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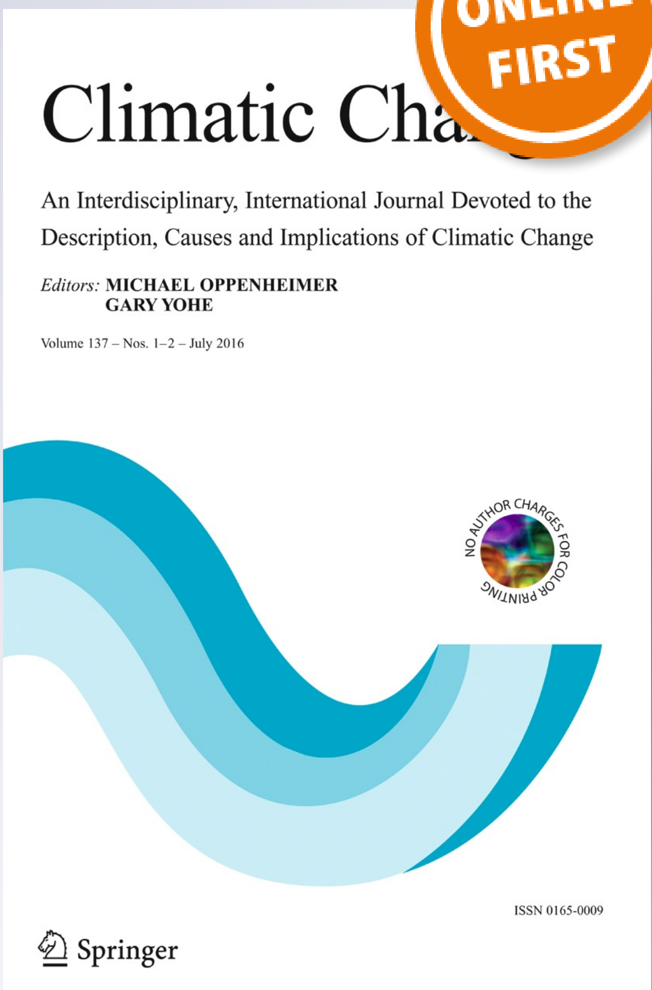

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Fine-scale spatial variation in ice cover and surface temperature trends across the surface of the Laurentian Great Lakes

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Abstract The effects of climate change on north temperate freshwater ecosystems include increasing water temperatures and decreasing ice cover. Here we compare those trends in the Laurentian Great Lakes at three spatial scales to evaluate how warming varies across the surface of these massive inland water bodies. We compiled seasonal ice cover duration (1973–2013) and lake summer surface water temperatures (LSSWT; 1994–2013), and analyzed spatial patterns and trends at lake-wide, lake sub-basin, and fine spatial scales and compared those to reported lake- and basin-wide trends. At the lake-wide scale we found declining ice duration and warming LSSWT patterns consistent with previous studies. At the lake sub-basin scale, our statistical models identified distinct warming trends within each lake that included significant breakpoints in ice duration for 13 sub-basins, consistent linear declines in 11 sub-basins, and no trends in 4 sub-basins. At the finest scale, we found that the northern- and eastern-most portions of each Great Lake, especially in nearshore areas, have experienced faster rates of LSSWT warming and shortening ice duration than those previously reported from trends at the lake scale. We conclude that lake-level analyses mask significant spatial and

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temporal variation in warming patterns within the Laurentian Great Lakes. Recognizing spatial variability in rates of change can inform both mechanistic modeling of ecosystem responses and planning for long-term management of these large freshwater ecosystems.

1 Introduction

Temperature is a fundamental factor influencing lake physical and ecological properties (Nicholls 1999). Over the last four decades, lake summer surface water temperatures (LSSWT) across the Laurentian Great Lakes have increased dramatically (Austin and Colman 2007; Dobiesz and Lester 2009) while ice cover has decreased (Magnuson et al. 2000; Assel et al. 2003; Austin and Colman 2007; Titze and Austin 2014). These changes, including the observation that water temperatures have been increasing faster than regional air temperatures (Austin and Colman 2007), have been interpreted as evidence of climate forcing mechanisms (Wang et al. 2005; Austin and Colman 2007; Wang et al. 2014). LSSWT warming rates in the Laurentian Great Lakes are higher than expected given their latitude and size, but are well within the global range of warming trends (mean of 0.034 °C yr.−1; O'Reilly et al. 2015).

The Laurentian Great Lakes are a focal point for global freshwater research due to their collective surface area and volume, long-term records of temperature and other environmental conditions, and extensive data on anthropogenic stressors (Allan et al. 2013). Changes in ice cover and LSSWT across this massive system, along with documented changes in lake heat content (Gronewold et al. 2015), have profound implications for water levels (Assel et al. 2003; Gronewold et al. 2013) and regional climate patterns (Bai et al. 2010). The ecology of large lakes is also dramatically altered by warming, including changes in lake circulation (Kraemer et al. 2015), ecosystem productivity (Magnuson et al. 1997; Woodward et al. 2010; Vadadi-Fülöp et al. 2012), regional economies (Allison et al. 2009), and habitat availability for both native and invasive species (Mandrak 1989; Rahel et al. 2008; Smith et al. 2012).

Long-term trends in ice cover and LSSWT within the Laurentian Great Lakes have provided important insights into climate change impacts on regional hydrology and ecosystem functioning (Magnuson et al. 2000; Assel et al. 2003; Austin and Colman 2007; Gronewold et al. 2015), but have been quite limited in spatial resolution. Previous analyses typically have been based on data from a few buoy or intake locations (e.g., McCormick and Fahnenstiel 1999; Austin and Colman 2007) or averaged across an entire lake surface from either multiple locations (Dobiesz and Lester 2009), or higher resolution, interpolated data (Assel et al. 2003; Wang et al. 2012b; Van Cleave et al. 2014). These approaches leave a gap in understanding of spatiotemporal variation in responses to climate change within each lake. Lake sub-basins offer the benefits of averaging across fine-scale variability, yet remain detailed enough to address individual restoration projects, management decisions at local to regional scales, and potential synergies with other stressors. As such, analyses at intermediate scales are called for by the Council of Governors (Seelbach et al. 2014) as well as by the Great Lakes Restoration Initiative (http://greatlakesrestoration.us) to aid in measuring what has been accomplished with federal restoration funding. As a complement, evaluating warming trends at even finer spatial scales could help to identify the influence of particular geomorphic characteristics as well as providing guidance for localized climate adaptation efforts in the Laurentian Great Lakes.

In this paper, we evaluate trends in seasonal ice cover duration and LSSWT across the Great Lakes at lake-wide, lake sub-basin, and fine spatial scales, and compare those to previously reported lake-wide and Great Lakes Basin trends (Assel et al. 2003; Schneider and Hook 2010;

O'Reilly et al. 2015). Our approach leverages recent advances in geospatial referencing for the Great Lakes region, particularly the Great Lakes Aquatic Habitat Framework (Wang et al. 2015). This nested, hierarchical spatial framework enables attribution and trend analysis of data at lake-wide, intermediate (lake sub-basin), and fine (grid cell) scales; and thereby facilitates ice cover and LSSWT analyses at multiple spatial scales. Our study has two major objectives: 1) to develop new long-term ice cover and LSSWT data sets at fine spatial scales for the entire Laurentian Great Lakes; and, 2) to enhance quantitative understanding of spatiotemporal variability in long-term impacts of climate change in the Great Lakes region.

2 Methods

2.1 Dataset development

We obtained historical ice cover and LSSWT data for the entire surface of the Laurentian Great Lakes and attributed it to the common spatial framework outlined above (Wang et al. 2015). Daily ice cover records from the Canadian Ice Service and the U.S. National Ice Center have been compiled and maintained in the Great Lakes Ice Atlas (GLIA) for the period from 1973 to 2005 (http://www.glerl.noaa.gov/data/ice/atlas/; Assel 2003, 2005) on a 2.5 km x 2.5 km grid. Daily ice cover records in the GLIA include a combination of observed and interpolated data beginning on December 1 and we associate the duration of ice cover with the calendar year in which the ice season ends. From 2006 to 2013, we used a separate database of ice cover that includes observed values only (Wang et al. 2012a) on a 1.275 km x 1.275 km grid. To harmonize across the differences in grid resolution and data continuity, we used the temporal interpolation scheme of Assel (2005) and resampled the GLIA data onto the higher-resolution grid used from 2006–2013, removing any non-coincident cells between grids. Our metric of seasonal ice cover duration was the number of days per year for which a grid cell had >10 % ice cover.

Daily LSSWT was based on satellite-derived imagery that used algorithms that account for cloud cover (Leshkevich et al. 1993; Schwab et al. 1999) and were obtained from the NOAA CoastWatch Great Lakes Node database (http://coastwatch.glerl.noaa.gov/). This database, commonly referred to as the Great Lakes Surface Environmental Analysis (GLSEA), starts in 1994. Data from 1994 to 2007 have a 2.5 km x 2.5 km resolution, while data from 2007 to 2013 have a 1.8 km x 1.8 km resolution. For this study, we resampled the 1994–2007 data onto a 1.8 km x 1.8 km grid in order to obtain a continuous record of daily gridded surface temperatures from 1994 to 2013 at the same spatial resolution and calculated mean LSSWT during the warm season (July–September; Austin and Colman 2007; Schneider and Hook 2010).

2.2 Statistical analyses

We analyzed trends in seasonal ice cover duration and LSSWT at three spatial scales to evaluate the effect of spatial scale on our interpretations of changes in thermal regimes in the Great Lakes over the last few decades at the lake-wide, intermediate (lake sub-basin) and fine (individual grid cell) scales. For the lake-wide and intermediate analyses, we calculated the average seasonal ice cover duration (d) and LSSWT (°C) of all grid cells aggregated across each of the five Great Lakes and the 17 lake sub-basins by year (Fig. 1).

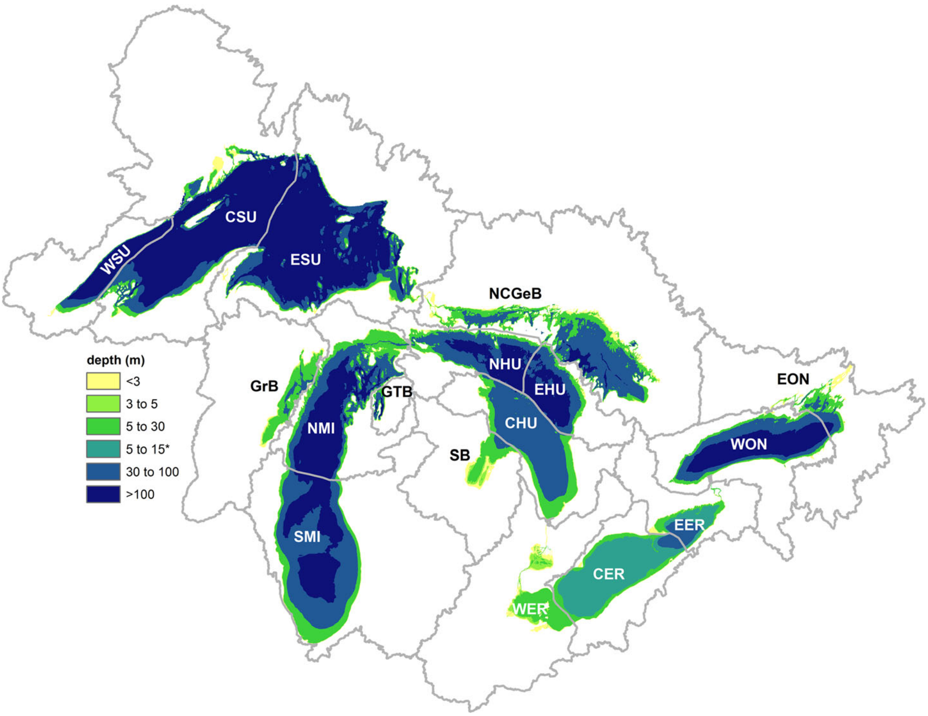

Fig. 1 Laurentian Great Lakes lake sub-basins (Wang et al. 2015) and depth strata (m). Lake sub-basins are labeled as Western Lake Superior (WSU); Central Lake Superior (CSU); Eastern Lake Superior (ESU); North Channel and Georgian Bay (NCGeB); Northern Lake Huron (NHU); Eastern Lake Huron (EHU); Central Lake Huron (CHU); Saginaw Bay (SB); Northern Lake Michigan (NMI); Southern Lake Michigan (SMI); Green Bay (GrB); Grand Traverse Bay (GTB); Western Lake Erie (WER); Central Lake Erie (CER); Eastern Lake Erie (EER); Western Lake Ontario (WON); and Eastern Lake Ontario (EON). *5 to 15 m depth contour only shown in Lake Erie

At both lake-wide and intermediate spatial scales we evaluated trends in ice duration by applying three Bayesian Markov chain Monte Carlo simulation statistical models to datasets for the five lakes and 17 lake sub-basins. We used linear regression models to test the extent to which a single non-zero trend explains long-term changes in ice duration and broadened this conventional perspective by exploring change-point and equal-mean models. We included equal-mean models to calculate and compare skill metrics across all three models using deviance information criteria (DIC; Spiegelhalter et al. 2002). We ran a change-point model to compare the explanatory power of linear and change-point modeling approaches and to explore the spatial extent of linkages between historical shifts in Great Lakes ice cover and the strong winter El Niño of 1997–1998 (Rodionov and Assel 2003).

At the lake-wide and intermediate scales we assessed changes in LSSWT (°C; 1994–2013) for each of the five Great Lakes and 17 lake sub-basins using ordinary least squares (OLS) linear regression models. We only used the OLS linear regression models because the limited time span of the LSSWT data did not allow for the rigorous Bayesian analysis using the three models described above for seasonal ice cover duration.

We analyzed fine scale patterns in both ice duration and LSSWT by calculating the long-term mean and trend of ice duration and LSSWT for each grid cell. Trends were estimated as the slope of an OLS linear trend models significantly different from zero ($p < 0.1$). To link ice duration with LSSWT in the following summer, we calculated Pearson's correlations across the years 1994 to 2013 for every grid cell. We also evaluated the cumulative frequency distribution of ice duration and LSSWT to examine the rates of changes and compare patterns in trends by lake.

Data processing were performed in Python 2.7 utilizing the Arcpy module and maps created in Esri ArcGIS version 10.3.1. We estimated parameters of the lake-wide and intermediate scale ice duration analysis Bayesian models in the statistical software package WinBUGS (see Online Resource 1 for code; Lunn et al. 2000). We calculated correlation and OLS linear regression model coefficients and their statistical significance (p < 0.05), and cumulative frequency distributions using the R environment (R Development Core Team 2015) and Python Numpy and Scipy modules.

3 Results and discussion

Our objectives were to evaluate spatiotemporal variability in historical seasonal ice cover duration and LSSWT trends in the Great Lakes at multiple scales to improve our understanding of the spatial variation of climate change effects on large lake systems. The lake-wide linear trend models identified significant, decreasing trends in seasonal ice cover duration (p < 0.05) for Lakes Superior, Huron, Michigan, and Ontario (−0.96, −0.67, −0.55, −0.43 d yr.$^{-1}$, respectively). Lake Erie also showed a decreasing trend in ice duration at −0.59 d yr.$^{-1}$, but was not significant. These rates of ice reduction are similar to those reported by Jensen et al. (2007) for small lakes in the upper Midwest (average of −0.53 d yr.$^{-1}$ from 1975–2004). Wang et al. (2012b) found similar patterns in decreasing ice cover for the upper Great Lakes with Lake Superior decreasing most rapidly at a rate of −599 km yr.$^{-1}$ followed by Lakes Huron and Michigan (−323 and −241 km yr.$^{-1}$, respectively) and much slower rates for Lakes Erie, Ontario and St. Clair.

The change-point models at the lake-wide scale suggested a temporal shift in ice duration and provided a better explanation for the observed data than either linear or equal-mean models (Online Resource 2). For Lakes Superior and Huron the shift in ice duration coincides with the strong El Niño Southern Oscillation (ENSO) winter of 1997–1998, but for Lakes Michigan, Erie, and Ontario the shift occurred in the mid-1980s. The widely-referenced results of Wang et al. (2012b) indicate that the Great Lakes have lost roughly 70 % of their surface ice cover since 1973. Our analysis indicates that the decrease in ice duration on Lakes Superior and Huron since the 1970s can be attributed almost entirely to a state-shift in the late 1990s, but varied by lake with Lake Superior decreasing by roughly 54 % and Lake Huron roughly 35 % underscoring the additional insights gained from exploring ice cover data at different spatial scales and using different models.

The lake-wide OLS linear trend models for LSSWT identified significant, increasing LSSWT (p < 0.05) for Lakes Ontario and Huron (0.10, 0.09 °C yr.$^{-1}$, respectively), which are higher than those reported for 167 large inland lakes from 1985–2009 satellite data (0.05 to 0.06 °C yr.$^{-1}$; Schneider and Hook 2010). We also found positive although not significant trends for Lakes Erie, Michigan and Superior (0.06, 0.09, and 0.14 °C yr.$^{-1}$, respectively). Our lake-wide warming trends are comparable and in some cases higher than warming trends estimated by Austin and Colman (2007) from 1979–2006 buoy data (range 0.01 to 0.16 °C yr.$^{-1}$) although significance of the trends was not reported.

We evaluated trends at the intermediate scale (Fig. 1) for seasonal ice cover duration, and found more spatially and temporally variable patterns within lakes than historical studies (Wang et al. 2012b) depending on the model evaluated. While the Bayesian linear models identified significant decreasing trends in ice duration for 11 of the 17 lake sub-basins, the change-point models provided the best explanation for changes in 13 of the 17 sub-basins based on DIC metrics (Fig. 2). The change-point coincided with the strong 1997–1998 winter ENSO in the six northern-most sub-basins and either before or during this event for 11 of the sub-basins. Previous studies have suggested strong impacts of the 1997–1998 ENSO on the thermal regime of the Great Lakes (Van Cleave et al. 2014), but our intermediate scale analysis is the first to show that the repercussions vary between and within lakes. The apparent strength of breakpoints in many sub-basins suggests that changes in ice duration have not been consistent through time throughout the basin (Fig. 2) and that extrapolating trends fitted from linear models into the future (e.g., Austin and Colman 2007) may not be adequate to explain the variability in warming trends throughout the Great Lakes. Future work should explore alternative models that account for autocorrelation when fitting patterns in time series data such as the approach suggested by Qian (2014) comparing four common models for time series data including: simple linear, change-point, ”hockey stick”, and ”broken hockey stick” models.

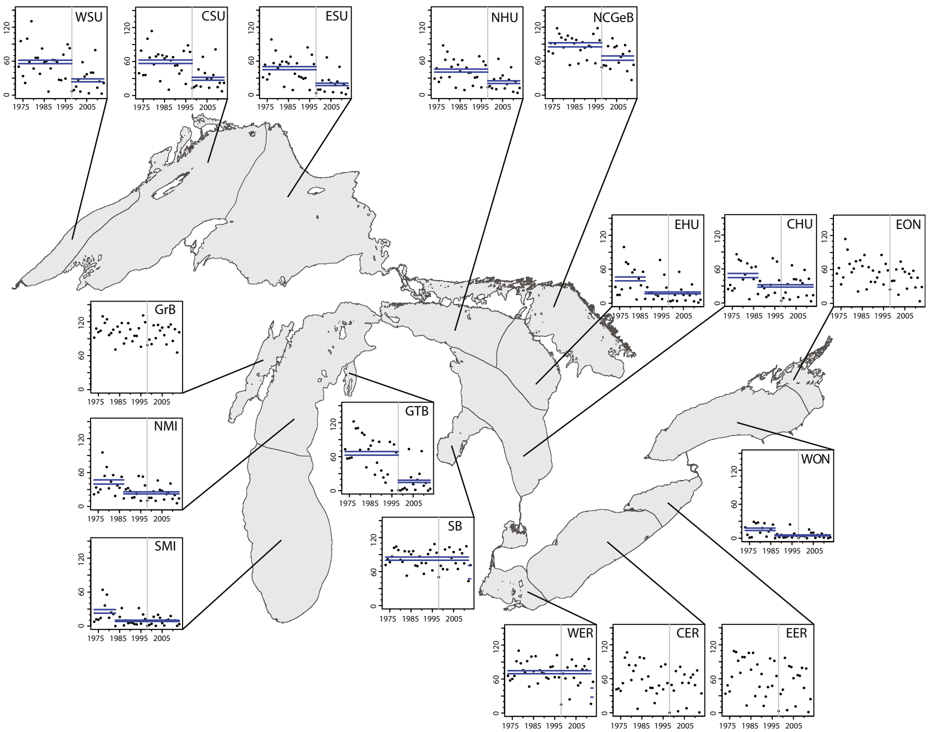

Fig. 2 Great Lakes seasonal ice cover duration and lake summer surface water temperature (LSSWT) results by lake sub-basin. The slope of the linear model results for ice duration are shown in *blue* (significance denoted by *), and for LSSWT shown in *orange* (significance at $p < 0.05$ denoted by ** and $p < 0.1$ denoted by *). The graphs show the change-point model results where the *black dots* represent observed mean ice duration, *blue lines* represent the 95 % credible interval based on the change-point model, and *vertical grey lines* indicate the year 1998

Using OLS linear models we found consistent warming trends in LSSWT for the 17 lake sub-basins (Fig. 2). The eight northern- and eastern-most lake sub-basins were warming significantly and at faster rates than other sub-basins within each lake and across the Great Lakes suggesting a consistent spatial pattern of warming within all of the lakes ($p < 0.05$: EHU, EON, NCGeB, and WON at 0.11, 0.10, 0.07, and 0.08 °C yr.$^{-1}$, respectively; $p < 0.1$: CHU, EER, ESU, and NMI at 0.07, 0.05, 0.16, and 0.09 °C yr.$^{-1}$, respectively). Ten of the lake sub-basins are warming at similar rates to lake-wide trends (0.06–0.14 °C yr.$^{-1}$), with one lake sub-basin warming faster (ESU; 0.16 °C yr.$^{-1}$) and six sub-basins warming slower than lake-wide trends; the slowest warming trends occurred in WER and WSU (0.04 °C yr.$^{-1}$).

Our analysis of fine-scale trends in ice duration and LSSWT (Fig. 3a and b) reveals substantial spatial heterogeneity in the effects of climate change across the Laurentian Great Lakes. The highest rates of declining ice duration were found in the northern areas of the Great Lakes, but rapid declines also predominated in coastal areas on the eastern shoreline of each lake. Lake Superior, the northern-most and deepest lake, has experienced the most extreme declines in ice duration of at least 0.5 d yr.$^{-1}$, but remarkably, along the Lake Superior shoreline, especially in the north and east, ice duration has been declining at a rate of ~2 d yr.$^{-1}$. This is a two- to four-fold increase in lake-wide rate of ice loss. Other areas with similarly high rates of diminishing ice duration include Grand Traverse Bay in Lake Michigan, small portions of southern Lake Huron, and Georgian Bay (Fig. 3a). Historically, ice cover duration was relatively long in these areas where it has declined so rapidly (Fig. 3c), although this pattern does not apply to certain other high-ice regions, including Green Bay, Saginaw Bay, and much of central Lake Erie.

From 1994 to 2013, LSSWTs have been increasing significantly across roughly half of the surface area of the Great Lakes while showing no discernable trend elsewhere (Fig. 3b). In

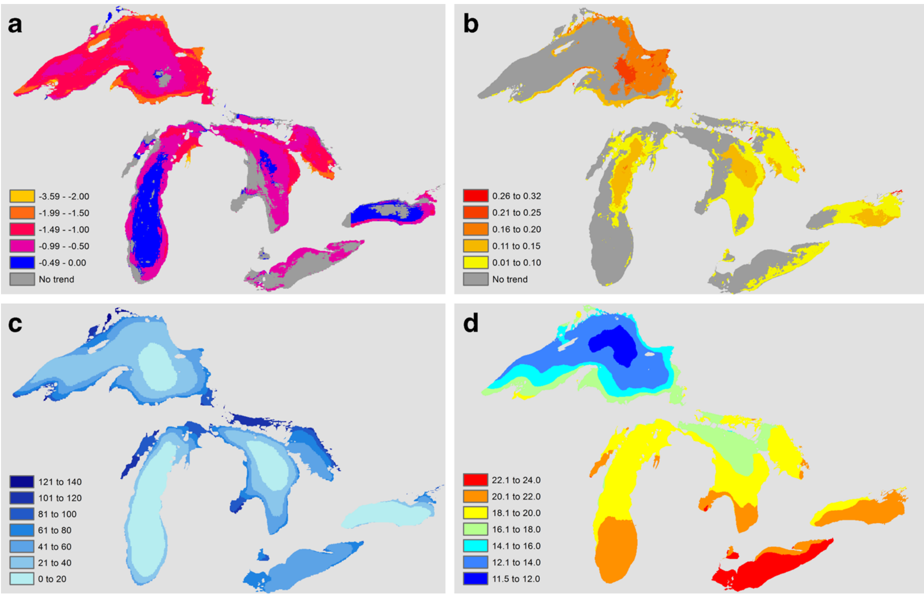

Fig. 3 (**a**) Seasonal ice cover duration slope (d yr.$^{-1}$) of the linear regression trend model from 1973 to 2013; (**b**) summer surface water temperature (SWT) slope (°C yr.$^{-1}$) of the linear regression trend model from 1994 to 2013; (**c**) mean ice duration (d) for the years 1973–2013; and (**d**) mean summer SWT (°C) for the years 1994–2013

Lake Superior, LSSWT has warmed fastest around the coastline and the eastern portion of the lake. Warming on the other lakes has been primarily confined to either the north-central (Lake Michigan) or eastern regions (Lakes Huron, Erie, and Ontario). We compared our fine scale trends with trends in the buoy data for the same time period and found general agreement for Lakes Superior, Huron, Michigan, and Erie.

The enormous spatial variability in the rate of LSSWT change offers insights into lake physical processes above and beyond those from research based on lake-wide average temperatures alone (Fig. 3d). Previous studies using lake-wide averages have shown a relatively rapid rate of LSSWT increase for Lake Superior (Austin and Colman 2007). Our fine-scale analysis (Fig. 3b), however, indicates that within a lake there are spatial patterns that reflect other geophysical factors such as bathymetry, predominant wind direction, and lake-wide circulation patterns that are consistent across lakes (Beletsky et al. 1999). Bathymetry influences spatial variability in LSSWT across the Great Lakes because heat storage capacity is proportional to water depth (Assel et al. 2003) and reflected in this analysis where depths greater than 100 m (Fig. 1) have the fastest warming trends in Lakes Superior, Michigan, Huron, and Ontario (Fig. 3b). Consistent patterns of upwelling of cooler water along the western coasts caused by southwest to northeast wind pattern in the summer and Ekman drift (Bennington et al. 2010; Pilcher et al. 2015; Wang et al. 2015) coincide with areas that experience the slowest rate of warming identified in our fine-scale analysis. Frequent upwelling buffers surface warming rates by the input of hypolimnetic waters, which have both a cooler baseline temperature and lower rate of warming than the epilimnion (Kraemer et al. 2015). Climate change could affect wind speed and direction over the lake surface (Desai et al. 2009) which would influence the frequency of upwelling events and thermal patterns in the Great Lakes as was observed in Africa's Lake Tanganyika (O'Reilly et al. 2003).

Our fine-scale analysis also elucidates major differences among the five Laurentian Great Lakes in rates of ice cover loss and surface water warming (Fig. 4). For example, the median rate of decrease in ice duration in Lake Superior is double that in Lakes Michigan and Ontario (−1.067, −0.511, −0.400 d yr.$^{-1}$, respectively), while Lake Erie shows intermediate rates of ice

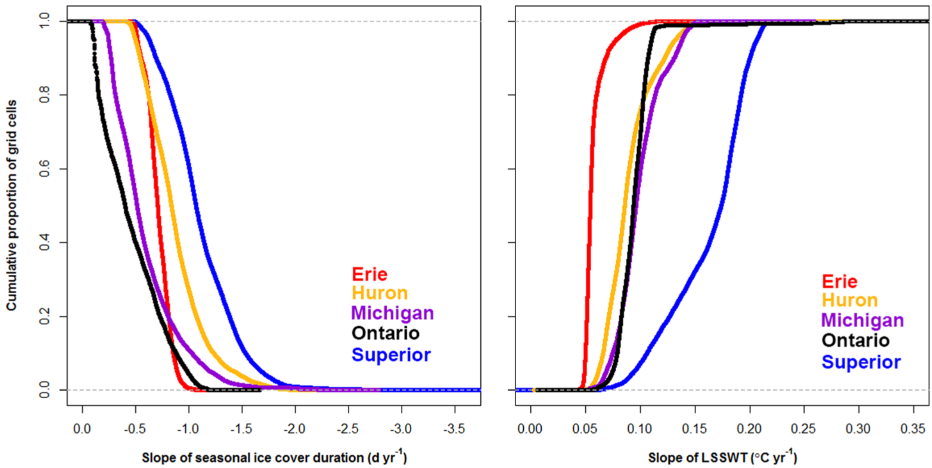

Fig. 4 Cumulative frequency distributions of rates of ice cover loss observed from 1973–2013 (left) and warming of summer surface water temperature observed from 1994–2013 (right). Each curve depicts the cumulative proportion of all grid cells in a lake that were changing more rapidly than a given rate

cover loss that are surprisingly uniform across its surface. Similarly, the median rate of surface water warming in Lake Superior (0.174 °C yr.$^{-1}$) exceeds that observed anywhere in the other lakes (0.054 to 0.96 °C yr.$^{-1}$), whereas even the 90th percentile of warming rates in Lake Erie (0.068 °C yr^{1}) is lower than the 20th percentile in all other lakes (0.071 to 0.127 °C yr.$^{-1}$). These lake-level comparisons reveal a lack of consistent latitudinal or longitudinal ordering of warming rates and ice loss; rates of LSSWT change in Lake Huron are intermediate between those in Erie and Ontario despite lying north and west of both. Rates of LSSWT change also reveal an ordering based on average depth as shallow Lake Erie (mean depth 19 m) has substantially lower rates than the other four lakes (mean depths 57–150 m) and deep Superior (150 m) is substantially higher. Moreover, the rank order of lakes differs between ice loss and surface water warming; Huron is the second slowest in water warming yet the second fastest in ice cover declines.

Spatial patterns of correlation between ice duration and LSSWT from 1994–2013 indicate strong concordance of these two metrics (Fig. 5). The correlations are very strong along the northern, eastern, and southern shorelines of Lake Superior, and in relatively small discrete regions of Lakes Michigan and Huron (−0.92 to −0.80). The central region of Lake Superior, most of Lake Huron, northern Lake Michigan, and the southern coastline of Lake Michigan also show strong correlations (−0.79 to −0.60). These areas have experienced, and will likely continue to experience, remarkably rapid surface water warming and loss of ice cover.

The combination of long-term decline in ice duration and increased LSSWT could result in wide-ranging economic and ecological effects. Many of the coastal regions impacted by severe ice loss are significant population centers or tourist destination for which winter ice cover has important implications for the regional economy and human health (Allan et al. 2015). For example, change in ice cover in the Apostle Islands, Lake Superior has a profound impact on tourism; when ice cover is high because low ice cover leads to decreased visitation due to safety and accessibility concerns (http://www.nps.gov/apis/learn/news/upload/Economic-Impact-of-APIS-2013.pdf). Shifts in lake heat budgets as ice and surface temperature dynamics are altered can also lead to changes in evaporation rates that affect water levels (Gronewold et al. 2013) with ensuing effects on shipping activity. For example, Millerd (2011) found an increase from 8 to 12 days in the average navigation season between the years of 1994–1998 and 2004–2008 for the sections of the St. Lawrence Seaway and the Welland Canal, respectively, due to a shortened ice cover season.

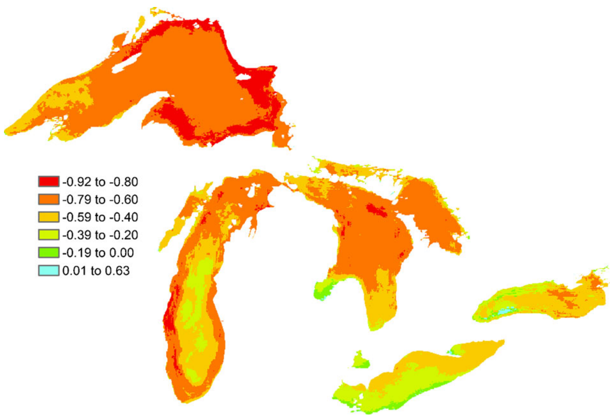

Fig. 5 Pearson's correlation coefficient across years (1994–2013) between seasonal ice cover duration (d; December–May) and mean lake summer surface water temperature (°C; July–September) for the following summer for each year and grid cell

Heterogeneity in long-term changes in ice duration and LSSWT also have profound implications for Great Lakes food webs. Fish recruitment and reproductive success (Brown et al. 1993), growth potential (Kao et al. 2015), and community structure (Magnuson et al. 1997) are all influenced by the thermal regime. Fish physiological processes are strongly temperature dependent, and may show strong thermal thresholds (Ficke et al. 2007). Long-term sampling has identified changes in fish community structure as temperatures have shifted in Lake Ontario (Casselman 2002), Lake Superior (Cline et al. 2013), and across the Great Lakes (Bunnell et al. 2014). Inshore areas of Lake Ontario, like the Bay of Quinte, have experienced increased LSSWT and decreased ice cover since the 1970's in conjunction with increased abundances of warmwater species (small mouth bass, *Micropterus dolomieu*), decreased abundance of cold water species (lake trout, *Salvelinus namaycush*) and a nonlinear response for abundance of cool water species (northern pike, *Esox lucius*) (Casselman and Scott 2003). Thermally suitable habitat may occur in different regions of the lakes resulting in range expansion or contraction (Ficke et al. 2007; Lynch et al. 2010). Moreover, the phenology of both plankton growth (Vanderploeg et al. 1993) and fish spawning (Lyons et al. 2015) in the Great Lakes is changing as the waters warm.

The fine-scale variation in the magnitude of warming within the Great Lakes suggests that effects on species ranges and ecological dynamics are likely to be patchy. Thus, high-resolution spatial data on warming can help local managers protect thermal refuge habitats in regions where rapid warming is most likely to affect vulnerable species such as cold-water specialists such as lake trout (*Salvelinus namaycush*) or those requiring specific ice conditions to protect overwintering eggs (e.g., lake whitefish, *Coregonus clupeaformis*; Lynch et al. 2010; Woodward et al. 2010). Further, Mandrak (1989) estimated that 27 fish species have a high potential for invading the Great Lakes due to expanding thermal ranges in Great Lakes habitats. Documenting spatial variation in rates of change in thermal habitat could help mangers to identify locations where invasive species are most likely to become established.

Shorter ice duration and warmer LSSWT would likely increase the length of the stratification period, which varies with winter air temperature and the depth of the lake (Titze and Austin 2014). Increased duration of stratification could result in decreased concentration of dissolved oxygen in the hypolimnion, release of phosphorus from the sediments contributing to eutrophication, and reductions in cold-water habitat (Bates et al. 2008). Earlier onset of stratification can hasten the onset of phytoplankton blooms, thereby disrupting trophic transfer to zooplankton and the upper food web already extensively altered by invasive species (Woodward et al. 2010). Early stratification could also buffer the impacts of the invasive filtering dreissenid mussel on concentrations of chlorophyll a by isolating the mussels from the water column earlier during the spring algal bloom (Barbiero and Tuchman 2004; Cha et al. 2013). Declines in ice duration can also have strong effects on terrestrial ecosystems. For example, population dynamics of wolf and moose on Isle Royale in Lake Superior depend on access from the mainland via ice bridges; loss of ice cover has reduced wolf densities and boosted moose populations (Peterson et al. 2014).

4 Conclusions

Our fine- and intermediate-scale analyses reveal extensive spatial variation in rates of warming and ice cover loss across the surface of these enormous lakes and leverages the power of satellite remote sensing for assessing climate change impacts (Schneider and Hook 2010;

O'Reilly et al. 2015). Ultimately, diagnosing both spatial and temporal patterns of changing ice duration and LSSWT will make it possible to tailor adaptation strategies to the local scale of potential impacts on aquatic communities and societal interests and may help to elucidate the complex physical linkages between the two. The extensive spatiotemporal data made accessible through this study (www.glahf.org) will enable a new generation of statistical exploration and hypothesis generation about how global climate change affects large temperate lakes.

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References

Allan JD, McIntyre PB, Smith SDP, et al. (2013) Joint analysis of stressors and ecosystems services to enhance restoration effectiveness. P Natl A Sci 110(1):372–377

Allan JD, Smith SDP, McIntyre PB, et al. (2015) Using cultural ecosystem services to inform restoration priorities in the Laurentian Great Lakes. Front Ecol Environ 13(8):418–424

Allison EHL, Perry MC, Badjeck N, et al. (2009) Vulnerability of national economies to the impacts of climate change on fisheries. Fish Fish 10(2):173–196

Assel, R (2003) Great Lakes ice cover, first ice, last ice, and ice duration. NOAA Great Lakes Environmental Research Laboratory. http://www.glerl.noaa.gov/ftp/publications/tech_reports/glerl-125/. Accessed 1 February 2016

Assel R (2005) Great Lakes ice cover climatology update: winters 2003, 2004, and 2005. NOAA Great Lakes Environmental Research Laboratory. http://www.glerl.noaa.gov/ftp/publications/tech_reports/glerl-135/tm-135.pdf. Accessed 1 February 2016

Assel R, Cronk K, Norton D (2003) Recent trends in Laurentian Great Lakes ice cover. Clim Chang 57(1–2): 185–204

Austin JA, Colman SM (2007) Lake superior summer water temperatures are increasing more rapidly than regional air temperatures: a positive ice-albedo feedback. Geophys Res Lett 34(6):1944–8007 L06604

Bai X, Wang J, Sellinger C, Clites A, Assel R (2010) The impacts of ENSO and AO/NAO on the interannual variability of Great Lakes ice cover. NOAA Great Lakes Environmental Research Laboratory. http://www.glerl.noaa.gov/ftp/publications/tech_reports/glerl-152/tm-152.pdf. Accessed 26 April 2016

Barbiero RP, Tuchman ML (2004) Long-term dreissenid impacts on water clarity in Lake Erie. J Great Lakes Res 30(4):557–565

Bates B, Kundzewicz ZW, Wu S, Palutikof J (2008) Climate change and water: technical paper VI. Intergovernmental Panel on Climate Change. http://ipcc.ch/pdf/technical-papers/climate-change-water-en.pdf. Accessed 1 February 2016.

Beletsky D, Saylor JH, Schwab DJ (1999) Mean circulation in the Great Lakes. J Great Lakes Res 25(1):78–93

Bennington V, McKinley GA, Kimura N, Wu CH (2010) General circulation of Lake Superior: mean, variability, and trends from 1979 to 2006. J Geophys Res-Oceans 115(C12)

Brown RW, Taylor WW, Assel RA (1993) Factors affecting the recruitment of lake whitefish in two areas of northern Lake Michigan. J Great Lakes Res 19(2):418–428

Bunnell DB, Barbiero RP, Ludsin SA, et al. (2014) Changing ecosystem dynamics in the Laurentian Great Lakes: bottom-up and top-down regulation. Bioscience 64(1):26–39

Casselman JM (2002) Effects of temperature, global extremes, and climate change on year-class production of warmwater, coolwater, and coldwater fishes in the Great Lakes basin. In: McGinn NA (ed) Fisheries in a changing climate. American Fisheries Society, Bethesda, pp. 39–60

Casselman JM, Scott KA (2003) Fish-community dynamics of Lake Ontario: long term trends in the fish populations of eastern Lake Ontario and the Bay of Quinte. In: Munawar M (ed) The state of Lake Ontario: past, present, and future, ecovision world monograph series. Aquatic Ecosystem Health and Management Society, Burlington, pp. 349–384

Cha Y, Stow CA, Bernhardt ES (2013) Impacts of dreissenid mussel invasions on chlorophyll and total phosphorus in 25 lakes in the USA. Freshw Biol 58(1):192–206

Cline TJ, Bennington V, Kitchell JF (2013) Climate change expands the spatial extent and duration of preferred thermal habitat for Lake Superior fishes. PLoS One 8(4):e62279. doi:10.137/journal.pone.0062279

Desai AR, Austin JA, Bennington V, McKinley G (2009) Stronger winds over a large lake in response to weakening air-to-lake temperature gradient. Nat Geosci 2(12):855–858. doi:10.1038/NGEO693

Dobiesz NE, Lester NP (2009) Changes in mid-summer water temperature and clarity across the Great Lakes between 1968 and 2002. J Great Lakes Res 35(3):371–384

Ficke AD, Myrick CA, Hansen LJ (2007) Potential impacts of global climate change on freshwater fisheries. Rev Fish Biol Fish 17(4):581–613

Gronewold AD, Fortin V, Lofgren B, Clites A, Stow CA, Quinn F (2013) Coasts, water levels, and climate change: a Great Lakes perspective. Clim Chang 20(4):697–711

Gronewold A, Anderson EJ, Lofgren B, Blanken PD, Wang J, Smith J, Hunter T, Lang G, Stow CA, Beletsky D, Bratton J (2015) Impacts of extreme 2013–2014 winter conditions on Lake Michigan's fall heat content, surface temperature, and evaporation. Geophys Res Lett 42:3364–3370. doi:10.1002/2015GL063799

Jensen OP, Benson BJ, Magnuson JJ, Card VM, Futter MN, Soranno PA, Stewart KM (2007) Spatial analysis of ice phenology trends across the Laurentian Great Lakes region during a recent warming period. Limnol Oceanogr 52(5):2013–2026

Kao Y-C, Madenjian CP, Bunnell DB, Lofgren BM, Perroud M (2015) Potential effects of climate change on the growth of fishes from different thermal guilds in lakes Michigan and Huron. J Great Lakes Res 41:423–435

Kraemer BM, Anneville O, Chandra S, et al. (2015) Morphometry and average temperature affect lake stratification responses to climate change. Geophys Res Lett 42. doi:10.1002/2015GL064097

Leshkevich GA, Schwab DA, Muhr GC (1993) Satellite environmental monitoring of the Great Lakes: a review of NOAA's Great Lakes CoastWatch program. Photogramm Eng Remote Sens 59(3):371–379

Lunn DJ, Thomas A, Best N, Spiegelhalter D (2000) WinBUGS: a Bayesian modelling framework: concepts, structure, and extensibility. Stat Comput 10:325–337

Lynch A, Taylor W, Smith K (2010) The influence of changing climate on the ecology and management of selected Laurentian Great Lakes fisheries. J Fish Biol 77(8):1764–1782

Lyons J, Rypel AL, Rasmussen PW, Burzynski TE, Eggold BT, Myers JT, Paoli TJ, McIntyre PB (2015) Trends in the reproductive phenology of two Great Lakes fishes. Trans Am Fish Soc 144:6. doi:10.1080/00028487.2015.1082502

Magnuson JJ, Webster K, Assel R, et al. (1997) Potential effects of climate changes on aquatic systems: Laurentian Great Lakes and Precambrian shield region. Hydrol Process 11(8):825–871

Magnuson JJ, Robertson DM, Benson BJ, et al. (2000) Historical trends in lake and river ice cover in the northern hemisphere. Science 289(5485):1743–1746

Mandrak NE (1989) Potential invasion of the Great Lakes by fish species associated with climatic warming. J Great Lakes Res 15(2):306–316

McCormick MJ, Fahnenstiel GL (1999) Recent climatic trends in nearshore water temperatures in the St. Lawrence Great Lakes. Limnol Oceanogr 44(3):530–540

Millerd F (2011) The potential impact of climate change on Great Lakes international shipping. Clim Chang 104: 629–652. doi:10.1007/s10584-010-9872-z

Nicholls KH (1999) Effects of temperature and other factors on summer phosphorus in the inner Bay of Quinte, Lake Ontario: implications for climate warming. J Great Lakes Res 25(2):250–262

O'Reilly CM, Alin SR, Plisnier P-D, Cohen AS, McKee BA (2003) Climate change decreases aquatic ecosystem productivity of Lake Tanganyika, Africa. Nature 424:766–768

O'Reilly CM, Sharma S, Gray D, et al. (2015) Rapid and highly variable warming of lake surface waters around the globe. Geophys Res Lett 42. doi:10.1002/2015GL066235

Peterson RO, Vucetich JA, Bump JM, Smith DW (2014) Trophic cascades in a multicausal world: Isle Royale and Yellowstone. Annu Rev Ecol Evol S 45:325–345

Pilcher DJ, McKinley GA, Bootsma HA, Bennington V (2015) Physical and biogeochemical mechanisms of internal carbon cycling in Lake Michigan. J Geophys Res Oceans 120:2112–2128. doi:10.1002/2014JC010594

Qian SS (2014) Ecological threshold and environmental management: a note on statistical methods for detecting thresholds. Ecol Indic 38:192–197

R Development Core Team (2015) R: a language and environment for statistical computing, R Foundation for Statistical Computing, Vienna. http://www.R-project.org/. Accessed 1 February 2016

Rahel FJ, Bierwagen B, Taniguchi Y (2008) Managing aquatic species of conservation concern in the face of climate change and invasive species. Conserv Biol 22(3):551–561

Rodionov S, Assel RA (2003) Winter severity in the Great Lakes region: a tale of two oscillations. Clim Res 24: 19–31

Schneider P, Hook SJ (2010) Space observations of inland water bodies show rapid surface warming since 1985. Geophys Res Lett 37(22). doi:10.1029/2010GL045059

Schwab DJ, Leshkevich GA, Muhr GC (1999) Automated mapping of surface water temperature in the Great Lakes. J Great Lakes Res 25(3):468–481

Seelbach PW, Read J, Buckner K, Eder T, Manninen C (2014) Great Lakes blue accounting: empowering decisions to realize regional water values, a report to the Council of Great Lakes Governors, in response to the governors' 2013 resolution on water monitoring. Great Lakes Commission, Ann Arbor

Smith AL, Hewitt N, Klenk N, Bazely DR, Yan N, Wood S, Henriques I, MacLellan JI, Lipsig-Mummé C (2012) Effects of climate change on the distribution of invasive alien species in Canada: a knowledge synthesis of range change projections in a warming world. Environ Rev 20(1):1–16

Spiegelhalter DJ, Best NG, Carlin BP, Van Der Linde A (2002) Bayesian measures of model complexity and fit. J Royal Statistical Society: Series B (Statistical Methodology) 64(4):583–639

Titze DJ, Austin JA (2014) Winter thermal structure of Lake Superior. Limnol Oceanogr 59(4):1336–1348

Vadadi-Fülöp C, Sipkay C, Mészáros G, Hufnagel L (2012) Climate change and freshwater zooplankton: what does it boil down to? Aquat Ecol 46(4):501–519

Van Cleave K, Lenters JD, Wang J, Verhamme EM (2014) A regime shift in Lake Superior ice cover, evaporation, and water temperature following the warm El Niño winter of 1997–1998. Limnol Oceanogr 59(6):1889–1898

Vanderploeg H, Liebig J, Omair M (1993) Bythotrephes predation on Great Lakes' zooplankton measured by an in situ method: implications for zooplankton community structure. Arch Hydrobiol 127(1):1–8

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

Wang J, Assel RA, Walterscheid S, Clites AH, Bai X (2012a) Great Lakes ice climatology update, winters 2006–2011, description of the digital ice cover dataset. NOAA Great Lakes Environmental Research Laboratory. http://www.glerl.noaa.gov/ftp/publications/tech_reports/glerl-155/. Accessed 1 February 2016

Wang J, Bai X, Hu H, Clites A, Colton M, Lofgren B (2012b) Temporal and spatial variability of Great Lakes ice cover, 1973-2010. J Clim 25(4):1318–1329

Wang J, Eicken H, Yu Y, Bai X, Zhang J, Hu H, Wang DR, Ikeda M, Mizobata K, Overland JE (2014) Abrupt climate changes and emerging ice-ocean processes in the Pacific Arctic region and the Bering Sea. In: Grebmeier J, Maslowski W (eds) The pacific arctic region. Springer, Netherlands, pp. 65–99

Wang L, Riseng CM, Mason LA, et al. (2015) A spatial classification and database for management, research, and policy making: the Great Lakes aquatic habitat framework. J Great Lakes Res 41(2):584–596

Woodward G, Perkins DM, Brown LE (2010) Climate change and freshwater ecosystems: impacts across multiple levels of organization. Phil T Roy Soc B 365(1549):2093–2106