Spatial and Temporal Variability of Midwest Winter Severity

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SPATIAL AND TEMPORAL VARIABILITY OF MIDWEST WINTER SEVERITY

by

Jefferson D. Wright

B.S., Southern Illinois University, 2014

A Thesis
Submitted in Partial Fulfillment of the Requirements for the
Master of Science Degree

Department of Geography and Environmental Resources
in the Graduate School
Southern Illinois University Carbondale
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THESIS APPROVAL

SPATIAL AND TEMPORAL VARIABILITY OF MIDWEST WINTER SEVERITY

by

Jefferson D. Wright

A Thesis Submitted in Partial Fulfillment of the Requirements for the Degree of Master of Science in the field of Geography and Environmental Resources

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June 3, 2019
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TITLE: Spatial and Temporal Variability of Midwest Winter Severity

MAJOR PROFESSOR: Dr. Trenton W. Ford

Severe winter weather is something that impacts everyone in some way, and there are always questions regarding how severe a winter season has been and how external factors can influence the severity of winter. Characteristics of severe winter weather include large snowfall accumulations, persistent snow depths, extreme cold temperatures, or extended cold snaps, and the Midwest United States is subject to these conditions on a multitude of spatial and temporal scales. A method of quantifying the severity of winter known as the Accumulated Winter Season Severity Index (AWSSI) has been employed for this study, and utilizes daily records of the aforementioned winter severity characteristics to generate a value that can represent how severe an individual winter season has been, as well as the long term average winter severity for a given location. The variability in Midwest winter severity has been a topic of many previous studies, but a study regarding the long term changes as well as the drivers of winter severity with respect to the AWSSI has not been accomplished. Using daily records of snowfall, snow depth, maximum temperature, and minimum temperature, the goal of this study is to use the AWSSI to quantify these long term changes and impacts of different teleconnection phases on Midwest winter severity. The teleconnection patterns explored in this study include the El Niño Southern Oscillation (ENSO), the Pacific-Decadal Oscillation (PDO), the Arctic Oscillation (AO), and the Pacific North American (PNA) pattern. The analysis is divided into three phases consisting of (1) establishing a general winter climatology within the study area, (2) determining the long term
changes in winter severity and the associated parameters, and (3) examining the impacts of teleconnection patterns on the inter-annual variability in Midwest winter severity.
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DEDICATED

I would like to dedicate this work to my entire family, including my parents, Mike and Sally Wright, my grandparents, Rick and Joan Erickson, and my many aunts, uncles, and cousins. They have been an outstanding support system for not only this project and grad school, but throughout my entire life. Lastly, I dedicate this to my beautiful wife, Dawn. She has always believed in me, even when I doubted myself. She truly has helped me sustain confidence in myself, and she keeps me going every day both good and bad.
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CHAPTER 1
INTRODUCTION

1.1 Background

Severe winter weather has implications for many, as it can harm agriculture (Wendland et al., 1983), disrupt transportation (Knapp et al., 2000), inflate heating costs (Changnon, 1979), and wreak havoc on large metropolitan areas (Hilberg et al., 1983; Schmidlin, 1993). The Midwest United States is subject to extreme winter weather conditions, as winter storms are the region’s second-most frequent weather-related catastrophe (Andresen et al., 2012). This region experiences not only large snowfall accumulations, persistent snow depths, extreme cold temperatures, and extended cold spells, but also great variability in these winter weather conditions on a number of both spatial and temporal scales (Changnon, 2007). The northern portion of the Midwest, especially downwind of the Great Lakes, experiences large snow events on a relatively frequent basis (Changnon, 2006; Changnon and Kunkel, 2006), and even the southern tier of the region is expected to see on average around one annual event that produces six inches of snow in 24 hours or less (Changnon and Kunkel, 2006). However, it is quite difficult to quantify the severity of a winter season from one location to another.

Though defining the severity of a winter season or climate can be difficult, the Accumulated Winter Season Severity Index (AWSSI, Boustead et al., 2015) provides the ability to assess the spatial and temporal variations in severe winter weather across many scales. The intent of AWSSI is to quantify the severity of winter seasons by using readily available daily meteorological reports, accumulated from the beginning until the end of the winter season (Boustead et al., 2015). This index assigns daily point values that are based on snowfall (SF), snow depth (SD), maximum temperature, (TMAX), and minimum temperature (TMIN), with
point thresholds designed to give greater weight to extreme or rare events that have a high impact (Boustead et al., 2015). Daily points are accumulated during the winter season, the season-total sum of which is reflective of the overall winter season weather severity (Boustead et al., 2015). Therefore, the AWSSI can be used to compare winter severity between multiple, diverse locations, as well as determining the inter-annual variability of winter season severity at a given location. In the past, climatological studies of winter weather have focused on individual events, such as single snowstorms, individual variables – such as temperature, or have centered on a specific region, while very few have addressed the daily or seasonal scale of winter severity (Boustead et al., 2015). The AWSSI provides the ability to resolve daily progression of a winter season, and give an accumulated value at the end of the season. It also allows the ability to track the length of the winter season, represented by the difference between the last day and first day of a season to accumulate an AWSSI point.

There still is uncertainty in exactly how and what external factors influence Midwest winter severity. The synoptic features associated with severe winter weather in the Midwest include the passing of a substantial low-pressure center with an associated upper-level trough in the jet stream, which work together to produce snowstorms and draw cold air from the Canadian Arctic (Changnon and Kunkel, 2006). However, the strength and position of the low-pressure center, as well as the strength and persistence of the jet stream trough can vary greatly from month-to-month, year-to-year, and decade-to-decade. Several climate oscillation teleconnection patterns operating on daily, monthly, inter-annual, and decadal time scales have been shown to influence the upper level jet stream, resulting in significant winter weather in the United States. The modes of climate variability and resulting teleconnection patterns that will be explored in-depth for this particular study include the El Niño Southern Oscillation (ENSO), the Pacific-
Decadal Oscillation (PDO), the Arctic Oscillation (AO), and the Pacific-North American Pattern (PNA). Little research has been done assessing the impacts of teleconnections on winter severity using an operational index like AWSSI. The purpose of this paper is to fill this knowledge gap and improve our understanding of both Midwest winter climatology, changes that have occurred in the associated winter severity parameters, as well as the role of large-scale teleconnection patterns in governing inter-annual Midwest winter severity.

1.2 Problem Statement and Research Questions

The goals of this study are to develop a winter season severity climatology for the Midwest using AWSSI and its parameters, assess the long term changes that have taken place in winter season severity, and determine the dominant driving factors that influence the inter-annual variability in winter severity. Because little research has been conducted regarding the AWSSI there is a need for an improved understanding of the factors that contribute to Midwest winter severity. Since the AWSSI is uniquely capable of evaluating winter season severity across the Midwest over time while capturing the effects of remote drivers, such as ENSO, PDO, AO, and PNA, using AWSSI provides a novel perspective.

Prior winter season climatology research has been mostly limited to studies that are solely based on temperature or snowfall. Very little research has been conducted using a specific winter severity index such as the AWSSI to test for changes in the associated parameters as well as the dominant modes of variability in winter severity. There is also very little research that has been conducted regarding winter severity over a specific region such as the Midwest United States. The specific research questions in which the study intends to answer include:

1. How does Midwest winter season severity vary both spatially and temporally?

2. How has winter severity changed over time?
3. *How is winter severity impacted by large-scale teleconnection patterns?*
CHAPTER 2
LITERATURE REVIEW

2.1 Long Term Changes in Winter Severity

2.1.1 Background Warming

Previous studies on Midwest winter weather have focused on the individual severe winters of the late 1970’s such as 1976-77 (Diaz and Quayle, 1978), 1977-78 (Changnon, 1979; Dare, 1981), and 1978-79 (Diaz and Quayle, 1980), and how the abnormally extreme cold and snowy conditions affected people and the economy. Other studies have centered on the drivers behind individual severe winters, such as 2013-14 (Hartmann, 2015; Marinaro et al., 2015; Wolter et al., 2015), as well as individual events within winters (Branick, 1997). A large number of other studies have focused on projected changes in winter weather with continued warming of the climate (Kunkel et al., 2000; Burnett et al., 2003; Kunkel et al., 2009; Andresen et al., 2012). Over the last several decades, as the mean temperature of the Earth has warmed, winter season temperatures have undergone the largest changes (Walther et al., 2011). As the climate warms, winter weather in the Midwest is expected to see large changes, such as longer frost-free seasons (Wuebbles and Hayhoe, 2003), and increased precipitation (Lawrimore et al., 2014). Kunkel et al., (2009) found large, negative trends in extreme low-snowfall years in the north-central part of the country. Background atmospheric warming has been shown to play a role in increased snowfall most notably in the Great Lakes region (Andresen, 2012), as waters have remained warmer and ice-free for longer periods of time, allowing more potential for lake effect snow. Areas downwind of the Great Lakes have seen an increase in total snowfall in the past 30-40 years (Kunkel et al., 2000; Burnett et al., 2003; Andresen et al., 2012), but warmer temperatures have been causing the snow to melt quicker and earlier, with snow depths decreasing most
rapidly in late March and early April (Dyer and Mote, 2006). This is consistent with modeling studies that have projected an increase in snowfall, but decrease in the length of the snow season in northern parts of the United States (Scott and Kaiser, 2004; Hosaka, et al., 2005; Räisänen, 2008). Northern areas of the Midwest outside of the lake effect region, such as parts of North Dakota, South Dakota, Minnesota, and Wisconsin have also seen increased snowfall potential with background warming. Even though the temperature has warmed slightly it still remains cold enough for snow in the winter in these northern locations, and with the temperature being slightly warmer, the atmosphere has a larger saturation mixing ratio (Trenberth, 2011), thus leading to larger snowfall rates (Notaro et al., 2014). However, with more time and increased warming, the rain/snow line is expected to migrate north, and snow seasons in these northern states are expected to become dramatically shorter by the late 21st century, with the largest reductions in springtime due to earlier onset of melting (Notaro et al., 2011; Demaria et al., 2016).

2.2 Drivers of Winter Severity Variability

2.2.1 El Niño Southern Oscillation

One of the main influences on winter-time temperature variability is the El Niño Southern Oscillation (ENSO). ENSO describes the cycle of equatorial Pacific sea surface temperature (SST) anomalies (Trenberth, 1997), and it consists of three phases: El Niño (warm), neutral, and La Niña (cold). Each phase has different effects on regional wintertime temperatures and circulation patterns (Wallace and Gutzler, 1981) (Figure 2.1).
In the Midwest, La Niña (cold phase) years generally are expected to produce more days below freezing than El Niño (warm phase) years (Smith and Sardeshmukh, 2000). Typically, the El Niño phase is expected to result in positive surface air temperature (SAT) anomalies over Alaska and western Canada, with weaker negative SAT anomalies over the southern and eastern United States (Wu et al., 2005). Smith and O’Brien (2001) showed that differences between ENSO warm and cold phases have different effects on the jet stream, most notably a weaker polar jet over the Midwest. This not only has an influence on surface temperature, but it also affects the ability for winter cyclones to draw moisture from the Gulf of Mexico, leading to large variations in annual snowfall. Typical synoptic scale snowstorms in the Midwest follow one of two midlatitudes cyclone tracks, being the “Alberta Clipper” and the “Colorado Low.” Kunkel and Angel (1999) examined winter cyclone tracks relative to the three phases of ENSO and found that much of the northern United States experiences below average snowfall during strong El Niño winters with statistically significant anomalies in the Ohio and Mid-Mississippi Valleys. Their results showed that Alberta Clipper type cyclones tracking southeast from Canada across the Northern Great Plains and eastward to the Great Lakes occur with much less (greater) frequency in El Niño (La Niña) winters. Colorado Low type cyclones developing on the lee of

Figure 2.1: Effects of El Niño and La Niña on winter time temperature and circulation. Sourced from NOAA.climate.gov
the Rockies and tracking northeast towards the Great Lakes occur in both El Niño and La Niña winters, but occur more frequently during La Niña winters (Kunkel and Angel, 1999).

### 2.2.2 Pacific Decadal Oscillation

The Pacific Decadal Oscillation (PDO) is a pattern that is tied to SST and pressure variations in the North Pacific, which can influence the direction and amplitude of circulation across the United States (Figure 2.2).

**Figure 2.2:** Sea level pressure (SLP) anomaly for positive PDO winters minus negative PDO winters. Positive values represent anomalous high pressure, while negative values represent anomalous low pressure. Colors represent SLP anomaly in units of millibars. Map derived from esrl.noaa.gov.

PDO is often regarded as the first empirical orthogonal function of the anomalies of monthly mean SST poleward of 20°N in the Pacific Ocean (Mantua et al., 1997). This pattern can also be described as a phenomenon in the North Pacific that is strongly associated with the
fluctuation in the strength of the wintertime Aleutian Low (Rodionov and Assel, 2003). In fact, the area of the North Pacific underwent a regime shift in 1977, going from a cool phase to a warm phase, and this shift is thought to have been related to three anomalously severe Midwest winters in the late 1970’s by influencing the strength and position of the Aleutian Low (Trenberth, 1990). Fluctuations in the PDO produce different results, as during a warm PDO anomalously warm SSTs along the west coast can result in enhanced sea level pressure (SLP) anomalies that are low (high) in the North (subtropical) Pacific, causing strengthened counterclockwise (clockwise) winds (Mantua and Hare, 2002). Generally, a warm (cool) PDO phase is expected to result in wintertime temperatures that are significantly cooler (warmer) in the southern and eastern United States. The opposite can be said about the northern and western part of the United States, as a warm (cool) PDO phase is expected to result in wintertime temperatures that are significantly warmer (cooler) in this part of the country (Budikova, 2005). However, there has been vast research regarding the PDO over the last few decades, and it cannot be attributed to a single phenomenon, rather the result of a combination of several physical processes (Newman et al., 2016). In fact, the effects of the PDO have been shown by Rodionov and Assel (2003) to be highly affected by the strength of El Niño phases, as in the absence of a strong El Niño, a warm PDO is conducive to a strong ridge-trough pattern over North America, with increased advection of cold air into the Midwest. When coupled with a strong El Niño episode, the trough over the eastern part of the country is not as prevalent, and winters are typically warmer in the Midwest. Newman et al. (2016) also noted that when El Niño events peak during boreal winter, the Aleutian Low deepens, and changes in surface heat fluxes as well as other atmospheric phenomena act together to create a positive PDO pattern.
2.2.3 Arctic Oscillation

The AO is a pattern that represents the flow of air around the high latitude Northern Hemisphere. It is often noted as the leading mode of sea level pressure (SLP) variability over the Northern Hemisphere, with its center over the Arctic, and opposing anomalies in the midlatitudes (Deser, 2000). It has a positive phase, which is associated with anomalously low pressure in the North Atlantic, and a negative phase, which is associated with anomalously high pressure in the North Atlantic (Budikova, 2008) (Figure 2.3). Its variation between positive and negative phase can have large impacts on winter time temperatures across the Midwest, as a negative AO favors anomalously cold temperatures over the United States east of the Rocky Mountains with increased storm activity in the midlatitudes (Thompson and Wallace, 1998), and a positive AO features stronger westerly winds that tend to keep cold Arctic air confined to northern locations (Budikova, 2005).

![Arctic Oscillation](image)

**Figure 2.3:** Effects of the Arctic Oscillation on the jet stream. Sourced from NOAA (National Oceanic and Atmospheric Administration) and NCDC (National Climatic Data Center).
Cohen et al. (2010) found that the AO explained greater variance of observed temperature across extratropical landmasses of the Northern Hemisphere than ENSO, and the severe winter of 2009-10 was strongly associated with the lowest AO phase on record since 1950. This particular winter was severe due to a redistribution of mass across North America due to anomalously high pressure at high latitudes and low pressure in the midlatitudes. However, there is also evidence suggesting an interaction effect between the PDO and AO on wintertime temperatures in the Midwest. Budikova (2005) found that the PDO can modulate the effects of the AO. For example, when the AO is in positive phase, a positive PDO phase results in significantly lower wintertime temperatures in the Ohio Valley than a negative PDO, with little difference in the Northern Great Plains. Generally, a negative AO phase would be expected to result in colder wintertime temperatures across the entire Midwest, but when the AO is in negative phase, a negative PDO results in significantly colder wintertime temperatures throughout the Midwest than a positive PDO due to greatly enhanced northerly flow, with the largest impact on the Northern Great Plains (Budikova, 2005). Another study highlighted the interaction between AO and ENSO, showing that the state of the AO plays a role in the influence of ENSO-related teleconnection patterns and resulting temperature and precipitation regimes across the eastern United States during winter months (Budikova, 2008). When the AO is negative, El Niño winters can expect to be significantly drier for the central Midwest and Ohio Valley, and the overall effects of El Niño are much stronger when the AO is in a negative phase (Bond and Harrison, 2006). When the AO is in neutral phase, El Niño coincides with a circulation pattern that resembles the positive phase of the PNA with strong meridional flow of the polar jet stream, while a La Niña would resemble the negative phase of the PNA (Budikova, 2008).
2.2.4 Pacific North American (PNA) Pattern

The PNA pattern is one of the most prominent modes of low-frequency variability in the Northern Hemisphere, with the positive phase featuring above-average heights near Hawaii and the North American intermountain region, and below average heights south of the Aleutian Islands and Southeastern United States (Climate Prediction Center). The different phases of the PNA can have impacts on the Midwest, as a positive phase results in a stronger Aleutian Low (Figure 2.4), with an enhanced upper-level trough over eastern United States, and stronger ridging over the Rocky Mountains and western United States (Leathers et al., 1991; Yin, 1994).

Figure 2.4: Sea level pressure (SLP) anomaly for positive PNA winters minus negative PNA winters. Positive values represent anomalous high pressure, while negative values represent anomalous low pressure. Colors represent SLP anomaly in units of millibars. Map derived from esrl.noaa.gov.
The positive phase generally leads to more meridional upper-level flow across North America, with warmer temperatures in the west and colder temperatures in the south and east due to the associated polar jet front that allows Arctic air masses to dive south on a more frequent basis (Leathers et al., 1991). A negative phase of the PNA typically results in more zonal upper-level flow, with troughs still existing over the Aleutian and eastern United States, albeit weaker, and reduced ridging over the Rockies (Leathers et al., 1991; Yin, 1994). This negative phase generally leads to cooler and wetter conditions in the west, with drier and warmer conditions in the east due to the polar front being displaced further north in this part of the United States. As shown by previous studies, winter surface temperatures are closely related to the 700 hPa height field, and a study by Erickson (1984), using 700 hPa height fields and anomalies, selected four warm and cold winters from a 30-year time period. The study found that warm winters in the United States tended to coincide with positive anomalies of the 700 hPa height field with an inverse pattern for cold winters (Erickson, 1984). The PNA itself is a large source of winter-time temperature variability, but it does not act alone, as typically, the PNA pattern can be excited by fluctuations in ENSO. El Niño winters can coincide with an enhanced PNA, which enhances meridional flow of the polar jet over the northern United States, resulting from a deep trough, or strong Aleutian low over the North Pacific, a strong ridge over the northwest United States, and a well-developed trough over the southeast United States (Budikova, 2008). Two case studies of the anomalously cold winter of 2013-14 revealed this winter was related to a warm SST anomaly in the North Pacific Ocean, which led to near record high 500 hPa heights over Alaska, creating a persistent blocking pattern that allowed a large trough over the central United States to persistently funnel cold air from the Arctic to the Midwest (Hartmann et al., 2015; Marinaro et al., 2015).
2.3 Summary

There have been many studies regarding projections of future winter climate conditions, as well as impacts from severe winter weather conditions. Attempts have been made to quantify winter severity in the past, such as a cumulative winter severity index based on consecutive days of below freezing temperatures and snow depth persistence (Schummer et al., 2010), as well as a winter severity index based on maximum freezing degree-days (Assel, 1980). However, no studies have either assessed the severity and changes over an extended period relative to all four AWSSI winter weather parameters across an entire region, or examined Midwest winter severity (and changes to winter severity) at a daily resolution. The first objective of this study is to develop an in-depth climatological assessment of winter severity across the Midwest United States using the AWSSI and assess the changes that have taken place over time in each contributing parameter on daily, monthly, annual, and decadal scales. The second objective of this study is to determine the dominant modes of climate variability and the impacts of teleconnection patterns on winter severity and examine how these relate to large scale forcing.
CHAPTER 3
DATA

3.1 Data Sources

The daily meteorological data for this study were obtained from the National Center for Environmental Information (NCEI) and the Midwest Regional Climate Center’s (MRCC) cli-Mate database, and contains daily summary reports of SF, SD, TMAX, and TMIN from a period starting in the 1950-51 winter season and ending in the 2017-18 winter season for a total of 68 winter seasons. The data from the cli-Mate database contains seven threaded stations that have complete or near-complete records. These threaded stations contain data that was combined from multiple stations in a city area in order to create a longer and more complete period of record (MRCC). Coverage of the data includes 44 Automated Surface Observation System (ASOS) weather stations across the Midwest. The utilization of station data allows for actual observational measurements, sufficient spatial coverage, as well as a requisite length in the study. For the purposes of this study the Midwest is comprised of parts of thirteen states, including Illinois, Indiana, Iowa, Kansas, Kentucky, Michigan, Minnesota, Missouri, Nebraska, North Dakota, Ohio, South Dakota, and Wisconsin. Bismarck, ND and North Platte, NE at around the 100th meridian represent the western extent of the study region, Cleveland, OH represents the eastern extent, International Falls, MN represents the northern extent, and Paducah, KY represents the southern extent. The data were selected strategically as a compromise between (1) covering the geographic extent of the Midwest and (2) working with complete, or nearly-complete records of high-quality data (e.g., Ford and Schoof, 2017). When assessing the average winter severity for each parameter, the threaded sites generally do well at capturing these values, but the results of the temporal changes in the threaded sites, especially
regarding snowfall and snow depth, should be approached with caution (Boustead et al., 2015). The Niño 3.4 index was used to represent ENSO, and data regarding each of the other teleconnection patterns was obtained through the National Oceanic and Atmospheric Administration (NOAA) containing monthly time series of the 68 aforementioned winters. The inter-annual variability of each teleconnection pattern is maximized in winter, therefore, the December, January, February (DJF) average was calculated and used to compare each teleconnection pattern’s time series to the time series of AWSSI.

3.2 Quality Control

Winter seasons which contain missing snow and temperature data were excluded if the missing data was estimated to contribute 5% or more to the total AWSSI for that season (e.g., Boustead et al., 2015). This was determined by assessing the number of missing instances in each parameter for a given season. The data was processed via MATLAB programming software to determine the number of missing values for a period ranging from September 1st to May 31st for each winter season. If one year had twenty or more total combined missing values from each parameter that winter season was excluded from the study. However, many seasons in the southern portion of the study area had large numbers of missing snowfall and snow depth reports in September and May, causing several seasons to be unnecessarily removed from the dataset. The solution to this was to determine the number of missing snow and temperature values from October through April in these instances for the southern portion of the study area, as these areas rarely, if ever, experience snow in September or May. This was accomplished through MATLAB programming software, as well as manual examination of the dataset. As seen in Table 3.1, 18 stations have a complete record containing each of the 68 winter seasons from 1950-51 through 2017-18. Three stations, Marquette, MI, Waterloo, IA, and Wichita, KS,
each have complete, unbroken records that begin after the 1966-67, 1955-56, and 1954-55 respective winter seasons. Two sites, Traverse City, MI and Columbia, MO both have records that were tied together from separate station locations in close proximity to each other that were most likely split up due to the moving of stations from a downtown location to an airport.

**Table 3.1:** AWSSI Sites and Missing Seasons (thr indicates threaded site from cli-Mate database)

<table>
<thead>
<tr>
<th>STATION</th>
<th>TOTAL MISSING</th>
<th>MISSING WINTER SEASONS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aberdeen, SD</td>
<td>2</td>
<td>1981/82, 1988/89</td>
</tr>
<tr>
<td>Bismarck, ND (thr)</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td>Champaign, IL</td>
<td>6</td>
<td>1984/85, 1986/87 - 1990/91</td>
</tr>
<tr>
<td>Chicago, IL (Midway Airport)</td>
<td>2</td>
<td>1979/80, 1980/81</td>
</tr>
<tr>
<td>Cincinnati, OH</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td>Cleveland, OH</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td>Columbia, MO</td>
<td>4</td>
<td>1996/97</td>
</tr>
<tr>
<td>Columbus, OH</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td>Des Moines, IA</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td>Detroit, MI (thr)</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td>Dodge City, KS</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td>Duluth, MN</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td>Evansville, IN</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td>Fargo, ND (thr)</td>
<td>7</td>
<td>1997/98 - 2003/04</td>
</tr>
<tr>
<td>Fort Wayne, IN</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td>Grand Rapids, MI</td>
<td>1</td>
<td>1999/00</td>
</tr>
<tr>
<td>Green Bay, WI</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td>Indianapolis, IN</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td>International Falls, MN</td>
<td>2</td>
<td>2001/02, 2002/03</td>
</tr>
<tr>
<td>Kansas City, MO (thr)</td>
<td>1</td>
<td>1996/97</td>
</tr>
<tr>
<td>La Crosse, WI</td>
<td>1</td>
<td>1985/86</td>
</tr>
<tr>
<td>Louisville, KY</td>
<td>2</td>
<td>1995/96, 2001/02</td>
</tr>
<tr>
<td>Madison, WI</td>
<td>1</td>
<td>1997/98</td>
</tr>
<tr>
<td>Marquette, MI</td>
<td>15</td>
<td>1950/51 - 1965/65</td>
</tr>
<tr>
<td>Mason City, IA</td>
<td>2</td>
<td>2000/01, 2001/02</td>
</tr>
<tr>
<td>Milwaukee, WI</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td>Minneapolis-St. Paul, MN</td>
<td>4</td>
<td>2000/01 - 2003/04</td>
</tr>
<tr>
<td>Moline, IL (thr)</td>
<td>4</td>
<td>1997/98 - 2000/01</td>
</tr>
<tr>
<td>North Platte, NE</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td>Location</td>
<td>Games</td>
<td>Years</td>
</tr>
<tr>
<td>----------------------------------</td>
<td>-------</td>
<td>--------------------------------</td>
</tr>
<tr>
<td>Omaha, NE</td>
<td>4</td>
<td>1995/96 - 1997/98, 2001/02</td>
</tr>
<tr>
<td>Paducah, KY</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td>Rockford, IL (thr)</td>
<td>9</td>
<td>1950/51, 1996/97 - 2004/05</td>
</tr>
<tr>
<td>Sioux Falls, SD</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td>South Bend, IN (thr)</td>
<td>1</td>
<td>2013/14</td>
</tr>
<tr>
<td>Springfield, IL</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td>Springfield, MO</td>
<td>1</td>
<td>2001/02</td>
</tr>
<tr>
<td>St. Louis, MO (Lambert Airport)</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td>Topeka, KS</td>
<td>1</td>
<td>2002/03</td>
</tr>
<tr>
<td>Traverse City, MI</td>
<td>3</td>
<td>1998/99, 2000/01, 2001/02</td>
</tr>
<tr>
<td>Waterloo, IA</td>
<td>5</td>
<td>1950/51 - 1954/55</td>
</tr>
<tr>
<td>Wausau, WI</td>
<td>4</td>
<td>1958/59, 2000/01 - 2002/03</td>
</tr>
<tr>
<td>Wichita, KS</td>
<td>4</td>
<td>1950/51 - 1953/54</td>
</tr>
</tbody>
</table>
4.1 AWSSI Calculations

Because the true definition of “winter” is not universal, in order to characterize a winter season, the AWSSI has certain principles that define the onset and cessation of winter. These were created in order to allow the impact of a long winter season to add points to the score, while acknowledging that winter does have a calendar-based definition (Boustead et al., 2015).

For a winter season to start accumulating AWSSI points, one of three criteria must be met:

1) The first measurable snowfall of 0.1 inches or greater
2) The first day where TMAX remains below 32°F
3) December 1st, which the first day of meteorological winter

For a winter season to stop accumulating AWSSI points, one of four criteria must be met:

1) The last measurable snowfall of 0.1 inches or greater
2) The last day with measurable snow depth of one inch or greater
3) The last day where TMAX remains below 32°F
4) The final day of February, which is the final day of meteorological winter

After being quality controlled, the data were processed via MATLAB based on the point threshold values of AWSSI (Boustead et al., 2015) (Table 4.1). These values were created in order to give greater weight to large events that are much rarer in occurrence. Trace snowfall and snow depth are treated as zeroes, and the point total for snowfall was designed in order to properly capture events that span multiple days (Boustead et al., 2015). The temperature thresholds are the same for each category, meaning TMIN accounts for substantially more points than TMAX. A theoretical winter day may see one inch of snowfall (2 points), existing snow
depth of one inch (1 point), a maximum temperature of 30°F (1 point), and a minimum temperature of 20°F (2 points). The points for each contributing parameter are summed together for a one day total, yielding a daily total of 6 AWSSI points. At the end of the season the daily point totals are summed together to create an accumulated winter severity for the entire season (Boustead et al., 2015). Winters in which missing data were estimated to contribute 5% or more to the total AWSSI were excluded from the study, and the resulting AWSSI numbers were used to assess the climatology, variability, changes that have taken place over time, and the impacts of teleconnections on winter severity.

Table 4.1: AWSSI Point Threshold Values (Boustead et al., 2015)

<table>
<thead>
<tr>
<th>Points</th>
<th>Temperature (°F)</th>
<th>Snow (in.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max</td>
<td>Min</td>
<td>Fall</td>
</tr>
<tr>
<td>1</td>
<td>25 - 32</td>
<td>25 - 32</td>
</tr>
<tr>
<td>2</td>
<td>20 - 24</td>
<td>20 - 24</td>
</tr>
<tr>
<td>3</td>
<td>15 - 19</td>
<td>15 - 19</td>
</tr>
<tr>
<td>4</td>
<td>10 - 14</td>
<td>10 - 14</td>
</tr>
<tr>
<td>5</td>
<td>5 - 9</td>
<td>5 - 9</td>
</tr>
<tr>
<td>6</td>
<td>0 - 4</td>
<td>0 - 4</td>
</tr>
<tr>
<td>7</td>
<td>From -1 to -5</td>
<td>From -1 to -5</td>
</tr>
<tr>
<td>8</td>
<td>From -6 to -10</td>
<td>From -6 to -10</td>
</tr>
<tr>
<td>9</td>
<td>From -11 to -15</td>
<td>From -11 to -15</td>
</tr>
<tr>
<td>10</td>
<td>From -16 to -20</td>
<td>From -16 to -20</td>
</tr>
<tr>
<td>11</td>
<td>-</td>
<td>From -20 to -25</td>
</tr>
<tr>
<td>12</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>13</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>14</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>15</td>
<td>&lt; -20</td>
<td>From -26 to -35</td>
</tr>
<tr>
<td>18</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>20</td>
<td>-</td>
<td>&lt; -35</td>
</tr>
<tr>
<td>22</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>26</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>36</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>45</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
4.2 Statistical Analyses

4.2.1 Average Winter Severity

The daily AWSSI points that were assigned to each parameter were summed together to generate a total number that represents the severity of a given winter, as well as each parameter’s contribution to total winter severity. In order to determine the contribution from the largest daily events, the total AWSSI points from the top 10% of days in each winter season was divided by the total AWSSI for each respective winter season. Because a winter season in the northern part of the Midwest is expected to last much longer than one the southern part, this gives the ability to show what proportion of the total annual AWSSI accumulation is accounted for by extreme days (i.e., those in the top 10% of AWSSI points), while also taking into account the large differences between stations in total AWSSI, length of season, and days that receive points. This allows for the assessment of how the contribution from the top accumulation days has changed over time.

4.2.2 Inter-annual Variability in Winter Severity

The coefficient of variation, or relative standard deviation, was used to assess the inter-annual variability of winter weather. The coefficient of variation ($C_v$) is computed as:

$$C_v = \frac{\sigma}{\mu}$$

where $\sigma$ is the annual or daily AWSSI standard deviation, and $\mu$ is the annual or daily AWSSI mean. Practically, $C_v$ represents the variability of AWSSI with respect to the mean AWSSI for each year. This was deemed the most appropriate method of comparing variability across sites, as comparing the raw standard deviation values between the northern and southern stations would be misleading. Since the northern stations have much higher AWSSI point totals in essentially every parameter, their standard deviation values are also much higher.
4.2.3 Long Term Changes in Winter Severity

To assess changes in each AWSSI parameter, a Theil-Sen median pairwise of slopes (MPWS) estimator was applied to each parameter’s entire time series, allowing for a nonparametric approach to fitting a regression trend line to the data (Lanzante, 1996). This approach is a method for fitting a line to sample points by choosing the median of the slopes of all lines through pairs of points, and was deemed the best approach to this particular dataset. Marquette, MI was excluded from this analysis due to the large number of years missing from the first half of the station’s record. Considerable skew of season-total AWSSI (positive at northern stations, negative at southern), and severe winter outliers precluded the use of ordinary least squares regression. The strengths of the Theil-Sen method are the estimator not being sensitive to outliers in the dataset, as well as the fact that the estimator does well with skewed datasets. Assessing the significance of the Theil-Sen results was achieved using a Spearman’s rank-order correlation, which is a non-parametric method of assessing the relationship between two variables using a monotonic function.

4.2.4 Dominant Modes of Variability of Winter Severity

We use a principal component analysis (PCA) to reduce the dimensionality of the annual Midwest winter severity data, and determine the role of large scale teleconnection patterns in governing winter severity variability. PCA reduces data dimensionality by transforming a number of possibly correlated variables into a smaller number of uncorrelated variables (i.e., principal components, PCs), with the first PC accounting for as much variability in the dataset as possible, and each succeeding component accounting for as much of the remaining variability as possible (Dunteman, 1989). For this particular dataset, a few preprocessing measures were taken before performing the analysis. The first was to standardize the annual AWSSI values in order
to give equal weight to each location. The next step was to account for missing years within the dataset by taking the average anomaly of the three nearest stations. For example, if a season in Columbia, MO was missing, the average anomaly of Kansas City, St. Louis, and Springfield, MO was used to replace said missing season. Marquette, MI was not included in the PCA because of over ten winter season with missing data. After preprocessing, the PCA was applied to the dataset using a correlation matrix in order for stations with milder winter conditions to be compared to stations with more severe winter conditions. A varimax rotation was used to maximize the sum of the variances and squared loadings. The selection of the number of PCs to retain, four in the end, was quite clear, based on scree plots (Figure 4.1) and eigenvalues of >1.0 (e.g., Comrie and Glenn, 1998).

![Scree Plot](image)

**Figure 4.1:** Principal component analysis scree plot displaying the eigenvalues of each PC in the analysis. PCs containing an eigenvalue of 1.0 or greater (4) were retained for the analysis. The four PCs explained 85% of the variance within the dataset. Subsequent analyses were performed to assess the drivers of Midwest winter severity variability. These include a mix of
correlative and composite techniques to explore the roles of large-scale teleconnection patterns in winter season variability in the Midwest.
5.1 AWSSI Climatological Assessment

5.1.1 Average Annual Winter Severity

Annual average AWSSI (Figure 5.1) follows a relatively predictable pattern, with the average winter severity being highest in the northernmost stations around the Great Lakes, and lowest in the southernmost stations around the Ohio Valley.

**Figure 5.1:** Average winter season AWSSI total values across the Midwest United States.

The same generally can be said about the average length of winter season (Figure 5.2a) and the average number of days that receive AWSSI points (Figure 5.2b), as the stations that have the highest AWSSI averages typically experience the longest winter seasons, and experience AWSSI point accumulation on a large majority of the days in a winter season. The difference in what would be referred to as an “average winter” between the northernmost stations
and southernmost stations is quite large, as two stations, Marquette, MI and International Falls, MN each have an average AWSSI of greater than 2000, while four stations, Paducah, KY, Louisville, KY, Evansville, IN, and Springfield, MO all have an average AWSSI of less than 300.

![Map of stations with AWSSI values]

**Figure 5.2:** Panel A: Average winter season length (days). Panel B: Average number of days that receive ≥1 AWSSI point per season.

The differences in the length of season and days with points between the northernmost and southernmost stations are similarly large, as 13 stations see average winter seasons lasting at least 160 days, while most of the stations south of Interstate 70 see winter seasons that last around 120 days or fewer on average. The southernmost stations typically experience winter seasons that are defined by the start and end of meteorological winter (December 1 – February 28/29), with occasional seasons in between receiving an early (late) season snowfall or freeze in November (March). As latitude increases slightly, the first (last) snowfall would generally be expected sometime in November (March), with occasional seasons lasting from October through
April. The northernmost stations typically experience their first (last) snowfall in October (April), with rare September and May snowfall events, making for prolonged winter seasons that last over 180 days on average and in many instances lasting well over 200 days. In the northern stations, most days within a winter season will receive at least one AWSSSI point due to nighttime minimum temperatures consistently falling below freezing, while the southernmost stations do not experience nearly as many days with AWSSSI point accumulation, as their temperatures on many nights fail to drop below freezing. For example, Marquette, MI on average experiences a winter that lasts 198 days with 182 (92%) of those days receiving at least one AWSSI point, while Paducah, KY on average experiences a winter that lasts 102 days with 68 (67%) of those days receiving at least one AWSSI point.

5.1.2 Winter Severity by Parameter

When examining winter severity by each parameter, the patterns are slightly different, not strictly following a north-to-south gradient in every case. The highest snowfall point averages generally are found in the eastern portion of the study region, with the highest averages coming in the Great Lakes lake effect snow belt (Figure 5.3a). The largest snow depth point averages (Figure 5.3b) do not explicitly line up with the largest snowfall averages, as the snow depth points follow more of a north-to-south gradient, likely tracking patterns in maximum and minimum temperature. Areas that receive both relatively large snowfall totals and persistent stretches of subfreezing temperatures will experience snow continuously accumulating throughout the winter, leading to high snow depths that last well into spring. The stations that see the highest snow depth values generally are the ones that see the highest total AWSSI scores. Northern stations outside the lake effect snow belt may receive less total seasonal snowfall than areas under the influence of lake effect snow, but the snow they receive tends to stick around
much longer due to prolonged freezing temperatures, leading to high snow depth point averages. For example, South Bend, IN and Cleveland, OH, both under the influence of lake effect snow, each receive substantially more snowfall and snowfall points on average than all five stations in the Dakotas. However, the temperature in South Bend and Cleveland does not stay below freezing for long periods of time like it does in the Dakotas, leading to snow depths that are less persistent, and fewer snow depth points on average despite more total snowfall. The highest temperature point averages (Figure 5.3c and 5.3d) follow a northwest-to-southeast gradient with stations such as Bismarck, ND, Grand Forks, ND, Fargo, ND, International Falls, MN, and Duluth, MN seeing the coldest temperatures and most temperature AWSSI points, and stations such as Paducah, KY, Louisville, KY, and Evansville, IN seeing the fewest temperature points. As latitude increases, temperatures can be expected to be colder, but there are some exceptions. The east-west gradient in temperature points is quite obvious when comparing stations such as Sioux Falls, SD, North Platte, NE, Omaha, NE, or Dodge City, KS to other stations at similar latitudes, but farther east. Despite being at almost equal latitude, Sioux Falls receives substantially more total temperature AWSSI points than both La Crosse and Green Bay, WI. Dodge City, KS also receives substantially more total temperature points than either Louisville, KY or Evansville, IN, despite being located south of either of the two stations. These examples show that there is a longitudinal component in winter-time temperatures, as stations located in the Great Plains can expect to be colder than relatively equal latitude stations farther east. There could be a range of factors that explain the reasons for these large temperature differences, including continentality, elevation, proximity to a large moderating body of water, and general air circulation (Perlwitz et. al, 2017).
Figure 5.3: Winter season average AWSSI points contributed by (panel A) snowfall, (panel B) snow depth, (panel C) TMAX, and (panel D) TMIN. Values shown are averaged over all winter seasons.

When looking at which parameters account for the largest percentage of points relative to their total AWSSI (Figure 5.4), snowfall contribution shows a clear east-west gradient, with eastern stations seeing higher snowfall contribution to total AWSSI than western stations. Snow depth shows more of a northeast-to-southwest gradient, with areas that receive both relatively heavy snowfall and prolonged freezing temperatures having the highest snow depth contributions. Farther west in the northern plains, snow falls less, but sticks around for long periods of time, making for a relatively substantial snow depth contribution for this area despite
much less snow than stations farther east. Due to the fact that TMAX and TMIN follow the same point thresholds, TMIN points dominate TMAX points in terms of percent contribution. TMAX exhibits a range of 9 – 19% contribution at stations generally following a north-to-south gradient. There are exceptions to this however, as Marquette and Sault Ste. Marie, MI see only about 10% of their AWSSI coming from TMAX points, but this is due to snowfall and snow depth points dominating their total AWSSI. TMIN contributes the largest majority of the points for almost every station, with 25 locations seeing over 50% of their AWSSI points coming from nightly low temperatures falling below freezing (Figure 5.4). The southernmost stations see a higher percentage of their points come from TMIN than stations farther to the north. In only four stations, Marquette, MI, Sault Ste. Marie, MI, Traverse City, MI, and Duluth, MN, was TMIN not the highest contributing parameter to AWSSI, as these four stations see snow depth as the dominant mode of winter severity. These four stations receive the highest snowfall total averages, and are located in the northernmost tier of the Midwest. TMAX remains below freezing for long periods of time at these stations, allowing for snow to accumulate and persist for months. Stations at the southern edge of the Great Lakes, such as Grand Rapids, MI, South Bend, IN, and Cleveland, OH see the highest snowfall percentage contributions. However, they also experience warmer temperatures than their northern Great Lakes counterparts, increasing their percentage contribution from snowfall. The stations along the southern edge of the Great Lakes also would expect to see snow melt faster than northern areas outside the lake effect snow belt, making their snow depth contribution smaller than areas that may receive less total snow. Overall, the percentage contributions from each parameter suggest that Midwest winter severity, as measured using AWSSI, is largely temperature driven, as 41 out of 44 stations see over 50% of their total AWSSI points coming from combined TMAX and TMIN points, and 35 of these 41
stations see a total combined temperature contribution of over 60%. The three remaining stations, Marquette, Sault Ste. Marie, and Traverse City each see over 50% of their total AWSSI coming from combined SF and SD points. In the southern part of the Midwest, temperature represents the dominant mode of winter severity, and as latitude and proximity to the Great Lakes increase, snowfall and snow depth are much larger contributors to winter severity.

Figure 5.4: Contribution of each parameter to the winter season AWSSI total, expressed as a percentage of the total. (Panel A) snowfall, (panel B) snow depth, (panel C) TMAX, and (panel D) TMIN. Values shown are averaged over all winter seasons.
5.1.3 Historical Extreme Events

To assess the historical extreme events over the course of the 68-season time period, each station’s ten highest (severe) AWSSI seasons and ten lowest (mild) AWSSI seasons were determined. The most severe and mild winter seasons followed a relatively uniform spatial pattern, as the winters of 1976-77, 1977-78, 1978-79, 1981-82, 1995-96, and 2013-14 appeared in most stations’ top ten most severe winters. At the same time, the 1953-54, 1982-83, 1991-92, 1997-98, 1999-00, 2011-12, 2015-16, and 2016-17 respective winter seasons appeared in most stations’ top ten mild winters, with 2011-12 being the mildest winter for 27 stations and appearing in every single stations’ top 5 mildest winter (Figure 5.5).

Figure 5.5: (A) Frequency of extreme severe (blue) and extreme mild (red) winters by season. (B) Cumulative frequency of extreme severe (blue) and extreme mild (red) winter seasons from 1950/51 – 2017/18, expressed as a percent of total extreme seasons. Values are shown across all stations.

The decade from 1990-91 until 1999-00 saw some of the most extreme and variable winter weather on each end of the spectrum. In the stations in the Northern Great Plains, such as Aberdeen, SD, Bismarck, ND, Fargo, ND, Grand Forks, ND, and Sioux Falls, SD, numerous
blizzards, huge snowfall accumulations, and cold air outbreaks occurred relatively frequently, while many stations in the Southern Great Plains and Ohio Valley regions, such as Cincinnati, OH, Evansville, IN, Louisville, KY, Paducah, KY, Topeka, KS, and Wichita, KS saw some of their warmest winter-time temperatures in the time period with little variability. The 1993-94, 1995-96, and 1996-97 winters were particularly extreme for the Northern Great Plains and upper Midwest, especially 1996-97, as it appeared in the five Dakota stations’ top two most extreme winters, and as the number one for Aberdeen, Fargo, and Grand Forks. These three extreme winters produced some of the largest snow totals on record for this region, as multiple blizzards tracked over the area. The 1996-97 winter was particularly extreme for North Dakota, as Bismarck, Fargo, and Grand Forks each were hit by nine blizzards and all recorded their snowiest winter on record for the time period, which in turn led to devastating record flooding of the Red River in the spring (Kocin et al., 1998). Despite the extreme conditions of the three previously mentioned winters, this region also experienced very mild winters in this decade with 1991-92 and 1999-00 appearing in the top tier of mild winters for four out of the five stations (1999-00 missing in Fargo) in the Dakotas. After 1996-97 the following winters of 1997-98 and 1999-00 were two of the mildest for most stations throughout the entire Midwest.

The following winters of the 2000’s, especially the 2010’s have been defined by great inter-annual variability, with some of the most extreme and mild winters having occurred over the last 8 seasons. As previously stated, 27 out of the 43 total stations saw 2011-12 to be the mildest winter on record, and in the top five mildest winters for the remaining stations. That followed what had been a severe winter for many stations in the 2010-11 season, and would be followed two years later by the extreme winter of 2013-14. The 2013/14 winter was extreme for essentially the entire Midwest, appearing in the majority of stations’ top ten extreme winters, and
as the number one extreme winter in the time period for Detroit, MI, Duluth, MN (tied), Grand Rapids, MI, Green Bay, WI, Traverse City, MI, and Wausau, WI. This winter broke cold records dating back to 1895 for a December – March time period in parts of northern Illinois, southern Wisconsin, and eastern Iowa (Marinaro et al., 2015). Snow records were broken in Detroit, and threatened in many other locations east of the Great Lakes. The following winter of 2014-15 was very cold and severe for many stations in the eastern half of the region, which in turn was followed by back-to-back exceptionally mild winters in 2015-16 and 2016-17. At least one of those two winters appear in several station’s top five mild winters, and even surpassed the 2011/12 mild winter in some cases, and these were the only two winters besides 2011/12 in which more than 30 stations reported a top 10 mild winter. The most recent winter of 2017/18 showed a lot of variability within the season, as a large wave of subfreezing cold air persisted for over the Midwest for more than a week in early January, followed by a warm, wet, and mild February. The following March was actually colder on average than February in several locations, as was April. April 2018 saw some of the most severe winter weather for that particular season, as this month was one of the coldest and snowiest Aprils on record for the Midwest. This was especially the case in Wisconsin. Several locations within the state broke cold record extremes for the month (NOAA), and most locations in the state, including Green Bay and Wausau were hit by a record April snowstorm mid-month that dropped over 20 inches in some locations. By the end of the winter, April 2018 stood out in many stations as being one of the most severe Aprils on record from an AWSSI standpoint.

Whether examining year-to-year occurrence of extreme AWSSI seasons (Figure 5.5a), both severe and mild, or a cumulative distribution of extreme seasons (Figure 5.5b) it is clear that the most extreme severe winters collectively occurred in the late 1970’s and early 1980’s, while
the most extreme mild winters have collectively occurred since the 1990’s. There is a remarkable increase in the occurrence of mild extreme winters since the beginning of the 1980’s consistent with the findings of Screen et al. (2013), Barnes et al. (2014), Wallace et al. (2014), and Wolter et al. (2015). Over 70% of all severe extreme winters over the study period had occurred by the start of the 1990s (Figure 5.5b), while only about 40% of the mild extremes had occurred at that time. In the 40 winter seasons prior to the 1990-91 winter, there had been only five in which ten or more stations reported a mild extreme winter. In the 28 winter seasons since 1990-91, there have been nine winters in which ten or more stations have reported a mild extreme winter. The mild extremes have undoubtedly been much more prevalent in this time frame than severe extremes, but the 2013-14 winter saw over 30 stations report a top ten extreme winter for that particular season, meaning the potential still exists for severe extreme winters. However, mild extreme winters are seemingly becoming more likely.

5.1.4 Inter-annual AWSSI Variability

While the southern stations in the study area have more mild winters on average than northern stations due to their overall warmer temperatures, they see much greater inter-annual variability in their winter severity (Figure 5.6). The northern stations generally experience consistently severe winter seasons with less inter-annual variation in their snow and temperature points, while the stations in the southern portion of the Midwest experience larger inter-annual variability in their snow and temperature points (Figure 5.7), with the highest coefficient of variation values coming from snow depth points (Figure 5.7b). Stations in the southernmost part of the Midwest such as Paducah, KY and Louisville, KY have seen entire winter seasons with no measurable snow depth, such as the 1991-92 winter, while in contrast, both stations experienced more than 40 straight days with measurable snow depth in the 1977-78 winter season. This was
due to both severe cold, as well as the repeated passing of intense low pressure systems that brought very heavy snowfall to the Midwest, some of which were record snowfall totals for several stations (Diaz and Quayle, 1980).

**Figure 5.6:** Inter-annual variability of season-total AWSSI, expressed as the coefficient of variation (AWSSI point units)

The stations in the southern Midwest also see large differences in their temperature points from season-to-season. Cold air outbreaks associated with a strong Aleutian low (Dare, 1981) result in a persistent deep trough over the central United States (Namias, 1978; Marinaro et al., 2015) in the most severe winter seasons. These two factors work to keep temperatures in these areas below freezing for weeks at a time in some seasons (1976-77, 1977-78, and 2013-14) allowing for snow to continuously accumulate and persist on the ground. On the other hand there have been entire winter seasons that pass with only a few days total remaining below freezing in these locations, leading to minor temperature and snow depth AWSSI accumulations.
Conversely, International Falls’ mildest winter (1999-00) still saw a period of 23 straight days in which temperatures remained below freezing, which would be a record length in Paducah.

Figure 5.7: Inter-annual variability of season-total AWSSI points separated by parameter, expressed as the coefficient of variation (AWSSI point units). Panels show (A) snowfall, (B) snow depth, (C) TMAX, and (D) TMIN.

The southern portion of the Midwest, generally from around central Illinois and southward can see virtually any type of weather in the winter months. This is not to say that the northern stations do not experience variability in their yearly conditions, but they can generally expect to see persistent cold and snowy conditions every winter after a certain point, while the southern stations truly can experience any type of weather in the winter months.
5.1.5 Daily AWSSI Variability

The distribution of daily AWSSI points changes with latitude (Figure 5.8), as farther north, the accumulation of AWSSI points is more evenly distributed throughout an entire winter due to more persistent snow depths and freezing temperatures. Farther south, the accumulation of AWSSI points is driven more by a handful of individual days with large point totals, as these areas typically expect to see relatively mild conditions with large snow events and cold air outbreaks in between. Many of the southern stations can go days to weeks at a time without accumulating a single point, meaning large accumulation days, or extreme events will account for a larger proportion of their total AWSSI than the northern stations.

Figure 5.8: Average season-total AWSSI point contribution from top 10% of days in each season expressed as a percent of season-total points.

An example of this came on March 24, 2013 in St. Louis, MO when over a foot of snow fell on the city. The 2012/13 winter had been relatively mild for St. Louis leading up to that day,
but that one extreme event led to 35 extra points being accumulated in the latter days of March that normally might not have been. These extra points accounted for almost 15% of their total AWSSI for that particular season. Had this event happened in a Wisconsin or Minnesota station, the points most likely would have accounted for a much smaller proportion of that year’s total AWSSI, as after a certain point in the winter, the northern stations rarely go more than a day without accumulating at least one point. In the northernmost stations it is rare for a day in late December, January, or early February to not receive double digit points, as temperatures consistently stay well below the freezing mark, meaning when a large point day, or extreme event comes along, it will account for a smaller proportion of their total AWSSI than an extreme event in the southern stations.

As seen in Figure 5.9a the differences in the daily accumulation values between Duluth, MN and St. Louis, MO (two North vs. South stations with a complete record) are quite large, as 8 points represents the 90th percentile of daily accumulated AWSSI points, or an extreme day in St. Louis, while 21 points represents the 90th percentile of daily accumulation for Duluth. This makes sense, as Duluth’s winter season would be expected to start earlier and end later, making small TMIN point accumulations more common. Duluth also averages about 60 more total inches of snowfall than St. Louis, and consistently experiences temperatures that stay below the freezing mark for weeks at a time, even in the mildest of their winters. These factors allow for longer snow persistence and high snow depth point values. An extreme day in Duluth, or any other northern location is far different from an extreme day in St. Louis, or any other southern location. However, the southern stations can experience days of large accumulation that would be considered extreme for northern stations, but these extreme days do not occur as frequently. As seen in figure 5.9b the overall distribution of daily points changes with latitude, but a
southern station such as Louisville, KY still has the potential to see an extreme event in any given winter. On January 17, 1994 Louisville experienced a large snowstorm that dropped 15.5 inches of snow, leading to a day in which 36 AWSSI points were accumulated. This one-day extreme was a higher total than Des Moines, Iowa’s top one-day extreme, despite being much farther south. However, there is a much smaller probability of Louisville seeing a day that extreme compared to the probability of seeing a day that extreme in Des Moines. That particular day in Louisville was one of only nine days in the entire time period in which 20 AWSSI point were accumulated, while Des Moines, on the other hand has seen 144 days in the time period in which they received 20 AWSSI points.

**Figure 5.9:** (Panel A) Cumulative distribution functions of daily AWSSI point accumulations from (blue) Duluth, MN and (red) St. Louis, MO, and (Panel B) Cumulative distribution functions of daily AWSSI point accumulations from (blue) Bismarck, ND, (orange) Sioux Falls, SD, (yellow) Des Moines, IA, (blue) Springfield, IL, and (green) Louisville, KY

### 5.1.6 Long-term Changes in Winter Severity

The MPWS test results show that winter severity has changed over time in different ways for different stations within the study region. Almost every station in the study area has exhibited at least a slight decrease in total AWSSI (Figure 5.10) over the study period, with 23%
of the stations exhibiting a statistically significant decreasing trend (Figure 5.10, enclosed circles). Ten of the stations showed a statistically significant decrease in their total AWSSI points at $\alpha = 0.1$, seven at $\alpha = 0.05$ and one (Topeka, KS) at $\alpha = 0.01$. Duluth, MN has seen the largest annual decrease in their total AWSSI, an average of 6.8 points per years.

![Figure 5.10: Total season AWSSI MPWS trend](image)

**Figure 5.10:** Total season AWSSI MPWS trend (One white circle denotes significance level $\alpha = 0.1$, two circles denotes significance level $\alpha = 0.05$, three circles denotes significance level $\alpha = 0.01$). Units are in annual AWSSI Points.

When looking at the changes in each individual AWSSI parameter, the results are quite spatially different, especially for snowfall points. Several stations showed a statistically significant increase in their snowfall points, while others showed a statistically significant decrease (Figure 5.11), with the largest, and most significant increases coming in the northern part of the study area. In fact, there is a clear gradient going through central Iowa and northern Illinois in which stations go from an increase to a decrease in snowfall points. Eight stations saw a significant increase in snowfall points at $\alpha = 0.1$, and six of these eight showed a significant
increase at $\alpha = 0.05$. Three stations saw a significant decrease in snowfall points at $\alpha = 0.1$, and two of these three showed a significant decrease at $\alpha = 0.05$. The gradient between South Bend, IN and Madison, WI, separated by about one and a half degrees of latitude and about 300 miles in a northwest to southeast direction, is quite large, as Madison has seen a statistically significant increase, while South Bend has seen a statistically significant decrease in snowfall points. This is most likely due to the rain-snow transition line migrating north over time, as more of South Bend’s winter precipitation has been falling in the form of rain, rather than snow (Trenberth, 2011), as their wintertime temperatures have warmed. While Madison’s temperatures have warmed in relatively equal proportion to South Bend’s, they still are cold enough to produce snow, and with more water vapor available (Notaro et al., 2011; Notaro et al., 2014), average snowfall has increased.

**Figure 5.11:** Total season snowfall points MPWS trend (One white circle denotes significance level $\alpha = 0.1$, two circles denotes significance level $\alpha = 0.05$, three circles denotes significance level $\alpha = 0.01$). Units are in annual snowfall AWSSI points.
Even though many locations have seen an increase in snowfall points, none of the stations with a significant increase in snowfall points showed a significant increase in snow depth points (Figure 5.12). Only three of the stations in total showed a statistically significant decrease in their snow depth points, with two of those three, South Bend, IN and Topeka, KS, also seeing a significant decrease in snowfall points. This suggests that despite more snow falling in many locations, it is melting at faster rates (Scott and Kaiser, 2004; Hosaka et al., 2005; Räisänen, 2008; Demaria et al., 2016).

![Figure 5.12: Total season snow depth points MPWS trend](image)

*Figure 5.12: Total season snow depth points MPWS trend (One white circle denotes significance level $\alpha = 0.1$, two circles denotes significance level $\alpha = 0.05$, three circles denotes significance level $\alpha = 0.01$). Units are in snow depth AWSSI points*

The changes in temperature points are more uniform across the study area, as a large portion of the stations (40%) showed a significant decrease in TMAX points (Figure 5.13), with 30% of the stations showing a significant decrease at $\alpha = 0.05$, and one station (Wichita, KS) at $\alpha = 0.01$. An even larger number of stations (74%) showed a significant decrease in TMIN points.
(Figure 5.14, with 63% showing a significant decrease at $\alpha = 0.05$, and 33% at $\alpha = 0.01$. When combining TMAX and TMIN points, 30 of the stations have seen a significant decrease in total temperature points at $\alpha = 0.1$, with 25 showing a significant decrease at $\alpha = 0.05$, and 8 at $\alpha = 0.01$. These temperature point decreases are consistent with background warming that has taken place in the winter months across the Midwest (Wuebbles and Hayhoe, 2004; Austin and Colman, 2007; Pryor et al., 2014; Demaria et al., 2016). Many of the stations in the Midwest have seen no significant decrease in the length of season (Figure 5.15), and some locations have seen a slight increase, though not significant. However, 11 stations in Missouri, Illinois, and Indiana have experienced significantly shorter winter seasons in the latter half of the dataset, with 9 of those 11 significant at $\alpha = 0.05$ and five at $\alpha = 0.01$, suggesting that winters in these locations are starting later and ending earlier than in the past. These same stations, as well as several more generally following a southwest-to-northeast gradient, have also experienced significantly fewer days that receive AWSSI points (Figure 5.16), with 16 significant at $\alpha = 0.01$. This demonstrates that winter season length and the number of days accumulating AWSSI points within those winter seasons has decreased. Two stations, Aberdeen, SD and Mason City, IA have seen either a small increase or no change in days with points, though neither is statistically significant.
**Figure 5.13:** Total season TMAX points MPWS trend (One white circle denotes significance level $\alpha = 0.1$, two circles denotes significance level $\alpha = 0.05$, three circles denotes significance level $\alpha = 0.01$)

**Figure 5.14:** Total season TMIN points MPWS trend (One white circle denotes significance level $\alpha = 0.1$, two circles denotes significance level $\alpha = 0.05$, three circles denotes significance level $\alpha = 0.01$)
Figure 5.15: Length of winter season MPWS trend (One white circle denotes significance level $\alpha = 0.1$, two circles denotes significance level $\alpha = 0.05$, three circles denotes significance level $\alpha = 0.01$)

Figure 5.16: Days with AWSSI points MPWS trend (One white circle denotes significance level $\alpha = 0.1$, two circles denotes significance level $\alpha = 0.05$, three circles denotes significance level $\alpha = 0.01$)
5.1.7 Summary

Severe winter weather in the Midwest can be characterized in different ways for different locations within the region. The sites around the Great Lakes, especially downwind, experience long, snowy winters in which large snowfall totals, snow depths, and cold temperatures can last from late fall well into spring. Winter severity at these sites is strongly driven by snowfall and snow depth with a considerable temperature contribution as well. Northern areas west of the Great Lakes experience long, cold, and snowy (albeit less than downwind of the lakes) winter seasons, with snow depths and freezing temperatures that persist from late fall well into the spring months. At these sites, snow depth is typically a large contributor to winter severity, despite much less total snowfall than around the Great Lakes. Cold temperatures are the dominant driver of winter severity for stations west of the Great Lakes, and these allow for very little snowmelt, giving these sites a high snow depth contribution. The winters in the northern part of the Midwest region see much higher AWSSI point totals in every category, but less inter-annual variability in their winter severity from season-to-season than sites in the southern part of the study area. Sites from central Illinois and Indiana southward typically see more mild winter weather conditions that are intertwined with extreme events, which in turn will account for a large proportion of that given season’s AWSSI points. These areas see TMIN as the dominant driver of winter severity, with snow falling less frequently, and persisting on the ground for shorter periods of time than the northern stations. The southern portion of the Midwest typically experiences relatively milder winter conditions, but the inter-annual variability in this part of the study region is much greater, with the most variable aspect of winter severity in this area being snow depth. Some of the southern stations, such as Paducah and Louisville have gone entire winter seasons without recording any measurable snow depth on the ground, while in other
winters, these areas have seen snow persist on the ground for weeks at a time, such as in the 1976-77 and 1977-78 winter seasons. Stations in the southern part of the study region also can see large temperature differences from season-to-season, and week-to-week within seasons, as some of the more severe winters see days and even weeks at a time in which the temperature fails to rise above freezing, while other milder winter seasons see only a couple days in which the temperature fails to rise above freezing. This differs greatly from the stations in the northernmost part of the Midwest, as even in the mildest winters, weeks can pass without the temperature rising above freezing.

When examining the changes over time, the question begs, “Are Midwest winters becoming more severe, or milder?” The answer to this question is different for different locations. Since winter severity in the Midwest is largely temperature driven, changes in temperature points result in changes in total AWSSI points. Several sites in the southern part of the Midwest have seen a statistically significant decrease in their total AWSSI points over time, as temperatures have warmed, seasons have become shorter in length, less snow has fallen, and snow depths are not as persistent. Many sites in the northern part of the Midwest have seen a statistically significant decrease in their temperature points, with a statistically significant increase in their snowfall points, which have made decreases in total AWSSI much smaller.

The stations that have seen the greatest snowfall point increases have been areas that have warmed significantly, yet still remain cold enough to snow. With slightly warmer temperatures, the atmosphere has higher saturation vapor pressure, thus more snowfall potential. The Midwest, especially the northern portion, has also seen more variability in their recent winter conditions from year-to-year. The time period from 1990-91 until present has seen greater variability in year-to-year AWSSI values for many locations in the Midwest than in past decades, with several
of the most extreme and mild winters occurring in this recent time frame. This is especially true in the 2010’s, as some of the most severe (2010/11, 2013/14, and 2014/15) and mild winters (2011/12, 2015/16, and 2016/17) on record have occurred in the last several years. There clearly has been an increase since the 1990’s of mild extreme winter occurrences, and it is hard to argue against the robust trend in temperature points over time, as the majority of stations have shown a significant decrease. Concurrently, the significant positive increase in snowfall points for many northern stations, such as Grand Forks and Fargo, suggests that their winters may be getting more severe in these locations, as huge snowstorms would be expected to cause widespread social and economic issues more than persistent subfreezing temperatures. The probability of extreme winters, especially in the southern stations, is declining as temperatures warm, but as the 2013/14 winter showed, the potential is still present for extreme winter weather conditions in the Midwest.

5.2 Impact of Teleconnections on Midwest Winter Severity

5.2.1 Principal Component Analysis

For this part of the analysis, a principal component analysis (PCA) was performed to reduce the dimensionality of the inter-annual AWSSI data. After this step was taken, subsequent statistical analyses were performed in order to assess how each mode of climate variability and the resulting teleconnection patterns impact the inter-annual variability of Midwest winter season severity. Figure 5.17 shows the spatial loading patterns for the four PCs, with PC1 representing 65% of the variability in the rotated solution, and PCs two, three, and four representing successively less variance. When examining the spatial loadings for each PC, it seems that there is a dipole effect between the northwest Plains region of the Midwest and the Ohio River Valley (southeast) region. The first PC exhibits strong loadings around the Ohio Valley and weak
loadings at stations in the Plains. The second PC exhibits strong loadings at stations in the northwest Plains, and relatively weak loadings over the Ohio River Valley stations. The third PC exhibits a southwest to northeast gradient, and the fourth PC shows a pattern in which stations within proximity of the Great Lakes contain relatively higher coefficient values, with these values decreasing as distance from the lakes becomes greater.

Figure 5.17: Spatial Loadings for first four principal components. Colors represent correlation coefficient values. Darker colors indicate stronger correlation with each respective principal component, while lighter colors indicate weaker correlation.
PDO and AO are significantly correlated (95% confidence level) with the first PC (Table 5.1), with PDO exhibiting a positive correlation (0.33), and AO a negative correlation (-0.34). This suggests a potential interaction between PDO and AO, consistent with the findings of Budikova (2005). ENSO, PDO, and PNA all exhibit moderate negative correlation with the second principal component, significant at the 95% confidence level, suggesting that the second PC is related to Pacific forcing. AO exhibits negative correlation with the third PC, significant at the 95% confidence level. None of the teleconnection patterns exhibit a statistically significant correlation with the fourth PC.

Table 5.1: Correlation coefficient values between the first four principal components and each mode of climate variability. Highlighted numbers indicate statistical significance at $\alpha = 0.05$.

<table>
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<th>PC2</th>
<th>PC3</th>
<th>PC4</th>
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5.2.2 Correlation Analysis

The northwest to southeast gradient in the PDO-AWSSI correlation is very similar to the gradients that are present in both PCs 1 and 2 (Figure 5.18). There is a clear dipole effect in the coefficient values between the northwest Plains (negative correlation) and the Ohio Valley stations (positive correlation), as well as the first two PCs, which suggests that the PDO may be a primary driver of Midwest winter severity. A similar pattern is present in regards to the AO, as its correlation with annual AWSSI is quite strong over the Ohio Valley. Because PC 1 is strongly correlated with the AO and exhibits strong loadings over the Ohio Valley stations, this also suggests that the AO is a large driver of winter severity, especially for the southern portion.
of the Midwest. The correlation patterns for both ENSO and PNA show stronger correlation with stations that are in the northern and western portions of the Midwest and weak or no correlation with the stations that are in the southern and eastern portion, consistent with the findings of Wu et al. (2005). These two teleconnection patterns, as well as the PDO show significant correlation with PC 2. ENSO, PDO, and PNA all are also significantly correlated with each other (Table 5.2). Since these three patterns all exhibit strong correlation with PC 2, as well as being significantly correlated with each other suggests that Pacific forcing as a whole is a large driver of Midwest winter severity.

**Table 5.2:** Correlation coefficient values among each of the modes of climate variability. Highlighted numbers indicate statistical significance at $\alpha = 0.05$.

<table>
<thead>
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<th>AO</th>
<th>PNA</th>
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Figure 5.18: Correlation coefficient values between AWSSI and each mode of climate variability. Colors represent correlation coefficient values. Red denotes a negative correlation, while blue denotes a positive correlation.

5.2.3 Impact of the PDO and AO on Winter Severity

Given the strong correspondence between PC 1, which accounts for two-thirds of the variance in annual AWSSI variability, and PDO and AO, we focus this part of the analysis on exploring how PDO and AO interact to govern winter weather severity in the Midwest. To explore the roles of PDO and AO on winter severity in the Midwest, we use the National Centers for Environmental Prediction – National Center for Atmospheric Research (NCEP – NCAR R1)
reanalysis datasets to composite upper-level circulation features induced by PDO and AO forcing. From these composites we can clearly see positive PDO results in a deeper, stronger Aleutian low (Figure 5.19), consistent with previous studies by Leathers et al. (1991) and Yin (1994). The stronger Aleutian low appears to be conducive to enhanced southerly flow into the North Pacific, with enhanced northerly flow into the middle and southern part of the United States (Figure 5.20), resulting in enhanced cold air advection into the southern Midwest.

**Figure 5.19:** SLP anomaly for positive PDO winters minus negative PDO winters. Positive values represent anomalous high pressure, while negative values represent anomalous low pressure. Colors represent SLP anomaly in units of millibars. Map derived from esrl.noaa.gov
Figure 5.20: 850mb meridional wind anomaly for positive PDO winters minus negative PDO winters. Positive values represent enhanced southerly flow, while negative values represent enhanced northerly flow in units of meters per second. Map derived from esrl.noaa.gov

Budikova (2005) find PDO and AO interact to modulate each other’s effects on Midwest winter temperatures. Similarly, we find PDO-AO interaction effects resulting in an effect on the Aleutian Low (Figure 5.21), as during a positive AO phase, the strong Aleutian Low associated with a positive PDO phase is weakened, and this results in the low pressure center being weaker and positioned much farther south than during the negative phase of AO. The Aleutian Low is particularly strong when AO is in negative phase and PDO is in positive phase, resulting in a high pressure anomaly over the Rocky Mountains and western United States. Figure 5.22 shows the location of the Aleutian Low and the high pressure anomaly over the western United States results in greatly enhanced southerly flow, characteristic of positive PDO, farther into the north Pacific during the negative AO phase, with enhanced northerly flow over the middle of the country.
Figure 5.21: SLP anomaly for positive AO and positive PDO minus negative PDO winters (top) and negative AO and positive PDO minus negative PDO winters (bottom). Positive values represent anomalous high pressure, while negative values represent anomalous low pressure. Colors represent SLP anomalies in units of millibars. Map derived from esrl.noaa.gov
Figure 5.22: 850mb meridional wind anomalies for positive AO plus positive PDO minus negative PDO winters (top) and negative AO plus positive PDO minus negative PDO winters (bottom). Positive values represent enhanced southerly flow, while negative values represent enhanced northerly flow in units of meters per second. Map derived from esrl.noaa.gov
Budikova (2005) specifically examined surface air temperature anomalies between phases of the PDO in regards to the different phases in the AO, and found that when the AO is in positive phase, the difference in extreme PDO phases has the greatest influence on the Ohio Valley, while when the AO is in negative phase the difference in extreme PDO phases has the greatest influence over the northern Plains. This was assessed through composite maps of AWSSI with interaction effects of the AO on PDO (Figure 5.23), and the results are very similar.

![Composite maps of AWSSI with interaction effects of the AO on PDO](image.png)

**Figure 5.23:** Percent difference in means of AWSSI showing the impact of extreme phases of the PDO on AWSSI relative to the phase of the AO. Left map displays impact of extreme phases of the PDO on the positive phase of the AO. Right map displays impact of extreme phases of the PDO on the negative phase of the AO. Colors represent percentage difference in mean AWSSI between phases relative to the total mean AWSSI.

When the AO and PDO are both in positive phase, the stations in the Ohio Valley and southern portion of the study region are likely to see greater AWSSI values than if the AO is in positive phase and PDO is in negative phase, with only minor differences in the northern and western portion of the Midwest. Conversely, when the AO is in negative phase and the PDO is in positive phase, the stations in the northern Plains exhibit far lower AWSSI values than if the AO and PDO are both in negative phase with minor differences in the southern and eastern
portion of the Midwest. When the two are in negative phase, winters across the northern Midwest are quite severe due to high pressure in the Canadian Arctic that displaces the jet stream southward resulting in greatly enhanced northerly flow across the entire Midwest. This is displayed as a schematic (Figure 5.24) that provides the pathways connecting PDO-AO variability and variations in winter weather severity across the Midwest. However, when the PDO is in positive phase, high pressure over the Pacific off the west coast of the United States weakens, and this appears to have a moderating effect on the AWSSI response in the northern Plains from the AO (e.g., Budikova, 2005).
Figure 5.24: Schematic representing the steps in which PDO and AO interact to influence winter severity.

5.2.4 Summary

The PCA presents an opportunity to examine the dominant modes of Midwest winter weather severity variability, and the first PC accounts for two-thirds of the variability. Based on the correlation and composite analyses, the dominant mode of Midwest winter severity variability is associated with interactions between PDO and AO, oppositely affecting the Ohio
Valley and northern Plains regions. PDO and AO are individually large contributors to Midwest winter severity, with an interaction effect that has been demonstrated by Budikova (2005), and confirmed here. The interaction between the two teleconnection patterns affects the strength and position of the Aleutian Low and high pressure in the Arctic, which in turn affect meridional air flow across the central United States, aiding in the ridge/trough pattern. Generally, when the AO is in negative phase most of the Midwest experiences higher (i.e., more severe) AWSSI winters, but when the PDO is in positive phase, this can moderate the effect of the AO on the northern Plains region, making the signal weaker in this region.

Another potential source of variability in Midwest winter severity is the North Atlantic Oscillation, as this has been shown to have large influence on winter time temperature and precipitation variability (Wanner et al., 2001; Wettstein et al., 2002). However, Deser (2000) determined that the AO is nearly indistinguishable from NAO variability as the two patterns have a 0.95 monthly temporal correlation. Therefore, the NAO was not explored for this particular study, as the results would likely closely follow those of the AO. This could be a potential route for future research regarding variability in winter severity. The research that has been carried out shows that ENSO itself can have an effect on winter severity, but the signal is much stronger over the northern and western portion of the Midwest, with a weaker signal in the southern and eastern portion consistent with the findings of Wu et al. (2005). The PDO and PNA each individually have an effect on the strength of the Aleutian Low, which in turn impacts meridional wind flow over the middle part of the country, and the PDO itself has a dipole effect in which a positive phase would result in fewer AWSSI points over the northern Plains, and greater AWSSI points over the Ohio Valley. The fluctuations of the AO affect the Ohio Valley region more than the other parts of the Midwest, and it has been shown that the phase of the PDO can modify the
impact of the AO. This particular study sheds light on the impacts of these patterns on winter severity responses in the Midwest, but there is still a great amount of research that could be carried forward regarding the impact of each of the teleconnection patterns on winter severity.
CHAPTER 6

SUMMARY AND CONCLUSIONS

This study utilized the AWSSI to determine the climatology of winter season severity in the Midwest United States, measure changes that have taken place in the associated winter severity parameters over a 68 year period (1950/51 – 2017/18), and ascertain the impacts of large-scale teleconnection patterns on winter severity.

The significance and intellectual merit of this research include a better understanding of the factors that contribute to Midwest winter severity, both in terms of contributing parameters as well as the climate teleconnection patterns that influence winter severity. Many previous studies have focused only on temperature related contributions and have not utilized an operational index such as the AWSSI to track changes or assess the impacts of the previously mentioned teleconnection patterns on winter severity. The ability to understand what factors are contributing to Midwest winter severity are important for both those who live in the region, as well as climate forecasters. Long-term patterns of climate variability that influence winter severity, such as the PDO can be leveraged to improve seasonal forecasting of severe winter conditions. The ability to assess the winter climatology of this region as well as track the length of winter seasons could have large implications for both agriculture and transportation sectors. The significant shortening of the length of the winter season over time could have large agricultural implications, most notably a longer growing season.

This study effectively determined the winter climatology of the Midwest, showing that average winter severity follows a north-south gradient, primarily a temperature driven pattern. When looking at the contributing parameters, total temperature points are the driving factor behind Midwest winter severity, with stations in close proximity to the Great Lakes showing a
higher snowfall and snow depth contribution. Northern stations see less inter-annual variability in their total AWSSI than southern stations. The stations in the southern Midwest typically see relatively mild winter conditions, but have experienced some very severe winters over the course of the 68-season study period, specifically 1976-77, 1977-78, 1978-79, and 2013-14. These severe winters in the southern Midwest were associated with a strong Aleutian Low (Dare, 1981) that enhanced the upper-level jet stream trough (Namias, 1978; Marinaro et al., 2015), leading to persistent cold air outbreaks as well as the repeated passing of strong low pressure systems (Diaz and Quayle, 1980), which brought record snowfalls to many locations throughout the Midwest.

This study also highlights the changes that have occurred over time in Midwest winter severity. The negative total temperature AWSSI point trend is consistent with the background warming that the region has experienced over time (Kunkel et al., 2000; Burnett et al., 2003; Kunkel et al., 2009; Walther et al., 2011; Andresen et al., 2012). However, this background warming has also led to an increasing trend in snowfall points in several of the northern stations where temperatures are still cold enough for snow (Kunkel et al., 2000; Burnett et al., 2003; Scott and Kaiser, 2004; Hosaka, et al., 2005; Räisänen, 2008; Andresen, 2012; Notaro et al., 2014). However, the increased warming does not allow the snow to stay on the ground for long periods of time (Notaro et al., 2011; Demaria et al., 2016), therefore the trends in snow depth points have not increased simultaneously with snowfall points. There have also been changes in the length of the winter season as well as the number of days in a season that receive AWSSI points, most significantly in southern stations, which is consistent with the findings of Wuebbles and Hayhoe (2003).

The impacts of teleconnection patterns on the inter-annual variability in Midwest winter severity was assessed through means of a PCA, followed by correlative and composite
techniques. These analyses reveal that the PDO and AO individually are large factors in governing the inter-annual variability in Midwest winter severity. The impact of the PDO shows a dipole pattern in which the northwest Plains and Ohio Valley are affected in opposite ways. When the PDO is in positive phase, the Aleutian Low is anomalously strong, which leads to an enhanced ridge/trough pattern and the ability for cold Arctic air to travel farther south than normal, leading to higher AWSSI accumulations in the Ohio Valley stations. The fluctuations in the AO seem to affect the inter-annual variability of winter severity in Ohio Valley region more than any other. When the AO is in positive phase, cold air is confined in more northern locations do to a strong temperature gradient between the Arctic and midlatitudes and stronger westerlies. When it switches to the negative phase, there is a reduced temperature gradient between the Arctic and midlatitudes, leading to a wavier jet stream that pushes cold Arctic air much farther south than normal. An interaction effect between the PDO and AO was also highlighted in this study, consistent with the findings of Budikova (2005). When the two are in positive phase the Ohio Valley stations generally see high AWSSI values due to the preservation of the strong Aleutian Low that is present during a positive PDO. When the two are in negative phase together, high pressure in the Polar region leads to a southward shift in the jet stream, which leads to greatly enhanced northerly flow over the entire Midwest. This leads to higher than normal AWSSI values in the Midwest, most notably so in the northwest Plains region. Both ENSO and PNA have a clear effect on the inter-annual variability in Midwest climate, with the greatest influence on the stations in the northern and western portions of the region, and less of an influence on the southern and eastern portions, which are consistent with the findings of Wu et al. (2005).
One of the most notable limitations of this study is the fact that the AWSSI does not account for freezing rain and ice storm events (discussed in Boustead et al. 2015), which can cripple transportation, agriculture, and large cities. The fact that AWSSI is dominated by TMIN contributions is another limitation, as nightly minimum temperatures would not be expected to have as great of an impact as large snowstorms. Another limitation includes the fact that the dataset only goes back to 1950-51. There is also inhomogeneity in the data between stations, as well as possible sensor changes at certain stations that are nearly impossible to detect. This could be a source of error when assessing trends that have taken place over time. A primary limitation of the PCA is difficulty of interpretation, such that no single teleconnection contributes entirely to the variability of a PC.

There are many potential routes for future research regarding this particular topic, such as examining changes over time in the annual and daily distribution of AWSSI points, or how each teleconnection pattern has an influence on what could be considered extreme days. There are also other modes of climate variability that could be explored, such as the North Atlantic Oscillation (NAO) as well as the impact of declining Arctic sea ice. Future research also could be carried out regarding interaction effects between other teleconnection patterns on winter severity, such as an interaction between ENSO and PDO, or ENSO and AO. This research also could be extended in order create some sort of predictive model in which different phases of each mode of climate variability are analyzed preceding winter to create a winter severity forecast.
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