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TORNADO OUTBREAK DAY SEQUENCES: HISTORIC EVENTS AND CLIMATOLOGY (1875-2003)

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1. INTRODUCTION

Extended tornado outbreak sequences, such as the 3–11 May 2003 event, not only cause enormous damage and loss of life, but also strain resource limits within the severe weather forecast, warning, communication, and emergency management communities (NWS Service Assessment Survey Team 2003). Although relatively rare, these intense episodes of approximately one-week duration can alone determine the character of an entire severe weather season.

The notion of a tornado outbreak is common within the severe weather community; however, specific criteria defining these events vary from manuscript to manuscript. Galway (1977) provided the most widely used definition with a focus on approximately 6-10 tornadoes as an initial threshold for an outbreak and progressively higher thresholds used to define a major outbreak. This threshold criterion requires some modification for use with the widely varying character of the historic tornado report database, with only tornadoes greater than F2 intensity (Fujita 1971) generally available for early portions of the record (Grazulis 1993) and with numerous weaker tornadoes routinely reported during the past decade (Schaefer et al. 2002).

For the purposes of this study, a tornado outbreak sequence or extended tornado outbreak is defined as a continuous or near-continuous sequence of tornado outbreak days. A variety of definitions for an outbreak "sequence" are explored, including definitions tailored to fit the recent tornado outbreak sequence from 3–11 May 2003. This manuscript explores the basic climatology of tornado outbreak sequences under a variety of event definitions, isolates and describes the most significant events within the historic record, and uses these results to provide historic perspective on the recent May 2003 outbreak sequence

After this introduction, Section 2 describes data content and preparation. Section 3 outlines three basic approaches for exploring extended tornado outbreaks and discusses simple advantages and disadvantages of each. A brief summary of the 3-11 May 2003 event is provided in Section 4, and Section 5 describes initial climatological results. Section 6 details the most intense historic events during the period from 1875 to 2003 and Section 7 uses the results from the climatological information and historic events to place the 2003 extended outbreak in historic perspective. In Section 8, an estimate of recurrence frequency is made for sequences of varying length and magnitude. Finally, Section 9 presents a summary, a few conclusions, and describes future directions for this research.

2. DATA PREPARATION

Severe weather databases from NOAA (Kelly et al. 1978; Schaefer and Edwards 1999) and Grazulis (1993) were used to construct a daily record of severe weather activity spanning the period from 1875 to 2003. The quality of this significant tornado record declines markedly in the years prior to 1916, but a subjective assessment of event sequences prior to 1916 was performed looking for extended outbreak sequence candidates (Grazulis et al. 1993).

A day is defined as midnight-to-midnight Central Standard Time as done in the NOAA tornado database (Schaefer and Edwards 1999). As described in Schneider et al. (2004), a wide variety of summary parameters was created for each. Two data sets were created: 1) summary data for tornadoes of F2 intensity or greater (referred to as "significant tornadoes") from Grazulis (1993) for the period spanning 1875 to 1995, and 2) daily summaries of reported tornadoes, regardless of intensity, from the NOAA data from 1950 to 2003, inclusive. The tornado data were augmented with daily summaries of severe wind and hail reports for the period from 1955 to 2003 (Schaefer and Edwards 1999).

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3. SEQUENCE DEFINITION

A variety of outbreak sequence definitions were considered to avoid focus on a single threshold for event occurrence or continuation. Two objective approaches for defining a sequence, Fixed Duration and Continuous Threshold, are used. However, both of these methods underestimate the number of cases in the earlier years due to the relatively sparse number of reports prior to 1953 and particularly prior to 1916. Therefore, a third approach, Near-continuous Threshold—which allows greater subjective judgment in the continuation or termination of an outbreak sequence—is also used. In this approach, the investigator assesses nuances of the data content and quality across the record. A brief description of each approach along with some of its attributes follows.

3.1 *Fixed Duration Sequence*

The sum of all severe weather events within a sliding block of days is considered and periods with the largest aggregate tornado activity are recorded. The strengths of this approach are the uniform treatment of the entire record and the ability to systematically vary the fixed length to investigate sequences of both short and long duration. One weakness is the dominance of some single extraordinary events within analyses of even month-long periods, e.g., the 3 April 1974 Superoutbreak. This technique does not require a near-continuous severe weather episode.

3.2 *Continuous Threshold Sequence*

This technique requires that a specific threshold of severe weather activity was met on *each* successive day. This stresses the continuous nature of the sequence. An example is consecutive days with at least one significant tornado (Drton et al. 2003). Unfortunately, this method is sensitive to arbitrary assignment of severe weather to specific days, particularly for events near midnight. It also does not give uniform treatment to the complete record, given the inconsistencies in severe weather reporting during the 130 years of record.

3.3 *Near-Continuous Threshold Sequence*

This subjective approach allows for short periods of reduced tornadic activity within an otherwise continuous sequence without immediately truncating the event. The length of the "short," apparently quiescent, period can be tailored to fit the characteristics of the historic tornado record. For sequences prior to 1950, two consecutive days with no significant tornado activity were allowed if the respite was surrounded by significant event sequences. In the modern record, only a one-day respite was allowed, and this day had to feature either weak tornadoes or widespread, severe hail or damaging winds.

4. MAY 2003 SEQUENCE

The near-continuous tornado outbreak sequence in early May 2003 (Table 1) extended from 3 May through 11 May and was responsible for 41 fatalities, 642 injuries, and approximately 829 million dollars of property damage (NWS Service Assessment Team 2003). This event covered much of the eastern two-thirds of the United States, stretching from the Great Plains to East Coast (Fig. 1).

During the 9-day period, at least one significant tornado and more than 10 total tornadoes occurred each day. However, 3 of the 9 days had only one significant tornado reported and one of these significant events occurred very close to midnight. On 4 May, 25 significant tornadoes ravaged the Great Plains in the largest tornado outbreak in the sequence. This sequence also contained outbreaks of significant tornadoes on 6, 8, and 10 May.

Date	Number of Tornadoes	Number of F2 – F5 Tornadoes	Number of F4 – F5 Tornadoes	Number of Fatalities
May 3	13	1	0	0
May 4	81	25	4	38
May 5	25	1	0	0
May 6	74	7	1	2
May 7	29	1	0	0
May 8	48	10	1	0
May 9	31	2	0	0
May 10	51	11	0	0
May 11	14	5	0	1
Total	**366**	**63**	**6**	**41**

Table 1 – Total number of tornadoes, significant tornadoes, violent tornadoes, and tornado fatalities for each day (midnight to midnight CST or 0600 UTC to 0600 UTC) between 3 and 11 May 2003 based on National Weather Service Storm Data.

5. CLIMATOLOGY

Initial climatological investigation of tornado outbreak sequences focused on assessing the historical uniqueness of the 3–11 May 2003 event. As such, the 128-year daily tornado and severe weather summary from 1875 through 2003 was searched for continuous or near-continuous tornado outbreak sequences with a daily threshold of one or more significant tornadoes. This manual examination uncovered an array of candidate sequences, but further examination revealed that only three events in the record, one each in 1917, 1930 and 1949, clearly approached or exceeded the duration and magnitude of the May 2003 sequence.

To further examine the historic record, analysis of a spectrum of fixed duration sequences (1, 3, 7, 14, 21, and 28 days) was performed for both the Grazulis and the NOAA data sets. The annual maximum duration sequences for 3, 7, and 14-day periods for both significant (F2 – F5) and violent (F4 – F5) tornadoes are shown in Figs. 2 and 3. The 7 and 14-day fixed duration significant tornado sequences (Figs. 2b, 2c), like the manual examination, highlight the 1917, 1930, and 1949 events. The violent tornado sequences also highlight the 1917 and 1930 events, but do not show the 1949 event (Figs. 3b, 3c).

The fixed duration analysis shows the influence of two singular events of remarkable intensity; the 3 April 1974 Superoutbreak and 10 April 1965 Palm Sunday Outbreak standout. The single day total for both these events dominated the fixed period sums, even though they were associated with only short duration sequences. Amazingly, the 1-day total of 30 violent tornadoes during the 1974 Super Outbreak exceeds the 28-day total for any other year!

Finally, it is readily apparent that during May 2003 the number of both significant and violent tornadoes within a 7-day or 14-day fixed duration sequence was large, but not unprecedented. In fact, one can argue that the sum for violent tornadoes is merely on the high side of average. What was most remarkable about the May 2003 event is that there was at least one significant tornado on nine consecutive days and that four tornado outbreaks occurred within a 7-day period.

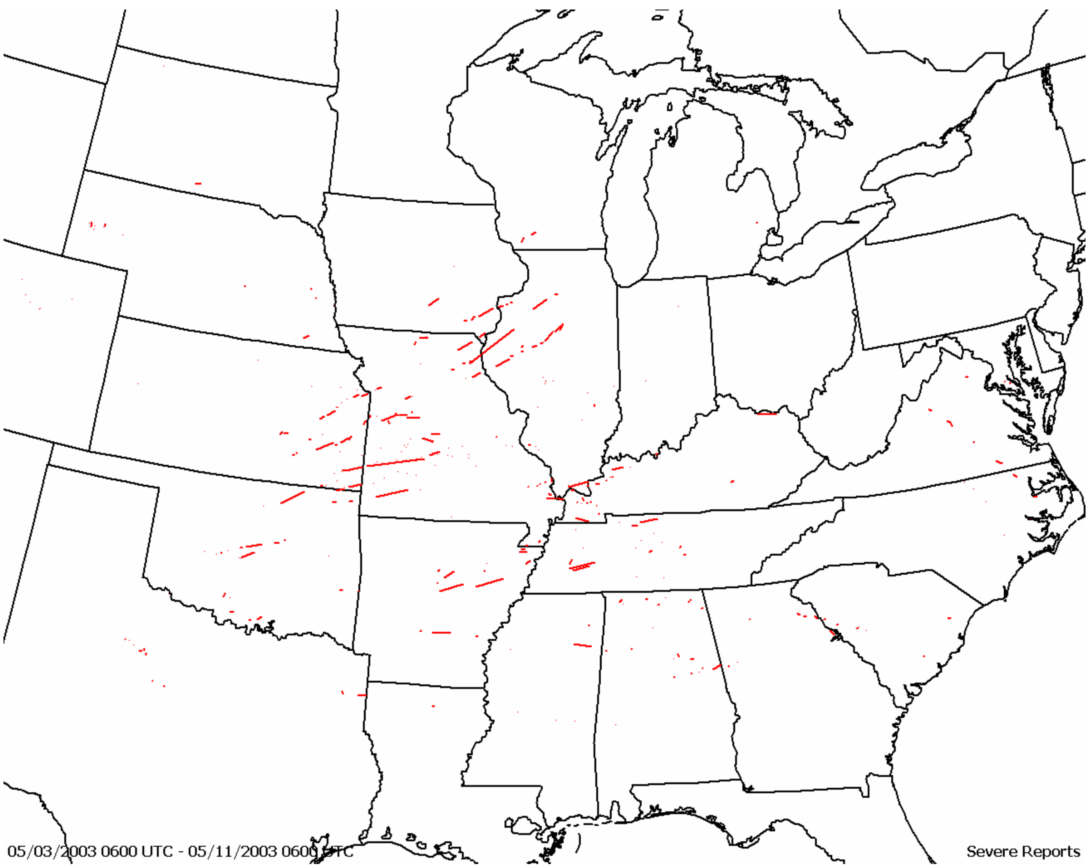

Figure 1: Tornado tracks (red line segments) for the Tornado Outbreak Sequence from 0600 UTC 03 May (midnight CST 3 May) through 0600 UTC 12 May (11:59 CST 11 May) based on National Weather Service Storm Data.

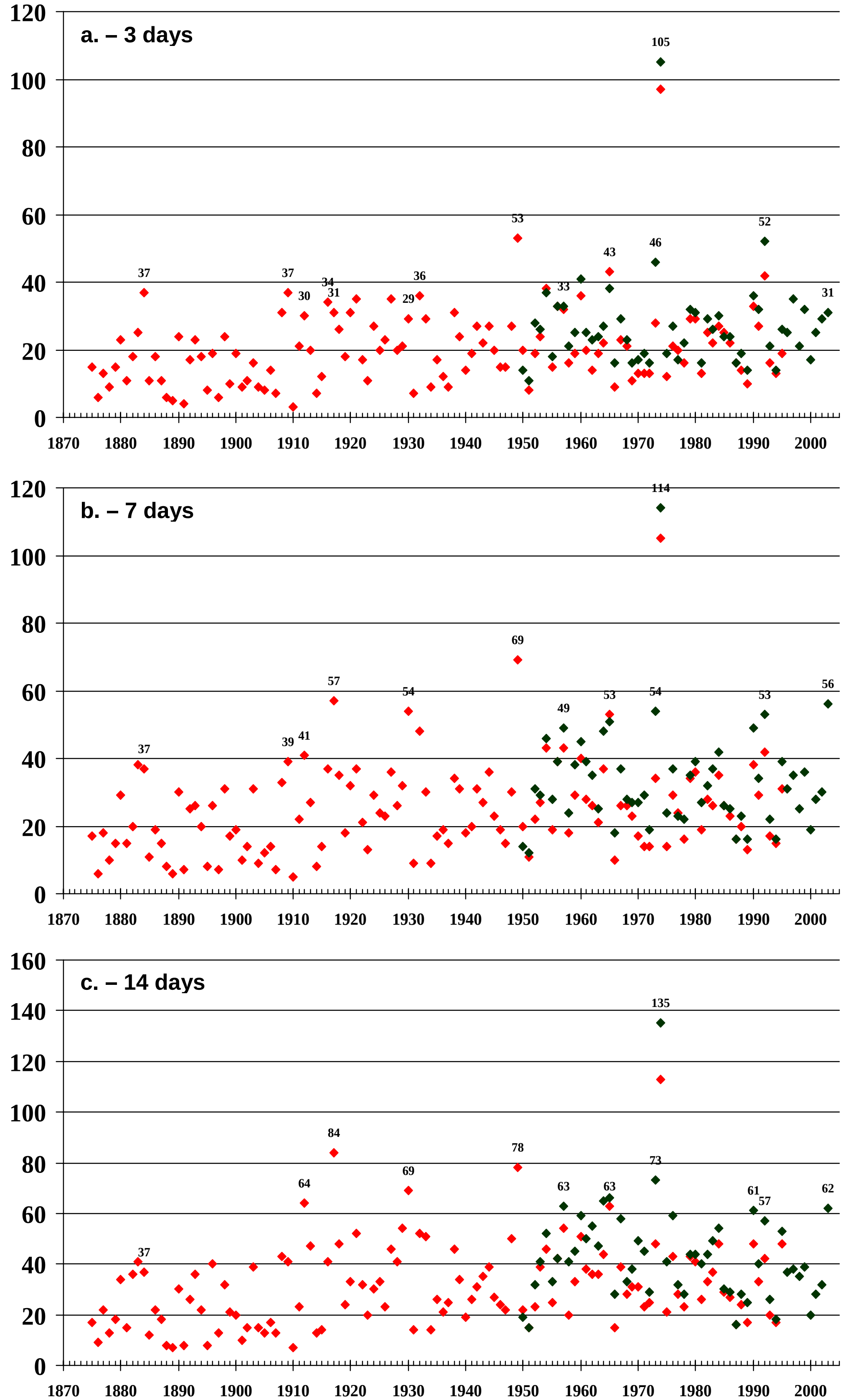

Figure 2: Maximum number of F2 – F5 tornadoes each year for fixed duration periods of a) three days, b) seven days, and c) fourteen days for data from Grazulis (1993) (red) and NWS (green) for the period from 1875 to 2003.

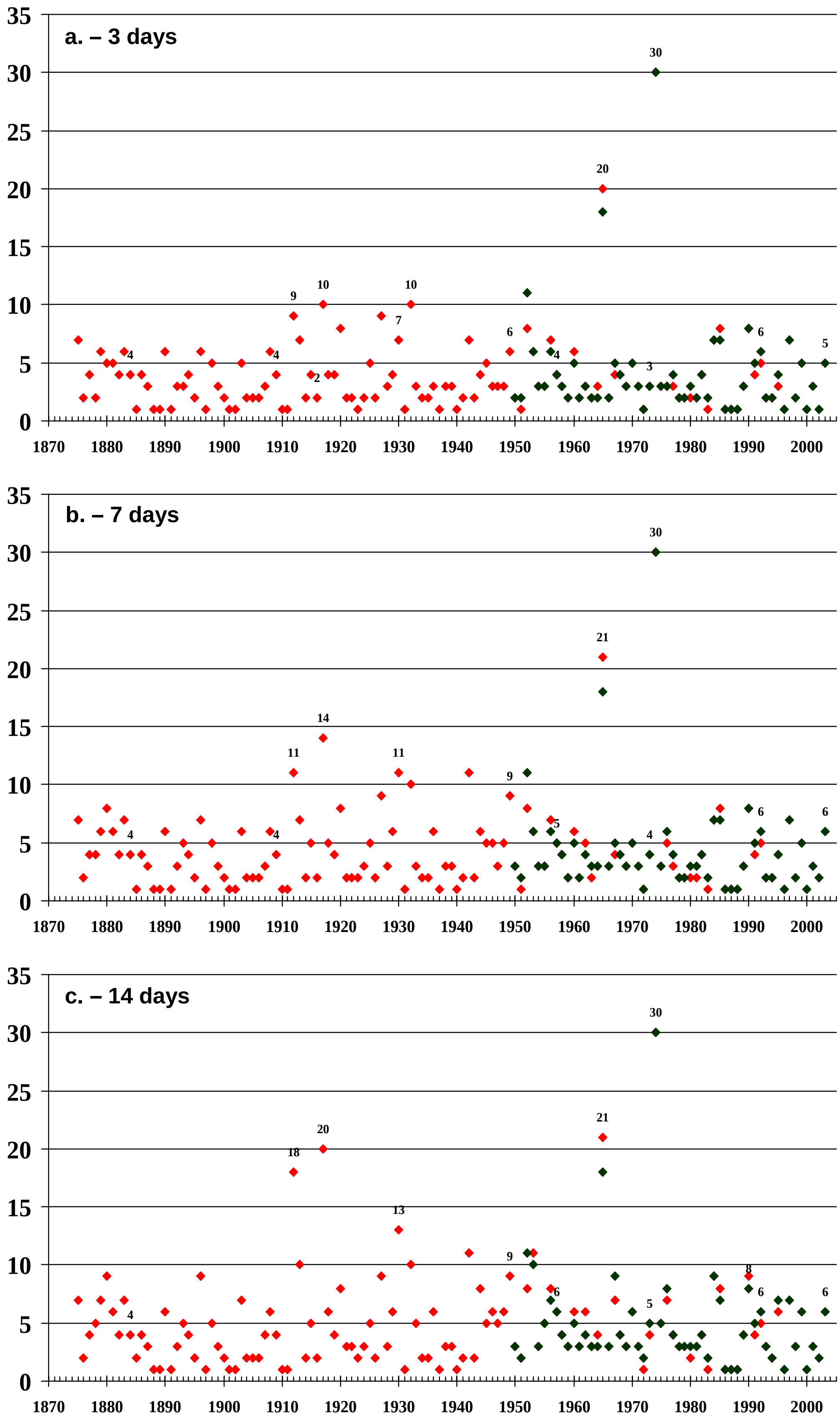

Figure 3: Maximum number of F4 – F5 tornadoes each year for fixed duration periods of a) three days, b) seven days, and c) fourteen days for data from Grazulis (1993) (red) and NWS (green) for the period from 1875 to 2003.

6. HISTORIC OUTBREAK SEQUENCES

Three historic near-continuous tornado outbreak sequences comparable in duration and severity to the May 2003 event are summarized in Table 2. The research of Grazulis (1993) is used extensively in the preparation of this summary.

6.1 *1917: 25 May–1 June*

This was an 8-day near-continuous outbreak sequence punctuated by five tornado outbreaks (Table 2a). The sequence peaked on 26 and 27 May when there were violent tornadoes for two days in a row: an F4 long-track tornado family that resulted in 101 fatalities in Mattoon, Illinois, and the F4 tornado centered near Fulton County, Tennessee, that resulted in 67 fatalities. Another notable aspect of the sequence was the occurrence of 15 violent tornadoes that contributed to a distinct maximum in the fixed duration sequence time series (Fig. 3b, c). Counts of significant tornadoes during this event are likely underestimates, in part due to clustering of likely tornado families into single tracks (e.g., the Mattoon, Illinois, tornado). The event was tightly clustered around the mid-Mississippi River Valley with recurring tornado activity over a relatively small area of southeast Missouri and western Tennessee (Fig. 4a).

6.2 *1930: 1–9 May*

This was a 9-day near-continuous sequence that contained two outbreak and several significant outbreak days (Table 2b). Two separate 1-day respites with no significant tornado reports occurred during the event. The climax of the sequence was an F4 tornado that struck the town of Frost, Texas, on 6 May 1930, and resulted in 41 fatalities. The sequence exhibited little meridional translation, with each day's activity focused within an arc stretching from southern Texas northward through the Great Plains and northeastward into Iowa and Wisconsin (Fig. 4b).

6.3 *1949: 15–22 May*

Although there were fewer reported violent tornadoes than the 1917 and 1930 events, the total of nine violent tornadoes on 15–22 May 1949 (Table 2c) exceeded the total of six during the 2003 sequence (Table 1). The sequence began with five consecutive days (15–19 May) of activity in the Great Plains. This prelude was followed by a strong progressive system that resulted in a

TABLE 2

a) 25 May – 1 June 1917
Mattoon, Illinois – 26 May 1917

Date	F2 – F5	F4 – F5	Fatalities
5/25/1917	6	1	24
5/26/1917	6	5	110
5/27/1917	19	4	151
5/28/1917	3	0	8
5/29/1917	0	0	0
5/30/1917	14	3	65
5/31/1917	2	1	3
6/1/1917	13	1	22
Total	**63**	**15**	**383**

b) 1 – 9 May 1930
Frost, Texas – 6 May 1930

Date	F2 – F5	F4 – F5	Fatalities
5/1/1930	20	4	14
5/2/1930	1	0	0
5/3/1930	4	0	0
5/4/1930	0	0	0
5/5/1930	22	5	7
5/6/1930	7	2	81
5/7/1930	0	0	0
5/8/1930	4	0	1
5/9/1930	9	2	7
Total	**67**	**13**	**110**

c) 15 – 22 May 1949
Cape Girardeau, Missouri – 21 May 1949

Date	F2 – F5	F4 – F5	Fatalities
5/15/1949	5	2	8
5/16/1949	1	0	0
5/17/1949	7	1	1
5/18/1949	3	0	0
5/19/1949	6	0	1
5/20/1949	29	2	5
5/21/1949	18	4	51
5/22/1949	4	0	0
Total	**74**	**9**	**66**

Table 2: Daily count (midnight to midnight CST; 0600 UTC to 0600 UTC) of significant tornadoes (F2 – F5), violent tornadoes (F4 – F5), and tornado-related fatalities for 3 near-continuous outbreak sequences.

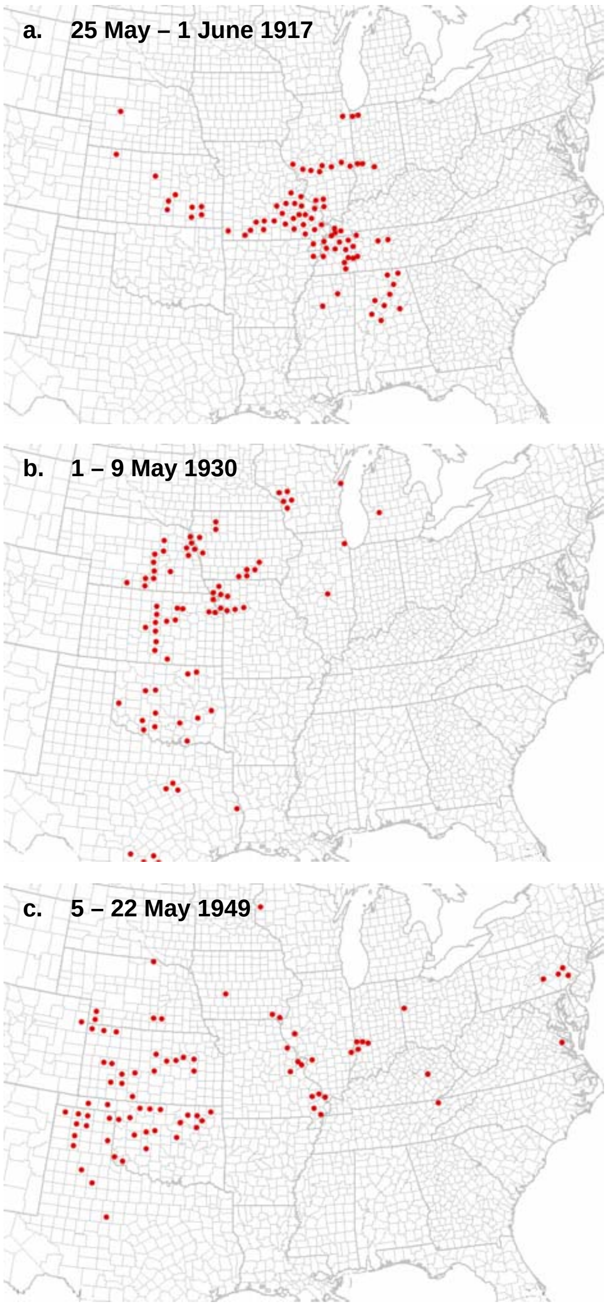

Figure 4: Plot of each county experiencing *at least one* significant (F2 – F5) tornado (red dot) during the a) 25 May – 1 Jun 1917, b) 1 – 9 May 1930, and c) 5 – 22 May 1949 tornado outbreak sequences. The data source is Grazulis (1993).

tornado outbreak over the Great Plains on 20 May, followed by another outbreak on 21 May focused in Oklahoma and Missouri but extending eastward into the Ohio River Valley. This second outbreak climaxed with an F4 tornado that struck the town of Cape Girardeau, Missouri, on 21 May 1949 and resulted in 23 fatalities. A small outbreak over Pennsylvania and West Virginia on 22 May ended the sequence.

This event illustrates the need for manual quality control when determining tornado outbreak sequences. A single F2 tornado occurred on the afternoon of 23 May at Hennessey, Oklahoma, more than 22 hours after the last outbreak had ended in eastern Pennsylvania and northern Virginia. Thus, there was a continuous 9-day span with at least one significant tornado, the same as in May 2003, but the last day was not really associated with the tornado outbreak sequence.

6.4 *Singular Events*

The two most notable “singularities” in the fixed sequence data were the 3 April 1974 Superoutbreak and the 10 April 1965 Palm Sunday Outbreak (Table 3) that were discussed in section 5. Although these events were dominated by single one-day outbreaks, they were each associated with short sequences of tornado activity.

TABLE 3

a) 7 – 11 April 1965
“Palm Sunday” outbreak on 11 April 1965

Date	F2 – F5	F4 – F5	Fatalities
4/7/1965	2	1	0
4/8/1965	6	0	0
4/9/1965	1	0	0
4/10/1965	5	1	1
4/11/1965	37	19	255
Total	**51**	**21**	**256**

b) 1 – 4 April 1974
Superoutbreak

Date	F2 – F5	F4 – F5	Fatalities
4/1/1974	8	0	2
4/2/1974	1	0	1
4/3/1974	88	30	302
4/4/1974	6	0	4
Total	**103**	**30**	**309**

Table 3: Daily count (midnight to midnight CST; 0600 UTC to 0600 UTC) of significant tornadoes (F2–F5), violent tornadoes (F4–F5) and tornado-related fatalities for 2 “short” outbreak sequences characterized by a single exceptional event.

6.5 *Other Notable Events*

During 20–29 April 1912, there were two separate intense 3-day and 5-day sequences that combined to spawn 18 violent tornadoes. The sequences were interrupted by an apparent 2-day break within an impressive 14-day fixed duration sequence (Fig. 3c). The break eliminated this event from our current definition of a near-continuous outbreak sequence, but reporting quality in 1912 may have played a role in this report hiatus. A second interesting near-continuous sequence occurred across a 14-day period from 29 April to 13 May 1933. Although not as intense as the sequence outbreaks highlighted above, 13 of the 14 days in the sequence had at least one significant tornado with a maximum 1-day significant tornado count of nine. The numerous small to intermediate-sized outbreaks during the event included five violent tornadoes and resulted in 198 fatalities.

7. COMPARISONS TO 3–11 MAY 2003

Results indicate that the May 2003 sequence—with nine consecutive days that had more than 10 tornadoes and at least one significant (F2 – F5) tornado—is rare, but not unprecedented. When allowances are made for increased reporting of tornadoes in recent years, at least three other events detailed in Section 6 approached or exceeded the May 2003 event in some measure of intensity and duration (Table 4).

Year	Number of "strong" (F2 – F5) tornadoes	Number of "violent" (F4 – F5) tornadoes	Number of Fatalities
1917 (7 of 8)	63	15	383
1930 (7 of 9)	67	13	110
1949 (8 of 8)	73	9	66
1965 (5 of 5)	51	21	256
1974 (4 of 4)	103	30	309
2003 (9 of 9)	63	6	41

Table 4: A summary table for four major near-continuous long-sequence outbreaks (1917, 1930 and 1948) and two intense short-sequence outbreaks (1965 and 1974). Daily details are given in Tables 1, 2, and 3. Parenthetical values after the year indicate the number of days with at least one significant tornado out of the total days in the sequence.

Despite the intensity of the May 2003 tornado outbreak sequence, there were far fewer fatalities than in the sequences prior to 1950 despite having comparable numbers of significant tornadoes. This can likely be attributed to improved understanding and detection of severe storms, resulting improvement in forecasts and warnings, superior communication of those forecast and warnings, and better preparedness (Doswell et al. 1999; Schaefer and Brooks 2000; Moller 2001; Brooks and Doswell 2002).

Spatially, the May 2003 sequence appeared slightly more prolific in the eastern third of the United States than the three major sequences from 1917, 1930 and 1949 (Figs. 1 and 5). In particular, the 1930 and 1949 events were predominantly centered over the Great Plains. Although the epicenter of the 1917 event over the Mississippi River Valley was similar to the 2003 outbreak sequence, the 1917 event had no significant tornadoes east of 85° West longitude.

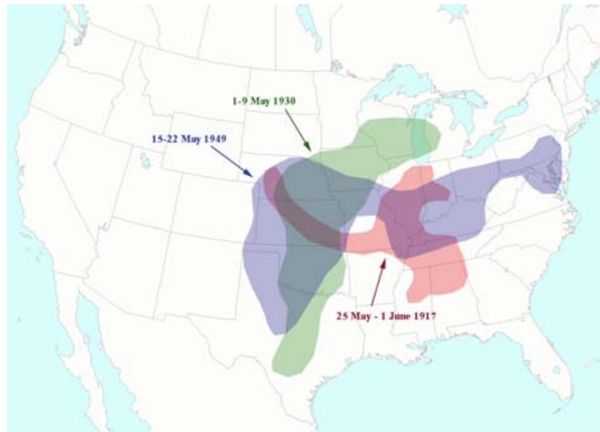

Figure 5: Map of areas affected by major near-continuous outbreak sequences in 1917, 1930, and 1949.

Other than May 2003, there are no recorded long outbreak sequences with at least 50 F2 strong tornadoes since 1949. However, there are two notable short sequence events with 50 strong tornadoes over a period of only a few days. The clustering of a few less-intense neighboring days with unique singular events such as the 1974 Superoutbreak or 1965 Palm Sunday Outbreak results in a sequence whose intensity dominates sequences of longer duration. It is important to realize that the single day Superoutbreak had more significant or violent tornadoes than any of our weeklong sequence outbreaks, including the May 2003 event. In fact, the 1-day Superoutbreak exceeded the violent tornado count for any other 28-day period within the 130-year record.

Despite their relatively short duration, major outbreak sequences such as the events of 1917, 1930, 1949, and 2003 play a key role in the character of their respective severe weather seasons (Fig. 6). Approximately one week in length, these four extended outbreaks each account for at least one-half of the violent tornadoes and over one-third of the significant tornadoes for the entire year. Based on fatalities (not shown), three of the four extended sequences (1917, 1930 and 2003) accounted for more than two-thirds of the entire year's death toll.

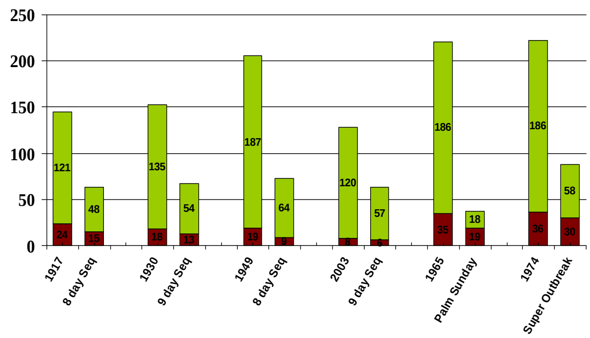

Figure 6: Number of significant (F2 and greater), violent (F4 and F5; red), and strong (F2 and F3; green) tornadoes for the entire calendar year. Based on Grazulis (1993) data prior to 1977 and on NOAA data from 1977 on.

8. ESTIMATED RECURRENCE INTERVAL

The occurrence of three long outbreak sequences from 1917 to 1949 and the lack of long outbreak sequences between 1949 and 2002 can be explained, to a large degree, by the small sample size. Thus, the three sequences in slightly over 30 years and their absence during the following 50 years may be due to randomness in the small sample size coupled with the rarity of the event.

Evaluating the rarity of events that have occurred only once or twice in the period of record is problematic. One solution is to estimate the frequency of less-rare but related events. Since the return interval is the inverse of the occurrence frequency, i.e., an event with a 1% occurrence probability in a given year is a 100-year return interval event (Court 1952), it is possible to estimate the statistical recurrence period.

Estimates for various duration periods out of a 7-day period for different threshold counts of significant tornadoes are given in Table 5. These calculations were based on the data of Grazulis (1993). To prevent over-counting of longer sequences, overlapping runs were not counted for each permutation. A linear regression fit to the log of these data was performed to give estimates of the recurrence rate of the various sequences (Table 6).

The major sequences previously discussed all had unique characteristics, some well-measured with a 7-day period, some better fit to a longer period. The 1949 sequence had 5 of 7 days with more than 5 significant tornadoes which suggests a recurrence rate of about 78 years. Both the 1917 and 1912 sequences each had 5 of 8 days with 6 or more significant tornadoes, but each only met the 4 of 7 days condition of Table 6. One can assume the recurrence rate for these events is somewhere between 32 (4 of 7) and 178 (5 of 7) years.

	Threshold Number of Significant (F2 – F5) Tornadoes							
Days out of 7 that Meet Threshold	3	4	5	6	7	8	9	10
1	1075	711	486	360	266	203	154	122
2	463	256	133	74	47	35	27	16
3	119	49	28	16	8	5	1	
4	32	12	4	2				
5	8	3	1					
6	1							
7								

Table 5: Number of events during the period from 1921 – 1995 for various event counts and duration (number of days meeting threshold intensity) during moving 7-day period based on Grazulis (1993).

It is easy to imagine a single unique characteristic for most outbreak sequences that might suggest the event was the only of its kind in the 130-year record. For instance, the 2003 sequence featured 7 or more significant tornadoes on 4 of 7 days, an unprecedented condition that, based on visual analysis, had not occurred previously throughout the entire 130-year record. However, the estimated recurrence rate for this attribute is approximately 54 years (Table 6). This frequency is consistent with the observed record of long sequence outbreaks in 1917, 1949, and 2003.

9. SUMMARY AND CONCLUSIONS

The climatology of tornado outbreak sequences was examined to gain historic insight into the 3–11 May 2003 event. At least three other outbreak sequences of approximately one week in length that had more violent tornadoes than the 2003 event were identified within the 130-year record (1917, 1930 and 1949). Thus, although the May 2003 event, with nine consecutive significant tornado days and seven or more significant tornadoes on four of seven days, was historic, it was not unique.

Extended tornado outbreaks are of enormous importance. Only about one week in length, each of the four extended outbreaks identified above accounted for at least one-half of the violent tornadoes and over one-third of the significant tornadoes for the entire year. Three of the four events (1917, 1930, and 2003) were also responsible for over two-thirds of the annual fatalities. Despite these numbers, the May 2003 tornado outbreak sequence was associated with far fewer fatalities than in the prior sequences. This reaffirms the enormous strides that have been made in all facets of severe weather forecasting and warning.

Although the identified extended tornado outbreak sequences were remarkable events, the single-day 3 April 1974 Superoutbreak had more significant or violent tornadoes than any of our week-long sequence outbreaks. In fact, the *single-day* Superoutbreak alone exceeded the violent tornado count for any other *28-day* period within the 130-year record. The Superoutbreak was truly an unprecedented exceptional event.

Future work on this project will focus on a more complete climatological analysis of the tornado outbreak sequence phenomenon. Events of shorter duration, such as the historic 7–9 June 1953 sequence whose 50-year anniversary actually triggered the start of this research, were only examined briefly. The temporal and geographical distribution of the sequences will also be better developed and the typical temporal evolution within events will be examined. Finally, the climatology will be used to identify the large-scale conditions and environments that lead to the occurrence of outbreak sequences.

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	Threshold Number of Significant (F2 – F5) Tornadoes					
Days out of 7 that Meet Threshold	3	4	5	6	7	8
1	0.06	0.09	0.13	0.19	0.28	0.36
2	0.20	0.37	0.65	1.05	1.62	2.28
3	0.69	1.49	3.21	5.81	9.32	14.54
4	2.40	6.05	15.84	32.14	53.72	92.63
5	8.36	24.52	78.12	177.88	309.78	590.21
6	29.11	99.38	385.29	984.50	1,786.30	3,760.70
7	101.33	402.87	1,900.31	5,448.89	10,300.32	23,962.47

Table 6: Recurrence interval in years as a function of event count and duration (number of days meeting threshold intensity) during a 7-day fixed period based on log-linear best fit to Grazulis (1993, 1997) records from 1921 – 1995.

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