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LAURENTIAN GREAT LAKES ICE COVER AND ATMOSPHERIC TELECONNECTION PATTERNS: A DECISION-TREE ANALYSIS

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1. INTRODUCTION

Great Lakes ice cover affects the winter lake aquatic system, winter navigation and hydropower generation, winter recreational activity, and lake effect snowfall. Many factors determine the severity of an ice season and among the most important is atmospheric circulation. Advection of warm or cold air masses and wind speed affect latent and sensible heat exchange between the atmosphere and the lakes and thus the rate of winter cooling and ice formation.

Teleconnections are an effective, parametric way to describe atmospheric circulation. When examining relationships between Great Lakes ice cover and large-scale atmospheric circulation it is important to consider not only separate teleconnection patterns but their combinations as well. The combined action of several teleconnections characterizes the state of the atmosphere over the entire hemisphere. The objective of this study is to improve our understanding of which teleconnection indices, or the interaction between indices, drive the interannual variations in Great Lakes ice cover and to give simple characterizations of the conditions that determine when ice cover is above normal or below normal.

2. DATA AND METHOD

We applied a simple ice cover model (Assel et al., 1996) to estimate the annual maximum ice cover for the combined area of the five Great Lakes. Figure 1 compares modeled and observed data. In this study we are using modeled data to extend the period of record back to 1950. Atmospheric teleconnection indices were as follows: Polar/Eurasian (POL), West Pacific (WP), East Pacific (EP), Pacific/North American (PNA), Tropical/Northern Hemisphere (TNH), East Atlantic (EA), and North Atlantic Oscillation (NAO). To characterize El Niño/Southern Oscillation (ENSO) events we used two indices: 1) the Southern Oscillation

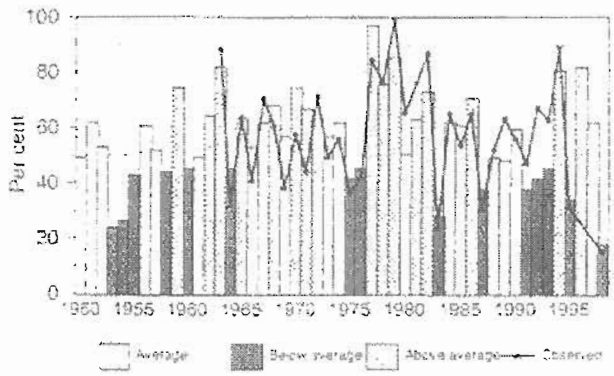

Fig. 1. Modeled and observed maximum annual ice cover on the Great Lakes, 1950-1998.

Index (SOI), and 2) the Multivariate ENSO Index (MEI).

To examine an association between the teleconnection indices and ice cover we used a binary tree-growing method developed by Breiman et al. (1984), known as Classification and Regression Tree (CART). The CART tree is constructed by splitting subsets of the data set using all predictor variables to create two child nodes repeatedly, beginning with the entire data set. CART works by evaluating each predictor to find the best groupings of classes based on improvement score, or reduction of impurity. Then the predictors are compared, and the predictor with the best improvement score is selected for the split. The process repeats recursively until one of the stopping rules is triggered. A tree-structured output of the CART procedure provides easily understood and interpreted information regarding a relationship between the target variable and its predictors. This information can also be presented as a set of IF-THEN rules.

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Reprinted from the preprint volume of the ***Eighth Conference on Climate Variation****, 13-17 September 1999, Denver, CO, by the AMS, Boston, MA.*

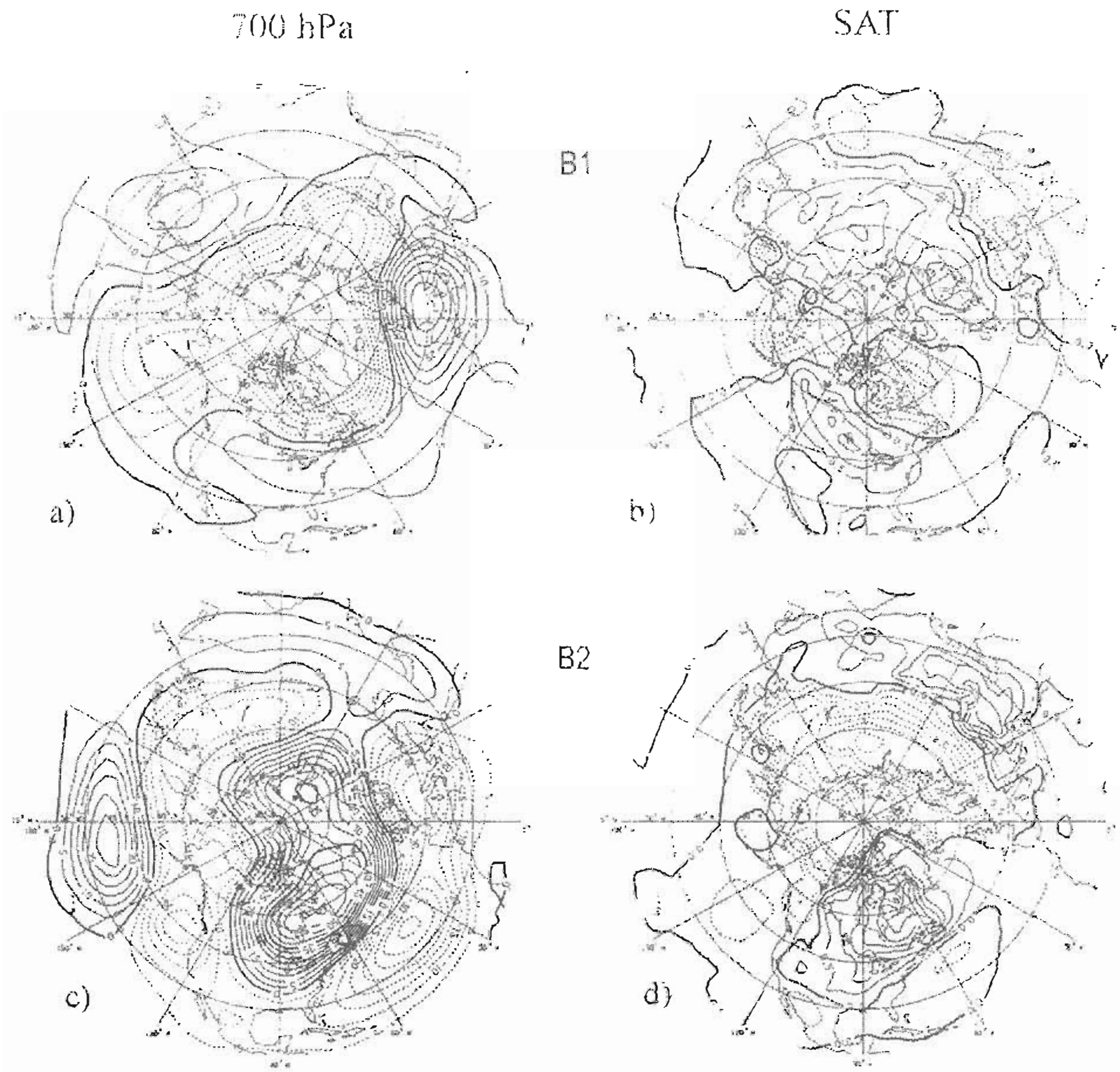

Fig. 2. Composite 700-hPa height anomaly maps (left column) and associated SAT anomaly maps (right column) characteristic of below-normal ice cover. Reference period 1950-1998). a-b) type B1 (below normal: 1954, 58, 64, 75, 76, 83, 91, 92, 93, 95, 98; normal: 80, 89, 90, 97); c-d) type B2 (below normal: 1953, 60, 87; normal: 56, 66, 69).

3. CIRCULATION PATTERNS ASSOCIATED WITH BELOW-NORMAL ICE COVER

A predictor with the highest improvement score in the root node was the POL index. A simple rule

IF POL > 0.23
THEN ice cover = below normal

correctly classifies 11 out of 15 (or 73%) of all winters with below-normal ice cover. It is important to note that a group of winters formed by this rule was remarkably pure; there were no winters with above-normal ice cover in this group. A composite map of 700-hPa height anomalies for the years in this group is presented in Fig. 2a. It shows that negative 700-hPa height anomalies are concentrated in the high latitudes, suggesting a developed Polar vortex and enhanced zonal circulation over the entire Northern Hemisphere. For further reference, we will call this type of circulation B1. Surface air temperature (SAT) anomalies associated with B1 (Fig. 2b) are mostly positive over central parts of North America, particularly in the area stretching from northwestern Canada to the eastern United States completely covering the Great Lakes. Strong negative SAT anomalies are centered over the Bering Sea and northeastern Canada.

The next best predictor after the POL index in the root node was the WP index. In those years when WP > 0.18 ice cover was mainly below normal. Out of 17 years that satisfy this condition, 10 (or 67% of this class) had below-normal ice cover, 6 years were normal, and only 1 year had above-normal ice cover. The distribution of 700-hPa height anomalies for the years in this group (not shown) is very close to type B1, while emphasizing strong zonal circulation over the western North Pacific.

We also found a strong association with the MEI index. There were 10 winters during the 1950-1998 period when the MEI exceeded 0.79 (strong El Niño events), and 7 of these winters were characterized by below-normal ice cover, 3 normal, and 0 above-normal ice cover. We did not find, however, a correspondingly strong tendency for above-normal ice cover during La Niña events. The relationship between ice cover and ENSO events is not symmetric.

The composite maps for those years for which MEI > 0.79 (not shown) has much in common with type B1, that is, during strong El Niño events atmospheric circulation over the Northern Hemisphere tend to be zonal.

Some of the winters with below-normal ice cover on the Great Lakes occurred when atmospheric circulation over the Northern Hemisphere was meridional rather than zonal. Those winters can be described as follows:

IF POL ≤ 0.23 & NAO ≤ 0.20 & TNH ≤ -0.72,
THEN ice cover = below normal.

This rule singles out a group of six winters, of which three are below normal, and three are normal. Atmospheric circulation for this group of winters (which we call B2) is characterized by a weaker than normal circumpolar vortex that is also shifted toward the North Atlantic sector (Fig. 2c). The corresponding SAT anomaly map (Fig. 2d) features strong positive anomalies in northeastern Canada, which are apparently associated with the negative phase of the NAO and reduced advection of Arctic air to this region. Typically, a distribution of positive SAT anomalies over North America under the negative phase of the NAO is confined by about 50°N. In this situation both temperature and ice cover in the Great Lakes are near normal. In some relatively rare situations, however, when this phase of the NAO is combined with a strongly negative phase of the TNH, positive SAT anomalies may extend farther south making winters on the Great Lakes mild.

4. CIRCULATION PATTERNS ASSOCIATED WITH ABOVE-NORMAL ICE COVER

Unlike below-normal ice cover, which can often be successfully classified using just one teleconnection index, classification of above-normal ice cover is more complex and requires two or three teleconnection indices. When these indices are combined they are usually in the phase that corresponds to the meridional rather than zonal circulation. As a result, all three types of atmospheric circulation, associated with above-normal ice cover (A1, A2, and A3), are meridional in nature (Fig. 3). Type A1 is described by the rule:

IF POL ≤ 0.23 & NAO ≤ 0.20 & TNH ≥ -0.7
THEN ice cover = above normal.

This relatively complex rule singles out 88% (14 out of 16) of years with above-normal ice cover in a surprisingly pure group with only one year of below-normal class (1955) and one normal year. This rule is similar to that for type B2 except for the TNH index. A comparison of Figs. 3a and 3b for type A1 with Figs. 2c and 2d for type B2 shows the significance of this index. In case of A1, positive SAT anomalies over North America are limited by northeastern Canada, while over much of the continent, including the Great Lakes, SAT anomalies are negative.

Types A2 and A3 are based on two different subsets of above-normal years and are opposite to each other. They reflect different climatic situations leading to above-normal ice cover on the Great Lakes. Both of them, however, involve the PNA index. This index by itself is not strongly associated with ice cover. Ironically, both the coldest (1976/77) and the warmest (1997/98) winters on the Great Lakes during the 1950-1998 period were El Niño winters with the highest and second highest positive PNA indices respectively. Figure 4 schematically illustrates the principal difference in atmospheric circulation between these two winters.

The winter of 1976/77 (Fig. 4a) was characterized by a well-developed ridge-trough system over North America, that is, enhanced meridional circulation. The ridge over the North American west coast was so strong that it effectively blocked Pacific cyclones from entering the continent. According to the stormtrack maps published in the *Climatological Data, National*

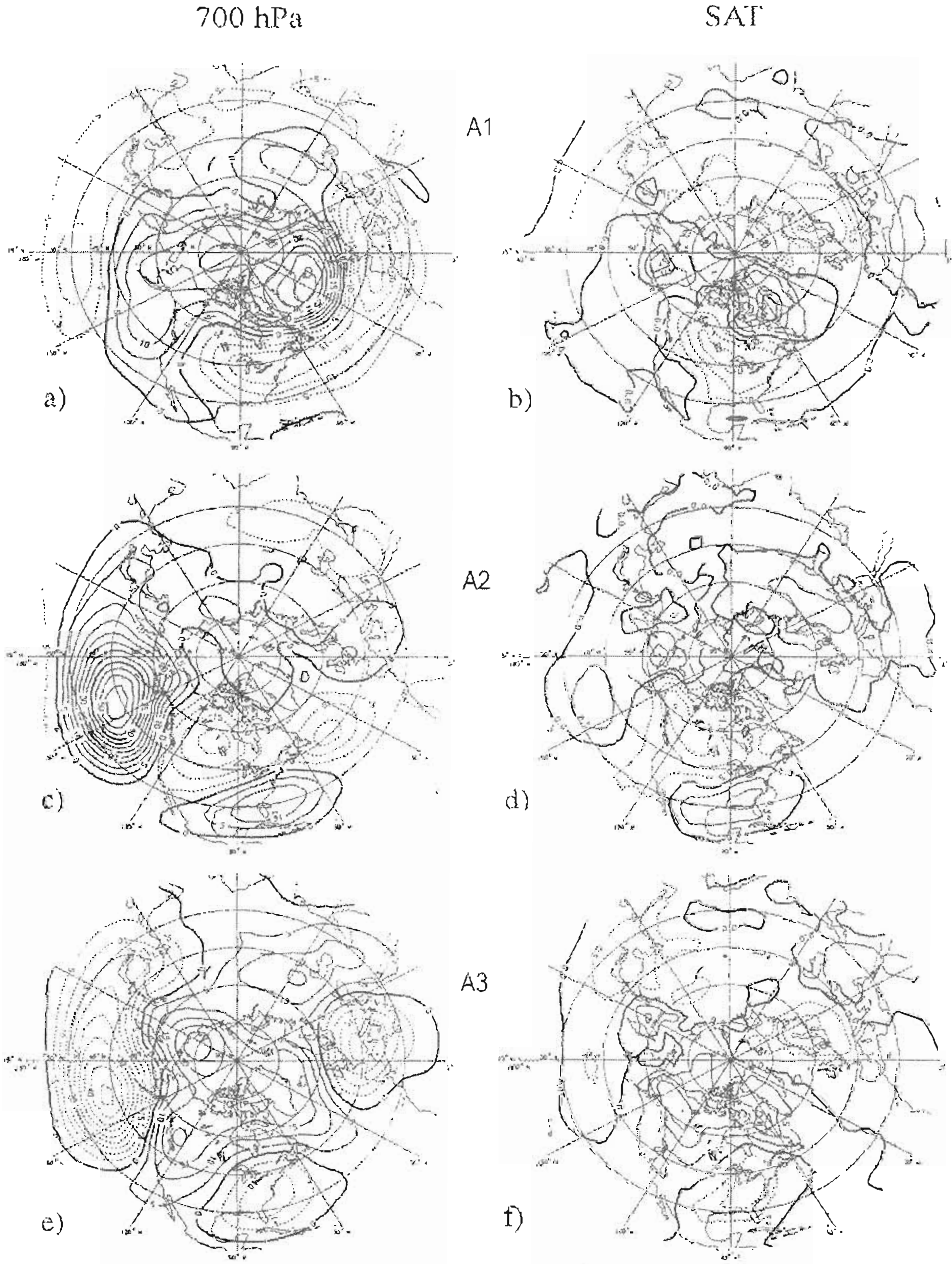

Fig. 3 Same as Fig.2 except for above normal ice cover. a-b) type A1 (above normal: 1959, 62, 63, 65, 68, 70, 71, 72, 77, 78, 79, 82, 86, 96; normal: 85; below normal: 55), c-d) type A2 (above normal: 1959, 62, 65, 71, 72, 79, 82; normal 50, 52, 57, 85, 89, below normal: 55, 75), e-f) type A3 (above normal: 1963, 68, 70, 77, 78, 81, 86, 94, 96; normal: 61, 74, 84; below normal. 53, 60, 87).

Summary (NOAA), a large portion of the cyclones over North America were originating over west-central Canada. The stormtrack was oriented from northwest to southeast along the western periphery of the upper ridge in Fig. 4a. Frequent cold arctic air outbreaks in the Great Lakes region were associated with the cold fronts of these cyclones and the eastern periphery of anticyclones that also moved in the same direction.

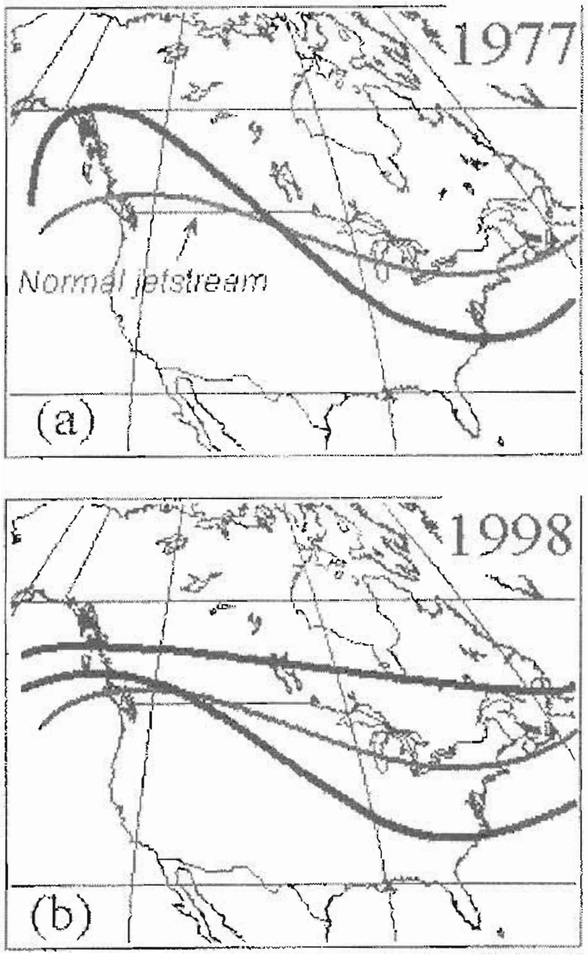

Fig. 4. Schematic illustration of atmospheric circulation during a) winter 1976/77, and b) winter 1997/98.

During the winter of 1997/98 (Fig. 4b) the jet stream was split, and its northern branch had almost straight zonal orientation thus blocking the intrusion of arctic air to the eastern half of the United States. A really significant upper air ridge over the west coast failed to form and numerous cyclones easily penetrated from the Pacific into the continent, moving there in a nearly zonal direction. The Great Lakes region often found itself in a warm sector of these cyclones.

These examples clearly show that great distortions of the PNA pattern are possible, to the extent that the resulting anomaly pattern only vaguely (if not at all) resembles the PNA configuration. Thus, the geographical position of the Great Lakes regarding to the PNA pattern (too close to the nodal point of this standing oscillation), instability of the pattern itself, and the inability of the PNA index to unambiguously characterize atmospheric circulation does not make this index a good classifier for the ice cover. Still it can be useful if it is combined with other teleconnection indices. Type A2 (Fig. 3c) is formed by a combination of negative PNA and positive TNH patterns:

IF PNA $\leq$ -0.20 & TNH > -0.05,
THEN ice cover = above normal.

Negative phase of the PNA is characterized by frequent troughing over the west of North America and ridging over the east. However, when this is accompanied by a positive TNH pattern, which features a negative 700-hPa height anomaly north of the Great Lakes, the ridging on the east is suppressed. As seen from Fig. 3d, the strongest negative SAT anomaly under this pattern is over west-central Canada, and the Great Lakes is located on the periphery of this anomaly. In this situation even the slightest variations in the atmospheric circulation pattern may have significant consequences for the Great Lakes. The probability of above-normal ice cover is highest for Lake Superior and lowest for lakes Erie and Ontario.

Type A3 (Fig. 3e) represents a combination of the PNA and POL indices:

IF PNA > -0.20 & POL $\geq$ 0.22,
THEN ice cover = above normal.

It is very similar to the classical PNA pattern featuring a deep upper atmospheric trough over the central North Pacific, a ridge over western Canada, and again a trough over the east coast of the United States (Wallace and Gutzler 1981). Out of the three coldest consecutive years on the Great Lakes: 1977, 1978, and 1979, two (1977 and 1979) were of this type, and the third was type A2. The most significant negative temperature anomalies during type A3 are in the southeastern part of North America (Fig. 3f). Again, like with the type A2, the Great Lakes region is on the periphery of this anomaly, but this time the lower lakes have a higher chance to have above-normal ice cover than Lake Superior.

5. CONCLUSION

Relationships between maximal annual ice cover on the Great Lakes and winter atmospheric teleconnection patterns are examined using the CART method. This method is particularly useful when a relationship between the target variable and predictors is not symmetric relative to the sign of anomaly. Thus, we found that below-normal ice cover in the Great Lakes was strongly associated with El Niño events in the equatorial Pacific. However, the association between above-normal ice cover and La Niña events was much weaker. This result is consistent with the maps of SAT anomalies during El Niño and La Niña events in Hoerling et al. (1997) who showed that the nonlinearity of the ENSO effect reaches its maximum in the Great Lakes region.

The CART method allowed us to reveal individual teleconnection indices and combinations of indices that are most characteristic of below-normal and above-normal classes of ice cover. Below-normal ice cover on the Great Lakes tends to occur during periods of zonal atmospheric circulation over the Northern Hemisphere. It is important to note, however, that zonal circulation over the Northern Hemisphere does not always translates into zonal circulation over North America, if we measure the degree of zonality by the PNA index. This index turned out to be a poor classifier for ice cover. This can be explained in part by the fact that it cannot unambiguously characterize the type of atmospheric circulation over the continent. Thus, two years with almost equally high PNA indices (1977 and 1998) had different types of atmospheric circulation and, as a result, extremely opposite ice cover anomaly on the Great Lakes.

Although there is a clear tendency for above-normal ice cover to occur during years of meridional circulation over the Northern Hemisphere, the structure of the relationship between ice cover and atmospheric circulation for these years is more complex than for the years with below-normal ice cover. There is a sort of hierarchy between types A1, A2, and A3. Type A1 is characterized by a composite map that includes a majority of years (14 out of 16) with above-normal ice cover and thus represents the most common type of atmospheric circulation for this class. Two other types, A2 and A3, are based on subsets of years with above-normal ice cover and represent different aspects of atmospheric circulation important for the formation of extensive ice cover. Both these types involve the PNA index and show that above-normal ice cover may occur under both negative and positive phase of this pattern. If the negative phase of the PNA is accompanied by a positive phase of the TNH, the strongest negative SAT anomalies are located over west-central Canada, extending toward the Great Lakes. In this situation the probability of above-normal ice cover is higher for Lake Superior, than for the lower lakes. On the contrary, under the A3 type of circulation, when positive phase of the PNA is accompanied by normal or negative phase of the POL, the probability of above-normal ice cover is higher for the lower lakes.

Acknowledgement

This is Great Lakes Environmental Research Laboratory Contribution No. 1133.

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