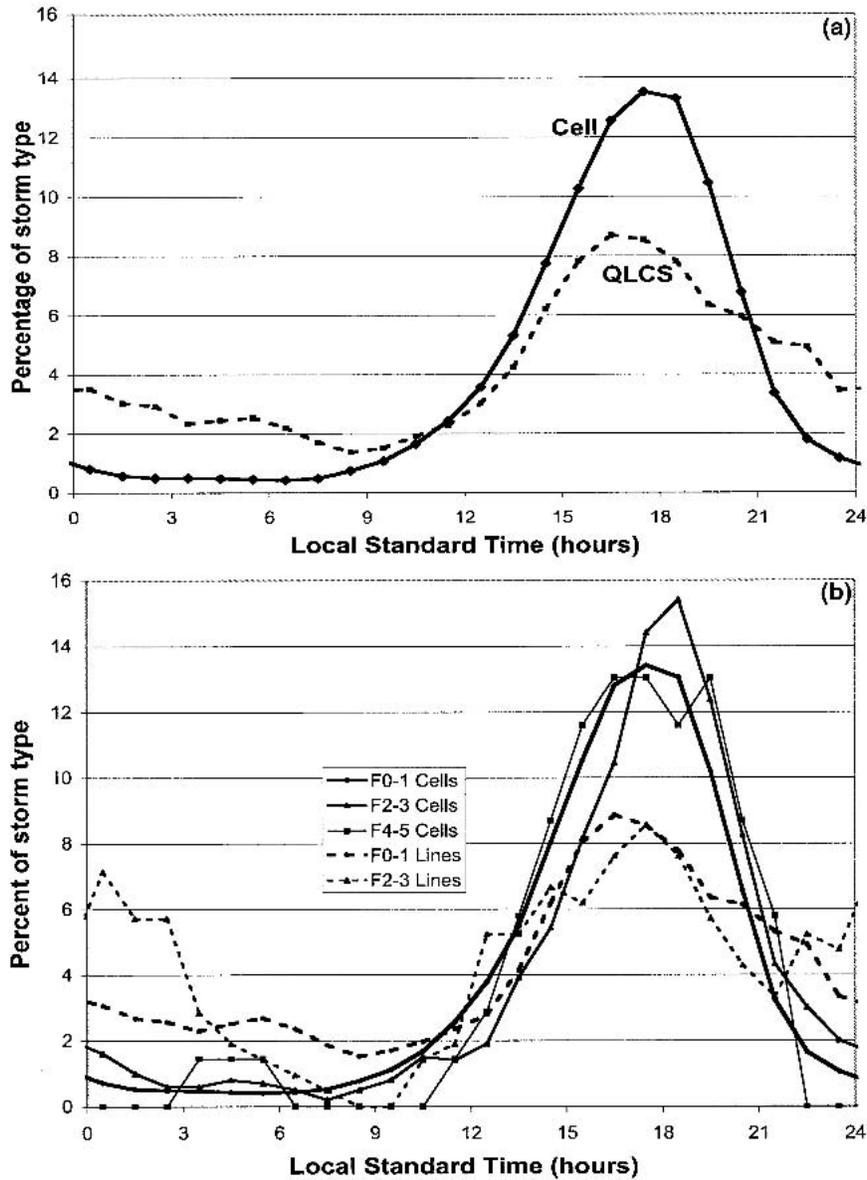
FIG. 8. Three-hour running mean of 1998–2000 U.S. tornado distribution by LST of occurrence and parent storm type (cell or QLCS), for (a) all tornadoes and (b) tornadoes as a function of F scale. Percentage in (a) is based on total number of events per storm type; percentage in (b) is based on total number of events per storm type in an F-scale range.

nificance of the higher occurrences of QLCS tornadoes during the nighttime hours. Hence, we again applied the Monte Carlo technique, in this instance to evaluate the null hypothesis that the probability of a nighttime tornado, given a QLCS, is the same as the probability of a nighttime tornado, given a cell. All tornadoes were again considered, and thus 10 000 693-member samples (total number of QLCS tornadoes) of random numbers between 0 and 1 were drawn. Each random number in a sample was binned according to the cumulative probabilities of cell tornado occurrence by hour (see Table 4). The resultant hourly distributions for each of the

10 000 simulated years were compared to the hourly distribution of observed QLCS-tornado occurrence, and then quantified as a percentage of realizations in which there were more observed QLCS tornadoes in a particular hour bin than simulated (cell) tornadoes.

At or above the 99% confidence level, there were significantly more tornadoes from QLCSs than from cells during the nighttime and morning hours of 2100–0900 LST (Fig. 9). At this same confidence level there were significantly fewer tornadoes from QLCSs than from cells between 1600 and 2000 LST. We conclude that there is a statistically significant difference be-

TABLE 4. Cumulative probabilities of cell tornadoes by LST, based on 1998–2000 U.S. tornadoes.

Local time	Cumulative cell-tornado probability
Midnight–1	0.007
1–2	0.013
2–3	0.017
3–4	0.022
4–5	0.028
5–6	0.032
6–7	0.036
7–8	0.041
8–9	0.046
9–10	0.058
10–11	0.073
11–12	0.096
12–1	0.131
13–14	0.181
14–15	0.256
15–16	0.363
16–17	0.489
17–18	0.632
18–19	0.769
19–20	0.888
20–21	0.946
21–22	0.972
22–23	0.989
23–midnight	1

tween the hourly distributions of QLCS and cell tornadoes, and in particular note that QLCS tornadoes appear more likely to occur during the nighttime and early morning hours than do cell tornadoes.

Other intriguing characteristics of the diurnal distribution are revealed when the hourly tornado data are separated by F scale. The weak (F0–F1) and strong (F2–F3) tornadoes from cells display a similar distribution throughout the day, with peaks in both between 1600 and 1900 LST (Fig. 8b). In contrast, the percentage of strong QLCS tornadoes (21%) is noticeably higher than weak QLCS tornadoes (9%) during the overnight hours of 2300–0300 LST. We propose two possible explanations for this disparity between weak and strong QLCS tornadoes: (i) the genesis mecha-
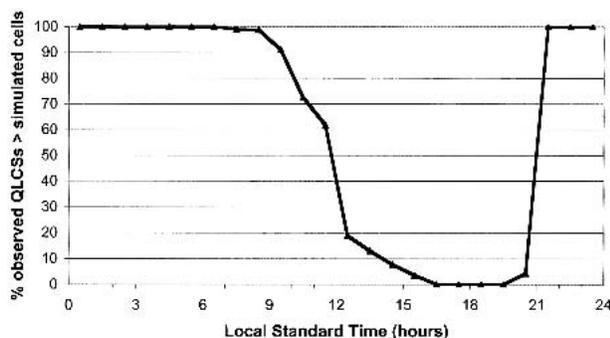

FIG. 9. Percentage of the 10 000 Monte Carlo realizations in which there were more observed QLCS tornadoes in a given hour than simulated (cell) tornadoes. Realizations are based on all (682) cell tornadoes during 1998–2000 in the United States.

nisms and/or intensity-limiting processes of weak versus strong QLCS tornadoes are fundamentally different throughout the day, or (ii) weak QLCS tornadoes are underreported. The first explanation is plausible, but beyond the scope of the current study. The second explanation has support in other studies such as Knupp (2000), which suggest that (weak) QLCS-tornado damage may be masked by and hence mistakenly reported as straight-line wind damage. Visual confirmation of tornadoes during the night is also less likely.

If, for the moment, we assume that whatever physical processes limit QLCS tornado intensity do not change fundamentally throughout the day, then the percentage of weak (F0–F1) QLCS tornadoes occurring in the near-midnight hours (2300–0200 LST) should be the same as the percentage of strong (F2–F3) tornadoes during these hours. Thus, $N_{\text{w-l-unrep}}$, the number of weak QLCS tornadoes not reported during the near-midnight hours, can be estimated as

$$N_{\text{w-l-unrep}} = (N_{\text{w-l}}) \times \left[\frac{\% \text{ weak } (0200 - 2300)}{\% \text{ strong } (0200 - 2300)} - 1 \right].$$

(1)

For $N_{\text{w-l}} = 609$, the percentage of weak tornadoes between 0200 and 2300 LST is 91%, and the percentage of strong tornadoes between 0200 and 2300 LST is 79%, Eq. (1) yields 92 tornadoes. In other words, it is possible that ~12% of all QLCS tornadoes in 1998–2000 were not reported. A similar calculation suggests that ~1% of all cell tornadoes in 1998–2000 were not reported.

4. Summary and conclusions

The objective of this study was to estimate the percentage of U.S. tornadoes that are spawned annually by squall lines and bow echoes, or quasi-linear convective systems (QLCSs). This was achieved by examining national composite radar reflectivity images for every tornado event recorded during 1998–2000 in the contiguous United States. Based on radar reflectivity criteria applied to these images, we determined the type of the storm associated with each tornado. Our list of possible parent storm types was limited to cell, QLCS, or other.

Of the 3828 tornadoes in our database, 79% were produced by cells, 18% were produced by QLCSs, and the remaining 3% were produced by other storm types, primarily rainbands of tropical cyclones. The percentage of QLCS tornadoes increased to 25% when the number of tornado days due to each storm type was considered. Geographically, these percentages exhibited wide variations. Of note are the states along a curved axis from Louisiana to Pennsylvania whose percentages of QLCS tornado days exceeded 25%. Of these states, Indiana had the highest percentage (50%) of QLCS tornado days during the 3-yr study period.

In an examination of the Fujita scale of cell versus QLCS tornadoes, we found comparatively more F1 tor-

nadoes from QLCSs, and comparatively more F2–F3 tornadoes from cells. A Monte Carlo test demonstrated that the probability of a weak tornado, given a QLCS, is much greater than the probability of a weak tornado, given a cell. No significant conclusions could be drawn about violent tornadoes because these events are particularly rare, regardless of parent storm type.

Finally, the distributions of cell and QLCS tornado occurrence by month and by local time of day were considered. The occurrence of QLCS tornadoes was biased toward the first half of the calendar year, with a relatively high likelihood in January through March. A different Monte Carlo test confirmed this, showing that QLCS tornadoes were statistically more probable during the cool season than were cell tornadoes. As with cell tornadoes, however, QLCS tornadoes were most frequent during the months of April through June.

Regarding local time of occurrence, cell tornadoes had a clear peak near 1800 LST, as did QLCS tornadoes. But, the QLCS events additionally displayed a comparatively higher and statistically significant tendency to occur in the late night/early morning hours. An examination of these events revealed a noticeably larger percentage of strong (F2–F3) versus weak (F0–F1) QLCS tornadoes during the period 2300–0300 LST. The lack of such a disparity in the diurnal distributions of cell-tornado intensities prompted us to pose that (i) the genesis mechanisms and/or intensity-limiting processes of weak versus strong QLCS tornadoes were fundamentally different throughout the day, or (ii) weak QLCS tornadoes were underreported. While thought-provoking, the first explanation was left for future research. Calculations based on a consideration of the second explanation suggest that as many as 12% of all QLCS tornadoes in 1998–2000 may not have been reported.

The results from this study should provide a baseline than can help forecasters anticipate the risk of tornadic winds in QLCSs, especially in a given geographic location and season. Future research will address forecasting issues more specifically by characterizing the environmental conditions under which tornadic QLCSs occur, and by describing their Doppler radar–derived attributes.

REFERENCES

Bentley, M. L., and T. L. Mote, 1998: A climatology of derecho-producing mesoscale convective systems in the central and eastern United States, 1986–95. Part I: Temporal and spatial distribution. *Bull. Amer. Meteor. Soc.,* **79,** 2527–2540.

Bluestein, H. B., and M. H. Jain, 1985: Formation of mesoscale lines of precipitation: Severe squall lines in Oklahoma during the spring. *J. Atmos. Sci.,* **42,** 1711–1732.

Brady, R. H., and E. J. Szoke, 1989: A case study of nonmesocyclone tornado development in northeast Colorado: Similarities to waterspout formation. *Mon. Wea. Rev.,* **117,** 843–856.

Brooks, H., and C. A. Doswell III, 2001: Some aspects of the international climatology of tornadoes by damage classification. *Atmos. Res.,* **56,** 191–201.

——, ——, and M. P. Kay, 2003: Climatological estimates of local daily tornado probability for the United States. *Wea. Forecasting,* **18,** 626–640.

Browning, K. A., 1964: Airflow and precipitation trajectories within severe local storms which travel to the right of the winds. *J. Atmos. Sci.,* **21,** 634–639.

Brunk, I. W., 1953: Squall lines. *Bull. Amer. Meteor. Soc.,* **34,** 1–9.

Carbone, R. E., 1983: A severe frontal rainband. Part II: Tornado parent vortex circulation. *J. Atmos. Sci.,* **40,** 2639–2654.

Davies-Jones, R., R. J. Trapp, and H. B. Bluestein, 2001: Tornadoes and tornadic storms. *Severe Convective Storms, Meteor. Monogr.,* No. 50, Amer. Meteor. Soc., 167–222.

Forbes, G. S., and R. M. Wakimoto, 1983: A concentrated outbreak of tornadoes, downbursts, and microbursts, and implications regarding vortex classification. *Mon. Wea. Rev.,* **111,** 220–235.

Fujita, T. T., 1981: Tornadoes and downbursts in the context of generalized planetary scales. *J. Atmos. Sci.,* **38,** 1511–1534.

Fulks, J. R., and C. D. Smith Jr., 1950: A December storm accompanied by tornadoes. *Mon. Wea. Rev.,* **78,** 220–225.

Geerts, B., 1998: Mesoscale convective systems in the southeast United States during 1994–95: A survey. *Wea. Forecasting,* **13,** 860–869.

Godfrey, E. B. S., 2003: A study of the environment and intensity of tornadoes from quasi-linear convective systems. M.S. thesis, School of Meteorology, University of Oklahoma, 83 pp. [Available from School of Meteorology, University of Oklahoma, 100 E. Boyd, Norman, OK 73019.]

Hamilton, R. E., 1970: Use of detailed intensity radar data in meso-scale surface analysis of the July 4, 1969 storm in Ohio. Preprints, *14th Conf. on Radar Meteorology,* Tucson, AZ, Amer. Meteor. Soc., 339–342.

Kelly, D. L., J. T. Schaefer, R. P. McNulty, C. A. Doswell III, and R. F. Abbey Jr., 1978: An augmented tornado climatology. *Mon. Wea. Rev.,* **106,** 1172–1183.

Kennedy, P. C., N. E. Wescott, and R. W. Scott, 1993: Single-Doppler radar observations of a mini-supercell tornadic thunderstorm. *Mon. Wea. Rev.,* **121,** 1860–1870.

Knupp, K. R., 2000: Narrow streaks of "straight-line" wind damage. Do tornadoes or microbursts produce them? Preprints, *20th Conf. on Severe Local Storms,* Orlando, FL, Amer. Meteor. Soc., 644–645.

——, R. L. Clymer, and B. Geerts, 1996: Preliminary classification and observational characteristics of tornadic storms over northern Alabama. Preprints, *18th Conf. on Severe Local Storms,* San Francisco, CA, Amer. Meteor. Soc., 447–450.

Lloyd, J. R., 1942: The development and trajectories of tornadoes. *Mon. Wea. Rev.,* **70,** 65–75.

McCaul, E. W., Jr., 1987: Observations of the Hurricane "Danny" tornado outbreak of 16 August 1985. *Mon. Wea. Rev.,* **115,** 1206–1223.

Moller, A. R., C. A. Doswell III, and R. Przybylinski, 1990: High-precipitation supercells: A conceptual model and documentation. Preprints, *16th Conf. on Severe Local Storms,* Kananaskis Park, AB, Canada, Amer. Meteor. Soc., 52–57.

Parker, M. D., and R. H. Johnson, 2000: Organizational modes of

midlatitude mesoscale convective systems. *Mon. Wea. Rev.,* **128,** 3413–3436.

Robe, F. R., and K. A. Emanuel, 2001: The effect of vertical wind shear on radiative–convective equilibrium states. *J. Atmos. Sci.,* **58,** 1427–1445.

Rotunno, R., and J. B. Klemp, 1985: On the rotation and propagation of simulated supercell thunderstorms. *J. Atmos. Sci.,* **42,** 271–292.

Spratt, S. M., D. W. Sharp, P. Welsh, A. Sandrik, F. Alsheimer, and C. Paxton, 1997: A WSR-88D assessment of tropical cyclone outer rainband tornadoes. *Wea. Forecasting,* **12,** 479–501.

Trapp, R. J., and M. L. Weisman, 2003: Low-level mesovortices within squall lines and bow echoes. Part II: Their genesis and implications. *Mon. Wea. Rev.,* **131,** 2804–2823.

——, E. D. Mitchell, G. A. Tipton, D. W. Effertz, A. I. Watson, D. L. Andra Jr., and M. A. Magsig, 1999: Descending and nondescending tornadic vortex signatures detected by WSR-88Ds. *Wea. Forecasting,* **14,** 625–639.

von Storch, H., and F. W. Zwiers, 2002: *Statistical Analysis in Climate Research.* Cambridge University Press, 491 pp.

Wakimoto, R. M., 1983: The West Bend, Wisconsin storm of 4 April 1981: A problem in operational meteorology. *J. Climate Appl. Meteor.,* **22,** 181–189.

——, and J. W. Wilson, 1989: Non-supercell tornadoes. *Mon. Wea. Rev.,* **117,** 1113–1140.

Weisman, M. L., and R. J. Trapp, 2003: Low-level mesovortices within squall lines and bow echoes. Part I: Overview and dependence on environmental shear. *Mon. Wea. Rev.,* **131,** 2779–2803.

Wilhelmson, R. B., and L. J. Wicker, 2001: Numerical modeling of severe local storms. *Severe Convective Storms, Meteor. Monogr.,* No. 50, Amer. Meteor. Soc., 123–166.

Wilks, D. S., 1995: *Statistical Methods in the Atmospheric Sciences.* International Geophysics Series, Vol. 59, Academic Press, 464 pp.

Witt, A., M. D. Eilts, G. J. Stumpf, E. D. Mitchell, J. T. Johnson, and K. W. Thomas, 1998: Evaluating the performance of WSR-88D severe storm detection algorithms. *Wea. Forecasting,* **13,** 513–518.