2015

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Mayes Boustead, Barbara E.; Hilberg, Steven D.; Shulski, Martha; and Hubbard, Kenneth, "The Accumulated Winter Season Severity Index (AWSSI)" (2015). *Papers in Natural Resources*. 584.
http://digitalcommons.unl.edu/natrespapers/584

VOLUME 54 JOURNAL OF APPLIED METEOROLOGY AND CLIMATOLOGY AUGUST 2015

The Accumulated Winter Season Severity Index (AWSSI)

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(Manuscript received 22 August 2014, in final form 6 March 2015)

ABSTRACT

The character of a winter can be defined by many of its features, including temperature averages and extremes, snowfall totals, snow depth, and the duration between onset and cessation of winter-weather conditions. The accumulated winter season severity index incorporates these elements into one site-specific value that defines the severity of a particular winter, especially when examined in the context of climatological values for that site. Thresholds of temperature, snowfall, and snow depth are assigned points that accumulate through the defined winter season; a parallel index uses temperature and precipitation to provide a snow proxy where snow data are unavailable or unreliable. The results can be analyzed like any other meteorological parameter to examine relationships to teleconnection patterns, determine trends, and create sector-specific applications, as well as to analyze an ongoing winter or any individual winter season to place its severity in context.

1. Introduction

How bad was this winter? Was it the worst on record? What other winters had a similar severity? Questions such as these are commonly asked of meteorologists and climatologists, but, to date, the current literature indicates a gap in the means to quantify the severity of a winter season to allow for objective comparison. Previous research has provided a means to quantify the intensity of hurricanes (Saffir–Simpson scale; Simpson 1974), tornadoes (Fujita and enhanced Fujita scales; Fujita 1971; Edwards et al. 2013), droughts (Drought Monitor; Svoboda et al. 2002), and winter storms (Zielinski 2002; Northeast snowfall impact scale; Kocin and Uccellini 2004; Cerruti and Decker 2011). The use of scaling allows comparison of event characteristics, as well as impacts that either are explicitly included as an index factor or are compared against the background of the scales that are more meteorological or measurable in nature. No such broadly applicable scaling is available for winter season severity, however. The accumulated winter season severity index (AWSSI, pronounced to rhyme with "bossy") was created to fill that gap.

Climatological studies of winter weather often have focused on event-specific quantities, such as individual storms. Branick (1997) utilized the National Climatic Data Center (NCDC) *Storm Data* publication to create a national "climatology" of winter-weather events, including snow and freezing precipitation, to characterize the frequency, areal coverage, and seasonal behavior of such events. Changnon et al. (2006) established a climatology of snowstorms that is based on station data from across the

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DOI: 10.1175/JAMC-D-14-0217.1

continental United States, and Changnon et al. (2008) connected the snowstorm climatology to a climatology of surface cyclone tracks east of the Rocky Mountains. Hirsch et al. (2001) more narrowly focused on a climatology of East Coast winter storms, whereas Market et al. (2002) narrowed the focus to thundersnow events. Schwartz and Schmidlin (2002) completed a climatology of blizzard events, providing an analysis of frequency, seasonality, and areal coverage of blizzard events in the continental United States over 41 winters. Whereas most of the winter event–based literature focuses on snow and freezing precipitation, the climatology of cold-air outbreaks is addressed by Portis et al. (2006) for select stations east of the Rocky Mountains, including frequency and trend analyses. Taken together, all of these elements could define the severity of a winter season, but they are incomplete and incompatible in both their temporal and areal coverage; even the collection of these studies neglects some winter impacts, such as the cumulative impact of winter duration, the occurrence of lighter snow events, and the effects of subfreezing temperatures.

A few studies have addressed a seasonal scale of winter, but many of those were specific to one sector or to a particular region, with results that may not extrapolate to wider use in other applications or in other climate regimes. Attempts as early as Angot (1914) focused on characterizing winter severity by cumulative freezing degree days, or the sum of minimum temperature departures below 0°C, for the purpose of comparing cities such as Washington, D.C., and Paris, France (Abbe 1914). Although effective for comparing temperature behavior among sites, this method neglects any contribution of winter severity due to precipitation, and it also would fail to characterize the daytime temperature severity. Other early studies (Hellmann 1918; Henry 1925) followed a similar method that was based on freezing degree days for average daily temperatures. The temperature-based description also was adapted by Assel (1980) to characterize winter severity in the Great Lakes region, using mean temperature freezing degree days, but it faces limitations that are similar to those of the early works.

Winter classification studies have been conducted specific to particular applications. One cluster of applications has centered on the transportation industry. Gustavsson (1996), for example, evaluated three different winter indices to determine their relationship with road-salting activity; the study suggested that a successful index would match treatment-action thresholds to weather parameters that cause slippery roads, but it ultimately determined that none of the three indices successfully matched action thresholds to treatment action. The Hulme (1982) index included road surface temperature, days with snow on the ground, and frost days while noting that temperature and snowfall are perceived by individuals to best characterize a winter; in addition, it was developed to be a seasonal index and not to be capable of daily index contribution. Parameters included in these indices are specific to road impacts, and several include information that is not readily available in daily climatological data, such as coincidence of relative humidity and temperature thresholds, as well as the observed drifting snow. Another sector interested in winter season severity is wildlife management. Schummer et al. (2010) examined winter parameters in Missouri to correspond to dabbling-duck abundance. The index produced in that study was the weather severity index and included temperature (focusing on daily average temperature and consecutive days with an average daily temperature below freezing) and snow depth (focusing on consecutive days of snow cover of 2.54 cm or greater). The duration of these occurrences had the greatest impact on the ability of ducks to feed and rest. These sector-specific indices can be used by those sectors with some success, but their applicability to other sectors is ultimately limited. Therefore, the need still exists for an index of winter season severity that is more broadly applicable and that uses widely available climatological data.

The intent of AWSSI is to use widely available daily meteorological parameters to quantify the severity of a winter season, cumulative from the onset of winter, as defined in the study, to winter's termination. AWSSI is calculated with a temperature component and a snow component, allowing an end-of-season total AWSSI to represent the severity of a season but also allowing a daily running calculation through a winter to track its severity. The temperature component uses maximum and minimum temperature data and is fairly straightforward. By contrast, the snow (precipitation) component is a little more complex. Snowfall and snow-depth data are not available through the entire period of record at most stations, and, even where available, the quality can be suspect (Robinson 1989; Ryan et al. 2008; Doesken and Robinson 2009). Precipitation measurements during snowfall also can contain errors—gauge undercatch of snowfall is a known concern in precipitation measurements (Groisman and Legates 1994; Rasmussen et al. 2012). To address periods with no or unreliable snow data, the AWSSI was created in two forms: one that uses snow data and one that uses precipitation data, with snow information ''proxied'' on the basis of precipitation amounts and temperatures. Both snow and precipitation measurements contain some errors; thus, both the snow and precipitation versions of AWSSI should be applied with appropriate caution. For further discussion of snowfall and snow-depth measurement and estimation challenges, see Boustead (2014).

Several attempts have been made to estimate snowfall, or at least the precipitation equivalent of snow, on the basis of temperature and precipitation observations. The National Weather Service (NWS) published a table to estimate snowfall from temperature, but it is merely a chart of ratios that increase steadily from higher to lower temperatures (NWS 1996), likely neglecting the jump in snowfall ratio for dendritic snow growth at favored temperatures. Trnka et al. (2010) used an average daily temperature of 0°C or less to determine when snow falls and then used thresholds of minimum temperature to further refine the fraction of precipitation that accumulates as snowfall. Kienzle (2008) included a method that is similar to that of Trnka et al. (2010), but Kienzle calculated a threshold temperature at which 50% of precipitation falls as snow and 50% falls as rain. The calculations in this approach were considered to be too time consuming for widespread use across a high number of stations and continual updating. Like Trnka et al. (2010), Kienzle (2008) ultimately provided liquid equivalent of snowfall as the output, rather than an estimate of snowfall. Byun et al. (2008) created a snowfall ratio that is based on regression analysis of observed temperature, precipitation, and snowfall, but the method requires 3-hourly precipitation rate, which prevents the use of daily observational data. Their analysis concluded that the relationship between snow ratio and temperature for a sample of stations in South Korea was stronger at the surface than at 925, 850, and 500 hPa, supporting the notion that surface temperatures affect snow wetness more than temperatures at other levels do. Ye et al. (2013) established probabilities of rain or snow that are based on surface temperature and dewpoint temperature thresholds but also included data that are not available when using a daily-data perspective. Their results did indicate some reliability for using temperature alone, without dewpoint temperatures, although dewpoint temperatures did provide additional clarity. Fisk (2008) created a multivariate regression analysis of snowfall at Minneapolis–St. Paul, Minnesota, that used daily temperature and precipitation records, assigning five groups on the basis of "cold" or "mild" temperatures and "light," "moderate," or "heavy" precipitation. This method was found to be most applicable to this study, and its findings were adjusted and used as described in section 3c.

Snow-depth determinations also are complex. Changes in snow depth depend on the character of the snow, temperature, wind, humidity, land use, solar radiation, and precipitation. Since the AWSSI uses only daily temperature and precipitation (snowfall), any calculations of snow depth, when measurements are not available, are limited to being estimated or calculated from those variables. A number of methods to estimate or calculate snowmelt do exist. The U.S. Department of Agriculture (USDA) included a degree-day method in its directives to determine snowpack ablation (USDA 2004), using the difference between the average daily temperature and a base melt temperature of 0°C, scaled by a melt-rate factor, to determine total daily melt. A seasonal snow-cover calculation by Motoyama (1990) used the same degree-day formula as the USDA did and then added a densification factor, calculating snow depth by means of the snow density and water equivalence profiles. In this study, the USDA degree-day calculation was the basis for calculating snow depth, with additional formulation addressed in section 3c.

Once calculated, AWSSI provides information for investigating the historical context of a winter season, as well as site-to-site comparisons. Within the period of record of one station, quantities such as averages, percentiles, and extremes can be calculated to establish a baseline with which individual seasons can be compared. AWSSI can be compared among stations to assess the severity from one station to another. The station-based AWSSI also can be normalized by the mean at that station, and the percentile thresholds at a station can be assessed, allowing a comparison of normalized AWSSI to assess the relative severity at those stations.

AWSSI information can be used as a baseline with which innumerable impact-based data can be examined. The range of possibilities includes comparisons with car accidents or other transportation factors, home heating costs or other energy expenditures, number of school-closure days or other effects on education, and number of mental- or physical-health treatments or other health impacts, just to name a few examples. In addition to examining the total AWSSI, users of AWSSI information can pull apart the index into its temperature and snow/precipitation components in any number of ways to meet their goals of assessing the impacts of winter severity on their fields of interest.

Data sources are reviewed in section 2, and the method of calculation is described in section 3. Section 4 includes a review of the results, and potential applications are discussed in section 5. A concluding summary follows in section 6.

2. Data

Daily maximum, minimum, and average temperature, precipitation, snowfall, and snow-depth data were taken from the Applied Climate Information System (ACIS) database (Hubbard et al. 2004). Use of ACIS data gives NWS weather forecast offices the ability to replicate this study and to produce AWSSI results for any sites that have daily data available in ACIS. In this study, single stations and select threaded sites (see online at http://threadex.rcc-acis.org/) were analyzed for a period from 1950 to 2014, with the winters from 1950/51 through

2012/13 being analyzed to develop an AWSSI climatology. We determined that the slight differences between the widely available ACIS data and the homogenized station data that are available from NCDC were likely to be too small to significantly affect the AWSSI threshold-based calculation. Threaded data were not used in the initial analysis of AWSSI, but we believe that AWSSI would be useful for threaded sites to provide a longer historical analysis of AWSSI behavior. For that reason, we have included a small sample of threaded sites. That being said, we feel that caution should be used when analyzing trends or sample statistics that are based on threaded data.

Winter seasons with missing snow or temperature data were excluded if the missing data were estimated to contribute 5.0% or more of the total AWSSI for that season. Estimates were completed for each site by comparison with nearby observations for the date in question, as well as with the values of the surrounding days, to determine the most likely threshold of temperature or snow for the missing data. If the missing data affected only the snow accumulation (as described in section 3b) but would not affect the temperature accumulation by changing the beginning or end dates of the season (as described in section 3a), then the total and snow components of AWSSI were disregarded while the temperature component was retained for analysis. In particular, a number of sites had missing snowfall and snow-depth data for extended periods—sometimes entire seasons—during the mid- to late 1990s and through the 2000s, necessitating the omission of the total and snow component, as well as often the temperature component. In addition, ACIS draws data from the Global Historical Climate Network, which sets to missing any days on which snow-depth values increase without a corresponding amount of snowfall. Snow depth is measured at 1200 UTC, however, whereas snow may have fallen after 1200 UTC on the previous day. As a result, a majority of sites used in the study have at least one instance of one missing snowfall and two missing snow-depth observations. These missing data alone were not usually enough to require omission of an entire season, but they do have an impact on the score for that year. Addressing these gaps is among the motivations for deriving a version of AWSSI that does not use snowfall or snow-depth data, which will be discussed in section 3c.

Because the scale is expected to be used in real time by operational forecasters working with daily observations, the scale was designed to use the standard reporting units in the United States: degrees Fahrenheit for temperature (°F = 1.8 × °C + 32°) and inches for snowfall and snow depth (1 in. = 2.54 cm). All thresholds discussed in the study will therefore use those units.

Sites included in the analysis are listed in Table 1. The selected sites contained relatively complete periods of

TABLE 1. Sites included in the AWSSI analysis (ID indicates station abbreviation), along with their respective mean AWSSI and number of missing years of total AWSSI for the analysis period. Sites marked with an asterisk are threaded sites.

City, state	ID	Avg AWSSI	No. missing
Aberdeen, SD	ABR	1265	1
Albany, NY	ALB	785	0
Atlanta, GA	ATL	65	0
Bismarck, ND	BIS	1348	2
Boise, ID	BOI	312	0
Boston (Logan), MA	BOS	417	11
Buffalo, NY	BUF	813	0
Chicago, IL*	CHIthr	602	8
Cleveland, OH	CLE	585	0
Cheyenne, WY	CYS	725	0
Dubuque, IA	DBQ	916	8
Washington (Reagan National), DC	DCA	170	0
Dodge City, KS	DDC	383	0
Denver (Stapleton), CO	DEN	614	0
Dallas–Fort Worth, TX*	DFWthr	57	1
Duluth, MN	DLH	1986	0
Des Moines, IA	DSM	722	1
Detroit (Metro), MI*	DTWthr	574	0
Erie, PA	ERI	707	7
Evansville, IN	EVV	258	0
Fargo, ND	FAR	1567	7
Helena, MT	HLN	907	8
Huron, SD	HON	1116	5
Havre, MT*	HVRthr	1171	5
Indianapolis, IN	IND	427	0
International Falls, MN	INL	2247	2
Lansing, MI	LAN	790	12
North Platte, NE	LBF	711	0
New York (LaGuardia), NY	LGA	236	0
La Crosse, WI	LSE	1016	4
Milwaukee, WI	MKE	774	0
Moline, IL	MLI	655	0
Madison, WI	MSN	946	0
Minneapolis–St. Paul, MN	MSP	1219	12
New York (Central Park), NY*	NYCthr	258	9
Oklahoma City, OK	OKC	164	0
Omaha, NE	OMA	650	4
Paducah, KY	PAH	203	1
Philadelphia, PA*	PHLthr	241	1
Pierre, SD	PIR	939	10
Pittsburgh, PA	PIT	504	1
Portland, ME	PWM	924	2
Rapid City, SD	RAP	803	5
Rochester, NY	ROC	816	0
Louisville, KY	SDF	232	1
Springfield, MO	SGF	294	1
Salt Lake City, UT	SLC	504	0
Springfield, IL	SPI	441	1
Sault Ste. Marie, MI	SSM	1880	2
St. Louis (Lambert), MO	STL	319	0
Toledo, OH	TOL	587	12
Urbana, IL	URB	484	0

record at least from 1950 to 2013, and many were selected because their period of record extends back into at least the 1880s, to allow for subsequent historical analysis. Many sites were from a region of interest in the Midwest and central to the northern Great Plains, but a few sites were selected from climatological datasets that are from outside this primary study area to examine the utility of AWSSI in multiple climate regimes. For each site, the average AWSSI from 1950 to 2013 is listed, as well as the number of missing years.

3. Calculating AWSSI

AWSSI was conceived to be a site-specific threshold-based score of the severity of a winter season, in which points are acquired daily on the basis of reaching thresholds of maximum and minimum temperatures, snowfall, and snow depth. These daily points are tallied through the winter season, with a final ‘‘score’’ that is representative of the severity and duration of that winter. The annual totals then can be investigated as a time series, compared with the totals of other sites, and analyzed statistically to create a description of one winter or a series of winters. Critical to defining AWSSI is defining the beginning and end of the AWSSI accumulation period.

a. *Defining ‘‘winter’’*

Even among meteorologists and climatologists, the definition of ‘‘winter’’ is not necessarily standard. For seasonal meteorological and climatological analyses, months are divided such that winter comprises the months of December–February. Astronomical winter, however, is determined by the duration from winter solstice to vernal equinox, which can vary slightly from year to year., Informal polling of Community Collaborative Rain, Hail, and Snow (CoCoRaHS) observers around the country revealed that the definition of winter onset varies substantially among individuals; definitions often included sensible weather conditions such as the first snowfall, the first freezing day, or the first frost, as well as highly subjective conditions such as the use of salt on roads or the need for a winter coat. As one might expect, perception of winter onset varied on the basis of location, as well.

After collecting user input and evaluating objective and measurable thresholds of winter, we determined that a combination of sensible weather conditions and calendar definition would best define a winter season, to allow the impact of a long winter season to add points to the score while acknowledging that winter season has a calendar-based definition. In this study, the definition of winter onset is when the first of three conditions is met: 1) daily maximum temperature ≤ 32°F (0°C), 2) daily snowfall ≥ 0.1 in. (0.25 cm), or 3) it is 1 December. Once one of these conditions is reached, AWSSI begins accumulating on the basis of the criteria described below in section 3b.

As with winter onset, the cessation of winter also has both subjective and objective definitions that are based on calendar month, vernal equinox, or sensible weather conditions. In this study, the end of winter is defined as the last of the weather conditions that defined its onset, with one addition to account for the melting of lingering snowpack, and with a calendar-based fallback date. Thus, the definition of winter cessation is when the last of the following four conditions is met: 1) daily maximum temperature ≤ 32°F (0°C) no longer occurs, 2) daily snowfall ≥ 0.1 in. (0.25 cm) no longer occurs, 3) daily snow depth ≥ 1.0 in. (2.5 cm) is no longer observed, or 4) it is 1 March.

Once the last of these criteria has occurred, AWSSI accumulation ceases. Note that in real time it is not possible to assume that a winter season has ended; rather, the individual site must be analyzed in retrospect well after the season has realistically ended as based on occurrence of past extremes or the likelihood of future extremes to exceed winter thresholds. For example, for Omaha, Nebraska (OMA), it is safe to presume that the winter accumulation has ceased by 1 June, but because winter conditions have occurred into early May in previous years, it may not be safe to declare a winter ‘‘done’’ on 1 May.

Some winter climatologies are more prone to early or late-season winter-weather events that would prolong the winter season in calculations, and one alternative that was considered was to establish a duration beyond which an event is considered to be outside winter and would not contribute to the AWSSI accumulation. Early and late-season cold-air and snow events often have significant impacts on sectors such as transportation, agriculture, and education, however, and omitting those events would subsequently render AWSSI less representative of the impact of winter in a given year. Since little accumulation of AWSSI would occur in a gap between more consistent winter conditions and an early or late-season event, the impact of the extended duration on the overall AWSSI accumulation for the season would be minimal.

b. *AWSSI calculation*

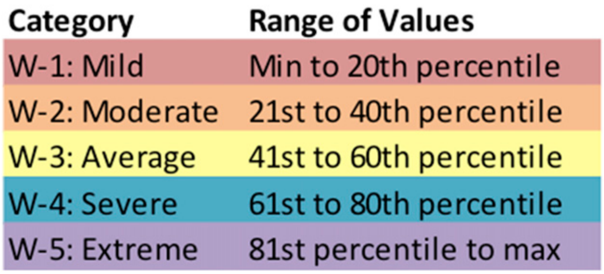
The daily total AWSSI point accumulation is determined on the basis of thresholds of maximum and minimum temperature, snowfall, and snow depth, which are listed in Table 2. Point thresholds were created to give greater weight to extreme or rare occurrences, which would have a higher impact, although the thresholds are admittedly somewhat arbitrary. Trace snowfall and snow-depth measurements were treated as zeroes and did not accumulate points. The point total for snowfall was designed such that a snowfall of 6 in. would have the same

TABLE 2. Point contributions to daily AWSSI as based on thresholds of daily maximum and minimum temperature, snowfall, and snow depth.

	Temperature (°F)		Snow (in.)	
Points	Max	Min	Fall	Depth
1	25–32	25–32	0.1–0.9	1
2	20–24	20–24	1.0–1.9	2
3	15–19	15–19	2.0–2.9	3
4	10–14	10–14	3.0–3.9	4–5
5	5–9	5–9	—	6–8
6	0–4	0–4	4.0–4.9	9–11
7	From −1 to −5	From −1 to −5	5.0–5.9	12–14
8	From −6 to −10	From −6 to −10	—	15–17
9	From −11 to −15	From −11 to −15	6.0–6.9	18–23
10	From −16 to −20	From −16 to −20	7.0–7.0	24–35
11	—	From −20 to −25	—	—
12	—	—	8.0–8.9	—
13	—	—	9.0–9.9	—
14	—	—	10.0–11.9	—
15	<−20	From −26 to −35	—	≥36
18	—	—	12.0–14.9	—
20	—	<−35	—	—
22	—	—	15.0–17.9	—
26	—	—	18.0–23.9	—
36	—	—	24.0–29.9	—
45	—	—	≥30.0	—

point total as a snowfall of 2 in. plus a snowfall of 4 in., thus accounting for snowfall events that cross calendar days. Because the temperature thresholds are the same for both maximum and minimum temperature, the temperature accumulation is dominated by minimum temperatures.

The points assigned in each category are summed for the calendar day into the categories of temperature, snowfall, and total AWSSI. For example, a day with a maximum temperature of 24°F (2 points), a minimum temperature of 11°F (4 points), new snowfall of 2.5 in. (3 points), and snow depth of 5 in. (4 points) would have a temperature score of 6 points, a snowfall score of 7 points, and total daily AWSSI of 13 points. The daily point totals then are summed through the winter season, creating a cumulative point total through the season. Calculations were completed for each site in the study using a Perl programming-language script, with text output imported into a spreadsheet for statistical analysis and graphical display.



Category	Range of Values
W-1: Mild	Min to 20th percentile
W-2: Moderate	21st to 40th percentile
W-3: Average	41st to 60th percentile
W-4: Severe	61st to 80th percentile
W-5: Extreme	81st percentile to max

FIG. 1. Category labels, descriptions, percentiles, and color coding for AWSSI.

Sensitivity testing on the numerical values assigned to the temperature and snow thresholds indicated little sensitivity to those values. Broadening the temperature point thresholds, for example, changed the AWSSI for all years at a site in the same direction. The largest changes in the AWSSI occurred during severe-winter years, with smaller changes in mild years. Ultimately, though, the rankings of winters from most severe to mildest changed little, with some of the distinction of years with close scores being lost by broadening the categories. Similar results were noted for other sensitivity tests, with minor changes that had little impact on the calculated severity or ranking of winters.

In past years, some NWS observers have reported hail as an accumulation of snow/frozen precipitation. These observations were able to trip AWSSI to begin accumulation well ahead of wintry conditions or to extend AWSSI accumulation well into summer. To remove hail contamination, AWSSI was restricted from accumulating any snowfall points if the minimum temperature was greater than 40°F (4.4°C).

Give the combination of weather-based and calendar-based accumulation, with point accumulations that begin with objective criteria, AWSSI should be useful as an indicator of winter severity across multiple climate regimes. Cooler climates with longer duration of winter conditions will have higher accumulations that start earlier, end later, and accumulate more substantially in the midst of winter. Winter seasons in Minnesota, for example, would be expected to have higher AWSSI, on average, than would winters in Kansas. Milder climates would be more likely to have a calendar-based accumulation season, with low accumulations that mainly result from minimum temperatures that fall below freezing, along with rare snow events. One can compare AWSSI values to compare the severity of winter at one site with that of another, or one year with another, using either the calculated AWSSI values or by normalizing the AWSSI. Thus, one could compare a normalized AWSSI for a given winter in Omaha with the same winter in Minneapolis–St. Paul (MSP), to determine which site had a more severe winter relative to its own climatology.

Because numbers alone may not provide a helpful description of the characteristics of a winter, we have created a five-tiered category system that is based on percentiles; these are listed in Fig. 1. Categories are delineated at 20th-percentile intervals, with both a scaling number (from W-1 to W-5) and word descriptors (mild, moderate, average, severe, or extreme) to describe the severity, similar to indices used for drought and tornadoes. Users of the index can add the category label as a descriptive tag to the numerical value of AWSSI to provide both a value and context to that value.

AWSSI does have limitations, as is the case with any objective index of a weather or climate phenomenon. It does not explicitly include points for freezing rain, which is reported as liquid precipitation and would not trip the AWSSI snowfall thresholds, nor does it account for mixed precipitation explicitly, which can have impacts that are disproportionate to the recorded snow total. Freezing rain certainly can have a substantial impact on life and property, but a national repository of freezing-rain events does not exist, and past studies have included limited spatial and temporal coverage (e.g., Call 2010; Changnon and Creech 2003; Rauber et al. 2001). Also, because daily climate records are used, wind is excluded from consideration in AWSSI, despite its connection to both wind chills and blowing snow. Wind has a pronounced impact on visibility (e.g., Huang et al. 2008; Li and Pomeroy 1997), road conditions as a result of blowing and drifting snow (e.g., Carmichael et al. 2004; Shulski and Seeley 2004), and human and animal health and comfort (e.g., Osczevski and Bluestein 2005; Mader 2003), but, for the sake of simplicity and applicability to observational networks that do not contain wind data (such as the Cooperative Observer Network), it was omitted in this study. The one climate regime in which AWSSI would not be expected to work well is a climatology that experiences year-round winter conditions such as a persistent snowpack or maximum temperatures below freezing in all months.

c. *Precipitation-based AWSSI calculation*

The precipitation-based AWSSI (pAWSSI) requires a calculation algorithm to convert precipitation data to a snowfall proxy, or a representation of the character of snowfall and wintry precipitation through the season, using daily temperature data. This algorithm was based strongly on that of Fisk (2008), with a few adjustments to better represent heavy-precipitation events and milder climatologies. Fisk (2008) delineated categories of temperatures and precipitation using trial-and-error linear regression on data from October 1964 through April 2007 for MSP, excluding data from late 2000 through early 2004, when official observations were moved from the Minneapolis–St. Paul airport to the NWS forecast office in Chanhassen, Minnesota. In Fisk (2008) and in this study, the "cold" classification encompassed daily average temperatures of 27.5°F (−2.5°C) or lower, and the "mild" category encompassed temperatures of 28°F (−2.2°C) or higher. Precipitation was divided into three categories: light precipitation of 0.01–0.06 in. (0.25–1.52 mm), moderate precipitation of 0.07–0.42 in. (1.78–10.67 mm), and heavy precipitation of 0.43 in. (10.92 mm) or greater. The Fisk (2008) original calculations were modified slightly to fit a wider range of climatologies, because the original version produced too much snowfall for heavy/cold conditions. We now give the original Fisk (2008) daily proxy snowfall (SF; in.) calculations for each of five combinations of temperature and precipitation classifications. For light/cold,

$$\mathrm{SF} = 0.259 + 15.413P - 0.007(T_{\mathrm{avg}} + 20), \tag{1}$$

where P is the daily precipitation (in.) and T_{avg} is the daily average temperature (°F). For moderate/cold,

$$\mathrm{SF} = 2.081 + 12.331P - 0.031(T_{\mathrm{avg}} + 20) - 0.186(T_{\mathrm{max}} - T_{\mathrm{min}})^{1/2}. \tag{2}$$

For heavy/cold,

$$\mathrm{SF} = 19.237 + 7.266P - 0.346(T_{\mathrm{avg}} + 20) - 0.245(T_{\mathrm{max}} - T_{\mathrm{min}}), \tag{3}$$

where T_{max} is the daily maximum temperature (°F) and T_{min} is the daily minimum temperature (°F). For light/mild,

$$\mathrm{SF} = 0.551 + 5.017P - 0.014T_{\mathrm{max}}. \tag{4}$$

For moderate–heavy/mild,

$$\mathrm{SF} = -3.563 + 4.346P^{1/2} + 3969.927T_{\mathrm{max}}^{-2}. \tag{5}$$

Although fitted well to MSP, the heavy/cold formulation overestimated snowfall across the majority of sites in the study, especially for very heavy amounts of snowfall. To correct this problem, we subdivided the category into additional categories of precipitation amounts: "heavy-1," from 0.43 to 1.49 in. (10.92–37.85 mm) and "heavy-2," at 1.50 in. (38.10 mm) or greater. The average of the errors across all stations was used for each precipitation cluster to define the adjustment that was applied to the measurements. For heavy-1/cold and heavy-2/cold, respectively, the adjusted formulas for the heavy/cold category are

$$\mathrm{SF} = 19.237 + 7.266P - 0.346(T_{\mathrm{avg}} + 20) - 0.245(T_{\mathrm{max}} - T_{\mathrm{min}}) - 3.3 \quad \text{and} \tag{6}$$

$$\mathrm{SF} = 19.237 + 7.266P - 0.346(T_{\mathrm{avg}} + 20) - 0.245(T_{\mathrm{max}} - T_{\mathrm{min}}) - 3.8. \tag{7}$$

Snowfall was overestimated in the milder climatologies in the moderate–heavy/mild formulation, but an investigation showed that several of these instances

TABLE 3. Seasonally varying values of T_b and C_m used to calculate pAWSSI.

Period	T_b	C_m
Up to 1 Dec	32	0.30
1 Dec–15 Jan	25	0.25
16 Jan–9 Feb	23	0.25
10 Feb–6 Mar	30	0.25
7 Mar–end	30	0.30

included ice storms that were occurring under these conditions. Not every one of the "false hits" of a snowfall accumulation under the moderate–heavy/mild criteria corresponded to a wintry mix of precipitation, of course. At Urbana, Illinois (URB), of seven events that had "false" snow accumulations under the moderate–heavy/mild criteria, two of the events were associated with major ice storms, two were associated with thunderstorms, and the remaining three were cold-rain events. The impact of the ice events was deemed to be high enough to be worth capturing even with a few false snow hits in the mild climate regimes. Bias on moderate–heavy/mild was low in cold climate regimes. Therefore, the moderate–heavy/mild formula was left unadjusted.

Stations in the southern Great Lakes with milder temperatures but moderate to heavy snow that was due to lake-effect snowfall (defined more clearly in section 4a below), such as Buffalo, New York (BUF), were noted to have a negative snow bias through all regimes when the Fisk (2008) formulation was used. The biases were present even before the adjustments were applied across all sites and increased after the adjustments. The station climatologies are still self-consistent, in that the relative severity of one station through its historical period of record will still be meaningful, but the absolute severity should be used with caution when compared with other stations, particularly those that are located outside lake-effect zones. The causes for the negative bias, and potential solutions, are left to be explored in future studies.

Snow depth was calculated based on the degree-day method used in USDA (2004). Using the degree-day method, daily snowpack ablation can be calculated as

$$M = C_m(T_a - T_b), \tag{8}$$

where the "melting" factor M is proportional to the difference between the daily average temperature T_a and a base temperature T_b (°F; in this case, 32°F), as well

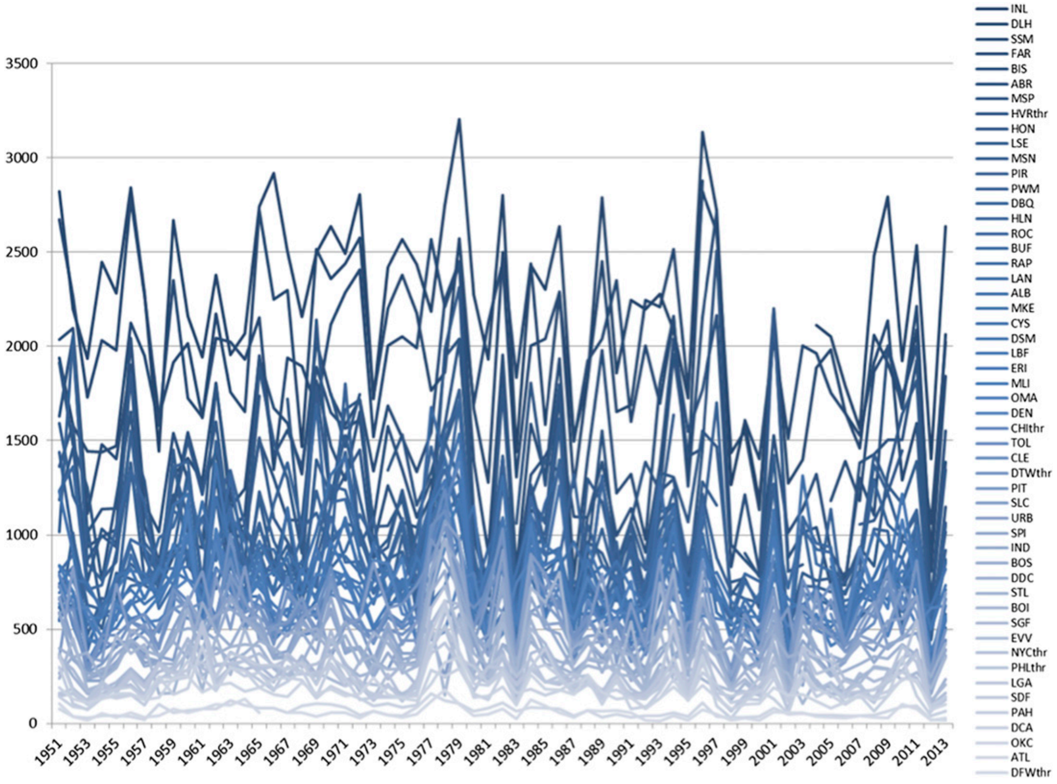


FIG. 2. AWSSI total accumulation for each winter from 1950/51 to 2012/13 (excluding years with missing data) for all sites.

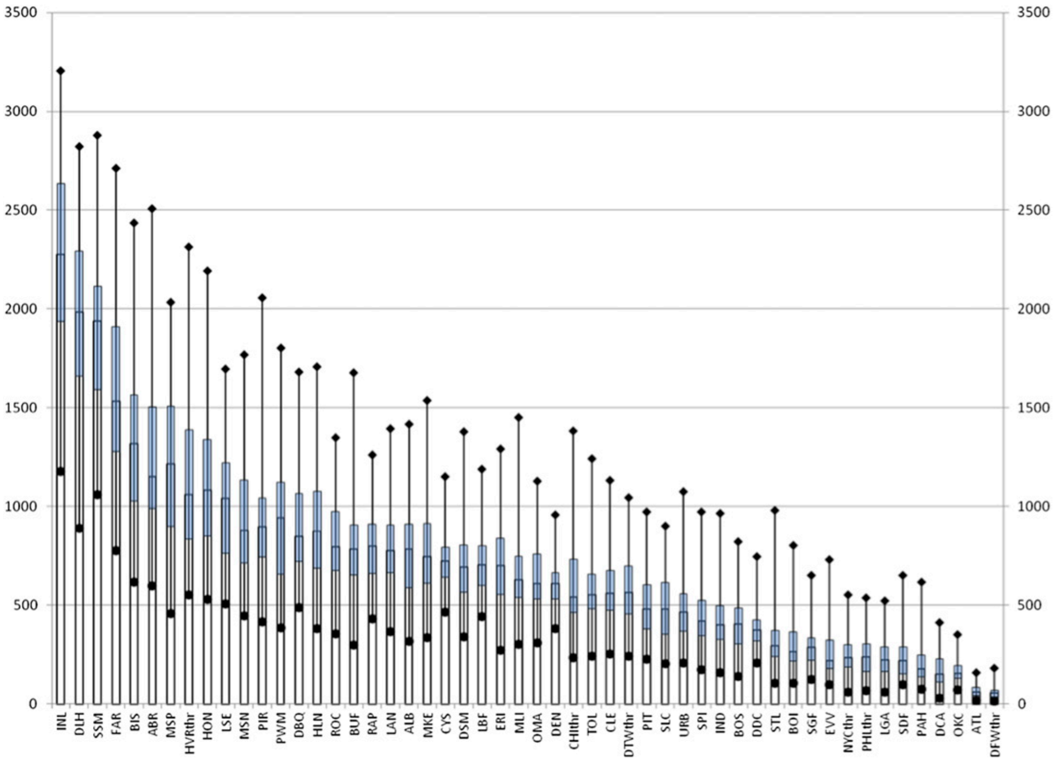


FIG. 3. Box-and-whiskers diagram of AWSSI through the analysis period from 1950/51 to 2012/13 (excluding years with missing data) for each site. Middle line is the median, blue box includes the 25th–75th percentiles, bottom dot is the minimum value, and top dot is the maximum value. Sites are arranged in order from highest mean to lowest mean.

as to a degree-day coefficient C_m (°F^{-1}). Both T_b and C_m can vary seasonally and by location; in this study, the same values are applied across all locations, with T_b and C_m both varying seasonally with changes in the length of daylight and the solar angle (Table 3).

Both the existing snowpack and the daily snowfall are subject to an adjustment for decay. The compaction factor adjustment C_f (which is based on the formulation created by E. Mahoney and the NWS Buffalo Weather Forecast Office, as documented by the Iowa Environmental Mesonet online at http://www.meteor.iastate.edu/~ckarsten/bufkit/compaction.html, and then is adjusted empirically) is given by

$$C_f = \exp(-0.08 \times 0.2^{1/2}). \tag{9}$$

When added to or subtracted from the previous day, the snow-depth calculation is

$$\mathrm{SD}_n = \mathrm{SD}_{n-1} C_f - M + \mathrm{SF}_n C_f , \tag{10}$$

where SD_n is the snow depth on the current day, SD_{n-1} is the snow depth on the previous day, and SF_n is the snowfall on the current day. The formulation is not able to recognize differences in snowpack ablation that are due to factors such as minutes of sunshine, rain falling on snow, ice crusting or other crystal-type differences, and winds. That said, it provides a reasonable and consistent estimate of snow depth that can be consistently applied across all sites and across all time periods for which snow-depth measurements are unavailable or unreliable.

In calculating pAWSSI, the triggers to start and cease accumulation and the temperature and snow-proxy thresholds are the same as in AWSSI, using the snow proxy as a substitute for snowfall and the snow-depth estimation as a substitute for snow depth. In climate regimes that are dominated by snowfall in the winter, such as the original site of interest of the Fisk (2008) study in Minneapolis–St. Paul, the two indices should be very similar. In locations that experience winter precipitation in mixed or ice phases rather than snow, the snow proxy actually may be expected to exceed the snowfall observations because it detects wintry precipitation events that were undetected by snowfall observations. In all locations, the prevalence of precipitation data should allow gaps from snow observations to be filled, and the more reliable history of precipitation measurement techniques

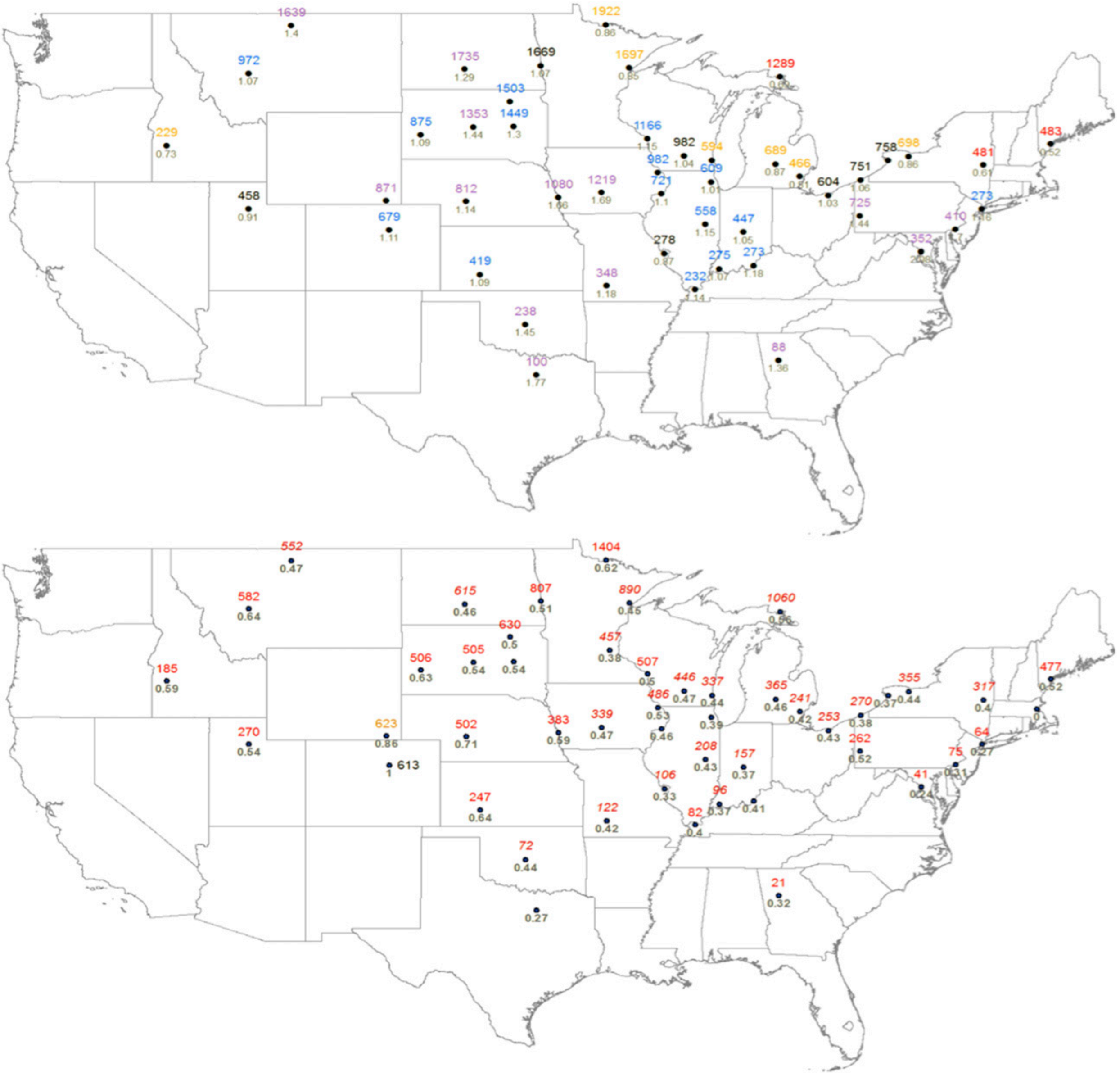


FIG. 4. AWSSI (top number) and normalized AWSSI (bottom number) for the winters of (top) 2009/10 and (bottom) 2011/12, with AWSSI values color coded by category per Fig. 1. Italicized values are record lows at that site.

should allow the snow proxy to correct some biases that are present in historical snow measurements while temperature observations will be mostly unaffected. Keeping in mind that the beginning and end of winter include snowfall and snow-depth thresholds, it is possible that these beginning and end dates may differ between indices on the basis of how well pAWSSI captures early- and late-season snow events; this could have a downstream impact on the total winter accumulation, because dates that were included in one database may be excluded from the other and thus not allow contribution from minimum temperatures that fall within accumulation thresholds.

4. Results

a. AWSSI

AWSSI was calculated at all sites listed in Table 1, for all winters from 1950/51 through 2012/13, excluding those winters with missing data (Fig. 2). The temperature component of AWSSI (referred to as "AWSSI-temperature") and the snowfall and snow-depth component ("AWSSI-snow") also were calculated for each year at each site. At each site, for the AWSSI totals through the analysis period, statistics such as mean, median, maximum, minimum, percentile thresholds, and standard deviations

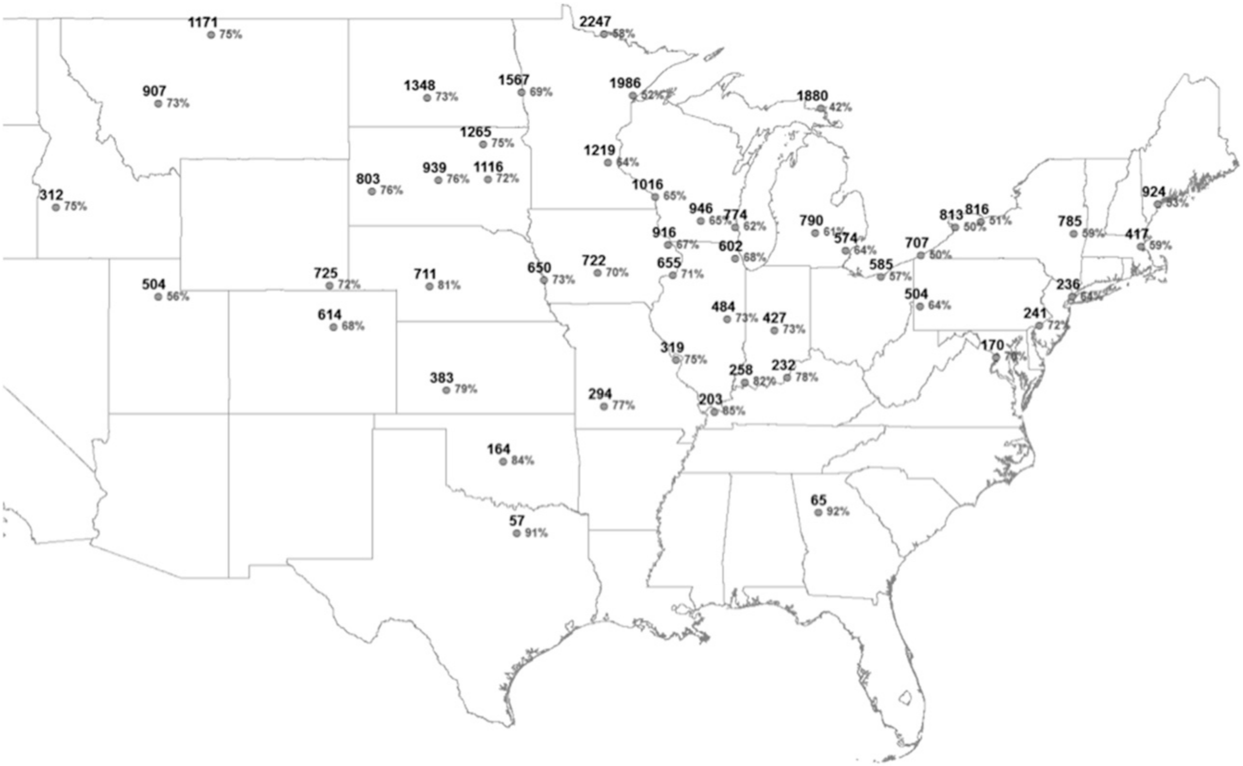


FIG. 5. Average AWSSI for the analysis period (from 1950/51 through 2012/13) at each site, with percent contribution from the temperature component.

were determined to provide a description of the character of winter seasons at each site. Figure 3 includes the median, maximum, minimum, 25th percentile, and 75th percentile for each site, with sites in order from highest mean to lowest.

Winter severity is site specific, relative to the climatology of the region and the experiences of its citizens. A total AWSSI of 600 would be of near-average severity in OMA, would be the record mildest in Fargo, North Dakota (FAR), and would be the record extreme of severity at Reagan National Airport in Washington, D.C. (DCA). Normalizing AWSSI at each site by its mean allows for comparison of relative severity among different sites for the same season. In Fig. 4, the AWSSI and normalized AWSSI for each site are displayed for the recent winters of 2009/10 and 2011/12, which had widespread severe conditions and widespread mild conditions, respectively. From the perspective of AWSSI, the winter of 2009/10 had nearly the same severity at Des Moines, Iowa (DSM), and Sault Ste. Marie, Michigan (SSM), at 1218 and 1289, respectively. From the normalized perspective, though, it is clear that, while DSM was well above average at 1.69 and ranked as extreme, the winter in SSM was well below average at 0.69 and ranked as mild. During the winter of 2011/12, the values of AWSSI clearly were more consistently mild across the country, but the meaning of the numbers is easier to discern when coupled with the normalized AWSSI. Here, normalized AWSSI indicates that the sites were dominated by significant outliers of mild conditions, with many sites recording their record lowest AWSSI.

Geographical clusters of winter characteristics were noted with even this small sample of sites. Figure 5 provides a spatial perspective of the average AWSSI, as well as the percent contribution of the temperature component, through the analysis period at each site. The character of the winter is determined not only by the AWSSI itself, but also by the relative contributions of AWSSI-temperature and AWSSI-snow, with some sites dominated by the temperature contribution and others with a more equal snow and temperature contribution. For example, the highest AWSSI averages occur in the northern Great Lakes, with the index slightly dominated by the very high AWSSI-snow as well as a very high AWSSI-temperature; this was the only region where AWSSI-snow dominated AWSSI-temperature. South of this region, encompassing the Corn Belt to the central Great Lakes, extends a region of moderate to high AWSSI-temperature that still receives a moderate AWSSI-snow contribution that was slightly dominated by AWSSI-temperature. The

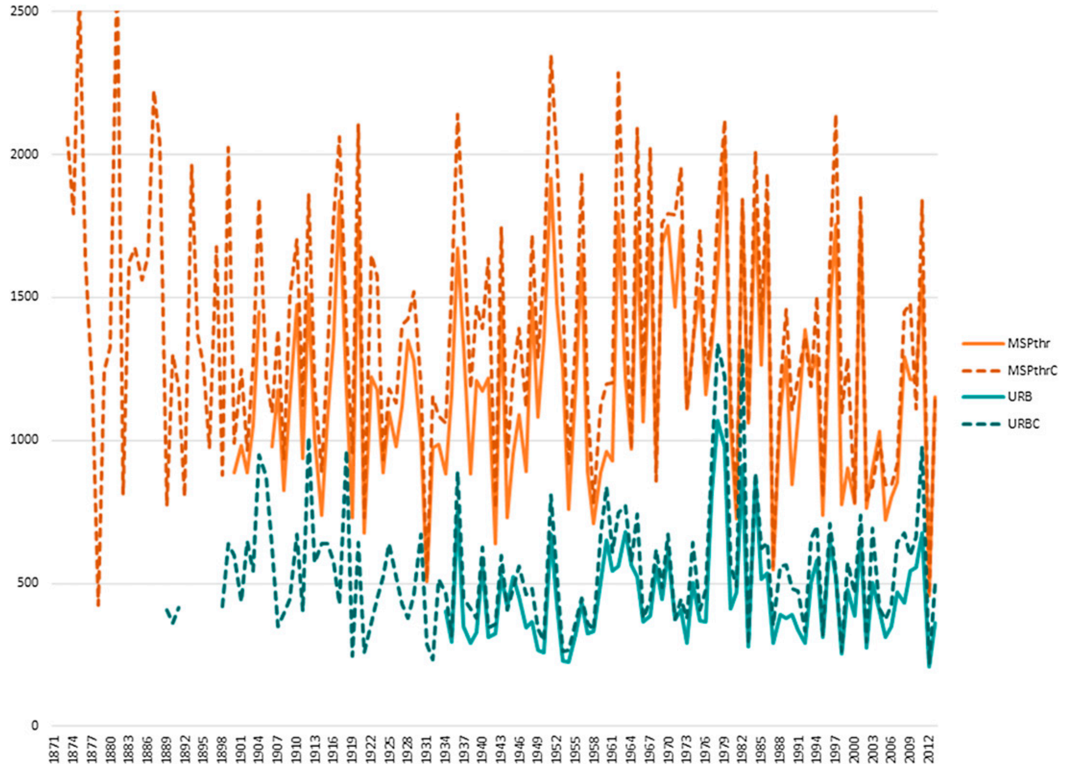


FIG. 6. AWSSI (solid lines) and pAWSSI (dashed lines) for the MSP area (MSPthr) and URB.

southern Great Lakes were milder yet, but still receive ample snow, and the ratio of the contribution of temperature to that of snow was slightly lower than it was in areas just to the north that were a little colder and thus had a higher temperature contribution. The northern Great Plains to the upper Mississippi River valley had higher temperature dominance, with lower AWSSI-snow, and sites in the high plains to northern central plains also had high dominance of temperature and moderately cold temperature climatologies, indicating that snowfall overall is a low contribution. Rocky Mountain and foothills sites tended to have a higher temperature contribution for their latitude than did the nearby plains sites, with a moderate-to-high snow total that still was dominated by the temperature contribution. Both the southern Great Plains and the Southeast were characterized by low AWSSI-temperature, very low AWSSI-snow, and a high ratio of temperature-to-snow contribution, although the plains climatology overall is drier in the winter than that of the Southeast.

b. pAWSSI

Agreement between AWSSI and pAWSSI was demonstrated to be acceptable among a sample of stations for which both indices were run (DSMthr, DTWthr, HONthr, LANthr, MSPthr, OMAthr, and URB, where ‘‘thr’’ indicates threaded station data were used for the site; see Table 1 for station locations). In this case, the authors chose to run the indices on threaded datasets to create the longest possible periods of record; only the winters from 1950/51 through 2012/13 were analyzed for correlation, with missing years removed from analysis. Squared correlation coefficients R^2 ranged between 0.81 and 0.94 for the seven test stations, indicating strong agreement between the two indices. Visual inspection shows that the agreement between the AWSSI and pAWSSI indicates that pAWSSI is indeed capturing the character of the winters of each site, as exemplified by MSPthr and URB (Fig. 6).

Using pAWSSI demonstrated the ability to extend the period of record for analysis beyond the available snowfall and snow-depth records, which were shorter than the temperature and precipitation periods of record at all sites. The calculation did not sacrifice accuracy over the period of record; agreement was acceptable at all sites, despite a few year-to-year variations.

c. In-depth site analysis: Omaha

As an example of the type of analysis that can be conducted for a given site, a number of AWSSI characteristics were examined for OMA. The accumulation of every winter season at OMA from 1950/51 through

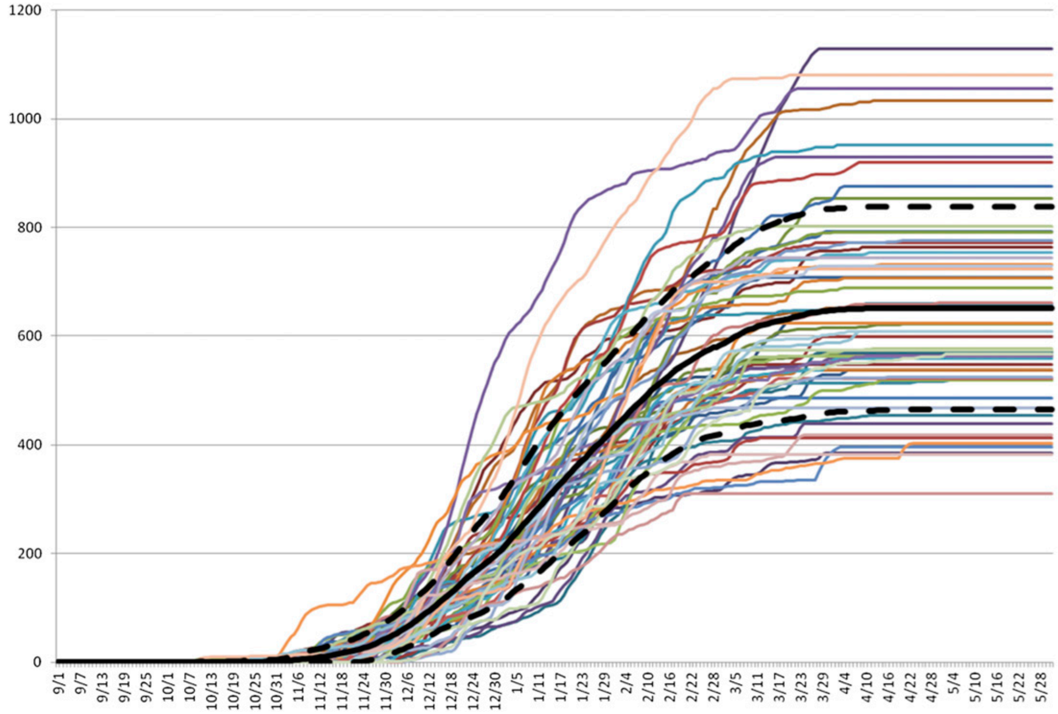


FIG. 7. AWSSI accumulations from 1950/51 through 2012/13 for OMA (excluding 1979/80, 1985/86, 1996/97, 1997/98, and 2003/04). The thick black line is the average for the analysis period, and the thick dashed lines are ±1 std dev.

2012/13, from the beginning to the end of the season, is plotted in Fig. 7. Each winter season has a particular character, not only in the final AWSSI value for the season, but also in the pattern of rises in the accumulation. The average accumulation is a smooth slope that starts slowly early in the season, peaks from around January to early February, and rises more slowly again late in the season, but individual years can rise with some larger jumps during significant snow or cold-outbreak events, with lower or even nil accumulation (flat lines) between events. Some winters are characterized by early-season severity and late-season mildness, and others have the opposite accumulation pattern. In OMA, as in many locations, there are several clear outliers, with a tighter clustering around the average and within the 1-standard-deviation envelope.

Investigating the relative contribution of AWSSI-temperature and AWSSI-snow also provides insight into the character of winter seasons. In Fig. 8, the total AWSSI for each season is shown with its temperature and snow components separated. Many of the lowest AWSSI totals in OMA were during winters with low snow accumulation, whereas the highest accumulations were associated with high snow accumulations, indicating that variability in AWSSI-snow is more of a driver of winter season severity in OMA than variability in temperatures. Indeed, 4 of the top 5 and 8 of the top 10 AWSSI totals for the analysis period are among the top 10 of snowfall totals in the same period.

5. Applications

As a subject of future study, AWSSI should be paired with socioeconomic data to investigate potential applications. Potential data to investigate could include sectors such as energy (i.e., heating costs), transportation (i.e., road maintenance and repair costs), and health care (i.e., emergency-room visits due to accident or injury). Awareness among such sectors that AWSSI is approaching a critical threshold of severity may invoke protective or preventative measures to offset potential costs accumulated during higher severity. In addition to these applications yet to be explored, other analyses of AWSSI data are possible.

a. Trend analysis

Trends in both temperatures and precipitation were noted by several previous studies on climate variability and change (e.g., Karl et al. 2009; Kunkel et al. 2009a,b; Peterson et al. 2013; Wang et al. 2009). While the warming signal is consistent across the contiguous United States in the winter season, precipitation and snowfall

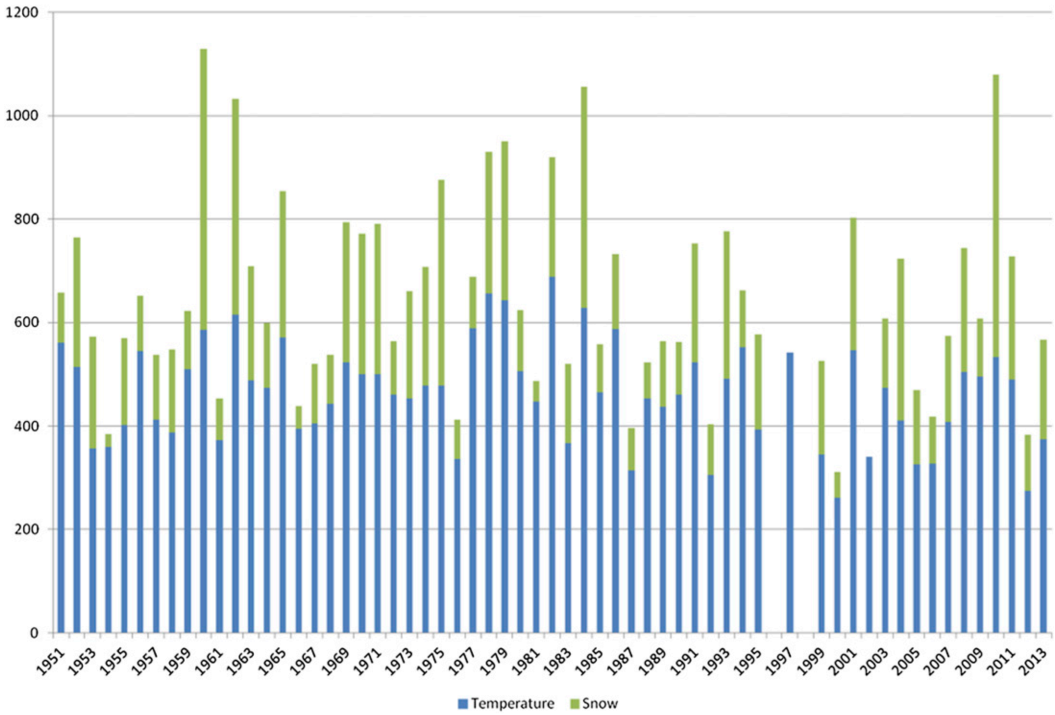


FIG. 8. Total AWSSI accumulation, broken into temperature (blue) and snow (green) contributions, at OMA from 1950/51 through 2012/13. Snow data are excluded from 1979/80, 1985/86, 1996/97, 2001/02, and 2003/04; all data are excluded from 1997/98.

trends are less robust and more spatially dependent. Trends were calculated for both AWSSI and pAWSSI through the analysis period at all sites, though it is worth repeating here that these trends were calculated using an index based on nonhomogenized data, and on threaded data in a few cases, and should be interpreted with caution. With the higher number of missing years in the AWSSI calculations, the pAWSSI trends are more robust and more reliable, but even AWSSI exhibits trends that are significant at some sites.

Table 4 shows the trend in AWSSI, AWSSI-temperature, and AWSSI-snow for each site in the study, as well as for pAWSSI, pAWSSI-temperature, and pAWSSI-snow where calculated. The Mann–Kendall test for trends and Sen's slope analysis were used to quantify the significance of each trend at each site, using the "MAKESENS" spreadsheet template (Salmi et al. 2002). Every station in the analysis exhibited a downward trend in AWSSI/pAWSSI-temperature, many of which were statistically significant; this result is consistent with observed trends in winter temperatures. Also consistent with previous studies is that the direction of changes in AWSSI/pAWSSI-snow were somewhat regionally dependent, and several were statistically significant. In most locations with increasing AWSSI/pAWSSI-snow, the decrease in AWSSI/pAWSSI-temperature overwhelmed that increase, resulting in downward AWSSI/pAWSSI trends at nearly every station. Because of the dampening effect of opposing snow trends, most of those locations were not statistically significant; a handful of those sites with downward trends in both AWSSI/pAWSSI-temperature and AWSSI/pAWSSI-snow exhibited downward trends in AWSSI/pAWSSI that were statistically significant.

b. *Current and historical analysis and context*

One of the potentially most useful applications of AWSSI is to track a winter season in progress, placing it in the context of previous winters to ascertain its severity to date and to explore the range of outcomes of winters with similar severity to date. The running accumulation for the current season can be updated on a daily basis with input from the ACIS database, providing a tool for real-time assessment of the severity of the winter season to date. Such a summary is included in Fig. 9 for 2013/14 at OMA. The total AWSSI for the winter, which ranked as a category W-4 (severe), was driven largely by an extreme temperature contribution, given that the snowfall contribution fell in the mild category.

The period of record for AWSSI and pAWSSI allows extreme events to be placed into historical context; pAWSSI, in particular, allows analysis of winter severity before snowfall and snow-depth records were kept. For

TABLE 4. Trends in AWSSI, AWSSI-temperature, and AWSSI-snow for the period from 1950/51 to 2012/13. Italicized sites show pAWSSI, with periods of record starting in years ranging from 1872 (OMAthr-C) to 1889 (URB-C). Statistically significant sites are marked with boldface type, with level of significance $P(x)$ denoted as plus sign = 0.10, asterisk = 0.05, double asterisks = 0.01, and triple asterisks = 0.001.

	AWSSI significance	AWSSI-temperature significance	AWSSI-snow significance
ABR	−1.44	−2.06	0.62
ALB	**−3.12**$^{+}$	**−1.94****	−1.17
ATL	**−0.41**$^{+}$	**−0.38***	0.04
BIS	−1.23	**−3.70***	1.94
BOI	−1.19	−0.89	−0.30
BOS	0.18	−0.63	0.14
BUF	−1.12	**−1.12**$^{+}$	0.00
CHIthr	−0.68	−0.55	−0.27
CLE	−0.43	**−1.23**$^{+}$	0.80
CYS	−0.79	**−0.99**$^{+}$	0.21
DBQ	−1.71	−1.59	−0.32
DCA	**−0.78**$^{+}$	**−0.66***	−0.11
DDC	−0.70	−0.66	−0.04
DEN	−1.14	−0.50	**−0.64**$^{+}$
DFWthr	**−0.41***	**−0.35***	−0.05
DLH	**−7.47***	**−3.94****	−3.53
DSM	−1.78	**−2.35***	0.71
DSMthr-C	−1.08	−0.67	−0.40
DTWthr	−0.23	−0.91	0.68
DTWthr-C	**−1.94*****	**−0.61***	**−1.32*****
ERI	0.42	**−1.42***	1.59
EVV	**−1.44***	**−1.03***	−0.41
FAR	2.17	**−3.72***	**4.90***
HLN	**−5.56****	**−2.66***	**−2.34***
HON	−2.99	**−2.87***	0.12
HONthr-C	**−2.68****	**−1.80*****	**−0.88**$^{+}$
HVRthr	−2.76	−2.44	−0.60
IND	−1.13	**−1.54***	0.42
INL	**−6.01**$^{+}$	**−4.07***	−1.93
LAN	−2.03	**−1.44**$^{+}$	−0.59
LANthr-C	**−2.71*****	**−1.02*****	**−1.69*****
LBF	−1.33	−0.87	−0.46
LGA	−0.22	**−0.80***	0.58
LSE	−2.12	**−2.66***	0.16
MKE	**−3.53**$^{+}$	**−2.92*****	−0.61
MLI	−1.89	**−2.01****	0.12
MSN	−0.77	**−2.58****	**1.81**$^{+}$
MSP	−5.49	**−3.66****	−1.50
MSPthr-C	**−1.98***	**−1.36****	−0.62
NYCthr	−0.13	−0.63	0.55
OKC	**−0.67***	**−0.63***	−0.04
OMA	−0.92	−1.12	0.16
OMAthr-C	**−1.07***	**−0.70***	−0.37
PAH	−0.78	−0.57	−0.15
PHLthr	−0.87	**−1.01***	0.14
PIR	−4.27	**−3.47***	−0.87
PIT	−1.17	**−1.09**$^{+}$	−0.14
PWM	−3.20	**−2.10*****	−1.19
RAP	−0.69	−0.64	0.07
ROC	−2.19	**−1.27**$^{+}$	−0.92
SDF	**−1.13***	**−1.38****	−0.27
SGF	−0.68	**−0.77**$^{+}$	0.08
SLC	−1.07	**−1.20***	0.13
SPI	−1.75	**−1.47***	−0.24
SSM	−1.75	**−2.59***	0.88
STL	−1.34	**−1.38****	0.05
TOL	−2.28	**−2.37****	0.04
URB	−0.39	−0.45	0.06
URB-C	0.30	−0.31	0.49

example, in the Detroit, Michigan, area (DTWthr), 2013/14 ranked as the highest AWSSI on record when compared with the analysis period from 1950/51 to 2012/13, surpassing notably cold and snowy winters in the late 1970s (Fig. 10). Meteorological records in Detroit, however, date back to 1874/75, encompassing a number of severe winters from the 1870s through the 1910s. Was the winter of 2013/14 in Detroit as bad as those winters, or worse? Among the longer period of record allowed by pAWSSI, the winter of 2013/14 would rank as the third most severe, trailing the winters of 1874/75 and 1911/12 and just passing the winters of 1876/77, 1903/04, and 1880/81 (Fig. 11). AWSSI and pAWSSI allow the ability to place the winter of 2013/14 into the context of the full period of record, noting that it was the most severe winter in over 100 years, although not the most severe on record.

It would not be recommended to use pAWSSI to describe the accumulation from individual events, but it does capture the seasons well enough to allow real-time analysis of a current, observed winter in the context of past, calculated winter seasons. The highest- and lowest-ranking winters, frequency above or below certain thresholds, and duration of winter seasons are just a few of the parameters that can be assessed for each site when historical records of AWSSI and pAWSSI are available.

6. Conclusions

AWSSI provides a concise method to capture the character of winter seasons at any site that experiences a winter season with an intervening warm season. The index, using thresholds of temperatures and snow or precipitation, accumulates a score through the winter season, with the final score for the season representing the severity of that winter. The index can be examined, in both its total and contributing temperature and snow/precipitation components, for its climatology, including trends, variability and responses to teleconnection patterns, and rate of accumulation through the season. Sites can be intercompared, either using the value of AWSSI

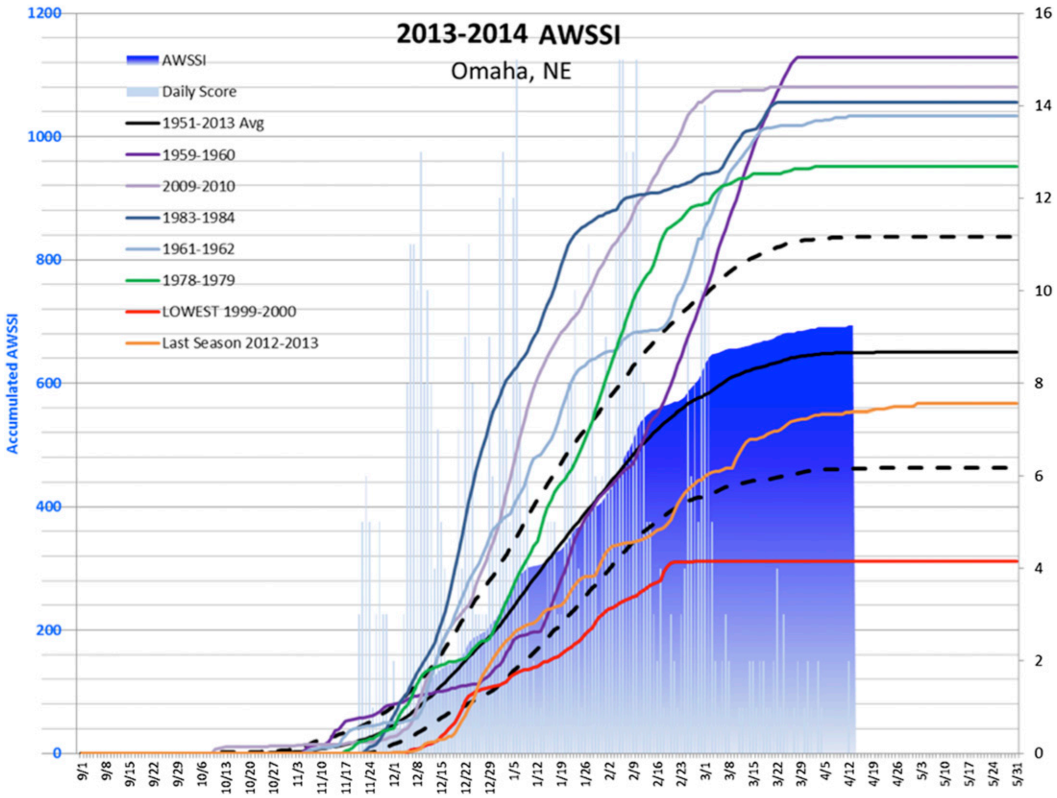


FIG. 9. Sample graphic for tracking an ongoing winter season, in this case for 2013/14 for OMA. The blue shaded curve is the accumulation for the current season, and the light blue bars are the contributions from individual days (scaled on the right side). Other curves include the highest-ranking (most severe) 5 years, the lowest-ranking (least severe) year, and the previous year (2012/13), along with the mean (solid black line) and curves for ±1 std dev (black dashed curves).

to directly compare severity or using normalized values to compare relative severity. The threshold-based calculations are forgiving of minor observational errors and adjustments, such as station moves, thus allowing the method to be applied successfully to threaded and long-term historical sites. In cases in which snow observations do not exist or are not reliable, such as when examining long-term historical stations or stations with gaps in modern observations, pAWSSI allows consistent analysis that still characterizes the severity of winters through the period of record at that station.

As with any objective index of complex weather and climate phenomena, limitations do exist. AWSSI does not capture freezing rain, which is reported as liquid precipitation and does not trigger a snow accumulation; pAWSSI does compensate for this to a limited extent by triggering snow accumulation when temperatures fall below freezing. Wind and its associated impacts, including wind chill and blowing snow, are not included because these are not reported in widely accessible daily climate reports and are not measured at the majority of climate stations. Temperature and snow thresholds, although set with impacts in mind and tested for sensitivity, are arbitrary and are set using non-SI units for consistency with daily observations in the United States. The index is not designed to properly capture winter season severity in climate regimes that maintain snowpack or experience maximum temperatures below 0°C throughout the year; it depends on a beginning and cessation of winter that are defined by lack of snow and temperatures above freezing. These limitations do not, however, overwhelm the extent of information that can be gleaned from the data regarding winter season behavior and climatology across most climate regimes in the United States.

A number of potential applications and uses of AWSSI remain unexplored. Chief among these are the range of potential sectoral applications. While not explicitly explored here, there are many possibilities for applications. AWSSI and/or its contributing components could be correlated with the dabbling-duck abundance explored by Schummer et al. (2010), as well as with other wildlife populations and their markers of abundance, migration, or health. The index could be

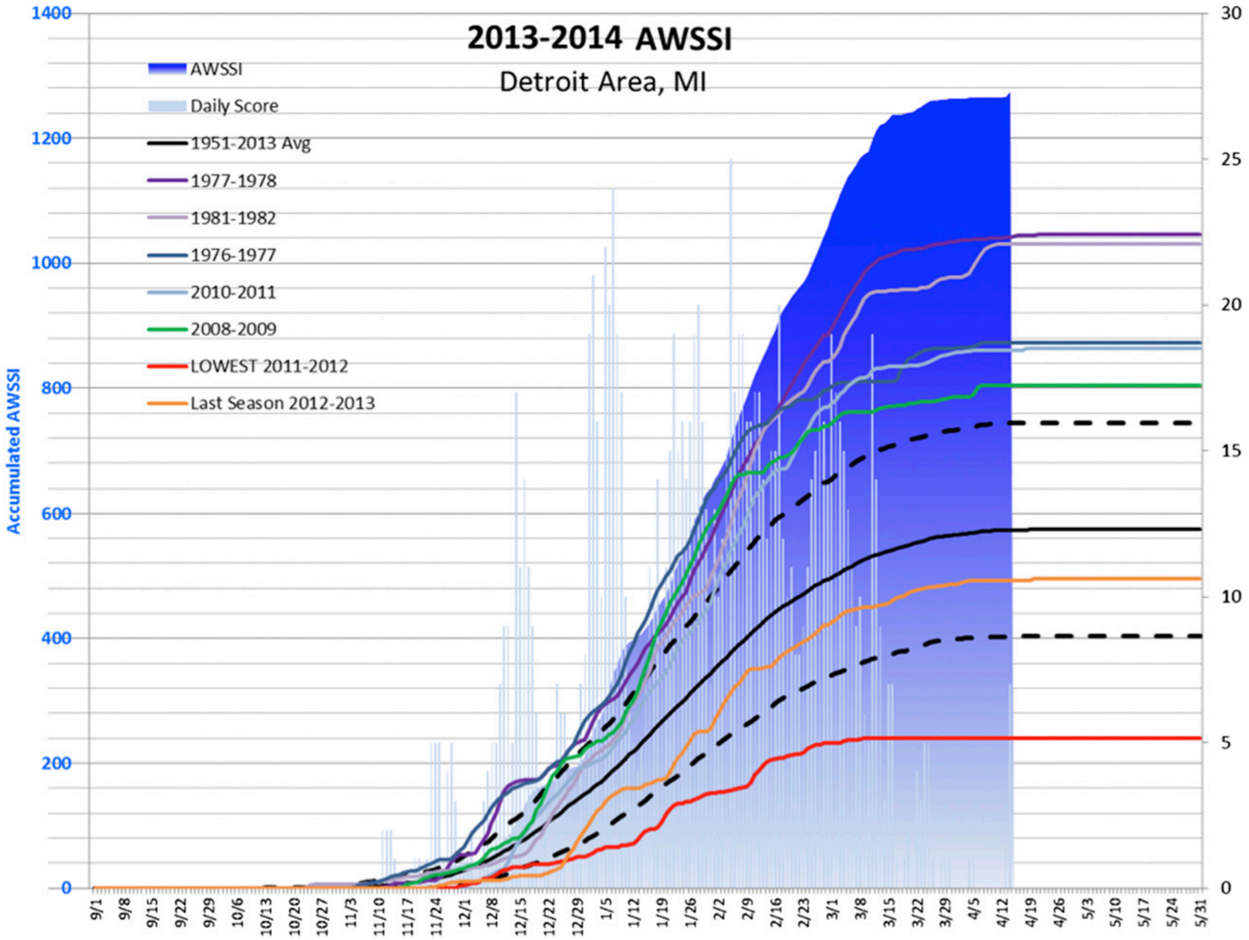


FIG. 10. As in Fig. 9, but for the Detroit area (DTWthr).

applied to transportation and road maintenance to correlate cost, supplies, or traffic accidents and delays, as well as to health factors such as hospital and emergency-room visits or mental-health incidents.

As with any meteorological or climatological parameter, the relationship of AWSSI and pAWSSI to climate-variability signals such as the El Niño–Southern Oscillation (ENSO), Arctic Oscillation, North Atlantic Oscillation, and Pacific decadal oscillation, can be assessed from both statistical-conditional-climatology and dynamical-attribution perspectives. The time series of AWSSI lends itself well to analysis of other time series with known impacts in the winter season. Given known impacts of ENSO on wintertime temperature and precipitation across much of the United States, the site-based calculations are likely to also exhibit correlations that can be explained by changes in atmospheric patterns.

Another unexplored application of AWSSI is a predictive capability. Given output from an ensemble of climate-model output, such as NWS's Climate Forecast System, version 2 (CFSv2; Saha et al. 2014), an ensemble of potential AWSSI accumulations could be calculated at a point, with the envelope of resulting AWSSI possibilities displayed and interpreted. Seasonal outlooks such as those produced by the NWS Climate Prediction Center could be adjusted or interpreted to fit AWSSI categories, providing an outlook of the probability of each category from W1 to W5, or at least predicting the potential severity of the temperature and snow/precipitation components on the basis of outlooks of shifts in the probability distribution function of temperatures and precipitation. On a longer time scale, decadal-scale climate projections could include changes in the distribution of AWSSI climatology, including impacts on both temperature and precipitation.

Future work with AWSSI is focused on creating a centralized repository of AWSSI data with a user interface that would allow researchers to interrogate the AWSSI and pAWSSI climatologies for any station. Once a wider range of station AWSSI data is available, the values (e.g., climatological averages or seasonal totals) could be more reliably mapped and displayed for

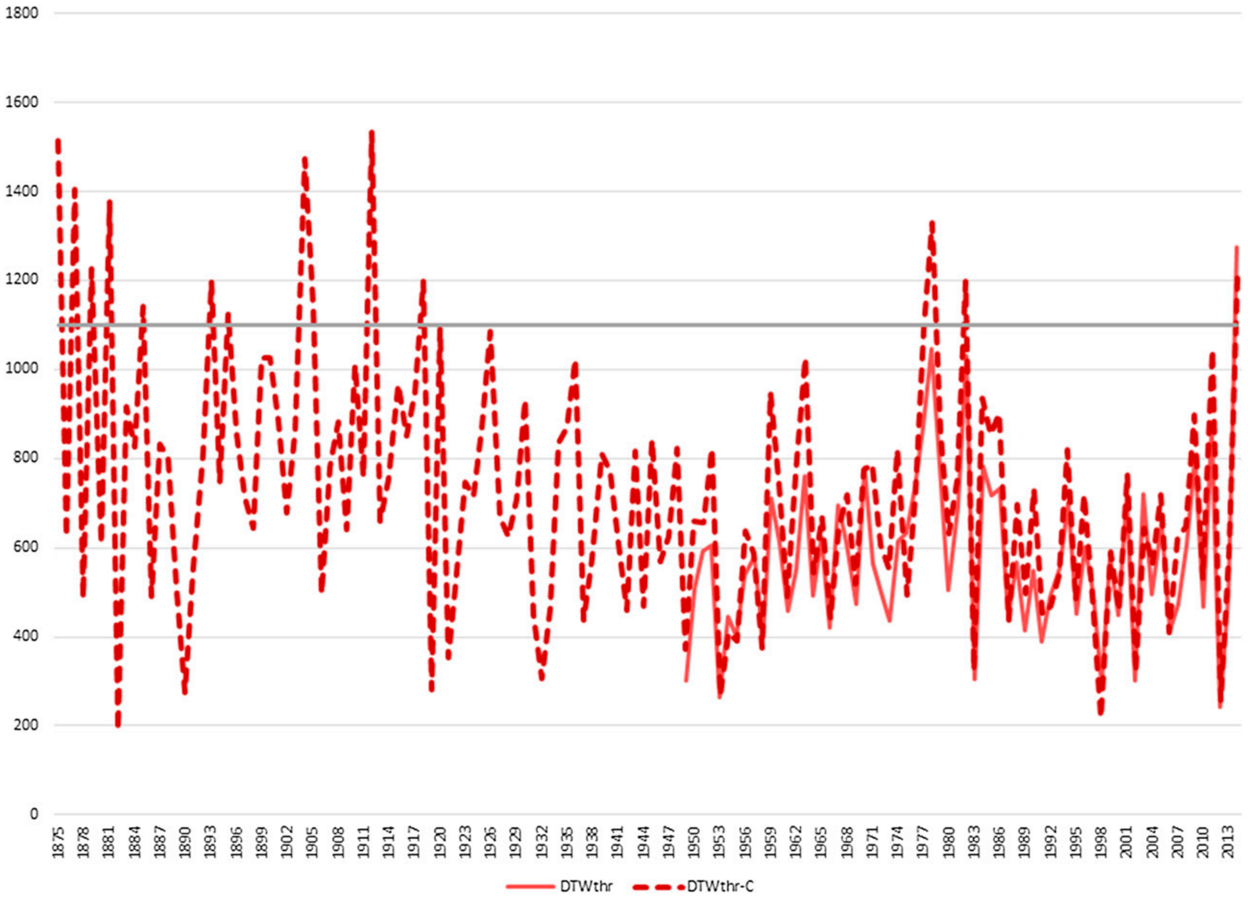


FIG. 11. Period of record for DTW AWSSI (solid) and pAWSSI (dashed). Seven years have had either AWSSI or pAWSSI exceed 1100: 1874/75, 1876/77, 1880/81, 1903/04, 1911/12, 1977/78 (pAWSSI only), and 2013/14.

regional and national perspectives, as well as analyzed for climate trends and variability, relationships to broader weather patterns, and relationships to nearby stations. Real-time updating also would facilitate operational applications of AWSSI, such as winter-to-date severity analysis that returns to the ever-present questions: *Is this winter severe or mild, when was the last one like it, and how does it rank through our history of winters?*

Acknowledgments. The authors thank Kayla Novak (San Jose State University/Midwestern Regional Climate Center student intern) for processing data. Rebecca Kern (NOAA/NWS Weather Forecast Office Omaha/Valley, Nebraska) provided map graphics. The first author also acknowledges the NWS Central Region and NWS Omaha/Valley for support through the University Assignment Program. Comments and suggestions from three anonymous reviewers improved the quality of this manuscript and are appreciated. Any opinions, findings, and conclusions or recommendations expressed in this publication are those of the authors and do not necessarily reflect the views of the National Weather Service, the Illinois State Water Survey, or the University of Nebraska.

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