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Great Lakes Ice and Climate Research and Forecast

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This paper describes recent progress made by a team from the NOAA Great Lakes Environmental Research Laboratory (GLERL) and the University of Michigan (UMich) Cooperative Institute for Limnology and Ecosystems Research (CILER). Over the past six years (since 2007), this team has studied Great Lakes ice and regional climate in response to global climate changes and how to transfer scientific research results into predictions of lake ice on the scales of several days to several months. The Great Lakes are located at the edge of the action centers of the North Atlantic Oscillation (NAO) and the nodal points of the action centers of the Pacific-North America (PNA) pattern. Aloft, there exists a strong highly-fluctuating annual south-north displacement of the westerly jet. Great Lakes ice responds linearly to the NAO and nonlinearly (quadratically) to the El Niño and South Oscillation (ENSO or Nino3.4). As a result, both NAO and ENSO have impacts on lake ice, but neither of them solely dominates the Great Lakes regional climate and lake ice cover. The combined effects of both NAO and ENSO on lake ice provide high predictability skills using statistical regression models. For the first time, fully-coupled Great Lakes Ice-circulation Models (GLIM) with both dynamics and thermodynamics have been developed at GLERL/CILER to simulate and investigate the lake ice variations on the synoptic, seasonal, interannual, and decadal time scales. The hindcast results were validated using in situ, airborne, and satellite measurements for various periods. The validated GLIM has been used since the 2010-2011 ice season to forecast Great Lakes ice cover concentration, thickness, velocity, and associated air-ice-sea variables for up to five days in advance.

1. Introduction

The Laurentian Great Lakes, located in the mid-latitude of eastern North America, contain about 95% of the U.S. and 20% of the world's fresh surface water supply. Nearly one eighth of the population of the United States and one third of the population of Canada live within their drainage basins. The Great Lakes can be considered a mini climate system, even though small compared to the global climate system or Arctic regional climate system, since all five important climate components are included: regional atmosphere and climate, hydrosphere (hydrodynamics), cryosphere (lake ice), biosphere (aquatic ecosystem and terrestrial ecosystem), and land process (hydrology). In addition, the human dimension is another important component affecting the Great Lakes climate system. In this mini-climate system, there are strong interactions and associations among the components. Because of this concentration of population (human dimension), the ice cover that forms on the Great Lakes each winter and its year-to-year variability affect the regional economy (Niimi, 1982). It also affects the lake's abiotic environment and ecosystems (Vanderploeg et al. 1992) in addition to influencing summer hypoxia, lake effect snow, water level variability, and the overall hydrologic cycle of the region.

Studies showed that teleconnection patterns such as the Pacific/North America (PNA; Wallace and Gutzler 1981), North Atlantic Oscillation (NAO), Pacific Decadal Oscillation (PDO), and West Pacific (WP), are associated with anomalous ice cover on the Great Lakes and other small lakes in North America (Bonsal et al. 2006; Mishra et al. 2011). Rodionov and Assel (2001) found that the relationship between ENSO (El Niño and Southern Oscillation) and severity of winters in the Great Lakes is highly nonlinear. Strong El Niño events are associated with warmer temperatures in the Great Lakes region. The stronger the event, the milder the winter. Ice-off dates for Lake Mendota, Wisconsin, have been associated with El Niño. The observed changes in Canada's lake ice cover have also been influenced by large-scale atmospheric teleconnections (Bonsal et al. 2006). Ice phenology was shown to be more responsive to the extreme phases of the teleconnections, with the Pacific indices (PNA, PDO, SOI, and NP) having the strongest correlation to ice cover, with the exception of the extreme eastern areas, which were more affected by NAO (Bonsal et al. 2006). A recent study (Mishra et al. 2011) also shows that lake ice phenology of small lakes around the Great Lakes region is associated with these major climate teleconnection patterns, including NAO, AO (Arctic Oscillation), and AMO (Atlantic Multidecadal Oscillation).

Before 2007, although there was some trials to develop numerical models of ice transport in the Great Lakes (Rumer et al. 1981) based on Hibler's (1979) dynamic-thermodynamic sea-ice model. There existed no viable ice model for use as a research or as an operational forecast tool in the Great Lakes. Ice-ocean coupled models have proven to be useful for understanding the ice-water coupling and predict the regional circulation system. Wang et al. (2010) made a first attempt to develop the Great Lakes Ice-circulation Model (GLIM) and applied it to Lake Erie. They performed a hindcast from April 2003 to December 2004 with a spatial resolution of 2 km, reproducing the seasonal variation of ice cover as well as the water surface temperature. The influences of anomalous ice cover on lake circulation and thermal structure have not been known well. Recent studies by Fujisaki et al. (2012, 2013) showed that ice cover could significantly dampen the coastal flow in winter due to the ice-water stress coupling, based on a sensitivity study in 2003-2004 using the ice-lake model for Lake Erie.

2. Teleconnection Patterns Affecting the Great Lakes

2.1 Response of Great Lakes Ice Cover to Individual NAO and ENSO

Scatter plots between ice coverage and the NAO index (Fig. 1a), and the Nino3.4 index (Fig. 1b) were computed, respectively. Niño3.4 index is defined as the Niño region3.4 SST anomalies in degrees Celsius, where the Niño3.4 region is bounded by 120°W-170°W and 5°S- 5°N. The relationship between NAO and Great Lakes ice cover is basically linear, with the correlation coefficient being 0.27, implying that the ice cover tends to be lower (higher) than normal during positive (negative) NAO. To confirm the linearity relationship, we also calculated the correlation between ice cover and square of NAO index, which is only 0.10 with no significance even at the 90% significance level.

A systematic investigation by Bai et al. (2012) suggests that Great Lakes ice cover is influenced by NAO. The Great Lakes region tends to be colder (warmer) than normal and have higher (lower) ice cover during negative (positive) NAO (Fig. 1, left). The nonlinear relationship between Nino3.4 and Great Lakes ice cover is clearly identified in Figure 1 (right). The higher-than-average ice cover years are generally between -1.0 and 1.0 (weak or neutral ENSO episodes), while the lower-than-average dots are more scattered and tend to occur during strong El Niño or strong La Niña events, indicating that most of the maximal ice cover occurred during weak or neutral ENSO episodes, and most of the minimal ice cover occurred during strong El Niño or strong La Niña events.

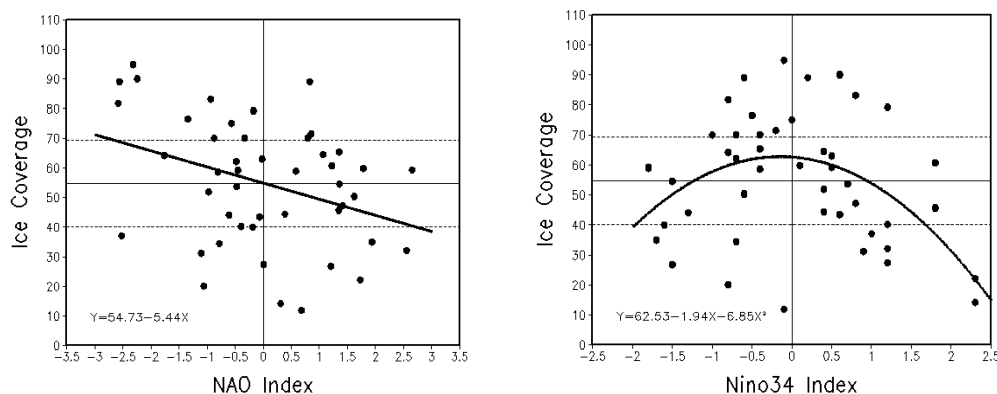


Figure 1. The plane scatter plot between ice coverage and NAO index (left) and Nino3.4 index (right) for the period 1963-2010. The regression curves are also calculated using the least square fit. The climatological, maximal, and minimal ice concentrations are 54.5%, 69.2%, and 39.8%, respectively. Note that $-0.5 < \text{index} < 0.5$ is a neutral event, $0.5 < |\text{index}| < 1.0$ is a weak event, and $1.0 < |\text{index}|$ is a strong event.

The above evidence suggests that the Great Lakes tend to be warmer than normal and thus, have lower ice cover during El Niño events, especially during strong El Niño events (Assel 1998). During La Niña events, although ice conditions on the Great Lakes are difficult to project, the Great Lakes tend to be warmer (colder) than normal during strong (weak) La Niña events, which is similar to the El Niño events. This non-linear, asymmetric response of Great Lakes ice to ENSO is due to the phase shift of the teleconnection patterns during the different phases of

ENSO, which is consistent with recent finding that impacts of ENSO on North American surface temperature is nonlinear and asymmetric.

2.2 Response of Great Lakes ice Cover to Combined NAO and ENSO

To demonstrate the combined effects of NAO and ENSO, the winters were simply classified into four climate states based on phases of ENSO and NAO (see Table 1): 1) +NAO/El Niño, 2) +NAO/La Niña, 3) –NAO/El Niño, and 4) –NAO/La Niña. In general, the Great Lakes tend to be warmer than normal and have less ice cover during El Niño events or +NAO events, and are colder than normal during -NAO or La Niña events. Note that La Niña events have weaker impacts on lake ice than El Niño events (i.e., the asymmetric influence). Thus, when a winter falls into simultaneous +NAO and El Niño episodes (state 1), it is expected to be warmer and have less ice cover, since +NAO and El Niño have the same warming effect on the Great Lakes. When a winter falls into –NAO and La Niña events at the same time (state 4), it is expected to be colder and produce more ice cover. Furthermore, if a winter happens to be in the state of –NAO/El Niño (state 3) or +NAO/La Niña (state 2), the competition of the two opposite effects (NAO and ENSO) could complicate the relationship.

Table 1. Four climate states and their possible combined impacts on Great Lakes surface air temperature, which is inverse to lake ice cover. Red (blue) indicates warm (cold).

Four Climate States	+AO/NAO (warm)	-AO/NAO (cold)
El Niño (warm, dry)	Extremely warm (State 1) 1973,1983,1992,1995,2007 (predictable @80%)	Normal (to cold) (State 3) 1966,1969 (less predictable)
La Niña (neutral-weak: cold; Strong: warm)	Normal (State 2) 1975, 1976, 1989, 2000, 2008, 2011/12 (less predictable)	Cold (neutral and weak La Niña) (State 4) Normal (strong La Niña , eg. 2010/11) 1965, 1985, 2001 (predictable @80%)

3. Prediction of Lake Ice

3.1 Long-Term Prediction of Great Lakes Ice Cover Using ENSO and NAO Indices

Although the combined NAO and ENSO cross-composite analyses as discussed above are based on limited samples in each climate state due to the limited length of the ice data records, the findings do shed light into the complexity of the nature in Great Lakes ice variability. Thus, regression models can be developed based on the findings to hindcast and forecast long-term (several months ahead as long as the NAO and Nino3.4 indices are available based on projection) Great Lakes ice coverage. The model takes the following form

$$z = a + bx + cy + dxy + exy^2 \quad (1)$$

where z is the normalized ice coverage, x and y are the predictors, NAO index and Nino3.4 index, respectively; a , b , c , d , and e are constants that are determined from observational data.

Through many trials of different regression models, the best hindcast/forecast model should include two important predictors: one is the NAO index and quadratic form of Nino3.4 index (nonlinear term), and the other is the product of NAO index and quadratic Nino3.4 index (the interference effects of NAO and ENSO).

When the interactive term $NAO \times Nino3.4^2$ is included, the model is expressed as:

$$z = 0.40 - 0.12Nino3.4 - 0.50Nino3.4^2 - 0.45NAO + 0.28NAO \times Nino3.4^2 \quad (2)$$

The statistic summary (Table 5 of Bai et al. 2012) indicates that including the product of NAO and quadratic Nino3.4 index significantly improves the prediction. Some ice maxima and minima are better captured (Fig. 2, green line).

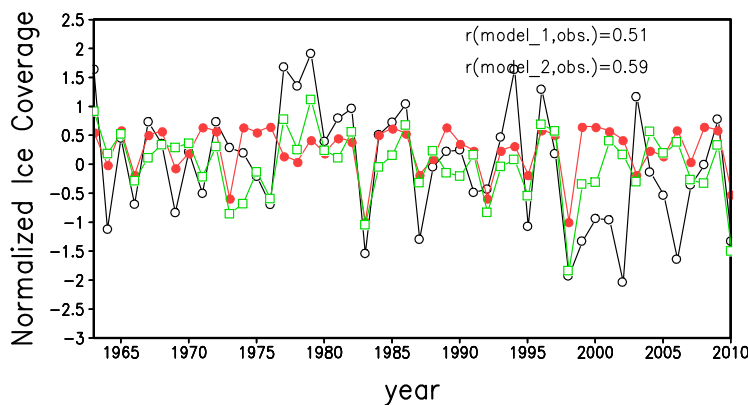


Figure 2. Modeled and observed normalized ice coverage for 1963-2010. Black is observations, red is estimated by regression model with Nino3.4 index, quadratic Nino3.4 index and NAO index as predictors (model 1), while green is estimated by regression model with Nino3.4 index, quadratic Nino3.4 index, NAO index and $NAO \cdot Nino3.4^2$ as predictors. The correlation coefficients are: $r(model_1, obs.) = 0.51$, $r(model_2, obs.) = 0.59$.

3.2 Short-Term Prediction of Great Lakes Ice Cover Using Coupled GLIM

To meet the increasing needs for winter rescue efforts, navigation, weather and lake condition forecasts, and recreation activities, a short-term forecast capability has been established using GLIM (Wang 2010). The GLIM was adapted from the Coupled Ice-Ocean Model (CIOM) developed by Wang et al. (2002, 2005), which fully couples a dynamic and thermodynamic ice model to the Princeton Ocean Model (POM). The GLIM is a combination of the CIOM developed and applied to the Arctic Ocean and subpolar seas (Yao et al., 2000; Wang et al., 2002, 2003, 2005, 2009; Long et al. 2012) and the Great Lakes version of the POM (Schwab and Bedford 1999; Beletsky and Schwab 2001). The ice model of CIOM is based on a thermodynamic and a dynamic model with a viscous-plastic sea ice constitutive law (Hibler 1979) and a multi-category ice thickness distribution function (Thorndike et al. 1975; Hibler 1980). The coupling between the ice and water is governed by the boundary processes as discussed by Mellor and Kantha (1989). The difference between GLIM and the CIOM is the adaptation of heat and momentum flux submodels from the POM-based Great Lakes Coastal Forecasting System (Schwab and Bedford, 1999) so that during ice-free season, the model is identical to the Great Lakes version of POM.

Wang et al. (2010) developed GLIM and validated it with available in situ (Fig. 3) and satellite measurements. Fujisaki et al. (2012) further improved the GLIM in ice-water coupling. Fujisaki et al. (2013) confirmed that wintertime lake circulation is significantly impacted by lake ice

cover and that with no ice model, thermal structure associated with extreme cooling and warming events associated with NAO and ENSO cannot be reproduced. Figure 3 shows the model-data comparison and indicates that the ice model reproduces very well the seasonal cycle and year-to-year changes in lake ice concentration in response to a changing climate.

In the GLCFS, GLIM not only predicts the previous hydrodynamic variables, but also lake ice cover (concentration), thickness, velocity, etc. Heat fluxes and lake ice growth rate can be estimated using GLIM (Fujisaki et al. 2013).

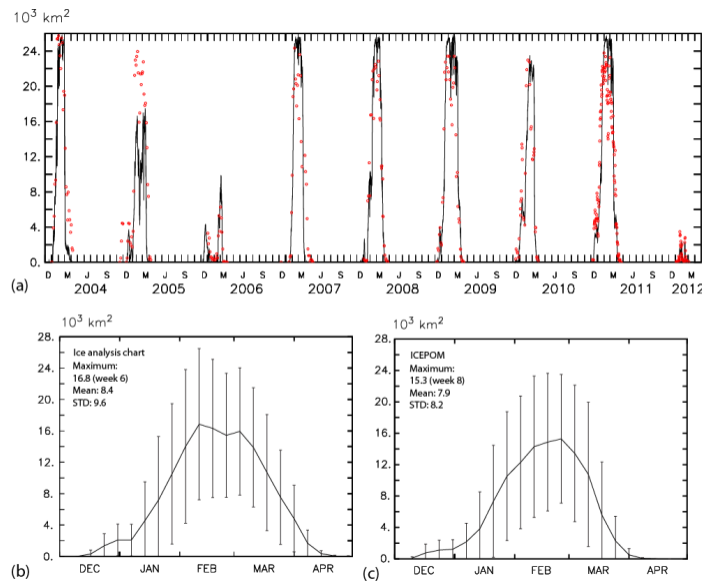


Figure 3. (a) Time series of total ice area from December 2003 to April 2012. Thick lines are from the model result, and red symbols are from the observational analyses based on the National Ice Center Great Lakes Ice Analysis Chart. The observational analyses are bi-weekly until the winter of 2009-2010, and daily afterwards. Weekly 9-year means are also shown for the ice analysis chart (b) and the model results (c). Bars in (b) and (c) denote the standard deviation.

GLIM was implemented into GLCFS lake by lake with different horizontal resolutions (Superior: 10km, Ontario: 5 km, and the others: 2 km), and forced by hourly atmospheric forcing using NOAA NAS National Digital Forecast Database (NDFD) to forecast lake ice and circulation conditions from 00 to 120 hours (5 days). Figure 4 shows the 5-day forecast of lake ice concentration in the 2011-12 ice season on 25 January 2012 (Fig. 4b), which compares very well with the National Ice Center (NIC) ice chart on the same day (Fig. 4a). The difference between the GLIM's forecast and NIC ice chart (Fig. 4c) shows that the GLIM prediction skills are very promising. GLIM is now in an operational forecast mode providing not only lake conditions, but also ice conditions to broader users and the interested community (<http://www.glerl.noaa.gov/res/glcfs/>).

7. Conclusions and Perspectives

Significant advances have been made during the past six years in Great Lakes ice research with respect to atmospheric teleconnection patterns. At the same time, coupled ice-lake modeling has been carried out over the Great Lakes for testing scientific hypotheses, hindcasting and forecasting. The NAO and ENSO are two leading, interactive forcings to the Great Lakes regional climate and ice variability; nevertheless neither of them alone can interpret the changes in regional climate and ice cover. The most important finding is that lake ice responds linearly to the NAO, but non-linearly to the ENSO, and that NAO and ENSO together influence the Great

Lakes. In addition, NAO and ENSO were used in statistical regression models to hindcast/forecast lake ice variation.

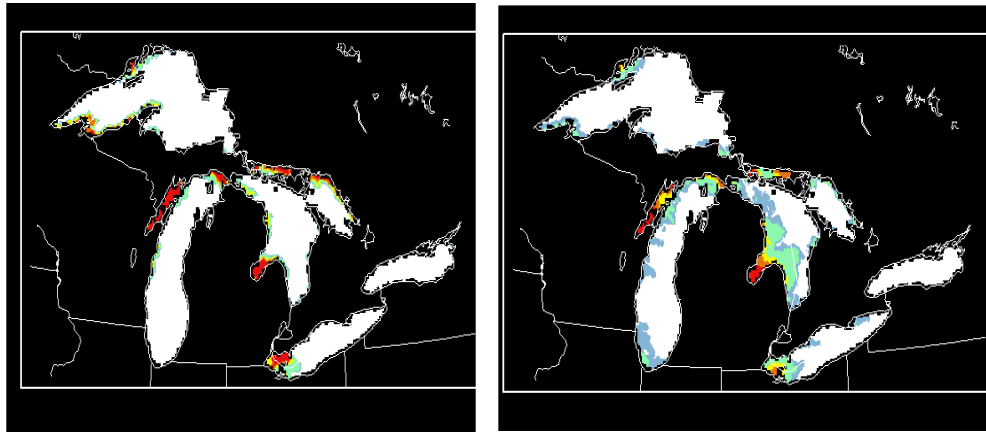


Figure 4. Satellite-measured lake ice concentration (left) and GLIM-forecasted 120 hour lake ice concentration (right).

GLIM was first developed to simulate the coupled ice-lake circulation system and to test research hypotheses. After model-data verification, GLIM was incorporated into the GLCFS for an operational 5-day prediction, providing timely lake and ice conditions on the NOAA GLERL website to broader users. This forecasting product provides significant benefits to the local economy by aiding winter navigation, rescue efforts, and winter recreation.

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