7.B.2

PROPOSALS FOR MODERNIZING THE DEFINITIONS OF TORNADO AND SEVERE THUNDERSTORM OUTBREAKS

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1. INTRODUCTION AND BACKGROUND

The term "tornado outbreak" currently has no official definition, and its interpretation can be highly variable in spatial and temporal coverage. As Galway (1977) stated: "A tornado 'outbreak' can mean many things to many people." In the 1940's the NWS and Air Weather Service defined a "family outbreak" as five or more tornadoes associated with a weather system on a given day (Pautz 1969). He referred to outbreaks by tornado count as small (6-10), moderate (11-20) and large (>20). Galway's (1975) definition was slightly more stringent: small (6-9), moderate (10-19), large (>20), but justified it based on spatial distribution analysis of the climatological tornado data set available to him.

Since then, however, tornado reports have become more profuse, particularly on the low end of the damage spectrum (F0-F1), which casts into question the utility of previous outbreak definitions. Nonetheless, relatively recent formal definitions (McCaul 1991) consisted of three tiers of criteria based on tornado count, essentially matching the Pautz (1969) guidelines.

Grazulis (1993) defined an outbreak as a group or family of six or more tornadoes spawned by the same general weather system. For landfalling tropical cyclones, whose climatologically favored quadrant (Novlan and Gray 1974) is mesoscale in size, Curtis (2003) used Galway's "large" outbreak criteria of $\geq$20 tornadoes. Because clustered peninsular Florida tornado events typically aren't subsets of outbreaks in the adjoining U.S. mainland, Hagemeyer (1997) referred to Florida "outbreaks" as being four or more tornadoes in four hours or less, from 30 deg latitude southward. Such criteria are firmly mesoscale and smaller in space and time, however, and have limited utility to studies focusing on synoptic scale aspects of tornado outbreaks. Interchanging of terminology sometimes further complicates the matter. For example, Zipser and Golden (1979) referred to the same three-tornado event near the town of Bennett, Colorado, as an "outbreak" in the paper's title, and a a "mini-outbreak" in its text.

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When considering the definition of nontornadic severe thunderstorm outbreaks, precedent in the literature is scant or altogether absent, aside from anecdotes and localized events of greatly varying magnitudes referred to as "outbreaks." No standardization exists for nontornadic severe local storm events containing multiple reports; therefore, we will propose a rather arbitrary but consistent means of establishing and comparing severe weather events that do not qualify as tornado outbreaks.

Available definitions that are spatially precise may be nebulous in time, or vice versa. Moreover, many historical attempts to define the term "tornado outbreak" have failed to account for the spatial outliers, far removed from tornado clusters but within the same time domain (i.e., a brief, weak tornado report in Arizona temporally coincident with multiple, cyclic, long-lived, violent-tornado producing supercells in the Ohio Valley).

Little is available, therefore, by which to judge the "density," "importance" or "quality" of a severe thunderstorm or tornado outbreak on a nationwide basis. This is particularly crucial in this era of "modernized" warning and verification operations, where aggressive report gathering practices, proliferation of storm observers and improved communications capabilities, cumulatively, have drastically altered the severe weather climatology (Schaefer et al. 2004; Weiss et al. 2002, hereafter W02).

Regarding tornadoes, one promising comparative tool for evaluating the attributes of an outbreak is the informal Destruction Potential Index (DPI, after Thompson and Vescio 1998). DPI may be used to map and contrast tornado events by measuring an aggregate of tornadoes' F scales (Fujita 1971) and path areas.

As part of a broader study relating roughly three decades of severe weather events to Storm Prediction Center convective outlooks, it is necessary to consistently identify and categorize severe weather events on a national scale, particularly tornado outbreaks. In this paper we will include DPI among the criteria for tornado outbreaks, develop an outbreak index for tornado events, and propose a strategy for ranking severe thunderstorm days that are dominated by wind and/or hail reports.

Table 1. Summary of variables comprising the O index. Columns are as follows: Number of tornadoes, number of violent (F4+) tornadoes, number of significant (F2+) tornadoes, DPI, cumulative path length (km), number of killer tornadoes, and number of long-track (50+ mi or 80+km) tornadoes in each tornado day.

	Number Tor.	Number Violent	Number SigTor	DPI	Path Length	Deaths	Number Killers	# 80+km Tracks
Cutoff Value	37	2	13	131	349	8	3	1
Rank at Cutoff	50	48	52	51	53	49	59	82
Mean	26.9	1.14	9.6	145	319	9.09	2.05	0.61
Std Dev	18.8	2.57	9.5	258	358	26.6	3.93	0.92
Weight	1	4	8	7	10	2	5	4

2. TORNADO OUTBREAK CRITERIA

With a calculated DPI or similar parameter being unavailable in previous studies that defined tornado outbreaks, no means was present to differentiate days with several long-track, violent tornadoes from those with similar quantities of weak, brief touchdowns. The impact and importance of those two extremes is different to the severe local storms forecaster, the emergency manager and the public alike, compelling a quantitative method (i.e., DPI) of ranking the significance of an outbreak. Since tornadoes producing F0 and F1 damage comprise the bulk of the increase in tornado reports during NWS modernization, while tornado days per year remained nearly constant (McCarthy and Schaefer 2004), we emphasized "significant" tornadoes ($\geq$F2 damage, after Grazulis 1993) in establishing outbreak criteria.

We used a 2001 version of SVRPLOT software (Hart 1993) and the SPC severe weather database (Schaefer and Edwards 1999) to plot and rank severe weather days (12 UTC one day to 1159 UTC the next) each year from 1970-2002 according to eight variables (see Table 1). Note that these are not necessarily independent variables – just commonly utilized means of judging event significance in the meteorological community.

Each of the eight values was assigned a subjective weight (W_g), 10 being highest, based on consensus confidence among the authors that this value represents an outbreak. For example, cumulative path length was heavily weighted because of their more precise recording. Deaths and killer tornadoes were weighted relatively low because of their strong dependence on non-meteorological factors (i.e., population distribution and density). On the other hand, a multitude of killer tornadoes, while still population dependent, indicates more of a relatively widespread and organized pattern, rather than an isolated unfortunate event.

Violent tornado numbers also typically have some non-meteorological dependence, beholden both to construction standards and to the subjective and inconsistent elements of judgment inherent in damage surveying (Doswell and Burgess 1988). DPI is a nonlinear combination of the two highest weighted criteria (significant tornadoes and path length, as in Table 1), and therefore is weighted less than either of those components. Long track tornadoes are dependent on the speed of motion, whereas longer-lived but relatively slow moving tornado groups also constitute many events commonly deemed "outbreaks."

Each tornado day falling within the top 50 ranking[1] of *any* of the eight variables was set aside for the next phase of the test. In other words, we included any day which could be considered a "top 50" outbreak for any single measure used. There were 182 such nonexclusive case days, with the 3 April 1974 "Super Outbreak" attaining top rank in each of the eight variables. A mean and standard deviation was computed in each of the eight variables for all 182 days, collectively (Table 1).

For each variable on each outbreak day we compiled a normalized outbreak value O_g as follows:

$$\mathbf{O_g} = [(D-M_g)/S_g] * W_g$$

where D is the daily value for that variable, M_g is the mean value for the "top 50" members in that category, S_g is the standard deviation for the top 50

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[1] Where a variable value was constant through the rank of 50, the nearest discontinuity to the 50th place was used as a cut off. See Table 1.

members in that category and W_g is the aforementioned weighting factor for the member. The members' O_g values are summed to produce an "**O** Index" which then is used to define the significance of a tornado outbreak:

$$\mathbf{O} = \sum_{I=1}^{n} O_g$$

where n=8 members. Positive values suggest relatively strong overall contribution (above average) from the 8 gauntlet members, and/or extreme contribution from a few members. For 49 days from 1970-2002, **O**>0; and these days were called tornado outbreaks.

The top 25 tornado outbreaks for the same period are listed in Table 2. The 3 April 1974 "Super Outbreak", having ranked highest in each of the gauntlet variables, overwhelmingly dominates the **O** index rankings. Using this measure, tornado outbreak events can be compared in a more broad-based manner than by using any of the individual criteria alone (i.e., tornado count or DPI), in a way that still accounts for those criteria.

3. CLASSIFYING SEVERE THUNDERSTORM OUTBREAKS

Largely nontornadic severe thunderstorm events that are unusually dense and/or widespread in scale – such as derechos (i.e., Evans and Doswell 2002), merit some form of numerically derived measure of significance as well, in order that events may be compared in some meaningful way.

An important factor is the notion of mutually exclusive events. Tornadoes are the only core component used to define tornado outbreaks; and hail and wind are excluded. With nontornadic severe local storms, there are three variables to consider (if excluding tornadoes themselves): hail size, wind speed and wind damage. Nontornadic severe thunderstorm events, by NWS definition, consist of hail $\geq$2 cm in diameter and $\geq$25 m s^{-1} gusts (either measured or estimated). In practice, the third nontornadic severe variable is damaging convective wind reports, whether or not associated with any particular wind speed. Hail and severe thunderstorm wind reports sometimes may occur independently, but often do not. [In our analyses they will be treated both as a collective and analyzed on their own merit.]

Unlike tornadoes, length and width information of affected wind and hail areas – by which some sort of DPI analog could be derived – are not recorded systematically or consistently. Instead, they are recorded by county and latitude-longitude, and unlike tornado segments (Schaefer and Edwards 1999), cannot be reconstituted from county format into whole path information, given current and historical reporting practices.

Table 2. Top 25 tornado outbreaks from 1970 through 2002, as ranked by O index.

Rank	Outbreak Date	O Index
1	4/3/1974	9.79
2	5/31/1985	2.00
3	3/13/1990	1.64
4	11/21/1992	1.41
5	4/26/1991	1.40
6	4/2/1982	1.36
7	11/22/1992	1.34
8	3/28/1984	1.33
9	6/2/1990	1.32
10	5/27/1973	1.272
11	11/10/2002	1.268
12	3/27/1994	1.13
13	6/7/1984	1.04
14	3/1/1997	1.01
15	4/8/1999	0.96
16	4/17/1970	0.93
17	2/21/1971	0.89
18	5/3/1999	0.88
19	3/20/1976	0.87
20	1/21/1999	0.65
21	6/8/1974	0.55
22	4/10/1979	0.52
23	5/7/1993	0.481
24	5/8/1988	0.477
25	6/16/1992	0.46

Furthermore, even within a given county-report the true character of the event often is masked by the oversimplifications inherent to the process of recording severe events for warning verification. For example, the occurrence of one measured 10 cm hailstone found among many smaller ones might be treated in severe weather magnitude tables identically to a swath of estimated 10 cm hail covering several km^2. In county reporting, there is areal inconsistency, with most events assigned a spot time and location, some recorded as "countywide" or given a time range. More precise coverage and swath information on the county scale typically is supplementary, only marginally used by the warning verification process, and may either be relegated to text remarks in *Storm Data* or not recorded at all. Still, this is the information potentially most meaningful to assessing the relative impact of events. [For more discussion on reporting practices and their impact on the data as applied to thunderstorm wind, see W02, and as applied to hail, Schaefer et al. 2004.]

A related matter is event clustering, and how it should be treated. Whereas tornado events can be analyzed for spatial and density considerations (i.e., the "practically perfect" outlook verification scheme as described by Brooks et al. 1998), their magnitude and areal coverage are specifically recorded in some form and as such can be given systematic treatment in comparative assessment of clustered events. This capability remains elusive for convective wind and hail events.

Despite those challenges, we believe that severe weather outbreak assessment and comparison is possible, and have begun an effort to do so that remains in development as of this writing. Because of the lack of more precise reporting, the number and concentration of nontornadic events remains of primary importance, with collective groupings of individual event magnitudes or "significance" also available as a comparative measure.

For our analyses, a second tier of severe weather days (also for the period from 12 UTC one day to 1159 UTC the next) is partitioned from tornado outbreaks as an initial filter. Only 1980-2002 cases are used for the severe thunderstorm group, however, because of the sharp increase in nontornadic severe storm reports coinciding with the onset of intensive NWS emphasis on warning verification (W02). Any event that was a tornado outbreak by previous definition (positive **O** index) is excluded.

Events then can be sorted in several ways to determine "dominance" of nontornadic severe reports; and these remain under testing. One is a simple count of number of severe events. This alone is proving to be an unreliable measure because of the great increase in reports over the past 10-20 years, especially for marginal events such as estimated 60 mph (26 m s^{-1}) gusts and hail in the 2-3 cm diameter grouping. However, in order to impart some robustness to the report sample size for each outbreak candidate, the lower bound for number of reports may be established at an arbitrary threshold such as 50 .

Table 3. Top 25 severe thunderstorm outbreak days, 1980-2002, as ranked by the unweighted SO index.

Rank	Outbreak Date	SO Index
1	6/24/1994	3.06
2	6/20/1997	2.39
3	6/4/2002	1.46
4	4/14/2001	1.423
5	6/14/2001	1.418
6	6/15/2002	1.28
7	7/21/2000	1.18
8	4/6/2001	1.12
9	4/9/2001	1.08
10	5/18/1996	1.06
11	5/2/2002	0.91
12	5/22/1999	0.84
13	7/25/1995	0.81
14	7/15/1995	0.73
15	7/4/1992	0.70
16	7/30/1999	0.66
17	8/16/2002	0.633
18	7/8/2001	0.632
19	6/19/1998	0.59
20	9/11/2000	0.56
21	7/19/1983	0.53
22	3/8/2002	0.48
23	5/17/2001	0.46
24	8/24/1998	0.45
25	6/29/1994	0.41

Another method being tested is a ratio of tornado reports to total severe events for all negative- **O** events with 50 or more total reports. This gives some indication of the relative importance of tornadic and nontornadic severe storm reports. One problem with this approach, however, is the introduction of considerable inverse dependence on tornado count,

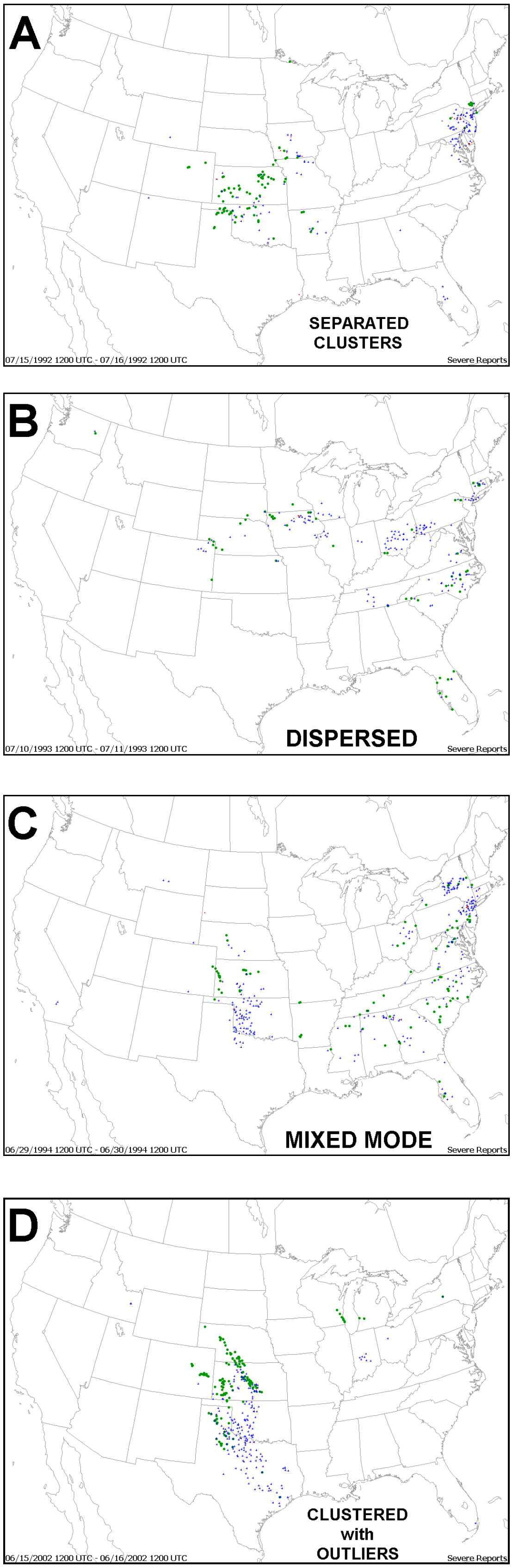

Figure 1 (at left). Plots of severe reports for four types of distributions, representing hail (green), wind (blue) and tornadoes (red), for the 24 hour period beginning at 12 UTC on each of these days with negative O Index: a) 15 July 1992, b) 10 July 1993, c) 29 June 1994 and d) 15 June 2002.

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beyond the exclusion of positive-**O** tornado outbreaks themselves, for gauging nontornadic severe weather. Furthermore, another problem is the lack of consideration of event magnitude.

In effort to address those concerns we have formulated a severe weather outbreak index (**SO**) analogous to the **O** index for tornado events. The **SO** utilizes "nearest to top 50" natural breaks using variable criteria. Six variables are used: total hail reports, total wind reports (damage and speed), total severe, significant ($\geq$5 cm) diameter hail, significant ($\geq$32 m s^{-1}) wind speed events, and total significant severe reports. As with **O**, a mean and standard deviation were computed for each "top 50" set. The formulation is:

$$\mathbf{SO_g} = [(D-M_g)/S_g]$$

and

$$\mathbf{SO} = \sum_{I=1}^{n} SO_g$$

where n=6 members as described above. Significant severe reports are included because they have been shown (i.e., W02) to be more robust over the time span of the data set. Still, note the absence (preliminarily) of a weighting factor combined with the predominance of events from the mid 1990s through 2002 in the rankings of Table 3. As a result, **SO** weighting factor(s), analogous to that in the **O** index, will be tested. Such weights should heavily favor the more temporally stable significant-event criteria, in order to address the report inflation problem (i.e., W02) and thereby impart more representative temporal balance to the outbreak listings.

Once we settle on a finalized version of **SO**, or perhaps some other second-step filter, further analysis will be needed to address the aforementioned clustering issue. This is necessary in order to exclude, in a systematic and measurable way, "outlier" events on severe weather days which may be far removed from the primary outbreak corridor(s), and which are not directly related meteorologically. An extreme but plausible example could be a few isolated, damaging downdrafts from Florida sea breeze convection early in the eastern afternoon, followed by a few large hail and severe gust reports in Utah in the late western afternoon. Those in turn are followed nocturnally by a 300-report derecho crossing large portions of six northern plains and Great Lakes states, with significant severe winds measured at several locales. Clearly the derecho forms the "outbreak" in this scenario, and the Florida and Utah events are the unrelated outliers. Most of our event plots are not quite so sharply delineated, however; and further development of this is underway.

In examining the spatial distribution of events on severe weather report days, four modes of report distribution were evident empirically, in no particular order of frequency:

1. *Separated Clusters*: Severe reports were large in number but concentrated in two or more discrete and obvious clusters with geographic separation, and a distinct lack of reports in between. However, neither cluster, on its own merit, would qualify in top-five yearly totals for Tier 3. This is the smallest group representing the most uncommon distribution of disqualified events. Examples include the event in Fig. 1a.

2. *Dispersed*: Severe reports were large in number but widely scattered about a broad swath or area of the country, without densely discrete clustering (Fig. 1b). This is the most questionable "outbreak" sort because of the implicit lack of organization to the severe weather event, and the one most compelling of further filtering.

3. *Mixed Clustering/Dispersion Modes*: A blend of the first two categories (i.e., Fig. 1c). Pronounced concentrations or nodes of relatively dense report coverage were present -- either embedded within or separated from dispersed distributions occurring the same day. So far, this appears to be the most common type among outbreak candidates, relative to the other three.

4. *(Singularly) Clustered with Outliers:* Severe reports were bunched overwhelmingly in one swath or corridor, but a relatively small number of stray events occurred far from the main cluster (Fig. 1d).

Our preliminary examination leads to these questions: How should severe weather days be described with comparable numbers of reports yet with widely dispersed reports versus dense concentrations? How should outliers be filtered most consistently? And how can two clusters on the same day be sorted and compared effectively to determine if one or both constitutes its own outbreak (leaving the possibility of two separate outbreaks in one day)?

Based on our initial findings, we are concentrating on the use of kernel density estimation (KDE) techniques (Bowman and Azzalini 1997) in order to approach the challenge in a systematic way. Following SO filtering, we intend to further define severe thunderstorm outbreak events based on thresholds of report distributions analyzed consistently through KDE, which can objectively analyzes report distributions by density, and enclose within chosen contour values any given percentage of total reports representing the "core" of the event, at a specified smoothing level. This mechanism is quite similar to the "practically perfect" analysis technique (Brooks et al. 1998) and the daily tornado probability methods more recently employed by Brooks et al. (2003).

KDE trends may increase toward the end of our period compared to the beginning based on report inflation. Also, the same "core" percentage value can be assigned to any given day; the main variation from event to event will be in the spatial area covered by the contour. Therefore, a systematic, reproducible way is needed to weight the area covered by events, versus simply assessing the contour, value to arrive at a final definition for the nontornadic severe local storm outbreak. To do so, we may calculate the area encompassed by severe outbreak threshold contour(s) and develop weights of some form associated with each area. A weighting system that accounts for event significance is necessary; but a potential weakness is that the severe weather database characteristics are insufficient to fully support a robust, weighted **SO** metric.

4. SUMMARY AND DISCUSSION

A diverse menagerie of definitions and applications for the term "outbreak" has appeared since at least the 1960s. The great changes in severe weather reporting practices during the past ~15 years render most of those earlier criteria unrepresentative and outmoded. Further, a consistent means of defining outbreak events, applicable both to current reporting practices and historical events, is a crucial part of a broader project we have undertaken to compare severe weather outbreak days and null events with SPC outlooks. It is recognized that *the most significant severe "outbreak" days of a given year do not necessarily correspond to the greatest daily report totals.*

For those reasons we have proposed modernized methods for assessing and defining tornado and severe thunderstorm outbreaks. These have quantitative bases but empirical thresholds – realizing that some element of arbitrariness in the process is unavoidable at this juncture. Though the O-index (SO-index and KDE analyses) may yield useful means of comparing tornadic (nontornadic) outbreak days, it must be noted that sampling time, spatial domain and weighting choices remain subjective selections in the process. As such, we recognize that defining and categorizing outbreaks is a fluid endeavor over time, as severe weather reporting practices and other relevant factors evolve. Therefore our intent is not to define an outbreak in perpetuity, but instead, to represent the current state and to improve the process for those who may make future refinements once our approach become antiquated.

As the parent project progresses we will finalize criteria for nontornadic severe outbreaks, and include

2003 and 2004 data, once it becomes available, enlarging the sample size in both tornado and severe thunderstorm outbreak listings.

5. ACKNOWLEDGMENTS

The authors thank Steve Weiss (SPC) for his guidance and helpful discussions in compiling this article. Hamish Ramsay (University of Oklahoma) has been very helpful in providing his insight on KDE and tutelage on software used to perform such analysis.

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