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Interannual Variations of Snowfall in the Lower Peninsula of Michigan and Impacts of Local and Remote Meteorological Conditions

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INTERANNUAL VARIATIONS OF SNOWFALL IN THE LOWER PENINSULA OF MICHIGAN AND IMPACTS OF LOCAL AND REMOTE METEOROLOGICAL CONDITIONS

by

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Inter-annual variation of snowfall and its relation to climate indices will help clarify and improve the prediction of total snowfall in the Lower Peninsula of Michigan (LPM). This study examines the trend and variability of annual snowfall (November- March) using 8 homogeneous weather stations in the LPM. The statistical relationship between snowfall and air temperature, Sea Surface Temperature (SST), North Atlantic Oscillation (NAO), Pacific Decadal Oscillation (PDO) and Maximum Ice Coverage(MIC) of Lake Michigan is calculated. The long-term trend in the snowfall data set from 1950 to 2015 is removed before any statistical correlation analysis is conducted. My analysis suggests that annual total snowfall has increased over the period from 1950 to 2015 in all 8 stations with significant trends at the 90 % confidence level except for the Kent City station. An inverse relationship between regional air temperature and snowfall, obtained through correlation analysis, suggests that snowfall increases with a drop-in air temperature and vice versa. Inter- annual snowfall across the study area exhibits large temporal variations and SST anomalies representing ENSO have significant impacts on average annual snowfall. The impacts of NAO and PDO do not have significant influences on the average annual snowfall within the LPM.

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CHAPTER I

INTRODUCTION

Background

Snowfall is an essential meteorological event that has social and environmental impacts (Krasting et al., 2013). Several small to large snow impacts during winter can be seen from various aspects such as a huge snowfall event bringing many inconveniences to daily life in terms of road salting, sanding, accidents, and the disruption of ground and air transportation to the business of ski resorts. Heavy snowfalls cause major snow removal difficulties and raise the removal expenses too (Eichenlaub, 1970; Norton & Bolsenga, 1993; Serreze et al., 1998; Bard & Kristovich, 2012).

The Laurentian Great Lakes (Lake Superior, Lake Michigan- Huron, Lake Erie and Lake Ontario), taken together with their adjoining channels form the largest reservoir of fresh surface water on the Earth (Ashworth, 2003). Snowfall in the Great Lakes region in North America is derived primarily from lake-effect, or large-scale (synoptic) weather systems moving across the region, or a combination of both (Braham & Kelly, 1982). The state of Michigan, located in the Great Lakes and Mid-Western regions of U.S. is divided into two peninsulas, The Upper Peninsula Michigan (UPM) and the Lower Peninsular Michigan (LPM) (Dunbar & May 1995). The LPM lies to the east of Lake Michigan and has constantly experienced enhanced snowfall during winter seasons. Most of the snowfall that occurs in this region is due to the impact of the adjoining lakes. Areas of lake proximity can contribute to more than a doubling of snowfall in places downwind of the lakes, relative to regional places not influenced by the lakes

(Bard & Kristovich, 2012). Thus, usually, snowfall in this area is characterized as lake-effect snowfall (Notoro et al., 2013; Wright et al., 2013). An important proportion of the total winter precipitation in the regions of the Laurentian Great Lakes is contributed by snowfall produced through surface heat and moisture fluxes leading to the development of snow within convective liquid and ice clouds (Bard & Kristovich, 2012; Eichenlaub, 1970; Leathers & Ellis, 1996).

Significant variations in precipitation and snow cover extent have occurred over the conterminous United States during the past 50 years (Changnon et al., 1998; Kunkel & Angel, 1999; Groisman et al., 2001). Several studies have indicated that total annual snowfall has increased dramatically across areas of the Great Lakes region during the twentieth century (Notoro et al., 2013; Wright et al., 2013; Eichenlaub, 1970; Norton & Bolsenga ,1993; Ellis & Johnson, 2004). An analysis of interannual midwinter precipitation to the lee of Lakes Erie and Ontario for the period of 40 years (early 1930s to early 1970s) suggested that the significant increases in snowfall were a product of several factors: a shift toward more precipitation events that were snowfall rather than rainfall, an increase in the intensity of individual snowfall events and an increase in the snowfall-snow water equivalence ratio (Ellis & Johnson, 2004). Braham & Dungey (1984) used seventy snowfall seasons ending with 1980/81 to find the difference in snowfall in both shores (East and West) of Lake Michigan and found that of all snowfall occurring over Lake Michigan, 8 % of the total snowfall was along the west shore of the lake and 39 % was along the east shore. Similar research which used only two seasons based on daily GOES satellite images and daily snowfall records in four geographical areas over

Lake Michigan found that 29 % snow out of the total annual snowfall occurred along the West shore and 50% snowfall occurred along the east shore (Kelly, 1986).

However, the snowfall at the Great Lakes region is not only controlled by the lake and other local climate factors. Studies have shown that snowfall in the Great Lakes region is also often associated with both synoptic and mesoscale atmospheric dynamics (Wright et al., 2013; Alcott & Steenburgh, 2013), as well as large-scale atmospheric oscillations (Kousky et al., 1984; Kunkel & Angel, 1999; Leathers & Ellis, 1996; Patten et al., 2003; Lehr et al., 2012, Kunkel et al.,2013; Ning & Bradley, 2016). The intensity and frequency of U.S. winter storms are influenced by two dominant factors, El Niño–Southern Oscillation (ENSO) and the North Atlantic Oscillation (NAO) (Kunkel et al., 2013). Large-scale atmospheric circulations are produced by events like ENSO and NAO that influence the eastward movement of chilly air over the warm lake surface in the Great Lakes region, thus affecting the amount of snowfall on the leeward side of the Great Lakes (Bai et al., 2012). Wang et al., (2005) suggested that negative NAO events tend to weaken the westerly winds and create a trough-ridge system between the Great Lakes and the West Coast that promotes the penetration of Arctic air into the Great Lakes region. When studying the causes of anomalously large snowfall that fell during in the winter of 2009/10, it was found that positive snowfall anomalies in the eastern U.S. are often associated with La Niña events and negative NAO. Research studies suggest that El Niño events tend to reduce precipitation and snowfall in northwestern North America through the equatorward shift in the subtropical jet (Seager et al., 2005; Seager et al., 2010). It has also been demonstrated that a negative NAO value is often associated with increased snowfall in the mid-Atlantic states (Seager et al., 2010). Kluver and Leathers (2015) used multiple discriminant analysis for winter snowfall prediction in the U.S. and suggested that NAO is one of the dominant variables in influencing seasonal snowfall variability. The coherence analysis between snow, local climate with Pacific Decadal Oscillation (PDO) and NAO at Lake Mendota, Wisconsin from 1905 to 2000 was the focus of a study by Ghanbari et al. (2009). Results showed significant impacts on local climate because of PDO on snowfall and snow depth and the effects of NAO on snowfall at inter-decadal frequencies. It was also found that the influence of PDO on ice-cover appears to be transmitted through temperature, while the influence of the NAO appears to be transmitted through temperature and snowfall (Ghanbari et al., 2009).

Thus, snowstorms caused either by the effect of lake effect weather or synoptic scale atmospheric oscillations, often have broad negative social and economic impacts including school closures, property damages, increased traffic accidents, high utility repair costs and snow removal expenditures (Eichenlaub, 1970; Norton & Bolsenga 1993; Serreze et al., 1998; Bard & Kristovich, 2012; Schmidlin, 1993).

Rationale of the study

In the LPM, where snowfall impacts life for almost five months in most years, snowfall becomes very interesting subject for research. It is very important to keep information current and update studies on weather and climate elements as often as possible as heavy snowfall is a basic fact of day to day life. However, most of the studies done in the past are focused mostly on the Great Lakes precipitation and its connections to large oscillations (Kousky et al., 1984; Kunkel & Angel,1999; Leathers & Ellis, 1996; Patten et al., 2003; Lehr et al., 2012, Ning &

Bradley, 2016; Eichenlaub, 1970). Few research showing a specific focus on LPM snowfall was found, which suggests the need of greater research attention on this topic.

This thesis investigates the inter-annual variability of snowfall in the LPM and its probable causes through a statistical approach. It also deals with snowfall variation and its relation to large-scale oscillations. In this regard, the study will provide an effective tool for the planners, policymakers, and general public who is directly or indirectly related to this field of knowledge. Understanding the causes and variability of snowfall will improve the predictability of hazardous weather like snowstorms. In addition, the present study will provide valuable information for other researchers who want to conduct research in the same field.

Objectives of the study

The objectives of this study are: -

1. To study wintertime inter-annual variation in snowfall of eight homogeneous stations located within the LPM;
2. To correlate annual mean snowfall in the area with large-scale atmospheric circulations like ENSO, PDO, and NAO and to determine if any relations exist between oscillations and snowfall or not;
3. To examine the impact of Lake Michigan maximum ice coverage and air temperature on snowfall levels throughout the LPM.

Chapter summary

This thesis is structured as five chapters. The first chapter introduces information on Michigan and Great Lakes snowfall and large-scale atmospheric oscillations, the rationale of this study and my research objectives. The second chapter provides a review of past studies of snowfall and teleconnections. The third chapter introduces the study area and presents the data and methodology that are used in this study. The fourth chapter presents the results and discussions followed by conclusions in Chapter 5. The upcoming chapter two is divided into five different topics where previous literature related to these topics are presented.

CHAPTER II

REVIEW OF LITERATURE

Snowfall and atmospheric oscillations were summarized in chapter I. This thesis literature review consists of five sections. Section one and two will discuss some existing literature for snowfall and will also discuss total annual snowfall variations within the Great Lakes region and LPM. Section three and four will summarize the relationship between atmospheric oscillations and snowfall. The last section will discuss research related to ice coverage and snowfall in the Great Lakes region.

Snowfall across the Great Lakes region

According to many previous as well as recent studies, excessive snowfall occuring to the region adjacent to lakes are frequently linked with the Lake-effect process (Norton & Bolsenga., 1993; Schmidlin, 1993; Kunkel et al., 2009; Notaro et al., 2013; Wright et al., 2013). Air masses have comparatively colder temperatures than over water (Braham & Kelly, 1982). During the fall and winter, chilly air masses from Canada moving across the Great Lakes result in strong convection currents within the Planetary Boundary level. This movement leads to a steep environmental lapse rate and enhanced instability and shallow convection and forms snowfall, which is commonly called Lake- Effect snowfall (Wright et al., 2013). Most of the snowfall in the lee of Lake Michigan is also formed due to the eastward movement of cold and dry air masses (i.e., Continental Arctic and Continental Polar air masses) over the relatively warm water surface of Lake Michigan. (Wright et al., 2013; Braham & Kelly, 1982; Notaro et al., 2013). The amount of lake – effect snowfall increases when the difference between air and lake temperatures increase. Local scale lake – atmosphere interactions and topography determine the spatial distribution and the intensity of lake effect snowfall (Braham & Dungey, 1984).

Geographical position and geological properties of large water bodies and changes in their properties and structures also impact the distribution and intensity of precipitation that potentially occurs in the adjoining areas (Alcott & Steenburgh, 2013; Wright et al., 2013). In areas with complex downstream terrain, snowfall is formed both through lake shore convergence and by local orographic enhancement. Orography and the fetch length of a lake also are factors that make a significant contribution to snowfall (Alcott & Steenburgh, 2013). A Weather Research and Forecasting Model was used to examine how changes to lake surface properties effect on snowfall distribution and volumes in the Great Lakes region. It was found that upslope enhancement of precipitation due to elevated topography downwind of the lakes is critical in determining the response of precipitation to changes in lake surface properties (Wright et al., 2013).

Variability and trends of snowfall

Studies shows that snowfall has increased across the Laurentian Great Lakes (Kunkel et al., 2009; Norton & Bolsenga, 1993). Kunkel et al., (2009) used a restricted set of temporally homogeneous stations in the Laurentian Great Lakes for trend analysis and found that the total annual snowfall in Lake Michigan and Superior generally increases from 1900 to 2005 but the trend is not apparent in Lakes Erie and Ontario. A slight increase in total snowfall in the entire Laurentian Great Lakes region and a significant increase in Lake Ontario was found in research conducted over the period from 1950 to 1980, which was the result of analysis over 30 winters

(Norton & Bolsenga, 1993). One difference that exists between these two analyses (i.e. Kunkel et al., 2009; Norton & Bolsenga, 1993) is the duration of the study period, Kunkel et al., (2009) used three stations to represent Lake Ontario while another study used more than three. Similarly, other two differences include the number of stations and the domain size for the Great Lakes. However, both studies showed an increase in snowfall in the Great Lakes region overtime.

Leathers & Ellis (1996) investigated the mechanism responsible for large observed snowfall increases across the eastern Great Lakes region of the U.S. Their results indicated mean snowfall amounts across section of Western New York and North -western Pennsylvania had increased by up to 100 cm over the 60-year period which included the snowfall seasons from 1930-1931 through 1989-1990. Monthly snowfall values regressed against time, yielding the slope of the snowfall-time relationship in centimeters of snow per year. During the month of November, no spatially coherent snowfall trends were found across the study region, but large positive snowfall trends were found along the lakeshores areas of both Lakes Erie and Ontario with increases as large as 1.0 centimeter per year during December. This increasing trend was also found along the lake shore areas during February which were slightly smaller than those of December and January. Maximum average values of snowfall for whole snowfall season were 2.6 centimeter per year in the Oswego area which lies South of Lake Ontario whereas the least was 1.7 centimeter per year.

The spatiotemporal snowfall trends examined by Hartnett et al., (2014) in Central New York also found a strong increase between 1931/32 to 1971/72 but a slight decrease from 1971/72 to 2011/2012 in total annual snowfall.

Braham & Dungey (1984) studied seasonal snowfall amounts in Michigan and parts of Wisconsin, Illinois and Indiana that occurred in the period of November through March at many individual stations. Interpolated results were used from surrounding stations in cases of missing records and they simply ignored irregular data sequences. Snowfall amounts recorded from 1909/10 through 1980/81 in stations around Lake Michigan showed year to year variation in snowfall amounts whereas stations within the Snowbelt of Lower Michigan showed a distinct pattern with a minimum snowfall during 1930s or early 1940s and sharp increase in snowfall after that.

ENSO and snowfall

Several past studies have found a connection between large scale atmospheric oscillations like ENSO and snowfall (Kunkel & Angel, 1999; Smith & O'Brien, 2001; Patten et al., 2003). ENSO is well known as large-scale oceanic-atmospheric oscillation which affects climate worldwide (Lehr et al., 2012; Kousky et al., 1984; Kunkel & Angel, 1999; Seager et al., 2010). El Niño and the Southern Oscillation (SO) were considered two separate phenomena prior to 1969. Early evidence of a link between the SO and El Niño was provided by Rasmusson et al., 1982) who identified a strong relationship between interannual surface pressure variations at Djakarta and SST at Puerto Chicama on the Peru coast. Bjerknes (1969) provided convincing evidence of links between the equatorial Pacific and the Northern hemisphere westerlies. A significant new dimension of the SO/ El Niño was uncovered by Wyrtki (1975), when he showed the El Niño events association with changes in the east-west slope of sea level in the tropical pacific. A Norwegian – American meteorologist, Jacob Bjerknes synthesized these ideas in 1969 by proposing a physical relationship between the ocean and atmosphere which linked El Niño and SO (Sweeny, 1996). El Niño referred to the anomalously warm water that occurred along Peru/ Ecuador coast periodically at Christmas and the inter-annual pressure fluctuations found between the Indian Ocean and eastern tropical Pacific (Bjerknes, 1969).

The oceanic parameter Sea Surface Temperature (SST) is used to describe the intensity and expressions of ENSO. El Niño is described using positive SST in which trade winds weaken, while negative SST indices are related with a cool La Niña (Lehr et al., 2012). The relationship between warm SST episodes in the eastern equatorial pacific and global-scale climate variations is best viewed within the framework of the SO (Rasmusson et al., 1982). Kousky et al (1984) studied the climate anomalies associated with SO and identified that ENSO events derived from strong coupling between atmosphere and ocean are highly persistent in nature. ENSO related precipitation anomalies in North America are related to changes in the paths of storm systems across the Pacific Ocean, with a more southern route into southwestern North America during El Niño and a more northern route into the Pacific Northwest during La Niña (Seager et al., 2010).

The investigation of relationships between century-long precipitation time series data over North America with Northern Hemisphere surface air temperature and the South Oscillation Index (SOI) showed that ENSO is usually accompanied by an increase of precipitation whenever it affects the Midwest region of United States (Groisman & Easterling, 1994). During the winter seasons from 1957 through 1962, a sizable proportion of the winter snowfall and ice coverage in lee areas of Lake Michigan and Superior was due to the impact of large-scale atmospheric oscillations (Eichenlaub, 1970).

Kunkel & Angel (1999) conducted a study about the relationship of ENSO with snowfall in the contiguous United States for the period 1951 to 1997 using 3841 Cooperative observer network (COOP) stations. Snowfall that occurred for 34 winters was compared with snowfall during seven strong El Niño and five strong La Niña events. It was found that generally the northern half of the United States had below average snowfall during these seven El Niño events whereas during strong La Niña, above normal snowfall occurred in the northwest United States and northern Great Lakes.

Patten et al. (2003) collected daily snowfall data (November – March) from 442 US stations between 1900 to 1997. Based on the magnitude of daily snowfall amounts in millimeters, three ordinary categories were created for each ENSO phase as light (0-50.8), moderate (50.8 -152.4) and heavy (152.4 -304.8). Independent tests were conducted at each station to identify shifts between ENSO extreme- and neutral-phase distributions in this study. Results showed the frequency of light snowfall, (0–50.8] mm, generally decreases (increases) in the central (eastern) United States during ENSO cold-phase winters. The Northwest and the eastern Great Lakes regions all have increased in the number of light snowfall events for more than 40% of the stations in their respective regions.

Smith & O’Brien (2001) analyzed regional snowfall distributions associated with ENSO using data from skiing forecasts during the 1997 ENSO warm phase over the continental United

States. Daily snowfall data from the first order summary of the day (FSOD) by the National Climatic Data Center (NCDC) using 143 weather stations data from 1950 to 1994 were extracted. (SST) anomalies averaged over the Pacific Ocean from 4 ^{o} N to 4 ^{o} S and 150 ^{o} W to 90 ^{o} W was used. Results indicated that ENSO cold phases are associated with increased snowfall relative to warm and neutral phase winters in the north-western states from early winter through midwinter. Of the SST index that was greater than + 0.5 ^{o}C (- 0.5 ^{o}C) for 6 consecutive months beginning before October and including October, November and December, then the year was classified as an El Niño (warm phase). The results of this study found that the frequency of snow during an El Niño year is dependent on location, but during cold events, fewer hours of snow occurred in the east and more hours of snow occurred in the west.

ENSO, PDO, NAO, and snowfall

Ghanbari et al., (2009) examined the frequency domain relationship between snow, local climate and their connection with PDO and NAO at Lake Mendota, Wisconsin from 1905 to 2000. These results showed significant impacts on local climate because of PDO on snowfall and snow depth and the effects of NAO on snowfall at inter-decadal frequencies. It was also found that the influence of PDO on ice-cover appears to be transmitted through temperature, while the influence of the NAO appears to be transmitted through both temperature and snowfall volume.

PDO is a pattern of North Pacific Climate variability that shifts phases on inter-decadal time scales, about twenty to thirty years. During a positive phase (warm), the central and western Pacific sea surface become cooler and the eastern portion warms. However, during the negative phase (cool), the opposite dipole pattern occurs (Mantua & Hare 2002). PDO is often characterized with ENSO and indeed there are some parallels, but the timescale of the variability is very different. PDO is dominated by oscillations or regime shifts that occur approximately every two decades, or close whereas ENSO events last a few months to a year individually as El Niño or La Niña phases and typically occurs once every two to seven years (Whitfield et al.,2010). Seager et al. (2010) investigated the causes of anomalously large snowfalls in the winter of 2009/10 and found that positive snowfall anomalies in the eastern U.S. are often associated with La Niña events and negative North Atlantic Oscillation (NAO). Kluver & Leathers (2015) used multiple discriminant analysis for winter snowfall prediction in the U.S. and suggested that NAO is one of the dominant variables in influencing seasonal snowfall variability. It has also been demonstrated that a negative NAO value is often associated with increased snowfall in the mid-Atlantic states (Seager et al., 2010).

The North Atlantic Oscillation (NAO) is defined as the hemispheric oscillation in atmospheric pressure with centers of action near Iceland and over the sub-tropical Atlantic which means there is a north-south dipole structure (Lehr et al.,2012). The NAO index is a weather phenomenon produced due to fluctuations in the difference of atmospheric pressure at sea level between the Icelandic low and the Azores high (Rodwell et al. 1999). It reflects the fluctuations of the sea level pressure (SLP) difference between the Icelandic Low and the Azores High and during the positive phase of NAO, the SLP difference is larger than the normal condition and vice versa (Ning & Bradley, 2016; Barnston & Livezey, 1987; Wallace et al. 1981; Wanner et al.,2001). Together with the ENSO phenomenon, the NAO is considered an important source of seasonal to interdecadal variability in the global atmosphere. NAO dynamics can be described as a purely internal mode of variability of the atmospheric circulation on inter-annual and shorter time scales (Wanner et al.,2001). The positive NAO strengthens the polar vortex and the westerlies. During the positive event, the mid-latitude high anomaly advects warm air from the south via the southerly winds to the Great Lakes region causing higher probabilities for warm winters. But an opposite situation occurs during the negative NAO which causes weakening of the polar vortex and thus the westerly. During negative events, a polar trough (convergence) near the Great Lakes and a ridge over the West Coast are developed, creating pressure difference promoting the penetration of Arctic air (northerly wind) into the Great Lakes region increasing chances for chilly winter (Bai et al.,2012).

NAO have strong influences on regional climate over the eastern US and it was found that Great Lakes tend to have lower ice cover during the winter years with a positive phase NAO and vice versa (Bai et al., 2012). Ning & Bradly (2016) evaluated the general circulation models (GCMs) performances on simulations of the relationship between NAO and regional winter climate over the eastern US and when doing this, the spatial patterns of the simulated NAO are first compared with the observed data. It was found that NAO has a significant positive correlation ($r=0.94$, $p= 0.05$) with winter average temperature, 0.5degree resolution, over most part of the eastern US.

Ice Cover across the Great Lakes

Ice cover and snowpack significantly affect both the energy budget and water exchange at the surface and, as a consequence influence regional and global weather and climate (Feng & Hu, 2007). The maximum fraction of lake surface area covered by ice for each Great lake, the largest median annual maximum ice coverage was found to be for Lake Erie (94%), followed by Michigan (33%), Superior (80%), Huron (63%) and finally Ontario (21%) from 1963 to 2001 (Assel et al., 2003).

Lake ice has been shown to be sensitive to climate variability through observations and modelling, and both long-term and short-term trends have been identified from ice records. The inclusion of lake ice in climate modelling is an area of increased attention in recent studies. The ability to accurately represent ice cover on lakes will be a crucial step in the improvement of global circulation models, regional climate models and numerical weather forecasting (Brown & Duguay,2010).

Robertson et al., (2000) studied the influence of El Niño events on the ice cover in the Northern Hemisphere by using years of strong or moderate El Niño between 1900 and 1987 from Quinn et al. (1987). In this study additional strong events were added in 1992 and 1998 and a moderate event in 1993, the specific year of each event was chosen by examining the intensity of the Southern Oscillation index. A study conducted from 1963 to 2010 found that teleconnections like the North Atlantic Oscillation (NAO) and ENSO cause a significant impact on Great Lakes ice cover. The Great Lakes experienced lower ice cover during positive a NAO and warm El Niño events whereas higher ice cover was found during a negative NAO. In case of La Niña effects on ice cover, it was found to be intensity dependent where strong La Niña events were often related with lower ice cover and weak La Niña events were often associated with higher ice cover (Bai et al.,2012). This study investigates mild ice cover over the North American Great Lakes during the 2009/10 winter which experienced a strong negative Arctic Oscillation and El Niño event. The mild ice conditions in the Great Lakes were mainly caused by a strong El Niño event. Negative Arctic oscillation generally produces significant colder surface air temperature and heavy ice cover over the Great Lakes (Bai et al., 2011).

Assel & Rodionov (1998) found that much above or below - average ice cover occurs on the Great Lakes during ENSO events. During the 1997/98 El Niño (warm phase) which is also considered as one of the strongest El Niño events to the present, the Great Lakes experienced one of the least extensive ice covers of the century (Assel et al., 2000). They also compared the winters of 1983 and 1998 with other normal ice seasons by using Ice charts showing the spatial distribution of ice concentration produced by Canadian Ice Service (CIS) for the 1998 winter and the and National Ice Center (NIC) for the 1983 winter. They calculated daily lake-averaged ice concentration using linear interpolation to facilitate comparisons among the above mentioned two winter years. The maximum ice cover for the Great Lakes did not exceed the normal for January compared to winters 1998 and 1983. In both winter years, maximum ice coverage occurred in the last half of January and the first week of the February. The seasonal development and extent of ice cover of the Great Lakes in the winter of 1998 was less than during winter of the 1983 except for Lake Huron.

The next chapter will introduce the methods used to compile the data employed in my analyses and the nature of these analyses.

CHAPTER III

DATA AND METHODOLOGY

Study area

The Laurentian Great Lakes (Lake Superior, Lake Michigan- Huron, Lake Erie and Lake Ontario) along with and their adjoining channels form the largest reservoir of fresh surface water on the Earth. (Ashworth ,2003). About 1,100 miles from end to end and 500 miles from top to bottom, the lakes collectively sprawl over nearly 100,000 square miles and contain nearly 5,500 cubic miles of fresh water, just under 20 % of the total world supply. The USA has over 4,000 miles of coastline on the Great Lakes, which is more than the Atlantic Ocean coast and Gulf of Mexico coasts added together (Ashworth ,2003).

Lake Michigan (44^{o}N latitude and -87^{o}W longitude) has a surface area of 22,394 mi^2. The State of Michigan is located to the east of Lake Michigan. Michigan's coast alone extends for more than 2,232 miles, accounting for a longer shoreline than any other state in the Union except Alaska. It is generally located within the Great Lakes and Mid-Western regions of U.S. and known as only state which is divided into two peninsulas, The UPM and the LPM (Ashworth ,2003). (Geography of Michigan. *In Wikipedia*. Retrieved April 9th, 2016 which can be accessed in the link below,

https://en.wikipedia.org/wiki/Geography_of_Michigan).

The LPM is the study area of this research which lies to the lee of Lake Michigan. Lower Peninsula Michigan is 446 km long from north to south and 314 km from east to west and occupies nearly two-thirds of the state's land area. The surface of the peninsula is generally level, broken by conical hills and glacial moraines usually not more than a few hundred feet tall. It is divided by a low water divide running north and south. The larger portion of the state is on the west of this and gradually slopes toward Lake Michigan. The highest point in the Lower Peninsula is at 1,705 feet and the lowest point is the surface of Lake Erie at 571 feet (Geography of Michigan. *In Wikipedia*. Retrieved April 9th, 2016 which can be searched in the link, https://en.wikipedia.org/wiki/Geography_of_Michigan).

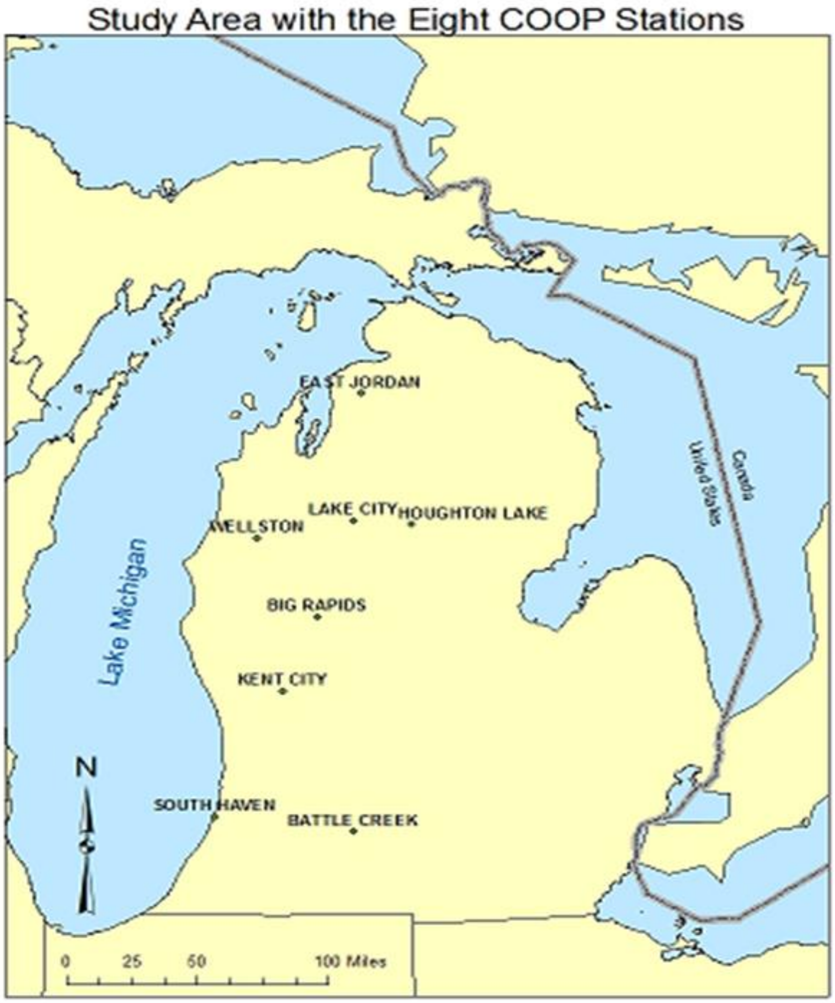


Figure 1: Study area.

Source: created by author

Figure 1 displays the locations of the eight stations in the LPM. These 8 COOP (Cooperative Observer Network) stations were determined to be homogeneous through the expert quality assessment as defined in Kunkel et al. (2009). Based on the criteria used in Kunkel et al. (2009), the possible causes of a station's heterogeneous behavior include: station relocation, changes in instrument exposure, observer changes, and changes in observer practices.

Data

Data used in this research includes snowfall, air temperatures, SST, PDO, NAO and maximum ice coverage for Lake Michigan. All data for this study were obtained from online records of different climate data websites which are briefly described in the following subsections.

Elevation, latitude and longitude data of all eight stations in LPM

Table 1 shows the elevations for all the 8 stations from mean sea level and the latitude and the longitude for the exact locations of the 8 stations. This information was retrieved from the Western Regional Climate Centre (WRCC) website which is accessible at (http://www.wrcc.dri.edu/inventory/sodmi.html).

Table 1: Location information for eight stations incorporated in the study.

COOP Stations	Stations ID	Elevation (ft.)	Latitude (decimal degrees):	Longitude (decimal degrees):
East Jordan	20-2381	585	45.15	-85.13
South Haven	20-7690	620	42.24	-86.17
Wellston	20-8772	650	44.15	-85.57
Kent city	20-4320	840	43.12	-85.46
Big Rapids	20-0779	930	43.71	-85.48
Battle creek	20-0552	930	42.22	-85.16
Houghton Lake	20-3932	1135	44.19	-84.53
Lake City	20-4502	1230	44.31	-85.21

Source: WRCC (August 2010). *COOP stations.* Retrieved from http://www.wrcc.dri.edu/inventory/sodmi.html

Snowfall data

Monthly snowfall county level data for LPM from 1950 to 2015 were obtained from the National Weather Service's (NWS's) cooperative observer network (COOP). (accessible at https://www.ncdc.noaa.gov/data-access/land-based-station-data/land-based-datasets/cooperative-observer-network-coop). Only 8 COOP stations in the LPM are used in this study (Figure 1). These 8 stations were determined to be homogeneous through the expert quality assessment method defined in Kunkel et al. (2009). Therefore, snowfall data from these 8 stations are considered to be appropriate for trend analysis and for studying the inter-annual variability of snowfall. To avoid the influence of missing data on the results, the individual snow year is excluded in this analysis, if snowfall data are missing from any one station out of the 8 weather stations. Average or mean annual snowfall refers to the sum of monthly snowfall between November and March.

Air temperature data

Monthly air temperature (^{o} C) data at 4km^2 resolution were obtained from the Parameter-elevation Relationship on Independent Slope Model (PRISM) working group at Oregon Station University (accessible at http://www.prism.oregonstate.edu/) (Daly et al.2008). Winter season air temperatures are calculated from the mean monthly temperatures of November through March.

SSTs, PDO and NAO data

Sea surface temperatures (SSTs) data (1950-2015) were obtained from the Earth System Research Laboratory (ESRL) of National Oceanic &Atmospheric Administration (NOAA) (http://www.esrl.noaa.gov/psd/gcos_wgsp/Timeseries/Nino34/). PDO datasets are also obtained through same website.

SST anomalies from 1951 to 2000 averaged over the Nino 3.4 region (5N-5S, 170W-120W) is used to represent the El Niño Southern Oscillation (ENSO) phenomena. Average monthly SST anomalies between November and March are used to represent winter season ENSO conditions.

The tropical Pacific Ocean is subdivided into several regions for monitoring and identifying a developing El Niño or La Niña. The most common regions are NINO 1+2 (0-10S; 80-90W), NINO 3 (5S-5N; 150W – 90W), NINO 3.4 and NINO 4 (5S-5N; 160E-150W). NINO 3.4 is the region that has large variability on El Niño time scales, and it is also closer to NINO 3 region where changes in local SST are important for shifting the large region of rainfall typically located in the far western Pacific. (ENSO. Retrieved February 18,2018).

The Hurrell North Atlantic Oscillation (NAO) monthly index (station-based) (1950-2015) is used in this study (accessible at https://climatedataguide.ucar.edu/climate-data/hurrell-north-atlantic-oscillation-nao-index-station-based). November-March averaged NAO represents winter-season pressure conditions. A positive NAO index value is often associated with stronger-than-average westerlies over the mid-latitudes and vice versa (Hurrell, 1995).

Maximum Ice coverage data of Lake Michigan

The maximum ice cover (MIC) dataset for Lake Michigan (1973-2015) is obtained from the NOAA Great Lakes Environmental Research Laboratory at http://www.glerl.noaa.gov/. An additional 10 years MIC data from 1963-1972 are digitized from Figure 2 in Bai et al. (2012). Therefore, the full MIC dataset is available from 1963 to 2015. My analysis related to the MIC dataset is restricted to the period from 1963-2015.

Methodology

This study uses 65 years of data for studying the interannual variation of snowfall. Monthly snowfall data in inches for the period of 1950 to 2015 are collected from NWS's COOP stations. Snowfall data in inches are changed to centimeter (cm) before using it for analysis. For extensive years of data and to study trends in such data, it is very important to carefully screen the data to identify stations with suitable temporal homogeneity. Some key factors that can bring heterogeneities into the time series data are changes in station location, observer, and measurement practices (Kunkel et al., 2009).

Out of 19 stations which were determined to be homogeneous stations through expert quality assessment defined in Kunkel et al. (2009), 8 COOP stations in the LPM were used. Thus, snowfall data used are supposed to be appropriate for trend analysis and for a study of the variability of snowfall. Average or mean snowfall refers to the sum of monthly snowfall between November and March. Similar is the case for SST anomalies, NAO index and PDO data. An individual snow year is excluded in this analysis if a measurable snowfall value is missing from any one station out of the 8 weather stations.

For data analysis of this study, Microsoft Excel 2016 and Pandas library in Python is used. Python is one of the most widely used programming languages for data analysis. Many researchers and students like this language because of its simplicity and its readability compared to other programming languages. The Pandas library for Python provides many data structures (data series, data frame) and many applicable statistical tools for analyses similar to those proposed for this study (Mckinney, 2012).

Mann – Kendall's test

Trend analysis is a common used tool for detecting changes in climatic and hydrologic time series data. Among several statistical tests used to assess the significance of trends in time series, the Mann – Kendall's (MK) trend test is one of the most commonly used tests with a null hypothesis that the data are independent and randomly placed (Hamed & Rao, 1998). Since, the trend value can be misleading in the case of time series data; it is usually removed by subtracting the trend from original snowfall data. It is believed that detrended snowfall data will serve as a reliable source for unbiased results. Thus, in this study snowfall data are detrended first and before further statistical analysis. The detail of MK test is provided as Appendix A. Snowfall trends for each station are seen more clearly using this test.

Snowfall trends in each station is seen using this test. Z_{MK} is calculated as follows,

(1) H_o: No monotonic trend and (2) Ha: Monotonic trend is present; two hypotheses are established in the beginning.

(a) Snowfall data over time is listed in the order, $x_1, x_2, x_3 \ldots\ldots x_n$ which denote the measurements obtained at different years 1, 2…………n respectively.

(b) Sign of all n(n-1)/2 possible differences $x_j - x_k$, where j>k, are determined. The differences are $x_2 - x_1$, $x_3 - x_1$, $x_n - x_1$, $x_3 - x_2$, $x_4 - x_2$, ………., $x_n - x_{n-2}$, $x_n - x_{n-1}$

(c) Sign function returns as follows, Sign $(x_j - x_k) = 1$ if $x_j > x_k$; Sign $(x_j - x_k) = 0$ if $x_j = x_k$; Sign $(x_j - x_k) = -1$ if $x_j < x_k$

(d) Then computed,

$$S = \sum_{k-1}^{n-1} \sum_{j-k+1}^{n} sign(x_j - x_k)$$

The variance of S calculated as,

$$var(S) = 1/18[n(n-1)(2n+5) - \sum_{p-1}^{g} t_p(t_p - 1)(2t_p + 5)]$$

Where, g is the number of tied groups and t_p is the number of observations in the p^{th} group.

Z_{MK} is calculated as,

$$Z_{MK} = \frac{(S-1)}{\sqrt{var(S)}} \ if \ S > 0$$

=0 if S=0

$$=\frac{S+1}{\sqrt{var(S)}}\ if\ S < 0$$

Then H_0 is rejected and H_a is accepted if $Z_{MK} \geq Z_{1-\alpha}$, Where $Z_{(1-\alpha)}$ is the $100(1-\alpha)^{th}$ percentile of the standard normal distribution.

A positive (negative) value of Z_{MK} indicates that the data tend to increase (decrease) with time. If $H_o \leq H_a$; H_o: No monotonic trend versus the alternative hypothesis ≤ Ha: Upward monotonic trend at the Type I error rate α, where 0 < α < 0.5. (Note that α is the tolerable probability that the MK test will falsely reject the null hypothesis.) Then H_o is rejected, and Ha is accepted if $Z_{MK} \geq z_1 - \alpha$, where $z_1 - \alpha$ is the 100(1- α)*th* percentile of the standard normal distribution. To test H_o above versus Ha: Downward monotonic trend. at the Type I error rate α, H_o is rejected, and Ha is accepted if $Z_{MK} \leq - z_1 - \alpha$. To test the H_o above versus H a: Upward or downward monotonic trend at the Type I error rate α, H_o is rejected, and Ha is accepted if $|Z_{MK}| \geq z_1 - \alpha/2$, where the vertical bars denote absolute value (Gilbert, 1987).

Gutzler et al. (1992) derived linear trend statistics from time series data for mean annual snow cover and removed the trend value before performing any other further analysis. Monaghan et al. (2008) in their research on air temperature and snowfall have also found significant results using trended and detrended data, but differences in results were quite small.

Ordinary least square fitting is conducted for the snowfall data using the Ordinary Least Square (OLS) regression of stats model's module in Python. This method takes vector data as an input and generates slope and y-intercept values as the outputs (Appendix B). The trend line is drawn using OLS regression test.

Pearson's correlation between two variables is calculated using the "scipy.stats.pearsonr(x,y)"method found in the Scipy library in Python ,where x and y are two data sets (Appendix C). This method returns correlation coefficient (r) and two tailed level of significance (p-value) as an output. Pearson's product moment correlation is used to find correlations between regional air temperature and average annual snowfall, MIC in Lake Michigan and air temperature over LPM. The same method correlation coefficients for SST/ NAO/ PDO and Snowfall.

The correlation coefficient is calculated as follows:

$r = \Sigma (x-m_x) (y-m_y) / \sqrt{} \Sigma (x-m_x)^2 (y - m_y)^2$, where m_x is the mean of the variable x and m_y is the mean of variable y.

The upcoming chapter presents t results and discussion of this study.

CHAPTER IV

RESULT AND DISCUSSION

This chapter discusses the results of the analyses performed using the statistical tools described in chapter three. This chapter opens with a report of the descriptive statistics for snowfall including, Box and whisker plot describing minimum and maximum snowfall values. Temporal trend in snowfall, Man- Kendall's test results and correlation test results are presented in second and third portions of this chapter.

Statistics of snowfall in the eight stations of LPM

The monthly mean snowfall data from 1950 – 2015 of the eight selected COOP stations representing LPM was processed for the annual mean snowfall for each station. Annual mean snowfall for the year 1951 in this study may be defined as the average snowfall from November and December 1950 and January, February and March 1951, the five months of winter season. Along with the mean (cm) snowfall, the Standard Deviation, the Minimum and the Maximum snowfall of that stations in 65 years is also in Table 2.

Table 2: Statistics of snowfall in the eight stations of LPM (1950-2015).

Stations	**Mean (cm)**	**Standard Deviation**	**Minimum**	**Maximum**
Battle Creek	139.15	49.02	68.58	278.38
Big Rapids	166.01	53.06	65.53	292.36
East Jordan	277.06	80.07	64.26	465.83
Houghton Lake	146.31	43.52	66.04	272.79
Lake City	195.62	48.58	96.52	322.32
Kent City	134.44	35.84	43.43	210.82
South Haven	161.14	58.17	44.45	288.79
Wellston	239.16	61.56	108.204	396.74

Source: Calculated by author

Among all eight snowfall stations, the highest mean obtained is 277.06 cm (East Jordan) and lowest among all is 134.44 cm (Kent City). The maximum and minimum snowfall amount from 1949 to 1950 is 465.83 cm and 43.43 cm respectively. Even though East Jordan recorded the highest maximum mean snowfall, its standard deviation value of 80.07 shows that noticeable snowfall obtained in the region is far from mean average snowfall (Table 2). Maximum and minimum average annual snowfall of each snowfall station can be understood much better in the Box plot provided as Figure 2.

Kunkel et al. (2009) identified 19 homogeneous stations which were in the South and East sides of Lakes Superior, Michigan, Erie and Ontario covering almost all parts of Great Lakes region. The mean annual snowfall measured at the East Jordan station in Michigan for the period from 1926 to 2006 was found to be 271 cm. The Lake City station mean snowfall recorded from 1898 to 2006 was found to be 195 cm, Wellston station mean snowfall from 1918-2006 was found to be 234 cm, Houghton Lake station mean snowfall recorded for same period of time was 140 cm, the Big Rapids stations mean snowfall measured from 1896 to 2006 recorded 175 cm, from 1929 to 2006 the Kent city station mean snowfall was found to be 140 cm, Battle Creek station mean snowfall was found to be 135 cm which was the average from 1895 to 2001, and similarly the South Haven station reported a mean snowfall of 152 cm for the years from 1895 to 2006.

Out of these 19 homogeneous COOP stations studied in Kunkel et al. (2009) data for eight stations in LPM are used in this thesis and the results of mean snowfall of only these eight stations is discussed in above paragraph. East Jordan has the highest mean snowfall and Kent city and have the lowest mean snowfall. The Wellston's station mean snowfall is less (139.70 cm) during the earlier study by Kunkel et al. (2009), while in our study period from 1949 to 2015, it is higher (239.16 cm).

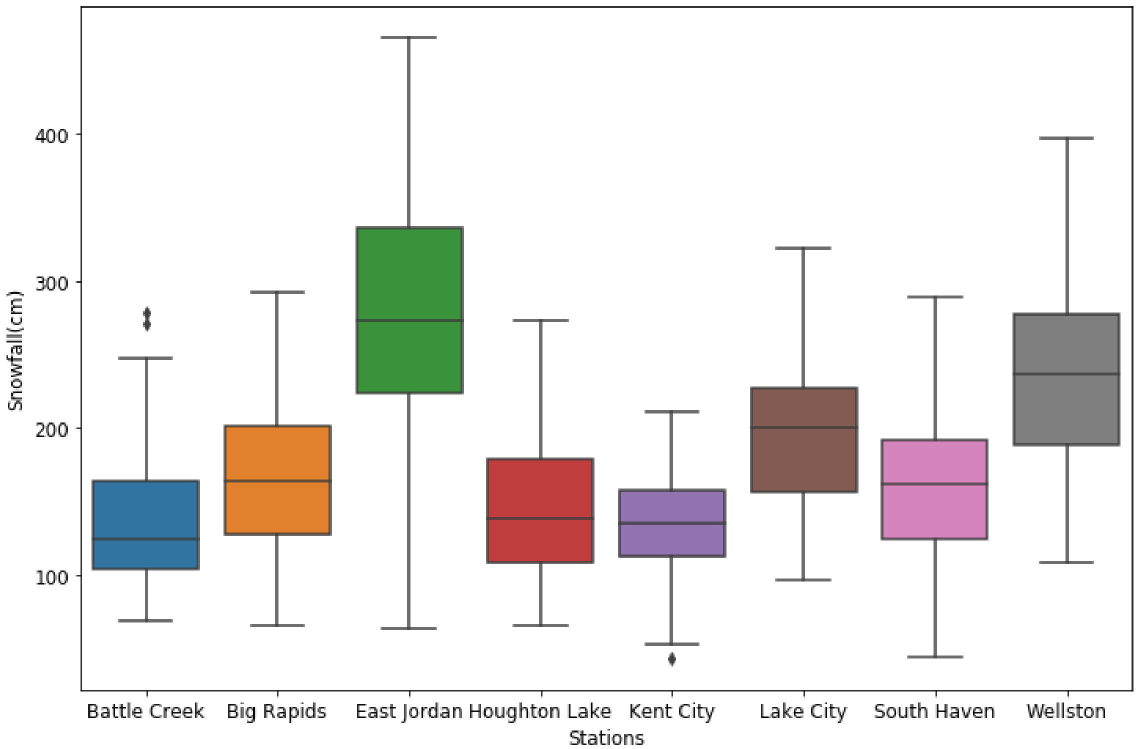


Figure 2: Box and whisker showing distribution of snowfall data of each station.

Source: Calculated by author

Figure 2 shows the distribution of snowfall data based on the minimum, first quartile, median, third quartile and maximum snowfall values. A few larger outlier snowfall values in the Battle Creek station can be seen, few smaller outlier snowfall values in the Kent City station can be seen.

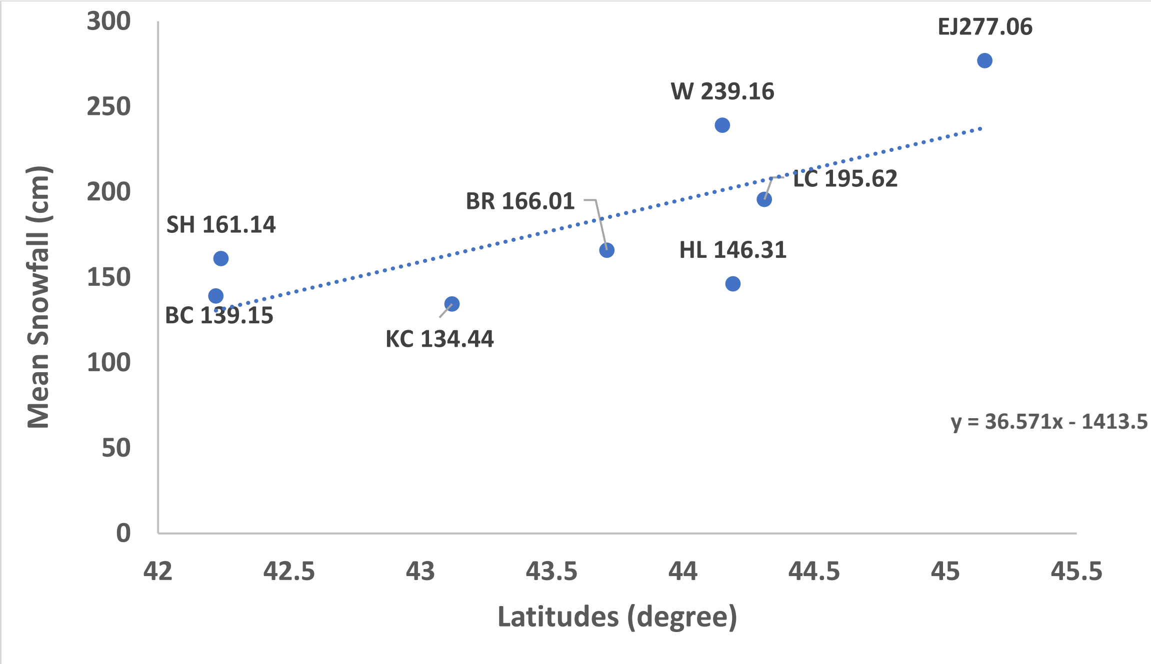


Figure 3: All eight stations with latitude and average annual snowfall.

Source: Calculated by author

Figure 3 shows the average annual snowfall of each station according to latitudes of each station in the LPM. The position of the station also plays a key role in the occurrence of snowfall which can be seen in this study data. It is observed that higher average snowfall occurred in stations located further higher North since snowfall is also a function of cold air. Thus, the more northerly the station, is the more snowfall has been occurred in the duration from 1950 to 2015.

Temporal trends in snowfall

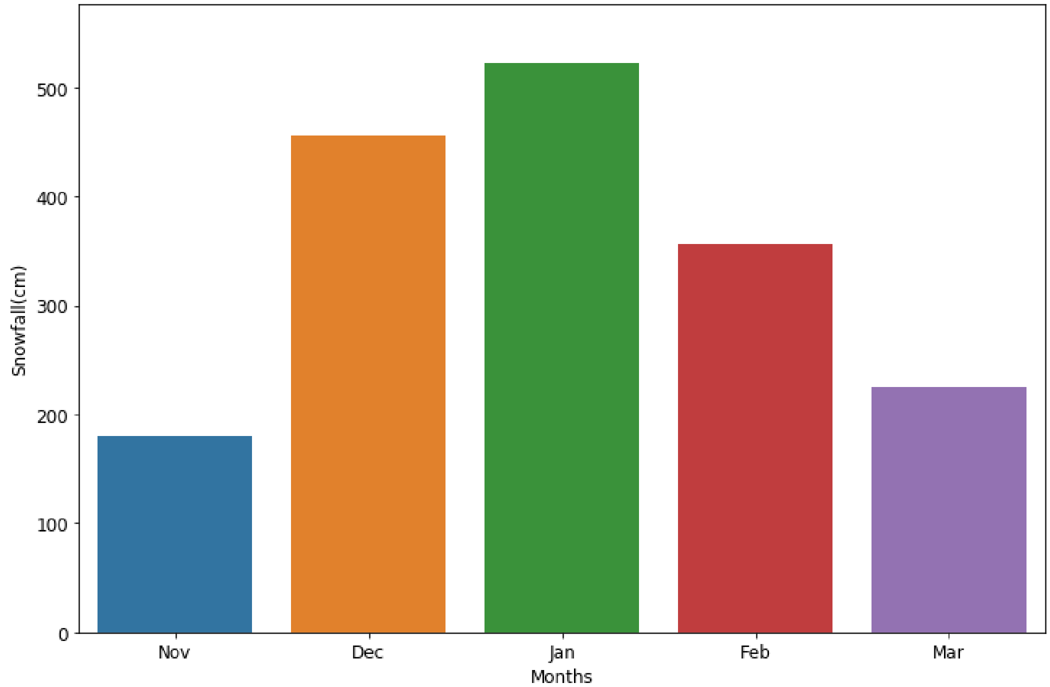


Figure 4: Monthly average snowfall over LPM.

Source: Calculated by author

Figure 4 shows the monthly mean snowfall data for each year. For example, the November in Figure 4 represents all the snowfall that occurred in the month of November from 1950 to 2015. A similar process may be applied for the rest four months. Thus, monthly average snowfall over LPM is clearly described through these graphs.

The monthly average snowfall (cm) from November to March represents the snowfall distribution for the winter season. In the LPM it is found that snowfall normally starts from the month of November and slowly and gradually increases. Peak snowfall occurs in January and after that a decreasing pattern is seen. A simple normal distribution of snowfall can be seen in Figure 4.

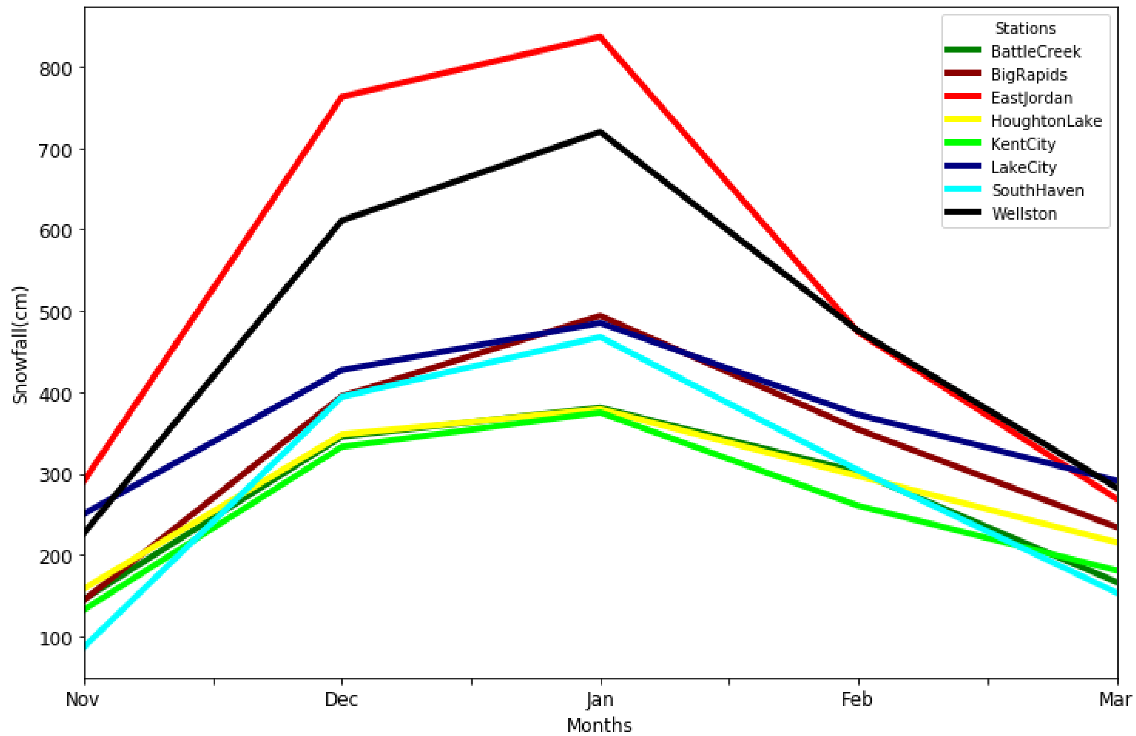


Figure 5: Monthly averaged snowfall in all eight stations of LPM.

Source: Calculated by author

Figure 5 shows the average snowfall for each month for each station. Significant differences can be found among the peaks of snowfall for the eight stations. Maximum snowfall occurred during the month of January in almost all stations.

The Kent City station got the least snowfall in that month among all eight stations whereas East Jordan had the highest snowfall among all. Snowfall peaked in January and started to decrease afterwards.

Results from Mann Kendall's test

For Mann-Kendall test, instruction in a link (Appendix -A) is used to create function for Man-Kendall in Python programming language. This function takes data (a vector data) and significance level (float number) as an input and gives p-value (float number) and trend (increasing, decreasing or no trend) as an output.

Table 3: The trend analysis of snowfall at 90 % confidence level.

Stations	**p-value**	**Slope**	**Trends** 90 % Conf. Interval
Battle Creek	0.0001	1.0376	increasing
Big Rapids	0.05	0.4991	increasing
East Jordan	0.0001	2.0309	increasing
Houghton Lake	0.03	0.4667	increasing
Kent City	0.67	0.1015	**no trend**
Lake City	0.01	0.6544	increasing
South Haven	0.0001	0.8264	increasing
Wellston	0.07	0.549	increasing

Source: Calculated by author

Table 3 shows the trend statistics for the eight stations of the LPM at the 90 % confidence interval. The null hypothesis is that no trend exists in the snowfall occurred in these stations and any trend identified in any station means I accept the alternative hypothesis.

Based on results from the Mann Kendall's test, it is found that except for Kent City Station, the snowfall slope showed increasing trends that were statistically significant.

Large increasing trend was found for snowfall of the Battle Creek station and the East Jordan station throughout the years from 1950 to 2015 ($p = 0.0001$). The East Jordan station has the highest increase rate (2.0309 cm/ year) among all eight stations. A similar increasing trend ($p = 0.001$) was found in South Haven with due increase of 0.8264 cm increment per year. The Kent city station did not show any trend.

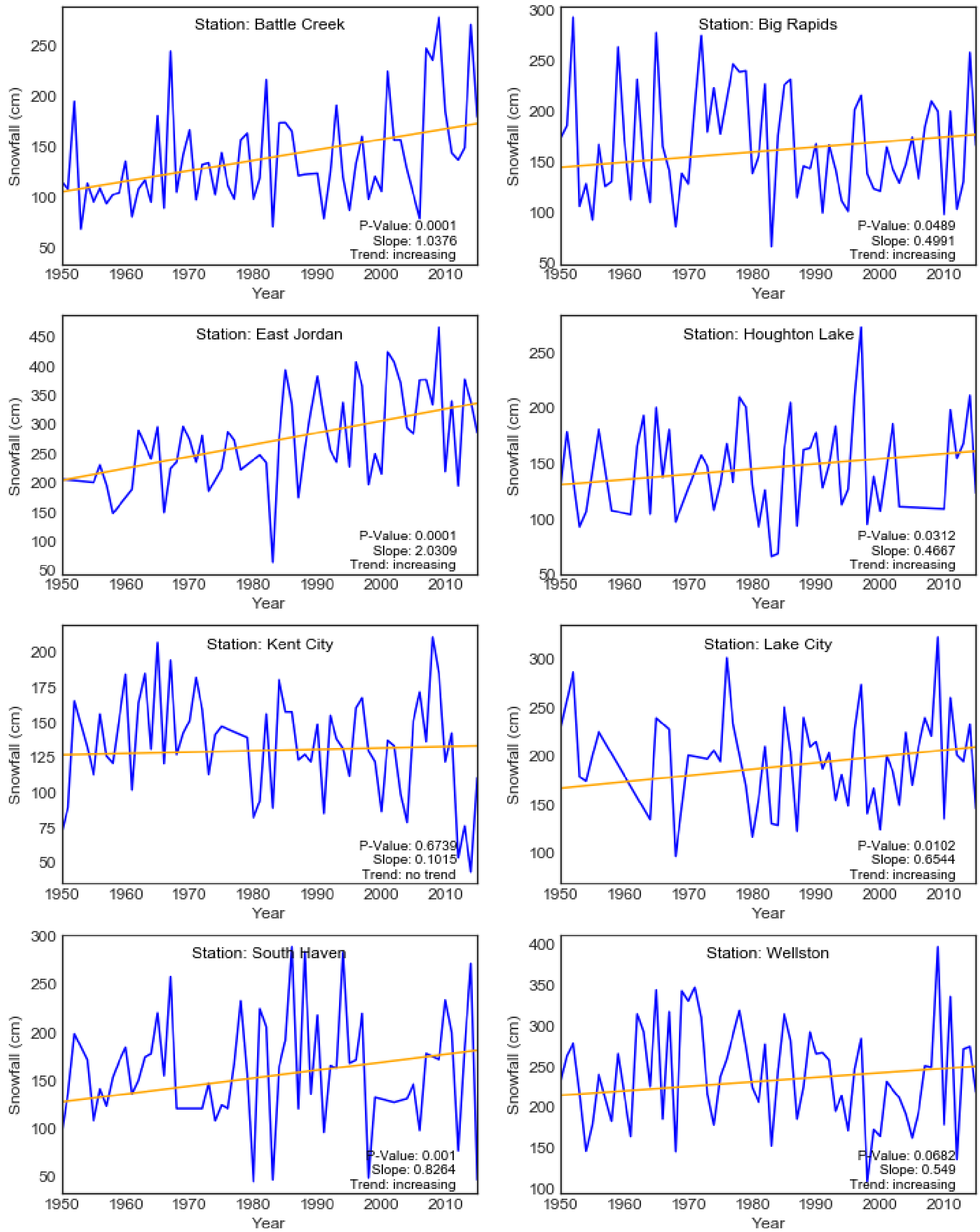


Figure 6: Increasing trends of annual averaged snowfall except in Kent City.

Source: Calculated by author

Figure 6 provides graphical representations of the snowfall for all eight stations including a trendline. The Ordinary Least Square (OLS) method for regression analyses was used to compute linear formula for these data (Appendix B). All stations except the Kent City station shows increasing trend. Figure 6 shows the snowfall data before removing the trend. As time is not itself a parameter and the use of time series data could mislead us by suggesting a trend in the snowfall data of several years, these data must be detrended. In this study, also original data were subtracted from the trend to detrend. The detrended data for all eight stations is shown as figure 7.

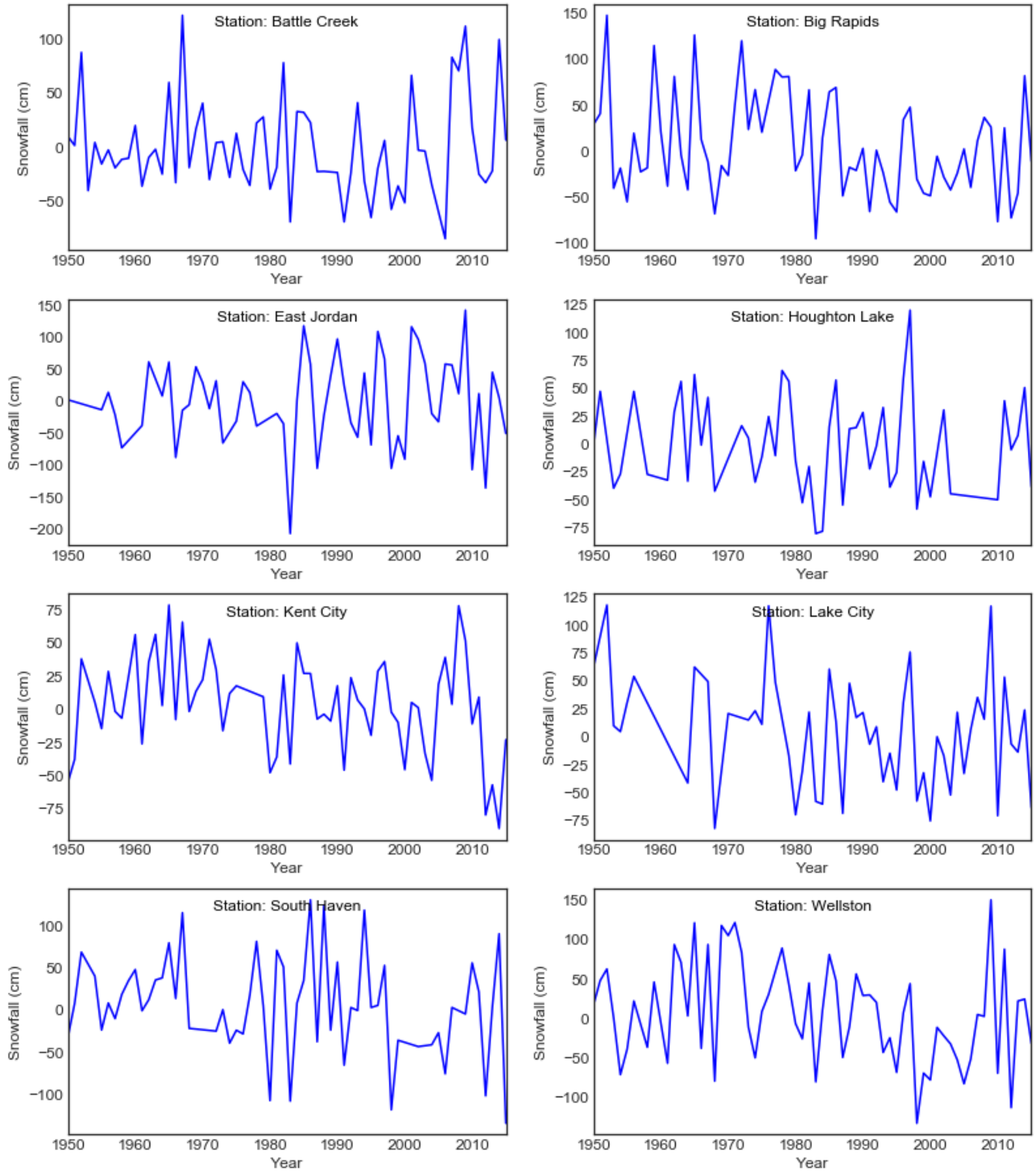


Figure 7: Snowfall anomalies of the eight stations in LPM after de-trending.

Source: Calculated by author

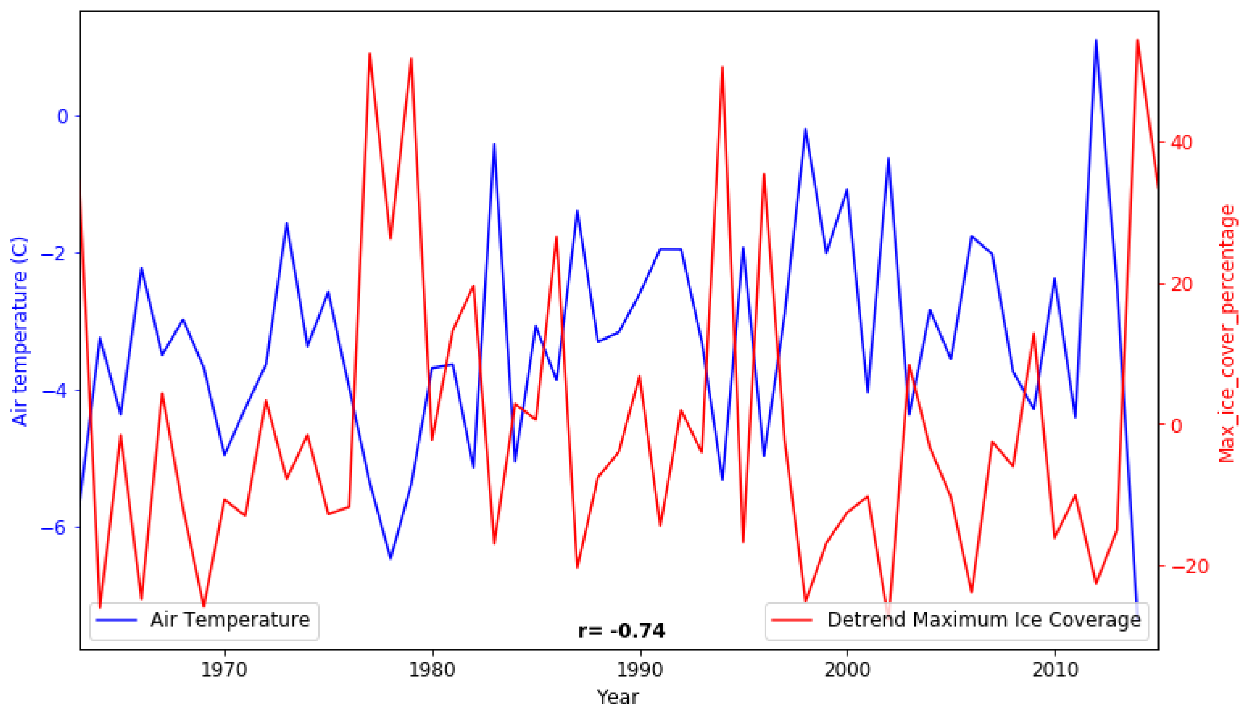
Maximum Ice Cover in Lake Michigan (MIC)

Table 4: Correlation results for maximum ice coverage with air temperature.

Variables	**MIC**	
	Pearson's correlation Coefficient(r)	Significance value(p)
Average Air temperature over LPM	-0.75	0.0001

Source: Calculated by author

Maximum ice coverage and air temperature correlation



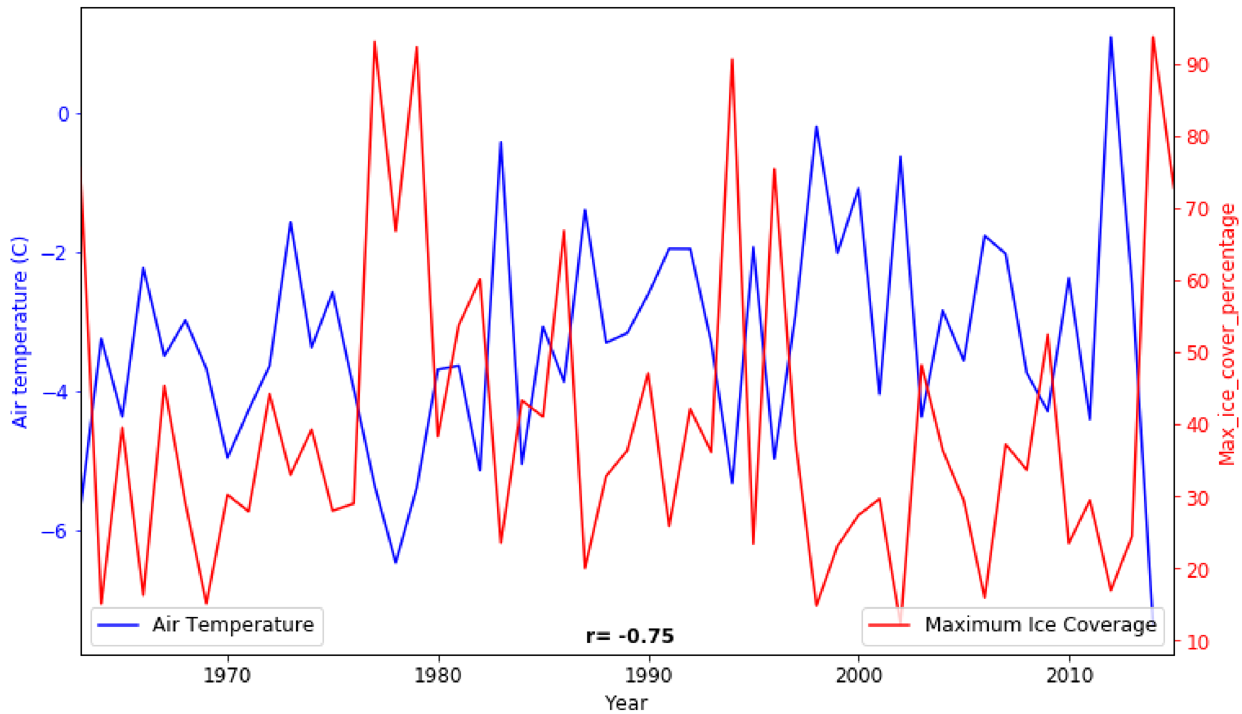


Figure 8: Pearson's correlation between MIC (before and after de-trend) of Lake Michigan and air temperature.

Source: Calculated by author

A strong negative correlation (r = -0.74; p-value = 0.0001) was found between air temperature over the LPM and de-trended MIC over Lake Michigan which indicates maximum ice coverage over the Lake Michigan and its adjacent area occurs during low air temperature periods which is also explained by figure 8.

Average annual snowfall and air temperature

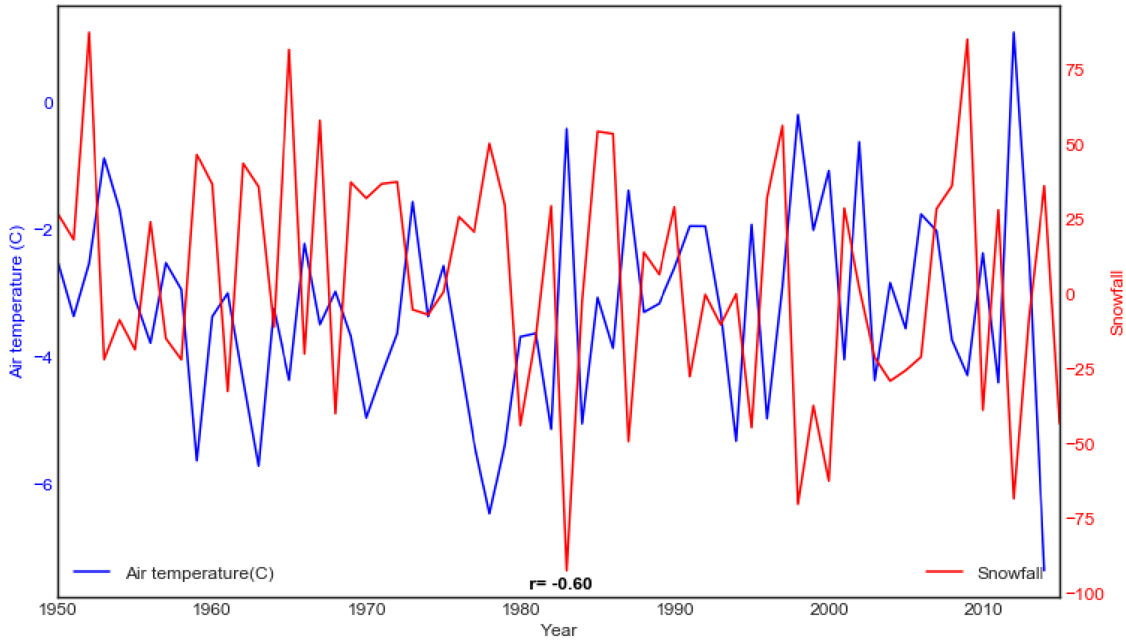


Figure 9: Pearson's correlation between air temperature over LPM and average annual detrended snowfall.

Source: Calculated by author

The negative correlation between air temperature and snowfall in figure 9 shows that as air temperature decrease, the snowfall amount increases and vice- versa. The Blue colored line in Figure 9 represents snowfall (cm) while the winter air temperature (degree Celsius) is shown in red color. When averaged, snowfall is negatively correlated with air temperature, and the correlation coefficient (r) is found to be -0.60 with p-value of 0.0001.

Table 5: Correlation results of detrended snowfall with regional air temperature.

Stations	Correlation between Winter Air Temp. over LPM & Snowfall for each station			
	Pearson's r (Trend)	P- value	Pearson's r (Detrend)	P- value
Battle Creek	-0.35	0.06	-0.43	0.00
Big Rapids	-0.55	0.0001	-0.54	0.0001
East Jordan	-0.32	0.02	-0.46	0.00
Houghton Lake	-0.38	0.07	-0.40	0.00
Kent City	-0.31	0.02	-0.29	0.03
Lake City	-0.26	0.06	-0.26	0.06
South Haven	-0.53	0.00	-0.53	0.00
Wellston	-0.58	0.0001	-0.57	0.0001

Source: Calculated by author

Pearson's correlation analysis was performed between winter air temperature (November to March) and averaged snowfall (November to March) for all 8 stations with both trend data and detrended data. The results of the analysis are shown in Table 5. The correlation results presented in the Table 5, shows very slight differences between the correlation coefficients for snowfall data before removing the trend and after removing trend. Analyses for all 8 stations showed negative correlations between air temperature and snowfall. For stations including South Haven, Lake City, Big Rapids and Wellston, the correlation coefficients are almost same whereas in other stations, the difference in coefficient range from 0.02 to 0.14.

The maximum correlation found is 58 % for Wellston station which can be taken as moderate one. Big Rapids and South Haven are the other two stations which recorded correlation greater than 0.5. Lake City station showed lowest correlation which is just 0.26.

Winter air temperature is negatively correlated with snowfall in all stations, which means lower temperature increases snowfall volume. The strongest negative correlation was found for the Wellston station (-0.57) while Lake city is the station with the weakest correlation coefficient (r =-0.26). The correlation between trended data and de-trended data have nearly similar values. Not only in the case of Wellston but in all other stations as well. A slight increase is seen in values for Battle Creek and the East Jordan stations while using detrended snowfall data.

Karl et al. (1993) used weekly snow cover data derived from NOAA satellites. Monthly temperature, snowfall and precipitation data measured from station networks in Canada, the contiguous United States and Alaska were used to study variations in snow cover and snowfall in North America in relation to precipitation and temperature. For their study period from October 1972 through September 1991, they found a strong correlation between snow cover and temperature where up to 78 % of the variance in regional snow cover and snowfall was explained by the anomalies of monthly mean maximum temperature.

Pearson's correlation of average annual snowfall with SST, NAO and PDO

Table 6: Correlation results of snowfall data before and after detrends with SST, PDO, NAO.

Stations	SST & Snowfall			
	Before Detrend		After Detrend	
	r	p-value	r	p-value
Battle Creek	-0.13	0.31	-0.14	0.27
Big Rapids	-0.24	0.05	-0.24	0.05
East Jordan	-0.40	0.00	-0.46	0.00
Houghton Lake	-0.32	0.02	-0.34	0.01
Kent City	-0.25	0.05	-0.25	0.04
Lake City	-0.38	0.00	-0.37	0.06
South Haven	-0.07	0.62	-0.07	0.62
Wellston	-0.29	0.02	-0.29	0.02

Source: Calculated by author

Stations	PDO & Snowfall			
	Before Detrend		After Detrend	
	r	p-value	r	p-value
Battle Creek	-0.14	0.24	-0.00	0.10
Big Rapids	-0.03	0.71	-0.00	0.10
East Jordan	-0.03	0.83	-0.17	0.23
Houghton Lake	-0.12	0.42	-0.18	0.20
Kent City	-0.18	0.16	-0.09	0.49
Lake City	-0.32	0.01	-0.32	0.02
South Haven	-0.09	0.56	-0.08	0.54
Wellston	-0.18	0.15	-0.14	0.25

Source: Calculated by author

Table 6 - continued

Stations	NAO & Snowfall			
	Before Detrend		After Detrend	
	r	p-value	r	p-value
Battle Creek	-0.02	0.87	-0.12	0.31
Big Rapids	-0.03	0.75	-0.05	0.65
East Jordan	-0.002	0.10	-0.15	0.26
Houghton Lake	-0.03	0.81	-0.06	0.67
Kent City	-0.14	0.26	-0.08	0.50
Lake City	-0.02	0.88	-0.01	0.89
South Haven	-0.03	0.78	-0.04	0.76
Wellston	-0.13	0.28	-0.12	0.34

Source: Calculated by author

Table 6 depicts the results of Pearson's product moment correlation analysis of snowfall volume with SST, NAO and PDO for each station separately over time with snowfall data showing both trend and de-trended snowfall data. As shown above, the correlation coefficients for NAO and PDO with snowfall are found consistently low when compared to the correlation coefficients for SSTs.

Seager et al. (2010) explored the connections between northern hemisphere seasonal snow anomalies and large scale atmospheric circulations for the winter of 2009/10. In their study, they hypothesized that snowy winters in the mid-Atlantic region, including the continental and hemispheric scale snow anomalies, are caused by a combination of El Niño (warm phase) and a negative NAO (Seager et al. 2005; Hurrell et al. 2003). These researchers found that an El Niño is related to positive snowfall anomalies in the Southern and Central United States and along the Eastern seaboard and negative snowfall anomalies in the North. In the case of NAO, these studies also found that across Eastern North America and in Northern Europe, a negative NAO causes positive snow anomalies.

Table 7: Correlation of annual average snowfall of eight stations with NAO, PDO and SST.

Variables	Average Snowfall			
	Before Detrend		After Detrend	
	Pearson's r	p-value	Pearson's r	p-value
Air Temp.	-0.55	0.0001	-0.56	0.0001
SST	-0.34	0.01	-0.35	0.009
PDO	-0.07	0.57	-0.16	0.21
NAO	-0.07	0.53	-0.12	0.33

Source: Calculated by author

Table 7 shows the result of correlation analysis for annual average snowfall data for all eight stations with SST, PDO and NAO. With both trended and de-trended data and anomalies of large scale atmospheric oscillations like NAO and PDO are found to have very slight negative correlations (r= -0.07).

Among all three SST anomalies tested, SST seem to be slightly better correlated (r= -0.34) than the other two. Looking at results from correlation analysis provided in Table 6 & 7, further analysis was carried on SST. National Oceanic and Atmospheric Administration (NOAA) have officially listed the warm episodes or El Niño (0.5 and above) and cold episode or La Niña (-0.5 and below) since 1950 for nino 3.4 region (Appendix D). Past ENSO event years are also listed by NOAA (Appendix -D). Thus, SST anomalies equal to and greater than 1 representing El Niño are categorized as strong warm episodes and SST anomalies equal to and smaller than -1 representing La Niña are categorized as strong cold episodes. To further the analysis, the corresponding ENSO years are selected. Pearson's correlation test between SST and average annual snowfall over LPM during those of ENSO years is performed. The results are presented in Tables 8 and 9.

Table 8: ENSO years with SST (≥1) and its correlation with average snowfall over LPM.

El Niño		
Year	SST (≥1)	Average annual snowfall (de-trended)
1958	1.24	-34.64
1966	1.156	-29.62
1973	1.464	-13.12
1983	2.148	-95.85
1987	1.124	-50.99
1992	1.498	0.061
1998	2.142	-67.33
2010	1.396	-30.70
Correlation coefficient(r)=-0.64	p-value = 0.08	

Source: Calculated by author

The correlation between ENSO years with SST greater than and equal to 1 and average annual snowfall over LPM is found to be -0.64. A quite moderate negative correlation is found between warm episodes of ENSO and annual average snowfall over the LPM. This result indicated that when SST increases, snowfall decreases.

Table 9: ENSO years with SST (≤-1) and its correlation with average snowfall over LPM.

La Niña		
Year	SST (≤-1)	Average annual snowfall (de-trended)
1950	-1.23	1.56
1951	-1.012	-1.86
1956	-1.314	8.79
1971	-1.2	29.39
1974	-1.84	-16.13
1976	-1.326	20.11
1985	-1.094	51.51
1989	-1.762	5.43
1999	-1.32	-33.92
2000	-1.506	-58.97
2008	-1.57	42.89
2011	-1.428	36.35
Correlation coefficient(r) = 0.25 p-value = 0.43		

Source: Calculated by author

The correlation between ENSO years where SST is less than and equal to -1 and average annual snowfall over the LPM is found to be 0.25. A slightly positive correlation coefficient is found between cold episodes of ENSO and annual average snowfall over the LPM. This result explains that when SST decreases, snowfall increases in the LPM and vice versa. Since the value of correlation coefficient is very low, it is difficult to suppose that cold episodes are strongly related to annual average snowfall in the LPM.

Ropelewski & Jones (1987) defined strong El Niño events in the years 1900,1912, 1919, 1926, 1932, 1941, 1958, 1973, 1983, 1992 and 1998 and years of moderate El Niño included; 1903, 1907, 1914, 1931, 1940, 1942, 1952, 1953, 1966, 1977, 1978, 1987 and 1993. Three major El Niño events (1957, 1965, 1972) and three additional minor El Niño (1951, 1953 and 1969) were identified during the period of 1950 to 1973 (Wyrtki (1975); Ramage (1975); Wooster & Guillen (1974)). Quinn (1979) classified El Niño events as strong, moderate, weak and very weak. Their expanded list places the 1963 event and the 1975 event in the very weak category.

The upcoming chapter will present the conclusion of my thesis, which summarizes the chapters one to four.

CHAPTER V

CONCLUSION

Snowfall contributes an important proportion of the total winter precipitation in the LPM and those of surrounding States. Investigations about long term snowfall in the Great Lakes region were conducted from various perspectives by previous studies. However, there are very few studies that focus on winter annual snowfall in Michigan, and none of these studies were specific to snowfall factors in the LPM. Inter- annual variability of snowfall influences both the meteorology and climatology of LPM. This study had two main objectives: 1) study inter-annual variation in snowfall from 1950 to 2015 for the eight homogeneous stations located within the LPM; and 2) Determine if any relationships exist between local meteorological variables and large – scale atmospheric dynamics and snowfall.

In this study, snowfall data and the relationship between snowfall in the LPM with ENSO, NAO, PDO, air temperature over LPM region and maximum ice coverage are investigated and analyzed using statistical methods including the Mann-Kendall test, OLS regression, Pearson's Product Moment Correlation tests. Eight stations with homogeneous time series dataset as defined by Kunkel et al. (2009) are used. Mean monthly snowfall volume for each year are used to find annual averages by adding up the sum of snowfall that occurred each year from November to March. For example, the annual average snowfall of 1951 is the averaged snowfall from November and December of 1950 and January, February and March of 1951. Inter- annual snowfall across the study area exhibits large temporal variations and SST anomalies representing ENSO have significant impacts on average annual snowfall. The impacts of NAO and PDO do not have significant influences on the average annual snowfall within the LPM.

The maximum amount of the annual average snowfall occurred in the LPM throughout this study period was 465.83 cm and the least were 43.33 cm at East Jordan station and Kent city stations respectively (Table 2). The East Jordan (277.06 cm average) is at higher latitude when compared to Kent city (134.44 cm average) (Figure 1). Statistical analyses of average inter-annual snowfall at eight different stations showed that the study area received more snowfall in the northern-most portion of the LPM through these 65 years of study period (1950-1951). A moderate correlation of 0.5438 was found between average snowfall over the LPM and the geographical location of the stations. Generally, snowfall in the study area begins in November and gradually increases through December, while peaking in January and again slowly the snow decreases through March. Two Distinct peaks were found for all station for the month of December and January. Sharp increases in snowfall between December and the January Peak and a sharp decrease between January and February is typical of this region ((Figure 5).

Mann Kendall tests for snowfall trend analysis showed interesting results. The trend analysis at 90 % confidence level indicated an increasing snowfall trend at all stations except Kent City. This is very strange and could be a subject of further analysis. Kent City station showed no trend (Table 3). Only a slight difference is seen between trend and detrend snowfall data. Statistical analysis suggests that regional air temperature in LPM is the dominant factor influencing annual total snowfall, followed by ENSO events. Regional air temperatures have negative correlations with annual total snowfall. Maximum ice coverage (MIC) as measured in percent for Lake Michigan resulted a strong negative correlation coefficient (-0.75) with regional air temperature. This study also suggests that increased annual total snowfall occur is found during years with higher MIC in Lake Michigan. It was determined that that NAO and PDO are not significantly related to snowfall in the LPM (Tables 6A, 6B and 6C). Positive correlations exist between snowfall and La Niña events and negative correlation exist between snowfall and El Niño events.

In summary, this study of long term climate data for eight stations in the LPM suggests that air temperature is moderately correlated (R = -0.60) with annual snowfall in the LPM. During the period from 1950 to 2015, the winter air temperature averaged for the LPM has slightly decreased (Figure 9), which corresponds well with the increased trend in snowfall. Correlations between snowfall and ENSO (cold phase) are found to be significantly weaker or insignificant, further rigorous studies are required to determine the details regarding how atmospheric oscillations influence snowfall variability.

APPENDICES

Appendix A

Mann Kendall's (MK)Test

Instruction in this link below is used to create function for Mann-Kendall function in python programming language. This function takes data (a vector data) and significance level (float number) as an input and gives p-value (float number) and trend (increasing, decreasing or no trend) as an output.

https://vsp.pnnl.gov/help/Vsample/Design_Trend_Mann_Kendall.htm

MK test function in Python:

```
from SciPy. Stats import norm, mstats
def mannkendall_test (x, alpha = 0.1):
    """
    Input:
        x:    data
        alpha:(0.05 default) significance level

    Output:
        trend: increasing, decreasing or no trend
        h: True (if trend is present) or False otherwise
        p: p value of the significance test
        z: normalized test statistics
```

Examples

```
  >>> x = np.random.rand(200)
  >>> trend,h,p,z = mannkendall_test(x,0.1)
"""
n = len(x)
# calculating S
s = 0
for k in range(n-1):
   for j in range (k+1, n):
      s += np.sign(x[j] - x[k])

# calculating unique data
unique_x = np.unique(x)
g = len(unique_x)

# calculating the var_s
if n == g: # there is no tie
   var_s = (n*(n-1) *(2*n+5))/18
else:
   tp = np.zeros(unique_x.shape)
   for i in range(len(unique_x)):
      tp[i] = sum(unique_x[i] == x)
   var_s = (n*(n-1) *(2*n+5) + np.sum(tp*(tp-1)*(2*tp+5)))/18

if s>0:
   z = (s - 1)/np.sqrt(var_s)
elif s == 0:
      z = 0
elif s<0:
```

```
    z = (s + 1)/np.sqrt(var_s)

# calculating the p-value
p = 2*(1-norm.cdf(abs(z))) # two tail test
h = abs(z) > norm.ppf(1-alpha/2)

if (z<0) and h:
    trend = 'decreasing'
elif (z>0) and h:
    trend = 'increasing'
else:
    trend = 'no trend'

return trend, h, p, z
```

Appendix B

Ordinary least square fit

Ordinary least square fitting is done in snowfall data using Ordinary Least Square (OLS) method of stats models module in python. This method takes vector data as an input and gives slope and y-intercept as an output.

http://www.statsmodels.org/stable/index.html

After fitting the snowfall data, predicted snowfall from OLS fit is subtracted from actual snowfall data to get the detrend snowfall data.

OLS fitting in Python

```
import statsmodels.formula.api as smf

lm = smf.ols(formula='Snow~Year’, data).fit()
preds = lm.predict(data['Year'])
data['Trend’] =preds
data['Detrend’] =data['Snow']-data['Trend']
data=data[['Year','Detrend']]
```

Appendix C

Pearson's product moment correlation method in Python

Pearson's correlation coefficient (r) between two variables is calculated using "scipy.stats.pearsonr(x,y)"method of scipy library in Python. Where x and y are two data sets. This method returns correlation coefficient and two tailed p-value as an output.

https://docs.scipy.org/doc/scipy/reference/generated/scipy.stats.pearsonr.html

Appendix D

ENSO years

https://www.esrl.noaa.gov/psd/enso/past_events.html

http://origin.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ONI_v5.php

BIBLIOGRAPHY

Alcott, T. I., & Steenburgh, W. J. (2013). Orographic influences on a Great Salt Lake–effect snowstorm. *Monthly Weather Review*, *141*(7), 2432-2450.

Ashworth, W. (2003). *Great Lakes Journey: A New Look at America's Freshwater Coast*. Wayne State University Press.

Assel, R., & Rodionov, S. (1998). Atmospheric teleconnections for annual maximum ice cover on the Laurentian Great Lakes. *International Journal of Climatology*, *18*(4), 425-442.

Assel, R., Cronk, K., & Norton, D. (2003). Recent trends in Laurentian Great Lakes ice cover. *Climatic Change*, *57*(1-2), 185-204.

Bai, X., Wang, J., Liu, Q., Wang, D., & Liu, Y. (2011). Severe ice conditions in the Bohai Sea, China, and mild ice conditions in the Great Lakes during the 2009/10 winter: Links to El Niño and a strong negative Arctic Oscillation. *Journal of Applied Meteorology and Climatology*, *50*(9), 1922-1935.

Bai, X., Wang, J., Sellinger, C., Clites, A., & Assel, R. (2012). Interannual variability of Great Lakes ice cover and its relationship to NAO and ENSO. *Journal of Geophysical Research: Oceans*, *117*(C3).

Bard, L., & Kristovich, D. A. (2012). Trend reversal in Lake Michigan contribution to snowfall. *Journal of Applied Meteorology and Climatology*, *51*(11), 2038-2046.

Barnston, A. G., & Livezey, R. E. (1987). Classification, seasonality and persistence of low-frequency atmospheric circulation patterns. *Monthly weather review*, *115*(6), 1083-1126.

Bjerknes, J. (1969). Atmospheric teleconnections from the equatorial Pacific. *Monthly Weather Review*, *97*(3), 163-172.

Braham Jr, R. R., & Kelly, R. D. (1982). Lake-effect snow storms on Lake Michigan, USA. *Cloud Dynamics*, 87-101.

Braham Jr, R. R., & Dungey, M. J. (1984). Quantitative estimates of the effect of Lake Michigan on snowfall. *Journal of climate and applied meteorology*, *23*(6), 940-949.

Brown, L. C., & Duguay, C. R. (2010). The response and role of ice cover in lake-climate interactions. *Progress in Physical Geography*, *34*(5), 671-704.

Brunetti, M., Buffoni, L., Maugeri, M., & Nanni, T. (2000). Precipitation intensity trends in northern Italy. *International Journal of Climatology*, *20*(9), 1017-1031.

Changnon, S. A., Karl, T. R., & Knight, R. W. (1998). Comments on" Secular Trends of Precipitation Amount, Frequency, and Intensity in the United States"/reply. *Bulletin of the American Meteorological Society*, *79*(11), 2550.

Daly, C., Halbleib, M., Smith, J. I., Gibson, W. P., Doggett, M. K., Taylor, G. H., ... & Pasteris, P. P. (2008). Physiographically sensitive mapping of climatological temperature and precipitation across the conterminous United States. *International journal of climatology*, *28*(15), 2031-2064.

Dunbar, W. F., & May, G. S. (1995). *Michigan: A History of the Wolverine State*. Wm. B. Eerdmans Publishing.

Eichenlaub, V. L. (1970). Lake effect snowfall to the lee of the Great Lakes: Its role in Michigan. *Bulletin of the American Meteorological Society*, *51*(5), 403-412.

Ellis, A. W., & Johnson, J. J. (2004). Hydroclimatic analysis of snowfall trends associated with the North American Great Lakes. *Journal of Hydrometeorology*, *5*(3), 471-486.

"ENSO." *ENSO*, Https:// Iridl.ldeo.columbia.edu/Maproom/ENSO/Diagnostics.html, 18 Feb. 2018, 4;01, iridl.ldeo.columbia.edu/maproom/ENSO/Diagonostics.html.

Feng, S., & Hu, Q. (2007). Changes in winter snowfall/precipitation ratio in the contiguous United States. *Journal of Geophysical Research: Atmospheres*, *112*(D15).

Geography of Michigan. *In Wikipedia*. Retrieved April 9th, 2016 which can be searched in the link, https://en.wikipedia.org/wiki/Geography_of_Michigan

Ghanbari, R. N., Bravo, H. R., Magnuson, J. J., Hyzer, W. G., & Benson, B. J. (2009). Coherence between lake ice cover, local climate and teleconnections (Lake Mendota, Wisconsin). *Journal of Hydrology*, *374*(3), 282-293.

Gilbert, R. O. (1987). *Statistical methods for environmental pollution monitoring*. John Wiley & Sons.

Groisman, P. Y., Knight, R. W., & Heim Jr, R. R. (1993). Recent variations of snow cover and snowfall in North America and their relation to precipitation and temperature variations. *Journal of Climate*, *6*(7), 1327-1344.

Groisman, P. Y., & Easterling, D. R. (1994). Variability and trends of total precipitation and snowfall over the United States and Canada. *Journal of Climate*, *7*(1), 184-205.

Groisman, P. Y., Knight, R. W., & Karl, T. R. (2001). Heavy precipitation and high streamflow in the contiguous United States: Trends in the twentieth century. *Bulletin of the American Meteorological Society*, *82*(2), 219-246.

Gutzler, D. S., & Rosen, R. D. (1992). Interannual variability of wintertime snow cover across the Northern Hemisphere. *Journal of climate*, *5*(12), 1441-1447.

Hamed, K. H., & Rao, A. R. (1998). A modified Mann-Kendall trend test for autocorrelated data. *Journal of Hydrology*, *204*(1-4), 182-196.

Hanson, H. P., Hanson, C. S., & Yoo, B. H. (1992). Recent Great Lakes ice trends. *Bulletin of the American Meteorological Society*, *73*(5), 577-584.

Hartnett, J. J., Collins, J. M., Baxter, M. A., & Chambers, D. P. (2014). Spatiotemporal snowfall trends in central New York. *Journal of Applied Meteorology and Climatology*, *53*(12), 2685-2697.

Hurrell, J. W. (1995). Decadal trends in the North Atlantic Oscillation: regional temperatures and precipitation. *Science-AAAS-Weekly Paper Edition*, *269*(5224), 676-678. Karl, T. R.,

Hurrell, J. W., Kushnir, Y., Ottersen, G., & Visbeck, M. (2003). An overview of the North Atlantic oscillation. *The North Atlantic Oscillation: climatic significance and environmental impact*, 1-35.

Karl, T. R., Groisman, P. Y., Knight, R. W., & Heim Jr, R. R. (1993). Recent variations of snow cover and snowfall in North America and their relation to precipitation and temperature variations. *Journal of Climate*, *6*(7), 1327-1344.

Kelly, R. D. (1986). Mesoscale frequencies and seasonal snowfalls for different types of Lake Michigan snow storms. *Journal of climate and applied meteorology*, *25*(3), 308-312.

Kluver, D., & Leathers, D. (2015). Winter snowfall prediction in the United States using multiple discriminant analysis. *International Journal of Climatology*, *35*(8), 2003-2018.

Kousky, V. E., Kagano, M. T., & Cavalcanti, I. F. (1984). A review of the Southern Oscillation: oceanic-atmospheric circulation changes and related rainfall anomalies. *Tellus A*, *36*(5), 490-504

Krasting, J. P., Broccoli, A. J., Dixon, K. W., & Lanzante, J. R. (2013). Future changes in Northern Hemisphere snowfall. *Journal of Climate*, *26*(20), 7813-7828.

Kunkel, K. E., & Angel, J. R. (1999). Relationship of ENSO to snowfall and related cyclone activity in the contiguous United States. *Journal of Geophysical Research: Atmospheres*, *104*(D16), 19425-19434

Kunkel, K. E., Easterling, D. R., Hubbard, K., Redmond, K., Andsager, K., Kruk, M. C., & Spinar, M. L. (2005). Quality control of pre-1948 cooperative observer network data. *Journal of Atmospheric and Oceanic Technology*, *22*(11), 1691-1705.

Kunkel, K. E., Palecki, M., Ensor, L., Hubbard, K. G., Robinson, D., Redmond, K., & Easterling, D. (2009). Trends in twentieth-century US snowfall using a quality-controlled dataset. *Journal of Atmospheric and Oceanic Technology*, *26*(1), 33-44.

Kunkel, K. E., Ensor, L., Palecki, M., Easterling, D., Robinson, D., Hubbard, K. G., & Redmond, K. (2009). A new look at lake-effect snowfall trends in the Laurentian Great Lakes using a temporally homogeneous data set. *Journal of Great Lakes Research*, *35*(1), 23-29.

Kunkel, K. E., Karl, T. R., Brooks, H., Kossin, J., Lawrimore, J. H., Arndt, D., ... & Emanuel, K. (2013). Monitoring and understanding trends in extreme storms: State of knowledge. *Bulletin of the American Meteorological Society*, *94*(4), 499-514.

Leathers, D. J., & Ellis, A. W. (1996). Synoptic mechanisms associated with snowfall increases to the lee of Lakes Erie and Ontario. *International Journal of Climatology, 16*(10), 1117-1135.

Lehr, C., Ward, P. J., & Kummu, M. (2012). Impact of large-scale climatic oscillations on snowfall-related climate parameters in the world's major downhill ski areas: a review. *Mountain Research and Development*, *32*(4), 431-445.

McBean, E., & Motiee, H. (2008). Assessment of impact of climate change on water resources: a longterm analysis of the Great Lakes of North America. *Hydrology and Earth System Sciences Discussions*, *12*(1), 239-255.

McKinney, W. (2012). *Python for data analysis: Data wrangling with Pandas, NumPy, and IPython*. " O'Reilly Media, Inc.".

Monaghan, A. J., Bromwich, D. H., & Schneider, D. P. (2008). Twentieth century Antarctic air temperature and snowfall simulations by IPCC climate models. *Geophysical Research Letters*, *35*(7).

Ning, L., & Bradley, R. S. (2016). NAO and PNA influences on winter temperature and precipitation over the eastern United States in CMIP5 GCMs. *Climate dynamics*, *46*(3-4), 1257-1276.

Norton, D. C., & Bolsenga, S. J. (1993). Spatiotemporal trends in lake effect and continental snowfall in the Laurentian Great Lakes, 1951-1980. *Journal of Climate*, *6*(10), 1943-1956.

Notaro, M., Zarrin, A., Vavrus, S., & Bennington, V. (2013). Simulation of Heavy Lake-Effect Snowstorms across the Great Lakes Basin by RegCM4: Synoptic Climatology and Variability*, +. *Monthly Weather Review*, *141*(6), 1990-2014.

Patten, J. M., Smith, S. R., & O'Brien, J. J. (2003). Impacts of ENSO on snowfall frequencies in the United States. *Weather and forecasting*, *18*(5), 965-980.

Quinn, W. H. (1979). Monitoring and predicting short-term climate changes in the South Pacific Ocean. In *Proc. Int. Conf. on Mar. Sci. and Tech., Part* (Vol. 1, pp. 26-30).

Quinn, W. H., Neal, V. T., & Antunez de Mayolo, S. E. (1987). El Niño occurrences over the past four and a half centuries. *Journal of Geophysical Research: Oceans*, *92*(C13), 14449-14461.

Ramage, C. S. (1975). Preliminary Discussion of the Meteorology of the–El Niño. *Bulletin of the American Meteorological Society*, *56*(2), 234-242.

Rasmusson, E. M., & Carpenter, T. H. (1982). Variations in tropical sea surface temperature and surface wind fields associated with the Southern Oscillation/El Niño. *Monthly Weather Review*, *110*(5), 354-384.

Robertson, D. M., Wynne, R. H., & Chang, W. Y. (2000). Influence of El Niño on lake and river ice cover in the Northern Hemisphere from 1900 to 1995. *Internationale Vereinigung für theoretische und angewandte Limnologie: Verhandlungen*, *27*(5), 2784-2788.

Ropelewski, C. F., & Jones, P. D. (1987). An extension of the Tahiti–Darwin southern oscillation index. *Monthly Weather Review*, *115*(9), 2161-2165.

Schmidlin, T. W. (1993). Impacts of severe winter weather during December 1989 in the Lake Erie snowbelt. *Journal of climate*, *6*(4), 759-767.

Seager, R., Harnik, N., Robinson, W. A., Kushnir, Y., Ting, M., Huang, H. P., & Velez, J. (2005). Mechanisms of ENSO-forcing of hemi-spherically symmetric precipitation variability. *Quarterly Journal of the Royal Meteorological Society*, *131*(608), 1501-1527.

Seager, R., Kushnir, Y., Nakamura, J., Ting, M., & Naik, N. (2010). Northern Hemisphere winter snow anomalies: ENSO, NAO and the winter of 2009/10.*Geophysical research letters*, *37*(14).

Serreze, M. C., Clark, M. P., McGinnis, D. L., & Robinson, D. A. (1998). Characteristics of snowfall over the eastern half of the United States and relationships with principal modes of low-frequency atmospheric variability. *Journal of Climate*, *11*(2), 234-250.

Smith, S. R., & O'Brien, J. J. (2001). Regional snowfall distributions associated with ENSO: Implications for seasonal forecasting. *Bulletin of the American Meteorological Society*, *82*(6), 1179-1191.

Wang, J., Ikeda, M., Zhang, S., & Gerdes, R. (2005). Linking the northern hemisphere sea-ice reduction trend and the quasi-decadal arctic sea-ice oscillation. *Climate dynamics*, *24*(2-3), 115-130.

Wooster, W. S., & Guillén, O. (1974). Características de El niño en 1972.

Wright, D. M., Posselt, D. J., & Steiner, A. L. (2013). Sensitivity of lake-effect snowfall to lake ice cover and temperature in the Great Lakes region. *Monthly Weather Review*, *141*(2), 670-689.

Wyrtki, K. (1975). El Niño—the dynamic response of the equatorial Pacific Ocean to atmospheric forcing. *Journal of Physical Oceanography*, *5*(4), 572-584.