77 IDENTIFYING AND RANKING MULTI-DAY SEVERE WEATHER OUTBREAKS

Chad M. Shafer[1*] and Charles A. Doswell III[2]

[1] Department of Earth Sciences, University of South Alabama, Mobile, Alabama
[2]Cooperative Institute for Mesoscale Meteorological Studies, Norman, Oklahoma

1. INTRODUCTION

Recent studies have attempted to rank severe weather outbreaks of particular types (e.g., major tornado and primarily nontornadic outbreaks – Doswell et al. 2006; hereafter, D06) or of any type (Shafer and Doswell 2010; 2011 – hereafter, SD10; SD11) using a multivariate, linear-weighted index. The variables included in the ranking scheme are severe reports archived in the Storm Prediction Center (SPC) severe weather database (Schaeffer and Edwards 1999; see Table 1 in SD10 for the specific variables). Results of the studies agreed with preconceived notions of the events. For example, D06 found that the 3 April 1974 tornado outbreak was the highest-ranked outbreak for multiple variations of the index. Additionally, SD11 observed that major tornado outbreaks were consistently ranked highest of any severe weather outbreak, with less significant severe weather outbreaks of various types (i.e., hail-dominant, wind-dominant, and mixed-mode) ranked lower.

The so-called middle-50% parameter (D06; SD10) was a variable used to lower the rankings of days with multiple, spatially distinct clusters of severe reports or with large but sparse coverage. However, SD11 introduced kernel density estimation (KDE; Bowman and Azzalini 1997) to account for the undesirable effect of associating distinct clusters of severe weather as the same event. KDE permits the objective identification of regions associated with a cluster of severe reports by incorporating threshold values of the approximated probability density functions. As a result, SD11 included a considerably larger number of events (by approximately a factor of 4) for ranking, including spatially distinct events occurring on the same day as others.

One constraint used in the aforementioned studies is that each day (defined as 1200 UTC on the nominal date to 1159 UTC the following day) is considered separately. A large majority of severe weather outbreaks occur for durations under 24 hours (see Section 3); however, some of the most severe outbreaks can occur for considerably longer than 24 hours (e.g., the tornado outbreaks in May 2003; Hamill et al. 2005). To consider these events more appropriately, this study proposes a relatively simple technique to eliminate the 24-h time constraint and identify severe weather events of sufficiently long (but unconstrained) duration associated with single synoptic-scale systems. As SD10 and SD11 noted, the identified outbreaks are not guaranteed to be associated with one synoptic-scale system, but the methods are intended to maximize this association. Section 2 discusses the data and methods used in the study. Section 3 presents the multi-day outbreaks and rankings. Section 4 provides some discussion and summarizes the findings.

*Corresponding author address: Chad M. Shafer, Univ. of South Alabama, Dept. of Earth Sciences, 5871 USA Drive North Room 136, Mobile, AL, 36688-0002; e-mail cmshafer@usouthal.edu

2. DATA AND METHODS

Severe reports from 1 January 1960 to 31 December 2011 were collected from the SPC severe weather database. KDE was performed for each 6-h time period from 1200 UTC 1 January 1960 to 0000 UTC 1 January 2012. A latitude-longitude 1º grid encompassing the conterminous United States was used for computation of the KDE. The objective of KDE in this study is to identify the locations associated with the greatest density of severe weather for a given time window. KDE approximates a probability density function (PDF) associated with the variable of interest (in this study, the presence of severe weather) as follows (for a Gaussian kernel):

$$f(x) = \frac{1}{n}\sum_{i=1}^{n}\frac{1}{2\pi\sigma^2}\exp\left[-\frac{1}{2}\left(\frac{D}{\sigma}\right)^2\right] \quad (1).$$

In (1), *n* is the number of reports in a 6-h time window, *σ* is the bandwidth (tunable smoothing parameter), and *D* is the distance between a report and the grid point being evaluated. The smoothing parameter selected was 120 km, as done by Brooks et al. (2003) and Doswell et al. (2005) and as supported by SD11 (see the discussion of the distance method in their Section 2). A grid point was considered to be a part of the event if the threshold value of the approximated PDF exceeded $5*10^{-6}$ km^{-2}, which is similar to that used by SD11 (cf. their Fig. 9c). These regions will be referred to as *KDE regions* for the rest of the paper.

KDE regions are computed for each 6-h time window every three hours. Thus, the first time window is 1200 UTC 1 January 1960 to 1800 UTC 1 January 1960, the second time window is 1500 UTC 1 January 1960 to 2100 UTC 1 January 1960, and so on. *Any KDE region in a time window that intersects a KDE region from the immediately preceding time window is associated with the same severe weather event.* Intersecting time windows are used to prevent subsequent KDE regions from being separated from relevant antecedent severe weather.

Based on this technique, each KDE region is associated with a minimum of a 9-h time window. An event's *duration* is considered to be the difference between the initial time of the first KDE region to the final time of the last KDE region, subtracted by 6 hours. For example, if an event includes KDE regions from the time window of 1200-1800 UTC 1 January 1960 to the time window of 0000-0600 UTC 2 January 1960, the duration of the event is considered to be 12 hours. As no single severe report can be obtained in one time window (owing to the 3-h overlap), the identification of one severe report would be considered a 3-h event because the initial and final three hours would not feature a report.

After each event is identified and duplicate reports (because of time overlap) are removed, all cases not meeting minimum report number and density (number of reports divided by total number of grid points in the union of KDE regions associated with the event) criteria are excluded. These two quantities exhibit secular trends, owing to the large increase in severe weather reports from 1960 to the present (SD11). Thus, the annually averaged single-event report numbers and densities are detrended (as in SD11). If an event does not exceed the detrended single-event mean report number or mean report density, it is excluded from consideration.

The remaining cases then are ranked, using the same techniques as those used by SD11. The same 14 variables (replacing the middle-50% parameter in SD10 with density ratio in SD11) are used in this study. All report variables are summed annually and divided by the total number of clusters in that year. These "event means" were detrended, if necessary, using the techniques introduced by D06. Because the report variables are subject to widely varying magnitudes, all of the variables for each event are standardized so that each report variable has zero mean and a standard deviation of unity. That is:

$$\tilde{x}_i^{(j)} = \frac{x_i^{(j)} - \bar{x}_i}{s_i} \quad (2),$$

where $\tilde{x}_i^{(j)}$ is the standardized report variable for a given cluster, *i* is the individual report type (out of *n*=14 variables), *j* is the individual cluster (out of *m*=4731 total clusters), $\bar{x}$ is the mean of the detrended report variable, and *s* is its standard deviation.

Each standardized report variable is given a whole number weight *w* (0 to 10), and the ranking index score for each event is given by:

$$I^{(j)} = \frac{\sum_{i=1}^{n} w_i \tilde{x}_i^{(j)}}{\sum_{i=1}^{n} w_i} \quad (3).$$

Thus, Eq. (3) indicates that the *relative* weights of the report variables are pertinent. To address the uncertainty in the report variables (see D06 for a discussion), we develop 26 indices (with weights identical to those in SD11; see also Fig. 4 in SD10) with varying weights for the report variables. Specifically, N0 is the control index, where each report variable is given the same weight. The N1-N16 indices weigh the tornado variables most, whereas the N17-N25 indices exclude several of the tornado variables and give specific emphasis to significant severe weather of all types.

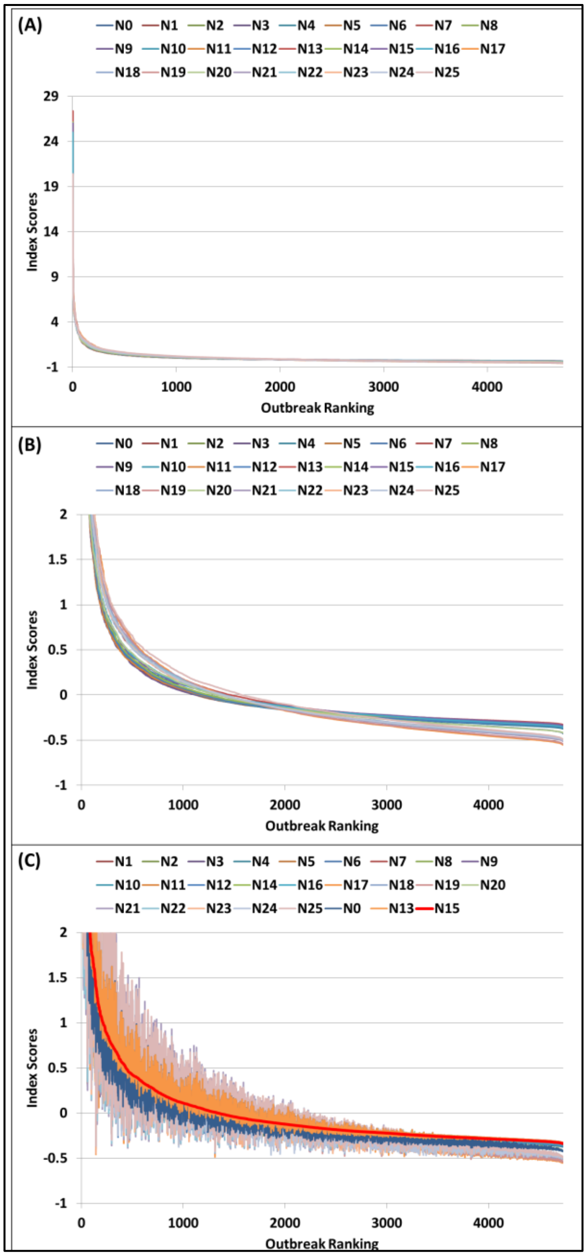

Figure 1: (a) Scores for each linear-weighted multivariate index (legend) as a function of increasing rank number for each index. (b) As in (a), zoomed in to scores between -1 and 2. (c) As in (b), except scores for each index are indicated as a function of the outbreak rankings for the N15 index.

3. RESULTS

Using the methods outlined in Section 2, a total of 4731 severe weather outbreaks were identified in the 1960–2011 period, considerably lower than the 6072 cases identified by SD11 from the period 1960–2008. This indicates that a substantial number of severe weather outbreaks identified using 24-h time constraints are associated with multi-day severe weather outbreaks. The index scores for each of the 26 indices, plotted as a function of increasing rank number, indicate a steep decrease in scores for cases with low rank number, followed by a more gradual decrease for the remaining cases (Fig. 1). This trend is similar to that observed by SD11 (cf. Fig. 10a). Also similar are the distinct trends of the N0-N16 indices versus the N17-N25 indices (Fig. 1b) and the increasing variability in the scores with decreasing rank number (Fig. 1c). The latter is observed because of the strong sensitivity of the highest-ranked cases to tornado reports, which are weighted highest for all of the indices. The variability in the scores is lowest for the cases with highest rank number, owing to the small number and lack of severity of tornadoes and the relatively small number of nontornadic report variables being considered (6 of the 14 variables).

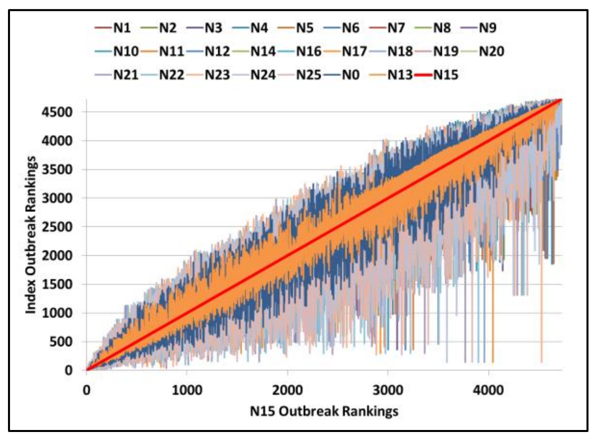

Figure 2: Rankings of the outbreaks for each linear-weighted multivariate index (y-axis) as a function of the outbreak's N15 rank number.

In contrast, the variability of the rankings for all of the indices as a function of increasing rank number for a selected index (Fig. 2) indicates a large range of rankings for the less significant outbreaks. In some cases, the rank numbers range by >3000, in part owing to the discrepancies between the weights implemented in indices N0-N16 versus indices N17-N25. Nevertheless, the large variability in the rankings is a consistent finding, associated with the small number of nontornadic report variables used in the index and the qualitatively similar

Table 1: The top 25 severe weather outbreaks for the N0, N15, N16, and N25 indices, and their associated index scores. Some cases are highlighted for convenience. Case IDs are YYYYMMDD_ST_1_CL#, where YYYYMMDD is the starting date of the outbreak, ST is the starting time in UTC, and CL# is the cluster number for the given starting time (a means of distinguishing events that may begin at the same time). For example, 19940424_33_1_1 is the severe weather outbreak beginning at 0900 UTC 25 April 1994 (cluster number 1).

	N0		N15		N16		N25
20110426_15_1_1	18.83	**20110426_15_1_1**	26.03	**20110426_15_1_1**	25.01	**20110426_15_1_1**	20.42
19740403_12_1_1	16.53	19740403_12_1_1	20.60	19740403_12_1_1	19.52	20110521_18_1_2	12.59
20110521_18_1_2	11.28	20110521_18_1_2	12.20	20110521_18_1_2	12.13	**20030429_18_1_2**	12.40
20030429_18_1_2	10.88	**20030429_18_1_2**	10.67	**20030429_18_1_2**	10.88	19740403_12_1_1	11.32
19650411_15_1_1	7.90	19650411_15_1_1	8.92	19650411_15_1_1	8.14	20040520_21_1_3	9.86
20040520_21_1_3	7.00	20110414_15_1_1	8.03	20110414_15_1_1	7.89	20080522_15_1_1	7.32
19920615_15_1_2	6.01	19921121_18_1_1	7.77	19921121_18_1_1	7.61	**20040529_18_1_1**	6.85
20040529_18_1_1	5.43	19990503_21_1_4	6.29	19990503_21_1_4	6.35	19920615_15_1_2	6.78
19990503_21_1_4	5.35	19920615_15_1_2	6.28	20080522_15_1_1	6.34	20050602_18_1_3	6.42
20110414_15_1_1	5.32	20080204_24_1_1	6.27	19920615_15_1_2	6.29	**19960419_21_1_1**	6.26
20030507_18_1_2	5.00	20080522_15_1_1	6.24	20080204_24_1_1	6.28	19940424_33_1_1	5.68
19921121_18_1_1	4.96	**20060310_24_1_3**	6.13	20040520_21_1_3	5.98	20030507_18_1_2	5.58
20080522_15_1_1	4.92	**20021109_24_1_2**	6.10	**20060310_24_1_3**	5.89	19930606_24_1_1	5.49
20021109_24_1_2	4.76	20040520_21_1_3	5.84	**20021109_24_1_2**	5.87	20110612_33_1_2	5.46
20060310_24_1_3	4.64	20030507_18_1_2	5.53	20030507_18_1_2	5.64	20110414_15_1_1	5.45
19960419_21_1_1	4.62	19730526_15_1_2	5.49	19730526_15_1_2	5.47	19950515_18_1_2	5.37
19930606_24_1_1	4.62	19850531_18_1_1	5.30	20100616_12_1_1	5.13	19950605_15_1_2	5.25
20080204_24_1_1	4.61	20100616_12_1_1	4.96	19850531_18_1_1	5.00	19990503_21_1_4	5.15
20050602_18_1_3	4.55	19900312_21_1_1	4.80	**20040529_18_1_1**	4.90	19960525_15_1_1	5.02
20100616_12_1_1	4.38	**20040529_18_1_1**	4.78	19900312_21_1_1	4.79	20100616_12_1_1	5.00
19730526_15_1_2	4.28	19930606_24_1_1	4.68	19930606_24_1_1	4.75	20100423_15_1_1	4.83
19950515_18_1_2	4.21	19970228_18_1_1	4.67	19910425_21_1_2	4.72	19650411_15_1_1	4.73
19940424_33_1_1	4.17	19910425_21_1_2	4.66	19970228_18_1_1	4.66	19980529_24_1_3	4.68
19950605_15_1_2	4.13	20070504_18_1_2	4.53	**19960419_21_1_1**	4.58	19921121_18_1_1	4.59
20110612_33_1_2	4.02	19600505_18_1_2	4.36	20070504_18_1_2	4.55	**20060310_24_1_3**	4.48

characteristics among the lowest-ranked cases (few significant severe weather reports, relatively few total number of reports, small KDE region). This result was also observed by SD11 (e.g., their Fig. 12), and suggests the need for additional observations and information for nontornadic severe weather reports. However, the most significant severe weather outbreaks have relatively limited variability in rank numbers, a desirable result (see Table 1). That is, no matter what index is used, the same severe weather outbreaks are identified as the most significant events consistently.

The most severe outbreaks are universally major tornado outbreaks. All 26 indices identify the 26-29 April 2011 tornado outbreak as the most significant severe weather event in the 52-y period. The 3-4 April 1974 tornado outbreak is the second most significant severe weather outbreak for the tornado-dominant indices (N0-N16) and in the top 5 for the remaining indices. Other outbreaks featured in the top 5 of many of the indices include the 21-24 May 2011, 11-12 April 1965, 29 April – 7 May 2003, and 20-27 May 2004 multi-day severe weather outbreaks, all of which featured one or more days of anomalously large numbers of significant [(E)F2+] tornadoes.

By removing the time constraint on the identification of severe weather outbreaks, the annually averaged number of outbreaks with durations exceeding specified thresholds can be quantified (Fig. 3). In general, around 90 severe weather outbreaks occur per year (using the threshold report number/density criteria as a means of identifying such events), with ~20 (~10) of those events having durations longer than 24 (36) hours. There is less than one outbreak per year that exceeds durations of 84 hours or more, and only six events in the 1960-2011 period have durations exceeding 6 days.

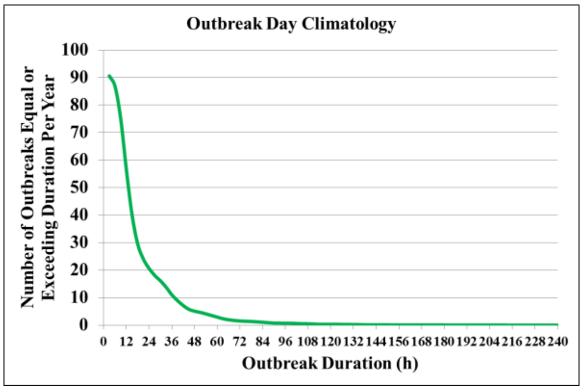

Figure 3: Average annual number of outbreaks (*y*-axis) at or exceeding durations (*x*-axis) for the 4731 events identified from 1960–2011.

For the 4731 outbreaks identified in this study, 60% of the cases had durations less than or equal to 12 hours, and nearly 80% (90%) had durations less than 24 (36) hours (Fig. 4). Durations of 12 hours were most commonly observed (~20% of all cases). There is a clear indication of a relative maximum in outbreak durations of 12, 36, and 60 hours, indicating the diurnal sensitivity of severe weather outbreaks (i.e., severe weather is at a diurnal minimum in the early morning hours, and most outbreaks tend to have final times during this portion of the day). It is likely that the relatively low percentage of outbreaks occurring for less than 12-h durations is because of the minimum threshold criteria for an event's consideration (report number and density criteria). That is, the threshold report numbers and density are sufficiently high to preclude many events that occurred for relatively short (< 12 h) time windows.

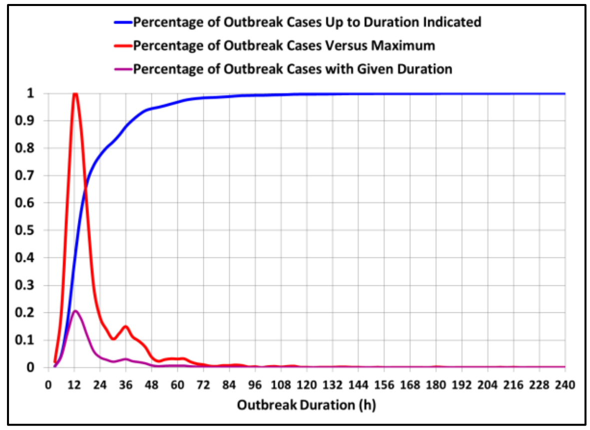

Figure 4: Percentage of cases with a given duration (*x*-axis) versus the duration with the maximum number of cases (red curve) or versus all cases (purple curve), and percentage of cases with durations less than or equal to the given duration (blue curve).

Although certainly not the only factor, the outbreak's duration tends to be associated with its severity (Fig. 5). The 25 highest-ranked severe weather outbreaks have an average duration considerably larger than 24 hours (92.76 hours for the N15 index). For the N15 index, only one of the top 25 outbreaks has a duration less than 24 hours (31 May 1985; see Table 2). Four of the six outbreaks exceeding six days are placed in the top 25 of the N15 index (a common result for the other indices; not shown). As Fig. 5 indicates, durations are most variable for the highest-ranked cases; less significant severe weather outbreaks predominantly have durations less than 48 hours.

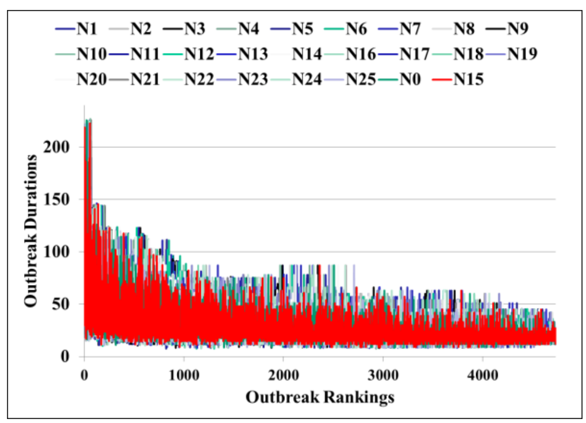

Figure 5: Durations (h) of each outbreak as a function of rank number for each of the 26 indices tested.

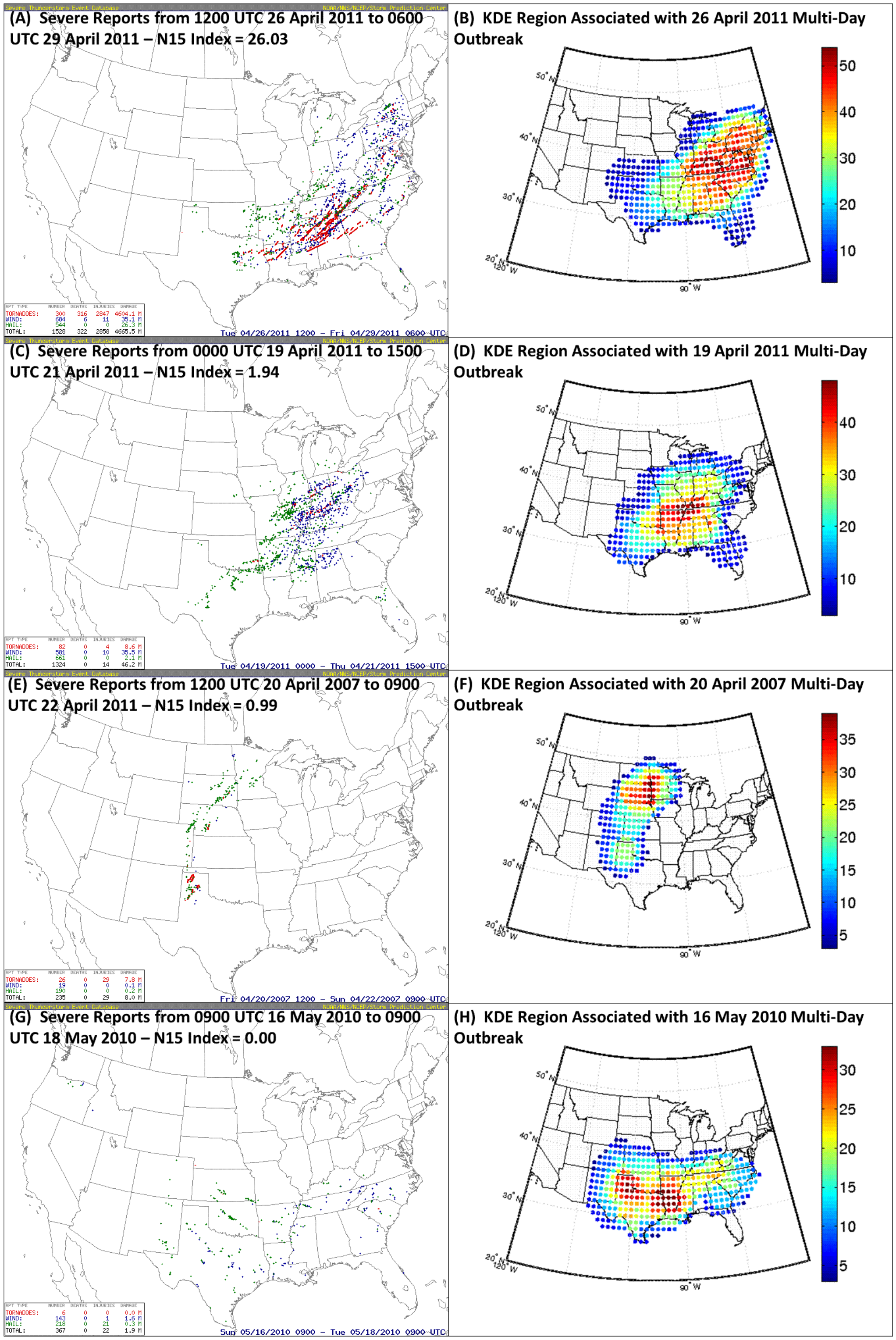

Figure 6: (a) Severe reports (hail in green; wind in blue; tornadoes in red) and the KDE regions (with durations in h of each associated grid point indicated in the legend) for the 26-29 April 2011 severe weather outbreak. (c),(d) As in (a),(b), for the 19-21 April 2011 severe weather outbreak. (e),(f) As in (a),(b), for the 20-22 April 2007 severe weather outbreak. (g),(h) As in (a),(b), for the 16-18 May 2010 severe weather outbreak. Plots of the reports courtesy of the Storm Prediction Center.

Table 2: The top 25 outbreaks of the N15 index and their durations (h). Cases highlighted in Table 1 are done so here for convenience.

20110426_15_1_1	66
19740403_12_1_1	42
20110521_18_1_2	138
20030429_18_1_2	216
19650411_15_1_1	33
20110414_15_1_1	66
19921121_18_1_1	48
19990503_21_1_4	111
19920615_15_1_2	141
20080204_24_1_1	57
20080522_15_1_1	144
20060310_24_1_3	84
20021109_24_1_2	72
20040520_21_1_3	186
20030507_18_1_2	111
19730526_15_1_2	90
19850531_18_1_1	18
20100616_12_1_1	150
19900312_21_1_1	63
20040529_18_1_1	132
19930606_24_1_1	90
19970228_18_1_1	78
19910425_21_1_2	45
20070504_18_1_2	93
19600505_18_1_2	45

In addition to the above tendencies, the rankings of the severe weather outbreaks herein have characteristics very similar to those of SD11, as desired. For example, the lowest-ranked outbreaks tend to be small in spatial coverage, feature few or no tornadoes and significant nontornadic reports. The characteristic curve of the index scores (refer to Fig. 1) is very similar to that of the rankings of the outbreaks in SD11. As explained in SD11 and Shafer et al. (2012), the lack of an initially gradual decrease in scores before the steep decrease (i.e., the lack of an apparent sigmoid function) implies the challenge in classifying events as major severe weather outbreaks or less significant events. There is no clear distinction between the two types of events using this technique and the severe weather report variables included in this study.

The tendency for severe weather outbreaks to have a decreasing number of tornadoes, decreasing spatial coverage and/or report density, and smaller durations is clearly illustrated in Fig. 6. The anomalous nature of the 26-29 April 2011 (Figs. 6a,b) is captured by very large index scores compared to the rest of the cases. As N15 scores decrease to ~2 (Figs. 6c,d), the presence of significant tornadoes remains, whereas for cases with N15 scores ~1 (Figs. 6e,f), the number of tornadoes and the spatial coverage and/or report density begin to decrease. As scores decrease to at or below zero (Figs. 6g,h), the number and severity of tornadoes are low and the density of the reports and/or the spatial coverage become(s) low. All of these tendencies agree with preconceived notions of the relative severity of outbreaks and appear to provide support for the technique proposed.

These trends are observed more generally in Fig. 7, with the standardized scores (averaged over 25 outbreaks) of each of the 14 variables included in the indices (in addition to the areal extent of the outbreak) as a function of the outbreak's rank number for the N15 index. Clearly, each of the report variables is anomalously large for the cases with the lowest rank number. These standardized scores generally are below zero for all cases with rank numbers > 2500. In addition, the variability of the standardized scores for the tornado variables is quite limited for the least significant outbreaks, an indication that these events nearly always do not feature tornadoes.

4. DISCUSSION

As discussed by D06, SD10, and SD11, the methods proposed for ranking outbreaks of any type and of any duration cannot be shown to be optimal. Other equally valid techniques for detrending the severe report variables, equations for developing the rankings, and methods for determining the relative importance of the report variables exist. Additionally, no attempt is made in this study to *define* severe weather outbreaks. Rather, the objective of this study is to identify prototypical severe weather outbreaks of any type and duration. The techniques presented here appear to (1) identify severe weather outbreaks of any duration, (2) distinguish spatially distinct clusters of severe

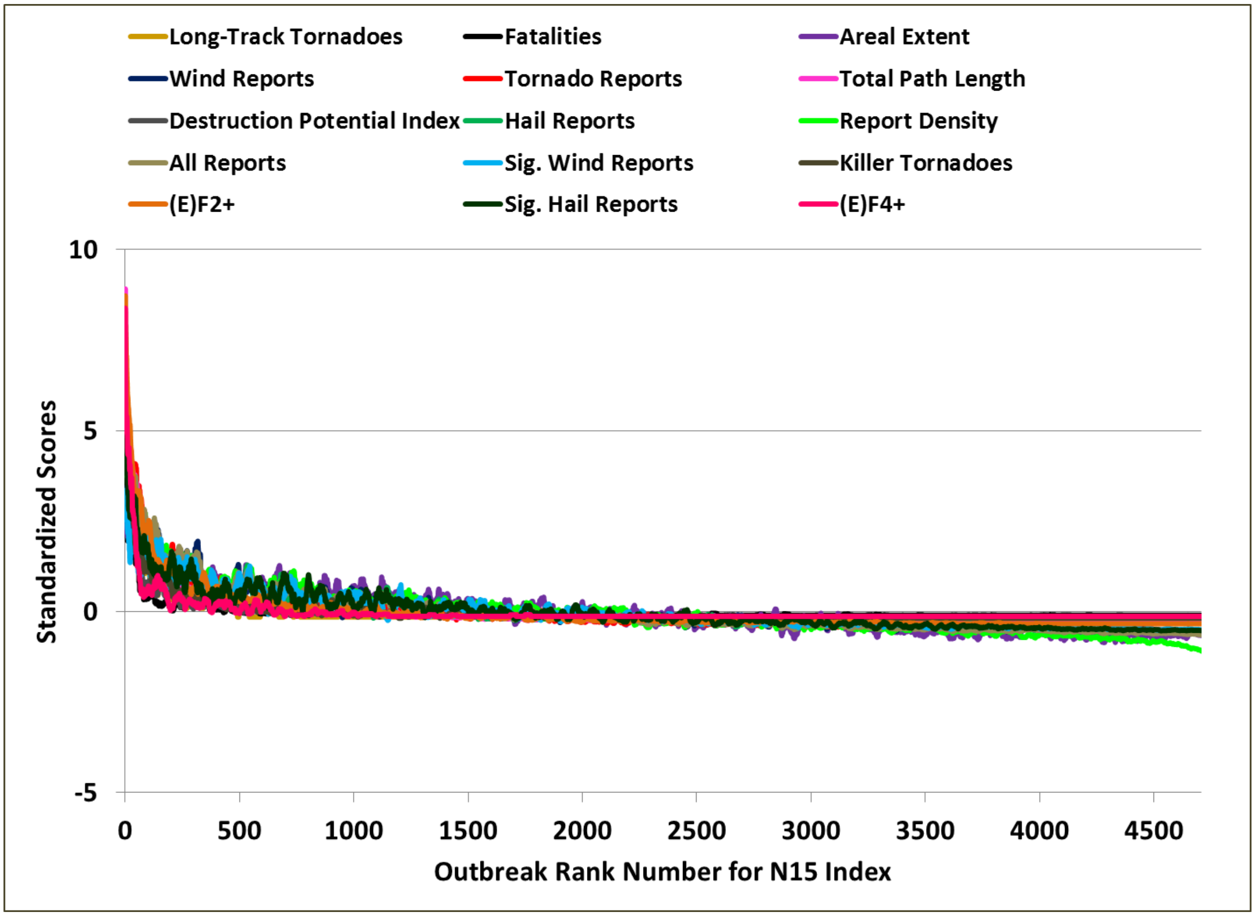

Figure 7: Standardized scores for each of the variables used in the 26 indices presented in the study (and the areal extent of the outbreaks) as a function of the outbreak rank numbers using the N15 index. The scores are averaged for 25 outbreaks, such that the plotted score for an outbreak of rank number 1 is the average score for outbreaks with rank numbers 1 through 25.

reports, (3) detrend adequately numerous secular trends in the severe reports dataset, (4) identify the most significant severe weather outbreaks (i.e., major tornado outbreaks) consistently, no matter the variations in the weights of the severe report variables, and (5) produce repeatedly the same outbreaks and rankings.

Variations to the techniques proposed here can be made. For example, a different bandwidth and/or a different threshold PDF magnitude can be used to identify KDE regions associated with the outbreaks. As SD11 noted (their Section 3), however, such variations tend to result in overly smoothed (larger bandwidths) or noisy (smaller bandwidths) borders that do not represent adequately the region affected by the severe weather, or tend to exclude reports clearly associated with the causal meteorological phenomena (larger PDF thresholds) or include reports clearly associated with unassociated phenomena (smaller PDF thresholds).

In addition, alternative time windows can be tested. Use of time windows less than 6 hours often affected outbreak durations substantially (not shown), particularly for cases with short-duration diurnal minima in severe reports associated with the same synoptic-scale system. Such results were undesirable, as a primary objective of this study is to associate severe weather events associated with the same synoptic-scale system. Use of time windows greater than 6 hours had the opposite effect, lengthening outbreak durations in some cases considerably. Such cases included multiple mesoscale convective systems traversing similar geographic regions with a sufficiently short span of time between the events. In these cases, distinct shortwave troughs commonly were observed – again, an undesirable characteristic. No selection of time window results in perfect results, but the selections presented here provided reasonable results for our objectives. Other studies with different goals may find alternative selections more appropriate.

The results of this work provide a large sample of severe weather outbreaks with no arbitrary time constraints. Investigation of multi-day severe weather outbreaks can be conducted using the methods introduced herein. Future research will attempt to identify commonly observed (and distinguishing) characteristics of synoptic-scale systems and processes associated with the occurrence of major long-duration severe weather outbreaks. The ranking methods for severe weather outbreaks also are planned to be implemented for other meteorological phenomena, including winter storms, hurricanes, and flash floods.

ACKNOWLEDGMENTS

This work is sponsored by NSF Grant AGS-0831359, and is supported in party by the Summer Professional Development Award granted by the University of South Alabama. We thank the Center for Hurricane Intensity and Landfall Investigation (CHILI) for providing the computing resources necessary for this project.

REFERENCES

Brooks, H. E., C. A. Doswell III, and M. P. Kay, 2003: Climatological estimates of local daily tornado probability for the United States. *Wea. Forecasting*, **18**, 626–640.

Bowman, A. W., and A. Azzalini, 1997: *Applied Smoothing Techniques for Data Analysis: the Kernel Approach Using S-Plus Illustrations*. Oxford University Press, 208 pp.

Doswell, C. A. III, H. E. Brooks, and M. P. Kay, 2005: Climatological estimates of daily nontornadic severe thunderstorm probability for the United States. *Wea. Forecasting*, **20**, 577–595.

——, R. Edwards, R. L. Thompson, J. A. Hart, and K. C. Crosbie, 2006: A simple and flexible method for ranking severe weather events. *Wea. Forecasting*, **21**, 939–951.

Hamill, T., M., R. S. Schneider, H. E. Brooks, G. S. Forbes, H. B. Bluestein, M. Steinberg, D. Meléndez, and R. M. Dole, 2005: The May 2003 extended tornado outbreak. *Bull. Amer. Meteor. Soc.*, **86**, 531–542.

Schaefer, J. T., and R. Edwards, 1999: The SPC tornado/severe thunderstorm database. Preprints, *11th Conf. on Applied Climatology*, Dallas, TX, Amer. Meteor. Soc., 603–606.

Shafer, C. M., and C. A. Doswell III, 2010: A multivariate index for ranking and classifying severe weather outbreaks. *Electronic J. Severe Storms Meteor.*, **5** (1), 1–39.

——, and ——, 2011: Using kernel density estimation to identify, rank, and classify severe weather outbreak events, 2011. *Electronic J. Severe Storms Meteor.*, **6** (2), 1–28.

——, A. E. Mercer, M. B. Richman, L. M. Leslie, and C. A. Doswell III, 2012: An assessment of areal coverage of severe weather parameters for severe weather diagnosis. *Wea. Forecasting*, **27**, 809–831.