Atmospheric teleconnection patterns associated with severe and mild ice cover on the Great Lakes, 1963–2011
Xuezhi Bai and Jia Wang

ABSTRACT
Atmospheric teleconnection circulation patterns associated with severe and mild ice cover over the Great Lakes are investigated using the composite analysis of lake ice data and National Center of Environmental Prediction (NCEP) reanalysis data for the period 1963–2011. The teleconnection pattern associated with the severe ice cover is the combination of a negative North Atlantic Oscillation (NAO) or Arctic Oscillation (AO) and negative phase of Pacific/North America (PNA) pattern, while the pattern associated with the mild ice cover is the combination of a positive PNA (or an El Niño) and a positive phase of the NAO/AO. These two extreme ice conditions are associated with the North American ridge–trough variations. The intensified ridge–trough system produces a strong northwest-to-southeast tilted ridge and trough and increases the anomalous northwesterly wind, advecting cold, dry Arctic air to the Great Lakes. The weakened ridge–trough system produces a flattened ridge and trough, and promotes a climatological westerly wind, advecting warm, dry air from western North America to the Great Lakes. Although ice cover for all the individual lakes responds roughly linearly and symmetrically to both phases of the NAO/AO, and roughly nonlinearly and asymmetrically to El Niño and La Niña events, the overall ice cover response to individual NAO/AO or Niño3.4 index is not statistically significant. The combined NAO/AO and Niño3.4 indices can be used to reliably project severe ice cover during the simultaneous −NAO/AO and La Niña events, and mild ice cover during the simultaneous +NAO/AO and El Niño events.

Key words | Arctic Oscillation, atmospheric teleconnection, El Niño–Southern Oscillation, Great Lakes, ice cover, North Atlantic Oscillation

INTRODUCTION
The impacts of the El Niño–Southern Oscillation (ENSO) and the North Atlantic Oscillation (NAO)/Arctic Oscillation (AO) on Great Lakes ice cover were previously investigated. Assel & Rodionov (1998) show that ice cover tends to be below average during El Niño events, but association between La Niña events and cold winters (above average ice cover) in the Great Lakes Basin is much weaker and less stable. Rodionov & Assel (2000, 2003) found that the relationship between ENSO and severity of winters in the Great Lakes is highly nonlinear. Strong El Niño events are associated with warm weather in the Great Lakes region, and the stronger the event, the milder the winter. The Pacific Decadal Oscillation (PDO) is also found to modulate the effect of the ENSO on the Great Lakes Winter Severity Index (WSI) (Rodionov & Assel 2003). WSI is defined as the temperature for Duluth, MN, Sault Ste. Marie, MI, Detroit, MI, and Buffalo, NY, averaged over November through February (Quinn et al. 1978). The correlation between ENSO and WSI is weak (−0.13) during the cold phase of PDO and strong (0.70) during the warm PDO phase. During the warm phase of PDO without a strong ENSO, winters are colder. This occurred in the late 1970s and early 1980s and was responsible for a high ice cover regime during those years. Assel & Rodionov (1998) found that the negative mode of the NAO appears to be associated with above-average ice cover on the Great Lakes.
Great Lakes. Great Lakes ice cover tends to be below average with a positive NAO mode.

The AO was defined by Thompson & Wallace (1998) as the leading empirical orthogonal function (EOF) mode of wintertime sea level pressure (SLP) anomalies over the extratropical northern hemisphere. The AO is the primary mode of wintertime variability over the extratropical northern hemisphere on timescales ranging from intraseasonal to interdecadal. The AO incorporates many of the features of the associated, more localized NAO (Hurrell 1996; Hurrell & van Loon 1997), but its larger horizontal scale and higher degree of zonal symmetry render it more like a surface signature of the polar vortex aloft. The temporal correlation between the AO and NAO is about 0.84 (Wang & Ikeda 2000). The AO accounts for a substantially larger fraction of the variance of northern hemisphere surface air temperature (SAT) than the NAO. Hodges (2000) showed that, in the positive phase of AO, lower-than-normal atmospheric pressure over the Arctic induces strong westerly winds in the upper atmosphere at northern latitudes, which keeps cold Arctic air to the north, leading to a warmer winter in much of the USA east of the Rocky Mountains and in central Canada. In the negative phase of AO, higher-than-normal SLP over the Arctic induces weaker westerly winds in the upper atmosphere, which allows cold Arctic air to reach more southerly latitudes, resulting in a colder winter in the USA, but warmer weather in northeastern Canada. Wu et al. (2006) studied the nonlinear association between the AO and North America winter climate and found that the linear component is dominant in the Atlantic sector, while the nonlinear component becomes increasingly important in the Pacific-West Coast area.

The Great Lakes are located between the Alberta High and the southeastern USA low of the PNA (Pacific/North America) pattern, close to the nodal point of this oscillation. Any distortion of the pattern and shift of the centers may result in different responses in the winter temperature and ice cover. Thus, this index should be used with caution for the winter severity in the Great Lakes (Rodionov & Assel 2000). The Great Lakes are located at the western edge of the Icelandic Low and Azores High, the action centers of the NAO/AO. Since the intensity and the sign of SAT is associated with NAO/AO (±NAO means a stronger/weaker Icelandic low), ice cover may vary (severe or mild) depending on any displacement of the Icelandic Low (Wang et al. 2010) and Azores High.

Significant change in ice cover on the Great Lakes has been occurring since the 1960s. Some recent studies (Bai et al. 2010, 2011, 2012; Wang et al. 2010, 2012) show that both ENSO and NAO/AO have competing effects on the overall ice cover in the Great Lakes, and a combination of both ENSO and NAO/AO indices has a higher predictability skill than the individual index (Bai et al. 2010, 2012). Due to the competition of both phases of NAO/AO and ENSO (El Niño and La Niña), both indices must be used to project ice conditions in the Great Lakes for individual winters (Wang et al. 2010; Bai et al. 2011). Bai et al. (2010, 2012) reveal that overall Great Lakes ice responds linearly and symmetrically to both phases of NAO/AO, i.e., positive (negative) NAO/AO leads to less (more) lake ice cover. More interestingly, lake ice responds nonlinearly and asymmetrically to El Niño and La Niña events. Strong El Niño events lead to less ice cover, while La Niña events lead to less ice cover if it is strong and to more ice cover if it is weak. Wang et al. (2012) use the updated lake ice data from 1973 to 2011 to investigate the seasonal cycle and variations, interannual variability, periodicity, and the trend. They found that the first two leading EOF modes of lake ice correspond to the teleconnection patterns associated with ENSO and NAO/AO. Nevertheless, the features of individual lake ice cover were not systematically examined in response to both ENSO and NAO/AO events.

In the northern hemisphere, the relationship between ice cover in small lakes and rivers and NAO and ENSO, as well as other major climate indices such as PDO and AMO (Atlantic Multi-decadal Oscillation) were investigated (Robertson et al. 2000; Bonsal et al. 2006; Mishra et al. 2011). The correlation analysis was based on linear regression. The signatures of climate patterns exist in the northern hemisphere. The difference between small lakes and rivers and the Great Lakes is that the latter is also significantly influenced by large water heat content in large and deep lakes, i.e., ice/water albedo feedback process (Wang et al. 2005; Austin & Colman 2007).

Severe and mild lake ice conditions must be caused by the distinct teleconnection patterns or climate forcings. Annual ice cover repeats each year with large interannual variability. For example, the maximum ice coverage over
all of the Great Lakes was 95% in 1978/79 and only ~5% in 2011/12 winter. Possible contributors include interannual and interdecadal climate variability, and long-term trends, which are possibly related to global climate warming. Even in response to the same climate forcing, Great Lakes ice cover may experience different spatial and temporal variability due to each lake’s orientation, depth (i.e., water heat storage), and turbidity (i.e., albedo due to sedimentation). The question is: what are the major teleconnection patterns when the Great Lakes experience severe and mild ice conditions? The purpose of this study is to reveal the teleconnection patterns behind severe and mild ice cover scenarios and explain the corresponding dynamic and thermodynamic mechanisms.

This paper is organized as follows. The data and the methods are briefly introduced in the next section. Following that, in the next section, the climatological mean of atmospheric conditions are constructed, the atmospheric teleconnection patterns for severe and mild ice cover are presented, and the relationships between overall and individual lake ice cover and ENSO and NAO indices are discussed. The final section summarizes the results.

DATA AND METHODS

Annual maximum ice coverage

Annual maximum ice coverage (AMIC) is defined as the greatest percentage of ice coverage in 1 day, by surface area, each winter for the entire Great Lakes. AMIC data for winters 1963–2011 were constructed using analysis of ice charts obtained from the National Ice Center and the Canadian Ice Service (Assel et al. 2003) (Figure 1). The long-term mean (1963–2008) AMIC is 53.9%, and the standard deviation is 21.3%. In this analysis, winters with normalized AMIC greater than or equal to 0.7 standard deviations (≥69.3%) were identified as severe ice cover winters, and winters with normalized AMIC less than or equal to −0.7 standard deviations (≤40%) were identified as mild ice cover winters.

NCEP/NCAR reanalysis

We used monthly reanalysis data from the National Center of Environmental Prediction/National Centers of Atmospheric Research (NCEP) (Kalnay et al. 1996) to investigate the relationship between Great Lakes ice and atmosphere circulation anomalies. The data are available from 1948 to present. The resolution is 2.5 × 2.5 degrees. The climatology of the period 1948–2011 was calculated, and monthly anomalies were obtained by subtracting the climatology from the individual months. Average (December–January–February, DJF) anomalies were calculated for each winter: 1949 (December 1948, January 1949, February 1949), 1950 (December 1949, January 1950, February 1950), and so on until 2011 (December 2010, January 2011, February 2011). In this study, SAT, SLP, surface winds, and 700 hPa geopotential heights were used. Note that regional SAT

Figure 1 | The 1963–2011 Great Lakes winter mean maximum ice coverage (WMIC) with a mean of 53.9% and standard deviation (STD) of 21.3%. Winters with ice coverage of greater than 69.3% and less than 40% are defined as severe and mild winters, respectively, using the 0.7 standard deviations.
may be influenced or moderated by the ice cover, and hence SAT may be not an independent predictor.

**Methods**

The methods used in this study are the composite analysis plus Student’s t-test and regression analysis (Wang et al. 1994). Composite analysis is a widely used method to distinguish the responses associated with two phases of a climate pattern such as ENSO and NAO by averaging the data over the years when certain events occurred. Due to the small samples available in this study, the Student’s t-distribution was used to determine the statistical significance between the two samples. Comparing the differences between two means using the Student’s t-test requires two independent samples of sizes \( n_1 \) and \( n_2 \), which possess means and standard deviations given by \( \bar{x}_1 \) and \( \bar{x}_2 \), and \( s_1 \) and \( s_2 \), respectively. Our null hypothesis, \( H_0 \), is that the two samples are statistically indistinguishable from each other. To test \( H_0 \), we use the following t-score, following Bai et al. (2012):

\[
t = \frac{\bar{x}_1 - \bar{x}_2}{\sqrt{\frac{(n_1 - 1)s_1^2 + (n_2 - 1)s_2^2}{n_1 + n_2 - 2} \cdot \left( \frac{1}{n_1} + \frac{1}{n_2} \right)}}
\]

which is the value of a random variable having the t distribution with \( n_1 + n_2 - 2 \) degrees of freedom. The null hypothesis is rejected if the two-tailed t-score exceeds the 90% confidence interval.

Since the severe and mild ice winters can be identified as two groups, with which we can track back what atmospheric circulation patterns are associated by constructing the composite and their difference maps with the Student’s t-test (Wang et al. 1994).

**RESULTS**

**Climatology**

To help interpret an anomaly of any variable, we first construct the climatology of 700 hPa height (Figure 2(a)), SLP and wind (Figure 2(b)), and SAT (Figure 2(c)) fields for the period 1948–2011. A variable (say SAT, \( T \)) can be decomposed into a time-mean climatology and an anomaly:

\[
T(x, y, z_0; t) = \bar{T}(x, y_0, z) + T'(x, y, z_0; t),
\]

where the bar denotes the time-mean climatology, the prime means the anomaly departing from the climatology, and \( (x, y, z_0; t) \) denotes the longitude, latitude, height (such as \( z_0 = 700 \) hPa, and \(-1,000 \) hPa at surface) and time, respectively.
The climatological 700 hPa height field (Figure 2(a)) indicates a polar vortex structure with a ridge–trough system over North America. The ridge line extends from Alaska to the Rocky Mountains, while the trough line extends from Hudson Bay to the Great Lakes region. The westerly winds dominate over the mid-latitudes at around 40° N.

The climatological SLP field (Figure 2(b)) is dominated by the Icelandic and Aleutian Lows, a high occupied in the US continent, and the Beaufort High in the Arctic. The climatological surface wind patterns are the cyclonic circulations in the North Pacific associated with the Aleutian Low and in the North Atlantic related to the Icelandic Low. Westerly winds dominate over the Great Lakes region. It is well-known that the subpolar lows and the high over North America are due to a land–sea temperature contrast during winter seasons.

The climatological winter SAT field (Figure 2(c)) shows the higher temperature in the subpolar oceans and lower temperature over the USA, consistent with the SLP field due to land–sea temperature contrast. In the Great Lakes region, climatological SAT ranges from −3 °C in Lake Erie to −12 °C in northern Lake Superior. Note that the isotherms have northwest-to-southeast orientation, consistent with the ridge–trough system over North America. This indicates that the origin of the cold air mass, under the climatological westerly wind forcing, is from the Arctic and located north of the Jet Stream (front), and the origin of the warm air is from the Pacific Ocean and the Gulf of Mexico and Gulf Stream (Lewis et al. 2008; Bai et al. 2012).

Composite atmospheric teleconnection patterns associated with severe and mild ice conditions

General speaking, one standard deviation apart from the mean is chosen to select severe and mild ice winters, which should be 75.2% for severe winters and 32.6% for mild winters. However, these criteria would provide few samples for both groups, which can lead to bias in statistical test. To avoid a small number of samples for both groups, 0.7 standard deviations was used, i.e., 69.3 and 40% were chosen for severe and mild ice winters, respectively.

From 1963 to 2011, severe ice cover (>69.3%) occurred on the Great Lakes during the winters of 1963, 1967, 1972,

As is well known, SAT has an inverse relationship to lake ice cover with a correlation of ∼0.8 to ∼0.9 (Bai et al. 2011, 2012). Large-scale atmospheric circulation pattern is usually represented by the 700 hPa geopotential height, which controls the advection of atmospheric temperature. SLP field is the surface reflection of the 700 hPa height field, which can be translated to surface wind field, and hence is the direct driver of SAT by advection. Therefore, to investigate the SAT’s impact on lake ice cover, large-scale atmospheric circulation (700 hPa height), SLP, surface wind field, and SAT should be analyzed to reveal dynamic and thermodynamic mechanisms.

The composite maps of mean winter 700 hPa heights, SLP, winds, and SAT anomalies for these two groups of years, and the differences are shown in Figures 3–5, respectively. The mean 700 hPa height pattern associated with severe ice cover on the Great Lakes during winter (Figure 3(a)) is similar to the negative phase of AO (Thompson & Wallace 1998) and negative phase of PNA pattern (Wallace & Gutzler 1987). The pattern has above-average 700 hPa heights along the west coast of North America, and north of 60°N eastward from Alaska to North Europe, with two major centers of positive anomalies over Alaska and East Arctic. The centers of negative anomalies are located over

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Figure 3 | Composite maps of mean winter 700 hPa height anomalies (relative to the long-term mean) for those years from 1963 to 2011 when winter ice cover on the Great Lakes was (a) severe and (b) mild, and (c) the differences between these two groups. Shaded areas indicate differences that are locally significant at the 5% level based on a two-tailed t-test. The intervals are 10 m.
the central North Pacific Ocean, the Great Lakes, over Western Europe, and the adjacent North Atlantic. Therefore, the teleconnection pattern associated with the severe ice conditions is the combined –NAO/AO and negative PNA pattern, consistent with the finding of Bai et al. (2010, 2012) using composite analysis based on indices of ENSO and NAO/AO.
At the surface, above-average SLP (Figure 4(a)) occupies an area west of the Great Lakes with a center near Alberta, and below-average SLP occupies the area east of the Great Lakes. The strong anomalous pressure gradient, in the vicinity of the Great Lakes, generates strong anomalous northwesterly winds over the area, leading to colder-than-normal temperatures in the Great Lakes. The SAT anomalies in the Great Lakes range from $-1.5$ to $-2.0$ °C (Figure 5(a)). Both colder-than-normal temperatures and the enhanced northwesterly winds are favorable for producing more ice cover.

The composite map of mean 700 hPa height anomalies for winters with mild ice cover (Figure 3(b)) is characterized by a train of high geopotential height anomalies over the subtropical North Pacific, similar to the positive PNA pattern (Wallace & Gutzler 1981): a low over the subpolar North Pacific, a high over and to the north of the Great Lakes, and a low over the southeast USA and subtropical North Atlantic. In the Pacific–North American sector, the pattern resembles the negative phase of the TNH (Tropical/Northern Hemisphere) teleconnection (Mo & Livezey 1986), especially the negative center over the west coast of North America and the positive center over the Great Lakes. The difference is that there is not a remarkable negative center over Mexico and the southern USA. The negative phase of the TNH pattern is often observed during December and January when Pacific warm (ENSO) episode conditions are present (Barnston et al. 1993). This TNH-like pattern implies weakening of the quasi-permanent ridge over the west coast and the trough over eastern North America, which results in a strengthened zonal flow, bringing moderate winter air temperatures to the Great Lakes. Over the Atlantic–Europe sector, a low anomaly is located in northern Russia, and a positive anomaly is located in Europe, indicating a positive phase of NAO/AO or the east Atlantic pattern. Thus, the teleconnection pattern associated with the mild ice cover is the combined patterns of both positive PNA-like (or negative TNH) and positive NAO/AO.

At the surface (Figure 4(b)), lower-than-normal SLP occupies most of North America. The strong negative center is located in the North Pacific with a below-average SLP tongue extending southeast from Alaska to the Great Lakes. The high center is located in the central North Pacific. Anomalous southeasterly winds dominate much of the USA (Figure 4(b)), leading to a warm winter in most of the USA, except the southeastern part (Figure 5(b)). In the Great Lakes area, anomalous southeasterly winds prevail over Lakes Superior and Michigan, while easterly winds prevail over the other lakes (Figure 4(b)). SAT anomalies over the Great Lakes range from $0.9^\circ$ to $1.8^\circ$ C, which is favorable for less ice cover. Note that the orientation of the anomalous SAT isobaths separate the upper and lower Great Lakes, with the stronger reduction of ice cover in the upper Great Lakes.
Lakes during the El Niño and +NAO/AO events, while Lake Superior has the highest reduction because the SAT anomaly is largest (around 1.8 °C).

The difference between the composite 700 hPa heights for severe and mild ice cover was constructed (Figure 3(c)). Significant negative difference centers are located in the subtropical belt, in the vicinity of the Great Lakes (negative), and in Europe (negative, Figure 3(c)). Centers of significant positive differences are located over Alaska and just east of Greenland to northern East Russia. Over North America, the significant positive anomaly over Alaska and the west coast enhances the ridge over the west coast, and the significant negative anomaly (low center) over the Great Lakes also reinforces the trough in the region. Therefore, the ridge–trough system is intensified, promoting advection of the cold, dry air from the Arctic to the Great Lakes.

In response to the intensified ridge–trough system (Figure 3(c)), the temperature difference between severe and mild ice cover winters shows a systematic cooling (warming) over North America during the severe (mild) ice winters. The temperature difference ranges from −2.5 to −4 °C in the Great Lakes. The significant difference is over the northeast USA and southern Canada with the Great Lakes near its center.

It is found from the composite analysis that both NAO/AO and ENSO have impacts on Great Lakes ice cover. The atmospheric circulation teleconnection pattern for severe ice cover resembles a mixture of a negative phase of NAO/AO and a negative PNA pattern. The atmospheric pattern for mild ice cover resembles a negative phase of TNH (or positive PNA-like) that is often observed during El Niño events and +NAO/AO. There are eight −NAO/AO years in the group of severe ice cover, and seven El Niño years in the group of mild ice cover.

To summarize the intensification and weakening of the North American ridge–trough system during the severe and mild ice cover, schematic diagrams are constructed (Figure 6). The climatological 700 hPa height (i.e., circulation pattern) has northwest-to-southeast orientation over North America (Figure 6(a)) based on Figure 2(a). During the severe ice winters, the positive anomaly over the west coast (Figures 3(a) and 3(c)) reinforces the ridge, and the negative anomaly over the Great Lakes also reinforces the trough. Thus, this causes a stronger (strongly tilted) ridge–trough system and produces the anomalous northwesterly wind (Figure 6(b)), which advects the Arctic cold, dry air to the Great Lakes region (Figure 6(b)). Similarly, during the mild ice cover winters, the negative anomaly over the Aleutian region and the west coast (Figures 3(b) and 3(c)) reduces the intensity of the ridge, and the positive anomaly over the Hudson Bay–Great Lakes region (Figures 3(b) and 3(c)) also reduces the intensity of the trough, flattening the ridge–trough system (Figure 6(c)), leading to a warm climate due to the advection of the dry and warm air by the westerly or southwesterly winds (Figure 6(c)).

**Lake ice relationship to NAO/AO (linear) and ENSO (nonlinear)**

Bai et al. (2010, 2012) have revealed that the overall Great Lakes ice extent as a whole has a linear relationship to NAO/AO and nonlinear and asymmetric relationship to ENSO, both with large scattering due to natural large interannual variability (Wang et al. 2012). However, they did not examine the relationship of individual lake ice cover to these two indices. Our working hypothesis is that lake ice in each lake may respond differently, even to the same climate pattern such as NAO and ENSO, due to their geographic location, depth, orientation, etc. Therefore, it is necessary to investigate the lake ice features of individual lakes.

Figure 7 shows the scatter plots of lake ice in each lake versus the Niño3.4 index (left column) and NAO index (right column) with their regression equations shown using the least square fit method. Generally speaking, except for Lake Erie, ice cover in the individual lakes nonlinearly and asymmetrically responds to the ENSO index, while linearly to the NAO/AO index, again with large scattering, indicating the complex nature (Bai et al. 2012; Wang et al. 2012). However, lake ice in each lake responds differently (see the distribution of the dots). The regression curve to the Niño3.4 index in Lake Ontario is relatively symmetric compared to the other lakes (Superior, Michigan, and Huron). Large scattering occurs in all the lakes, indicating that predicting lake ice coverage using individual Niño3.4 index or NAO index is not reliable. In response to the NAO/AO, Lake Superior ice has more scattering than the other lakes, possibly due to a strong ice–albedo feedback.
Figure 6 | Schematic diagrams for climatological 700 hPa flow patterns with a front (doubled red line) that separates the Pacific, Arctic, and tropical air masses with strong mixing areas covering northeast America, leading to heavy precipitation (a), the flow patterns associated with the intensified North American ridge-trough system during severe ice cover winters (b), and with the weakened/flattened ridge-trough system during mild ice cover winters (c).
Figure 7 | Scatter plot between lake ice coverage and Niño3.4 index (left column), and the NAO/AO index (right) for individual lakes.
process (Wang et al. 2005; Austin & Colman 2007) and its large water depth.

The most interesting feature in Lake Erie is the poor relationship to either Niño3.4 or NAO/AO indices in most years (cases). Due to its shallow depth, the lake is ice covered from 70 to 100% in most cases. However, three out of five mild ice cover winters were associated with strong El Niño events, and four out of five mild ice cover winters are associated with strong + NAO/AO events, still indicating the existence of both strong El Niño and strong + NAO/AO signatures.

To further quantitatively describe the above relationships between the entire Great Lakes AMIC and individual lakes AMICs, Table 2 shows that Lakes Superior and Huron have the highest correlation to the entire AMIC, while the lower lakes contribute less to the entire AMIC (see last column). For individual lakes, Lake Superior has higher correlation to the upper lakes than the lower lakes (see the second row). Lake Michigan has the highest correlation to Lake Huron ($C = 0.85$) and to Lake Ontario ($C = 0.81$) (see the third row). Lake Erie has the lowest correlation to all other lakes, indicating that the shallowest lake behaves differently from the deep-water lakes.

**Great Lakes ice cover associated with ENSO and NAO/AO**

During the period from 1963 to 2011, there were 17 El Niño events: 1964, 1966, 1969, 1970, 1973, 1977, 1978, 1983, 1987, 1988, 1992, 1995, 1998, 2003, 2005, 2007, and 2010 (see Figure 3(b) of Bai et al. (2012)). The average ice coverage during these 17 El Niño winters is 47.8% (Figure 8), which is below the long-term average (53.9% in Figure 1). Thus, the impact of the El Niño events on Great Lakes ice cover is significant, but limited to the strong ones, in agreement with Assel (1998).

There were 15 La Niña events during the study period: 1965, 1968, 1971, 1972, 1974, 1975, 1976, 1985, 1989, 1996, 1999, 2000, 2001, 2008, and 2010 (see Figure 3(b) of Bai et al. (2012)). The average ice coverage during the 15 La Niña winters is 53.5%, close to the long-term mean (53.9%; see Figure 8), implying that the impact of La Niña events on the Great Lakes ice cover is insignificant, i.e.,

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**Table 2** Zero-lag correlation coefficients ($C$) among the total Great Lakes AMIC (GLs) and individual lakes AMICs. Bold denotes the highest correlation of each column.

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asymmetric to the El Niño events. Based on linear theory, ice cover on the Great Lakes is expected to be above average during La Niña episodes (the opposite phase of El Niño). However, the average ice coverage of 14 La Niña events is close to the long-term mean. Ice cover on the Great Lakes can be either above (below) average during a weak (strong) La Niña event; some strong La Niña events even had mild ice cover. This suggests that the relationship between La Niña events and Great Lakes ice is unstable and asymmetric with the El Niño events (Bai et al., 2010, 2012). Although many mild ice cover winters on the Great Lakes can be explained by strong El Niño events, the severe ice cover events cannot be explained by La Niña events alone. This is why the linear correlation between the Niño3.4 index and Great Lakes ice cover is only –0.18 (Bai et al., 2012). Only strong El Niño events can act as a useful predictor for mild ice cover winters on the Great Lakes. This asymmetric response of Great Lakes ice between El Niño and La Niña is consistent with the finding that the impacts of ENSO on lakes ice cover (Assel, 1998) and on North America climate is nonlinear (Livezev et al., 1997; Hoerling et al., 1997, 2001; Wu et al., 2005).

During the period 1963–2011, there were 24 negative NAO/AO events (1963, 1964, 1965, 1966, 1968, 1969, 1970, 1971, 1972, 1977, 1978, 1979, 1982, 1985, 1986, 1988, 1996, 1997, 2001, 2004, 2006, 2009, 2010, and 2011) (see Figure 3(b) of Bai et al. (2012)). The mean ice cover for all negative NAO/AO winters is 60.2% (Figure 8(b)). Average ice coverage of the 11 strong negative NAO/AO winters is 68.2%. This suggests that a negative NAO/AO has significant impacts on Great Lakes ice cover and explains the severe ice events in the Great Lakes, which cannot be explained by La Niña events.

There were 20 positive NAO/AO events (1967, 1973, 1974, 1975, 1981, 1983, 1984, 1989, 1990, 1991, 1992, 1993, 1994, 1995, 1998, 1999, 2000, 2002, 2007, and 2008) (see Figure 3(b) of Bai et al. (2012)). The average ice cover of all positive NAO/AO events is 49.2% (Figure 8(b)), which is less than the long-term mean (53.9%). Strong El Niño and concurrent positive NAO/AO events can explain 10 of 15 mild ice cover events.

To demonstrate the combined effects of NAO/AO and ENSO, the winters were classified into four climate states based on phases of ENSO and AO: (1) El Niño/ + AO, (2) El Niño/ – AO, (3) La Niña/ + AO, and (4) La Niña/ – AO.

During 1963–2011, five winters fall into state 1 (El Niño/ + AO): 1973, 1983, 1992, 1995, and 2007. The average ice coverage for these winters is 41.4% (Figure 8(c)), which is well below the long-term mean (53.9%), and is also lower than the mean ice cover of all El Niño winters (47.8%). Seven winters (1965, 1968, 1985, 1996, 2001, 2009, and 2011) are in state 4 (La Niña/ – AO), and the mean ice cover is 62.4% (Figure 8(c)), which is larger than the long-term mean (53.9%) and larger than all –AO means (60.2%). Nine winters fall in state 2 (El Niño/ – AO): 1966, 1969, 1970, 1977, 1978, 1987, 1998, 2003, and 2010. Their mean ice coverage is 53.7% (Figure 8(c)), which is close to the long-term mean (53.9%), but lower than the –AO mean (60.2%) and larger than the El Niño mean (47.8%). This indicates a competition of the effects of El Niño (warming) and –AO (cooling). Six winters are in state 3 (La Niña/ + AO): 1975, 1976, 1989, 1999, 2000, and 2008 and the average ice coverage is 44.2% (Figure 8(c)), which is below the long-term mean (53.9%).

In summary, using the combined Niño3.4 and NAO indices, mild ice winters (state 1) and severe ice winter (state 4) can be reliably projected. For states 2 and 3, the competition of these two teleconnection patterns on influencing lake ice can be analyzed only case by case, depending on which index is stronger.

**SUMMARY AND CONCLUSIONS**

The atmospheric teleconnection patterns associated with severe and mild lake ice cover were examined, and the lake ice relationship with ENSO and NAO/AO were further investigated using lake ice observations for winters 1963–2011 and NCEP reanalysis data. Based on the above investigations, the following conclusions can be drawn:

1. During severe ice winters, Arctic dry and cold air mass was advected to the Great Lakes region by the predominant anomalous northwesterly winds. Associated with severe ice cover, the teleconnection patterns show a mixture of –NAO/AO and negative PNA pattern. The positive anomaly over the west coast and negative
anomaly over the Great Lakes intensify the North American ridge–trough system, which produces anomalous northwesterly winds and advects the Arctic dry and cold air masses to the Great Lakes region.

2. During mild ice winters, the anomalous southeasterly winds advected moist and warm air from the Gulf of Mexico to the Great Lakes region, which also significantly blocked (i.e., reduced) the climatological northwesterly winds. Associated with mild ice cover, the teleconnection patterns indicate a mixture of negative TNH (or positive PNA-like during the El Niño) and +NAO/AO pattern. The negative anomaly over the west coast and positive anomaly over the Great Lakes weaken the North American ridge–trough system, which advects the dry, less cold air masses from the west to the Great Lakes region.

3. Composite analysis of lake ice shows, except for Lake Erie, overall lake ice responds nonlinearly and asymmetrically to El Niño and La Niña. However, lake ice responds linearly and symmetrically to positive and negative phases of NAO/AO events. There exists large scattering between lake ice coverage and both the Niño3.4 index and NAO index in all the lakes, indicating the prediction of lake ice using an individual index is not reliable.

4. In response to ENSO, Lake Ontario is relatively symmetric compared to the other lakes. Lake Superior experiences a larger scattering than the other lakes. With the linear relationship to NAO/AO, Lake Superior also has the largest scattering. Both suggest that the ice-albedo feedback process plays a bigger role in this deepest and largest lake (Wang et al. 2005; Austin & Colman 2007).

5. Because it has the smallest depth of all the Great Lakes, Lake Erie is covered by ice in most years. Unlike the other lakes, the nonlinear (or quadratic) relationship of Lake Erie ice cover to ENSO and the linear relationship to NAO/AO are the poorest. However, the mild ice cover is mostly related to either the strong El Niño or the strong +NAO/AO events, and their combination.

6. Using the combined Niño3.4 and NAO indices, mild ice winters (state 1) and severe ice winters (state 4) can be reliably projected. For states 2 and 3, lake ice conditions that are competitively influenced by the two teleconnection patterns may be estimated only case by case, depending on which index is stronger.

ACKNOWLEDGEMENTS

We acknowledge the support of Great Lakes Restoration Initiative (GLRI) funds from EPA/NOAA. NCEP reanalysis data were provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, from their website at http://www.cpc.noaa.gov/. Niño3.4 index and NAO index was provided by NOAA/CPC, from their website at http://www.cpc.noaa.gov/products/precip/CWlink/. We also appreciate the help of Drs David Schwab and Brent Lofgren for constructive comments and discussion on the first draft, and Cathy Darnell for editing this paper. This is GLERL contribution 1641.

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First received 9 February 2012; accepted in revised form 19 September 2012.