THE REGIONAL SNOWFALL INDEX

by Michael F. Squires, Jay H. Lawrimore, Richard R. Heim Jr.,
David A. Robinson, Mathieu R. Gerbush, and Thomas W. Estilow

A new snowfall index quantifies the societal impact of snowstorms in the eastern United States from 1900 to the present.

Large snowstorms have a major impact on society in terms of human life, economic loss, and disruption. Examples include the Chicago blizzard of 1967 that caused the deaths of 45 people and economic losses to local business estimated to be $150 million (1967 U.S. dollars) (Doesken and Judson 1996). The 1993 "Superstorm" was responsible for 270 deaths and $1.8 billion in damages from the Deep South to New England (Kocin et al. 1995). Three large snowstorms struck the northeast in 1996, causing $1.1 billion in insured losses (Kocin and Uccellini 2005). Smith and Katz (2013) have identified 10 snowstorms occurring since 1980 whose damages have totaled over $29 billion. Changnon (2007) reports that monetary losses resulting from snowstorms are increasing. These examples highlight the need to better understand the impacts of snowstorms.

There have been several indices developed to characterize winter storms. Rooney (1967) used newspaper accounts and interviews to estimate the societal impact of snowfall on seven cities in the Midwest and Great Plains. He characterized these impacts as "disruptions" and, in addition to snowfall, included events such as traffic accidents, road closings, school closings, and canceled flights, as well as other negative effects. Call (2005) extended this work by describing disruptions of snowstorms for several locations in New York.

Cerruti and Decker (2011) developed the local winter storm scale (LWSS) and used a nomenclature in terms of disruptions to characterize winter weather indices. "Intrinsic disruption" is based on meteorological variables that have the potential to impact society while "societal susceptibility" is based on sociological variables. "Realized disruption" results from the interaction of intrinsic disruption and societal susceptibility. LWSS is based on measures of intrinsic disruption: snowfall, freezing rain, sustained wind, wind gusts, and visibility. LWSS is reported as a categorical value between 0 and 5 and is used to infer societal susceptibility. By definition it is a local index since it is calculated for a specific location using hourly data.

Kocin and Uccellini (2004) developed the Northeast snowfall impact scale (NESIS), which uses snowfall and population density to characterize the impact of snowstorms that affect the northeastern United States.

AFFILIATIONS: Squires, Lawrimore, and Heim—NOAA/National Climatic Data Center, Asheville, North Carolina; Robinson, Gerbush, and Estilow—Rutgers, The State University of New Jersey, New Brunswick, New Jersey
CORRESPONDING AUTHOR: Michael F. Squires, NOAA/NCDC, 151 Patton Avenue, Asheville, NC 28801
E-mail: mike.squires@noaa.gov

The abstract for this article can be found in this issue, following the table of contents.
DOI:10.1175/BAMS-D-13-00101.1

In final form 16 April 2014

NESIS uses snowfall and population information from the entire storm—both within and outside the Northeast—so it provides a measure of the total impact of a snowstorm, calibrated by the 30 largest Northeast storms from 1950 to 2000 (Kocin and Uccellini 2004). Therefore it can be thought of as a quasi-national index that is calibrated to Northeast snowstorms. NESIS combines one aspect of intrinsic disruption (snowfall) and one aspect of societal susceptibility (population) to estimate realized disruption. NESIS is the first measure of snowfall to include population density. The National Oceanic and Atmospheric Administration's (NOAA) Storm Prediction Center also uses population information to estimate potential societal impacts of severe weather episodes (Schneider et al. 2009).

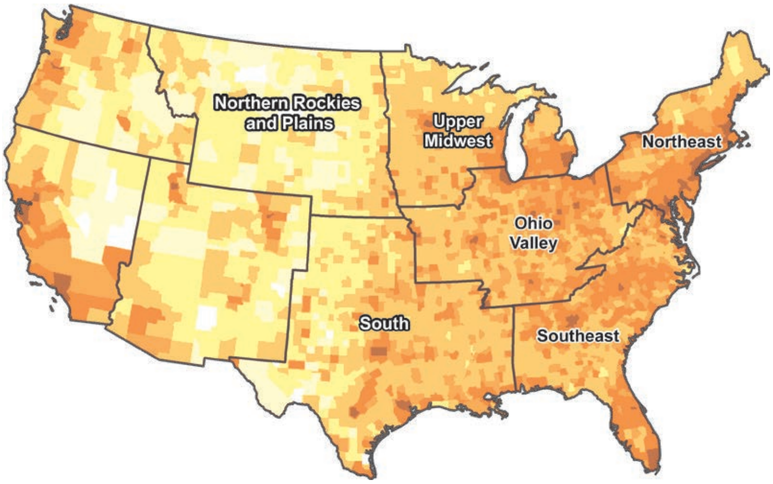


Fig. 1. NCDC climate regions and population density map. Darker shades indicate high population density and lighter shades indicate lower population density.

NOAA's National Climatic Data Center (NCDC) began calculating NESIS operationally in 2006. Since that time there have been numerous requests from users for a new index that produces NESIS-like scores for other regions that specifically estimate the impact of a storm within the borders of a region. The desire for a truly regional index is understandable because the societal susceptibility and the intrinsic disruptions that contribute to realized disruption vary between regions (Rooney 1967). For example, a rare one-half inch of snowfall along Florida's east coast in December 1989 brought most operations of the CSX, Norfolk Southern, and Florida East Coast railroads to a standstill (Changnon 2006). This would be considered a nonevent in snow-prone regions of the United States. Clearly there is a need for a regional snowfall index that attempts to quantify societal impacts (realized disruption).

This paper describes a new snowfall index that estimates the realized disruption of snowstorms within six climate regions of the United States as defined by the NCDC (Karl and Koss 1984). NOAA's NCDC in cooperation with Rutgers, The State University of New Jersey developed the regional snowfall index (RSI) using the spatial extent of a storm, amount of snowfall, and the juxtaposition of these elements with population. The RSI is an evolution of NESIS and, like NESIS, combines aspects of intrinsic disruption (snowfall accumulation and area) and one aspect of societal susceptibility (population) to estimate realized disruption. However, the RSI is a regional index calibrated and produced for each of the six NCDC climate regions in the eastern two-thirds of the nation (Fig. 1). The indices are calculated in a fashion similar to NESIS but with modifications allowing the index to be tailored to the climatology of different regions using region-specific parameters and thresholds. Unlike NESIS, which includes snowfall amounts for the entire storm (even outside the Northeast), the RSI is calculated only with snow that falls within a region's borders. Therefore RSI has a unique value for each region and storm. This allows the RSI to discriminate disruption between different regions for the same storm.

The RSI has been calculated for almost 600 snowstorms that occurred between 1900 and 2013. This new scale is intended to provide a century-scale historical perspective of the magnitude and frequency of snowstorms. The RSI is computed for category 1 or greater storms in near–real time, usually a day after the storm has ended when quality-controlled daily data are available to analysts at NCDC. Thus, the RSI helps meet NCDC's mission to sustain monitoring, understand extremes, and integrate societal impacts into its products. The remainder of this paper discusses the data, storm selection, quality control, RSI methodology, and results, and concludes with a summary.

DATA AND STORM SELECTION.

Identifying past snowstorms. The first task was to identify the starting and ending dates of large snowstorms back to 1900. While daily snowfall values are available for thousands of locations, there was no comprehensive list of starting and ending dates for snowstorms going back to 1900. A process was developed using a combination of objective and subjective analysis to identify the beginning and ending dates of large snowstorms. Gridded snowfall information was generated at the Rutgers University Global Snow Lab using daily observations quality controlled with criteria set forth by Robinson (1989). The Spheremap spatial interpolation program was used to generate 1° × 1° grid box values of daily snowfall (Dyer and Mote 2006). Average snowfall for each grid box was multiplied by the total population within the grid box and then summed within each region to obtain daily regional population-weighted snow values. Running four-day totals were calculated from these daily values, with the largest totals used to identify the occurrence of high-impact snow events in each region. The four-day running totals gave a good first guess of the beginning and ending dates of the snowstorms, but many storm intervals had to be shortened or lengthened for an event after examining daily snowfall maps. Storm event dates were determined by evaluating a combination of the daily population-weighted snow values, historical daily weather maps (source: NOAA Central Library U.S. Daily Weather Maps Project, www.lib.noaa.gov/collections/imgdocmaps/daily_weather_maps.html), and daily GIS snowfall maps. This was the process used to identify historical snowstorms. Operationally, beginning and ending dates of snowstorms are determined by examining various weather maps and radar/satellite animations.

For both historical and current storms, there are many cases when there are two or more snowstorms occurring in the United States between the beginning and ending dates of the snowstorm in question. In these cases, daily snowfall amounts for the locations that were not part of the storm being analyzed were set to zero. Snowstorm totals were then recomputed to ensure that only snowfall from the storm in question was used in the calculations. Figure 2 shows the original snowfall data extracted for the 15–19 January 1978 storm and the final data after the boundaries of the snowstorm were delineated and snowfall unrelated to this storm was removed.

Quality control process. Once the beginning and ending dates were identified, snowfall data were extracted from the Global Historical Climatological Network-Daily dataset (GHCN-D) (Menne et al. 2012). In GHCN-D, all observations are subjected to a series of automated quality control (QC) processes that are applied consistently throughout the period of record (Durre et al. 2008, 2010). The automated QC procedures used to produce GHCN-D do not change values; rather, elements that fail any checks are flagged. The data used in the current snowstorm study only include snowfall values that pass the automated quality control checks. While the methods for measuring daily snowfall have not changed much since 1900 (Changnon et al. 2008), actual procedures can vary between locations (summing six-hourly totals versus one daily total). While these differing procedures can lead to some spatial variance, they normally do not affect the overall spatial continuity. As will be explained in the next section, cumulative areas of snowfall above various regional thresholds were calculated so small-scale variance has little effect on the RSI.

Large errors at individual stations could adversely affect calculation of the RSI so an additional layer of manual quality control was also applied to identify snowstorm totals that appear to be in error. The QC process uses the local Moran's *I* index (Anselin 1995) and manual inspection using a GIS. See Squires and Lawrimore (2006) for details. This protocol was

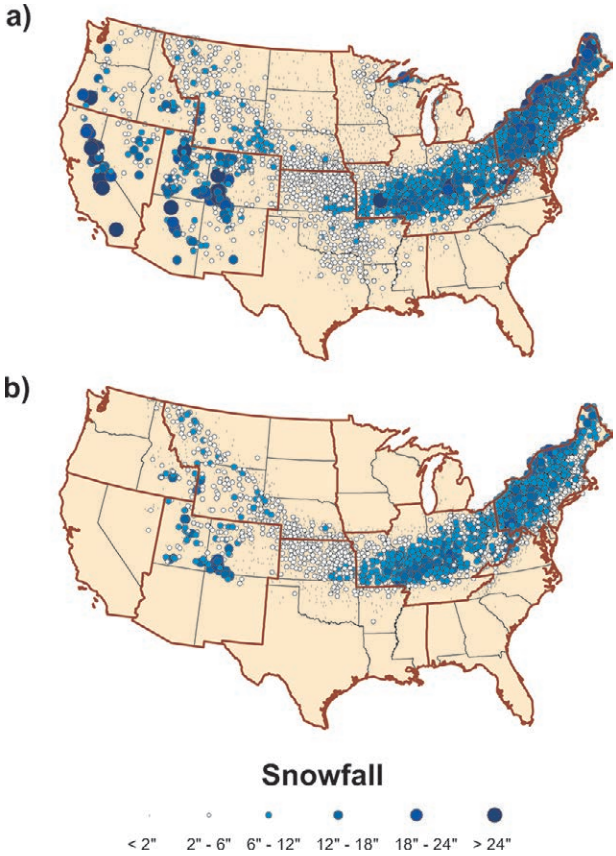


Fig. 2. Maps of the 15–19 Jan 1978 snowstorm showing (a) all nonzero snowfall data for that period and (b) final map showing stations contributing to the snowfall totals after quality control and removing unrelated snowfall.

enforced to minimize type I errors (false positives), which would result in the removal of valid snowfall values. It also ensures consistent manual QC between different analysts. In a typical snowstorm, fewer than 2% of the observations were eliminated. Most of the stations were removed because their snowfall totals were too small compared to their neighbors.

Population data. Population data were based on the 2010 Census. Although storms are analyzed from 1900 to the present, the 2010 Census data were used for all storms. This is similar to economists adjusting for inflation and ensures that the differences in rankings between storms are due to weather and climate, not changes in demographics. This methodology assumes constant population and allows comparison of recent RSI values to past values. County-level census data were converted to a 5-km grid in an Albers equal area projection to facilitate area calculations in a GIS (Fig. 1). The map clearly shows the highly populated areas of the Northeast, East Coast, and various metropolitan areas in the Midwest. By contrast, most areas of the Great Plains have a low population density.

REGIONAL SNOWFALL IMPACT SCALE.

RSI algorithm. The equation used to calculate the RSI is a modification of Eq. (1) from Kocin and Uccellini (2004):

$$\mathrm{RSI} = \sum_{(T-T_1)}^{(T_4)} \left[\left(\frac{A_T}{\bar{A}_T} + \frac{P_T}{\bar{P}_T} \right) \right], \tag{1}$$

where

T = region-specific snowfall thresholds,
A_T = area affected by snowfall greater than threshold T;
$\bar{A}_T$ = mean area affected by snowfall greater than threshold T;
P_T = population affected by snowfall greater than threshold T; and
$\bar{P}_T$ = mean population affected by snowfall greater than threshold T.

The region-specific snowfall thresholds T referred to above are specified for each of the six easternmost NCDC climate regions (Fig. 1) and they serve to calibrate the RSI to each region. For example, the regional snowfall thresholds for the South region are 2, 5, 10, and 15 in. while thresholds for the upper Midwest region are 3, 7, 14, and 21 in. Table 1 lists the thresholds for all the regions. These thresholds are based on return period statistics as described in the next section.

Each RSI value is calculated from a linear combination of four terms, with each term representing the sum of scaled snowfall area and population information. The snowfall area (A_T) and population (P_T) values are scaled using mean values of snowfall area ($\bar{A}_T$) and population ($\bar{P}_T$) within each of the four terms. The calculation of the region- and threshold-specific means is described in the appendix. Scaling the area and population terms is essential because in a typical storm the area (in square miles) is about two orders of magnitude less than the population. Scaling the area and population for a particular storm by their mean values transforms these terms into "percent of normal" expressions with similar magnitudes. Using the mean area and population to scale each term for each threshold also helps to ensure that the final statistical distributions for all the regions are similar, despite large differences in regional snowfall climatologies, region population, and region area (see Table 1, Fig. 1, and Fig. 3). This is a desirable attribute because it allows comparisons of snowstorms between regions. For example, a snowstorm in the Southeast may receive less snow than the Northeast for the same storm, but the societal impacts may be greater because the Southeast is generally less accustomed to dealing with snowfall, while the Northeast is better equipped to deal with heavy snow. The 24 mean area values (6 regions × 4 thresholds) and 24 mean population values are given in the appendix.

In addition to calculating impacts only within a region, there are other methodological differences between the RSI and NESIS. For example, calibration of NESIS is based on 30 high-impact storms in the Northeast that occurred between 1950 and 2000 (Kocin and Uccellini 2004), while the RSI uses storms that occurred between 1900 and 2013. More importantly, calibration for the RSI is based on the average snowfall coverage and population within each threshold category. The NESIS is normalized using only the average snowfall coverage and population in the Northeast for the second threshold category (>10 in.). Because the NESIS performs calibration using only the means from the second threshold category, weighting factors are necessary to give greater weight to the higher threshold categories (Kocin and Uccellini 2004). The RSI does not use weighting factors because calibration is specific to each threshold category. Given all of these differences, it is not appropriate to compare the RSI values/rankings to the NESIS values/rankings.

Choosing region-specific snowfall thresholds. Figure 3 is a map showing the 2-day total snowfall 25-year return period for 7,926 stations in the United States.

Table 1. Regional threshold parameters (T1, T2, T3, and T4, in inches) and population information for each of the six eastern NCDC regions.

Region	Area (mi^2)	Population 2010 Census	Population density (per mi^2)	T1	T2	T3	T4
Northeast	178,509	62,590,449	351	4	10	20	30
Southeast	285,895	55,430,570	194	2	5	10	15
Ohio Valley	310,367	49,378,331	159	3	6	12	18
Upper Midwest	254,766	23,920,906	94	3	7	14	21
South	563,004	42,166,617	75	2	5	10	15
Northern Rockies and plains	470,385	4,866,153	10	3	7	14	21

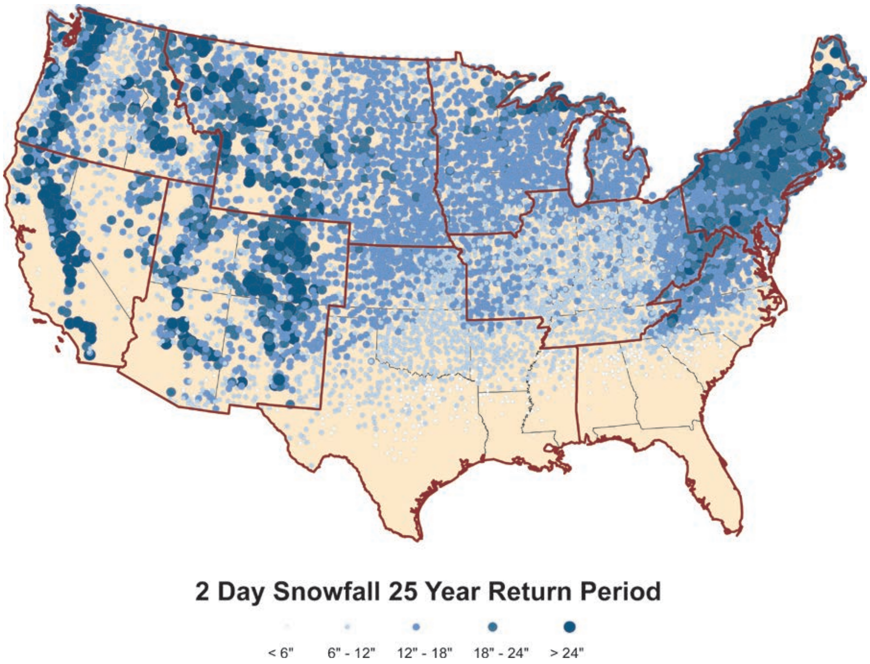


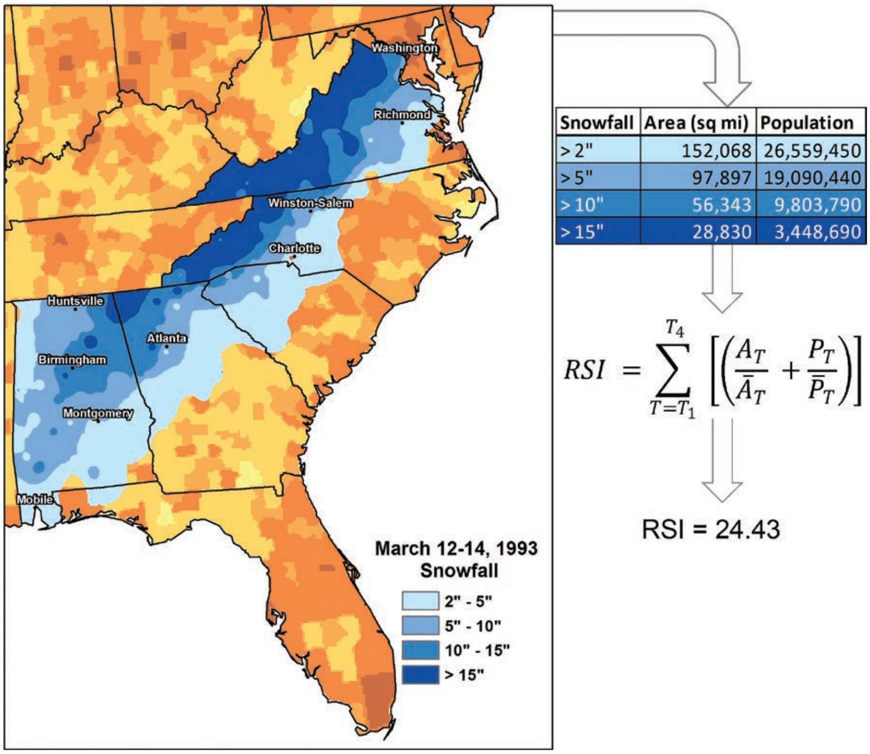
Fig. 3. Two-day snowfall total 25-year return period statistics for 7,926 stations showing the spatial variability of snowfall climatology across the United States.

(Heim and Leffler 1999). This map highlights the regional differences in snowfall climatology. The original NESIS algorithm uses snowfall thresholds of 4, 10, 20, and 30 in. These values were chosen by Kocin and Uccellini based on their expert knowledge of Northeast snowstorms. However, an objective method was needed to identify thresholds for the other climate regions. This was achieved through the use of return period statistics.

First, the average 2-day 10-year return period and the average 2-day 25-year return period for snowfall were computed for each region. This was done by averaging all the stations within a region. Next, a relationship was found between these average return period values in the Northeast and the existing NESIS thresholds. The first NESIS threshold (4 in.) is approximately one-quarter of the average 2-day 10-year return period for the Northeast. The second NESIS threshold (10 in.) is approximately one-half of the average 2-day 25-year return period for the Northeast. The third and fourth thresholds (20 and 30 in.) are just multiples of the second threshold. These relationships were applied to all of the six regions' average return period statistics to create regional snowfall thresholds that are consistent with the original NESIS thresholds. Table 1 lists the regional snowfall thresholds for all the regions.

RSI calculation. The process of calculating a southeastern RSI value for the 12–14 March 1993 Superstorm is shown in Fig. 4. The population density and snowfall grids are both 5-km resolution and the individual grid cells align with each other. The area of snowfall and population associated with each threshold are calculated within the GIS and written to a table that provides all the required inputs to the RSI equation. The final Southeast RSI value for this storm is 24.43, ranking it as the second highest snowstorm in the region.

Table 2 shows the relative contribution of each of the four terms in Eq. (1) to the final RSI score for a selection of Southeast storms. Using this



Snowfall	Area (sq mi)	Population
> 2"	152,068	26,559,450
> 5"	97,897	19,090,440
> 10"	56,343	9,803,790
> 15"	28,830	3,448,690

$$RSI = \sum_{T=T_1}^{T_4}\left[\left(\frac{A_T}{\bar{A}_T}+\frac{P_T}{\bar{P}_T}\right)\right]$$

RSI = 24.43

Fig. 4. Process used to calculate an RSI value in the southeastern region for the 12–14 Mar 1993 Superstorm. Cities in the Southeast with a population over 100,000 are shown on the map.

method, higher ranked RSI values are dominated by the third and fourth terms, which are associated with higher snowfall amounts. Lower ranked RSI values are dominated by the first and second thresholds, which are associated with lower snowfall amounts. In the middle of the rankings, there is a transition from the upper thresholds to the lower thresholds. In the March 1993 storm, 46% of the final value in the Southeast region came from the fourth term, which is associated with snowfall greater than 15 in. The contributions from the first two terms, which correspond to snowfall amounts greater than 2 and 5 in., respectively, have much lower contributions.

Table 2. Relative contribution of each of the four terms (>2 in., >5 in., . . .) in the RSI equation to the final index for example storms in the southeastern region. See text for details.

	Start	End	RSI	>2 in.	>5 in.	>10 in.	>15 in.
High RSI storms	6 Jan 1996	9 Jan 1996	26.37	7%	10%	22%	**61%**
	12 Mar 1993	15 Mar 1993	24.43	12%	15%	27%	**46%**
	27 Feb 1927	3 Mar 1927	24.42	9%	13%	25%	**54%**
	26 Jan 1922	30 Jan 1922	18.53	9%	12%	24%	**55%**
	21 Jan 1940	24 Jan 1940	18.14	18%	26%	27%	**29%**
Medium RSI storms	25 Jan 1966	28 Jan 1966	8.67	25%	30%	**32%**	13%
	29 Feb 1960	5 Mar 1960	8.63	29%	**34%**	30%	7%
	24 Feb 1914	27 Feb 1914	8.03	41%	**43%**	15%	1%
	24 Jan 2000	27 Jan 2000	7.86	26%	**34%**	33%	8%
	27 Jan 1998	29 Jan 1998	7.77	12%	16%	28%	**44%**
Low RSI storms	22 Dec 1966	26 Dec 1966	2.89	31%	**43%**	26%	0%
	3 Feb 1923	7 Feb 1923	2.85	**56%**	44%	1%	0%
	3 Apr 1915	5 Apr 1915	2.79	**55%**	43%	1%	0%
	19 Mar 1981	23 Mar 1981	2.66	**43%**	32%	22%	3%
	8 Feb 2010	13 Feb 2010	2.65	**84%**	16%	0%	0%

By contrast, the February 2010 storm, which had a relatively low RSI value of 2.65, is driven primarily by the first term, which contributed 84% to the final value and is associated with snowfall totals greater than 2in. This pattern of appropriate attribution of the individual terms to the final index values is a desirable characteristic because it verifies that the RSI algorithm is performing as expected and allows one to diagnose why a particular value was generated. All of the regions exhibited a similar behavior wherein the third and fourth terms contributed most to higher RSI storms, the first and second terms contributed most to lower RSI storms, and a transition occurs in between.

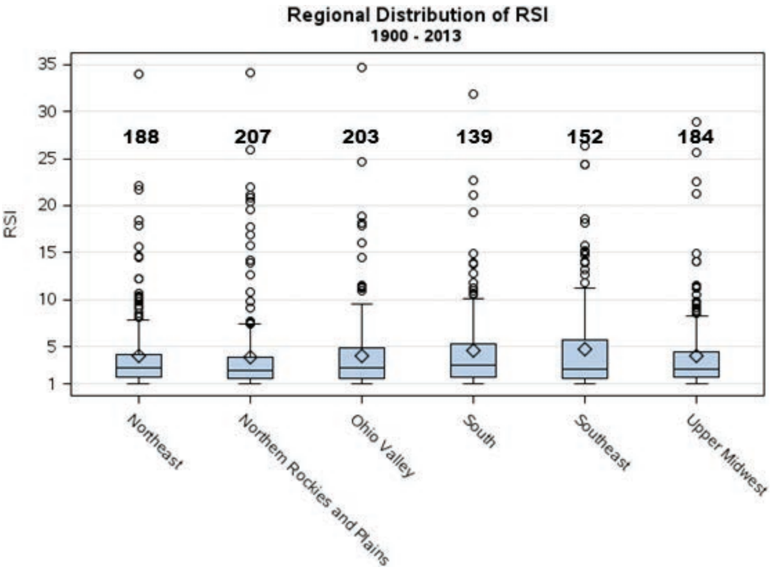


Fig. 5. Boxplots illustrating the regional distributions of RSI values of category 1 or greater for the six NCDC regions from 1900 to 2013. The boxes encapsulate the interquartile range, the whiskers extend 1.5 × interquartile range beyond the box, and the small circles are outliers beyond the whiskers. The median is represented by the solid horizontal line and the mean is depicted by the diamond. The number above each box represents the number of storms analyzed for that region.

Table 3. Relationship between RSI raw scores and RSI categories.

Category	RSI raw score	Approximate percent of storms	Description
5	≥18.00	1%	Extreme
4	10.00–17.99	2%	Crippling
3	6.00–9.99	5%	Major
2	3.00–5.99	13%	Significant
1	1.00–2.99	25%	Notable
0	<1.00	54%	Nuisance

Categorization of raw RSI scores. Figure 5 shows a series of box plots illustrating the regional distributions of RSI values for category 1 or greater storms from 1900 to 2013. Given that the median (horizontal line) is lower than the mean (diamond) and there are many outliers outside the upper "whisker," it is clear that all of the regional distributions are positively skewed (Wilks 2006). One must keep in mind that most of the storms in these distributions are large snowstorms owing to the nature of the selection process. Although there are some differences between individual regions, the distributions of all the regional snowfall indices are similar.

To better communicate the severity of each snowstorm, the raw RSI score is converted to a category between 0 and 5. The same categorical descriptions as NESIS are used: notable (category 1), significant (category 2), major (category 3), crippling (category 4), and extreme (category 5) (Kocin and Uccellini 2004). Since all of the regional RSI distributions are similar, it is possible to apply the same categorization scheme across all regions. The relationship between raw RSI scores and categories is shown in Table 3. The threshold for category 5 was chosen so only 1% or fewer of the storms are included in this category. Lower categories include increasingly larger proportions of storms. The RSI category boundaries get closer together for the lower categories owing to the positively skewed distribution of the raw index values (see Fig. 5). Category 5 storms occur rarely and are dominated by large areas of snowfall above the fourth threshold (T4 in Table 1) collocated with dense population within each region. The northern plains has had seven such storms since 1900, the Southeast five, and the other regions have had four. Category 4 storms are dominated by large areas of snowfall above third and fourth thresholds collocated with dense population. Seven to twelve category 4 storms have occurred in each of the six regions. The top 25 regional RSI values and their ranks within their respective regions are presented in Table 4. Snowstorms that have a raw index value of less than 1.00 are defined as nuisance—category 0 storms.

RESULTS. *Examples of specific storms.* The regional impacts of the 18–21 December 2009 storm are shown in Fig. 6. This is an example of one storm having very different impacts for different regions. The total snowfall in each of the regions is symbolized as a function of its

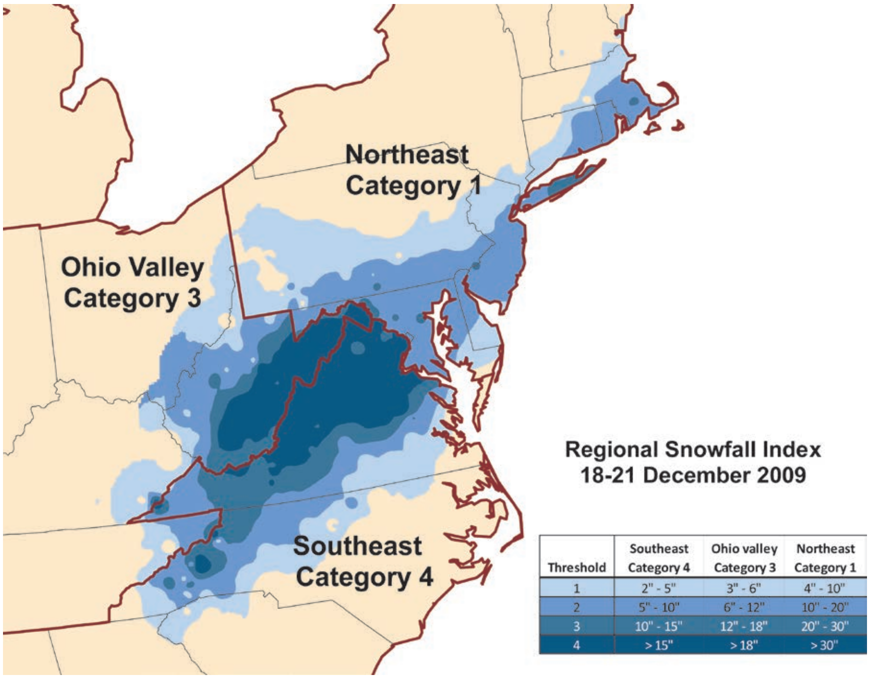


FIG. 6. Snowstorm on 18–21 Dec 2009. Snowfall is symbolized by region-specific thresholds.

TABLE 4. Top 25 storms in the (a) Northeast, (b) northern Rockies and plains, (c) Ohio Valley , (d) South , (e) Southeast, (f) and upper Midwest regions.

(a) Northeast				(b) Northern Rockies and plains			
Rank	Start	RSI	Category	Rank	Start	RSI	Category
1	22 Feb 1969	34.03	5	1	10 Apr 1927	34.20	5
2	12 Mar 1993	22.12	5	2	25 Apr 1984	25.95	5
3	6 Jan 1996	21.71	5	3	21 Nov 1993	22.00	5
4	4 Feb 1978	18.42	5	4	19 Jan 1943	21.14	5
5	21 Feb 2010	17.83	4	5	15 Apr 1920	20.84	5
6	26 Feb 1900	15.65	4	6	28 Feb 1966	20.38	5
7	14 Feb 2003	14.67	4	7	22 Dec 2009	19.62	5
8	22 Nov 1950	14.53	4	8	2 Mar 1915	17.67	4
9	28 Jan 1966	12.28	4	9	3 Apr 1955	16.93	4
10	3 Mar 1902	12.19	4	10	1 Jan 1949	15.79	4
11	27 Feb 1947	10.63	4	11	19 Mar 2006	14.22	4
12	26 Feb 1971	10.18	4	12	1 Mar 1985	13.91	4
13	25 Dec 1969	10.14	4	13	18 Apr 1933	12.69	4
14	12 Feb 1914	9.88	3	14	17 Nov 1979	10.81	4
15	4 Dec 2003	9.40	3	15	4 Apr 1997	9.88	3
16	8 Feb 2013	9.21	3	16	2 Oct 2013	9.78	3
17	4 Feb 2010	9.06	3	17	23 Nov 1983	9.11	3
18	1 Feb 1961	8.28	3	18	21 Dec 1987	7.65	3
19	25 Dec 1947	8.11	3	19	7 Apr 2013	7.55	3
20	12 Feb 1958	7.87	3	20	27 Mar 2007	7.52	3
21	10 Feb 1983	7.86	3	21	13 Mar 1943	7.48	3
22	28 Jan 1925	7.38	3	22	25 Mar 1975	7.35	3
23	18 Mar 1958	7.14	3	23	10 Mar 1929	7.10	3
24	29 Feb 1960	6.90	3	24	27 Apr 1967	7.05	3
25	11 Feb 2007	6.89	3	25	13 Nov 1958	6.60	3

(c) Ohio Valley

Rank	Start	RSI	Category
1	22 Nov 1950	34.69	5
2	12 Mar 1993	24.63	5
3	1 Feb 2011	21.99	5
4	25 Jan 1967	18.13	5
5	6 Jan 1996	17.93	4
6	7 Nov 1913	16.09	4
7	12 Jan 1979	14.42	4
8	1 Jan 1999	11.58	4
9	16 Feb 1910	11.34	4
10	20 Dec 2004	11.31	4
11	2 Apr 1987	11.21	4
12	8 Dec 1944	9.50	3
13	26 Feb 1900	9.49	3
14	14 Feb 2003	9.25	3
15	19 Feb 1912	9.00	3
16	3 Mar 1902	8.87	3
17	11 Jan 1968	8.18	3
18	24 Feb 1984	8.17	3
19	7 Feb 1985	8.10	3
20	17 Dec 1973	8.06	3
21	23 Jan 1978	7.73	3
22	4 Mar 1931	7.71	3
23	27 Nov 1974	7.45	3
24	3 Feb 1998	7.24	3
25	16 Jan 1994	7.00	3

(d) South

Rank	Start	RSI	Category
1	18 Feb 1921	31.89	5
2	5 Jan 1988	22.64	5
3	19 Dec 1929	21.13	5
4	19 Feb 1971	19.36	5
5	27 Mar 2009	14.95	4
6	2 Mar 1915	13.93	4
7	31 Jan 1956	13.78	4
8	8 Feb 2010	12.75	4
9	9 Feb 2011	11.80	4
10	3 Mar 1902	11.26	4
11	1 Feb 2011	11.07	4
12	26 Feb 1900	10.96	4
13	21 Dec 1918	10.61	4
14	5 Feb 1980	10.55	4
15	10 Feb 2010	10.07	4
16	13 Dec 1987	9.57	3
17	19 Feb 2013	9.23	3
18	12 Mar 1999	8.66	3
19	14 Jan 1987	7.98	3
20	10 Jan 1985	7.73	3
21	14 Mar 1960	7.35	3
22	14 Feb 1993	7.11	3
23	22 Mar 1957	7.06	3
24	24 Feb 2013	6.89	3
25	9 Jan 1918	6.85	3

(e) Southeast

Rank	Start	RSI	Category
1	6 Jan 1996	26.37	5
2	12 Mar 1993	24.43	5
3	27 Feb 1927	24.42	5
4	26 Jan 1922	18.53	5
5	21 Jan 1940	18.14	5
6	18 Dec 2009	15.71	4
7	28 Feb 1980	15.14	4
8	17 Feb 1979	15.01	4
9	10 Feb 1983	14.78	4
10	9 Feb 1973	14.01	4
11	13 Dec 1930	13.97	4
12	21 Jan 1987	13.16	4
13	5 Mar 1962	12.66	4
14	28 Feb 1962	11.80	4
15	6 Feb 1936	11.26	4
16	13 Feb 1902	10.16	4
17	4 Feb 2010	10.15	4
18	28 Feb 1942	9.73	3
19	28 Jan 1966	9.63	3
20	5 Jan 1988	9.27	3
21	25 Jan 1966	8.67	3
22	29 Feb 1960	8.63	3
23	24 Feb 1914	8.03	3
24	24 Jan 2000	7.86	3
25	27 Jan 1998	7.77	3

(f) Upper Midwest

Rank	Start	RSI	Category
1	23 Jan 1978	39.07	5
2	31 Oct 1991	30.18	5
3	7 Feb 1985	27.06	5
4	28 Nov 1985	22.19	5
5	1 Jan 1999	15.30	4
6	1 Mar 1985	15.18	4
7	25 Jan 1967	14.72	4
8	9 Mar 1951	12.97	4
9	1 Feb 2011	12.55	4
10	28 Feb 1966	11.08	4
11	16 Dec 1929	10.62	4
12	27 Jan 1947	10.18	4
13	28 Dec 1978	10.08	4
14	22 Dec 2009	10.07	4
15	4 Dec 1950	9.80	3
16	10 Mar 1940	8.96	3
17	22 Feb 2007	8.90	3
18	26 Feb 2007	8.66	3
19	7 Dec 2009	8.40	3
20	11 Dec 2010	8.19	3
21	12 Jan 1979	7.87	3
22	22 Mar 1996	7.76	3
23	4 Dec 1969	7.59	3
24	16 Mar 1965	7.30	3
25	4 Mar 1959	7.25	3

region-specific thresholds. The large area of snowfall in the Southeast region above the fourth threshold (>15 in.) resulted in a category 4 storm. This was the sixth highest rank storm since 1900 in the Southeast (Table 4e). By contrast, the storm was a category 1 storm in the Northeast and was only the 99th ranked storm. Note the apparent discontinuity in snowfall along the Maryland and Virginia border where there was 15–20 in. of reported snowfall. In the Southeast these amounts are in the fourth threshold (>15 in.) while these same amounts are in the second threshold (10–20 in.) in the Northeast. This is an unavoidable byproduct of using fixed regions containing several states.

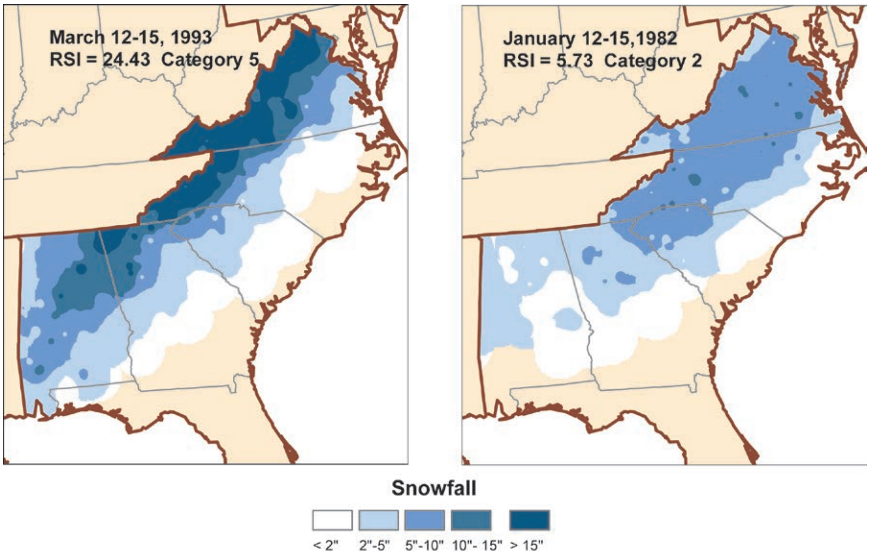


Fig. 7. Two Southeast snowstorms with similar areas but different RSI scores.

The RSI is unitless owing to the cancelation of units in the RSI algorithm, but the RSI provides an implied measure of realized disruption within each region through the combination of snowfall observations (intrinsic disruption) and population density (societal susceptibility). It is reasonable to ask what a particular RSI value looks like in terms of a traditional snowfall map. Figure 7 illustrates how maps of storms in the Southeast with similar footprints but different RSI values may appear. The category 5 March 1993 Superstorm actually has a slightly smaller footprint [206,144 mi^2 (1 mi = 1.6 km)] than the category 2 January 1982 storm (216,244 mi^2). However, the January 1982 storm has little snowfall over 10 in. and no snowfall over 15 in. On the other hand, the March 1993 storm has large areas of snowfall over 10 and 15 in., which results in a category 5 RSI. This comparison gives a sense of how different RSI values relate to spatial distributions of snowfall and population. Because of the multidimensional nature of the RSI (snowfall area, amount, population, and juxtaposition of all three), it is possible for two storms with similar RSI values to have maps that look very different from each other.

When two storms impact the same area within a few days of each other, the second storm is often more disruptive than the first (Call 2005). This is typically due to snow remaining from the first storm or equipment failure (snow mitigation equipment damaged in the first storm and not repaired in time for the second storm). Two large snowstorms struck the mid-Atlantic states on 5–7 and 10–11 February 2010 (Fig. 8). The first storm had a large area of snowfall greater than 20 in. and was a category 3 in the Northeast, category 4 in the Southeast, and category 2 in the Ohio Valley. The second storm had smaller snowfall totals and lower RSI categorical values. However, if the RSI was computed for both storms based on total snowfall for the 5–11 February 2010 period, the values would be much higher. The combined results indicate a large area of 30 in. of snowfall and greater across the mid-Atlantic region resulting in a category 5 for the Northeast and Ohio Valley and category 4 for the Southeast. In Baltimore, for example, it became difficult to dispose of snow during removal operations. Snow had to be dumped in city parks, school parking lots, and on the property of the Pimlico Race Course. The City of Baltimore also obtained a permit to dump snow into Baltimore Harbor (*Baltimore Sun*, 10 February 2010). The flexibility of the RSI allows for the accumulation of multiple snowstorms if necessary, which may be appropriate should two or more events occur very close in time to each other. This also allows for such events to be placed into historical context and future work could investigate such an analysis more thoroughly.

RSI users. NCDC began producing the RSI as an experimental product during the 2010/11 winter season. Since then it has been employed by a diverse group of public and private sector users. Businesses whose sales are related to snowfall, such as Honda Power Equipment, Raybestos Powertrain, Sears, and Kmart, have used the RSI to allocate products and resources in response to a storm. They also use the RSI to gain a historical sense of the magnitude of possible snowstorms within a particular region. Financial firms use the RSI to explain the fluctuations seen in key financial data during the winter. The RSI has also been used by economists at the Federal Reserve Board, the President's Council of Economic Advisors, and the Department of Commerce.

Federal, state, and county governments use the RSI for real-time assessment and hazard mitigation planning. Federal Emergency Management Agency (FEMA) uses the RSI to help anticipate resources needed after a storm, potential number of field applicants, field office locations, and staffing requirements. In addition, FEMA requires states and localities to create and maintain a Hazard Identification and Risk Assessment (HIRA). The RSI can aid emergency management officials developing an HIRA by identifying storms that have had the most impact in their areas. For example, the Virginia Department of Emergency Management has used the RSI as part of their mitigation planning. There are more than 400 current and historical snow observing locations in Virginia with some records going back to the late 1800s. This totals to nearly 5 million station day observations to filter through. NOAA's RSI now provides the capability to inspect and compare individual events (especially more significant regional events) and to do so in a very short timeframe (B. Crumpler, Virginia Department of Emergency Management, 2011, personal communication). It also helps inform emergency management agencies of what is possible in their region both in terms of typical and worst case storms. The National Weather Service has used the RSI to place storms into a historical perspective for the media. Researchers have used the area component of the RSI to study trends and variability of large snowstorms (Kunkel et al. 2013; Lawrimore et al. 2014).

SUMMARY. This paper has documented the need for a regional snowfall impact scale, summarized the development of the RSI, and given examples of how the RSI is used by various sectors of the economy. The RSI is a regional index that complements the NESIS (a quasi-national index) and the LWSS (a station-specific index). Thus, the RSI fits a need that is not available elsewhere. The regional nature of the index makes it possible to discriminate relative societal impacts between regions. The resulting RSI puts the societal impacts of snowstorms into a century-scale historical perspective. Therefore, the RSI helps support NCDC's mission to sustain monitoring, understand extremes, and integrate societal impacts into its products.

The RSI attempts to quantify societal impacts on a regional scale. To do so, several simplifying assumptions are made. Like NESIS, RSI uses population as a proxy for societal susceptibility. This is a reasonable

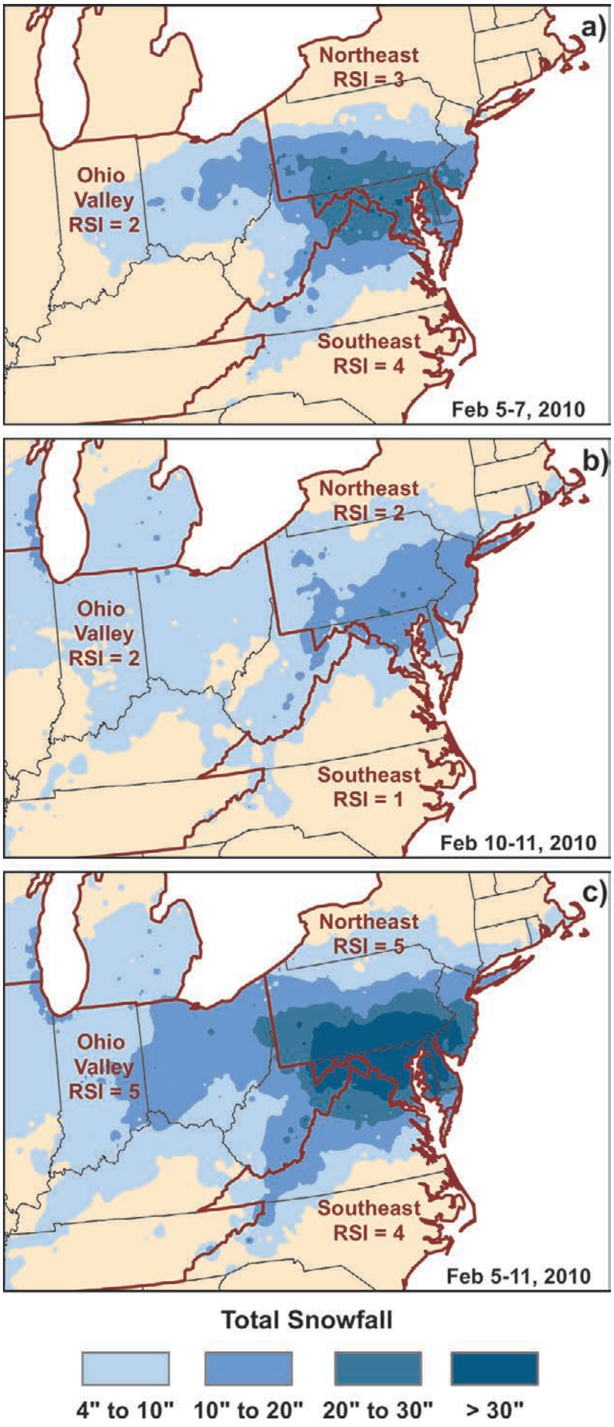


Fig. 8. (a) 5–7 Feb 2010 snowstorm, (b) 10–11 Feb 2010 snowstorm, and (c) a map of the storms combined and analyzed as one storm.

assumption but the relationship between societal impacts and population is likely more complicated. Another limitation of RSI is the lack of explicit temperature, snowfall intensity, freezing rain, and blizzard information. Other factors such as the time of day, time of year, or how well the storm was forecast are not included. Rooney (1967), Call (2005), and Cerruti and Decker (2011) have demonstrated the importance of these factors. However all of those studies investigated realized disruption on a local scale, typically within a city. Since RSI is regional, it would be difficult to integrate this disparate information into a single index.

Future work. RSI assumes the population (2010) is constant back to 1900, which allows the comparison of recent storms to past storms. While this is useful for many applications, it would be helpful to compute a version of RSI with time-dependent population. For example, storms in 1902 would use 1900 population data and storms in 1958 would use 1960 population data. This would give a sense of how the level of vulnerability has changed as a result of population changes over the last century. A future study is being planned to investigate this issue.

The RSI has been computed for almost 600 storms from 1900 to 2013. Besides the raw and categorical RSI values, the RSI output includes the area of snowfall above each of the four regional thresholds for each storm. These 36 time series [6 regions × (4 thresholds + 2 RSI values)] would be useful for an investigation of trends and variability of snowstorms. The authors plan to submit this work in a future article.

It would be useful to investigate the relationship between affected population and societal susceptibility in an objective manner. For example, Rooney (1967), Call (2005), and Cerruti and Decker (2011) used newspaper articles to quantify realized disruption for individual storms at specific cities. This is a challenging task for RSI because of its regional nature—one would need to look at many different newspapers for each storm. However, there may be other more easily accessible data sources available at the state or regional level on transportation, school closings, power outages, or some other measure of societal susceptibility. It would also be beneficial to investigate the effect of two storms occurring close to each other in time (as in Fig. 8). The results of such research could help inspire other sector-specific indices.

Availability. The RSI is computed operationally for category 1 or greater storms, usually a day after the storm has ended when the quality-controlled GHCN-D data are available to analysts at NCDC. RSI results, maps, background information, and storm-specific snowfall and population data are available at www.ncdc.noaa.gov/snow-and-ice/rsi/.

The snowfall and population data are grouped by region, snowstorm, and region-specific snowfall thresholds and can be freely downloaded. GIS shapefiles for all storms are also available for download: ftp://ftp.ncdc.noaa.gov/pub/data/surface-snow-products.

ACKNOWLEDGMENTS. The comments of Paul Kocin, Jeff Waldstreicher, Russell Vose, Brian Nelson, Michael Kruk, Karin Gleason, and two anonymous reviewers have markedly improved the content and appearance of this article. The authors thank the public and private sector users who provided examples of how the RSI is used in various sectors of the economy. Interns Anna Wilson, Clay Tabor, Leejah Rogers Ross, and Robert David quality controlled most of the snowstorms used in the analysis. Their internships were funded by the National Environmental Modeling and Analysis Center at the University of North Carolina at Asheville. Candice Boling, an intern funded by The Weather Channel, skillfully created the maps and also quality controlled snowstorms.

APPENDIX: VALUES OF MEAN AREA AND POPULATION.

The region- and threshold-specific values of mean snowfall area and mean population are given in Tables A1 and A2, respectively. These values serve two purposes: they calibrate the RSI to specific regions and they scale the observed area and population values to the same magnitude. Typically, the population values are two to three orders of magnitude larger than the area values (square miles). If these values were not scaled, the RSI would be dominated by population.

The calculation of mean area and population is done in the following manner:

1) Calculate the 48 cumulative areas and populations above each regional threshold in each region for each storm [(4 area + 4 population) × 6 regions].
2) Rank the values in each of these 48 groups.
3) Compute the mean value for the top 75 nonzero values in each of the 48 groups.

While the NESIS is calculated with the top 30 values from a set of Northeast storms occurring between 1950 and 2000, we have analyzed storms back to 1900, resulting in about 200 storms in the four snowy regions and about 150 storms in the South and Southeast regions. Since our datasets were much larger, we chose to use the top 75 values to compute the means. This is somewhat arbitrary but it ensures that relatively stable numbers are used to scale the snowfall area and population values used to calculate the RSI. Since we are using a relatively large number of storms to compute the mean, it is not necessary to compute new area and population means for each new storm.

The differences between these values and thresholds highlight the difference between regions in terms of size, population, and snowfall climatology. For example, the second threshold for the Northeast is 10 in. and its mean area and population above this threshold for the top 75 storms are 67,762 mi^2 and 27,785,225 people, respectively. In the northern Rockies and plains, the second threshold is 7 in. and its mean area and population above this threshold are 114,015 mi^2 and 1,096,858 people, respectively. These differences reflect the fact that the northern Rockies and plains receive less snow than the Northeast, are larger in area, and have a much smaller population.

Table A1. Region- and threshold-specific values of mean area (mi^2).

Region	Threshold 1	Threshold 2	Threshold 3	Threshold 4
Northeast	Area > 4 in.	Area > 10 in.	Area > 20 in.	Area > 30 in.
	149,228	72,318	9,254	1,152
Northern Rockies and plains	Area > 3 in.	Area > 7 in.	Area > 14 in.	Area > 21 in.
	258,882	107,222	21,356	4,968
Ohio Valley	Area > 3 in.	Area > 6 in.	Area > 12 in.	Area > 18 in.
	176,261	87,509	17,374	2,942
South	Area > 2 in.	Area > 5 in.	Area > 10 in.	Area > 15 in.
	195,408	79,952	14,500	2,423
Southeast	Area > 2 in.	Area > 5 in.	Area > 10 in.	Area > 15 in.
	100,885	52,267	15,975	4,013
Upper Midwest	Area > 3 in.	Area > 7 in.	Area > 14 in.	Area > 21 in.
	169,921	84,175	12,905	1,253

Table A2. Region- and threshold-specific values of mean population (2010 Census).

Region	Threshold 1	Threshold 2	Threshold 3	Threshold 4
Northeast	Area > 4 in.	Area > 10 in.	Area > 20 in.	Area > 30 in.
	51,553,600	27,571,556	2,886,427	171,896
Northern Rockies and plains	Area > 3 in.	Area > 7 in.	Area > 14 in.	Area > 21 in.
	2,683,146	1,281,985	205,524	40,393
Ohio Valley	Area > 3 in.	Area > 6 in.	Area > 12 in.	Area > 18 in.
	30,063,612	16,282,777	3,153,960	572,993
South	Area > 2 in.	Area > 5 in.	Area > 10 in.	Area > 15 in.
	12,180,470	4,334,897	724,039	63,426
Southeast	Area > 2 in.	Area > 5 in.	Area > 10 in.	Area > 15 in.
	19,372,985	10,077,690	3,132,697	873,775
Upper Midwest	Area > 3 in.	Area > 7 in.	Area > 14 in.	Area > 21 in.
	17,593,464	8,764,074	1,352,154	81,127

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