TREND REVERSAL IN LAKE MICHIGAN CONTRIBUTION TO SNOWFALL

BY

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THESIS

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ABSTRACT

One of the most notable ways the Laurentian Great Lakes impact the region's climate is by augmenting snowfall in downwind locations during autumn and winter months. Among many negative consequences, this surplus of snow can cause substantial property damage to homes and can escalate the number of traffic accident-related injuries and fatalities. The consensus among several previous studies is that lake-effect snowfall increased during the 20th Century in various locations in the Great Lakes region. The goal of the present study is to better understand variability and long-term trends in Lake Michigan's lake-contribution snowfall (LCS). LCS accounts for both lake-effect and lake-enhanced events. Additionally, this study updates findings from previous studies using snowfall observations found by a previous study to be appropriate for climate studies.

The present study demonstrates that considerable variability exists in 5-year periods of LCS east and south of Lake Michigan from 1920 to 2005. A general increase in LCS was found from the early 1920s to the 1950–1980 period at locations typically downwind of the lake. Thereafter, LCS decreased through the early 2000s indicating a distinct trend reversal not reported by earlier studies. The reasons for this reversal are unclear. However, LCS trend reversal is consistent with observed increasing minimum temperatures during winter months after the 1970s. LCS and minimum temperature trends are related via teleconnections to recent polarity transitions of the Arctic Oscillation and North Atlantic Oscillation.

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TABLE OF CONTENTS

CHAPTER 1: INTRODUCTION

The Laurentian Great Lakes are major contributors to regional snowfall through surface heat and moisture fluxes leading to the development of snow within convective liquid and ice clouds (Chang and Braham 1991, Niziol et al. 1995, Kristovich et al. 2003, Barthold and Kristovich 2011). Lake-effect processes can contribute to more than a doubling of snowfall in locations near and downwind of the lakes, relative to regional locations not influenced by the lakes (Braham and Dungey 1984, Kelly 1986, Norton and Bolsenga 1993). The increased snowfall elevates snow-removal costs, increases traffic accidents, reduces retail sales, inflicts severe property damage to homes, disrupts air travel, and raises the number of injuries and fatalities. However, the additional snowfall can benefit sectors of the local economy such as ski resorts, private snow-removal businesses, and winter-related product sales (Schmidlin 1993, Kunkel et al. 2002).

Several studies (Braham and Dungey 1984, Norton and Bolsenga 1993, Burnett et al. 2003, Ellis and Johnson 2005, Kunkel et al. 2009a) found that lake-effect snowfall increased in various locations in the Great Lakes region during the 20th Century. Figure 1 illustrates the direction of lake-effect trends determined by previous studies. Braham and Dungey (1984) found wintertime snowfall increased from the 1930s to the late 1970s within the Lake Michigan lake-effect snowbelt but remained nearly constant to the west of Lake Michigan and east of the snowbelt. Similarly, Norton and Bolsenga (1993) found that areas west of Lake Michigan experienced little trend between 1950 and 1980, but increases were noted for the central Great Lakes basin and the lake-effect snow region east of Lake Ontario. Burnett et al. (2003) noted similar patterns near Lake Ontario and pointed out the potential role of whole-lake thermal characteristics, including warmer surface water temperatures and decreased ice cover. In contrast, Grover and Sousounis (2002) found no change in lake-effect snowfall near the western Great Lakes and a possible decreasing trend farther east. However, their study does not represent season-total lake-contribution snowfall because their analysis focused on large-scale weather systems during autumn months, prior to the peak lake-effect snowfall season. More recently, Kunkel et al. (2009a) found an overall increase in snowfall within the Lake Michigan-Huron snowbelt that was approximately half the rate determined by previous studies. They evaluated trends using a data set of expert-assessed, quality-controlled, temporally homogeneous daily snowfall observations (Kunkel et al. 2009b) – the best quality data available for their study.

The present study investigates trends in contribution to local snowfall throughout the season, herein referred to as lake-contribution snowfall (LCS), due to the influence of Lake Michigan. This nomenclature emphasizes the inclusion of both lake-effect snow and lake enhancements of snowfall accompanying larger-scale events, such as mid-latitude cyclones. This study updates findings from previous studies using sites with quality-controlled, temporally homogeneous daily snowfall observations identified by Kunkel et al. (2009a, b). The goal of this study is to better understand trends and variability in Lake Michigan's contribution to snowfall.

CHAPTER 2: METHODOLOGY

2.1 Snowfall Observations

The present study uses quality-controlled, temporally-homogeneous, daily snowfall observations to determine long-term trends in lake contributions to snowfall. It is important to screen snowfall time series for inconsistencies and gaps which can affect long-term trends. Station moves, observer changes, measurement practice inconsistencies, and exposure changes are among many sources that affect the long-term continuity of a snowfall record (Kunkel et al. 2007).

Kunkel et al. (2009b) assessed the temporal homogeneity of daily snowfall observations from National Weather Service Cooperative Observer Program (COOP) stations in the contiguous United States. The original data assessed by Kunkel et al. (2009b) were provided and quality controlled by the National Climatic Data Center (NCDC). Sites were only considered for assessment if 10% or fewer days were missing from their time series, October through May 1930–2004. Observers may have intentionally not recorded a daily snowfall value of zero on a day when no snowfall occurred (Kunkel et al. 2007). Hence, daily snowfall observations left blank were replaced with zero values for months containing non-zero values under specific circumstances. A zero value insertion was performed by Kunkel et al. (2009b) if total precipitation was reported as zero or, if total precipitation was greater than zero, the minimum temperature was above 0°C. Seasonal data were compared with observer forms, *Climatologic Data* publications, or surrounding station data if seasonal snowfall exceeded ±5.0 standardized anomaly*, in which case any clerical errors found in the dataset were manually corrected.

* Standardized anomaly was calculated by normalizing the departure of seasonal snowfall from the time series mean by the standard deviation from the time series mean.

Stations receiving less than 12.5 cm average annual snowfall between the 1937–1938 and 2006–2007 snow seasons were not included in their assessment. Both the first 10 and last 10 snow seasons in each site's time series were required to have at least 5 valid snow seasons due to the sensitivity of linear least-squares trend analyses to the beginning and end of the time series.

Snowfall data, including the inserted zero values and meeting the above criteria, were assessed in Kunkel et al. (2009b) by a team of seven experts in snowfall observations. These experts sought to determine a subset of COOP sites with snowfall time series appropriate for long-term trend analysis. Each site's temporal homogeneity was subjectively and independently assessed. Subjective assessments were bolstered by objective change-point detection tests and Web-interface graphical tools. The results of the subjective screening techniques were considered alongside those of two objective screening algorithms provided by previous studies which consisted of several statistical tests and composite reference time series.

Sites which met the assessment criteria were separated into three categories by the expert team: temporally homogeneous, temporally inhomogeneous, and questionable (Kunkel et al. 2009b). Sites determined to have temporally homogeneous time series were considered appropriate for long-term trend analysis. Sites determined to have temporally inhomogeneous time series had several commonalities including: snowfall anomaly discontinuities related to documented station/observer changes; change points identified by the objective screen techniques; excessive missing data at the beginning or end of time series; and dissimilar trends in anomalies compared to nearby stations either during a continuous time series or across periods of missing data. Consequently, inhomogeneous sites were not recommended for use in long-term trend analyses. Sites determined to have questionable temporal homogeneity contained ambiguities in their time series but were suggested for usage at a user's discretion in areas where the availability of homogeneous data is nonexistent.

Figure 2 displays locations of the assessed sites in the Great Lakes region and their temporal homogeneity evaluations. Few sites in the region surrounding Lake Michigan were judged to have temporally homogeneous snowfall observations. The spatial distribution of sites is especially non-uniform in Michigan. Several homogeneous sites are clustered in the northern interior region of Lower Michigan. Contrarily, very few homogeneous sites are in the southern region of Lower Michigan and along the eastern Lake Michigan shoreline. Thus, the choices for sites appropriate for long-term study of lake contribution snowfall trends are quite limited.

2.2 Estimation of Lake-Contribution Snowfall

This study seeks to determine LCS for multiple locations in the Lake Michigan snowbelt in western Lower Michigan and northwestern Indiana (Figure 3). For a given location, LCS estimation is made by comparing the snowfall observed near the lakeshore with snowfall observed outside of the snowbelt, along an approximately east-west transect. Latitude variation in each transect was minimized in selecting sites to curtail its influences on non-lake-effect wintertime precipitation (Brooks 1915, Groisman and Easterling 1994, Changnon et al. 2006). Longitudinal variation among the selection of upwind, near-lake, and downwind sites was minimized due to the meridional orientation of Lake Michigan and its snowbelt region (Scott and Huff 1996). Two estimates of lake contribution were determined for each of the three snowbelt sites. First, LCS_u was determined by subtracting 5-year snowfall totals at upwind sites (1U, 2U, 3U in Figure 3) from corresponding snowbelt sites along the transects (1L, 2L, 3L, respectively). Likewise, LCS_d was determined as the difference between total 5-year snowfall amounts at snowbelt sites and corresponding downwind sites along the transects (1D, 2D, 3D). Both the upwind and downwind sites were located at least 80km from the lakeshore, outside of the lake-effect snowbelts as defined by Scott and Huff (1996).

Observations from eight of the sites were identified by Kunkel et al. (2009b) as being temporally homogeneous, the best quality data for the present study. A ninth site, Valparaiso, IN, (site 3L) was assessed by Kunkel et al. (2009b) as having questionable temporal homogeneity. Snowfall near the southern tip of Lake Michigan is quite sensitive to variations in the occurrence and intensity of north-south oriented lake-effect convective bands (e.g., Figure 21.3 in Kristovich 2009). The apparent lack of temporal homogeneity at the Valparaiso site may be a reflection of such variability (K. E. Kunkel 2010, personal communication).

It should be noted that for short periods, synoptic-scale snowbands can affect snowfall observations at a COOP site, thus making the calculated LCS incorrect. However, there is no evidence in the literature that any of the nine COOP sites used in this study would be affected by such snowbands more often than the other sites. Therefore, cyclone-related snowbands are thought to have little influence on the climatological analysis provided here.

In addition to expert assessments of temporal homogeneity provided by Kunkel et al. (2009b), the present study utilizes quality control (QC) assessments of the daily snowfall observations provided by their source, NCDC. NCDC assigned most daily observations a flag as an indication of its quality to provide users with supporting information about the reported values, including valid data elements (i.e., good-quality data). Table 1 summarizes the NCDC QC flags accompanying the daily snowfall observations from the DSI-3200, 3202 and 3205 datasets (http://www.ncdc.noaa.gov/doclib/index.php?choice=complete&searchstring=&submitted=1&submit_form=Search). Daily snowfall observations identified by NCDC as being invalid or missing were removed from the analysis. Remaining daily data were summed into monthly totals, and any months missing more than three days of data (~10%) were removed from the analysis data set. For analysis of lake contributions, it is essential to compare snowfall observations taken coincidentally at sites within each transect. Therefore, if monthly data were missing or removed at *any* of the three sites along a transect, data *from all three sites* were not used in calculations of multi-year snowfall totals. Five-year total snowfall was determined by summing monthly snow totals over five snow seasons. A snow season is defined as the period October through May, when nearly all lake-effect clouds are observed (Kristovich and Steve 1995, Rodriguez et al. 2007).

Removal of monthly snowfall observations could have large influences on calculated trends and variations in LCS, particularly if the removed months are during the peak of the lake-effect snow season. In the Lake Michigan region, lake-effect and lake-enhanced cloud and snow events are most common during December, January, and February (Norton and Bolsenga 1993, Kristovich and Steve 1995, Changnon et al. 2006, Rodriguez et al. 2007), referred to in this study as 'peak months'. In order to assess the potential impacts of the removal of peak months, the number of missing peak months for each 5-year period (Table 2) was compared to LCS estimates (Figure 4). Indeed, years with large numbers of missing peak months tended to have lower LCS values than those with few missing peak months. However, for years with less than about five missing peak months, no clear relationship with LCS was identifiable (particularly in Transects 1 and 3). Therefore, this study emphasized LCS estimates with fewer than five missing peak months. This finding is taken into account in the following discussions.

CHAPTER 3: RESULTS

Lake Michigan's contribution to snowfall was estimated using quality-controlled snowfall observations from nine COOP sites (Kunkel et al. 2009b) near the lake. The lake's contribution is defined as the surplus of snowfall at near-lake sites compared to sites outside of Lake Michigan's snowbelt (Figure 3, Scott and Huff 1996).

3.1 Variability and Trends in 20th Century Lake-Contribution Snowfall near Lake Michigan

Figure 5 shows time series of 5-year total LCS_u. The time series for each transect exhibits substantial temporal variability as well as multi-decadal trends. Although differences in timing exist, LCS_u tended to be relatively low during about 1930–1950, increased to a broad peak between about 1955–1985, and then decreased in more recent years at all transects. The broad peak during 1955–1985 also exhibited interesting shorter-term features. A period of high LCS_u values is evident approximately during 1955–1970 at all three transects, although the 5-year period with highest LCS_u varied among transects (local peak in 1965–1970 for Transects 1 and 2, 1960–1965 is slightly higher than 1965–1970 for Transect 3). Interestingly, after a period with lower LCS_u at all transects, relatively high values of LCS_u resumed after 1975. This is most prominent in Transect 1, where LCS_u was greater in 1975–1980 than its earlier local peak in 1965–1970. LCS_u exhibited a decreasing range from north to south, varying by about 620 cm, 325 cm, and 280 cm for Transects 1, 2, and 3, respectively.

Trends over the entire time series using 5-year periods with less than 5 missing peak months were determined for LCS_u (not shown). The linear trend for the entire time series for Transect 1 shows an approximate 2 cm yr^{-1} increase in LCS_u (66% significance), supporting the upward lake-effect snowfall trend reported in previous studies. LCS_u for Transect 3 shows no obvious increasing or decreasing linear trends over the entire time series. The overall LCS_u trend for Transect 2 is complicated by the large number of missing peak months at the end of the time series. During 1920–1980, Transect 2 shows an approximate 3 cm yr^{-1} (88% significance) increase in LCS_u, again supporting the upward lake-effect snowfall trend reported in previous studies.

Figure 6 shows time series of 5-year total LCS_d. Some differences with the time series of LCS_u can be seen; however, the overall patterns show considerable agreement. As before, LCS_d values increased from about 1930–1950 (with the exception of a high LCS_d value in 1930–1935 in Transect 3) to 1955–1985, and then decreased thereafter. A double-peak structure during 1955–1985 is evident in Transect 1, as it was for LCS_u, and to a lesser degree in Transect 2. Missing values in Transect 3 near that period may have obscured a secondary peak. Again, LCS_d exhibited a decreasing range from north to south, varying by about 520 cm, 400 cm, and 255 cm for Transect 1, 2, and 3, respectively. LCS_d exhibited less variability than LCS_u for all transects.

LCS_d long-term trends (not shown) show directional similarities with LCS_u for all three transects. The linear trend for the entire time series (not shown) for Transect 1, using 5-year periods with less than 5 missing peak months, shows an approximate 2 cm yr^{-1} increase in LCS_d (56% significance). The trend estimate of Transect 1 LCS_d supports the upward lake-effect snowfall trend reported in previous studies and agrees quite well with LCS_u trends in the present study. LCS_d for Transect 3 shows no obvious increasing or decreasing linear trends over the entire time series. As with LCS_u, the overall LCS_d trend for Transect 2 is complicated by several missing peak months at the end of the time series. During 1920–1980, Transect 2 shows an approximate 4 cm yr^{-1} (98% significance) increase in LCS_d, supporting the upward lake-effect snowfall trend reported in previous studies. Nevertheless, LCS_u and LCS_d during the 20th Century exhibited similar upward lake-contribution trends near the northern part of Lake Michigan and no trend near the southern part of the lake.

It should be noted that considerable differences were observed between LCS_u and LCS_d for individual 5-year time periods. The magnitude of differences average about 85 cm and range between about 5 cm – 230 cm. Approximately 20% of the magnitude of differences occurs between about 25 cm – 50 cm and another 18% between about 100 cm – 125 cm. Pearson's correlations between LCS_u and LCS_d for Transect 1, 2, and 3 inclusive of all 5-year periods are 0.83, 0.81, and 0.91, respectively, at about 100% significance. Thus, despite the differences between LCS_u and LCS_d totals for individual 5-year periods, the time series significantly agree with each other which is reflected in their coincident multi-decadal patterns.

3.2 Trend Reversal in Lake-Contribution Snowfall near Lake Michigan

Figures 5 and 6 provide strong evidence of a distinct trend reversal in LCS during the latter half of the 20th Century. For example, LCS_u increased from relatively low amounts during about 1930–1950 to a peak during about 1955–1985; some estimates suggest a doubling to tripling of LCS_u occurred between these periods. Thereafter, LCS_u decreased through 2005 signifying a distinct trend reversal. Excluding periods with ≥5 missing peak months, linear trends starting at the beginning of each time series through the 5-year period of peak LCS_u show increases of approximately 12 cm yr^{-1}, 5 cm yr^{-1}, and 3 cm yr^{-1} for Transects 1, 2, and 3, respectively. Linear trends developed independently starting at the Transect 1 LCS_u 1975–1980 peak and Transect 3 1960–1965 peak through 2005 show decreases of approximately -21 cm yr^{-1} and -3 cm yr^{-1}, respectively. The statistical significance of these trends is above the 99th percentile for Transects 1 and 2. Trends are not significant for Transect 3 (33rd and 68th percentiles for upward and downward trends, respectively). No post-reversal trends were determined for Transect 2 due to the large number of missing peak months for several 5-year periods at the end of the time series.

Linear trend values were determined independently for LCS_d pre- and post-reversal using the same peak-month criterion as LCS_u. Trends from the beginning of the record to LCS_d maxima for Transects 1, 2, and 3 show increases of approximately 9 cm yr^{-1}, 7 cm yr^{-1}, and 5 cm yr^{-1}, respectively. Trends starting at the 1960–1965 LCS_d peak periods through the end of the time series for Transects 1 and 3 show decreases of approximately -9 cm yr^{-1} and -3 cm yr^{-1}, respectively. As with LCS_u, post-peak downward trends were not given for Transect 2 due to missing snowfall data. Statistical significance of Transect 1's downward trend and Transect 2's upward trend is above the 99th percentile. Transect 1's upward trend (75th percentile) and Transect 3's upward and downward trends (70th and 85th percentiles, respectively) are non-significant.

There are no consistent trend magnitude differences between LCS_u and LCS_d. Both the upward and downward trends for Transect 1 LCS_d are notably less than those for LCS_u, likely due to the earlier and lesser 5-year total LCS_d peak. Upward trends for Transects 2 and 3 LCS_d are greater than LCS_u upward trends by approximately 2 cm yr^{-1}. The downward trends for Transect 3 LCS_d and LCS_u are estimated to be similar. Although pre-and post-reversal trend estimates for LCS can quantitatively vary, trend reversals evidently occurred at all locations near Lake Michigan during 1950–1980.

While the actual trend values are dependent on the specific chosen period of peak LCS, it is clear that locations farther north experienced greater long-term increases and decreases of local lake contribution and are perhaps more sensitive to changes in regional climate variables. Possible causes of LCS trends are discussed in the proceeding chapter.

CHAPTER 4: DISCUSSION

A distinct trend reversal in Lake Michigan's contribution to snowfall is evident in the latter half of the 20th Century. This reversal appears to conflict with the upward trends reported earlier by Braham and Dungey (1984), Norton and Bolsenga (1993), Burnett et al. (2003), Ellis and Johnson (2005), and Kunkel et al. (2009a). It is possible that this apparent contradiction is due to the length of records available. Because some previous studies (e.g., Braham and Dungey 1984, Norton and Bolsenga 1993) only included data up to the 1980s or 1990s, decreasing lake contribution trends would have been less evident. These studies may have found substantial long-term increases since the trend reversal occurred toward the end of their time series. Comparatively, Kunkel et al. (2009a) used a longer period of analysis and noted a smaller increasing trend in lake-effect snowfall on the leeside of Lake Michigan. This finding is consistent with that of the current study. Indeed, a visual examination of time series plots of wintertime snowfall in the Lake Michigan-Huron snowbelt region (Figs. 2 – 4 of Kunkel et al. 2009a) suggests that if linear trends were calculated starting in the 1960s, negative trends would have been evident through 2005.

4.1 Temperature and Lake-Contribution Snowfall

A full understanding of the reasons for the observed trend reversal is beyond the scope of this study. However, it is useful to seek confirmation of the long-term trends from an independent data source. It is well known that individual lake-effect events generally occur during cold-air outbreaks (Niziol 1987). Braham and Dungey (1984) found that for Lake Michigan seasonal average temperatures at locations typically upwind (west) of the lake are inversely related to season total snowfall typically downwind (south and east) of the lake. More complicated relationships between air temperature and snowfall were found for the eastern Great Lakes (Assel et al. 2003, Burnett et al. 2003). Therefore, temperature trends near Lake Michigan were examined to determine if they support the observed trends in LCS.

Five-year-average daily maximum, minimum, and average temperatures were calculated for peak LCS months (December, January, and February) at the same COOP sites utilized for the snowfall analysis, with one exception. Since temperatures were not observed at Wellston, MI, (site 1L in Figure 3) during the study period, those observed at Manistee, MI, were substituted. The Manistee COOP site, located about 28 km west-southwest of the Wellston site and about 5.5 km east of the Lake Michigan shoreline, is the closest COOP site to Wellston with daily temperature data and is well within the Lake Michigan snowbelt.

Average daily minimum temperatures at upwind sites exhibited an inverse relationship with LCS trends (Figure 7). Since scatter plots (not shown) suggest that a linear trend is suitable for describing the relationship between minimum temperature and LCS, Pearson's correlation coefficients and significance levels were calculated for the six non-lake-effect and three Lake Michigan snowbelt sites (Table 3). Table 3a shows significant negative correlations between minimum temperature at Marshfield, WI, (site 1U) and Transect 1 LCS_u and LCS_d. For Transects 2 and 3, correlations with upwind sites (2U and 3U) were also negative but not statistically significant (p-values >0.05) between upwind minimum temperature and both estimates of LCS. Lower correlation values are not surprising for Transects 2 and 3 because of the lack of data beyond 1980 (only 12 of 17 possible 5-year periods suitable for analysis are available in Transect 2) and less-frequent northerly wind conditions needed for lake-effect snowfall at Valparaiso, IN (site 3L). Table 3b shows that correlation coefficients between average minimum temperature at downwind sites and both LCS estimates were negative. However, the inverse relationships were not significant for any transects. Likewise, correlation coefficients using minimum air temperature at lake-effect snowbelt sites were negative (Table 3c). Correlations were significant for Transect 1, but not significant for Transects 2 and 3. Interestingly, the snowbelt sites exhibited the greatest correlation magnitudes between minimum temperature and LCS for Transects 1 and 3 while the downwind site exhibited the highest correlation for Transect 2. Reasons for minimum temperatures at snowbelt sites exhibiting the highest correlations with LCS are unknown.

Average daily maximum and average temperatures at upwind sites exhibited little relationship with LCS trends. The lack of a relationship may be expected because LCS generally occurs during the coldest periods, such as cold-air outbreaks. In addition, Kristovich and Spinar (2005) found a diurnal cycle in lake-effect precipitation with most snowfall during the morning hours, typically when daily minimum temperatures are observed.

Observed long-term trends in minimum air temperatures are generally consistent with opposite trends in LCS. There is a general decrease (increase) in minimum air temperatures (LCS) from the 1920s through the 1970s, and an overall increase (decrease) in minimum temperatures (LCS) thereafter. These temperature trends are consistent with those found by Braham and Dungey (1984) and Kunkel et al. (2009a). It should be noted, however, that shorter-term variations in minimum air temperatures are not always consistent with those for LCS, suggesting that other atmospheric processes also play important roles in LCS on these time scales.

4.2 Teleconnections

Previous studies have found that large-scale climate conditions in parts of North America are associated with large-scale atmospheric circulation fields over oceanic regions. The present study seeks to understand such teleconnections as one potential cause for the recently observed increasing minimum temperature trends and LCS trend reversal near Lake Michigan. Teleconnections refer to relationships between geopotential heights on an isobaric surface at widely separated geographic locations (Wallace and Gutzler 1981). The North Atlantic Oscillation (NAO), Arctic Oscillation (AO), and Pacific – North American (PNA) teleconnections are known to influence Eastern-US temperature and precipitation during winter months (Assel 1992, Serreze et al. 1997, Notaro et al. 2006, Archambault et al. 2008, Brown et al. 2010, Cohen and Jones 2011). Specific to the Great Lakes region, Assel (1992) found low correlations between 700 hPa geopotential heights at 4 locations (20°N 160°W; 45°N 165°W; 55°N 115°W; and 30°N 85°W) and regional monthly average snowfall and temperature. He also found that PNA was not related to regional lake-effect snow. Notaro et al. (2006) noted that for the Eastern Lakes, lake-effect snowfall is greatest during a positive PNA and negative NAO pattern.

The present study examined NAO, AO, and PNA relationships with minimum temperature and LCS near Lake Michigan. Previous studies (e.g., Cellitti et al. 2006, Notaro et al. 2006, and others) have chosen to examine either NAO or AO because the teleconnection patterns are very similar to each other. Despite their similarities, the present study examines both NAO and AO to determine if any differences in local scale interactions exist with LCS.

4.3 North Atlantic Oscillation

The North-Atlantic Oscillation (NAO) refers to geopotential height and thickness field regimes corresponding to the quasi-permanent sea-level pressure dipole and thermal advection patterns of the Azorean High and Icelandic Low in the North Atlantic (Rogers and van Loon 1979, Wallace and Gutzler 1981, Serreze et al. 1997). NAO phases are characterized by the strength of the pressure differences between the two pressure systems – a positive (negative) phase indicates a stronger (weaker) dipole with typically stronger (weaker) prevailing westerly winds in the North Atlantic (Wallace and Gutzler 1981, Cellitti et al. 2006). Long-term changes in NAO phases were documented by Ostermeier and Wallace (2003), who found a decrease in December–March NAO indices from the early 1920s through the late 1960s, followed thereafter to 2000 by increasing indices. The present study examines the relationships between LCS and minimum temperature trend reversals reported by the present study and the NAO trend reversal found by Ostermeier and Wallace (2003).

To further examine the teleconnection relationships between large-scale atmospheric circulations and average minimum temperatures observed near Lake Michigan, monthly average NAO Index data from the Climate Prediction Center (http://www.cpc.ncep.noaa.gov/products/precip/CWlink/pna/nao.shtml, cited 2012) for peak lake-effect months (December through February) during 1950–2005 were compared with corresponding monthly average minimum temperature for all three upwind COOP sites used in the LCS analysis. Monthly NAO index values were calculated by Barnston and Livezey (1987) using a Rotated Principal Component Analysis (RPCA) procedure. RPCA was applied to monthly standardized 500 hPa height anomalies north of 20°N (http://www.cpc.ncep.noaa.gov/data/teledoc/teleindcalc.shtml, cited 2012).

Figure 8 shows scatter plots of NAO and upwind average minimum temperature and LCS estimates. There appears to be little evidence in these plots that linear relationships are inappropriate. Table 4a shows that NAO exhibits a modest but significant positive correlation with monthly average minimum air temperature at upwind sites for all transects. Correlations are nearly equal for Marshfield, WI, (site 1U) and Morrison, IL, (site 3U) but somewhat surprisingly weaker for Richland Center, WI (site 2U). This may be due to fewer data available for Transect 2 (123 out of 168 possible months versus 135 for Transect 3 and 148 for Transect 1), especially during the 1990s, the warmest period of the time series. Temperature and NAO Index values were removed from analysis if LCS data were missing or removed. Also, it is possible that local effects on minimum temperature may have caused a correlation deviation from the other transects. Nevertheless, these data give strong evidence that minimum temperatures are directly related to NAO.

Because minimum temperature and LCS are inversely related, the direct relationship between NAO and minimum temperature implies that NAO should be negatively correlated with LCS. Indeed, the present study found weak negative correlations (Table 4a) between monthly NAO indices and monthly total LCS_u and LCS_d for all transects. Negative correlation values for Transect 1 LCS_u and LCS_d estimates were statistically significant. For Transect 2, NAO correlated significantly with LCS_d but not LCS_u. Negative correlations were not significant with Transect 3 LCS_d and LCS_u. Among transects, the correlations were strongest farther north and weakest farther south. This latitudinal relationship with NAO reflects the magnitude of LCS trends, which were greatest in magnitude farther north and smallest father south.

4.4 Arctic Oscillation

The Arctic Oscillation (AO) is the Northern Hemispheric counterpart of the NAO (Thompson and Wallace 2001). The AO refers to large-scale atmospheric mass imbalances between the Arctic and sub-Arctic regions north of 60°N latitude and the Northern Hemispheric mid-latitudes (45°N–60°N) which impart variations in the prevailing westerly winds, hemispheric thermal advection patterns, and geopotential height fields in the troposphere and lower stratosphere (Thompson et al. 2000). AO phases are characterized by the strength of the Northern Hemispheric pressure differences – a positive (negative) phase indicates stronger (weaker) hemispheric gradients with typically stronger (weaker) prevailing circumpolar westerly winds (Thompson and Wallace 2001). Long-term AO phase trends were documented by Ostermeier and Wallace (2003), who found a decrease in December–March AO indices from the early 1920s through the late 1960s followed thereafter to 2000 by increasing indices. Similarly, Thompson et al. (2000) found an increase in January–March AO indices during 1968–1997. Because the NAO is a subset of the AO, it is no coincidence to find their climatologic trends are similar to each other. The AO trend reversal is generally consistent with the LCS and minimum temperature trend reversals reported in the present study.

Monthly average AO Index data were provided by the Climate Prediction Center (http://www.cpc.ncep.noaa.gov/products/precip/CWlink/daily_ao_index/ao.shtml, cited 2012). AO indices for peak lake-effect months during 1950–2005 were correlated with corresponding monthly average minimum temperature for all three upwind COOP sites used in the LCS analysis and corresponding monthly total LCS_u and LCS_d for Transects 1–3. Monthly AO indices were determined by projecting the monthly mean 1000-hPa height anomalies onto the leading Empirical Orthogonal Function mode and normalized by the 1979–2000 monthly index standard deviation (http://www.cpc.ncep.noaa.gov/products/precip/CWlink/daily_ao_index/history/method.shtml, cited 2012).

Scatter plots (Figure 9) and correlations (Table 4b) of average AO Index with upwind average minimum temperature and LCS are nearly identical to those with NAO Index. AO exhibits a modest but significant positive correlation with monthly average minimum air temperature at upwind sites for all transects. AO Index and LCS were found to be negatively correlated for all transects. Negative correlations with LCS were only significant for Transect 1 and less significant for Transects 2 and 3. As seen with NAO, the correlations were strongest farther north and weakest farther south for LCS_u. AO correlations are notably lower than those for NAO, especially for Transect 2, and with exception of Transect 3 LCS_u.

4.5 Pacific–North American Oscillation

The Pacific–North American (PNA) Oscillation refers to atmospheric geopotential height anomaly patterns over the central and northern Pacific Ocean, western and eastern North America (Wallace and Gutzler 1981, Assel 1992, and Cellitti et al. 2006). Positive PNA phases are characterized by positive geopotential height anomalies over western Canada and negative anomalies over the central Pacific and eastern United States. The Aleutian Low is notably more intense during positive phases, and atmospheric flow has accentuated meridional character (Wallace and Gutzler 1981, Cellitti et al 2006). During negative PNA phases, positive height anomalies occur over the central Pacific and eastern United States and negative anomalies are found over western Canada. In addition, the Aleutian Low is weak, and atmospheric flow is relatively zonal (Wallace and Gutzler 1981). Long-term changes in PNA Index have been documented by Leathers and Palecki (1992). They found PNA to be generally negative during the late 1940s to the late 1950s; thereafter PNA consistently averaged positive indices were observed through the late 1980s. This shift in PNA indices suggests a change to more meridional flow starting in the 1960s.

The present study used PNA indices provided by the Climate Prediction Center (http://www.cpc.ncep.noaa.gov/products/precip/CWlink/pna/pna.shtml, cited 2012) for peak lake-effect months during 1950–2005. Monthly PNA index values were calculated by Barnston and Livezey (1987) using an RPCA procedure applied to monthly standardized 500 hPa height anomalies north of 20°N (http://www.cpc.ncep.noaa.gov/ data/teledoc/teleindcalc.shtml, cited 2012). PNA indices were compared with corresponding monthly average minimum temperature for all three upwind COOP sites used in the LCS analysis and corresponding monthly total LCS_u and LCS_d for Transects 1–3.

Figure 10 shows scatter plots of LCS versus PNA indices; again, linear relationships appear to be justifiable. Table 4c shows that PNA exhibits a weak but significant positive correlation with monthly average minimum air temperature at the upwind site for Transect 1 but not for Transects 2 and 3. The significant positive correlation for Transect 1 is somewhat surprisingly, since positive PNA phases are thought to be characterized by more meridional flow and subsequently colder temperatures in eastern North America, including the Great Lakes region (Wallace and Gutzler 1981, Assel 1992).

This result contrasts the findings of Assel (1992), whose methodology differs from that of the present study. Assel correlated 20 winter seasons of snowfall data during 1960–1979 from sites within all snowbelts of the Great Lakes region with 700 hPa height anomalies at each of the 4 locations for which PNA is calculated (see Section 4b). It is possible that the study period or local effects on 5-year average minimum temperature at upwind sites may have caused correlation deviations among transects and from the findings of Assel (1992).

The present study revealed weak positive correlations with PNA indices (Table 4c) for LCS_u and LCS_d for all transects. Positive correlation values for Transect 1 LCS_u estimates were significant but not for LCS_d. For Transects 2 and 3, PNA did not correlate significantly with either LCS_u or LCS_d. This latitudinal relationship with NAO may reflect the magnitude of LCS trends, which were greatest in magnitude farther north and smallest father south.

4.6 Implications of Observed Relationships between Scale Interactions and LCS Trends

Standing oscillations in planetary waves span a substantial range of time scales, from several days to a month or longer (Wallace and Gutzler 1981). Though mesoscale in nature, lake-effect snowband orientation, duration, and movement are largely determined by synoptic-scale airflow (Peace and Sykes 1966, Burrows 1990, Kristovich 2009). The occurrence of synoptic environments conducive for lake-effect snows (e.g. cold air outbreaks) can experience multi-decadal variability due to their teleconnections ties (e.g., with NAO). Ostermeier and Wallace (2003) found time series of average December–March AO and NAO indices decreased during 1920–1969 and increased thereafter to 2000. The AO and NAO trend reversals appear to have occurred during the late 1960s to early 1970s, consistent within the 1950–1980 LCS trend reversal and 1970s minimum temperature trend reversal periods reported in the present study.

Figure 11 illustrates two possible LCS outcomes through interactions with recent increases in N/AO indices found by Ostermeier and Wallace (2003). Observed increasing trends toward more positive N/AO phases since the late 1960s indicate intensified pressure gradients among the Arctic, North Atlantic Ocean, and North Pacific Ocean. Stronger pressure gradients yield stronger prevailing westerly winds encircling the polar region, and the coldest air is often trapped over the Arctic (Thompson and Wallace 2001). As a result, fewer cold-air outbreaks are likely to occur, and observations of warmer daily average minimum temperatures are likely in the Midwestern United States (Thompson and Wallace 2001, Cellitti et al. 2006). Fewer polar air masses traversing the Great Lakes during positive N/AO periods can reduce the number of cold frontal and air mass passages through the region (Notaro et al. 2006), leading to decreasing turbulent heat and moisture fluxes from Lake Michigan during these periods. Decreased fluxes, in turn, could lead to less LCS.

Contrarily, fewer cold-air outbreaks during typical positive N/AO phases can increase average surface air temperatures which diminish the percent coverage of ice on the Great Lakes, especially when positive N/AO phases are coupled with El Niño events (Assel 1992, Bai et al. 2012). As a result, more open lake water during winter months is exposed, allowing for greater heat and moisture fluxes to be available to fuel lake-effect storm events. This process can yield more LCS.

The present study found N/AO indices to be directly related to average minimum temperature and inversely related with LCS. This finding suggests that long-term Lake Michigan contribution to snowfall is more climatologically sensitive to air temperature than to lake ice extent and surface fluxes. However, this relationship may not hold for lakes farther north (e.g., Lake Superior) or shallower lakes (e.g., Lake Erie) where extensive ice cover is more common (Assel 2005).

4.7 Implications of Warming Arctic Air Masses and Lake-Contribution Snowfall Trends

It is possible that recent increases in observed average minimum temperatures in the western Great Lakes region are a manifestation of high-latitude climate change. Previous studies have shown that the Arctic region is experiencing warming at a faster rate than the global average (ACIA 2005, IPCC 2007). Consequently, surface temperatures associated with arctic air masses have become warmer (Hankes and Walsh 2011). Hankes and Walsh (2011) found extreme cold air masses (≤-46°C) originating in the North American sub-Arctic region of Alaska and northern Canada warmed during 1948–1997, occurred less frequently, and decreased in duration. Warming mechanisms in the arctic likely can be attributed to a combination of increased greenhouse gas concentrations, changes in water vapor, and possibly changes in heat and moisture fluxes from the mid-latitudes (Dai and Trenberth 1999, Hankes and Walsh 2011). These air masses are often impact the US Midwest and Great Lakes regions after being displaced southward from their source regions. It is possible the warming arctic air masses may be partially responsible for the recent observed warming of minimum temperatures near Lake Michigan.

Figure 12 illustrates processes by which warmer arctic air masses can interact with the Great Lakes to produce increases or decreases in LCS. Progressively warmer cold-air outbreaks can lead to increases in lake surface temperatures. The percent coverage of lake ice could diminish, exposing more open lake water during winter months. As a result, more heat and moisture fluxes can be available to fuel lake-effect storm events. This process could yield more LCS. Contrarily, warmer polar air masses traversing the Great Lakes can reduce the temperature differences between the lake surface and overriding air, reducing the atmospheric instability necessary for lake-effect storm events. Likewise, heat and moisture fluxes from the lake could be reduced, thus yielding less LCS. The indirect relationship between average minimum temperatures and LCS determined in the present study bolsters the notion that the latter process dominances near Lake Michigan.

4.8 Future work

Continuations of this study are strongly suggested. First, it would be important to investigate the possibility of LCS trend reversal in other locations within the Great Lakes region. The current methodology used to determine LCS for Lake Michigan presented in the present study should be modified for use with the other lake's snowbelt regions. Second, event-scale analysis using quality-controlled temporally-homogeneous snowfall observations is essential to the investigation of lake-effect storm characteristics. Daily temporal resolution is much closer to the temporal scale of individual lake-effect events allowing for a more detailed assessment of long-term lake-effect precipitation trends. Analysis should explore pure lake-effect events spanning several decades and examine trends in not only LCS but also lake-contribution precipitation and snow-water equivalence. Additional investigation of the relationships between LCS and teleconnections is encouraged, including the timing of cold-air outbreak events to teleconnection patterns which may provide insight into long-term synoptic variability impacting lake-effect precipitation trends.

CHAPTER 5: CONCLUSIONS

Cool-season total snowfall is substantially augmented in locations downwind of each of the Laurentian Great Lakes. The region endures many negative consequences caused by the surplus snow including substantial property damage and increased numbers of traffic accident-related injuries and fatalities. The consensus among previous studies is that lake-effect snowfall increased by varying degrees during the 20th Century. The present study investigates variability in Lake Michigan's contribution to snowfall embedded within long-term trends and updates findings from previous studies using a new quality-controlled snowfall observation dataset.

A reversal in Lake Michigan's LCS is evident during 1920–2005. A general increase in LCS was observed from the early 1920s to peak values in the early 1950s to early 1980s. LCS decreased thereafter through the early 2000s indicating a distinct reversal of trends not reported by earlier studies. Because some previous studies only included data up to the 1980s or 1990s, recent decreasing lake contribution trends would have been less evident. The LCS trend reversal appears to have occurred near the southern part of Lake Michigan before it occurred farther north. Trend magnitudes before and after the reversal increase northward. This latitudinal dependency suggests sensitivity of LCS to spatially-variable climatic conditions, such as temperature.

Average air temperature has been shown by previous studies to be inversely related to total snowfall. The present study notes the best correlation between LCS and minimum temperature. The LCS trend reversal is consistent with an opposite reversal in trends of increased minimum temperatures, which decreased until about 1950 and then increased after

1980. The northward propagation of LCS trend reversal supports the notion of recent regional wintertime warming.

Large-scale atmospheric circulation patterns have been shown by previous studies to influence temperature and precipitation in the Great Lakes Region. Recent phase transitions in the Arctic Oscillation (AO) and North Atlantic Oscillation (NAO) support previous research results indicating a relationship between AO and NAO indices and air temperature. The present study finds LCS trend reversal near Lake Michigan can be partially explained reversals in AO and NAO indices.

Continuations of the present study are strongly suggested. LCS trends near the other Great Lakes using temporally homogeneous daily snowfall observations should be investigated for exhibiting possible trend reversals. Observed trends in lake-effect storms must be related to changes in increased event frequency, intensity, or both. Relationships between LCS and large-scale atmospheric circulations, such as AO and NAO indices, indicate an important linkage between climatic variations in these two scales of atmospheric motions. Event-scale observational and reanalysis studies of lake-effect storms (e.g., changes in event intensity and/or frequency) are necessary to improve understanding of the physical linkages between LCS and large-scale circulation changes. Season duration and precipitation-type changes should be considered in long-term event-scale analyses.

TABLES

Removed	QC Flag 1	Description
	A	Accumulated amount since last measurement.
	B	Accumulated amount includes estimated values (since last measurement).
	E	Estimated. See Table "G" in DSI-3200 documentation (i.e., QC Flag 2 portion of the table below) for estimating method.
	J	Value has been manually validated.
✓	M	For fixed length records only. Flag1 is "M" if the data value is missing. In this case, the sign of the meteorological value is assigned "-" and the value of the meteorological element is assigned "99999".
	S	Included in a subsequent value. (data value = "00000" OR "99999")
	T	Trace (data value = 00000 for a trace).
	(	NCDC expert system edited value, not validated.
	)	NCDC expert system approved edited value.
	(Blank)	Flag not needed.

Removed	QC Flag 2	Description
	0	Valid data element.
	1	Valid data element (from "unknown" source, pre-1982).
✓	2	Invalid data element (subsequent value replaces original value).
✓	3	Invalid data element (no replacement value follows).
	4*	Validity unknown (not checked). *Not included in 9/30/2007 version of DSI-3200 documentation, not included in Kunkel et al. (2009b) or present study datasets.
	5	Original non-numeric data value has been replaced by its deciphered numeric value.
	6	Data element passed through Midwestern Climate Center QC.
	7	Value in MCCDP verifies, estimated value in DSI-3200 accepted as replacement (Wisconsin only).
	8	Estimated value from Michigan quality control (Michigan only).
	9	Value shifted by a day.

Table 1: (Adapted from NCDC Data Documentation for DSI-3200) Additional quality-control (QC) information concerning daily snowfall observations accompany the NCDC datasets used for the present study. Flags from the Sept. 30, 2007, documentation were used – currently only the Jul. 27, 2009, version is available online. The center column displays two separate QC codes, QC Flag 1 and QC Flag 2. In the data files, the two QC flags are written as adjacent characters. The right column gives the description of each character. The left column indicates which data were removed from the present study based on NCDC's QC assessment. Table 1 is continued on the next page.

Removed	QC Flag 2	Description
	A	Substituted TOBS for TMAX or TMIN.
	B	Time shifted value.
	C	Precipitation estimated from snowfall.
	D	Transposed digits.
	E	Changed units.
	F	Adjusted TMAX or TMIN by a multiple of + or -10 degrees.
	G	Changed algebraic sign.
	H	Moved decimal point.
	I	Rescaling other than F, G, or H.
	J	Subjectively derived value.
	K	Extracted from an accumulated value.
	L	Switched TMAX and/or TMIN.
	M	Switched TOBS with TMAX or TMIN.
	N	Substitution of "3 nearest station mean".
	O	Switched snow and precipitation data value.
	P	Added snowfall to snow depth.
	Q	Switched snowfall and snow depth.
	R	Precipitation not reported; estimated as "0".
	S	Manually edited value (could be derived by any of the procedures noted by Flags A-R).
✓	T	Failed NCDC internal consistency check.
✓	U	Failed NCDC aerial consistency check (beginning Oct. 1992).
	V*	Replacement value based on TempVal QC process (beginning Feb. 2006). *Not included in 9/30/2007 version of DSI-3200 documentation, not included in Kunkel et al. (2009b) or present study datasets.

Table 1 (cont.)

5-Year Periods	Transect 1	Transect 2	Transect 3
1920–1925	**8**	3	No data
1925–1930	**5**		No data
1930–1935	1		2
1935–1940	1		
1940–1945	**8**		
1945–1950	3	1	3
1950–1955	2		**8**
1955–1960			**6**
1960–1965		4	
1965–1970	3	1	3
1970–1975	1		4
1975–1980	1	2	3
1980–1985	2	**5**	2
1985–1990	4	**6**	3
1990–1995	2	**11**	
1995–2000	4	**8**	
2000–2005		**6**	2

Table 2: This table displays the number of missing peak lake-contribution months (December, January, and February) during each 5-year period for Transect 1–3, north to south respectively. The maximum possible number of missing peak months is 15. The bold font indicates ≥5 missing peak months from each period. Periods with zero missing peak months have been left blank to emphasize periods with missing peak months. No analyses were performed during the 1920s for Transect 3 due to a lack of data at Hoytville, OH.

a. Average minimum air temperature at upwind sites

	LCS_u		LCS_d	
	r	p-value	r	p-value
Transect 1 (1U)	-0.6597	0.0103	-0.6817	0.0073
Transect 2 (2U)	-0.4641	0.1286	-0.1906	0.5530
Transect 3 (3U)	-0.0696	0.8214	-0.2606	0.3897

b. Average minimum air temperature at downwind sites

	LCS_u		LCS_d	
	r	p-value	r	p-value
Transect 1 (1D)	-0.3867	0.1720	-0.4983	0.0697
Transect 2 (2D)	-0.5055	0.0936	-0.2844	0.3703
Transect 3 (3D)	-0.2281	0.4535	-0.3562	0.2322

c. Average minimum air temperature at lake-effect snowbelt sites

	LCS_u		LCS_d	
	r	p-value	r	p-value
Transect 1 (1L)	-0.7561	0.0018	-0.8426	0.0002
Transect 2 (2L)	-0.4082	0.1877	-0.0830	0.7976
Transect 3 (3L)	-0.2351	0.4393	-0.4522	0.1208

Table 3: Pearson's correlation ('r') and p-values are shown for 5-year December–February average minimum temperature at (a) upwind sites, (b) downwind sites, and (c) lake-effect snowbelt sites corresponding to 5-year total LCS_u and LCS_d for Transects 1–3. Only 5-year periods of LCS with <5 missing peak months were used in the analysis.

a. NAO Index

	LCS_u		LCS_d		T_{min} (upwind)	
	r	p-value	r	p-value	r	p-value
Transect 1	-0.1946	0.0178	-0.2292	0.0051	0.3101	0.0001
Transect 2	-0.1568	0.0832	-0.2201	0.0144	0.1958	0.0300
Transect 3	-0.0638	0.4626	-0.1500	0.0825	0.3215	0.0001

b. AO Index

	LCS_u		LCS_d		T_{min} (upwind)	
	r	p-value	r	p-value	r	p-value
Transect 1	-0.1594	0.0530	-0.1708	0.0379	0.3131	0.0001
Transect 2	-0.0993	0.2746	-0.0970	0.2859	0.1989	0.0274
Transect 3	-0.0793	0.3608	-0.1292	0.1353	0.3066	0.0003

c. PNA Index

	LCS_u		LCS_d		T_{min} (upwind)	
	r	p-value	r	p-value	r	p-value
Transect 1	0.1867	0.0231	0.1370	0.0969	0.1646	0.0456
Transect 2	0.1215	0.1806	0.0572	0.5297	0.1099	0.2261
Transect 3	0.1419	0.1008	0.0168	0.8469	-0.0244	0.7787

Table 4: Pearson's correlation ('r') and p-values are shown for monthly average (a) North Atlantic Oscillation (NAO) Index, (b) Arctic Oscillation (AO) Index, and (c) Pacific – North American (PNA) Index corresponding to monthly total LCS_u, LCS_d, and monthly average minimum temperatures at upwind sites for Transects 1–3 during peak lake-effect months.

FIGURES

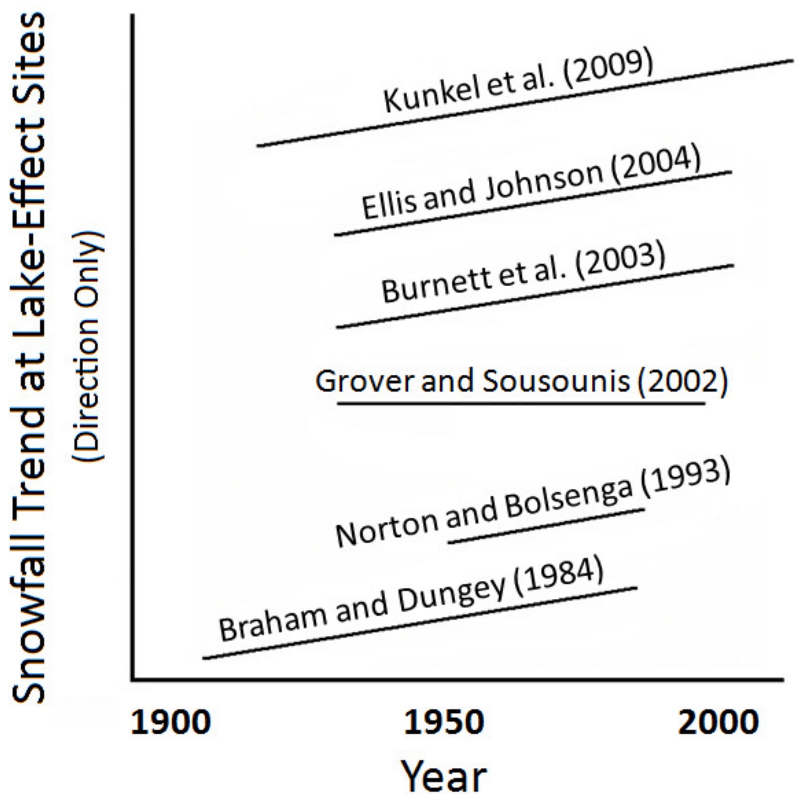

Figure 1: Adapted from Kristovich (2009), this figure summarizes the direction (not magnitude) of 20th Century lake-effect snowfall trends in the Laurentian Great Lakes region found by previous studies. Braham and Dungey (1984) exclusively focused on total snowfall trends near Lake Michigan whereas Burnett et al. (2003) examined lake-effect snowfall near Lakes Erie and Ontario. Norton and Bolsenga (1993) and Kunkel et al. (2009a) looked at total snowfall trends near all Great Lakes separately, including Lake Michigan. Ellis and Johnson (2004) examined snowfall trends at sites near the western lakes but placed emphasis on eastern lakes. Grover and Sousounis (2002) took a synoptic approach to look at lake-effect trends for the Great Lakes region but used a single site near Lake Michigan – Grand Rapids, MI.

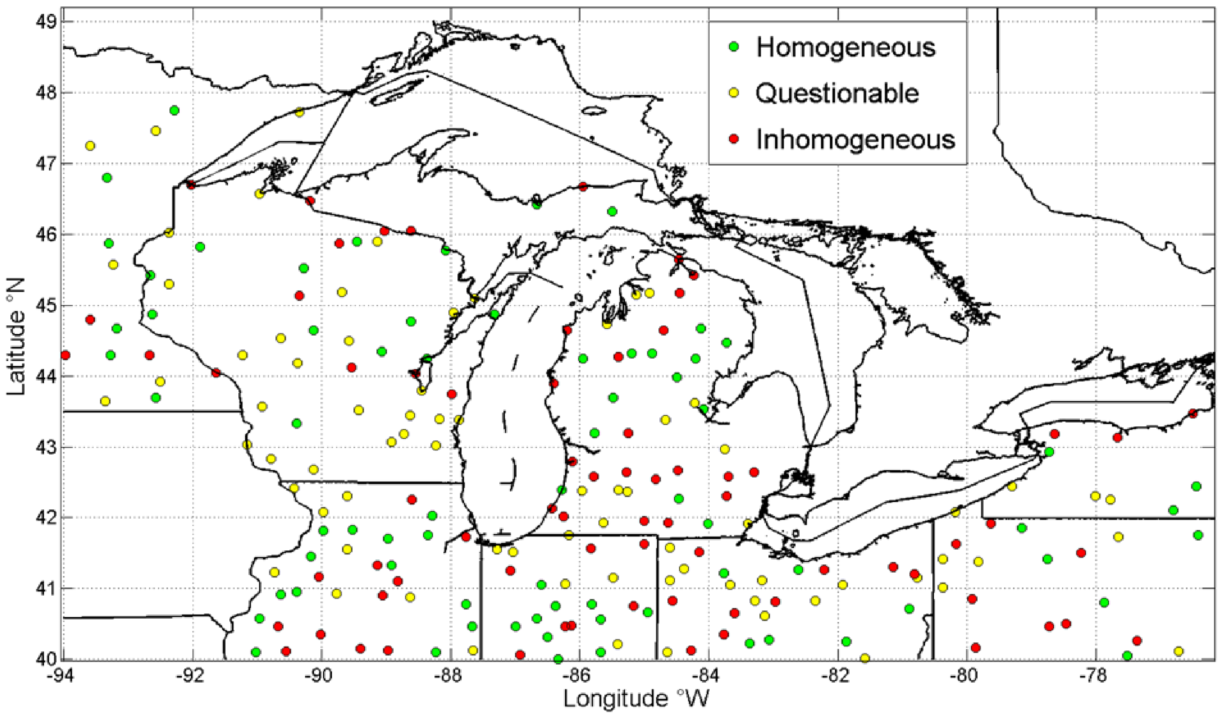

Figure 2: This map displays COOP sites in the Great Lakes region which met criteria set by Kunkel et al. (2009b) for expert assessment of temporal homogeneity. Each dot represents a COOP site, and its temporal homogeneity assessment is represented by a color. Green indicates a site with temporally homogeneous time series, red indicates inhomogeneous time series, and yellow indicates a questionable time series.

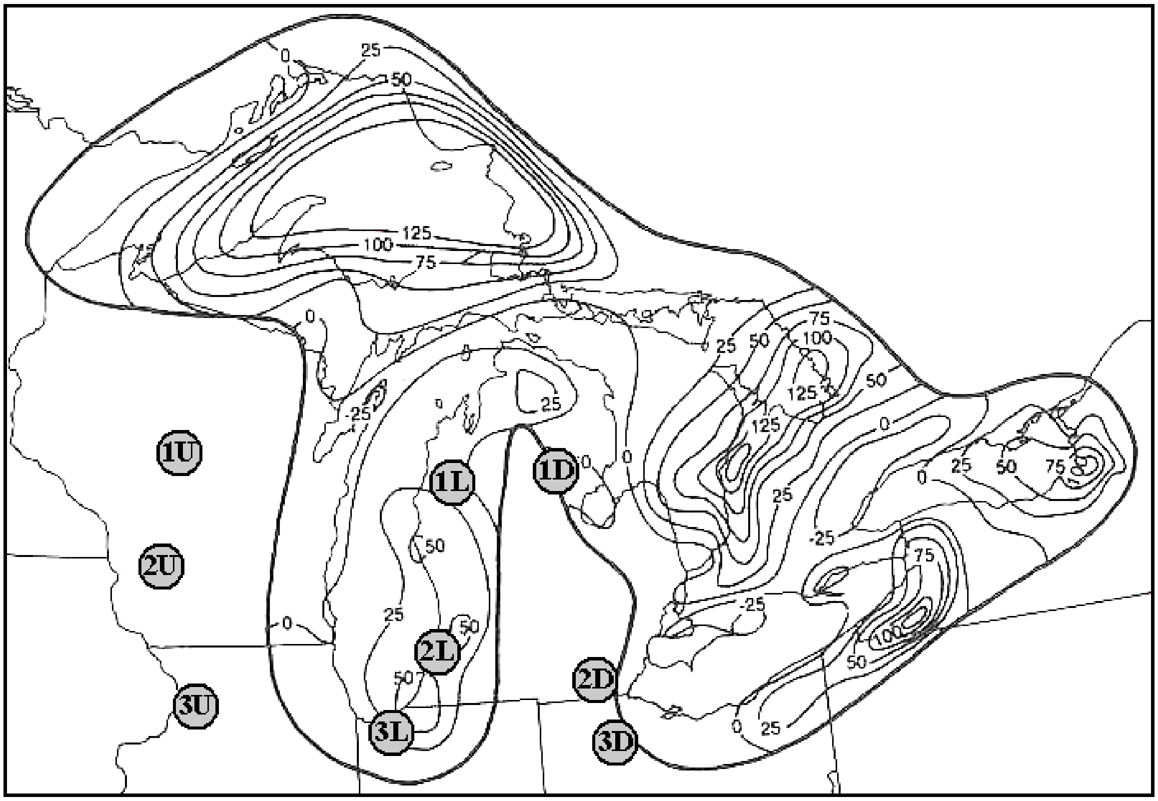

Figure 3: Adapted from Scott and Huff (1996), the thin contours indicate the climatic amount of snowfall in millimeters added by the presence of the Laurentian Great Lakes. The bold contour is the 80km boundary used by Scott and Huff to represent the extent of the lakes' meteorological influence on the region. Superimposed on this map are the sites chosen for the present study indicated by shaded dots. Numbers represent each transect, labeled 1 – 3 from north to south. Letters indicate whether the site is upwind (labeled 'U'), near-lake ('L'), or far downwind ('D'). Sites used in this study are Marshfield, WI (1U); Wellston, MI (1L); West Branch, MI (1D); Richland Center, WI (2U); South Haven, MI (2L); Adrian, MI (2D); Morrison, IL (3U); Valparaiso, IN (3L); and Hoytville, OH (3D).

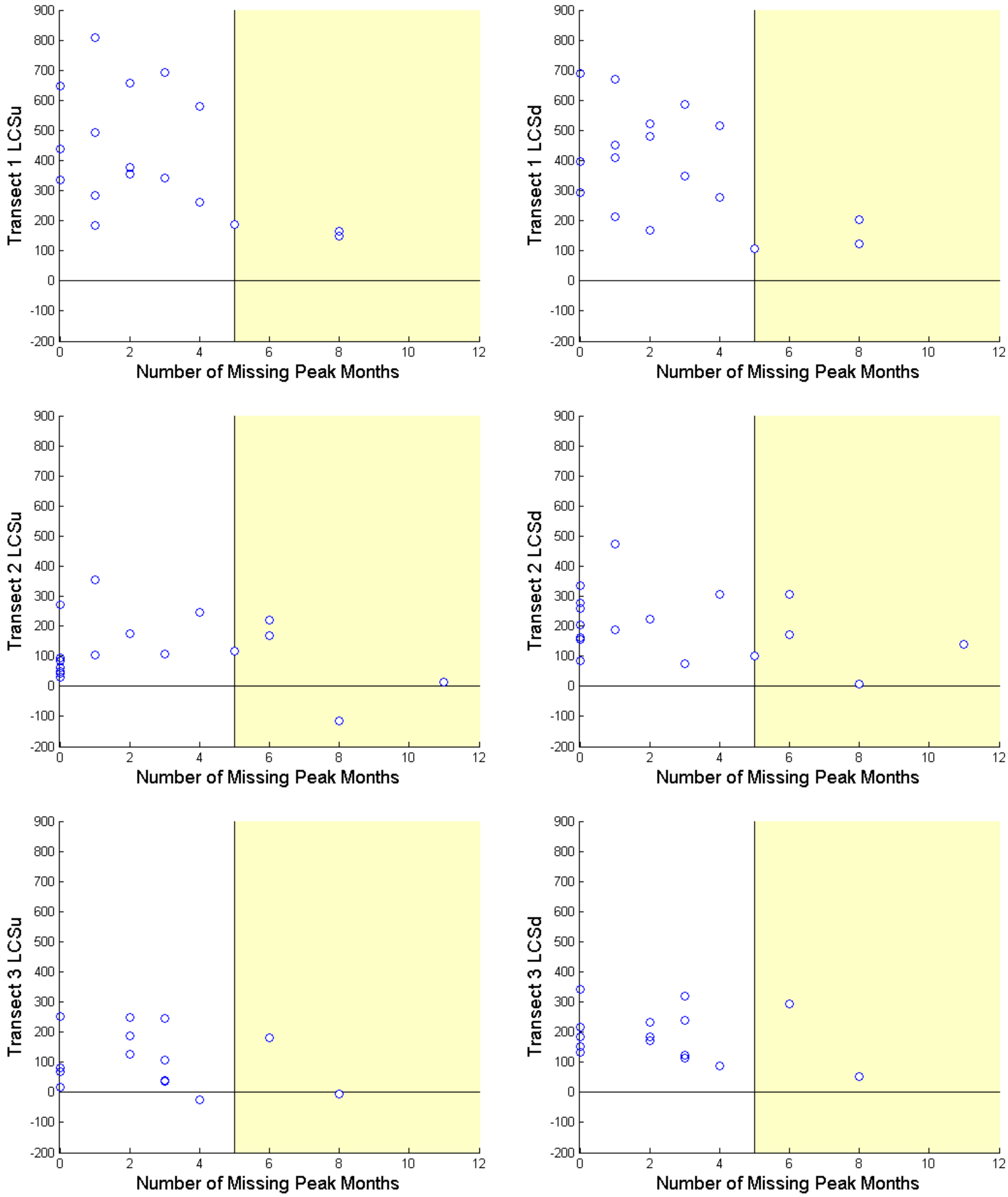

Figure 4: Scatter plots show lake-contribution estimates (LCS_u and LCS_d in cm) versus the number of missing peak lake-effect months. Regions of ≥5 missing peak months are highlighted. Transects 1–3 are displayed top to bottom. LCS_u is displayed in the left column and LCS_d in the right column.

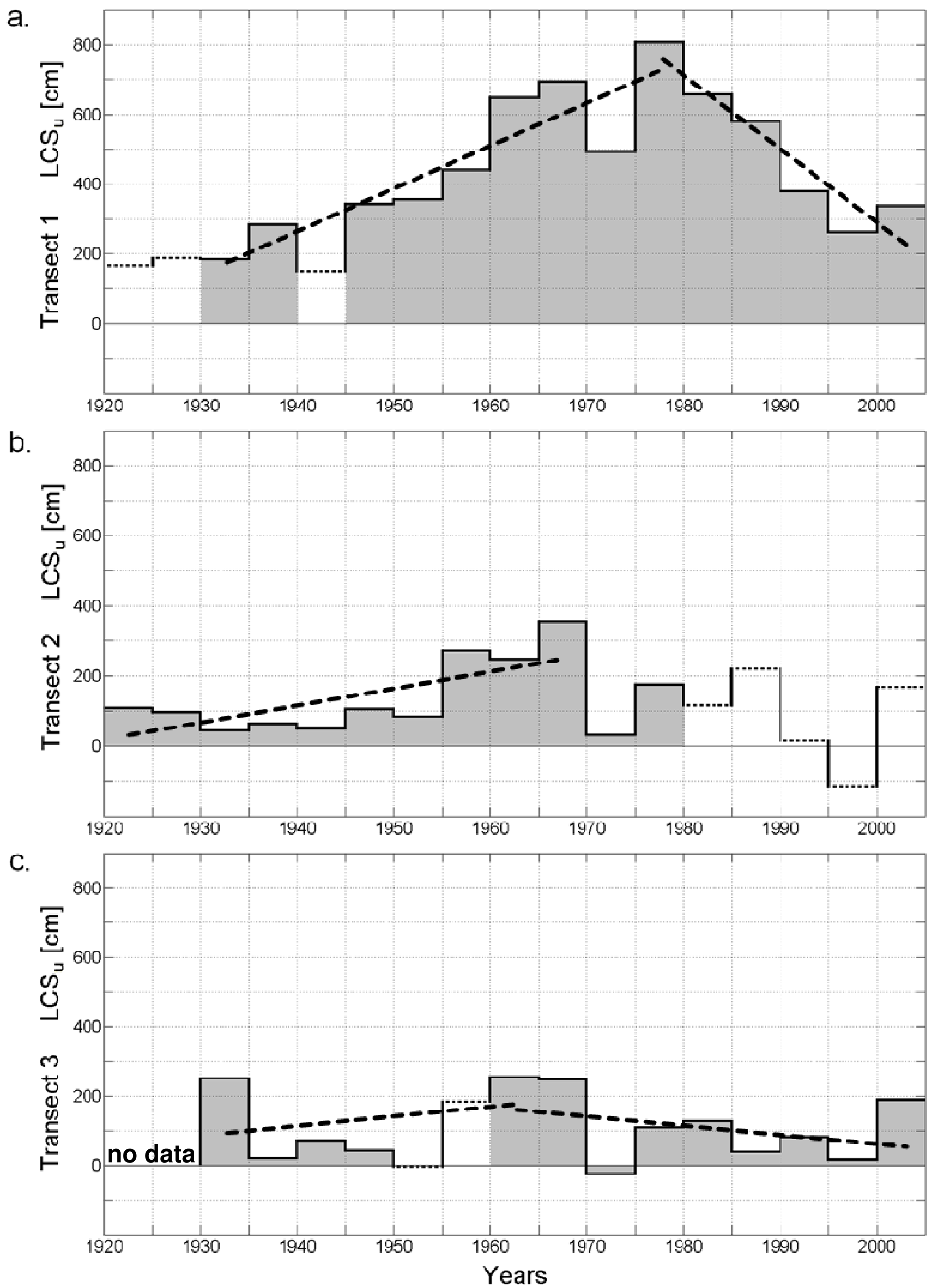

Figure 5: Time-series bar graphs show estimates of 5-year total lake-contribution snowfall (LCS_u) determined by subtracting the total snowfall at each lake-effect site from the total snowfall at their corresponding upwind site for all three transects across Lake Michigan. The graphs are aligned north to south, (a) to (c). Solid contours with shading indicate LCS estimates with <5 missing peak lake-effect months, and dotted contours without shading indicate LCS estimates with ≥5 missing peak months. See Table 2 for the number of missing peak lake-effect months for each 5-year period. Dashed lines indicate LCS trends via linear regression. Only the periods with <5 missing peak months were included in the trend calculations.

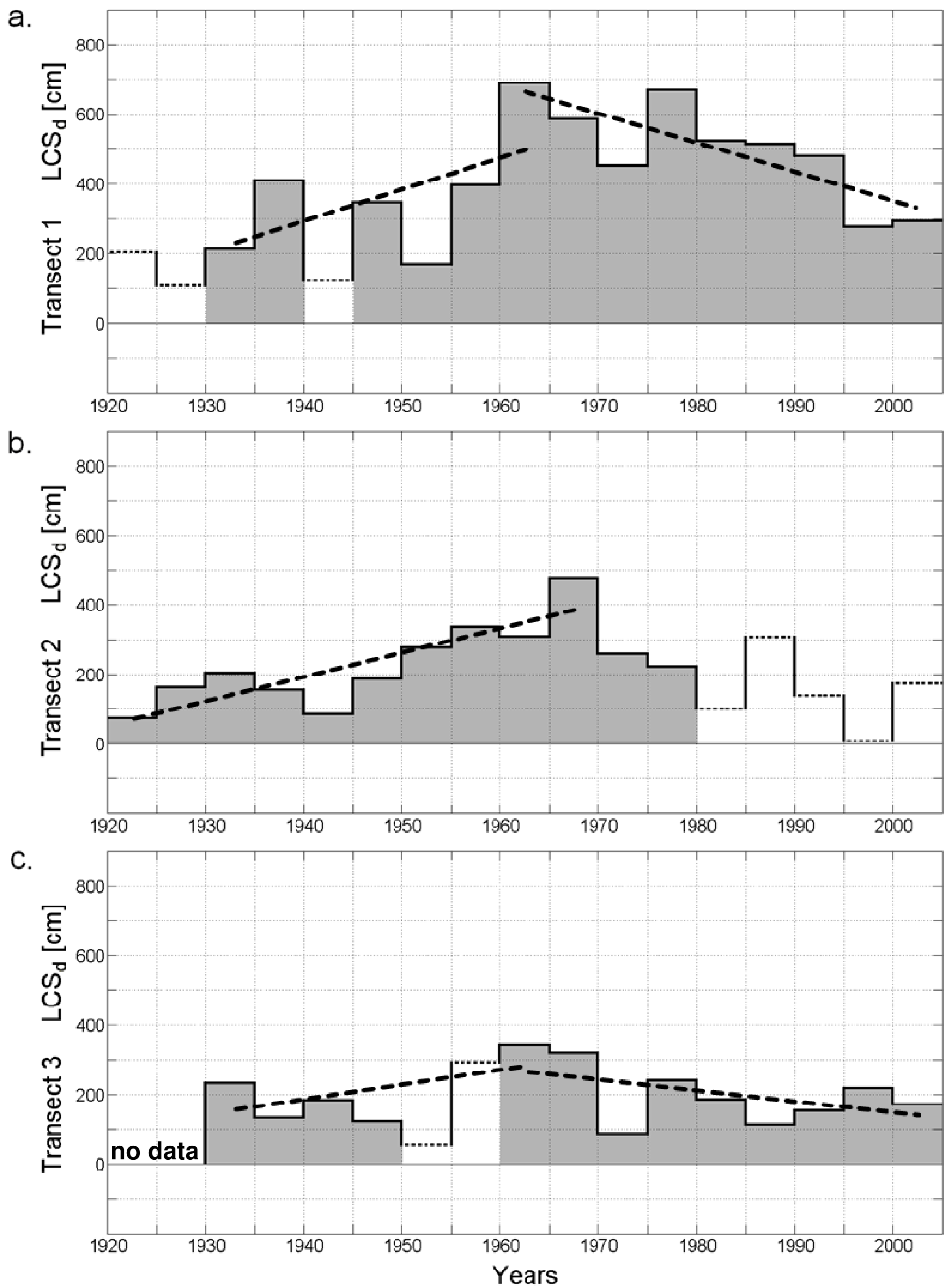

Figure 6: Time series are similar to Figure 5 except showing estimates of 5-year total lake-contribution snowfall (LCS_d) determined by subtracting the total snowfall at each lake-effect site from the total snowfall at their corresponding downwind site for all three transects across Lake Michigan.

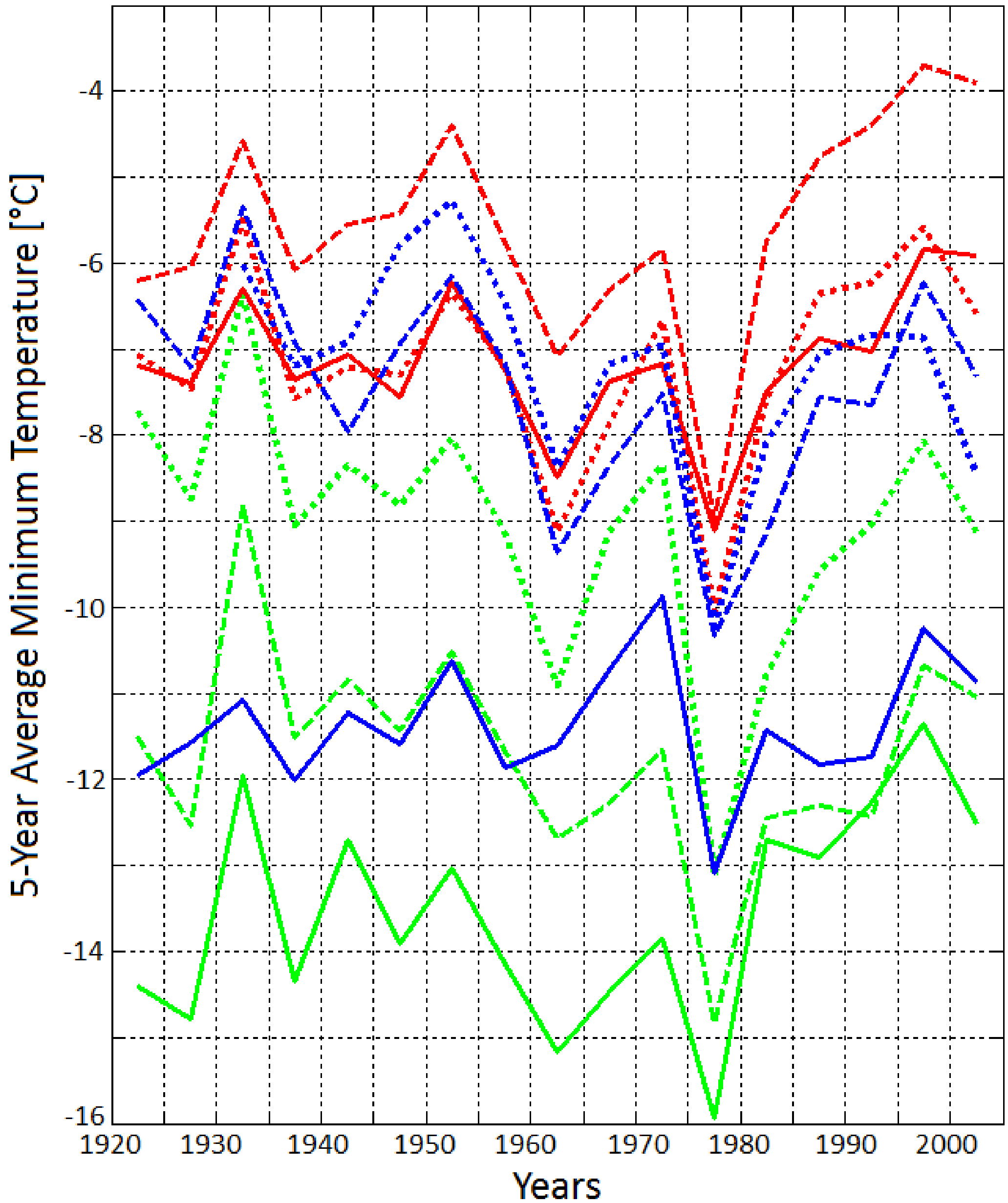

Figure 7: This time series shows the 5-year average daily minimum temperatures for the nine COOP sites provided in Figure 3 with one exception. No data were available for Wellston, MI (1L) and were subsequently replaced with data from Manistee, MI. Transects 1, 2, and 3 are represented by solid, dashed, and dotted lines, respectively. Near-lake, upwind, and downwind sites are represented by red, green, and blue lines, respectively.

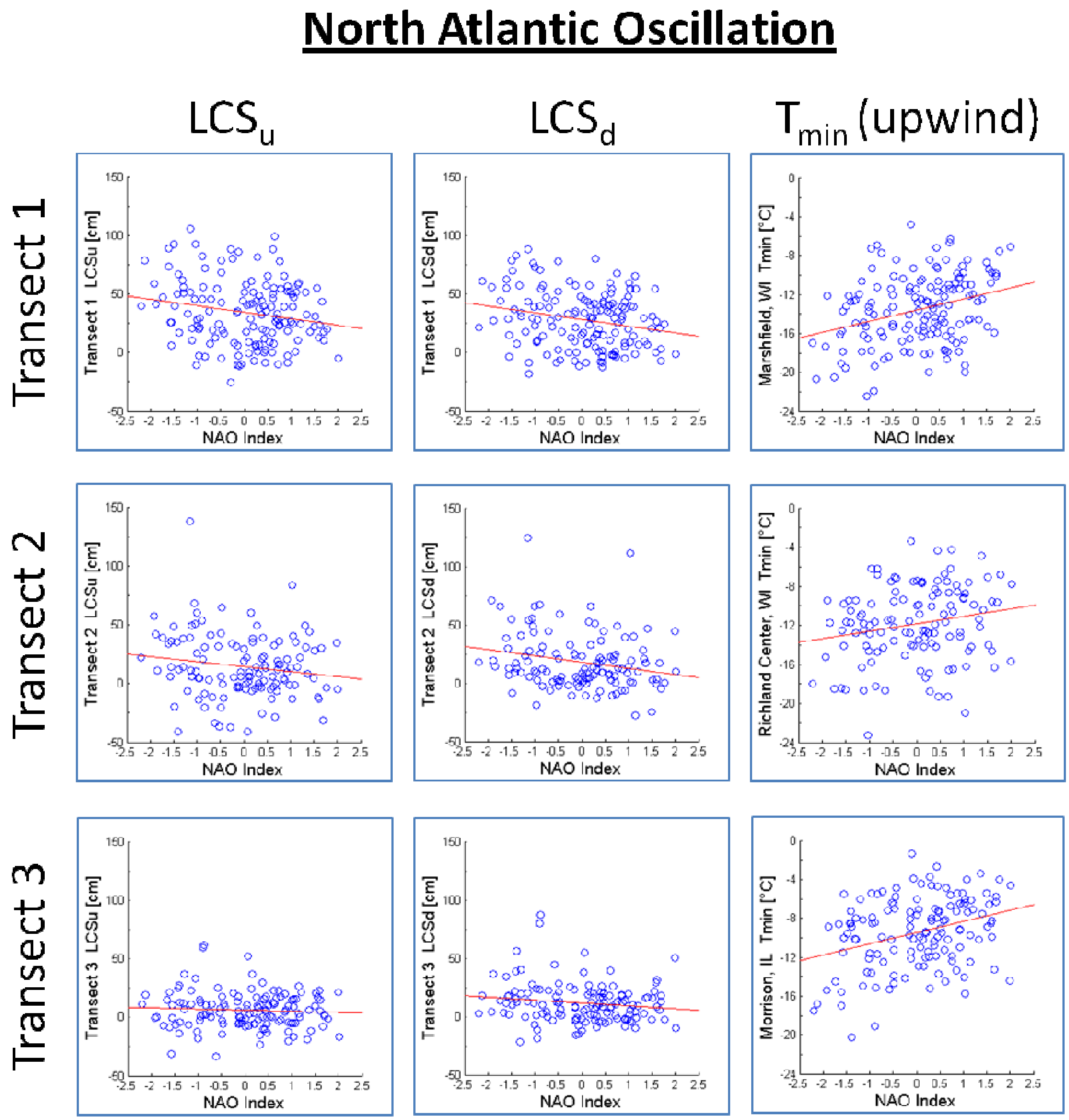

Figure 8: Scatter plots show relationships during peak lake-effect months between monthly average North Atlantic Oscillation (NAO) Index and monthly total LCS_u, LCS_d, and monthly average minimum temperature (columns) for upwind sites for all transects (rows). Linear least-squares lines are also displayed. Pearson's correlation coefficients and p-values are shown in Table 4a.

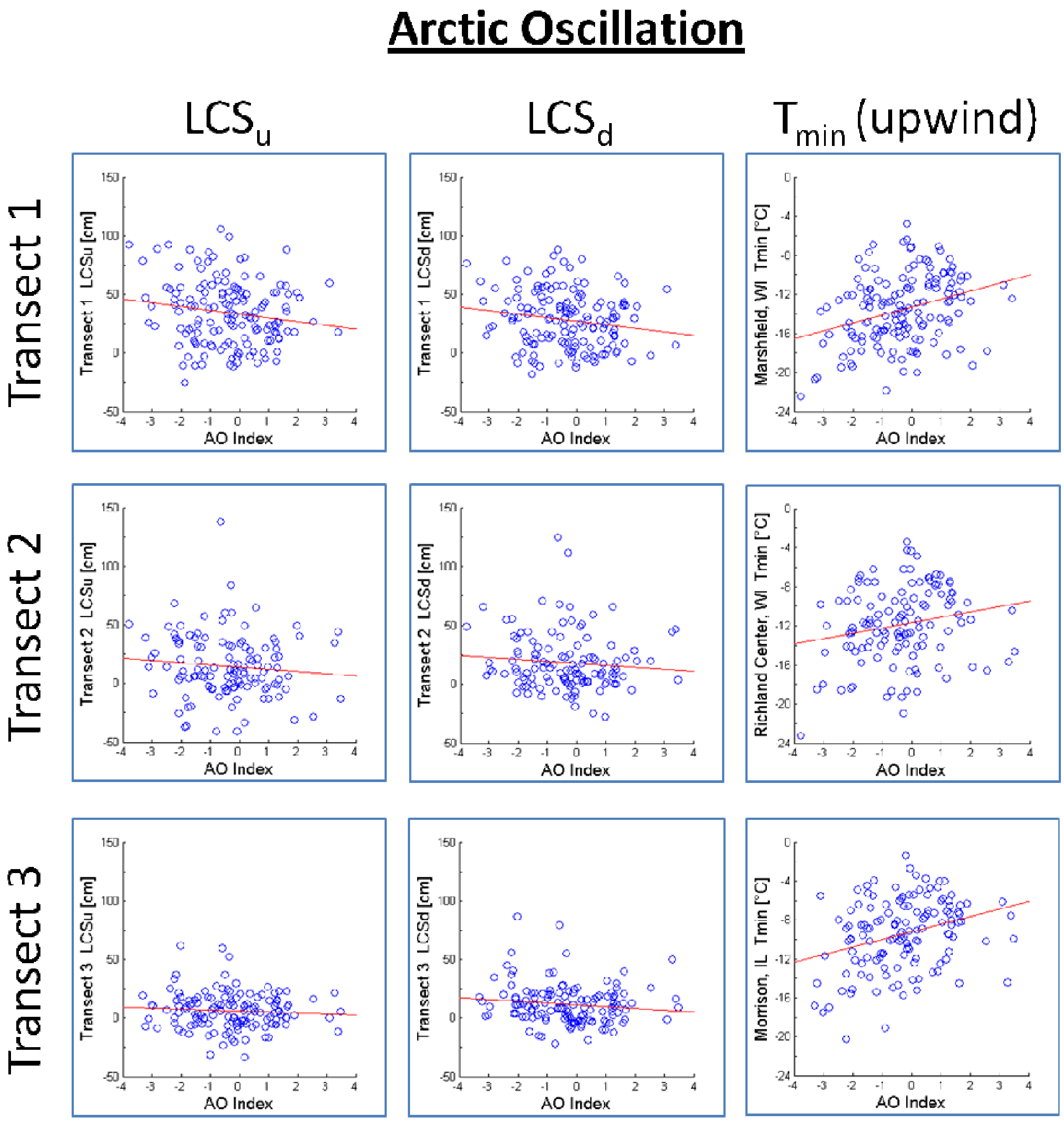

Figure 9: Scatter plots have the same configuration as Figure 8 with the exception of showing relationships with the Arctic Oscillation (AO) Index. Pearson's correlation coefficients and p-values are displayed in Table 4b.

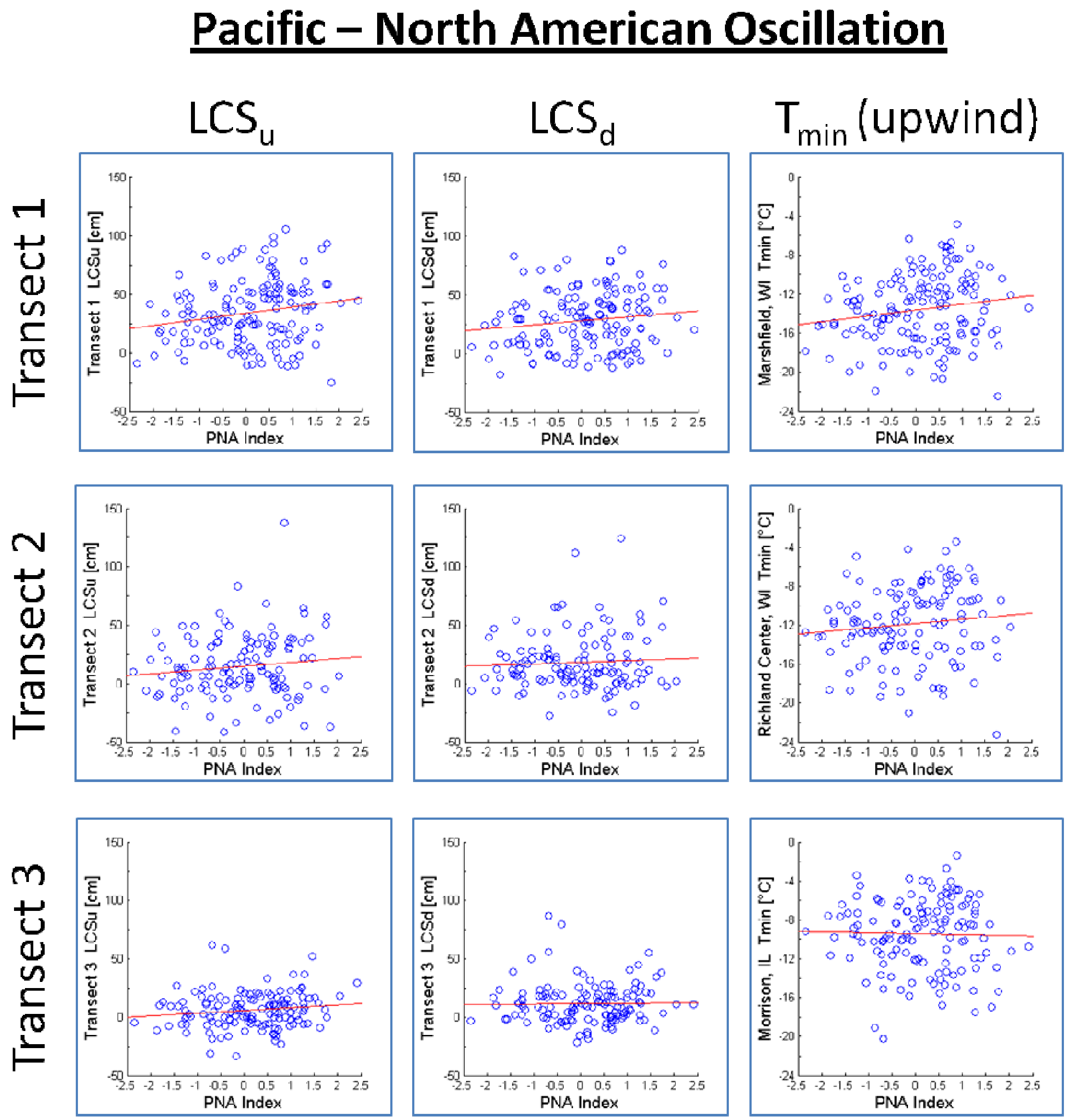

Figure 10: Scatter plots have the same configuration as Figure 8 with the exception of showing relationships with the Pacific – North American (PNA) Index. Pearson's correlation coefficients and p-values are displayed in Table 4c.

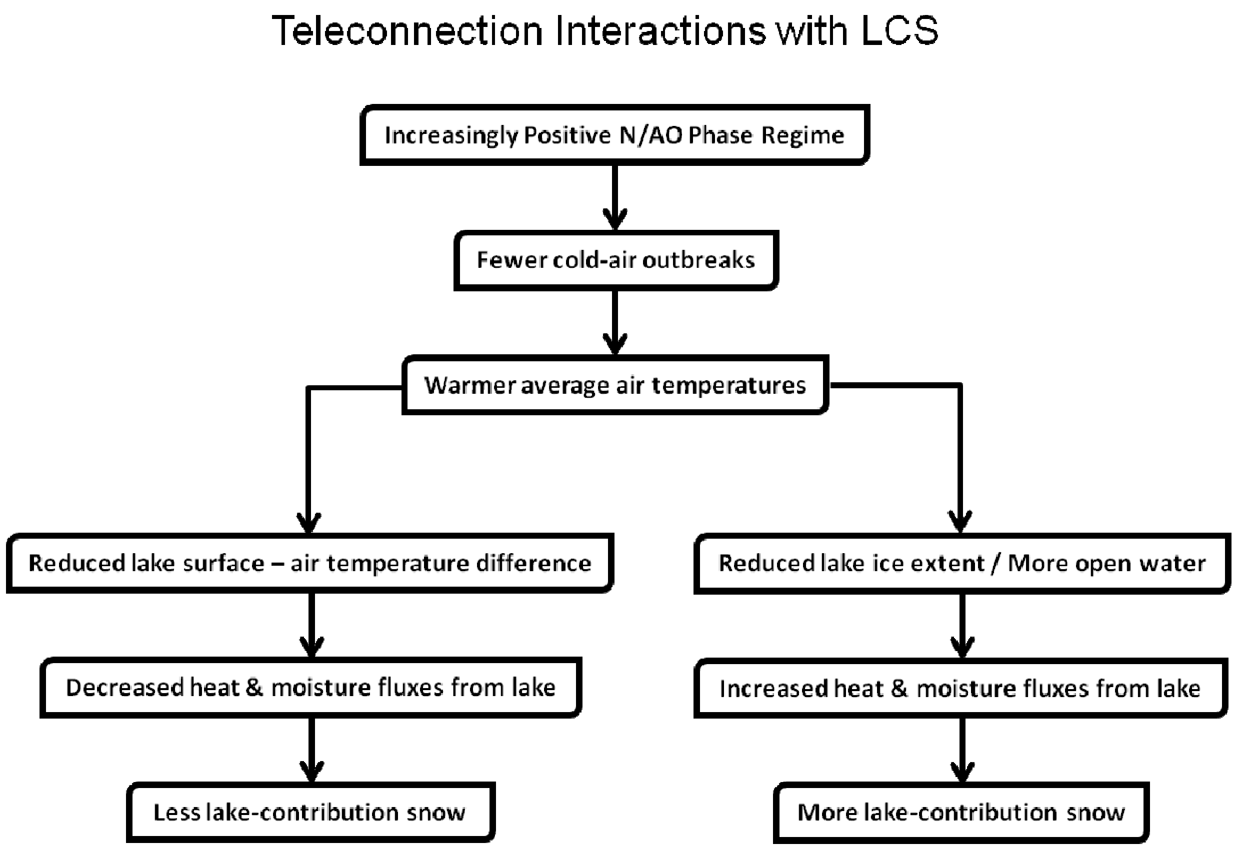

Figure 11: This schematic illustrates climate change scenarios pertaining to teleconnection interactions with LCS. The focus is on increasingly positive N/AO index values based on the findings of Ostermeier and Wallace (2003).

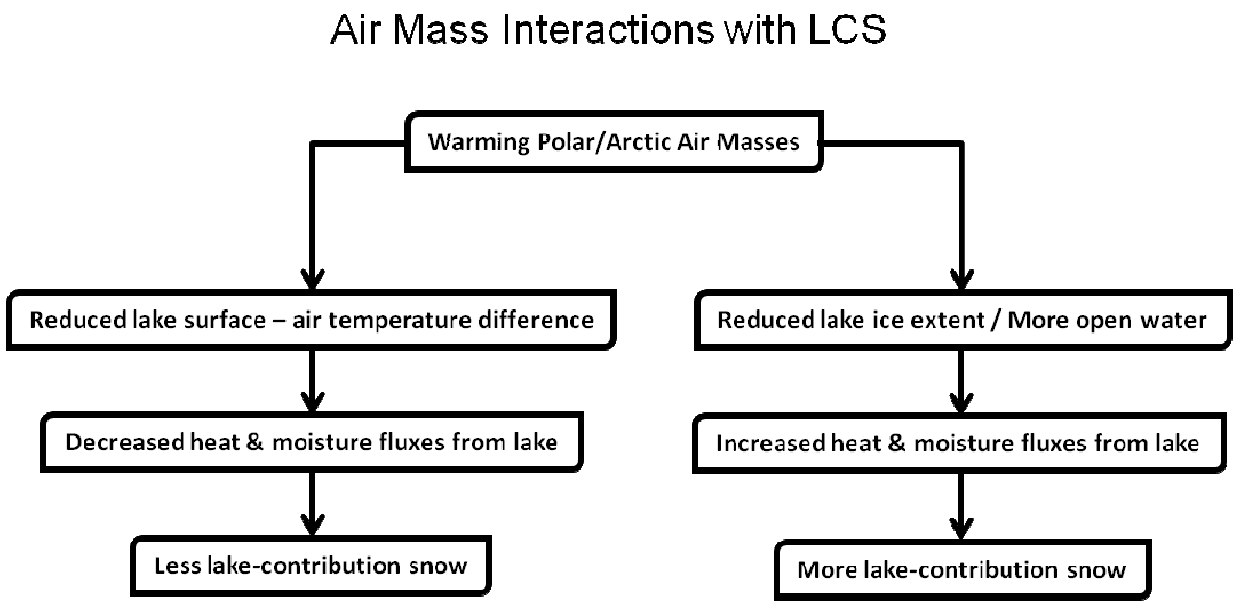

Figure 12: This schematic illustrates climate change scenarios pertaining to arctic air mass interactions with LCS. Warming polar and arctic air mass temperatures may act to either increase or decrease LCS.

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