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The Hard Winter of 1880-1881: Climatological Context and Communication via a Laura Ingalls Wilder Narrative

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THE HARD WINTER OF 1880-1881: CLIMATOLOGICAL CONTEXT AND COMMUNICATION

VIA A LAURA INGALLS WILDER NARRATIVE

by

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A DISSERTATION

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The Hard Winter of 1880-1881 was featured in the Laura Ingalls Wilder historical fiction account, *The Long Winter*, as well as in several town histories across the region. Both meteorological records and historical accounts indicate that the winter was particularly long, snowy, and cold. The question of how “hard” a winter is for a given location depends on the climatological context, which relies on an objective characterization of winter severity. The Accumulated Winter Season Severity Index (AWSSI) allows comparison of the winter of 1880-1881 among sites across the region, as well as in the context of the period of record, to quantify its severity. Additionally, investigating the impacts of both the El Niño/Southern Oscillation (ENSO) and the North Atlantic Oscillation (NAO) in the central United States provides context for the influence of both a strongly negative NAO and an El Niño event during the winter of 1880-1881. With an understanding of the climatological factors influencing the Hard Winter, along with the context for its severity, a more thorough analysis then was conducted to quantify and describe its severity.

The connection of the winter of 1880-1881 to a popular book written by an author who is a cultural icon provides a natural vehicle with which to communicate
weather and climate concepts to multiple non-technical audiences. The communication of complex weather and climate concepts is a well-documented challenge. One method to bridge between science concepts and public understanding is to relate those concepts to familiar subjects and stories, including Laura Ingalls Wilder’s books. A narrative constructed around the books, particularly *The Long Winter*, provides a means of audience engagement and interest in weather- and climate-related topics, which was at least partially quantified by surveying audiences of the narrative. Overall, the scientific background, combined with a familiar narrative voice, provides a means to transmit weather and climate understanding to a wide audience.
DEDICATION

To my mom, Susan, who bought me my first Little House book and urged me to give it a try, because she knew I would love it like I love the weather. Mothers just know.
AUTHOR’S ACKNOWLEDGMENTS

Many levels of support had to come together to make this dissertation possible. I am grateful to Drs. Kenneth Hubbard and Martha Shulski, who not only agreed to take me on as a student but also found financial support, allowed me the freedom to pursue an unusual idea, and never wavered in their encouragement. Committee members Drs. Lisa PytlikZillig, Russanne Low, and Amy Lauters provided valuable input to the direction and content of this work. Dr. Steven Hilberg, Midwest Regional Climate Center, provided critical partnership for the Accumulated Winter Season Severity Index in particular. Several other faculty members at the University of Nebraska provided additional feedback and discussion that improved the quality of this work, including Drs. Michael Hayes, Robert Oglesby, Merlin Lawson, Mark Burbach, Gina Matkin, and Kenneth Dewey.

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Last and never least, the work of completing a doctoral program simply could not have been achieved without the support of my husband, colleague, and best friend, Josh Boustead. His contributions include discussion and review of components of the work, conversations about historical weather and climate events, and covering shifts and duties at the office. His support, understanding, and compassion never failed, even during countless late nights, early mornings, and long days, trips for research and outreach, phonecalls at inconvenient times, closed-door writing sessions, and weeks of household neglect. Beginning to end, he stood by me as a partner, cheerleader, and coach, and I am forever indebted.
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CHAPTER 1. INTRODUCTION

“It’s going to be a hard winter,” Pa said. “The hardest we ever saw.”

“Why, Charles,” Ma protested. “We’re having fine weather now. That one early storm is no reason why the whole winter will be bad.”

“I’ve trapped muskrats a good many years,” said Pa, “and I never saw them build their walls so thick.”

“Muskrats!” said Ma.

“The wild things know, somehow,” Pa said. “Every wild creature’s got ready for a hard winter.”

“Maybe they just made ready for that bad storm,” Ma suggested.

But Pa was not persuaded. “I don’t like the feel of things, myself,” he said. “This weather seems to be holding back something that it might let loose any minute. If I were a wild animal, I’d hunt my hole and dig it plenty deep. If I were a wild goose, I’d spread my wings and get out of here.” – Laura Ingalls Wilder, The Long Winter

For six long months, the Ingalls family endured persistent blizzards, bitter cold, and near starvation; the experience of the Hard Winter of 1880-1881 was chronicled in Wilder’s book The Long Winter (Wilder 1940). While Wilder’s account of the winter was a work of historical fiction, the book contained many verifiable facts, including those regarding the meteorological events of the Hard Winter. The experience of the Ingalls family as told in The Long Winter poses several questions:
• Was the winter of 1880-1881 as severe as Wilder’s description suggests? What data are available to analyze the Hard Winter? How can the severity of one winter be quantified in the context of others?

• What climatological and meteorological factors contributed to its severity? Have these factors been repeated since then, and if so, what was the outcome of those winters?

• Can Wilder’s well-known narrative voice be channeled to communicate about weather and climate issues to audiences that may not be engaged in weather and climate, and if so, how? What lessons can be learned and communicated from Wilder’s experiences? Is such a narrative an effective way to reach audiences both to generate weather and climate literacy and to communicate about complex or highly emotional topics in a manner that reaches a range of audiences?

While there are those who are strictly scientists, and those who are clearly communicators, the effective communication of scientific concepts such as weather and climate requires at least a small population who are versed in both science and communication, in order to knowledgeably convey scientific information in a manner that is usable and useful to non-scientific audiences. A person who is able to flow comfortably between science and communication becomes a bridge between the scientific community and the community at large. The practice of bridging between science and the community would benefit from a methodology, an example, and an
investigation of how to apply the concept in practice. Thus, there is a need to see the process through from beginning, as a scientific investigation, to end, as a tool for education and communication; this study serves as that end-to-end demonstration and presents practices to apply in future studies, using the Laura Ingalls Wilder *Little House* book series as a vehicle that can cross the bridge between meteorology/climatology and communication to a wide audience of non-specialists.

The first step in the process, and the first problem addressed within this study, is to investigate rigorously the winter of 1880-1881, as well as other weather and climate events depicted in the Laura Ingalls Wilder books, in order to build scientific credibility. As a foundation to placing any historical winter in context, that context first needed to be created. The result of that effort, the Accumulated Winter Season Severity Index (AWSSI), is described in Chapter 2. The AWSSI, an objective index based on daily temperature and snow or precipitation records, assigns a score to a winter at a climatological station; this score can be placed in the context of surrounding sites to compare absolute severity, as well as in the context of the period of record to compare relative severity. By applying the AWSSI, it is possible to both quantify the severity of the Hard Winter of 1880-1881 and place it in the context of other winters in the region, allowing validation and quantification of the severity of the Hard Winter. An objective climatology also may provide a tool to diagnose the effects of climate variability and change that may have occurred in the region since the Ingalls family settled there, allowing a diagnosis of climatological shifts between then and now, with potential applications to future scenarios.
With a climatological context in place, the framework of climate variability and its impacts on winter weather severity in the region must be analyzed. In Chapter 3, the impact of both the El Niño/Southern Oscillation (ENSO) and the North Atlantic Oscillation (NAO), both separately and combined, on winter weather is investigated across much of the central United States. Based on both statistical analysis and synoptic composite analysis, the interplay of ENSO and NAO in the region is better understood, quantifying the impact of these teleconnection patterns on measurable, station-based winter weather parameters. Additionally, the composites of common synoptic parameters allow analysis of upper-level patterns and responses of surface parameters, providing links from teleconnection patterns to sensible weather that can be used to bridge between climate and weather.

Given the framework of both climatological context and known contributing factors to severe winters in the north central United States, the Hard Winter of 1880-1881 can be examined closely, as in Chapter 4. Because the books are historical fiction, the veracity of events must be confirmed with observational data, which were sparse in the late 19th century and can be supplemented with non-meteorological records. Specifically, regarding the Hard Winter of 1880-1881, the study characterizes the winter both local to Laura’s experiences as well as with a broader perspective, including the presence of teleconnection patterns or other climatic features that may have contributed to the extreme winter season.

The second step in the process, bridging from science to communication, is to create tools for education and communication, so that the information determined via
rigorous scientific investigation can be shaped for an audience that is not specialized in meteorology or climatology. The Laura Ingalls Wilder books are engrained in the culture of the United States, and particularly the Plains and Midwest regions featured in the books; thus, adults and children alike recognize and respond to the stories. Thus, regardless of the age of the audience, the books provide an opportunity for education by creating common ground between the scientist and the community. While children can respond to and learn from classroom activities, adults are more likely to respond to interactive presentations, discussion, and reading materials about the weather and climate of the Laura Ingalls Wilder books. Surveys of audiences who listen to a presentation about weather and climate with a Laura Ingalls Wilder narrative construction allow quantitative analysis of their engagement with climate-related topics. Qualitative analysis of the effectiveness of the narrative also can be gleaned from media coverage of aspects of the narrative, as well as from social media and other forms of interaction.

By allowing one author to conduct both the scientific investigation and the communication exercises, the project develops and demonstrates a precedent for those who are able and desire to serve as a bridge between the scientific and broader communities. The following chapters outline the process, from scientific inquiry through narrative development, ultimately answering the questions posed by reading *The Long Winter* and desiring to understand it more deeply and bring that knowledge to wider audiences.
But even after Laura was warm she lay awake listening to the wind’s wild tune and thinking of each little house, in town, alone in the whirling snow with not even a light from the next house shining through. And the little town was alone on the wide prairie. Town and prairie were lost in the wild storm which was neither earth nor sky, nothing but fierce winds and a blank whiteness. – Laura Ingalls Wilder, *The Long Winter*

References

CHAPTER 2: THE ACCUMULATED WINTER SEASON SEVERITY INDEX (AWSSI)

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 (AWSSI) incorporates these elements into one site-specific value that defines the severity of a particular winter, especially when examined in the context of climatology 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 as 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 [NESIS], Kocin and Uccellini 2004; Cerruti and Decker 2011). The use of scaling allows comparison of event characteristics, as well as impacts that are either explicitly included as an index factor or else 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.

Climatology studies of winter weather often have focused on event-specific quantities, such as individual storms. Branick (1997) utilized National Climatic Data Center (NCDC) Storm Data 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 based on station data across the continental United States, and Changnon et al. (2008) connected the snowstorm climatology to climatology of surface
cyclone tracks east of the Rocky Mountains. More narrowly, Hirsch et al. (2001) focused on a climatology of East Coast winter storms, while Market et al. (2002) narrowed its focus to thundersnow events. Schwartz and Schmidlin (2002) completed a climatology of blizzard events, providing analysis of frequency, seasonality, and areal coverage of blizzard events in the continental United States over 41 winters. While most of the winter event-based literature focuses on snow and freezing precipitation, cold air outbreak climatology is addressed by Portis et al. (2006) for select stations east of the Rocky Mountains, including frequency and trend analyses. Collectively, all of these elements could define the severity of a winter season, but they are incomplete and incompatible in both 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 departure below 0 °C, for the purpose of comparing cities such as Washington, D.C., and Paris, France (Abbe 1914). While 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 (Hellman 1918, Henry 1925) followed a similar methodology, 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 similar limitations to the early works.

Winter classification studies have been conducted specific to particular applications, and several of these are clustered around the transportation sector. Gustavsson (1996) evaluated three different winter indices to determine their relationship with road salting activity, ultimately determining that none of the three indices correlated adequately to salting. 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; additionally, it was developed to be a seasonal index, not capable of daily index contribution. The European Cooperation in the Field of Scientific and Technical Research (COST) 309 winter index (Voldborg and Knudsen 1988) summarized the number of days of frost formation, temperature that fall from > 0.5 °C to < -0.5 °C, snowfall of >10 mm, and subjectively determined presence of drifting snow. Finally, the “GAB” index incorporated snowfall thresholds, number of frost events, and a black ice parameter that includes both humidity and a temperature fall similar to that in COST 309. Parameters included in these indices are specific to road impacts, and several include information not readily available in daily climatological data, such as coincidence of relative humidity and temperature thresholds, as well as the observed drifting snow. Gustavsson (1996) suggested that a successful index would match treatment action thresholds to weather parameters that cause slippery roads, none of which were fully
met in these three indices. Carmichael et al. (2004) utilized a neural network to
diagnose a winter severity index in Iowa using observational data such as temperature,
dewpoint, mean sea level pressure, visibility, wind speed and gusts information,
precipitation amount, snow depth, and observed weather types with the resulting index
correlating to road maintenance costs specifically in Iowa. The index was able to find
relationships even when snow data were missing, as the neural network effectively
reconstructed snow data.

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 the study, dubbed the Weather
Severity Index (WSI), 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 above 2.54 cm of snow or greater. The
duration of these occurrences had the greatest impact on the ability of ducks to feed
and rest. Ultimately, these sector-specific indices can be used by those sectors with
some success, but their applicability to other sectors is limited. Thus, the need still
exists for an index of winter season severity that is more broadly applicable and 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 the 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 allows 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, as 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” based on 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.

Snowfall and snow depth data can be unreliable for any number of reasons, including gaps in observations, lack of historical observations, difficulty of measurement under some weather conditions (such as during wind or blowing snow), variability in depth of snow cover over short distances, and questionable or changing measurement practices (e.g. Doesken and Robinson 2009). Precipitation gauges often undercatch snow, especially during light snow events or on windy days when snow is lofted over the gauge opening. While precipitation measurements are not perfect, they face fewer of the challenges of snow measurements, and they often extend further back in time at a
given observation site than snow measurements. The challenge becomes estimating daily snowfall and snow depth given only daily observations of precipitation and maximum and minimum temperatures. Without a full atmospheric temperature and moisture profile, it is understood that any techniques to estimate snowfall will be imperfect. Techniques may either overestimate or underestimate the snowfall on any given day. However, with a seasonal accumulation, the daily errors are not nearly as important as biases that may skew a seasonal total, and if a technique remains relatively unbiased seasonally, it may provide information about the character of that winter’s precipitation. Also, using temperature and precipitation to estimate a proxy for snowfall also may capture precipitation events that occur below freezing temperatures but did not fall as snow, such as freezing rain, thus perhaps more accurately representing the severity of that contribution to the accumulated AWSSI than the observation-based version.

Several attempts have been made to estimate snowfall, or at least precipitation equivalent of snow, based on temperature and precipitation observations. The National Weather Service (NWS) published a table to estimate snowfall based on 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, then used thresholds of minimum temperature to further refine the fraction of precipitation that accumulates as snowfall. Kienzle (2008) included a similar methodology to Trnka et al. (2010), but it calculated a
threshold temperature at which 50% of precipitation falls as snow and 50% falls as rain, and this was considered to be too time-consuming to calculate for widespread use across a high number of stations and continually update. Like Trnka et al. (2010), Kienzle (2008) ultimately provided liquid equivalent of snowfall as its output, rather than an estimate of snowfall. Byun et al. (2008) created a snowfall ratio based on regression analysis of observed temperature, precipitation, and snowfall, but the method requires 3-hourly precipitation rate, which falls outside the scope of using 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 hPa, 850 hPa, and 500 hPa, supporting the notion that surface temperatures impact snow wetness more than temperatures at other levels. Ye et al. (2013) established probabilities of rain or snow based on surface temperature and dewpoint temperature thresholds, which 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, though dewpoint temperatures did provide additional clarity. Fisk (2008) created a multivariate regression analysis of snowfall at Minneapolis/St. Paul using daily temperature and precipitation records, assigning five groups based on “cold” or “mild” temperatures and “light”, “moderate”, or “heavy” precipitation. This methodology was found to be most applicable to the 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 temperature and precipitation (snowfall), any calculations of snow depth are limited to just those measurements. A number of methods to estimate or calculate snow melt do exist. The United States Department of Agriculture (USDA) included a degree-day method in its directives to determine snow pack 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 USDA, then added a densification factor, calculating snow depth by the snow density and water equivalence profiles. In this study, the USDA degree-day calculation was the basis of calculating snow depth, with additional formulation addressed in section 3c.

Once calculated, AWSSI provides a wealth of 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 to 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 to which innumerable impact-based data can be examined. The range of possibilities includes comparisons to 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. Users of AWSSI information can pull apart the index into its temperature and snow/precipitation components, as well as examine the total AWSSI, 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, with the method of calculation 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). Using ACIS data gives National Weather Service (NWS) Weather Forecast Offices (WFOs) the ability to replicate the study and produce AWSSI results for any sites with daily data available in ACIS. In this study, single stations and select threaded sites (http://threadex.rcc-acis.org/) were analyzed from 1950-2013. We determined that the slight differences between widely available ACIS data and homogenized station data 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, and for that
reason, we have included a small sample of threaded sites. That said, we feel that caution should be used when analyzing trends or sample statistics based on threaded data.

Winter seasons with missing snow or temperature data were excluded if the missing data was estimated to contribute 5.0% or more of the total AWSSI for that season. Estimates were completed for each site by comparing with nearby observations for the date in question, as well as 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 but would not impact the temperature accumulation by changing the beginning or end dates of the season, 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 through the 2000s, necessitating the omission of the total and snow component, as well as often the temperature component. Additionally, ACIS draws data from the Global Historical Climate Network (GHCN), which sets to missing any days on which snow depth values increase without a corresponding amount snowfall. However, snow depth is measured at 1200 UTC, while 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 impact 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 and inches for snowfall and snow depth. All thresholds discussed in the study will thus use those units.

Sites included in the analysis are listed in Table 1. The selected sites contained relatively complete periods of record at least from 1950-2013, 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 northern Plains, but a few sites were selected from climatologies outside of this primary study area to examine the utility of AWSSI in multiple climate regimes. For each site, the average AWSSI from 1950-2013 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 based on 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 to 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 analysis, months are divided such that winter comprises the months of December through February. Astronomical winter, however, is determined by the duration from winter solstice to vernal equinox, which can vary slightly from year to year. The definition of winter onset varies substantially among individuals, based on informal polling of Community Collaborative Rain, Hail, and Snow (CoCoRaHS) observers around the country; 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. Understandably, the perception of winter onset varied based on location, as well.

After collecting 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 the following conditions is met:

- Daily maximum temperature \( \leq 32 ^\circ F (0 ^\circ C) \);
• Daily snowfall >= 0.1 in (0.25 cm); or

• December 1

Once one of these conditions is reached, AWSSI begins accumulating based on the criteria described in section 3b.

As with winter onset, the cessation of winter also has both subjective and objective definitions 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 conditions is met:

• Daily maximum temperature <= 32 °F (0 °C);

• Daily snowfall >= 0.1 in (0.25 cm);

• Daily snow depth >= 1.0 in (2.5 cm); or

• March 1

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 based on occurrence of past extremes or 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 June 1, but because winter conditions have occurred into early May in previous years, it may not be safe to declare a winter “done” on May 1.
b. AWSSI calculation

The daily total AWSSI point accumulation is determined based on 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, though 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 inches would have the same point total as a snowfall of 2 inches plus a snowfall of 4 inches, 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 script, with text output imported into Microsoft Excel for statistical analysis and graphical display.
In past years, some NWS observers have reported hail as a snow/frozen precipitation accumulation. These observations were able to trip AWSSI to begin accumulation well ahead of wintry conditions or 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).

Given 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 winters in Kansas. Milder climates would be more likely to have a calendar-based accumulation season, with low accumulations that mainly derive from minimum temperatures that fall below freezing, along with rare snow events. Thus, a winter season freeze event in Georgia would drive a jump in accumulation. One can compare AWSSI values to compare the severity of winter at one site to another, or one year to another. To analyze the relative severity, one can compare the AWSSI at a site for a given season to the average over its period of record or another period of choice. Thus, one could compare the relative severity of a given winter in Omaha to the relative severity of the same winter in Minneapolis/St. Paul, Minnesota (MSP), to determine which site had a more severe winter compared to its own climatology.
Because numbers alone may not provide a helpful description of the characteristic of a winter, we have created a five-tiered category system, based on percentiles; these are listed in Table 3. Categories are delineated at 20th percentile intervals, with both a scaling number (W-1 to W-5) and word descriptors (mild, moderate, average, severe, 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 disproportionate to the recorded snow total. Freezing rain certainly can have substantial impacts 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 due to 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 observation 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 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 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 to 0.06 in (0.25 to 1.52 mm), “moderate” precipitation of 0.07 to 0.42 in (1.78 to 10.67 mm), and “heavy” precipitation of 0.43 in (10.92 mm) or greater. Fisk (2008) original calculations were modified slightly to fit a wider range of climatology, as the original version produced too much snowfall for Heavy/Cold conditions. For each of five combinations of
temperature and precipitation classifications, the original Fisk (2008) snowfall calculations are as follows:

**Light/Cold:**

\[ SF = 0.259 + (15.413 \times P) - (0.007 \times [T_{avg} + 20]) \] \[1\]

where \( SF \) is the daily proxy snowfall (in), \( P \) is the daily precipitation (in), and \( T_{avg} \) is the daily average temperature (°F);

**Moderate/Cold:**

\[ SF = 2.081 + (12.331 \times P) - (0.031 \times [T_{avg} + 20]) - (0.186 \times P^{1/2}) \] \[2\]

**Heavy/Cold:**

\[ SF = 19.237 + (7.266 \times P) - (0.346 \times [T_{avg} + 20]) - (0.245 \times [T_{max} - T_{min}]^{1/2}) \] \[3\]

where \( T_{max} \) is the daily maximum temperature (°F) and \( T_{min} \) is the daily minimum temperature (°F);

**Light/Mild:**

\[ SF = 0.551 + (5.017 \times P) - (0.014 \times T_{max}) \] \[4\]

**Moderate-Heavy/Mild:**

\[ SF = -3.563 + (4.346 \times P^{1/2}) + (3969.927 \times T_{max}^{2}) \] \[5\]

While well fitted to MSP, the Heavy/Cold formulation overestimated snowfall across the majority of sites in the study, especially for very heavy snowfall amounts. To correct this, we subdivided the category into additional categories of precipitation amounts: Heavy-1, from 0.43 to 0.69 in (10.92 to 17.53 mm); Heavy-2, from 0.70 to 0.89
in (17.78 to 22.61 mm); and Heavy-3, at 0.90 in (22.86 mm) or greater. The average of the errors across all stations was used for each precipitation cluster to define the adjustment applied to the measurements. The adjusted formulas for the Heavy/Cold category are:

**Heavy-1/Cold:**

\[
SF = 19.237 + (7.266 \times P) - (0.346 \times [T_{avg} + 20]) - (0.245 \times [T_{max} - T_{min}]) - 3.3 \ [6]
\]

**Heavy-2/Cold:**

\[
SF = 19.237 + (7.266 \times P) - (0.346 \times [T_{avg} + 20]) - (0.245 \times [T_{max} - T_{min}]) - 4.0 \ [7]
\]

**Heavy-3/Cold:**

\[
SF = 19.237 + (7.266 \times P) - (0.346 \times [T_{avg} + 20]) - (0.245 \times [T_{max} - T_{min}]) - 6.4 \ [8]
\]

Snowfall was overestimated in the milder climatologies in the Moderate-Heavy/Mild formulation, but after investigation, several of these instances included ice storms 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, while two were associated with thunderstorms, and the remaining 3 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. Thus, the Moderate-Heavy/Mild formula was left unadjusted.
Stations in the southern Great Lakes with milder temperatures but moderate to heavy snow due to lake-effect snowfall (defined more clearly in section 4a), such as Buffalo, New York (BUF), were noted to have a negative snow bias through all regimes using the Fisk (2008) formulation. 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 outside of 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 methodology used by the USDA (2004). Using the degree-day methodology, daily snowpack ablation can be calculated as follows:

\[ M = C_m (T_a - T_b) \]

where the “melting” factor, \( M \), is proportional to the difference between the daily average temperature \( T_a \) and a base temperature \( T_b \) (°F) as well as to a degree-day coefficient \( C_m \) (in °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 based on changes in the length of daylight and the solar angle (Table 4).

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

\[ C_f = e^{-0.08 \cdot \sqrt{0.2}} \]  

[10]

When added to or subtracted from the previous day, the snow depth calculation is as follows:

\[ SD_n = [SD_{n-1} \cdot C_f] - M + (SF_n \cdot C_f) \]  

[11]

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 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 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 as 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 should allow the snow proxy to correct some biases 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 based on how well pAWSSI captures early and late season snow events; this could have a downstream impact on the total winter accumulation, as 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 (Figure 1). The temperature component of AWSSI (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 were determined to provide a description of the character of winter seasons at each site. Figure 2 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 experiences of its citizens. A total AWSSI of 600 would be near average severity in Omaha, Nebraska (OMA), the record mildest in Fargo, North Dakota (FAR), and 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 Figure 3, 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 setting their record lowest AWSSI.

Geographical clusters of winter characteristics were noted with even this small sample of sites. Figure 4 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 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 moderate to high AWSSI-temperature, while still
receiving a moderate AWSSI-snow contribution that was slightly dominated by AWSSI-
temperature. The southern Great Lakes were milder yet, but still receive ample snow,
and the ratio of temperature to snow contribution was slightly lower than areas just to
the north that were a little colder and thus had a higher temperature contribution. The
northern Plains to 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 temperature dominance and moderately cold temperature climatologies, indicating
that snowfall overall is a low contribution. Rocky Mountain and foothills sites tended to
have higher temperature contribution for their latitude than the nearby Plains sites,
with a moderate to high snow total that still was dominated by the temperature
contribution. Both the southern Plains and the Southeast were characterized by low
AWSSI-temperature, very low AWSSI-snow, and a high ratio of temperature to snow
contribution, though the Plains climatology overall is drier in the winter than the
Southeast.

b. $p_{\text{AWSSI}}$
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). In this case, the authors chose to run the indices on threaded data sets to create the longest possible periods of record; only 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. Visually, 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 (Figure 5).

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, as agreement was acceptable at all sites, despite a few year-to-year variations.

c. In-depth site analysis: Omaha, Nebraska

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 2012-13, from beginning to end of the season, is plotted in Figure 6. 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.
While the average accumulation is a smooth slope that starts slowly early in the season, peaks around January to early February, and rises more slowly again late in the season, the individual years rise with some larger jumps during significant snow or cold outbreak events, with lower or even nil accumulation (flat lines) in between. Some winters are characterized by early season severity and late season mildness, while 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 one standard deviation envelope.

Investigating the relative contribution of AWSSI-temperature and AWSSI-snow also provides insight into the character of winter seasons. In Figure 7, 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, while 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

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; Kunkel et al. 2009b; 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 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 non-homogenized 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 5 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 Excel 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 is consistent with observed trends in winter temperatures. Also consistent with previous studies, 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 the AWSSI is to track a winter season in progress, placing it in the context of previous winters to ascertain its severity to date and 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 Figure 8 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, as 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 example, in the Detroit Area (DTWthr), 2013-2014 ranked as the highest AWSSI on record compared to the analysis period 1950-51 to 2012-13, surpassing notably cold and snowy winters in the late 1970s (Figure 9). Meteorological records in Detroit, however, date back to 1874-1875, 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 2013-2014 would rank as the third most severe,
trailing the winters of 1874-1875 and 1911-1912 and just passing the winters of 1876-1877, 1903-1904, and 1880-1881 (Figure 10). 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, though not the most severe on record.

While it would not be recommended to use pAWSSI to describe the accumulation from individual events, 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 I 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, using either the value of AWSSI to directly compare severity or normalized values to compare relative severity. The threshold-based calculations are forgiving of minor observational errors and adjustments, such as
station moves, thus allowing it to be applied successfully to threaded and long-term historical sites. In cases when 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 as these are not reported in widely accessible daily climate reports, nor are they measured at the majority of climate stations. Temperature and snow thresholds, though set with impacts in mind and tested for sensitivity, are arbitrary and 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 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 to the dabbling duck abundance explored by Schummer et al. (2010), as well as other wildlife populations and their markers of abundance, migration, or health. The index could be 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.

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.

As with any meteorological or climatological parameter, the relationship of AWSSI and pAWSSI to climate variability signals such as the El Nino/Southern Oscillation (ENSO), Arctic Oscillation (AO), North Atlantic Oscillation (NAO), and Pacific Decadal Oscillation (PDO), can be assessed from both statistical conditional climatology and dynamical attribution approaches. 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. 2013), 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 based on 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 are available, the values (e.g., climatological averages, seasonal totals) could be more reliably mapped and displayed for 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?*

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Table Captions

Table 1. Sites included in the AWSSI analysis, along with their respective mean AWSSI and number of missing years for the analysis period.

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

Table 3. Category labels, descriptions, percentiles, and color coding for AWSSI.

Table 4. Seasonally-varying values of \( T_b \) and \( C_m \) used to calculate pAWSSI.

Table 5. Trends in AWSSI, AWSSI-temperature, and AWSSI-snow for the period 1950-51 to 2012-13. Italicized sites are pAWSSI, with periods of record starting years ranging from 1872 (OMAthr-C) to 1889 (URB-C). Significance \( P(x) \) is denoted by + = 0.10, * = 0.05, ** = 0.01, and *** = 0.001.
Table 1. Sites included in the AWSSI analysis, 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.

<table>
<thead>
<tr>
<th>City, State</th>
<th>ID</th>
<th>Avg AWSSI</th>
<th>No. Missing</th>
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<tbody>
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<td>1265</td>
<td>1</td>
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<td>Albany, NY</td>
<td>ALB</td>
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<td>0</td>
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<td>0</td>
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<td>2</td>
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<td>0</td>
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<td>BOS</td>
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<td>11</td>
</tr>
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<td>BUF</td>
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<td>0</td>
</tr>
<tr>
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Table 2. Point contributions to daily AWSSI based on thresholds of daily maximum and minimum temperature, snowfall, and snow depth.
<table>
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<tr>
<th>Category</th>
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<tr>
<td>W-1: Mild</td>
<td>Min to 20th percentile</td>
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<td>W-2: Moderate</td>
<td>21st to 40th percentile</td>
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<tr>
<td>W-3: Average</td>
<td>41st to 60th percentile</td>
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<tr>
<td>W-4: Severe</td>
<td>61st to 80th percentile</td>
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<td>W-5: Extreme</td>
<td>81st percentile to max</td>
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Table 3. Category labels, descriptions, percentiles, and color coding for AWSSI.
<table>
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<tr>
<th>Period</th>
<th>$T_b$</th>
<th>$C_m$</th>
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<tr>
<td>Up to 1 Dec</td>
<td>32</td>
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</tr>
<tr>
<td>1 Dec to 15 Jan</td>
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<tr>
<td>16 Jan to 9 Feb</td>
<td>23</td>
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<tr>
<td>10 Feb to 6 Mar</td>
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<tr>
<td>7 Mar to end</td>
<td>30</td>
<td>0.30</td>
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Table 4. Seasonally-varying values of $T_b$ and $C_m$ used to calculate pAWSSI.
Table 5. Trends in AWSSI, AWSSI-temperature, and AWSSI-snow for the period 1950-51 to 2012-13. Italicized sites are pAWSSI, with periods of record starting years ranging from 1872 (OMAthr-C) to 1889 (URB-C).

Significance $P(x)$ is denoted by $+ = 0.10$, $* = 0.05$, $** = 0.01$, and $*** = 0.001$.

<table>
<thead>
<tr>
<th>Location</th>
<th>AWSSI Sig</th>
<th>AWSSI Temp Sig</th>
<th>AWSSI Snow Sig</th>
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Figure Caption List

Figure 1. AWSSI total accumulation for each winter from 1950-51 to 2012-13 (excluding years with missing data) for all sites.

Figure 2. Box-and-whiskers diagram of AWSSI through the analysis period of 1950-51 to 2012-13 (excluding years with missing data) for each site. Middle line is the median, blue box includes the 25th to 75th percentile range, lower dot is the minimum value, and upper dot is the maximum value. Sites are arranged in order from highest mean to lowest mean.

Figure 3. AWSSI and normalized AWSSI for the winters of 2009-10 (top) and 2011-12 (bottom), with AWSSI values color-coded by category per Table 3. Italicized values are record lows at the site.

Figure 4. Average AWSSI for the analysis period (1950-51 through 2012-13) at each site, with percent contribution from the temperature component.

Figure 5. AWSSI (solid lines) and pAWSSI (dashed lines) for Minneapolis/St. Paul Area (MSPthr) and Urbana, Illinois (URB).
Figure 6. AWSSI accumulations for 1950-51 through 2012-13 for OMA (excluding 1979-1980, 1985-86, 1996-97, 1997-98, and 2003-04). Thick black line is the average for the analysis period, and thick dashed lines are ±1 standard deviation.

Figure 7. Total AWSSI accumulation, broken into temperature (blue) and snow (green) contributions, at OMA for 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.

Figure 8. Sample graphic for tracking an ongoing winter season, in this case for OMA in 2013-2014. Blue shaded curve is the current season accumulation, and light blue bars are the contributions from individual days (scaled on the right side). Other curves included the highest-ranking (most severe) 5 years, the lowest-ranking (least severe) year, and the previous year (2012-2013).

Figure 9. As in Figure 8, but for Detroit Area (DTWthr).

Figure 10. Period of record for Detroit Area AWSSI (solid) and pAWSSI (dashed). Seven years have had either AWSSI or pAWSSI exceed 1100: 1874-1875, 1876-1877, 1880-1881, 1903-1904, 1911-1912, 1977-1978 (pAWSSI only), and 2013-2014.
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CHAPTER 3. THE INFLUENCE OF ENSO AND NAO ON WINTER WEATHER IN THE CENTRAL UNITED STATES.

Abstract

Climatological teleconnection patterns, including the El Niño—Southern Oscillation (ENSO) and the North Atlantic Oscillation (NAO), have known associations with variables such as winter seasonal and subseasonal temperature and precipitation in North America. Both ENSO and NAO events, individually and in combination, are demonstrated here to have significantly influenced station-based winter temperature, precipitation, and severity across the central United States during the period 1950-2013, and the statistical signals are supported by composite analysis of synoptic patterns influencing the region during the winter. Broad hemispheric diagrams of potential influence of both ENSO and NAO are widely available, but most of those available largely overlook the central United States as a region influenced by these teleconnection patterns. Thus, quantifying the influence of both patterns, as well as understanding the changes to the synoptic environment as a result of the patterns, is important to fill the gap, allowing meteorologists and climatologists to more confidently provide information about the impacts of both ENSO and NAO events to citizens and decision-makers. Additionally, the connection between statistical results and synoptic composites provides a bridge from climate to weather patterns that allows meteorologists to
anticipate potential cause-and-effect relationships between teleconnection patterns and local and regional sensible weather.
1. Introduction

Both the El Niño—Southern Oscillation (ENSO) and the North Atlantic Oscillation (NAO) are associated with variables such as winter seasonal and subseasonal temperature and precipitation in North America. ENSO affects synoptic patterns across the continental United States, particularly by its impact on the upper tropospheric jet stream position. Likewise, NAO is associated with changes in sea level pressure and upper-level jet strength over the Atlantic Ocean, with upstream impacts affecting North American temperatures and precipitation distribution. While ENSO and NAO are two of many factors that influence global circulations, and by distillation may have a less distinguishable influence on the synoptic weather pattern, coherent signals can be uncovered in the synoptic environment based on ENSO phase and NAO phase individually, as well as combinations of phases of each pattern, that influence winter temperatures and precipitation in the central United States.

Interannual variability in the mean climate state often is described by teleconnections, or oscillations in the mean atmospheric and oceanic circulations that are associated with changes in the mean state of the atmosphere elsewhere around the globe. Teleconnections are identified by statistical relationships between a source region (e.g. sea-surface temperatures in the equatorial Pacific Ocean, as with ENSO) and centers of action where atmospheric response is maximized (e.g. precipitation along the Gulf Coast). Numerous statistical methods exist to identify these relationships, ranging from simple statistical correlations to more complex rotated principal component analysis (RPCA). Barnston and Livezey (1987), for example, utilized RPCA to identify 700
hPa patterns associated with numerous modes of interannual variability. NAO was included in their analysis and was the only one of thirteen teleconnection patterns to indicate a significant pattern correlation in all twelve months of the year. (ENSO was not among the teleconnection patterns studied by Barnston and Livezey [1987].)

Sardeshmukh et al. (2000) determined that the seasonal atmospheric response of El Niño is stronger but more variable than that of La Niña, which they attribute to greater variability of seasonal rainfall in the central equatorial Pacific Ocean during El Niño. Centers of action with the highest correlation to SSTs in the equatorial Pacific Ocean focus on the Aleutian low, Canadian surface pressure, and pressure in the Gulf of Mexico, where roughly 25% of seasonal variance is explained (Diaz et al. 2001). Mid-continental North America is fairly far removed from these centers of action, with lower correlations. Even so, ENSO remains one of the few teleconnection patterns with at least some correlation in the continental regions that also has seasonal predictability.

The relationship between ENSO phase and cold season weather impacts in the central United States, while not as well covered as impacts to the coastal margins, has been investigated in previous publications. Patten et al. (2003) investigated the relationship between ENSO phase and snowfall frequency across the United States for the period 1900-1997, investigating light, moderate, or heavy snowfall frequencies by ENSO phase. The continental United States was divided into subregions to allow regional conclusions; the Midwest area (encompassing Iowa, northern Illinois, southern Wisconsin, and southern Minnesota) and the Northern Plains (encompassing Nebraska, South Dakota, and North Dakota) behaved similarly to each other and generally in an
opposite sense to the Northern Lakes region (encompassing northern Minnesota, northern Wisconsin, and the Upper Peninsula of Michigan). Compared to ENSO-neutral years, the Midwest and Northern Plains exhibited increased light snow frequency during El Niño events, with little signal for moderate or heavy snow frequency. The Northern Lakes region exhibited increased moderate snow frequency during La Niña events, as well as decreased frequencies of moderate and heavy snow during El Niño events, with little signal for light snow frequency. The gradient of snow frequency impacts from north to south in the central United States does raise the question of whether the changes are due to changes in precipitation amounts or temperatures. Bunkers et al. (1996) found significantly higher cold season precipitation in the Northern Plains during El Niño events, as well as significantly lower precipitation and temperatures during La Niña.

NAO is not as well documented as ENSO, and its influence on mean atmospheric circulation is less direct. Its characteristics are entwined with the closely related Arctic Oscillation (AO), which is defined by its impacts on polar stratospheric circulation. The trigger for NAO is not well known, though recent studies indicate a possible connection between the AO and October snow cover in Siberia (Cohen and Jones 2011). Unlike ENSO, which is associated with an SST anomaly that persists through the season, the NAO index is variable on a weekly to monthly timescale. Its seasonal impact is ascertained from the strength of the index and persistence of one phase over the other through the season (Hurrell and Deser 2009). Nonetheless, NAO is associated with as much as a third of the variance of sea level pressure over the northern Atlantic Ocean.
(Hurrell and Deser 2009). The positive phase of NAO is associated with an anomalously strong Icelandic low and Azores high, with an increased pressure and height gradient between the two pressure centers (Figure 3). Anomalously strong westerly winds are associated with the increased gradient, which in turn is associated with warm southerly flow into the eastern United States, increased warm air advection into western Europe, and cold air lingering over Greenland and the Canadian Arctic. The negative NAO phase is associated with a weakening of the pressure gradient, as the Icelandic low and Azores high both weaken. The resulting anomalously weak westerly flow is associated with a weaker, meandering jet, allowing troughing to persist in eastern North America and driving cold air southward into eastern North America and western Europe, while anomalous warming becomes entrenched over Greenland.

Far fewer studies have been conducted regarding the impact of AO/NAO on weather anomalies in the United States, but a few recent studies have begun to add to the knowledge base of the impact of AO/NAO. Cohen et al. (2010) documented the impact of the extreme negative AO event on the Northern Hemisphere during the winter of 2009-10. The study linked the very strong AO forcing to the anomalously cold temperatures across much of the central and eastern United States and Europe, and utilized model analysis to both demonstrate the predictive value of Siberian snow cover and isolate the impact of AO from ENSO forcing. Their results indicated that the contribution from AO explained most of the observed temperature variance over the Northern Hemisphere extratropical region during that winter. The results are consistent
with other studies that suggest that AO/NAO explains more variance in winter temperatures across the central and eastern United States than ENSO.

Additional studies have addressed the combined influence of ENSO and NAO during the winter in the United States. Higgins et al. (2002) explored relationships of ENSO and NAO, including the combinations of the two oscillations, to the frequency and probability of extreme temperature events across the United States. Their study determined that temperature extremes are more likely during La Niña and less likely during El Niño; also, negative NAO is associated with an increase in the number of cold days and a decrease in the number of warm days, while positive NAO brings an increase in warm days and a decrease in cold days, though little shift in the number of extreme temperatures was discernible. Griffiths and Bradley (2007) focused more specifically on the northeast United States while investigating temperature and precipitation extremes attributable to ENSO and NAO, also including the combinations of the two oscillations. The study defined nine indicators of climate extremes, including frost days, growing season length, and consecutive dry days, to investigate trends and interannual variability. The results were consistent with other studies, in that positive AO winters are associated with warmer conditions in the Northeast, while negative AO is associated with colder winters. Also, El Niño was associated with an increase in consecutive dry days in the Northeast, while the impact on consecutive dry days during La Niña was modulated more by AO, with a decrease in dry days during positive and neutral AO and more regional variability during negative NAO. Thus, a precedent for observational and
statistical studies of the combined influence of ENSO and NAO does exist, though previous studies have not specifically focused on the central United States.

The purpose of this study is to document the statistical relationships between both ENSO and NAO on winter season temperatures and precipitation in the central United States using a collection of station-based data, then analyze composites of synoptic parameters to provide physical reasoning for observed statistical shifts. Methods used in this study can be replicated for additional sites around the region, as well as around the country, to further document the influence of these teleconnections on those sites. The information can be used to provide context and attribution to historical winters, especially those on either the mild or severe extremes. Additionally, combinations of ENSO and NAO that produce particularly strong tendencies can be documented to provide information on past behavior to stakeholders and decision-makers when those combinations reoccur in the future.

Data sets used in this study, as well as the methodology for investigating the relationships among the teleconnection patterns and meteorological variables, are presented in section 2. Section 3 will provide statistical analysis of relationships of ENSO to winter weather parameters, as well as synoptic perspective on the statistical relationships; section 4 will do the same for NAO, and section 5 will draw relationships with both parameters. Finally, summary and conclusions are presented in section 6.

2. Data and Methodology

a. Statistical analyses
A sample of 26 stations was selected for analysis, largely located in the north central United States from the High Plains and central Plains to the Great Lakes and Ohio River valley (Table 1). Stations were chosen based on completeness of records and spatial distribution in representative locations. Both homogenized data and raw observations from the Applied Climate Information System (ACIS; Hubbard et al. 2004) were used, depending on the variable being analyzed. These 26 station-based temperature and precipitation variables were analyzed for statistically significant relationships with both ENSO and NAO. All variables were examined from the winter of 1950-51 through 2013-14.

In addition, the Accumulated Winter Season Severity Index (AWSSI; Boustead et al. 2014) was analyzed at several sites. AWSSI assigns points to each day of a winter season based on thresholds of maximum and minimum temperatures, as well as snowfall and snow depth; the sum of points through a winter season characterizes the severity of that season, as well as a time series of AWSSI for all winters on record at a station. Additionally, a precipitation-based AWSSI (pAWSSI) estimates snowfall and snow depth based on temperature and precipitation observations, allowing time series analyses of sites with incomplete or questionable snow records. For this study, sites with AWSSI time series that did not exhibit significant trends were analyzed in both AWSSI and pAWSSI calculations, as well as with the temperature and snow components of the calculation.

The statistical technique used in this study follows Timofeyeva et al. (2014), employing a sampling technique based on the conditional probability of a given event
occurring based on the ENSO phase or NAO index. The result is a conditional climatology of a given variable based on the ENSO phase or NAO index. The methodology incorporates a standardized method for developing climatologies of the given parameter for each ENSO phase (La Niña, neutral, and El Niño) or NAO index (negative, neutral, and positive) in comparison to the climatology of the period of record, as well as incorporating a test for statistical significance of the results to determine if deviations from the average climatology are significant relative to the null hypothesis that there is no relationship between ENSO phase or NAO index and each climatological variable. In order to test for statistical significance, the compositing analysis methodology determines whether a significant (α = 0.10) relationship exists between ENSO or NAO and the climatological variable. The probability of a given climatological variable occurring in the above, near, or below normal categories exactly \( x \) number of times, \( P(x) \), within a given ENSO phase or NAO index is determined by comparison to a hypergeometric distribution. If the number of occurrences, \( x \), falls within the lower 10% or upper 10% of the distribution, the event is deemed statistically significant, and the null hypothesis that the climatological variable occurred in the above, near, or below normal category during a given ENSO phase by chance is rejected.

Given the long history of analyzing ENSO, there are a number of indices that have been developed to quantify ENSO state. In this study, we will use the National Oceanic and Atmospheric Administration (NOAA) operational Oceanic Niño Index (ONI) data set available from NOAA Climate Prediction Center (CPC), which spans the period from 1950 to present. ONI is widely used in NOAA applications of ENSO studies, as well
as in the operational definition of El Niño and La Niña utilized by CPC, which defines an El Niño (La Niña) episode by the presence of a sea surface temperature (SST) anomaly greater (less) than 0.5 °C (-0.5 °C) in the Niño3.4 region for five consecutive three-month-average periods (Kousky and Higgins 2004). There are limitations with this data set, of course. The first is that it does only exist from 1950 to present, and thus historical analysis prior to 1950 will require use of additional data. Second, the requirement for five consecutive three-month periods does omit years in which the anomalies were met for a shorter period of time but did influence atmospheric patterns. In this case, the consistency of the ONI was deemed more desirable than being inclusive of all El Niño-like and La Niña-like atmospheric responses.

Most of the statistical testing was completed using the NOAA Local Climate Analysis Tool (LCAT), but some parameters not available in LCAT were tested using Microsoft Excel spreadsheet analysis that employs the same methodology. ENSO data are available from December-January-February 1950 through the most recent complete three-month period. For ENSO, LCAT allows trend-adjusted analysis of average, maximum, and minimum temperature and total precipitation for 3-month periods using homogenized station data (Menne et al. 2009). Additionally, LCAT allows trend-adjusted analysis of impacts of ENSO on monthly extremes of maximum and minimum temperature, precipitation, and snowfall using Applied Climate Information System (ACIS; Hubbard et al. 2004) station data. For each variable, the December-January-February (DJF) and January-February-March (JFM) data were examined for trends for
the period 1925-2014, then detrended for ENSO conditional climatology analysis for the period 1950-2014 to isolate the variability signal from the trend.

As with ENSO, there is no single data set that defines NAO, and many analyses exist (Hurrell and Deser 2009). In fact, there is no accepted definition of NAO that differentiates between positive, neutral, and negative phases, if a neutral phase is included in the analysis. For that reason, this study used thresholds of both ±0.5 and ±1.0 standard deviations to allow a comparison between a lower threshold that produces a more even distribution of years among the phases and a higher threshold that accounts for the more moderate to strong episodes but produces a smaller sample size in both the negative and positive NAO phases.

LCAT also was used to analyze the impact of NAO through the same time periods and variables. Analysis of NAO is available from January 1950 through the most recent month, but LCAT does not allow trend adjustment for NAO statistical analyses. Otherwise, the available data to analyze encompass the same fields and time periods. For the LCAT analyses, thresholds of both ±1.0 and ±0.5 were used, since the boundaries of a neutral phase of NAO remain undefined; while the results were substantially similar, they will be contrasted when that is not the case. NAO data within the LCAT system are compiled from the NOAA National Weather Service (NWS) Climate Prediction Center (CPC; available online at http://www.cpc.ncep.noaa.gov/products/precip/CWlink/pna/norm.nao.monthly.b5001.current.ascii). The data extend from January 1950 to the most recent day, with the most recent complete month available in LCAT by averaging the daily values to create a

AWSSI time series were not available in LCAT and were analyzed manually, following the same statistical methodology. Following the methodology of Timofeyeva et al. (2014), only sites with no significant trend in AWSSI or its contributing components and with minimized missing years were included in the variability analysis, leaving just a handful of sites in which all AWSSI components could be analyzed: Aberdeen, South Dakota (ABR), Dodge City, Kansas (DDC), North Platte, Nebraska (LBF), Omaha, Nebraska (OMA), Paducah, Kentucky (PAH), and Urbana, Illinois (URB), for AWSSI and Des Moines, Iowa (DSM) and URB for pAWSSI.

For the analysis of AWSSI and NAO, in addition to the CPC data, analyses were conducted utilizing data from the Climate Analysis Section of the National Center for Atmospheric Research (NCAR; Hurrell and NCAR 2013; available online at https://climatedataguide.ucar.edu/climate-data/hurrell-north-atlantic-oscillation-nao-index-station-based), with data extending from 1864 through the most recent complete winter season. In this data set, the NAO index is based on the difference in normalized sea level pressure (SLP) between Lisbon, Portugal, and Stykkisholmur/Reykjavik, Iceland. Hurrell normalized the SLP anomalies at each station by dividing the seasonal mean pressure by the standard deviation of the long-term mean (1864-1983). Normalization
is used by Hurrell to avoid the series being dominated by the greater variability of the northern station. The Hurrell and CPC methods will be compared among the results.

b. Composite analyses

In addition to the statistical analyses, composite analyses of synoptic environmental parameters were examined for physical reasoning to support statistical conclusions. Gridded data available from 1948 to 2014 through NOAA Earth Systems Research Laboratory (ESRL) were used to create composite synoptic plots (available online at http://www.esrl.noaa.gov/psd/cgi-bin/data/composites/printpage.pl) using NCEP/NCAR reanalysis (Kalnay et al. 1996). For this analysis, the winters of 1950-1951 through 2012-2013 were included, with anomalies based on the 1981-2010 base climatology. The 63 years in the sample were binned into the three ENSO phases for analysis; similarly, the three NAO phases were binned into three phases based on the $\pm0.5$ threshold. Then, all years were binned into one of the nine possible combinations of ENSO and NAO to examine the combined influence of both teleconnection patterns (Table 2). The composite plots were analyzed manually for synoptic pattern coherence to the tendencies noted in the statistical analyses.

The combination of statistical relationships among the data sets and analyses of average synoptic patterns during different combinations of teleconnection patterns provides insight into the impact on wintertime temperatures and precipitation in the central United States. The analysis period years from 1950-1951 through 2012-2013 first were investigated through their three ENSO phases and their three NAO phases,
separately, to ascertain dominant synoptic patterns and anomalies. Years in each of the categories were compositored to investigate common synoptic environmental parameters and their anomalies to search for prevailing patterns that characterize each phase. Then, the analysis period years were divided into nine categories based on the combination of ENSO and prevailing NAO phases through the winter months of DJF and/or JFM. For both ENSO and NAO, in years when a neutral phase existed for either DJF or JFM with a threshold into another phase reached during the other three-month period, the non-neutral phase was used to classify the winter. The periods of DJF, JFM, and December-January-February-March (DJFM) all were investigated and found to be substantially similar; thus, the broader DJFM analyses were used. The physical basis supporting the statistical anomalies can provide confidence in the direction of favored conditions during each ENSO and NAO phase, and the combined composites can help investigate whether ENSO or NAO dominates for given combinations of phases.

3. Statistical Results

a. ENSO

Robust statistical relationships were noted between ENSO phase and both temperature and precipitation at each of the 26 sites investigated, exhibiting spatial consistency (Table 3). A site can shift toward warm conditions, for example, via a significantly higher than usual chance for above normal temperatures or a significantly lower than usual chance for below normal temperatures; similarly, a site can shift
toward cold conditions via a significantly higher than usual chance for below normal
temperatures or a significantly lower than usual chance for above normal temperatures.

Every site in the sample exhibited a shift in the odds toward warmer conditions
during El Niño among at least one of the five temperature variables assessed for at least
one of the two three-month periods. Only one site displayed an apparent inconsistency,
as LBF exhibited a significant shift toward warmer temperatures in three temperature
variables (increased potential for warm minimum temperature in DJF and JFM and
average temperature in DJF) but also shifted toward colder temperatures with one
variable (increased potential for cold maximum temperatures). The results may not be
inconsistent if a strong signal for minimum temperatures is overwhelming the weaker
signal for maximum temperatures. Precipitation results were a little less robust.

Notably, twelve sites did exhibit a tendency toward lower snow extremes, and none
exhibited a tendency toward higher snow extremes. In two locations, Aberdeen, South
Dakota (ABR), and Bismarck, North Dakota (BIS), the snow tendency opposed the
precipitation tendency, which was toward wetter conditions, indicating that the
influence of temperatures may have overwhelmed the increase in winter precipitation
to lead to a decrease in potential for higher snow extremes. Six sites from the northern
Plains to the High Plains exhibited a tilt toward wetter conditions, while nine sites in the
Great Lakes to Corn Belt area tilted toward drier conditions. OMA exhibited a tendency
toward lower AWSSI and lower of both the temperature and snow components during
El Niño, while Huron, South Dakota (HON), tended toward lower AWSSI and
temperature component and URB tended toward lower AWSSI (Table 3).
A robust signal also was apparent for the ENSO-neutral phase, favoring cold conditions across a majority of sites from the central Plains to the Great Lakes. Conversely, not a single site among those studied exhibited a potential for warm conditions during the ENSO-neutral phase. Precipitation results indicated a tendency toward increase snow extremes at two sites, Moline, Illinois (MLI), and Madison, Wisconsin (MSN), with no decreased snow extremes indicated. Only one site exhibited a tilt toward wetter conditions during ENSO-neutral phase (URB), while seven sites across the central to northern Plains exhibited a tilt toward drier conditions. At URB, the neutral ENSO phase also exhibited a significant relationship with higher AWSSI. The results support an indication that the ENSO-neutral phase is not merely an in-between phase, but rather that it also carries tendencies and favored weather patterns that support such widespread and consistent results.

Temperature results for La Niña were more regionally divided. The northern Plains to northern Great Lakes sites exhibited the strongest tendencies toward cold conditions in La Niña. Southern sites exhibited tendencies toward warm conditions in La Niña, though two of those sites, St. Louis, Missouri (STL), and DDC, also had conflicting tendencies toward cold conditions for one temperature variable. Just two sites, Denver, Colorado (DEN), and DDC, indicated a tilt toward drier conditions, while twelve sites across the northern Plains to the Great Lakes exhibited a tilt toward wetter conditions. Additionally, seven sites in the same region exhibited a potential for increased snow extremes. DDC exhibited a tendency toward lower AWSSI as well as a lower snow
component of AWSSI during La Niña, consistent with the variable-based results. HON tended toward a higher snow component of AWSSI during La Niña (Table 4).

b. NAO

Relationships between NAO and temperature variables were robust and consistent for both the ±0.5 and ±1.0 thresholds of analysis (Table 5; ±0.5 shown). Every site in the analysis exhibited a trend toward cold conditions during the negative phase of NAO in at least five temperature variables with the lower ±0.5 threshold; when the more stringent ±1.0 threshold was applied, for at least one temperature variable at every site, no instances of temperatures in the above normal category were observed. Even among the larger sample size of the ±0.5 threshold, many sites still had at least one case of no observed instances of the above normal category for at least one temperature variable. No sites recorded any tilt toward warm conditions in the negative NAO phase.

The influence of the positive phase of NAO on temperature was nearly as strong as the negative phase, and it was more robust for the lower ±0.5 threshold than the more stringent ±1.0 threshold. With the ±0.5 threshold, every site exhibited an inclination toward warm conditions in at least two temperature variables; no sites exhibited a tendency toward cold conditions. At the ±1.0 threshold, the tilt toward warmer conditions existed at most but not all sites, with the northernmost sites largely excluded and with a tilt toward colder conditions at Havre, Montana (HVR).
Neutral phase temperature tendencies were more ambiguous, with fewer overall relationships and with several sites changing sign of their tendencies between the two thresholds as the sample size and years changed. The weak coherence indicates a lack of strong relationship between neutral NAO and temperatures, with trends and other climate forcings such as ENSO likely influencing the signal. That said, there was a signal with at least some spatial coherence for a weak tendency toward warmer conditions among the High Plains and Rocky Mountain foothills sites, such as Cheyenne, Wyoming (CYS), Rapid City, South Dakota (RAP), DDC, DEN, and LBF, with an even weaker signal at ABR, HVR, MLI, OMA, and URB that at least was not contradicted by changing thresholds.

While it is clear from the statistical analyses that NAO exerts a strong influence on temperature, its influence on precipitation is less clear and far less robust. Weak relationships between precipitation and NAO phase were observed. In several instances, the signals were in opposite directions for the same site depending on the variable, threshold, and three-month period being analyzed. The reliability of these signals is questionable and not considered robust enough to report. With those aside, a few weak but statistically significant signals do emerge. During the negative phase of NAO, a number of sites from the Great Lakes to the Corn Belt and Plains tend slightly toward dry conditions, while the more northern to northwestern sites of Duluth, Minnesota (DLH), International Falls, Minnesota (INL), BIS, DEN, HVR, and RAP tilt toward wet conditions. The Great Lakes to Corn Belt and Plains also tends slightly toward wet conditions during positive NAO.
The snowfall monthly extreme does not follow the tendency of precipitation to increase during positive NAO at all sites with a discernible tendency toward wet conditions; instead, the signal is split, almost certainly due to the competing influence of the tendency toward higher temperatures. Particularly compelling evidence that the influence of temperatures exceeds that of precipitation exists when noting that the sites with lower snowfall tendencies are dominated by those in climatologies with more marginal winter snow totals: DDC, DSM, STL, and URB. Just one site tends toward higher snow extremes coupled with a tendency toward wet conditions during positive NAO: Sault Ste. Marie, Michigan (SSM).

The influence of NAO on AWSSI was pervasive across all sites east of the Rocky Mountains (Table 4). Every site investigated exhibited either a significant tendency toward higher AWSSI during negative NAO or a significant tendency toward lower AWSSI during positive NAO, or in some cases both. The relationship was particularly strong with AWSSI-temperature, though some sites exhibited parallel tendencies in AWSSI-snow, as well.

4. Synoptic Environmental Analysis

To provide a baseline of comparison for anomalies, the anomalies for the full 1951-2013 period are in Figure 1. The full analysis period was compared to 1981-2010 climatology for the anomalies of six synoptic environmental parameters: 300-hPa vector winds, 500-hPa geopotential height, surface sea level pressure, surface air temperature, precipitable water, and 850-hPa specific humidity. Because the
precipitable water and 850-hPa specific humidity anomalies exhibit similar patterns, the remaining sections will focus on precipitable water to examine moisture anomalies.

a. ENSO

Canonical ENSO upper-level patterns and surface reflections of upper-level features were noted in the three-phase ENSO composites for DJFM. Anomalously strong 300-hPa winds were noted across the Gulf of Mexico during El Niño, with suppressed upper-level jet in the central US but anomalously strong northwesterly winds just off the Pacific Northwest coast (Figure 2 a-c). During La Niña, 300-hPa wind anomalies were maximized off the coast of the Pacific Northwest and western Canada but extended across the central US to the Great Lakes, with negative (easterly) anomalies along the US southern tier. The 300-hPa pattern for neutral phases resembled a weaker version of the La Niña pattern, but it even more closely mirrored the 1951-2013 composite average (Figure 1a). At 500 hPa (Figure 3 a-c), negative geopotential height anomalies during El Niño were focused from off the Pacific Northwest coast to the southern tier of the US and the Gulf Coast, including the central Plains to southern Great Lakes, consistent with the enhanced upper-level jet and storminess across the southern US, with anomalously high heights in northern Canada near Hudson Bay. During La Niña, the 500-hPa geopotential height anomalies were strongly positive off the western US coast, with negative anomalies focused from the northern Rockies and western Canada across the northern and central Plains to the Great Lakes. During the neutral phase, as with the upper-level wind anomalies, the 500-
hPa geopotential height anomalies were similar in pattern to the La Niña phase but weaker in intensity, with weakly negative height anomalies in the northern Plains to northern Great Lakes.

The surface reflection of the upper-level pattern indicates a sea level pressure pattern consistent with the upper-level patterns in all phases, including low pressure anomalies across much of the US with the exception of the northern Great Lakes during El Niño, high pressure anomalies off the Pacific coast and low pressure anomalies in the central US during La Niña, and weak high pressure anomalies off the Pacific coast but no notable anomalies in the continental US during the neutral phase (Figure 4 a-c). For the composite period, surface temperature anomalies during El Niño were relatively weak, with slightly positive temperature anomalies in the South and a hint of negative temperature anomalies in the north central to northwestern US (Figure 5 a-c). Stronger surface temperature anomalies were noted during La Niña, with a shift to higher temperatures in the South and lower temperatures across the north central to northwestern US. During the neutral phase, the negative temperature anomalies across the northern US shifted toward the north central US to the Great Lakes, plunging deeper into the mid-Mississippi River valley.

Positive precipitable water anomalies were noted from Mexico across the Gulf of Mexico toward Florida during El Niño (Figure 6 a-c), consistent with an expected increase in storminess associated with the anomalously strong upper-level jet stream. Positive anomalies also were noted in the Pacific Northwest, with negative anomalies across the western Gulf Coast states toward the Ohio River valley. During La Niña,
strongly negative anomalies were noted across the Gulf of Mexico, including Florida. Negative anomalies also extended from Texas westward across the southwestern US, with weaker negative anomalies across much of the central and western US. Positive anomalies extended across parts of the Gulf Coast states toward the mid-Atlantic region. During neutral conditions, weakly negative anomalies were noted across the central Plains to Corn Belt, as well as in California, with positive anomalies spreading from the Gulf of Mexico into the South.

b. NAO

Distinct upper-level patterns and surface reflections emerged in the composites of the three NAO phases, again supporting known impacts and indicators. Negative NAO patterns are associated with anomalously high pressure in the north Atlantic and low pressure in the south Atlantic, weakening the gradient and hence the winds between the two centers of action; the reverse occurs during positive NAO. Composites of negative NAO show that 300-hPa wind speeds were anomalously strong along the jet axis across the southeast US toward Bermuda, with significantly suppressed upper-level winds from the northern Great Lakes and eastern Canada toward Greenland (Figure 2 d-f). In contrast, 300-hPa wind anomalies were weaker during positive NAO, with slightly enhanced winds from the Great Lakes and eastern Canada toward Greenland, while winds across the Gulf of Mexico toward Bermuda were slightly suppressed. Wind anomalies also were weak during neutral NAO, with slightly positive enhanced northwesterly winds off the coast of the Pacific Northwest that were reminiscent of the
1951-2013 composite average. Strong 500-hPa height anomalies were noted for negative NAO, with negative height anomalies across the entire continental US but especially in the eastern half of the country, and with positive height anomalies from northeastern Canada toward Greenland, both indicating a weakened height gradient across the US and Canada (Figure 3 d-f). As with the upper-level winds, anomalies during positive NAO were weaker, with negative height anomalies across most of Canada into the northern High Plains to Pacific Northwest and positive anomalies in the eastern US indicating an increased height gradient across the eastern half of the US in particular. During neutral NAO, anomalously low 500-hPa heights were noted from western Canada to the northwestern and north central US, in a pattern similar to composites of both ENSO-neutral years and the 1951-2013 composite average but with stronger anomalies.

Surface reflections of anomalies during the phases of NAO were even more distinct than the upper-level anomalies (Figure 4 d-f). Negative sea level pressure anomalies during negative NAO extended from the northern Atlantic Ocean across the eastern US and Great Lakes toward the central and southern Plains to central Rockies, with positive sea level pressure anomalies in northeastern Canada to northern Greenland and dipping into the northern Plains toward the Gulf of Alaska. During positive NAO, positive sea level pressure anomalies extended from the north Atlantic into New England, with negative pressure anomalies from central and western Canada through the north central US and as far south as the southern Plains. Neutral NAO sea level pressure anomalies again resemble the 1951-2013 composite average, with
negative anomalies in the lee of the Rockies and onto the High Plains and central Plains, and with positive anomalies off the northwestern US coast.

More than any other field, though, surface temperatures in the NAO phases were highly anomalous (Figure 5 d-f). During negative NAO, nearly the entire continental US was blanketed by negative temperature anomalies, with the strongest anomalies across the northern Plains to northern Great Lakes and also from the Ohio River valley toward the lower Mississippi River valley. Surface temperature anomalies were particularly intense in those regions during JFM (not shown). During positive NAO, positive temperature anomalies were strongest in the Southeast toward the mid-Atlantic region, though weakly positive anomalies extended into the central US. During neutral NAO, negative surface temperature anomalies were noted from the western Great Lakes northwestward into central and western Canada, similar to the 1951-2013 composite average; unlike the average, though, positive anomalies were noted from the Southeast toward the central Plains and also over the Great Basin.

Precipitable water anomalies were markedly negative across the continental US during negative NAO (Figure 6 d-f). The anomalies correspond to negative temperature anomalies in the same regions during negative NAO, and the two are interrelated as the water vapor capacity in the atmosphere decreases with decreasing temperature. During the positive phase of NAO, positive precipitable water anomalies extended from Mexico along the Gulf Coast and through the eastern Great Lakes toward the eastern US, with weakly negative anomalies from California through the southwestern states and toward
the southern High Plains. A similar pattern of anomalies was noted for neutral NAO conditions.

b. Combined ENSO-NAO

Upper-level features, particularly the 300-hPa winds, were dominated by ENSO tendencies rather than NAO. During El Niño, the anomalously strong westerly 300-hPa jet across the southern US and Gulf of Mexico were present in all phases of NAO, though it was strongest during negative NAO and the location of the strongest anomalies does shift based on NAO phase (Figure 7). The 300-hPa northwesterly wind anomalies off the coast of the Pacific Northwest that characterize La Niña were present in all phases of NAO, as were easterly 300-hPa wind anomalies across the southern US to the Gulf of Mexico that indicate suppressed upper-level jet activity there. The influence of negative NAO was present in all ENSO phases in the strongly anomalous easterly 300-hPa winds from northeastern Canada toward Greenland. Anomalous 300-hPa winds were weakest during ENSO-neutral conditions, regardless of NAO phase; the neutral and positive NAO phases in particular resembled the 1951-2013 composite average.

The 500-hPa geopotential height anomalies were a more pure combination of the influences of NAO and ENSO (Figure 8). Negative NAO, for example, was characterized by predominantly negative height anomalies across the continental US, and all phases of ENSO exhibited more negative height anomalies during negative NAO than neutral or positive phases. During La Niña, the anomalously low heights in western Canada and high heights from off the coast of the Pacific Northwest toward the Gulf of 
Alaska were dominant in all phases of NAO. The eastward extent of negative height anomalies were modulated by NAO phase, with more strongly negative anomalies during negative NAO and a tendency toward positive height anomalies in the eastern US during positive NAO. Height anomalies during El Niño were dramatically different depending on ENSO phase, with strongly negative height anomalies across the entire US and particularly in the central and eastern US during negative NAO, while positive height anomalies were noted from the northern Plains to Great Lakes and New England during positive NAO. During all phases of NAO, at least weakly negative height anomalies were noted during El Niño in the southern US, though the location of the lowest height anomalies differed.

As with the 500-hPa height anomalies, sea level pressure anomalies were a blend of the strongest features of the ENSO and NAO phases (Figure 9). Anomalously high pressure during La Niña dominated the northeast Pacific Ocean during all phases of NAO, with a similar but weaker tendency during neutral ENSO conditions in all phases of NAO. Conversely, negative sea level pressure anomalies in the same location were noted during El Niño, regardless of NAO phase, though the anomalies were strongest when El Niño combined with positive NAO. The negative pressure anomalies from the northeastern US and eastern Canada toward the northern Atlantic Ocean during negative NAO were present during all phases of ENSO. During positive NAO, the anomalously high pressure in the same region were noted distinctly during La Niña and ENSO-neutral phases; during El Niño, they were overwhelmed by the influence of negative pressure anomalies in the same region, though the negative anomalies in the
same region characteristic of El Niño were displaced southward during positive NAO, with the positive sea level pressure anomalies displaced further northwestward from northeastern Canada across Hudson Bay.

Surface temperature anomalies were dominated by NAO and modulated by ENSO (Figure 10). During all phases of ENSO, negative temperature anomalies dominated the US; the location of peak negative anomalies shifted based on ENSO phase, with peak anomalies in western Canada to the north central US during La Niña, while anomalies were maximized over the Southeast during El Niño. During positive NAO, positive temperature anomalies were noted in at least the eastern US; when combined with El Niño conditions, the positive anomalies extended westward through the Plains and to the Pacific Northwest. During neutral NAO, the temperature anomaly patterns closely resemble the ENSO patterns for each phase.

ENSO phase dominated the precipitable water anomalies, though NAO did heavily modulate the ENSO composite in at least some combinations (Figure 11). During La Niña, precipitable water anomalies were negative across the central and much of the western US. The region of positive anomalies in the southeastern US noted in the ENSO composite was larger in extent when combined with positive NAO, while the composites of La Niña and both negative and neutral phases were similar and more limited in extent. During El Niño, the combination with negative NAO produced a potent negative anomaly centered on the southeastern US but extending across much of the central and eastern US, bearing little resemblance to the composites of El Niño combined with either neutral or positive phases of NAO. The one common feature among the El Niño
composites was the positive anomaly across Mexico and the Gulf of Mexico, including at least the Florida peninsula. Positive anomalies were much more predominant across the central and eastern US during El Niño with neutral or positive NAO, particularly for the combination of El Niño and positive NAO. The significant variations in El Niño composites when combined with NAO phase underscore the variability of precipitation during El Niño events, which can make seasonal precipitation outlooks based on ENSO phase challenging when NAO phase and other teleconnection patterns are unknown or not considered.

5. Summary and Conclusions

The statistical results presented in section 3 align well with the composite analyses presented in section 4, creating a foundation of two influences of winter weather temperature and precipitation in the central US. While both ENSO and NAO exhibited statistically significant impacts on temperatures across the region, both the statistics and the composites indicate that NAO had a stronger influence. Additionally, while both ENSO and NAO exhibited statistically significant impacts on precipitation across the region, the statistics and composites both indicate a slightly stronger influence from ENSO.

NAO produced a distinct effect on surface temperatures in the region that was both statistically consistent and supported in the composite analyses. The impact of NAO on temperature was arguably the strongest influence among the synoptic parameters in this study. Negative NAO was distinctly anomalously cold, superseding
the influence of ENSO in the combined composites. Positive NAO had a significant warming influence in the region, though its impacts were more modulated by ENSO than the negative phase.

The most distinct ENSO effect was on the 300-hPa winds, with a strong ENSO influence on 500-hPa geopotential height also noted. The influence of ENSO on upper-level synoptic environmental parameters is unsurprising given the direction connection between ENSO and upper-level jet stream position. Statistically, ENSO exhibited a stronger influence on precipitation tendencies than NAO, with more significant relationships at more sites that were more spatially consistent. Thus, the strong relationships to upper-level wind and height anomalies – and thus, the locations of favored storm tracks – aligned well with the statistical expectation of a stronger influence of ENSO than NAO on precipitation.

Influences of both ENSO and NAO on more direct measures of moisture were more subtle and were influenced by temperature tendencies, as well. Moisture anomalies noted in precipitable water and specific humidity composites did not always translate to statistical anomalies at reporting stations. One possible explanation is that temperature anomalies can boost (when positive) or inhibit (when negative) moisture potential in the atmosphere that does not translate to a precipitation anomaly, if the moisture anomalies are counteracted by changes in the storm track via upper-level wind or geopotential height anomalies. Wet tendencies noted in the statistical analyses for the southeastern locations in the study during positive NAO and during La Niña were supported by the precipitable water composite, for example. However, the widespread
composite El Niño/positive NAO positive precipitable water anomalies were less supported by the statistical analyses of ENSO and NAO, indicating a potential influence from the warming tendencies of the statistical analyses of both El Niño and positive NAO.

Anecdotal and casual studies have attributed temperature and precipitation tendencies to both ENSO and NAO, but documenting these tendencies in a rigorous, statistically sound study allows analysis and application for a number of purposes. Statistical attribution studies can provide information regarding contributing factors to anomalous winter seasons, which can be used for historical studies of seasonal extremes as well as for risk analysis. Past events are not necessarily predictors of future events, but the tendencies can nonetheless be applied to outlooks when given phases of ENSO, NAO, or a combination of the two are predicted. More directly, the results can be used to aid in bridging between climate signals and weather patterns, providing information to decision-makers for a number of sectoral applications, including transportation (planning for road treatment), energy (anticipating elevated or diminished demand), and agriculture (understanding potential impacts on winter crops).

Much work remains to untangle the influences of ENSO and NAO on winter weather in the central US. In addition to the statistical and historical composite analyses presented here, model analyses should be conducted to both isolate and combine the impacts of the two teleconnection patterns. Subseasonal analyses also should be completed, especially considering the range of intraseasonal variability of NAO, to provide more detailed analysis of favored synoptic patterns that can lead to
temperature and precipitation tendencies. Modoki El Niño events were not separated from typical events in this analysis, nor were strong and moderate ENSO events separated from weak ones. Additional analyses should move beyond temperature and precipitation statistics to include storm frequency, wind chill, and other winter weather parameters that impact public health and safety. Finally, ENSO and NAO are just two known teleconnection patterns that influence winter weather in the central US. Additional analyses should determine the contributions of the Arctic Oscillation (AO), the Pacific-North American (PNA) pattern, the Madden-Julian Oscillation (MJO), and even longer-scale influences such as the Pacific Decadal Oscillation (PDO) and the Atlantic Multidecadal Oscillation (AMO). ENSO and NAO were chosen to analyze because of their known and, to some extent, predictable influences; the same level of understanding should be achieved for other teleconnection patterns, where such influences can be quantified.

While not a complete analysis of the impacts of both ENSO and NAO on winter weather in the central US, this study does provide a foundation for documenting and understanding the effects of both ENSO and NAO, separately and together, on sensible weather parameters in the region during December through March. The combination of statistical and composite analysis of the phases of ENSO and NAO allow analysis that is both rigorous and applicable to common inquiries in the region regarding the influences on winter weather patterns. Both ENSO and NAO do influence winter weather in the region, with discernible and spatially consistent tendencies for both temperatures and
precipitation, as well as synoptic environmental parameters that influence both of these.

Acknowledgments

The first author acknowledges NWS Central Region and NWS Omaha/Valley for support via the University Assignment Program.

References


Table Captions

Table 1. List of stations and available parameters included in the analysis. “E” denotes data available for trend-adjusted ENSO analysis, and “N” denotes data available for NAO analysis.

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Table 3. Sites with statistically significant (α = 0.10) tendencies for each phase of ENSO and for each parameter analyzed in the study. An “increasing” tendency indicates higher than usual probability for that variable to occur during that phase of ENSO at that location during either DJF or JFM (or, in some cases, both). Tendencies that trend cooler are shaded blue, and those that trend warmer are shaded red; tendencies that trend drier are shaded yellow, and those that trend wetter are shaded green. For example (upper left entry in table), during La Niña, there is an increased chance for BIS, FAR, LSE, and MSP to experience average temperatures in the below normal third, compared to 1981-2010 climatology; this is a cooling tendency that is shaded in blue. Variables ending in “X”, such as “TmaxX”, are those in the ACIS Monthly Extremes database, while the others are NCDC homogenized station data. For AWSSI data, only 6 sites were available: ABR, DDC, LBF, OMA, PAH, and URB.
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Figure 2. Composite anomalies of DJFM 300-hPa winds (m s\(^{-1}\)), relative to 1981-2010 climatology, for (a) La Niña, (b) ENSO-neutral, (c) El Niño, (d) negative NAO, (e) neutral NAO, and (f) positive NAO.

Figure 3. As in Figure 2, but for 500-hPa geopotential height (m).

Figure 4. As in Figure 2, but for surface sea level pressure (hPa).

Figure 5. As in Figure 2, but for surface temperatures (°C).

Figure 6. As in Figure 2, but for precipitable water (kg m\(^{-2}\)).

Figure 7. Composite anomalies of DJFM 300-hPa winds (m s\(^{-1}\)) relative to 1981-2010 climatology, for the nine possible combinations of ENSO and NAO phases.
Figure 8. As in Figure 7, but for 500-hPa geopotential height (m).

Figure 9. As in Figure 7, but for surface sea level pressure (hPa).

Figure 10. As in Figure 7, but for surface temperature (°C).

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CHAPTER 4. THE HARD WINTER OF 1880-1881: DOCUMENTATION, ATTRIBUTION, AND HISTORICAL SIGNIFICANCE

Abstract

The story of the Hard Winter of 1880-1881 has been retold in historical fiction, as well as in local histories and folklore. What story does the meteorological data tell, and how does it measure up when compared to the fiction and folklore? What were the contributing factors to the severity of the Hard Winter, and has it been or can it be repeated? Examining historical meteorological data, reconstructions, and reanalysis, the Hard Winter emerges as one of the worst since European-descended settlers arrived to the region and began documenting weather. Contributing factors to its severity include the colder background climate, an extremely negative North Atlantic Oscillation pattern, and a mild to moderate El Niño. The winter began early and was particularly cold and snowy throughout its duration, with a sudden spring melt that caused record-setting flooding. Historical accounts of the winter prove to be largely accurate in describing its severity, as well as its impacts on transportation, fuel availability, food supplies, and human and livestock health.
The winter of 1880-81 was strikingly difficult across much of the Plains and Midwest, so much so that it was featured in the Laura Ingalls Wilder historical fiction account, *The Long Winter* (Wilder 1940); the book, set in De Smet, Dakota Territory (present-day South Dakota; 60 km west of Brookings and 53 km east of Huron), was a fictionalized account of Wilder’s childhood experiences but contained verifiable historical information. The winter was featured in other historical fiction accounts (i.e. Rolvaag 1927), in the history of the Chicago & North Western Railroad (Stennett 1905), and in several town histories across the region (i.e. Jones 1937). In documentation, the winter is often referenced as the “Hard Winter” (Robinson 1904) or the “Starvation Winter” (Clark 1893). In fact, Wilder initially titled her book *The Hard Winter* on the first draft of the manuscript submitted to Harper and Collins Publishers; the publisher urged Wilder to change the title to be less frightening to her child readers (Hill 2007). Both meteorological records and non-meteorological accounts indicate that the winter was particularly long, snowy, and cold.

Nonfiction books about historical weather events are pervasive in popular literature, focusing on topics that include the Dust Bowl (Egan 2006), major hurricanes (Mykle 2002; Scotti 2003), tornadoes (Mathis 2007), floods (McCullough 1968; Barry 1997), and blizzards (Laskin 2004). These books enjoy wide circulation and appeal to an audience well beyond experts in meteorology and climatology. While historical weather and climate events are pervasive in popular literature, the events are less commonly analyzed in peer-reviewed and technical literature. Major historical weather and climate events hold the interest of the public, as is indicated by the success of books
similar to the ones listed above, “soft literature” such as the magazine *Weatherwise*, and anecdotal interest in descriptions of events in news and internet features. Historical high-impact events do appear in some peer-reviewed literature, often in the form of a case study and occasionally in placing events in context of broader meteorological or climatological patterns (e.g. Kocin 1983, Myers and Jordan 1956, Frye et al. 2004).

In addition to a case study of the winter of 1880-1881, including documenting available data and investigating contributing large-scale teleconnection patterns, this study returns to the literary and historical documentation to connect the event to its impacts. As recently as 2013-2014, an anomalously severe winter blanketed much of the United States east of the Rocky Mountains, with impacts ranging from a high number of school “snow day” closures to impeded transportation and commerce and increased energy costs. Understanding the impacts of recent severe winters in the context of historical extremes allows us to place these events in context, anticipating both their meteorological extremity and their potential for impacts that can be anticipated during future events.

**Meteorological Data**

Meteorological data in the Central Plains region in the early 1880s were sparse in coverage, especially when seeking stations with long-term records that pre-date the Hard Winter and continue through the present. As with many investigations of historical weather events, the few official and routine observations must be
supplemented with historical and anecdotal information to create a description of the winter of 1880-1881. The disparate data sets and qualitative information must be combined in a meaningful way to create an accurate description of the weather and climate events while also retaining their unique historical perspectives.

Station-based temperature and precipitation data were collected through the Applied Climate Information System (ACIS; Hubbard et al. 2004) for stations listed in Table 1. All of the sites used in this study are considered “threaded” records, with station moves across metropolitan areas collected into one continuous data record. Thus, an important caveat with the data is that each station may include multiple, though related, sites, with variations in site location and instrumentation through the period of record. While some conclusions may be drawn about the long-term record at these stations, they should be made with caution and supported by analysis of homogenized station data.

Digitization of historical weather observations provided by the Climate Database Modernization Project (CDMP; Dupigny-Giroux et al. 2007) yielded data previously unavailable for computer analyses and in closer proximity to DeSmet. Observations were taken at three military forts in the eastern half of South Dakota during the winter of 1880-1881: Fort Bennett (now under present-day Lake Oahe in central South Dakota), Fort Randall (near Pickstown in southeast South Dakota), and Fort Sisseton (between Sisseton and Britton in northeast South Dakota). In addition, observations were available for Yankton, South Dakota, a site that later established a long-term climate record. The historical data included not only temperature and precipitation
information, but also often included observations of precipitation type, wind
description, and other meteorological and astronomical phenomena. Locations of both
long-term and historical weather observing sites are in Figure 1.

Neither the long-term climate records nor the historical data included direct
measurements of snowfall or snow depth during the winter of 1880-1881, which is
typical of the period. Occurrences of snow must be derived from a combined
interpretation of temperature and precipitation data. The Accumulated Winter Season
Severity Index (AWSSI; Boustead et al. 2014a) assigns points to each day of a winter
season based on thresholds of maximum and minimum temperatures, as well as
snowfall and snow depth; the sum of points through a winter season characterizes the
severity of that season, as well as a time series of AWSSI for all winters on record at a
station. Additionally, a precipitation-based AWSSI (pAWSSI) estimates snowfall and
snow depth based on temperature and precipitation observations, allowing time series
analyses of the severity of the winter season by approximating snowfall based on
observed daily temperatures and precipitation. Some sites do have a period of record
that predates the winter of 1880-1881 and allows for direct comparison between that
winter and more recent ones; other sites only are available for one or a few winters and
will be compared to the longer records of nearby stations to be placed into context.

Historical reconstructions of the Hard Winter were used to investigate the
average synoptic scale weather patterns. Gridded historical data available through
NOAA Earth Systems Research Laboratory (ESRL) were used to create December to
March composite synoptic plots (available online at http://www.esrl.noaa.gov/psd/cgi-
bin/data/composites/plot20thc.v2.pl). The data are from the Twentieth Century
Reanalysis Project (Compo et al. 2011) version 2, which utilized synoptic pressure, sea
surface temperature, and sea ice distribution to create a reanalysis that spans the
period 1871 to 2008. The data do not have as fine of resolution as the NCEP/NCAR
reanalysis (Kalnay et al. 1996), but the ability to create composite analyses prior to 1948
makes the Twentieth Century data the preferred choice. Anomaly data were compared
to a 1981-2010 climatology, and anomaly patterns were compared to the composites of
combined El Niño and negative North Atlantic Oscillation (NAO) phase in Boustedt et al.
(2014b).

Overview of the Winter of 1880-1881

A number of specific events marked the winter of 1880-1881 and were
documented among the many sources of data. The winter began early, with a blizzard
in eastern South Dakota and surrounding areas on 15-18 October 1880. While October
blizzards are fairly rare (Herring et al. 2014), they are even rarer in the eastern half of
the state (Schwartz and Schmidlin 2002). Surface low pressure stalled in northwest
Iowa and northeast Nebraska (Figure 2); to its northwest, a prolonged period of
precipitation, combined with a cold air pocket that brought subfreezing temperatures
and gusty winds as a tight pressure gradient persisted, allowed snowfall to last for 2 to 3
days in the region, with anecdotal reports such as Wilder’s account supported by
observational data from both continuous and CDMP station records.
Following the October blizzard, milder weather did provide a brief respite, but wintry weather returned by mid-November. Station observations indicate a number of snow and potential blizzard events in December, including one that began on Christmas Day in eastern South Dakota that also was documented accurately by Wilder (1940). After a cold but relatively snow-free period in late December to early January, storm frequency increased from early January through the month of February. For the months of January and February, among all CDMP sites in eastern South Dakota as well as nearby Des Moines, Iowa (DSM), Minneapolis/St. Paul, Minnesota (MSP), and Omaha, Nebraska (OMA), there were just 12 days with no probable snow reported at any sites in the region. Otherwise, snow fell in at least one observing location on all the other days.

Milder days began to mix into the observations beginning in March, but most days remained below freezing at all sites in the region. Snowfall frequency decreased, but a number of potential snow days were noted across the region throughout the month. Cold conditions continued into the first half of April. The last suspected snow day occurred across the region on April 10-12. From April 14 onward, maximum temperatures rose above freezing and remained there throughout the spring, and even minimum temperatures only fell to near or below freezing readings at Fort Randall and Fort Sisseton, while no other suspected snow days occurred.

For the entire winter, the pAWSSI accumulation in the region are listed in Table 2, compared to period-of-record averages in the same or nearby locations. The Hard Winter ranked as second most extreme of all winters in the period of record of continuous stations, including DSM, MSP, and OMA. Even as far east as Detroit,
Michigan (DTW), and Lansing, Michigan (LAN), the winter ranked among the top 5.

While long station records are not available for the CDMP sites, their values can be compared to nearby records at ABR, FAR, HON, and PIR. In all cases, the CDMP sites are near the record values in those nearby locations. Yankton stands out as a maximum in AWSSI accumulation for the winter, and the accumulation at Fort Sisseton was remarkable considering data for the entire month of February were missing. The temperature component of AWSSI at continuous sites was the highest on record at both DSM and OMA, but fell all the way to ranking 19 at MSP; both DTW and LAN ranked as 4th highest. Readings among the CDMP sites were very close to record highest readings at nearby Dakota-area sites, though it is worth noting that the periods of record for those sites did not include the colder decades of the late 1800s to early 1900s. For the snow component of AWSSI, MSP endured its highest snow ranking on record and DSM ranked as second highest, while OMA fell down to 12th highest; DTW and LAN were in the top 3 and 6, respectively. Among the CDMP sites, most of the accumulations for the snow component were well above normal but not near records; the exception is at Yankton, where the reading was closer to those record values.

In many locations, the main impact of the Hard Winter arrived not with the winter itself but with the spring that followed it, as rapid snowmelt contributed to both ice jam and snowmelt flooding across much of the north central United States (Hoover et al. 1988). Ice jam flooding arrived first, in early to mid-April, as rain fell on top of snow and ran off, swelling rivers and breaking up thick ice covering them. Later, from April through May, rivers swelled again with copious amounts of runoff as the deep and
extensive snowpack melted. The Missouri and Mississippi Rivers, as well as most of their tributaries upstream of their confluence, were swelled to record levels that stood for decades and, in a few locations, still stand as the flood of record. In the northern Plains, the Red River and its tributaries also reached record to near-record readings. Towns such as Vermillion, South Dakota, and Green River, Nebraska, suffered severe damage due to floods (Hoover et al. 1988), prompting the movement of these settlements to higher ground or even spelling the end of some settlements.

**Teleconnections: Negative NAO and El Niño**

Analysis of the global teleconnection patterns during the winter of 1880-1881, including the El Niño—Southern Oscillation (ENSO) and NAO, provides context for the synoptic scale patterns and resulting sensible weather experienced in the central United States. The Oceanic Niño Index (ONI) data set available from NOAA Climate Prediction Center (CPC) spans the period from 1950 to present. ONI is widely used in NOAA applications of ENSO studies, as well as in the operational definition of El Niño and La Niña utilized by CPC, which defines an El Niño (La Niña) episode by the presence of a sea surface temperature (SST) anomaly greater (less) than 0.5 °C (-0.5 °C) in the Niño3.4 region for five consecutive three-month-average periods (Kousky and Higgins 2004). CPC experts are developing monthly SST anomaly data for the Niño3.4 region based on Extended Reconstruction SST version 3b (ERSST.v3b) data (Smith et al. 2008), generating monthly anomaly data from 1871 through 2010; this data set has been provided via personal communication (M. LeHeureux).
NAO influences temperature strongly in the central Plains, and also precipitation to some extent (Boustead et al. 2014). As with ENSO, there is no single data set that defines NAO, and many analyses exist (Hurrell and Deser 2009). This study utilized data from the Climate Analysis Section of the National Center for Atmospheric Research (NCAR; available online at http://www.cgd.ucar.edu/cas/jhurrell/indices.html), spanning 1864 to the present. In this data set, the NAO index is based on the difference in normalized sea level pressure (SLP) between Lisbon, Portugal, and Stykkisholmur/Reykjavik, Iceland. Hurrell normalized the sea-level pressure anomalies at each station by dividing the seasonal mean pressure by the standard deviation of the long-term mean (1864-1983). Normalization was used by Hurrell to avoid the series being dominated by the greater variability of the northern station.

The negative phase of NAO exerts a strong influence on temperatures, as well as an influence on precipitation, during the winter across the central and eastern US (Boustead et al. 2014b; Higgins et al. 2002). Temperatures tilt strongly toward the coldest third of climatology in the central US during negative NAO. During the winter of 1880-1881, one of the strongest negative NAO episodes since 1871 was in place, an analysis that was corroborated by Marsh (1998). According to the UCAR database, the December through March (DJFM) average NAO index was -3.80, which was tied for the fifth lowest DJFM NAO index from 1864-2014 (Table 3). The peak monthly station-based NAO index of -5.9 occurred in January 1881, which as of publication remains the lowest monthly index on record in any month.
While not as pronounced as the negative NAO, the ENSO phase was tilted toward an El Niño during the winter of 1880-1881. Sea-surface temperature anomaly data based on ERSSTv2 (L’Heureux, personal communication) indicates a weak El Niño during the winter months, with 3-month average SST anomaly in the Nino 3.4 region at or above 0.5 from DJF through JJA 1881. The highest 3-month average SST anomaly of 0.7 occurred in MAM. Allen et al. (1991) corroborates the conclusion that a weak to moderate El Niño was in place during the winter of 1880-1881.

Composite images of several common synoptic environmental parameters demonstrate the starkly negative temperature anomalies across much of the eastern U.S. during DJFM 1880-1881 (Figure 3). Compared to the anomalies for DJFM during all combined El Niño/negative NAO events from 1950-2013 (Boustead et al. 2014b; Figure 4), negative temperature anomalies in 1880-1881 were significantly stronger than the composite average and were displaced northward, centered from the eastern Plains across the Great Lakes and Corn Belt toward the mid-Atlantic states. The 300-hPa wind anomaly pattern in 1880-1881 departed significantly from the composite average, though. Both the 1880-1881 and the combined El Niño/negative NAO composites depicted easterly wind anomalies from Greenland into eastern Canada and northern New England, but the westerly wind anomalies across the southern US into the Gulf of Mexico exhibited in the composite average were replaced with easterly to northeast erly wind anomalies across much of the region in 1880-1881; the pattern replicates neither the negative NAO nor the El Niño composites (Boustead et al. 2014b) and indicates that other influences dominated upper-level flow during the Hard Winter. Geopotential
height anomalies at 500 hPa hint at a potential omega blocking pattern, with negative height anomalies over the northeastern Pacific and western Atlantic oceans and a positive height anomaly over Hudson Bay into the north central US. The surface reflection of this pattern, in the sea level pressure anomalies, indicate that the 1880-1881 pressure anomaly pattern was more amplified than but similar to the composite average. Precipitable water and 850-hPa specific humidity anomalies in 1880-1881 departed from the composite averages, with positive moisture anomalies spilling from the western US into the northern Plains to High Plains.

The combination of strongly negative NAO and varying strength of El Niño occurred two other times since 1950: 1968-1969 and 2009-2010. According to AWSSI analysis (Figure 3 in Boustead et al. 2014a), the winter of 2009-2010 was in the extreme category (81st percentile and higher) from the northern Rockies through the central Plains, as well as in the mid-Atlantic, though the Great Lakes ranged from mild (20th percentile and lower) to severe (61st to 80th percentile) categories. Thus, while several stations were near record severity, the impact was more regional than in 1880-1881. Similarly, the winter of 1968-1969 (not shown) was in the extreme category from the northern Rockies to the northern and central Plains, with more variability in intensity across the Great Lakes to eastern US. Additionally, the winters of 1976-1977 and 1977-1978 both were characterized by a weaker but still negative NAO and an El Niño; those two winters, especially 1977-1978, rank among the most severe at nearly every station in the AWSSI analysis for the period 1951-2013. Among the ten winters since 1951 with both negative NAO and El Niño, just two (1957-1958 and 1986-1987) had above-average
total AWSSI at more sites than below average. Overall, the characterization of El Niño/negative NAO winters as more likely to be more severe than average in the central US applies in most cases, particularly with a strongly negative NAO. Thus, the winter of 1880-1881 fit expectations given the teleconnections in place during the winter months.

When investigating the climatological patterns contributing to the winter of 1880-1881, it is imperative to consider the state of the background climate. Trend analysis is not available for CDMP sites, which have a short period of record, but can be conducted on continuous-record sites in the region. The Local Climate Analysis Tool (LCAT) allows trend analysis using homogenized station data from 1925-2014 (Timofeyeva et al. 2014; Menne et al. 2009). For that period, DJF and JFM average temperature trends are listed at sites around the region in Table X. Every site examined around the region exhibits a positive (warming) trend for winter temperatures. It is likely that temperature trends between the 1880s and the 1920s were at least stable, if not trending warmer, and thus a trend from 1925-2014 would characterize, if not specify, the difference between the 1880s and recent climatology. Given the colder background climate of the 1880s, departures from that climatology would appear even more significant compared to a modern 1981-2010 climate normal period.

**Impacts and Historical Significance**

Though meteorological data were scarce for the Hard Winter, evidence exists in documents including historical archives, journals, town histories, and newspapers. Such anecdotal data are subjective and could be prone to exaggeration, as well as a lack of
historical context or comparative value. That said, consensus of multiple voices from multiple sources about the nature of the winter provide confidence in conclusions about it. *The Long Winter* itself was a form of non-meteorological documentation of the winter; confidence increases in its description of the winter of 1880-1881 when matched to other documentary data, but it especially increases when matched to meteorological data. Wilder catalogued a series of events, from the October blizzard through the abrupt April thaw, that were supported by available meteorological observational data. Winter weather became not just a background, but rather an antagonist, threatening the survival of the Ingalls family.

Railroad impacts during the Hard Winter were documented in a number of sources, most notably Stennett (1905) and a reprint of Stennett (2007; Figure 5). Wilder (1940) documents cessation of railroad activity in late December, with trains not returning to De Smet, South Dakota, until early May; the timeline corroborates with Stennett (1905) and other sources. During that gap, food and fuel could not be transported to settlers in the region via rail. Because of the abundant snowfall, overland transport also was hampered, though some travel via horse and horse-drawn sleigh was possible. In the spring, roads and rails remained impassable for weeks due to flooding.

Without an influx of food and fuel, settlers turned to their local communities to compile and share resources. Wilder (1940) describes her community doling out food supplies based on needs of the families, though fuel was sold in a more opportunistic fashion to the highest bidder. The Ingalls family, like many in the Plains during that
winter and others, twisted prairie hay into sticks to burn as fuel after coal supplies were exhausted; hay sticks burn rapidly and thus are not favorable as a sustained heat source. While some communities did send their seed wheat to a flour mill to grind, the Ingalls family and many others (Stennett 1905) were forced to grind their wheat in home coffee mills to make a wheat mush that could be baked into bread or cooked into a gruel. The original Hard Winter manuscript authored by Wilder did indicate that the Ingalls family had a little more variety in their food than the published version of the book The Long Winter implied.

Casualty records for the Hard Winter are scarce, but no single event within the winter has been documented to have the casualty rate of the single blizzard documented in Laskin (2004). One can speculate that with harsh winter conditions beginning early and continuing through several months, those who lived in affected regions were not taken by surprise by individual blizzard events as they were in January 1888. The impact of the near-starvation of many area settlers on future health remains unquantified.

Meteorological records support the conclusion that the Hard Winter of 1880-1881 was among the most severe since settlers of European descent arrived in the Plains region and began keeping records. It likely was not the most severe winter on record at any one location, though it remains the coldest winter on record in a couple of locations, and likely the snowiest winter among a subset of locations, when examining the rankings among temperature records, precipitation records, and AWSSI and pAWSSI totals. It was and remains, however, among the top five in severity – by one or more
measures – in a wide swath from the central and northern Plains to the Great Lakes.

The winter struck early in the settlement of Dakota Territory and surrounding locations, and many settlers were not prepared with enough food and fuel resources to endure a winter with no or limited transportation by road or rail. Contributing factors to the cold and snowy winter include the colder background climate in the 1880s, combined with one of the strongest negative NAO episodes on record and a weak to moderate El Niño. Other contributing factors not assessed in this study may exist, warranting continued studies of extreme winters such as the Hard Winter to help anticipate conditions that favor extreme winter severity. Additional sources of data, such as the Dakota winter counts, also may provide additional context to the severity of the Hard Winter of 1880-1881.

Acknowledgments

The author acknowledges support from her advisors at the University of Nebraska-Lincoln, Drs. Kenneth G. Hubbard and Martha D. Shulski, as well as colleagues at the National Weather Service Forecast Offices in Omaha/Valley, Nebraska, and Sioux Falls, South Dakota. Iowa State Climatologist Dr. Harry Hillaker and South Dakota State Climatologist Dr. Dennis Todey contributed data and suggestions for anecdotal materials. CDMP project participants Leslie Stoecker and Nancy Westcott provided valuable historical data. Michelle L’Heureux, NOAA/NWS Climate Prediction Center, provided historical ENSO data and advice about its use. Rebecca Kern, NWS Omaha, provided assistance with map creation.
References


Table Caption List

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<table>
<thead>
<tr>
<th>City, State</th>
<th>Abbr.</th>
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</table>
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CHAPTER 5. EFFECTIVENESS OF A LAURA INGALLS WILDER NARRATIVE FOR COMMUNICATING ABOUT WEATHER AND CLIMATE

Abstract

Laura Ingalls Wilder is woven into the cultural fabric of the country, especially in the central United States where her books were set. She witnessed and recorded numerous weather and climate extremes throughout her Little House book series, many of which can be traced in historical records. Her description of these events can be drawn into a larger narrative about weather and climate, providing an accessible means to introduce wide audiences to scientific knowledge about many weather and climate subjects. The construction of a narrative around Wilder’s experience potentially allows even polarizing subjects like climate change to be opened and discussed, engaging previously disengaged audiences and opening listeners to the scientific context of weather and climate events, including climate change. The framework of Wilder's stories was used in multiple venues to raise interest in topics ranging from preparedness to climate change and was presented to the weather and climate professionals as an example of using a narrative that captures an audience and as a bridge to discussing difficult and sometimes controversial weather and climate topics. But the difficult question remains: Does it work? Using a series of surveys, this study begins to quantify the effectiveness of the Laura Ingalls Wilder narrative for increasing public interest and engagement in climate-related topics and basic climate literacy.
1. Introduction

Scientists are increasingly asked to not only perform basic research, but also communicate that research effectively to a range of potential audiences, rather than simply among other subject matter experts. It is incumbent upon the science community to communicate more effectively to a wide range of audiences. Public trust in scientists is fragile and can depend on the interaction between the framing of information and whether the information is being processed by recipients in a heuristic, faster-encoding but lower-elaboration processing pathway or a systematic, high-elaboration pathway (Goodwin and Dahlstrom 2011). Somerville and Hassol (2011) cite specific means for more effective science communication, including using clearer language and inverting the typical pyramid of science communication by starting with a focus on the results and meaning before broadening the message with supporting details about methodology and background information. Given the vast amount of misinformation surrounding climate and climate change, it is one field in particular in which effective communication is paramount. O’Neill et al. (2010) suggest framing climate change in multiple ways to best meet the interests and needs of audiences. Hoffman (2012) suggests that scientists engage climate information brokers who are members of and similar to the audiences that they are trying to reach, in addition to framing climate change discussions to fit the audience and recognizing the power of language and word choice.

Obstacles to effectively communicating climate and weather concepts abound, especially when communicating about climate change. Low science literacy may make
such communication challenging, though it is just one potential obstacle to understanding climate change and may not be the primary obstacle to addressing climate change (Scheufele 2013). Scientific literacy among American adults is similar to their European counterparts, answering roughly two-thirds of basic factual scientific knowledge questions correctly (National Science Board 2014). That said, only 74 percent of Americans correctly answered that the Earth revolves around the Sun. Even given similar literacy levels, though, American adults were less concerned than their European counterparts about climate change and less likely to attribute climate change to human causes. In fact, Kahan et al. (2012) identified a polarizing effect of science literacy on perceived climate change risk. Among those whose ideology supports a hierarchical, individualistic worldview, increased literacy correlated with decreased perception of climate change as a risk; those with an egalitarian, communitarian worldview perceived increased climate change risk with increased science literacy. Political ideology and acceptance of human-caused climate change are strongly correlated (Leiserowitz et al. 2013), more so than other indicators such as age or education level.

Audience-tailored topics, or frames, can serve as a vehicle to convey weather and climate information and potentially address some of these obstacles to understanding. Such a vehicle allows non-meteorologists and non-climatologists to gain understanding about weather and climate as it applies to the topic. For this communication bridge, the narratives of Laura Ingalls Wilder were chosen as a frame for communicating weather and climate concepts. The Laura Ingalls Wilder books are
engrained in American culture, and particularly the Plains and Midwest regions featured in the books; adults and children alike recognize and respond to the stories. Many people from a wide range of audiences, especially in the Midwest and Plains areas, are familiar with the series of children’s books written by Laura Ingalls Wilder, sometimes referred to collectively as the *Little House* books, or the television show based loosely on those books, “Little House on the Prairie” (1974-82). The books, which are historical fiction based strongly on the life of the author, provide a common ground from which lessons in weather and climate can be drawn. Weather events and climate extremes are featured prominently throughout the series, though nowhere as strongly as in *The Long Winter* (Wilder 1940). Other extreme weather and climate events throughout the books include tornadoes, prolonged drought, grasshopper plagues, cold snaps, and blizzard events outside of the Long Winter. The books thus provide a vehicle for discussing numerous weather and climate events to which a population could be vulnerable.

Historians and literary scholars have conducted extensive research on biographical information about Laura Ingalls Wilder (Zochert 1976; Anderson 1992; Miller 1998; Hill 2007; Fellman 2008) and have published books in popular literature. The research has focused on historical facts that support the information presented in the book, as well as missing and incorrect information; the life of Laura Ingalls Wilder and her family through her adulthood; the writing of the Little House series, including her strong collaboration with her daughter, author Rose Wilder Lane; and even some information about the town of DeSmet, South Dakota (Miller 1994), site of four books in
the series and one more published posthumously. Many of the events (including and beyond the weather and climate events) throughout the book series can be verified, and the veracity of those events provide a context of trust in her narratives, even when other events are revealed as fiction or fictionalized representations of actual events.

A narrative can be constructed, through the characters, plots, and settings of the *Little House* series, which enables the communication of weather and climate concepts that range from interesting tidbits, such as documenting correspondence between Wilder’s description of individual storms and meteorological records of the events, to complicated concepts, such as localizing impacts of climate change. The concept of bridging between science and the community would benefit from a methodology, an example, and an investigation of how to apply the concept in practice. Thus, there is a need to see the process through from beginning, as a scientific investigation, to end, as a tool for education and communication. This study represents the end phase of that end-to-end demonstration and delineates practices to apply in future studies (Boustead et al. 2014a, Boustead et al. 2014b, Boustead 2014), using the Laura Ingalls Wilder books as a vehicle that can create a bridge between meteorology/climatology and communication to a range of audiences. The narrative constructed about the weather and climate events in the *Little House* books will be referred to as the “Wilder Weather narrative” through the rest of this presentation.

2. Audience description
While the Wilder Weather narrative was presented to a number of audiences, evaluation was conducted with three specific audiences. The first audience comprised fans and scholars of Laura Ingalls Wilder at the Laurapalooza 2012 conference on 12 July 2012 in Mankato, Minnesota (http://beyondlittlehouse.com/laurapalooza-2012/laurapalooza-2012-overview/). Approximately 75 audience members were present, many of whom had engaged previously with the storyteller at Laurapalooza 2010 (http://beyondlittlehouse.com/about-2/press-releases/press-releases-2/laurapalooza-2010-schedule/), via social media and online discussion, by reading The Homesteader newsletter features about the work, and/or as an audience of an internet radio show, Trundlebed Tales. Thus, the majority of Laurapalooza attendees already were exposed to and familiar with the Wilder Weather narrative as well as to the storyteller – the first author. The Laurapalooza 2012 audience members were receiving updated and more in-depth information that built on previous interactions. Twenty-nine audience members volunteered to take the survey after hearing the presentation.

For both the second and third audiences, the interaction was the first time that members had heard any part of the Wilder Weather narrative, and all survey participation was voluntary. The second audience was a subset of the National Association of Interpreters Region V meeting in Aurora, Nebraska, on 4 April 2013. The audience of approximately 15 members included national, state, and local park interpreters, extension specialists, master naturalists, and high school to college students; 13 audience members participated in the survey. The third audience, students of a graduate-level Climate and Society course in the School of Natural Resources at
University of Nebraska, included a blend of graduate and advanced undergraduate students with a range of climate-related background and experience. All 17 students participated in the survey. In both cases, this was the first engagement of the storyteller with the audiences, and the audiences had a range of exposure to the *Little House* books from no previous experience to high familiarity with the books.

The three audiences differed in their level of prior engagement and knowledge. Thus, the samples were considered as three separate groups, as well as collectively, to investigate tendencies and unique characteristics among each audience as well as among all those who have been exposed to the Wilder Weather narrative. Survey results from random responders from the state of Nebraska to a general survey on societal issues were examined as a baseline for comparison, serving as a “control” audience of those who did not listen to the Wilder Weather narrative. The opportunities for presentation did not lend themselves to before-and-after direct survey comparisons.

3. **Constructing the Narrative**

It is no mystery that a well-crafted story will capture the attention of its audience more than a list of facts. Jones and McBeth (2010) described the relationship between narrative communication and its impact on the attitudes of its audience. A narrative, as described by Jones and McBeth (2010), is a story with a sequence of events, including the elements of setting or context, plot, characters (including both a hero and a villain),
and a moral of the story. While it has been noted in many studies that people are inclined to respond to and be persuaded by information that most closely matches their own expectations, it is possible to move people beyond those expectations. A story that exhibits congruence, or similarity to the life experiences of the listener, is more likely to be received. A break with expectations about the way things should be, referred to as a “breach,” is hypothesized to positively contribute to persuading the listener. Likewise, the ability of the storyteller to transport listeners is key to persuasion; the narrative should draw the audience into the narrative so that they become involved with the protagonists, allowing the audience members to “get lost” in the story and return changed by it. Finally, listeners are more likely to be persuaded by a story if they trust the storyteller or source. In particular, Jones notes that the depiction of the hero is critical (Pitzer 2010); if listeners like and relate to the hero, then they are more willing to believe other facets of the story. Jones noted that scientists are reluctant to accept storytelling as a valid means of communicating information (Vergano 2010), specifically citing an instance in which he presented the research to National Weather Service meteorologists, who resisted the idea of telling a story over listing facts. Meteorologists tend to be conservative and reluctant to stray outside their science, besides being among the most reluctant of physical scientists to view climate change as a concern (Doran and Zimmerman 2009). Nonetheless, narratives can be an effective tool to communicate to a non-scientist or non-specialist audience when applied for reasons that include increased comprehension and persuasion to reduce controversy, and with high levels of accuracy (Dahlstrom and Ho 2012).
The *Little House* books, and particularly *The Long Winter*, provide a strong narrative foundation to which a storyteller can connect weather and climate information. They include a protagonist or hero, Laura Ingalls Wilder, who is well known and even beloved by multiple audiences. The stories are familiar to their readers, and adding information about weather and climate beyond what is provided in the books or that corrects information in the books allows a credible breach from a story that otherwise meets expectations. Thus, the only element remaining is credibility in the storyteller, an element that can be achieved via affiliation, academic credibility, shared interest in the underlying narrative, and exposure to and comfort with audiences. The Wilder Weather narrative can be shaped to the audience and time allotted, expanded as needed, and delivered via multiple media.

The scientific basis of the Hard Winter-specific Wilder Weather narrative was outlined by Boustead (2014), as the winter of 1880-1881 was documented to be one of the worst since modern instrumental records began. The winter was exceptionally long in duration, beginning with an October blizzard and ending with an abrupt thaw in mid-April that led to significant ice-jam and snowmelt flooding in the Missouri and Mississippi River basins. In between, the winter was among the coldest and likely among the snowiest in the region. Contributing factors to the severity of the winter included the combination of El Niño and an extremely negative phase of the North Atlantic Oscillation, occurring in conjunction with an underlying base climatology that was colder than recent climatology.
From the scientific basis, the goal of the Wilder Weather narrative was to raise weather and climate literacy by focusing on three broad takeaway messages:

- Know your local climatology; understand and prepare for the range of potential extremes.
- Climate has changed from the late 19th Century to the present and will continue to change in the future; human activities have caused most of the observed and predicted changes.
- Know your sources of weather and climate information, and ask questions of meteorologists and climatologists to better understand weather and climate concepts, both in the Laura Ingalls Wilder books and in other experiences.

These messages were conveyed using details from the stories, as well as supporting information from weather and climate research to provide scientific context. For example, the concepts of the El Niño—Southern Oscillation (ENSO) and the North Atlantic Oscillation (NAO) were introduced as contributing factors to the severity of the Hard Winter of 1880-1881 (Boustead 2014) as described in *The Long Winter*.

The *Little House* books provide the structure needed to frame the message in a storytelling context. Wilder herself serves as the hero of the story, and weather and climate events are personified as villains. The setting varies by book; in the case of *The Long Winter*, the location is De Smet, Dakota Territory (present-day South Dakota). The conflict or problem in the narrative is that Wilder and her family did not have complete information; resolution is found by determining what we know now about weather and climate events that impacted Wilder and her family. Variants of the Wilder Weather
narrative include allowing the storyteller to serve as a detective to uncover the full story behind the clues left by Wilder, establishing Wilder as an early weather and climate observer, comparing awareness and preparedness tactics in Wilder’s time to modern efforts, and describing Wilder as an example of living an environmentally-friendly lifestyle.

4. Evaluating Effectiveness

Engagement with and interest in the weather and climate concepts, as communicated through the Wilder Weather narrative, were measured quantitatively using surveys. Knowledge and attitude questions were based loosely on those administered by the Yale Project for Climate Change Communication (Leiserowitz et al. 2013). The University of Nebraska Bureau of Sociological Research (BOSR) administered surveys to a randomly selected sample of Nebraska citizens via the Nebraska Annual Social Indicator Survey (NASIS) in 2011-2012, including a group of questions about climate change. The wording of these questions was replicated in surveys administered to Laurpalooza 2012 (LP), the National Association of Interpreters Region V (NAI), and a graduate-level course on Climate and Society (CS). Additional questions (after PytlakZillig et al. 2013) were administered to the LP, NAI, and CS samples, but not to the NASIS sample, in order to gauge trust in various sources of information, to measure engagement during the presentation, and to clarify demographic information.
The sample size of all Wilder Weather narrative survey results, collectively, was large enough to evaluate statistically with confidence, with a combined sample size of 59. Evaluating each of the three audience samples individually was less confident, as both the NAI and CS audiences were well below a typical sample size of 30 (Dowdy et al. 2004); that said, comparing the combination of the NAI and CS audiences to the LP audience allowed comparison of fresh audience exposure to more prolonged exposure to the narrative. Additionally, the three audiences were combined to compare to the baseline general survey responders. Overlap between the survey questions among the narrative audiences and the baseline audiences was not perfect, and thus some survey questions could not be compared between audience groups. An $F$-test was applied to compare the variance of samples; then Student’s $t$-tests were applied to compare pairs of sample means between LP and NAI/CS audiences, as well as between the NASIS respondents and the combination of all three narrative audiences, for equal and unequal sample variances, as appropriate (Dowdy et al. 2004).

Questions for which responses were significantly different between survey response groups, as well as select questions for which responses differences were non-significant, are in Table 1. While survey responses with significant differences are emphasized, it is instructive to investigate responses to questions for which answers among audience groups were similar. Between the collected narrative audiences and the general survey responders, these include whether responders need a little or a lot more information and a brief description of how the climate system works. Between the LP and combined NAI/CS audiences, these include identifying the percentage of
climate scientists who endorse anthropogenic climate change (which, collectively, was significantly higher than the general responders) and trust in NOAA as a source of climate information (not asked of the general responders). The high level of trust in NOAA and other federal agencies, as well as scientists in general, provides a foundation of trust from audience members in a storyteller who is a scientist representing NOAA or another science-based federal agency.

Combining the three narrative audiences, numerous significant differences from the NASIS survey responders appear. Among group demographics, the combined narrative audiences skewed more heavily toward females than the general responders, driven by a very female-heavy LP audience; the narrative audiences also were less conservative in ideology than the NASIS responders. The narrative audiences were more likely to have heard about climate change, more likely to feel informed, and more likely to agree that climate change is happening than the NASIS responders. When asked to give a “percentage of all climate scientists that think that the global climate is warming due to human actions,” the percentage given by the narrative audiences was 13.6% higher than the NASIS responders, which was significantly higher, though it still fell 20% short of the actual best estimate of 97% (Oreskes 2004; Doran and Zimmerman 2009; Anderegg et al. 2010; Cook et al. 2013). Additionally, the narrative audiences perceived significantly greater health, economic, and environmental risks due to climate change than the general audiences. Without a before-and-after study, it is impossible to know to what extent the differences were a predisposition of the narrative audiences
and how much was a result of exposure to a comfortable Laura Ingalls Wilder narrative about weather and climate, but clearly the audiences were distinct.

Significant differences were noted when comparing the LP audience to the NAI/CS audiences, as well, though these were fewer than the differences from the collected audiences to the general responders. Although ideology was not significantly different between groups, the gender makeup was, as the LP audience was nearly exclusively female, while the combined NAI/CS audience was closer to an even gender split. The NAI/CS audiences felt more informed about climate change than the LP audience, though the audiences gave nearly identical answers to the percent of climate scientists who attribute warming to human actions and were not significantly different in perception of risks or desire to have more information regarding climate change. When asked a series of questions about how they felt during the presentation, both audiences exhibited particularly high levels of inspiration, focus, careful consideration of all options, thorough consideration of issues, creativity, understanding perspectives different from one’s own, and relating the topic to ones already known. Both audience groups also exhibited particularly low levels of desire to do something else, boredom, anger, irritation, disinterest, and frustration. Among the questions with significantly different responses, the LP audience exhibited significantly higher feelings of inspiration, focus, and careful consideration of all options presented than the NAI/CS audiences, as well as significantly lower boredom and desire to do something else. Both audience groups exhibited highest trust in scientists, the National Oceanic and Atmospheric Administration (NOAA), and the National Park Service (NPS), with lowest trust in
Congress, religious leaders, and the media. The LP audience, however, exhibited significantly higher trust in both the media and television weather reporters than the NAI/CS audiences.

In addition to the quantifiable survey results, more qualitative measures of interest and engagement have been noted through the narrative development and engagement process. The narrative was picked up in 2011 by national (Vergano 2011; Associated Press 2011) and local (Abourezk 2011) media sources. Interest continued as new stories were written (Koerth-Baker 2012) and interviews were conducted (Stateside Staff 2014), particularly during the winter of 2013-2014 that was perceived as another “hard” winter. The first author also maintains a blog, Wilder Weather (http://www.bousteadhill.net/wilder_weather/), with intermittent postings of articles that either loosely or closely tie weather and climate to Laura Ingalls Wilder, as well as a Facebook presence, “Wilder Weather,” with 364 followers as of 23 May 2014, to engage interest and to add visibility to blog articles. While direct measurements of readership of all articles and blog entries is not possible, the continuation of interest in new articles and new angles of press coverage indicates public interest in the narrative.

5. Summary and Conclusions

A narrative of weather and climate awareness, preparedness, and inquiry was created via the stories of Laura Ingalls Wilder and presented to multiple audiences on multiple occasions. Three of these audiences were surveyed after hearing the Wilder
Weather narrative to assess their climate literacy as well as their reactions to the narrative, trust in various information sources, and demographical information. The results were compared from all of these audiences to a general group of responders to the NASIS survey, to the extent that questions overlapped. Results were also compared between the LP audience, which had been exposed to the Wilder Weather narrative repeatedly, and the NAI and CS combined audiences, which were exposed to the Wilder Weather narrative for the first time. Many of the responses to the survey were significantly different between the narrative audiences and the NASIS responders, including level of exposure to climate information, acceptance of anthropogenic climate change, perception of risk, and feeling informed. Due mainly to the strong slant toward a female audience at LP, the narrative audiences collectively were significantly more female than the NASIS responders, and they also were less strongly conservative. When comparing the LP audience to the NAI/CS audiences, the LP audience felt less informed but more focused, inspired, and careful in considering other viewpoints, as well as less bored and with less desire to do something else during the presentation. LP responders also put more trust in both the media and in television weather broadcasters than the NAI/CS audiences, though both audiences placed their highest trust in scientists in general and specifically in NOAA, NPS, the Centers for Disease Control and Prevention (CDC), and the Environmental Protection Agency (EPA).

Does this mean that the Wilder Weather narrative is working? The results at least imply that audiences are attentive and engaged when exposed to the Wilder Weather narrative, especially an audience that has a strong interest in the subject of the
narrative as was the case with the LP audience. The level of predisposition of the narrative audiences to be more likely to accept climate change and perceive risks is unknown, but the strong skew toward higher perceived risk and higher perceived consensus among scientists is notable. The audiences exhibited high trust in scientists, and particularly in NOAA, but whether the high level of trust is a result of exposure to a storyteller with a NOAA affiliation is unknown.

Work continues to more directly quantify the impact of a specific narrative on the climate literacy and engagement of audiences. Continued work will include direct before-and-after comparison surveys on targeted audiences, as well as control studies in which audiences hear the same speaker give a presentation but not in the context of the Laura Ingalls Wilder narrative. Additionally, increasing the sample size of audiences to whom the narrative is presented would allow continued statistical analysis. Finally, as work continues with the Laurapalooza conference series and its participants, additional surveys can continue to track key factors in acceptance of anthropogenic climate change and climate literacy with that particular audience.

The Wilder Weather narrative demonstrates the notion that a scientifically technical research project can be bridged to a general audience, given an effective narrative framework. Such narratives can increase the scientific literacy of general and targeted audiences by raising scientific awareness when enveloped in the frame of a comfortable and effective narrative. Results in this study indicate that the narrative selected could be expanded to other potential audiences, including teachers and students who are reading Little House books in the classroom, adults who read the
books when they were children, and historians whose interest is sparked by the
documentation of past events. Such interactions can help promote awareness of
weather and climate topics ranging from hazardous weather preparedness and safety to
climate change risk perception that may lead to steps toward adaptation and mitigation.

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Homesteader* newsletter), and Sarah Uthoff (Trundlebed Tales online radio program).
Dr. Michael Hayes (National Drought Mitigation Center) also provided the opportunity
to guest lecture for the graduate-level Climate and Society course.

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Appendix A. Narrative Audience Survey

The survey distributed to the Laurapalooza 2012, National Association of Interpreters, and Climate and Society audiences is included. Many questions are annotated with an abbreviation referenced in Table 1; those without an abbreviation were not analyzed. Questions marked with *** were not included in the Climate and Society survey.
## Views on Climate Change

Thank you for being willing to complete this survey! When you are finished, please return it to the person who gave it to you.

<table>
<thead>
<tr>
<th>1. While listening to the speaker <strong>today</strong>, I ...</th>
<th>Not at all</th>
<th>Slightly</th>
<th>Some-what</th>
<th>Moderately</th>
<th>Very much</th>
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</thead>
<tbody>
<tr>
<td>(INSPIRED) Felt inspired.</td>
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<tr>
<td>(MMADEUP) Felt like my mind was already made up.</td>
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<tr>
<td>(IDEAWOTH) Discussed my ideas about the topics with others.</td>
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<td>(OPENNEWIDEA) Felt open to hearing new ideas about the topics.</td>
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<tr>
<td>(DOELSE) Wished I were doing something else.</td>
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<td>(ANGRY) Felt angry.</td>
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<td>(NOVEL) Thought of novel or inventive issues related to the topic.</td>
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<td>(FINDANS) Tried to find answers to my questions about the topics.</td>
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<tr>
<td>(THOROUGH) Was thorough in my consideration of the issues.</td>
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<td>(TALK2OTH) Talked to others about the topics to get their opinions.</td>
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<td>(CREATIVE) Felt creative.</td>
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<tr>
<td>(CHKDSELF) Checked myself to see how well I understood the issues.</td>
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<tr>
<td>(BORED) Felt bored.</td>
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<tr>
<td>(UNDSTPERSP) Tried to understand perspectives different from mine.</td>
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<td>(IRRITATED) Became irritated.</td>
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<td>(NEWINFONOT) Felt like new information would not change my opinions.</td>
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<tr>
<td>(RELATETHINGS) Thought about how the topics related to things I know.</td>
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</table>
### Questionnaire Responses

<table>
<thead>
<tr>
<th>Question</th>
<th>Not at all</th>
<th>Slightly</th>
<th>Some-what</th>
<th>Moderately</th>
<th>Very much</th>
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<tr>
<td>(FOCUSED) Felt focused.</td>
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<tr>
<td>(UNINTERESTED) Was uninterested in the task I was asked to do.</td>
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<tr>
<td>(ASKOTHRS) Asked others what they thought about the topics and issues.</td>
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<td>(OPENMIND) Felt open-minded.</td>
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<tr>
<td>(IDQUES) Identified questions that I still had about the topics.</td>
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<td>(CAREFULCONSID) Gave careful consideration to all of the options presented.</td>
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<td>(FRUSTRATED) Felt frustrated.</td>
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2. (**HEARDABT**) Think about your exposure to information about climate change in the past year. How much have you heard or learned about climate change and related topics (e.g., global warming, glacial melting) in the past year?

- Nothing at all
- A little
- Some
- Quite a bit
- A great deal

3. (**INFORMED**) Personally, how well informed do you feel you are about how the Earth’s “climate system” works?

- Not informed
- Not very well informed
- Fairly well informed
- Very well informed
4. Where have you heard or learned about climate change and related topics? Indicate the extent to which you heard or learned about climate change and related topics from the following sources in the past year.

<table>
<thead>
<tr>
<th>Source</th>
<th>Not at all</th>
<th>A little</th>
<th>Some</th>
<th>Quite a bit</th>
<th>A great deal</th>
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<tr>
<td>Multimedia (e.g. TV, radio, movies)</td>
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<td>Social media (e.g. blogs, Facebook)</td>
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<td>Text material (e.g. magazines, books)</td>
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<td>Social settings (e.g. conversations)</td>
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<td>Formal learning (e.g. classes)</td>
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<td>Informal learning (e.g. museums)</td>
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<td>Work situations (e.g. at work)</td>
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<td>Community situations (e.g. clubs)</td>
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<tr>
<td>Other (please specify)</td>
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</tr>
</tbody>
</table>

5. (***GWHAPPENING) Global warming refers to the idea that the world’s average temperature has been increasing over the past 150 years, may be increasing more in the future, and that the world’s climate may change as a result. What do you think? Do you think that global warming is happening?

- Yes, definitely
- Yes, probably
- No, probably not
- No, definitely not
- Don’t know

6. (GWINFO) On some issues people feel that they have all the information they need in order to form a firm opinion, while on other issues they would like more information before making up their mind. For global warming, where would you place yourself?

- I need a lot more information
- I need a little more information
- I need some more information
- I do not need any more information
7. How much do you trust or distrust the following as a source of information about climate change?

<table>
<thead>
<tr>
<th>Source</th>
<th>Strongly DIStrust</th>
<th>Somewhat DIStrust</th>
<th>Neither or don’t know</th>
<th>Somewhat Trust</th>
<th>Strongly Trust</th>
</tr>
</thead>
<tbody>
<tr>
<td>(TRUSTNOAA) The National Oceanic and Atmospheric Administration (NOAA)</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>(TRUSTCONGRESS) Your U.S. Congressman/Congresswoman</td>
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</tr>
<tr>
<td>(TRUSTPRESOBAMA) President Obama</td>
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<tr>
<td>(TRUSTMEDIA) The mainstream news media</td>
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<tr>
<td>(TRUSTDOE) The U.S. Department of Energy (DOE)</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>(TRUSTSCIENTISTS) Scientists</td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>(TRUSTNPSS) The National Park Service</td>
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<td></td>
</tr>
<tr>
<td>(TRUSTCDC) The U.S. Centers for Disease Control &amp; Prevention</td>
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</tr>
<tr>
<td>(TRUSTEPA) The U.S. Environmental Protection Agency (EPA)</td>
<td></td>
<td></td>
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<tr>
<td>(TRUSTTVMETS) Television weather reporters</td>
<td></td>
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<td></td>
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<tr>
<td>(TRUSTRELIGIOUS) Your faith or religious leaders</td>
<td></td>
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</tr>
</tbody>
</table>

8. (%SCI) According to recent surveys, what is the approximate percentage of all climate scientists that think that the global climate is warming due to human actions?

(if you do not know, please indicate your best guess) __________ (0-100%)

9. Please indicate whether you think the following are true or false.

<table>
<thead>
<tr>
<th>Statement</th>
<th>Definitely False</th>
<th>Probably False</th>
<th>Probably True</th>
<th>Definitely True</th>
<th>Don’t know</th>
</tr>
</thead>
<tbody>
<tr>
<td>Increased carbon dioxide and other gases released into the atmosphere will, if unchecked, lead to global climate change.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Human activity, including industry and transportation, is a significant cause of climate change.</td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>If global warming occurs, it will increase crop yields in some places, and decrease it in others.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Currently observed climate change is mostly due to normal climate patterns.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>The Earth’s climate is warmer now than it has ever been before.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Compared to the climate of the past one million years, the last 10,000 have been unusually warm and stable.</td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>
Global warming is happening and is resulting in changes in climate in different places across the world.

If humankind suddenly stopped producing carbon dioxide today, climate change and global warming would still continue for many years.

Over time, any climate change that happens will be more beneficial than harmful.

Currently observed global warming (if any) is not caused by humans.

Actions taken to "stop global warming" are hurting society more than helping.

10. (**MODEL) People disagree about how the climate system works. Which one of the five descriptions best describes how you think the climate system works?

- Gradual: Earth’s climate is slow to change. If global warming occurs, it will gradually lead to dangerous effects.
- Fragile: Earth’s climate is delicately balanced. Small amounts of global warming will have abrupt and catastrophic effects.
- Stable: Earth’s climate is very stable. If global warming occurs, it will have little to no effects.
- Threshold: Earth’s climate is stable within limits. If global warming is small, climate will return to a stable balance. If it is large, there will be dangerous effects.
- Random: Earth’s climate is random and unpredictable. We do not know what will happen.

11. In your opinion, what is the risk of climate change exerting a significant impact on...

(HEALTHRISK) **public health** in your region?

(ECONRISK) **economic development** in your region?

(ENVIIRRISK) **nature**, that is, the natural **environment** in your region?
12. Please indicate the extent to which you do the following below:

<table>
<thead>
<tr>
<th>Activity</th>
<th>Not at all</th>
<th>A little</th>
<th>Some</th>
<th>Quite a bit</th>
<th>A great deal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Do my part to try to reduce carbon dioxide emissions (e.g., recycle, drive less, use less energy, consider environmental impact of food choices)</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
</tr>
<tr>
<td>Support higher prices for types of energy and other consumer goods that do contribute to climate change</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
</tr>
<tr>
<td>Work with other groups in my community to prepare for the risks of climate change</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
</tr>
<tr>
<td>Use information about how climate may change (e.g., over the next 2-50 years) in my personal decisions (e.g., home improvement decisions, investments decisions, choice of where I live/work)</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
</tr>
<tr>
<td>Support lower prices for types of energy and other consumer goods that do not contribute to climate change</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
</tr>
<tr>
<td>Learn about the ways in which climate patterns may change in the future (e.g., over the next 2-50 years)</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
</tr>
<tr>
<td>Use information about how climate may change (e.g., over the next 2-50 years) in my decisions at work in my profession/occupation</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
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</tr>
</tbody>
</table>

DEMOGRAPHIC QUESTIONS

Why do we ask demographic questions? By asking demographic questions we can see if the survey is being completed by people of all demographics.

13. (GENDER) What is your gender? ☐ Male ☐ Female

14. What is your age in years? __________

15. What is the highest level of education you have achieved?

☐ Less than High School ☐ Some High School ☐ High School Diploma
☐ Some College ☐ Two Year College or Technical Degree ☐ Four Year College Degree
☐ Some Graduate School ☐ Advanced Degree
16. (IDEOL) Ideologically, which of the following best describes you...

<table>
<thead>
<tr>
<th>Overall</th>
<th>Strongly liberal</th>
<th>Moderately liberal</th>
<th>Weakly liberal</th>
<th>Centrist/middle of the road</th>
<th>Weakly conservative</th>
<th>Moderately conservative</th>
<th>Strongly conservative</th>
</tr>
</thead>
<tbody>
<tr>
<td>When it comes to ECONOMIC issues</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>When it comes to SOCIAL issues</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

17. Are you Spanish, Hispanic, or Latino?  ○ Yes  ○ No

18. Which of the following describes your race? (Please check all that apply)

○ American Indian or Alaska Native  ○ Asian  ○ Black or African American
○ Native Hawaiian or other Pacific Islander  ○ White  ○ Some Other Race (Please Specify):

19. How closely do you identify with (i.e., share common views with) each of the following political groups?

<table>
<thead>
<tr>
<th></th>
<th>Not at all</th>
<th>Slightly</th>
<th>Somewhat</th>
<th>Quite a bit</th>
<th>A great deal</th>
<th>Don't know</th>
</tr>
</thead>
<tbody>
<tr>
<td>Republican Party</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
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<tr>
<td>Green Party</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>Democratic Party</td>
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<td>○</td>
<td>○</td>
<td>○</td>
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<td>○</td>
</tr>
<tr>
<td>Libertarian Party</td>
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<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>Tea Party</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
</tr>
</tbody>
</table>

20. What is your ZIP Code? __ __ __ __

21. We are working on planning educational opportunities for rural educators, producers, and communities. We hope to tailor the opportunities that we develop to meet the needs and wants of persons from these groups. Do you play any of the following roles in your community? (Please select all that apply.)

○ K-12 educator  ○ City or town official (volunteer or paid)
○ Science teacher/educator  ○ Tribe member
○ Farmer/ Rancher/ Ag Producer  ○ Rural community member
○ Tribal leader  ○ Agriculture teacher/educator  ○ Other (please specify):
22. Which of the following best describes where you grew up?

- I grew up mostly on a farm or ranch
- I grew up mostly in the open country but not on a farm or ranch
- I grew up mostly in a smaller rural town
- I grew up mostly in a city or urban area
- Other (Please Specify):

23. Which of the following best describes where you live now?

- I live on a farm or ranch
- I live in the open country but not on a farm or ranch
- I live in a smaller rural town
- I live in a city or urban area
- Other (Please Specify):

THANK YOU!

We appreciate your taking the time to complete this survey!

Please return it to the person from whom you received it or mail this survey to:

University of Nebraska Public Policy Center (c/o: Lisa PytlikZillig)
215 Centennial Mall South, Suite 401
Lincoln, NE 68588-0228
Table 1. Mean survey responses for the narrative audiences (combined LP, NAI, and CS) and the general NASIS responders, with significance of the differences between

<table>
<thead>
<tr>
<th>Variable</th>
<th>Narrative</th>
<th>NASIS</th>
<th>p</th>
<th>LP</th>
<th>NAI/CS</th>
<th>p</th>
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<td>EconRisk</td>
<td>3.45</td>
<td>2.62</td>
<td>0.00000001</td>
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<td>HeardAbt</td>
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<td>0.00008</td>
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<td>3.31*</td>
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<td>%Sci</td>
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<td>2.00*</td>
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<tr>
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<tr>
<td>TrustDoE</td>
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<td>TrustPresObama</td>
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<td>0.29</td>
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<td>0.01</td>
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<td>TrustReligious</td>
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<td>0.71</td>
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<td>TrustCongress</td>
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<td>2.19</td>
<td>0.64</td>
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</tr>
</tbody>
</table>
samples; mean survey responses of the LP and combined NAI and CS audiences, with significance of the differences between samples. Italicized \( p \) values are statistically significant for \( \alpha = 0.05 \). An asterisk (*) in the NAI/CS column indicates that data were not collected from the CS group for these questions. All abbreviations are provided alongside their corresponding questions in Appendix A.
CHAPTER 6. SUMMARY AND CONCLUSIONS

There were no more lessons. There was nothing in the world but cold and dark and work and coarse brown bread and winds blowing. The storm was always there, outside the walls, waiting sometimes, then pouncing, shaking the house, roaring, snarling, and screaming in rage. – Laura Ingalls Wilder, The Long Winter.

By many measures, the Hard Winter of 1880-1881 indeed was one of the most severe since instrumental records began in the central United States. Over a span of six months from mid-October 1880 through mid-April 1881, a series of cold air outbreaks, snow storms, and winds brought frequent blizzard or white-out conditions, along with temperatures persistently below freezing during the heart of winter. Deep snow drifts over the railroad tracks cut off the main means of transportation and supply into western Minnesota and the Dakotas for several months, with no ability to bring food or fuel resources to the settlers on the prairies. While the settlers and communities were resourceful in rationing and sharing their food and fuel supplies to endure the winter, these settlers also endured near-starvation in underheated homes for months on end, along with near-isolation from surrounding communities.

The experience of the Ingalls family, as documented by Laura Ingalls Wilder in The Long Winter and in other personal accounts, was fairly typical of the Dakota settlers. The family twisted hay to burn for fuel after their coal supply was exhausted. Without a mill in town, the family ground raw wheat in a hand coffee mill to bake into bread or
make into mush, which provided the bulk of their sustenance through the winter, especially after the trains ceased operations and food supplies in the town stores were consumed. Lacking kerosene for lamp light, Ma created a light using axel grease and cloth. The family huddled around the heat from the cookstove in the kitchen to stay warm, studying from schoolbooks and reciting Bible verses to occupy the dreary days.

When determining whether Hard Winter of 1880-1881, or other winters, are among the most severe on record at a location, the Accumulated Winter Season Severity Index (AWSSI) can be applied to analyze all winters on record. The winters, classified into five categories from Mild to Extreme, can then be ranked by severity to find the outlier winters. Analysis can be conducted on an ongoing winter, to track its severity as it accumulates, as well as on past winters. Additionally, the analysis was created in two forms to allow calculation based on either snowfall and snow depth data or precipitation data. The standard AWSSI calculation, with snow data, has the advantage of drawing directly from observations; however, snow data can be fraught with gaps and errors. The precipitation-based AWSSI (pAWSSI) calculation relies on estimation based on surface temperature and precipitation to approximate snowfall and snow depth data, which can be based on assumptions that do not match observations; however, the more complete precipitation records allow creating of longer periods of record, particularly for sites with missing or questionable snow data. AWSSI is being implemented operationally by the Regional Climate Centers and National Weather Service to make data available for ongoing winters in real-time at a large number of stations, as well as to make the period-of-record data available for analysis.
The Hard Winter of 1880-1881 was characterized by one of the strongest negative episodes of the North Atlantic Oscillation (NAO) on record, as well as by a weak to moderate El Niño. In order to understand the impacts of both NAO and the El Niño—Southern Oscillation (ENSO) in the central United States, the impact of both oscillations individually and in combination was examined. Using a period of 1950-2013, statistical analysis of 26 stations across the central United States found strong relationships between NAO and temperatures and weak relationships between NAO and precipitation. Additionally, statistical analysis also found relationships between ENSO and both temperatures and precipitation. With sample sizes being too small to statistically analyze the combined impact of ENSO and NAO on temperatures and precipitation, composite analysis allowed investigation of the combination of the two factors on a number of synoptic parameters, supporting the results of the statistical analysis. The combination of negative NAO and El Niño does favor colder conditions in the winter months across much of the United States, particularly the eastern half. That said, the upper-level jet stream pattern typically favored during that combination – an anomalously strong subtropical jet extending across the southern United States and the Gulf of Mexico – was not present during the winter of 1880-1881, as the anomalies indicated anomalously weak westerly winds in that region. Anomalously high moisture was noted across the eastern half of the United States, despite anomalously low temperatures, supporting the unusually high precipitation during the Hard Winter.

In addition to contributing factors such as the strongly negative NAO and the El Niño, one other factor contributing to the severity of the Hard Winter was the colder
background climate. Temperatures have trended upward through the 20th Century and into the 21st Century, particularly during the winter months. When extremes occur around a cooler mean state, they are likely to reach a given below-average threshold more frequently than when they occur during a warmer mean state. In other words, conditions that would be highly unusual in an early 21st Century climate likely were less unusual in the late 19th Century. The same combination of teleconnection patterns that occurred during the Hard Winter of 1880-1881, placed onto a warmer background climate state, may not produce an equally extreme winter in the 2000s. Put simply, the Ingalls family pioneered the prairies during a cooler climate, and the Hard Winter of 1880-1881 would be more difficult to replicate in extent, duration, and extremity now.

The events of *The Long Winter* have inspired many a reader to ask questions about the weather and climate presented in the story. Given the support of research to place the winter in context of severity, partially explain its severity, and even describe and verify individual events within the book, the story can be used as a narrative to communicate meteorological and climatological concepts to audiences that are not specialized in meteorology or climatology. A true narrative, with elements including a protagonist and antagonist, setting, and plot involving conflict and resolution, has been demonstrated as an effective tool for communicating information to an audience. With Wilder as a trusted protagonist, the narrative conveyed information about climate variability and change, weather safety, and preparedness and adaptation to audiences that included Wilder fans, naturalists, and graduate students in Natural Resources. Audiences were surveyed to gauge their climate literacy and engagement, and those
audiences with exposure to the Laura Ingalls Wilder narrative exhibited significantly higher perception of risk of climate change and perception of consensus among scientists than audiences who had not heard the narrative. Additionally, the narrative audiences exhibited high trust in scientists, particularly NOAA, high levels of inspiration, and low levels of negative emotions such as boredom or anger. More qualitatively, national media attention on the Laura Ingalls Wilder narrative indicates some broad interest in the subject among general readers, as well.

From creation of an objective index of winter season severity through quantification of the impacts of ENSO and NAO on winter weather to the documentation and investigation of one historical winter, this work has spanned a range of scientific questions inspired by one story of one severe winter in the central United States. By channeling that story into a narrative, the perceived gap between scientific analysis and communication to broad audiences may be bridged, creating a smooth flow from scientific process to creating public engagement and interest in both the process and its results. Narrative construction, when framed properly to an audience, provides a means to create excitement and interest in weather and climate topics that could otherwise be technically challenging, such as teleconnections, or ideologically charged, such as anthropogenic climate change. By allowing Laura Ingalls Wilder’s voice to speak about the weather and climate events that she observed, and providing scientific context and description of those events, audiences can absorb the information in a memorable story and access a trusted scientist for further inquiry. Audience survey
results are consistent with these goals, and further research is needed, with additional experimental controls, to fully establish the effectiveness of the narrative construction.

Operational meteorological entities, such as the National Weather Service, can benefit from applying several of the tools and techniques developed throughout this project. The AWSSI provides operational utility by allowing meteorologists to place an ongoing winter in the context of past winters, enabling them to translate the results to their media and other information users. Additionally, operational meteorologists can gain understanding of the range of potential winter severity in their areas of responsibility, both temporally and spatially. The investigation of the impacts of both ENSO and NAO on winter conditions allows operational meteorologists to understand the impact of both, in combination, on previous winters. While not a predictive tool, such context at least provides the range of past experiences, which can be useful to communicate in decision support settings as well as for broader public interest. Finally, the current demonstration of a narrative to communicate weather and climate concepts suggests a promising method to be used by meteorologists and climatologists seeking stronger tools for communication with broad audiences, particularly regarding climate change. The Laura Ingalls Wilder narrative itself can be used by other storytellers, or meteorologists can create their own narratives based on topics of local or personal interest.

From this study, future work can focus on building on the concepts presented. Tightly controlled experiments are needed to evaluate effectiveness of the Laura Ingalls Wilder narrative methodology compared to other communication that are more
representative of presentation methodologies used by meteorologists and climatologists. Additional means of audience engagement should be explored, including classroom curriculum, written publications, and expanded online engagement, including the potential for survey and feedback from audiences to continue to assess the effectiveness of the narrative. Given the number of weather and climate events throughout the Little House book series, additional narratives can be constructed for events including drought, flooding, tornadoes, hailstorms, climatologies of different regions, and impacts of land use changes. All of these potential narratives provide channels of access for audiences to engage in topics related to weather and climate, such as preparedness for extremes, interaction of humans and environment, and adaptation to changing or new climates.

And as they sang, the fear and the suffering of the long winter seemed to rise like a dark cloud and float away on the music. Spring had come. The sun was shining warm, the winds were soft, and the green grass growing. – Laura Ingalls Wilder, The Long Winter