P5.4 INTENSITY AND TEMPORAL DISTRIBUTIONS OF TORNADOES FROM QUASI-LINEAR CONVECTIVE SYSTEMS

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1. INTRODUCTION

Tornadoes are known to evolve from a variety of different parent storm types such as high- and low-precipitation supercells, squall lines, bow echoes, and other convective systems. Trapp et al. (2004; hereafter, TTGB04) classified reported tornadoes in the United States from 1998–2000 by parent storm type: cell, quasi-linear convective system (QLCS), or other. Tornadoes from QLCSs, such as squall lines or bow echoes, composed 18% of the reported tornadoes; in specific geographic regions, this percentage was much higher.

This nontrivial number of QLCS tornadoes motivates this investigation of the distribution of QLCS tornadoes by Fujita scale, and local time of occurrence. Specifically, we seek to answer the following questions:

> Q.1 Are QLCS and cell-based tornadoes distributed similarly in terms of intensity and hour of occurrence?
>
> Q.2 Is there truth to the perception that tornadoes from QLCSs are more likely to be weaker than those from cells?
>
> Q.3 How do the diurnal distributions of weak and strong QLCS and cell-based tornadoes compare?
>
> Q.4 Are weak QLCS tornadoes underreported?

These questions have remained unanswered in the literature, and are all related to a bigger question: do QLCS tornadoes form differently than cell tornadoes? This theoretical question is beyond the scope of this paper. Herein the focus is on the practical and statistical differences between QLCS and cell tornadoes. This work is part of a larger project on the topic of QLCS tornadoes, which includes modeling work and Doppler radar attribute studies (Manross et al. 2004). The answers to the above questions should benefit operational meteorologists.

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2. HISTORICAL WORK

The distribution of tornadoes by damage intensity has been established by previous studies and is necessary for risk assessment and climatology. Brooks and Doswell (2001) observed that the damage intensity distribution of tornadoes by F-scale (Fujita 1981) in the U.S. should approach log-linearity. Dotzek et al. (2003) examined tornado intensity distributions in the U.S. and Europe and found that the shape of the exponential distribution described above tended to deviate for F5 and F0–F1 tornadoes. The primary factor affecting the F0 tornado distribution is the propensity to overlook and underreport F0 tornadoes (Knupp 2000) due to their relatively short lifetimes and small damage potential. Dotzek et al. (2003) found that a Weibull fit to the F-scale distribution reproduced the classified observations appreciably better than the exponential fit. The Weibull solution creates an improved fit for the observed tornado damage intensity distribution, especially for F0–F1 and F5 tornadic events.

Research on the temporal distribution of tornadoes has been a topic of meteorological curiosity since the early twentieth century. Brown and Roberts (1935), the first to study the diurnal distribution of tornadoes, examined U.S. tornadoes from 1880–1931 (excluding 1894) and observed that most tornadoes occurred between 1400 and 2130 LT, with a peak between 1530 and 1730 LT. Skaggs (1969) studied the diurnal distribution of tornadoes east of 104°W in the U.S. from 1916–64 and compared them by region and state. The authors found that many of the 22 cases of “traveling squall lines” caused tornadoes between 0000 and 0300 LT in southern Illinois and southeastern Missouri.

Kelly et al. (1978) examined the 1950–76 logs of severe local storms from the National Severe Storms Forecast Center (now the Storm Prediction Center, or SPC) that had been screened against the climatological record to eliminate invalid reports. This was the first research on the distribution of tornadoes by intensity and time of occurrence. The authors suspected that weaker tornadoes may be reported more frequently when there are more potential observers, and that F0–F1 tornado damage may otherwise be attributed to straight-line winds or downbursts. Conversely, they suggested that strong and violent tornado damage may be more likely to be correctly classified as tornado-related, even without visual confirmation of the funnel. Out of the 17,659 tornadic events from 1950–76, Kelly et al. (1978) examined the 15,313 tornadoes that were classified by F-scale and found a definite diurnal trend in weak (F0–F1) and strong (F2–F3) tornadoes. No diurnal trend was found for violent (F4–F5) tornadoes. Interestingly, the authors commented that the number of tornadoes that was recorded between sunset and sunrise is likely an underestimate of the actual number of occurrences.

Knupp (2000) later theorized that weak tornadoes may be underreported, but did not examine the diurnal distribution of tornadoes. Tessendorf and Trapp (2000) did preliminary work examining the distribution of tornadoes by intensity, parent storm type, and time of day. The authors found that the percentage of tornadoes produced by cells peaked between 1500-1900 LST, which is consistent with previous work. They also noticed that the diurnal cycle of QLCS tornadoes was much less evident than that of tornadoes from cells. Tessendorf and Trapp (2000) only examined one year of U.S. tornado data, beginning 1 March 1998, but the dataset was too small to draw many conclusions. In continuation of this work, TTGB04 expanded the dataset with two supplementary years of storm-classified tornado data.

3. DATA AND METHODOLOGY

The current study made use of tornado data classified by parent storm type from events between January 1998 and December 2000. TTGB04 classified 3828 individual tornadic events between January 1998 and December 2000 by parent storm type. The TTGB04 data were developed by comparing National Climatic Data Center (NCDC) tornado report data with U.S. composite radar images from NCDC and other sources, and then determining a tornado parent storm type of cell, line (QLCS), or other.

4. RESULTS

4.1 *Tornado Damage Intensity*

Of the 3828 storm-classified events in 1998–2000, 79% came from cells, 18% came from QLCSs, and 3% came from other parent storm types. The authors found that these percentages exhibited considerable geographic variability, and that states from Louisiana through Illinois to Pennsylvania had percentages of QLCS tornado days that exceeded the national average. TTGB04 found that half of the tornado days in Indiana from 1998–2000 were associated with QLCSs.

TABLE 1. Classification of 1998–2000 U.S. tornado damage by F-scale intensity and parent storm type.

	F0	F1	F2	F3	F4	F5	Total
Cell	1992	667	237	94	20	3	3013
QLCS	356	263	58	12	3	0	692
Other	73	39	11	0	0	0	123

This study investigated whether or not the distribution of tornado damage intensity from QLCSs is different from the distribution of cells. To answer this, the results of the classification studies were separated by F-scale intensity (Table 1) and plotted on a log-linear axis. Figure 1 shows that tornadoes from QLCSs do not exhibit the log-linear distribution demonstrated by Brooks and Doswell (2001) for all tornadoes. Dotzek et al. (2003) indicated that the actual distribution may fall short of log-linearity at high F-values. The intensity distribution of tornadoes from cells displays the distribution discussed in Dotzek et al. (2003), while the QLCS tornado intensity distribution has a steeper slope. Statistical analyses were used to further compare and contrast the QLCS tornado distribution with that of cell tornadoes and to determine, for example, whether or not tornadoes produced by linear systems were less likely to be strong events.

A comparison of the distribution of cell tornado intensities with that of QLCS tornadoes was dubious due to the small QLCS sample size. The QLCS tornado intensity distribution was normalized to 237 F2 events (the number of observed cell tornadoes in 1998–2000) for better comparison. The normalized distributions are shown on a logarithmic scale in Figure 2. The QLCS tornado intensity distribution had a steeper slope than the cell tornado distribution. There were many more F1 tornadoes from QLCSs than from cells in this normalized dataset, and many fewer F3 and F0 QLCS tornado events. The F0 QLCS tornadoes fell well below the typical log-linear tornado distribution (Brooks and Doswell 2001; Dotzek et al. 2003), but it was hypothesized that F0 QLCS tornadoes were unreliably reported. F4 and F5 tornadoes were relatively infrequent, composing less

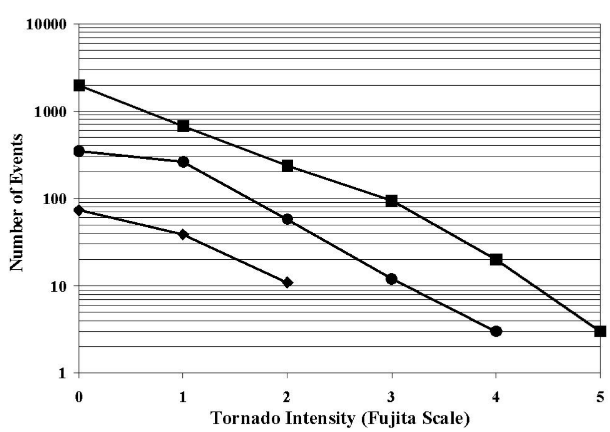

FIG. 1. 1998–2000 U.S. tornado distribution by intensity and cell (squares), QLCS (circles), or other (diamonds) parent storm type.

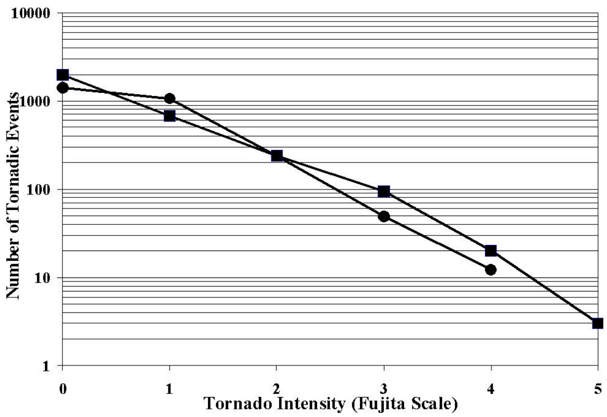

FIG. 2. 1998–2000 U.S. tornado distribution by intensity and cell (squares) and QLCS (circles) parent storm type, normalized to 237 F2 tornadoes.

than 0.8% of cell tornadoes in the dataset. Therefore, these very strong tornadoes occurred too infrequently to compare the frequency of occurrence between cells and QLCSs.

Since QLCS tornadoes did not occur nearly as often as cell tornadoes, the QLCS tornado dataset remained relatively small. Thus, it may not have been possible to distinguish between the two distributions, even if there were physical differences. For example, if an event (such as an F4–F5 tornado) were expected less than 0.8% of the time, it would take many years of smaller datasets (with only ∼231 events per year) before the lack of these violent events was significant.

It is difficult to be sure if the differences in the F0–F3 intensity distributions were due to the small QLCS tornado sample size or if the distributions were actually quite different. Ideally, the record of reliable storm classified data would have spanned many more years. Because it did not, statistical methods were used to produce a larger sample size. In effect, artificial data were created that were consistent with the observed cell tornado data. The Monte-Carlo method, which simulates the observed statistical data under the assumption that the null hypothesis (H_0) is true, was applied. A large number of realizations of the test statistic were generated by a computer and were used to construct an empirical estimate of the distribution of the test statistic under H_0 (von Storch and Zwiers 2002). The estimated distribution was used to determine the critical value, which would otherwise be available had the original dataset been large enough.

In many meteorological applications, statistical independence is crucial for hypothesis testing. However, given the relative infrequency and small-scale nature of tornadic events, it was assumed that the tornadic events were independent.

A Monte-Carlo resampling test was performed to evaluate, among other things, the null hypothesis that the probability of a violent tornado, given a QLCS, was the same as the probability of a violent tornado, given a cell. The approach was used to test if the observed QLCS F-scale distribution could have come from a random sample of the cell F-scale distribution. Hence, the observed distribution of tornadoes from cells in 1998–2000 was defined to be "truth." The cumulative probabilities of cell tornado F-scales were determined and random numbers between 0 and 1 were generated. Each random number was classified as F1–F5 according to the cumulative cell probability table.

Ten thousand cell distributions were generated, consisting of 336 tornadic events each, since the observed data contained 336 QLCS tornadoes at or above the F1 level. (F0 tornadoes were neglected in this analysis since these events are likely underreported.) At the 100% confidence level, there were significantly more F1 tornadoes from QLCS parent storms than from cells. In other words, every one of the 10,000 realization sets had fewer than 263 F1 tornadoes (the portion of the 336 total observed QLCS tornadoes that were rated F1). At the 99.4% confidence level, there were significantly fewer F2 tornadoes from QLCS parent storms than from cells, and fewer F3 tornadic events at the 100% confidence level. The confidence levels for all F-scales are shown in Figure 3. Although confidence levels for the strongest tornadoes were high, no significant conclusions could be drawn because these events were particularly rare, even in cell parent storm types.

There were statistically significant differences between tornado intensities from cells and from QLCSs during the three-year observation period. Thus the probability that tornadoes from cells could have had the same F1–F3 distribution as tornadoes from QLCSs is less than 1%. It was not impossible, but it was highly unlikely. QLCSs produced many more F1 tornadoes, but many fewer F2 and F3 tornadoes than did cells. QLCSs were less likely to produce tornadoes with a higher F-scale rating than cells. Thus, statistically, the distribution of QLCS tornadoes was significantly different than the distribution of cell-based tornadoes.

As previously mentioned, it was likely that the lowest-

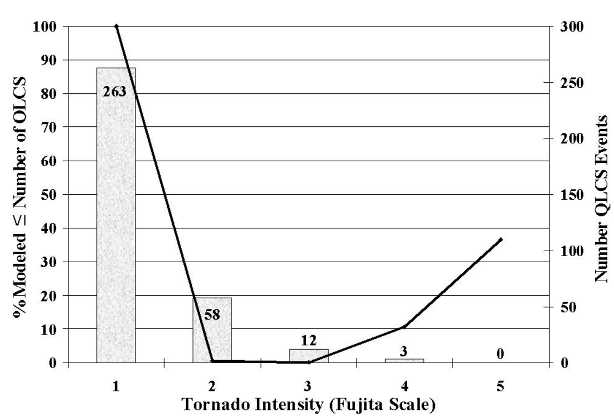

FIG. 3. Histogram of 1998–2000 U.S. QLCS tornado distribution by intensity (right scale) and the percent of model runs that had fewer events than the number of observed QLCS tornadoes (line, left scale). Numbers are based on 10,000 realizations of 336 cell tornadoes.

intensity (F0) tornadoes produced by linear convective storms were underreported. As documented by Brooks and Doswell (2001), tornado intensity appears to approach a log-linear distribution. Ideally, another dataset could be generated to compare the number of F0 tornadoes occurring in cells and lines. However, data cannot be simulated unless the actual size of the QLCS dataset is known. If the weakest QLCS tornadoes were indeed underreported, a dataset composed of 692 events (the number of all observed 1998–2000 tornadoes from lines) and similar to the distribution of cell tornadoes would simply decrease the number of stronger tornadoes in the sample. Thus, simulations would not be useful for comparison.

TTGB04 documented a high percentage of QLCS tornado days between 1998–2000, particularly in the Midwestern United States (LA arcing through PA, with a maximum in IN). Perhaps clouds, precipitation, and/or trees obscured weak tornadoes that occurred in these parts of the country, and their damage resembled (or was embedded within) straight-line wind damage. A further possibility, investigated next, is that tornadoes from QLCSs occurred more frequently at night than did those from cells.

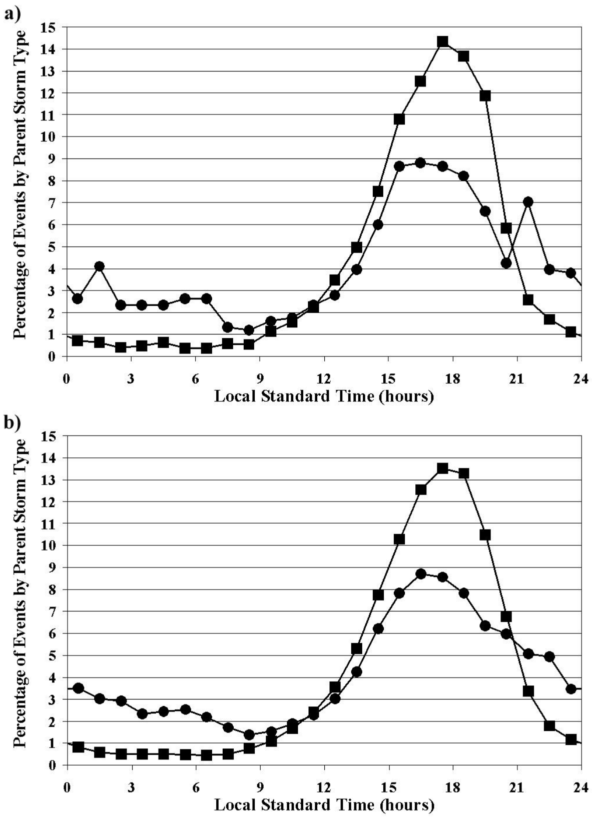

FIG. 4. Percentage of 1998–2000 U.S. tornado events separated by local time of occurrence for cells (squares) and QLCSs (circles) for a) the observed distribution and b) the three-hour running average.

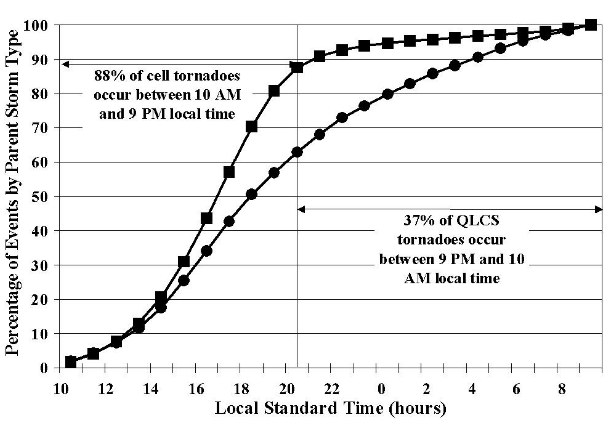

FIG. 5. Cumulative probabilities of a tornado occurring from a cell (squares) or a QLCS (circles) parent storm type as a function of time of day, based on three-hour averages of time of occurrence for 1998–2000 U.S. tornadoes.

4.2 *Temporal distribution*

Utilizing the same data from TTGB04 classified by parent storm type, the 1998–2000 tornado data were separated into hourly bins by the local time each tornado began. Figure 4 shows the distribution of cell and QLCS tornadoes over a 24-hour period and the three-hour running mean distributions. There appears to be a strong diurnal cycle in the distribution of tornadoes from both cells and QLCSs. Most of the tornadoes from cells occurred in the late afternoon hours, and this distribution peaked between 1700–1800 LST. The QLCS tornado distribution also peaked in the late afternoon hours (1600–1700 LST) but there was also a high frequency of tornadoes during the overnight hours.

A cumulative probability distribution of tornadoes by parent storm type demonstrates that 25% of QLCS tornadoes and 8% of cell tornadoes occurred between midnight and 1000 LST. If the same cumulative distribution is begun at 1000 LST, Figure 5 shows that 12% of tornadoes from cells and 37% of tornadoes from lines occurred from 2100 to 1000 LST. Not only did a greater percentage of QLCS than cell-based tornadoes occur during the overnight hours, but more QLCS tornadoes occurred between 0100–0400 and 0500–0700 LST. This is particularly noticeable in light of the fact that only 18% of all tornadoes in 1998–2000 came from linear systems.

To determine the statistical significance of the higher frequency of QLCS tornadoes in the nighttime hours, a second Monte-Carlo technique was performed to evaluate the null hypothesis that the probability of a nighttime tornado, given a QLCS, was the same as the probability of a nighttime tornado, given a cell. The idea was to test if the observed diurnal distribution of QLCS tornadoes could have come from a random sample of the diurnal distribution of cell tornadoes. Hence, the observed diurnal distribution of tornadoes from cells in 1998–2000 was defined to be "truth."

The cumulative probabilities of the time of occurrence of cell tornadoes were determined and random numbers between 0 and 1 were generated. Each of the 10,000 re-

TABLE 2. Distribution of 1998–2000 U.S. tornadoes from cells and from QLCSs by time of occurrence (LST) and F-scale damage intensity. Notice that between 0100–400 LST and 0500–0700 LST (bold) more tornadoes were reported from QLCSs than from cells.

	Cells							QLCSs					
	F0	F1	F2	F3	F4	F5	Total	F0	F1	F2	F3	F4	Total
Mid-1	13	2	3	3	0	0	21	9	7	2	0	0	18
1-2	10	6	3	0	0	0	**19**	9	11	6	1	1	**28**
2-3	3	8	0	1	0	0	**12**	6	7	3	0	0	**16**
3-4	6	6	1	1	0	0	**14**	4	10	1	1	0	**16**
4-5	11	4	1	2	1	0	19	8	7	1	0	0	16
5-6	2	6	3	0	0	0	**11**	5	12	1	0	0	**18**
6-7	5	5	0	1	0	0	**11**	7	10	0	1	0	**18**
7-8	9	7	1	0	0	0	17	4	5	0	0	0	9
8-9	11	5	0	0	0	0	16	7	1	0	0	0	8
9-10	25	5	2	2	0	0	34	8	3	0	0	0	11
10-11	36	7	4	0	0	0	47	7	5	0	0	0	12
11-12	51	10	6	1	0	0	68	7	6	3	0	0	16
12-13	77	24	2	1	1	0	105	8	10	1	0	0	19
13-14	111	29	7	2	1	0	150	13	7	6	1	0	27
14-15	159	38	23	4	2	0	226	22	16	3	0	0	41
15-16	235	69	12	6	2	1	325	34	21	2	2	0	59
16-17	260	79	22	14	3	0	378	40	14	3	3	0	60
17-18	279	100	34	16	2	1	432	32	21	6	0	0	59
18-19	267	85	44	13	2	1	412	30	19	4	2	1	56
19-20	231	79	32	14	2	0	358	25	15	4	0	1	45
20-21	101	51	17	3	4	0	176	18	9	2	0	0	29
21-22	49	13	9	7	0	0	78	18	27	3	0	0	48
22-23	24	20	6	1	0	0	51	17	8	2	0	0	27
23-Mid	17	9	5	2	0	0	33	8	12	5	1	0	26
Total	1992	667	237	94	20	3	3013	346	263	58	12	3	682

alization sets contained 682 events, corresponding to the total number of QLCS tornadoes in the TTGB04 dataset. In all of the realizations between 2100 and 0700 LST and 98.9% of the realizations between 0700 and 0900 LST, there were significantly more tornadoes from QLCS parent storms than from cells (Figure 6). However, there were significantly more tornadoes from cells than from QLCSs between 1600 and 2000 LST at or above the 99.8% confidence level. Therefore, there was a statistically significant difference between the observed daily distributions of tornadoes from QLCSs and cells. Tornadoes from cells displayed a strong preference for the late afternoon, while QLCS tornadoes additionally preferred the overnight hours. It was not clear which of the two distributions was special.

4.3 *Temporal and intensity distribution*

In order to address the diurnal distribution of weak and strong tornadoes from cells and QLCSs, the hourly data were separated by intensity (Table 2). Differences between the strong and weak tornado distributions became self-evident (Figure 7). The strongest tornadoes (F4–F5) were not plotted due to the relatively infrequent rate of occurrence. The weak and strong tornadoes from cells displayed a similar distribution throughout the day, peaking between 1600–1900 LST. There was a noticeably higher percentage of strong (F2–F3) QLCS tornadoes than weak (F0–F1) occurring during the overnight hours of 2300–0300 LST. This raised two possibilities: the mechanisms of linear convective storms are different in the near-midnight hours, or weak QLCS tornadoes are underreported. The first possibility is beyond the scope of this study. The second possibility, that QLCS F0–F1 night-time tornadoes are unreliably reported, is likely. Knupp (2000) suggested that weak tornadoes may occur more often than they appear in the SPC database, and are instead often reported as straight-line wind damage.

Thus, it is quite possible that weak QLCS tornadoes during the near-midnight hours are underreported. There are few witnesses during these hours because relatively few people are awake, and those who are watchful would have great difficulty spotting a tornado in the dark. Strong tornadoes will leave a much more evident dam-

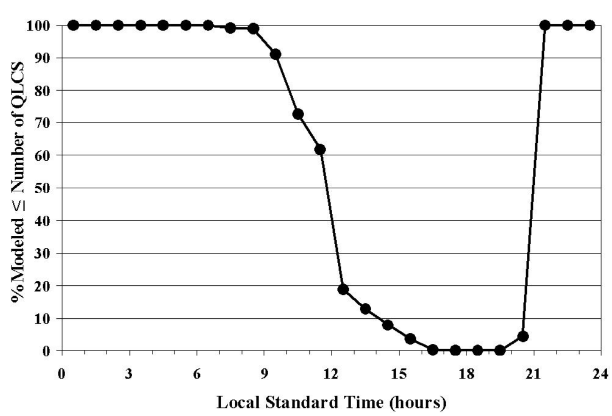

FIG. 6. Percentage of model runs that had fewer events than the number of observed QLCS tornadoes, by local time of day. Numbers are based on 10,000 model runs of 682 cell tornadoes.

age path than weaker ones, the latter of which may resemble or be embedded within strong wind events. With the passage of a severe linear convective system, emergency management personnel typically expect straight-line wind damage. Thus, reports of downed trees, damaged roofs, etc., are expected, reported as "wind damage" and may not be followed up with a damage survey.

Assuming that the mechanisms of QLCSs do not undergo fundamental changes throughout the day, it is expected that the percentage of weak (F0–F1) QLCS tornadoes occurring in the near-midnight hours (2300–0200 LST), 9%, should be the same as the percentage of strong (F2–F3) tornadoes, 21%. In order to estimate the number of unreported weak tornadoes from lines occurring near local midnight, an adjustment of the form

$$\left(\frac{W}{S}\right)(T) - (T), \tag{1}$$

where T is the total number of weak QLCS tornadoes (609), W is the percentage of weak tornadoes between 0200–2300 LST (91%), and S is the percentage of strong tornadoes between 0200–2300 LST (79%) yields

$$\left(\frac{91\%}{79\%}\right)(609) - (609) = 95. \tag{2}$$

Thus, it is estimated that about 95 weak QLCS tornadoes between 2300–0200 LST were not reported in 1998–2000. In other words, it is possible that ∼12% of all QLCS tornadoes in 1998–2000 were not reported.

Performing a similar calculation for the number of weak tornadoes from cells that may be underestimated between 0300–0600 LST, with $T = 2659$, $W = 99\%$, and $S = 98\%$ in equation (1) yields

$$\left(\frac{99\%}{98\%}\right)(2659) - (2659) = 30. \tag{3}$$

Therefore, it is estimated that about 30 weak cell-based tornadoes between 0300–0600 LST were not reported in 1998–2000. It is possible that ∼1% of all tornadoes from cells from 1998–2000 were not reported.

5. SUMMARY

This study examined the distribution of tornadoes from QLCSs by intensity and local time of occurrence in a hope to better understand the nature of these tornadoes. As 18% of all tornadoes in the U.S. come from QLCSs, their behavioral patterns are of great practical importance.

This study has shown that tornadoes that form from QLCSs have somewhat different intensity and diurnal distributions than tornadoes that form from cells (relates to Q.1). It was also demonstrated that tornadoes from QLCSs are more likely to be weak than are cell tornadoes (Q.2), and that the distribution by intensity has a steeper slope than that of cell tornadoes. QLCS tornadoes were also shown to have a different diurnal distribution than tornadoes from cells (Q.3). A significantly larger percentage of QLCS tornadoes than cell-based tornadoes from 1998–2000 occurred during the overnight/early morning hours between 2000 and 1000 LST. Since it was established that so few weak QLCS tornadoes and disproportionately more strong tornadoes occur in the near-midnight hours, it was suggested that as many as 95 weak events may have been underreported during 1998–2000, or about 12% of all QLCS tornadoes in this period (Q.4). Similarly, 30 weak tornadoes from cells may have been unreported between 0300–0600 LST, or about 1% of all cell tornadoes.

Hopefully the study of tornadoes by parent storm type and intensity will continue. With increased public awareness, the likely nocturnal underreporting of weak tornadoes may decrease, and the collection of subsequent tornado data classified by parent storm type may determine how significant the differences between the diurnal distributions of weak and strong tornadoes truly are. Then the mechanisms that cause the possible dissimilar distributions of weak and strong tornadoes could be examined.

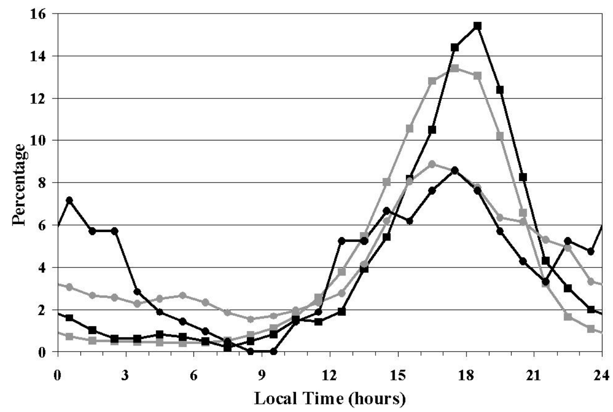

FIG. 7. Three-hour running average of the percentage of 1998–2000 U.S. tornadoes by intensity and parent storm type. Black lines indicate more damaging (F2–F3) tornadic events and gray lines indicate weaker (F0–F1) tornadic events. Square markers indicate tornadoes from cells, and QLCS tornadoes are marked by circles.

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