663

THE WINTER STORM SCALE: A MEASURE OF THE ABILITY OF WINTER STORMS TO DISRUPT SOCIETY

Brian J. Cerruti † and Steven G. Decker *
Rutgers, The State University of New Jersey, New Brunswick, NJ

1. INTRODUCTION

Classification scales provide a means to simplify communication of meteorological information to the public. The Saffir-Simpson (SS) hurricane scale (Simpson and Saffir 1974) and the Enhanced Fujita (EF) tornado scale (Marshall et al. 2004) are two such examples. The SS scale relies on a well-defined meteorological quantity (wind), whereas the EF scale relies on a realized societal impact (tornado damage). This distinction between scales based on meteorological quantities and those based on societal impacts will be important as we turn our attention to the focus of this study, winter storms.

Several attempts have been made to classify mid-latitude cyclone intensity. Some of them (Dolan and Davis 1992; Zielinski 2002) are defined in purely meteorological terms, similar to the SS scale. We use the term *intrinsic disruption* to describe what these classifications attempt to measure. Other schemes, like Rooney (1967) and the Northeast Snowfall Impact Scale (NESIS) of Kocin and Uccellini (2004) measure societal impacts; we call these measures of *realized disruption*. Still others (Qui 2008) account for sociological variables that we call *societal susceptibility*. To summarize, we consider the realized disruption at a particular location to result from a convolution of the meteorological conditions associated with the storm (intrinsic disruption, one aspect of which may be storm-total snowfall) and the societal susceptibility at that location (one aspect of which could be the number of snowplows per capita).

This abstract outlines a new scale measuring intrinsic disruption, which we call the Local Winter Storm Scale (LWSS). For complete details, please refer to Cerruti and Decker (2011).

TABLE 1. Definition of storm element scores for each weather element included in the Local Winter Storm Scale. For each range, an observation at the lower bound is assigned the storm element score listed. The value increases linearly to the upper bound to match the next integral storm element score. (For visibility, the bounds are reversed.) Storm element scores above six are calculated by linear extrapolation using data in the final two rows.

Storm Element Score (LWSS DESCRIPTOR)	Sus Wind kt *($m\ s^{-1}$)*	Wind Gust kt *($m\ s^{-1}$)*	Snow in *(cm)*	Ice in *(cm)*	Vis mi *(km)*
Weighting Function	20%	15%	50%	30%	15%
0 (NUISANCE)	0 *(0)*	0 *(0)*	0 *(0)*	0 *(0)*	10 *(16.1)*
1 (MODERATE)	7 *(3.6)*	13 *(6.7)*	2 *(5.1)*	T *(T)*	3 *(4.8)*
2 (SIGNIFICANT)	11 *(5.7)*	17 *(8.7)*	4 *(10.2)*	0.1 *(0.3)*	1 *(1.6)*
3 (MAJOR)	17 *(8.7)*	22 *(11.3)*	10 *(25.4)*	0.25 *(0.6)*	0.5 *(0.8)*
4 (CRIPPLING)	22 *(11.3)*	30 *(15.4)*	15 *(38.1)*	0.5 *(1.3)*	0.25 *(0.4)*
5 (PARALYZING)	27 *(13.9)*	41 *(21.1)*	20 *(50.8)*	0.75 *(2.5)*	0.125 *(0.2)*
6 (EXTREME)	34 *(17.5)*	48 *(24.7)*	25 *(63.5)*	1 *(5.1)*	0 *(0)*

2. THE LOCAL WINTER STORM SCALE

2.1 MATHEMATICAL FORM

The Local Winter Storm Scale is designed to measure the intrinsic aspect of winter storms at any location (Table 1). To ensure ample data availability and ease of use, LWSS is defined in terms of quantities available from the routine surface observation network. We calculate LWSS using the following expression:

$$LWSS = \sum_k w(k)\sigma_k \ . \tag{1}$$

Here, w represents a weighting function, σ represents the *storm element score* (defined in the next subsection), and k is an integer such that $1 \le k \le 5$, denoting the following variables (i.e., *storm elements*) in order: maximum sustained wind, maximum wind gust, storm-total snow

---

* *Corresponding author address:* Steven G. Decker, Dept. of Environmental Sci., 14 College Farm Rd., New Brunswick, NJ 08901; e-mail: decker@envsci.rutgers.edu

† Current affiliation: NOAA/NWS/Meteorological Development Laboratory, Silver Spring, MD

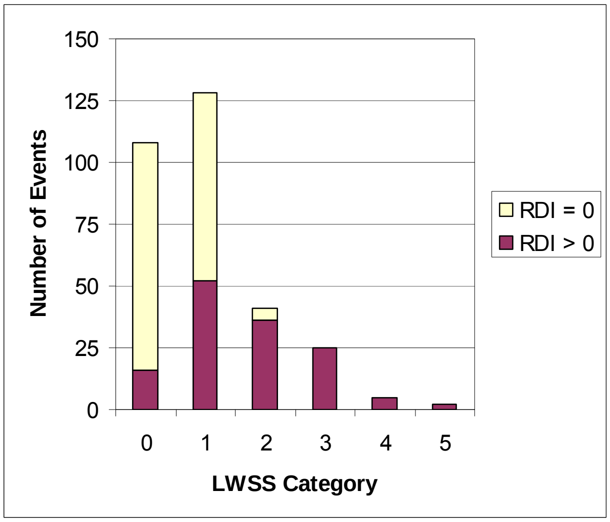

FIG. 1. Distribution of 15 years of winter weather events at Newark, NJ into LWSS categories. The proportion of storms in each category that received press mention (RDI > 0) is also shown.

accumulation, storm-total ice accretion, and minimum visibility. Storm element scores are determined using linear piecewise interpolation and the data provided in Table 1.

These data [e.g., that a 15-in (38-cm) snowfall means that $\sigma_3 = 4$] are referred to as *breakpoints*. The breakpoints are derived from various sources including NWS Eastern Region Winter Storm Warning/Advisory criteria, NESIS snowfall breakpoints, standard aircraft flight operation procedures, and the Beaufort wind scale (Table 1). To eliminate rounding errors and simplify usage, the breakpoints are expressed in terms of the units found in American METARs, but SI units, which are supplied in Table 1, can also be used. The descriptive wording to convey the intensity of each category is borrowed from Rooney (1967) and Kocin and Uccellini (2004).

2.2 APPLYING LWSS

Table 1 determines the storm element scores by linear interpolation according to the formula:

$$\sigma_k = \frac{s - c_l}{c_u - c_l} + C, \qquad (2)$$

where c_l is the categorical lower bound, c_u is the categorical upper bound, s is the storm element's observed value, and C is the appropriate category number. Eq. (2) is a continuous function consisting of six line segments (one for each of C = 0, 1, …, 5) corresponding to ranges for σ_k of 0–1, 1–2, …, 5–6. The Category-6 threshold allows storm element scores to exceed six via extrapolation from the Category-5 threshold. This implies that all the σ_k are unbounded (except σ_5, for visibility); thus, LWSS is unbounded as well.

3. THE RELATIONSHIP BETWEEN LWSS AND REALIZED DISRUPTION

3.1 WINTER STORM CLIMATOLOGY

Assuming societal susceptibility is fixed, the intrinsic disruption measured by LWSS should be proportional to the realized disruption. To check this, observations from a single location (to minimize fluctuations in societal susceptibility) were collected from 15 recent cold seasons. In particular, this study uses observations from Newark Liberty International Airport (EWR) over the period 1995-96 to 2009-10. EWR is chosen since it contains a first order climatological weather station located in a large city in the nation's most densely populated state. A dense population center provides ample information to determine realized disruption, and cities are often the focus of winter storm investigations (Rooney 1967; Kocin and Uccellini 2004).

While LWSS classifies a storm's intrinsic disruption, the Rooney Disruption Index (RDI), a rubric based on Rooney (1967), classifies realized disruption based on local newspaper archives. RDI scores were determined for each storm found in the 15-year climatology based on articles found in *The Star-Ledger*. Of the 309 storms identified within the meteorological data, 173 received no press mention, earning RDI scores of zero. These events are excluded, leaving 136 storms for further analysis. Figure 1 reveals that most of the events receiving no press mention were LWSS Category-0, MINIMAL, or Category-1, NUISANCE, events.

3.2 DATA INVESTIGATION

A box plot shows that RDI values increase as LWSS category increases (Fig. 2). RDI scores were always positive for LWSS ≥ 3, demonstrating that storms that have a MAJOR meteorological impact caused at least some realized disruption. A regression of LWSS and RDI values for storms with press mention (RDI > 0) yielded a coefficient of determination (R^2) of 0.56 (Fig. 3). While there is a clear relationship between LWSS and RDI, it is evident that additional factors lead to the RDI scores determined for each storm. These factors

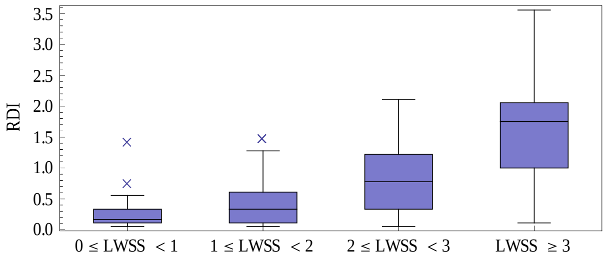

FIG. 2. Box plot of RDI distributions for four mutually exclusive LWSS categorizations. LWSS ≥ 3 represents all storms classified as MAJOR or higher.

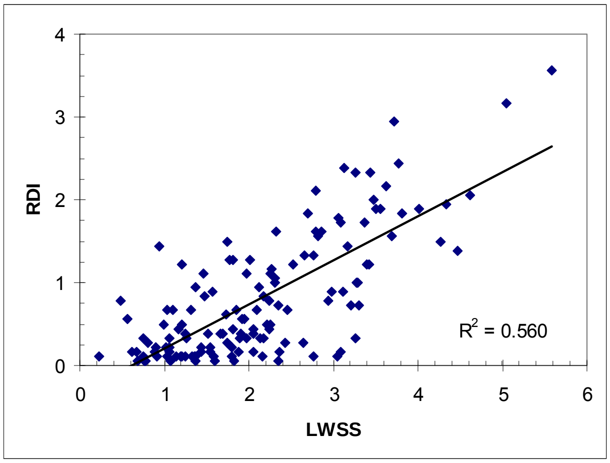

FIG. 3. Scatterplot of LWSS and RDI values, including the linear best fit and its associated coefficient of determination (R^2). Storms with no press mention (RDI = 0) are not included.

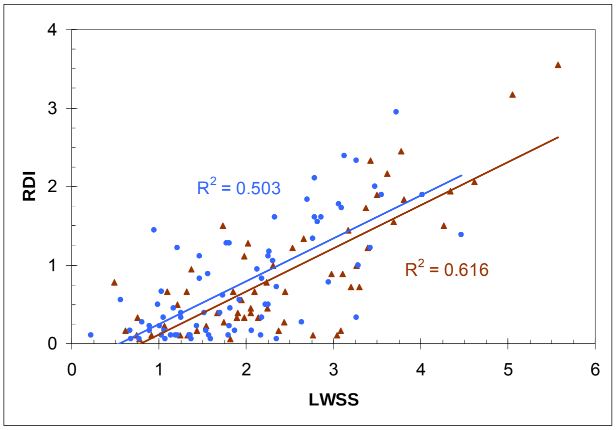

FIG. 4. As in Fig. 3, but for two subsets: storms that occurred solely on non-holiday weekdays (blue circles), and storms that occurred at least in part on weekends or holidays (red triangles). The R^2 statistics are colored to match their respective subsets.

could include variations in societal susceptibility from one storm to the next, the fact that the RDI is an imperfect measure of realized disruption, and an improper or incomplete formulation of LWSS.

Several works have noted the realized disruption a winter storm has on a weekday relative to a weekend or holiday (Rooney 1967; Kocin and Uccellini 2004). Figure 4 shows a scatterplot of the same data displayed in Fig. 3, but separated into two subsets. One subset consists of those storms that occurred at least in part on weekends or holidays. The other subset consists of the rest of the cases (i.e., those occurring only on non-holiday weekdays). This analysis shows that storms on weekdays (weekends/holidays) create more (less) realized disruption.

Previous work has also studied whether a storm occurring soon after another winter event will be more disruptive (Rooney 1967; Zielinski 2002). Figure 5 shows a scatterplot of the dataset separated based on the lag time between the end of an event and the start of the subsequent event. This analysis yields a steeper slope for storms occurring less than two calendar days apart and an R^2 value of 0.88 compared to 0.50 for storms occurring two or more days after the previous event ended (not shown). Therefore, if a storm is to occur less than 48 hours after the end date of the last winter storm, the expected societal disruption is likely to be larger, especially if the second storm is strong (high LWSS value).

Figure 6 shows a scatterplot of the data separated based on the month of the storm's start date. Several climatological studies of significant winter events show that the peak occurrence of heavy snowstorms and billion-dollar winter weather disasters is in January and February in the northeastern United States away from the lake-effect region (Changnon et al. 2006; Houston and Changnon 2009). This analysis shows a higher R^2 (0.59 to 0.52) and steeper slope for peak season storms. This leads to a tendency for weaker storms to have an outsized degree of realized disruption when occurring either early or late in the season, which implies that non-meteorological variables (which are not considered by LWSS) are more responsible for realized disruption in off-peak storms.

4. CASE STUDY: 9–11 FEBRUARY 2010

4.1 PURPOSE

We use the winter storm of 9-11 February 2010 to illustrate how the spatial variability of LWSS provides additional information concerning both societal susceptibility and possible LWSS

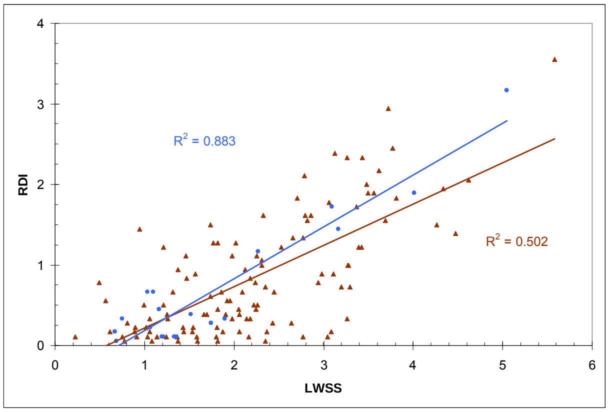

Fig. 5. As in Fig. 4, but for a storm lag time of less than two calendar days (blue circles) and at least two calendar days (red triangles).

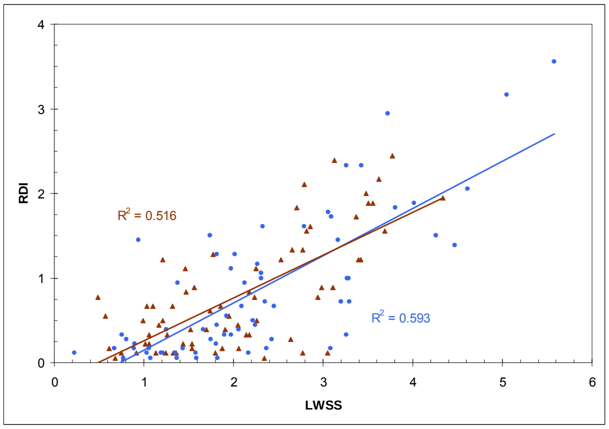

Fig. 6. As in Fig. 4, but for peak season (blue circles) and off-peak season (red triangles).

shortcomings. This section describes the intrinsic disruption at several first-order stations where hourly observations and storm-total snowfall were available. We compare the intrinsic disruption (LWSS values) to the RDI estimate of realized disruption for selected stations to investigate the relationship between intrinsic disruption and realized disruption and address differences that arise.

4.2 DATA ANALYSIS

Figure 7 shows a scatterplot of LWSS and RDI values from this event for a variety of affected locations. The best linear fit from Fig. 2 is provided for comparison purposes. Values above (below) the line have an RDI score higher (lower) than expected from the 15-year EWR climatology. Stations above (below) this line could be interpreted as reflective of higher (lower) societal susceptibility to this particular storm's intrinsic disruption, although other interpretations are possible. Figure 7 also includes a depiction of the standard error of the regression from Fig. 2 to indicate just how anomalous a particular city was relative to the Newark climatology. This section analyzes the data in greater detail to offer hypotheses explaining deviations from the linear fit in Fig. 7.

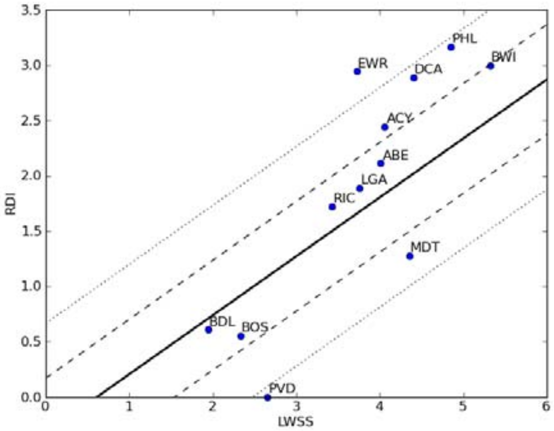

Fig. 7. Scatterplot of LWSS and RDI values at various locations affected by the 9–11 February 2010 winter storm. The best-fit line from Fig. 3 is also included, as are lines representing one (dashed) and two (dotted) standard errors above and below the best-fit line.

A few interesting patterns emerge upon such an analysis. Of the four stations incurring realized disruption one standard error higher than expected (ACY, DCA, EWR, and PHL), only EWR did not report icing. Conversely, three out of the five stations that reported icing had an RDI value one standard error higher than expected (RIC and BWI were the exceptions, which agrees with local newspaper reports that the disruption further south was primarily the result of heavy snow and high winds). This suggests that these locations (especially ACY and PHL) were particularly susceptible to ice accretion, in agreement with the findings of Houston and Changnon (2007). Additionally, three out of the four high-RDI stations reported snowfall greater than 10 inches (DCA, EWR, and PHL), which implies these areas were relatively more susceptible to higher snowfall totals than the EWR climatology would suggest.

Figure 8 shows that both LWSS and RDI identified similar areas of maximum disruption. The patterns along the southern New Jersey coast look similar, yet Atlantic City (ACY) was among the four particularly susceptible cities discussed above. ACY recorded 7.1 in (18 cm) of snowfall, and while this is less than the other susceptible stations, ACY is a coastal site where snowfall events of this magnitude are less frequent.

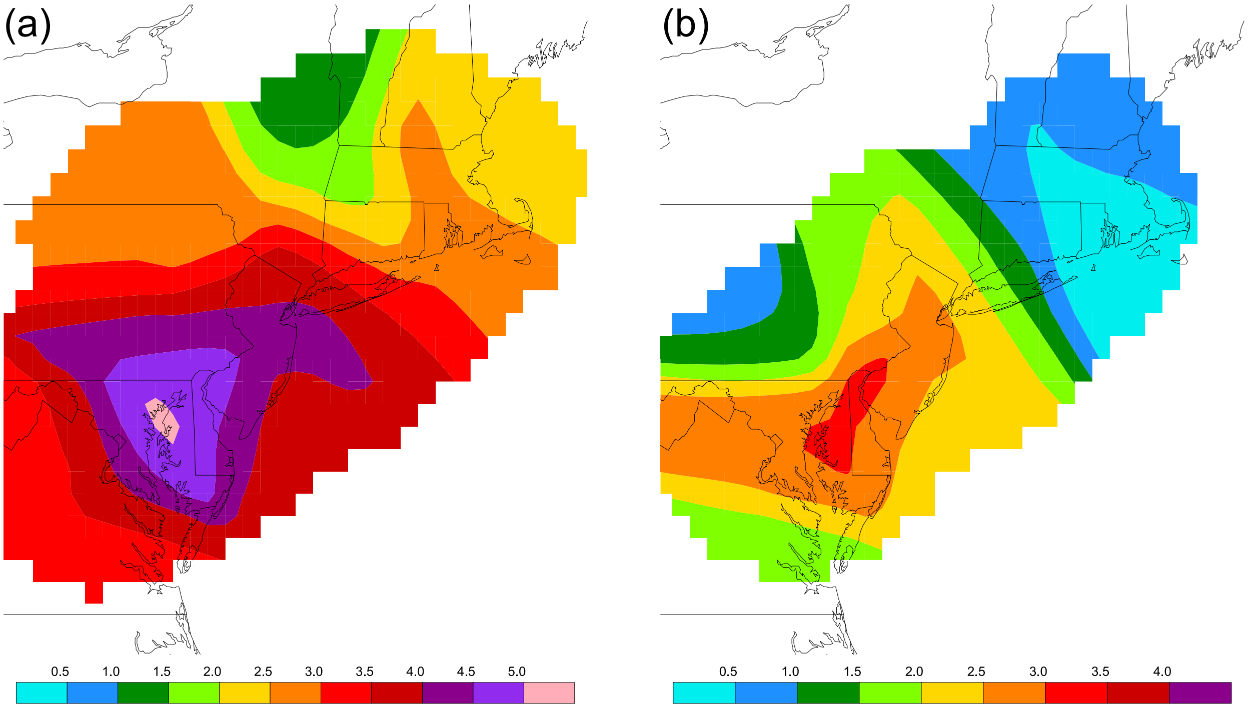

FIG. 8. Map of (a) LWSS and (b) RDI values calculated for the 9–11 February 2010 winter storm, shaded according to the legend.

Therefore, we suspect that ACY may be less prepared to handle heavy snowfall than other locations (i.e., has higher societal susceptibility). Furthermore, the snow mixed with rain at times on 10 February, and temperatures close to or above freezing resulted in partial melting on roadways, which later became icy as temperatures dropped after the storm. This resulted in a dense snowfall, which is more difficult to plow, and dangerous driving conditions. In addition, ACY observed a relatively long duration of gusty winds during this event (Fig. 9a). Since neither snow density nor wind duration is accounted for by LWSS, these factors may have led to ACY experiencing more realized disruption than expected for this event.

In contrast, Fig. 8 shows relatively low RDI scores when compared to the LWSS values in much of Pennsylvania. Allentown (ABE) and Harrisburg (MDT) reported snowfall totals of 17.8 and 15.7 inches, respectively, but their RDI scores were found to be within the expected range (for ABE) or below expectations (for MDT). Climatology indicates these two areas are less susceptible to heavy snowfall relative to the other stations as measured by their average annual snowfall (not shown). For ABE, the strongest winds clearly occur after the heaviest snowfall (Fig. 9b). For MDT, relatively colder surface temperatures indicate that relatively drier snow fell at this location, and the strongest wind gusts occurred well after the heaviest snowfall (Fig. 9c). The lack of realized disruption suggests that roadway maintenance crews may have been able to keep pace with the storm at ABE and MDT more efficiently than stations closer to the coast where the heaviest snow and strong winds occurred simultaneously. Drier snowfall at MDT may also have contributed to the low RDI value because dry snow is less disruptive than wetter snow (Rooney 1967). Again, we find that a combination of societal factors and intrinsic aspects of the storm not accounted for by LWSS likely led to the low realized disruption.

A notable discrepancy exists in Providence (PVD), where no press coverage occurred despite a LWSS classification of 2.65. In fact, no storm in the EWR climatology had a higher LWSS value without press mention. Perhaps the impact was minimal because the temperature was near or above freezing for most of the event, allowing the precipitation to mix with rain on 10 February 2010 (Fig. 9d), and these temperatures persisted for several hours at the storm's conclusion, likely contributing to substantial snowmelt. In addition, the relatively short duration of the precipitation may have contributed to the lower than expected RDI values.

The effects of the storm at Boston (BOS) were large enough to lead to a Category-2 rating primarily through the strength of the winds.

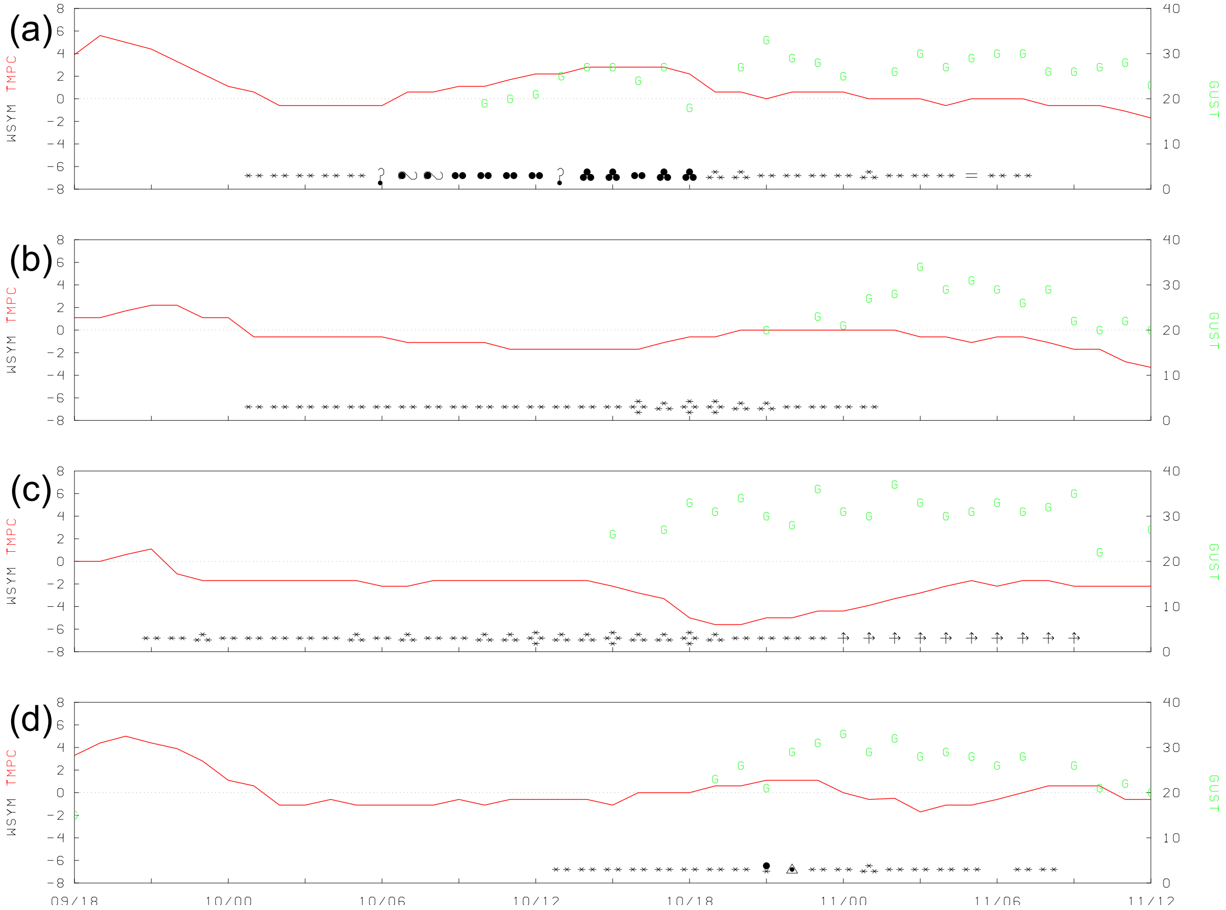

FIG. 9. Meteorograms of temperature (°C), wind gust (kt), and present weather at (a) ACY, (b) ABE, (c) MDT, and (d) PVD for the period 18 UTC 9 February through 18 UTC 11 February 2010.

However, the strongest winds occurred after the lowest visibilities, and the most intense precipitation was very short lived (not shown). Although RDI values are within the range expected given the LWSS classification, much of the disruption at BOS associated with this event was due to preemptive cancellations arising from weather forecasts that were too dire. Without those cancellations, the disruption at BOS would likely have been well below what LWSS would have suggested. These considerations highlight the complex nature of the relationship between intrinsic and realized disruption.

5. CONCLUSIONS

5.1 SUMMARY

A new scale classifies winter storms for historical comparisons by taking selected variables from surface observations and converting them into storm element scores. These scores are then weighted and summed to calculate the LWSS value. Although it is suggested that the overall score for a given winter storm be given as an integer running from zero to five when disseminating disruption values to the public, an arbitrary number of decimal places can be retained to facilitate comparisons between storms separated in space and time. This is identical to the NESIS approach, which at its heart also produces a real number that can then be truncated to an integer for public dissemination.

LWSS categorizes the multitude of weather scenarios caused by winter storms and the related intrinsic disruption at individual points. Internal politics, “bureaucratic snafus” (Rooney 1967), and the failure of snow removal companies to uphold their contracts may convolute the relationship between weather and societal impact (Call 2005). Environmental and natural impacts such as the time of year the storm strikes, weekend versus weekday, or proximity in time to a previous winter storm may further complicate matters, as shown in this study. However, diagnosing the sensible weather that produces the societal impacts independently from the impacts themselves allows comparison between storms separated in space or time based on their intrinsic ability to disrupt society.

A case study of the 9–11 February 2010 storm explored the spatial variability of LWSS values. The LWSS and RDI map comparison yielded encouraging results; specifically, the spatial patterns of maximum intrinsic disruption and realized disruption occurred in approximately the same area. The case study showed that snowfall accumulation is important, but does not tell the whole story. Snowfall density, surface temperature, the timing between the heaviest precipitation and strongest winds, and over-preparedness may cause deviations in the LWSS–RDI relationship.

5.2 FUTURE WORK

The 9−11 February 2010 case study showed that meteorograms helped to explain some of the deviation in expected RDI values. As such, perhaps an investigation of instantaneous meteorological conditions may provide a means of quantifying the brunt of a storm in terms of intrinsic disruption. An alternate version of LWSS that classifies intrinsic disruption based on instantaneous values from surface observations is currently under development.

Knowledge of the peak instantaneous intrinsic disruption may provide additional information the current LWSS cannot resolve. This instantaneous version would be an important extension to the existing scale because it will allow for the tracking of intrinsic disruption on any spatial and temporal scale to improve short-term decision making in areas such as emergency management, roadway maintenance, and public dissemination of storm attributes.

LWSS could be adapted for forecasting purposes as an extension of the current LWSS applied to forecasted parameters of sustained wind, wind gust, snowfall totals, ice accretion, and minimum visibility. The authors envision utilizing ensemble model output, such as the Short Range Ensemble Forecast (Du et al. 2009) for producing probabilistic threshold forecasts of LWSS. This method may reduce the uncertainty inherent in describing an upcoming winter storm mainly in terms of the forecasted snow and ice totals. Any instantaneous LWSS diagnostic developed in the future could also be used to generate a short-term forecast of LWSS real-time values, which may enhance societal response to storm predictions and lead to increased preparedness.

REFERENCES

Call, D. A., 2005: Rethinking snow storms as snow events: A regional case study from upstate New York. *Bull. Amer. Meteor. Soc.,* **86,** 1783–1793.

Cerruti, B. J., and S. G. Decker, 2011: The Local Winter Storm Scale: A measure of the intrinsic ability of winter storms to disrupt society. *Bull. Amer. Meteor. Soc.,* in press.

Changnon, S. A., D. Changnon, and T. R. Karl, 2006: Temporal and spatial characteristics of snowstorms in the contiguous United States. *J. Appl. Meteor. Climatol.,* **45,** 1141–1156.

Dolan, R., and R. E. Davis, 1992: An intensity scale for Atlantic coast northeast storms. *J. Coastal Res.,* **8,** 352–364.

Du, J., and Coauthors, 2009: NCEP short-range ensemble forecast (SREF) system upgrade in 2009. Preprints, *19th Conf. on Numerical Weather Prediction,* Omaha, NE, Amer. Meteor. Soc., 4A.4.

Houston, T. G., and S. A. Changnon, 2007: Freezing rain events: A major weather hazard in the conterminous United States. *Nat. Hazards,* **40,** 485-494.

Houston, T. G., and S. A. Changnon, 2009: Characteristics of the top ten snowstorms at first-order stations in the U.S. *Nat. Hazards,* **48,** 101-113.

Kocin, P. J., and L. W. Uccellini, 2004: A snowfall impact scale derived from Northeast storm snowfall distributions. *Bull. Amer. Meteor. Soc.,* **85,** 177–194.

Marshall, T. P., J. R. McDonald, and G. S. Forbes, 2004: The enhanced Fujita (EF) scale. Preprints, *22nd Conf. on Severe Local Storms,* Hyannis, MA, Amer. Meteor. Soc., 3B.2.

Qui, L., 2008: Performance measurement for highway winter operations. Ph.D. thesis, University of Iowa, 163 pp.

Rooney, J. F., Jr., 1967: The urban snow hazard in the United States: An appraisal of disruption. *Geogr. Rev.,* **57,** 538–559.

Simpson, R. H., and H. Saffir, 1974: The hurricane disaster-potential scale. *Weatherwise,* **27,** 169.

Zielinski, G. A., 2002: A classification scheme for winter storms in the eastern and central United States with an emphasis on “Nor’Easters.” *Bull. Amer. Meteor. Soc.,* **83,** 37–51.