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Great Lakes Ice Climatology Update of Winters 2012-2017: Seasonal Cycle, Interannual Variability, Decadal Variability, and Trend for the period 1973-2017

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INTRODUCTION

The 6-winter (2012-2017) digital ice cover data set includes 996 ice charts of total ice concentration, which were added to GLERL's ice dataset. This report updates GLERL's 45-winter ice climatology dataset, 1973-2017. The temporal distribution of the ice charts is also summarized. The original ice charts were produced by the U.S. National Ice Center (NIC) and downloaded from their website as ASCII files, http://www.natice.noaa.gov/products/great_lakes.html. The data format, quality control, processing using ArcGIS, and availability are the same as sections 2-6 of Wang et al. (2012a)

Since the last updated ice dataset (Wang et al. 2012a), there has been significant change in ice cover on the Great Lakes. This update of the ice dataset should be useful to the research community as well as others who rely on Great Lakes ice data for planning purposes. The technical memorandum that updated the ice atlas for winters 2006-2011 (Assel et al., 2013; Wang et al. 2012a) includes ArcGIS feature class files.

Lake ice cover is a sensitive indicator of regional climate and climate change (Assel et al (1995); Assel and Robertson (1995) ; Magnuson et al (1997,2000). Seasonal ice cover repeats each year with large interannual variability. For example, the maximum ice coverage over all of the Great Lakes was 95% in 1979 and only 11% in 2002 (Bai et al**.** 2012). Recently, 2014 and 2015 winter ice cover in the Great Lakes reached 92% and 88%, respectively, while ice cover in winters 2016 and 2017 experienced very low ice cover, 34% and 19%, respectively. Possible contributors include interannual and interdecadal climate variability, and long-term trends (Assel 1990; Wang et al. 2017), some of which may be 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 an individual lake's orientation, depth (i.e., water heat storage, Assel et al. 2003), and turbidity (i.e., albedo due to sedimentation).

DISTRIBUTION OF ICE CHARTS BY WINTER SEASON

The number of ice charts per winter season for the years 2012 to 2017 range from 136 to 195; the dates of first ice charts range from the middle of November to the beginning of December and the last ice charts range from the middle of April to the beginning of June. Since the winter season of 2011, the NIC has been producing daily charts for each winter season allowing for daily ice chart analysis.

Table 1. Summary of Ice Chart Statistics

Winter Season	Number of Ice Charts	Date of First Ice Chart	Date of Last Ice Chart
2012	136	November 29th	April 13th
2013	177	November 29th	May 28th
2014	192	November 24th	June 5th
2015	195	November 14th	May 29th
2016	160	November 27th	May 5th
2017	136	December 11th	April 26th

ANALYSIS OF UPDATED GREAT LAKES ICE COVER: 1973-2017

Seasonal Cycle

The spatial, long-term mean annual maximum ice cover in the Great Lakes was constructed based on ice chart data from the winter seasons of 1973 to 2017 (Figure 1). The biweekly climatology of ice cover in the Great Lakes was also produced for all six individual lakes (Figure 2). Shallow lakes (St. Clair and Erie) are seen to have an earlier ice cycle; reaching maximum ice cover and ice break-up sooner than the deep lakes. The seasonal ice cycle in the Great Lakes consists of an ice onset, growing period in which the annual maximum ice cover area is reached and then an ice offset. The average growth of ice cover over time follows a similar pattern in all of the Great Lakes; ice onset begins in all of the lakes during early December and has a growing period that lasts anywhere between mid-February (Erie) to early March (Superior). In general, ice melts completely during late April to late May.

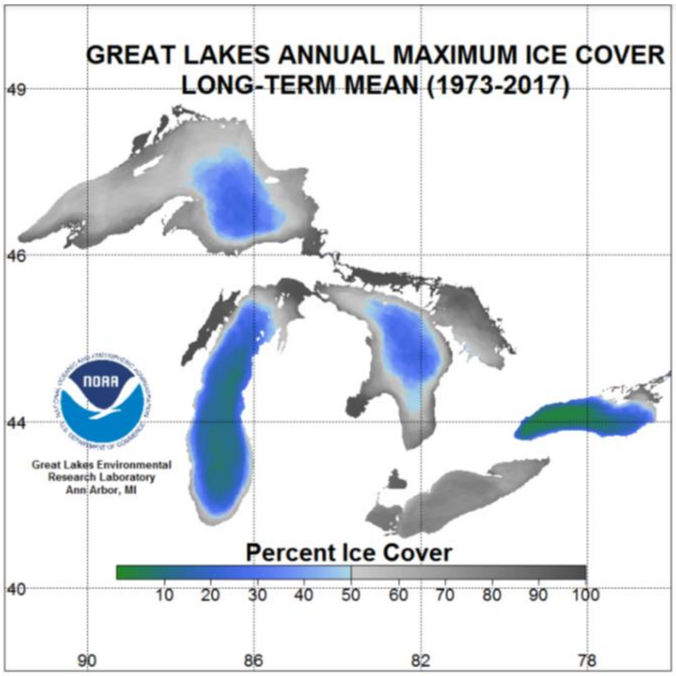


Figure 1. Long-term Mean Annual Maximum Ice Cover (AMIC) in the Great Lakes

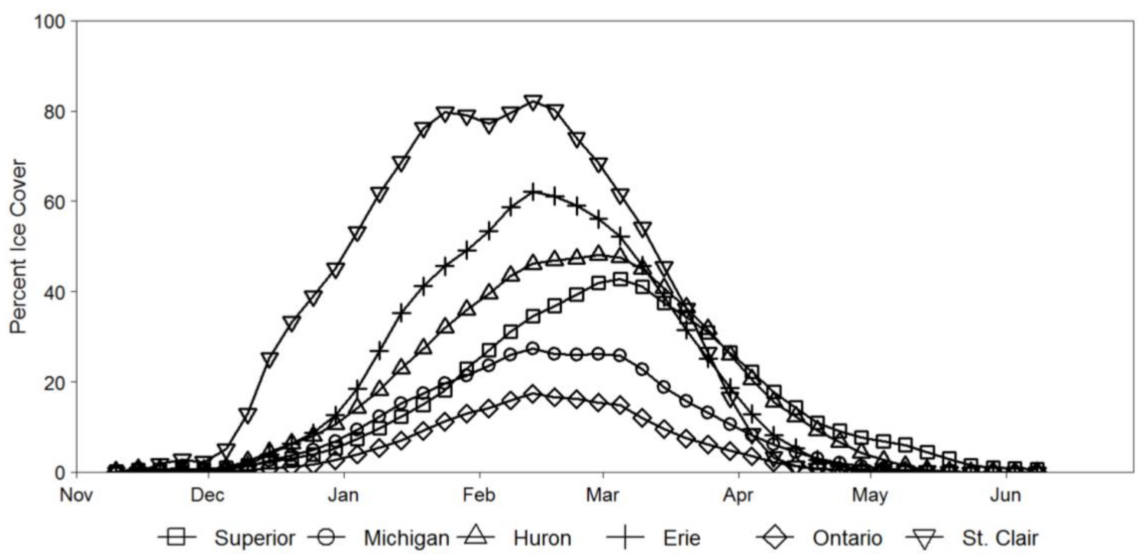
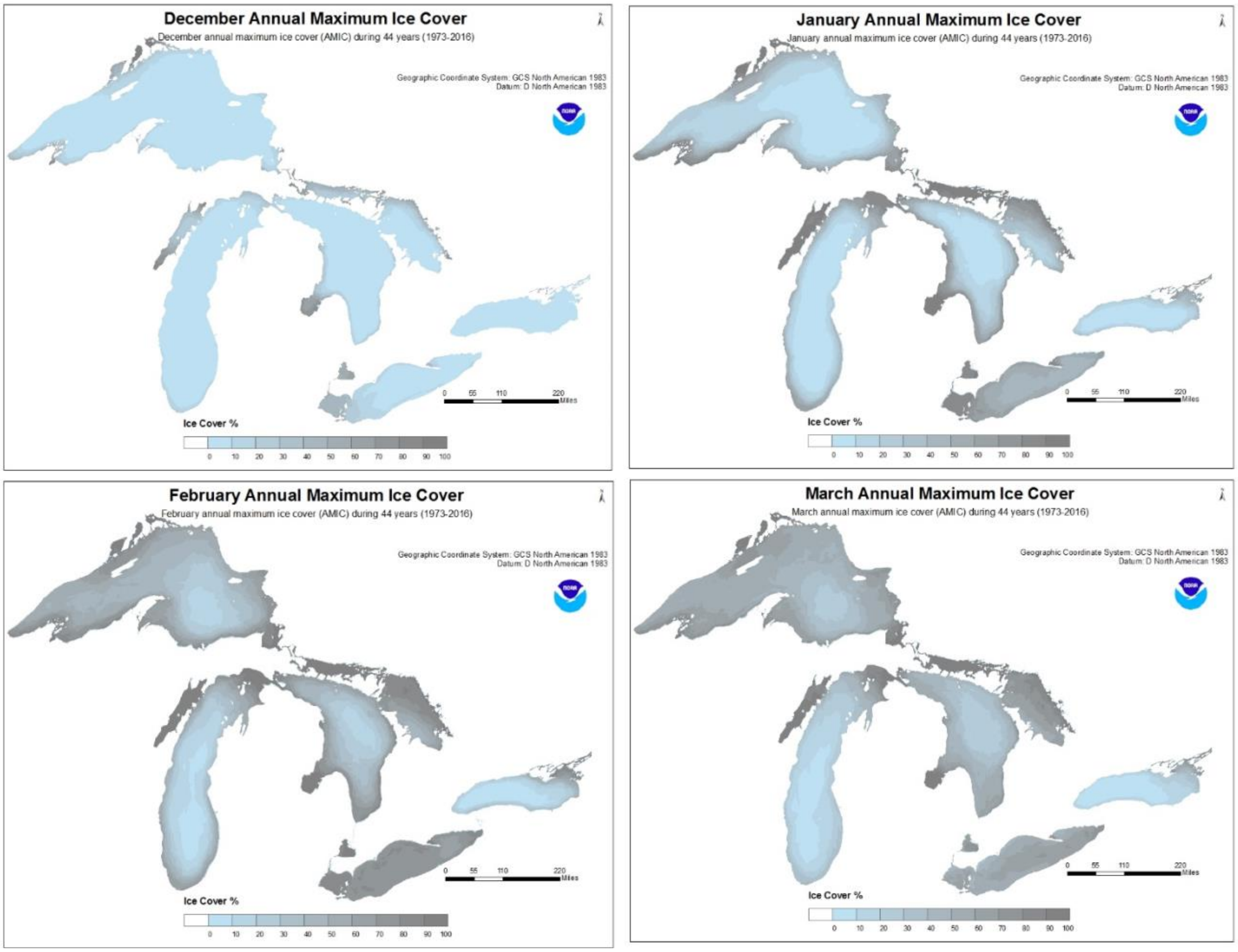


Figure 2. Biweekly Climatology of Ice Cover in the Great Lakes (1973-2017 Winter Seasons)



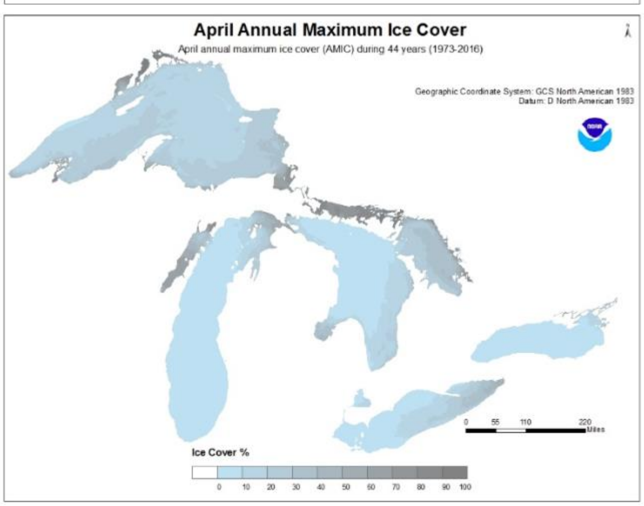


Figure 3. Climatological maps for monthly Annual Maximum Ice Cover (AMIC) in all five Great Lakes for December, January, February, March, and April for the period 1973-2017.

Figure 3 shows the spatial distribution of Great Lakes monthly AMIC for December to April average over the period 1973-2017. In November or December, ice starts to form along the shallow coast and embayments including western Lake Erie, and progresses into January, reaching the maximum ice cover in February in the southern lakes (Erie and Ontario) and in March in the northern Lakes (Superior and Huron). Ice gradually decays in April.

Seasonal Variations

To begin analyzing interannual variations in Great Lakes ice cover, the mean daily lake average ice cover for every measured date in the winter season is determined across the 45-winter period (Figure 4). On average, ice forms on Lake Superior in week 45, which is earlier than all the other lakes (Table 1). Ice-onset occurs in week 46 on Lakes Michigan and Huron; and week 47 on Lakes Erie, Ontario, and St. Clair. The growing period of ice cover ranges from 11 to 16 weeks. Lakes Superior reaches the seasonal maximum area during week 9, Lakes Michigan, Huron, Ontario, and St. Clair during week 7 and Lake Erie during week 6. Ice cover begins breaking within a week or two after maximum ice cover is reached and melts completely around week 20 for all lakes except Superior (week 21).

The corresponding weekly variations defined by standard deviations of annual ice cover indicates that Lakes St. Clair, Erie and Huron have the lowest ratio of standard deviations to the mean, and Lake Ontario has the highest ratio. The ratio is inversely proportional to predictability. This implies that ice cover in Lakes St. Clair, Erie and Huron have the highest predictability, while ice cover on Lake Ontario has the lowest predictability. The overall predictability in all of the Great Lakes is low since the climatological standard deviations of lake ice cover are often of equal magnitude (and at times greater magnitude) than the corresponding climatological mean.

Based on Figure 4, Lake St. Clair is observed to have an apparent, local ice cover minimum during week 5 and dual maxima during weeks 4 and 6. This large seasonal variability of lake ice may be a result of extreme weather events caused by natural, internal climate patterns (Wang et al., 2012a).

Table 2. Statistics of Seasonal Cycle Dates (Week Number)

	Superior	Michigan	Huron	St. Clair	Erie	Ontario
Onset	45	46	46	47	47	47
Maximum	9	7	7	7	6	7
Break-up	10	8	10	8	7	9
Offset	21	20	20	20	20	20

Interannual Variability

Time series of weekly ice cover area for all six lakes have been constructed based on the ice concentration data for the winters of 1973 to 2017 (Fig. 5). All lakes are observed to have high interannual variability of ice cover. For shallow water lakes Erie and St. Clair, almost complete ice cover is achieved for all 45-winter seasons (with the exception of 1983, 1991, 1998, 2002, 2006, 2012, 2013, 2016 and 2017 in Lake Erie and 1992, 2002, 2012, 2016 and 2017 in Lake St. Clair). This demonstrates that considering only lake ice cover may not be sufficient in detecting possible climate signals in shallow water lakes that are constrained by their bathymetry (Wang et al., 2012a).

Lake Erie experienced the least amount of ice cover during the 1983, 1991 and 1998 winter seasons (period of 7-8 years). Though this phenomenon is most apparent in Lake Erie, a similar result can be recognized across the other lakes as well. Furthermore, in recent years (starting in 1998), relatively low levels of ice cover have consistently occurred every 3-4 years. This might imply greater interannual variability of climate patterns in the Great Lakes within the past two decades compared to previous winter years.

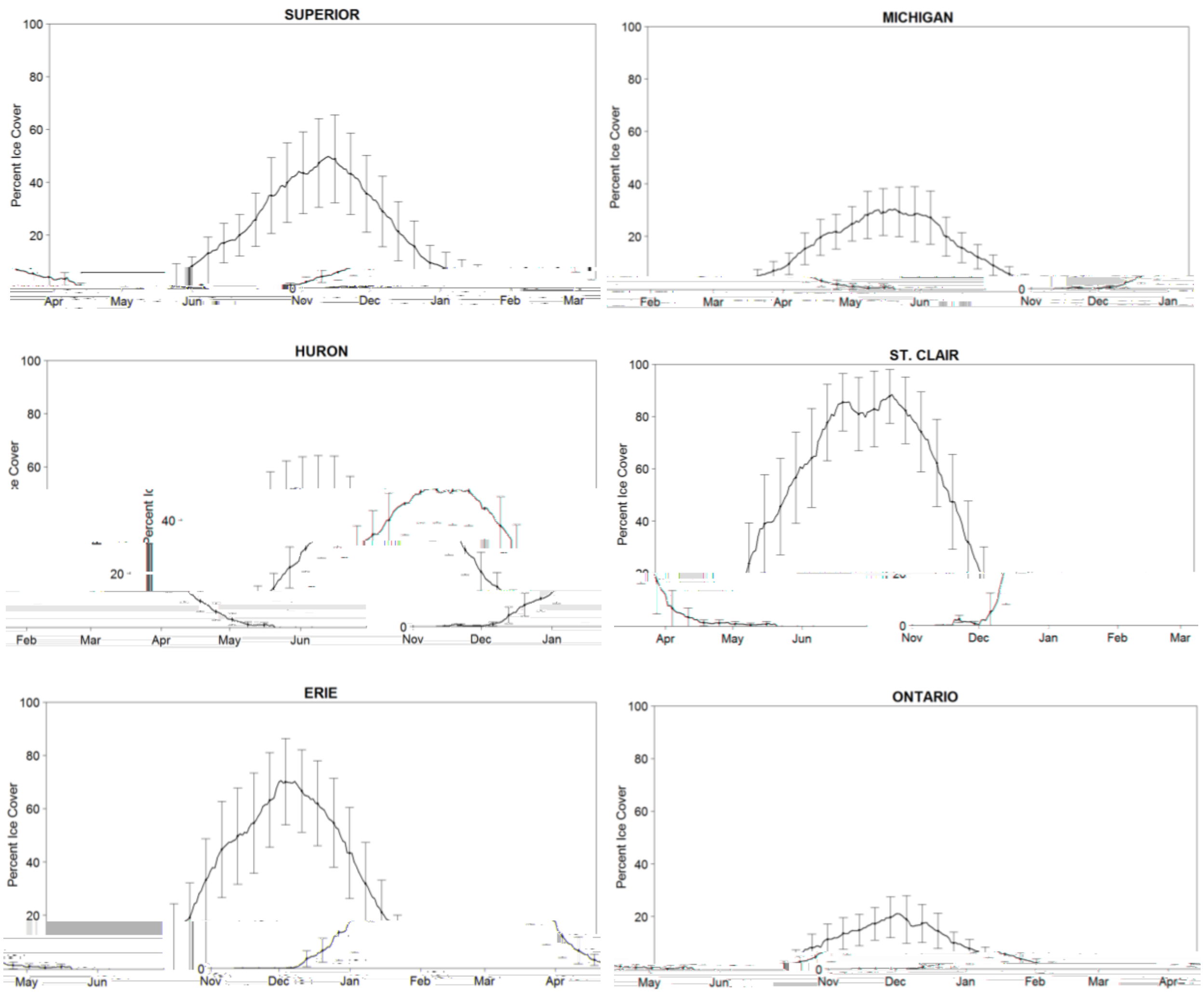


Figure 4. Seasonal Variation of Weekly Ice Coverage

Time series plots for the ice cover annual mean in the Great Lakes are produced for each lake (Figure 6). Each lake is observed to have large interannual variability over time. This may imply a uniform, major response of lake ice to atmospheric interannual variability of teleconnection patterns such as NAO and ENSO (Bai et al. 2012).

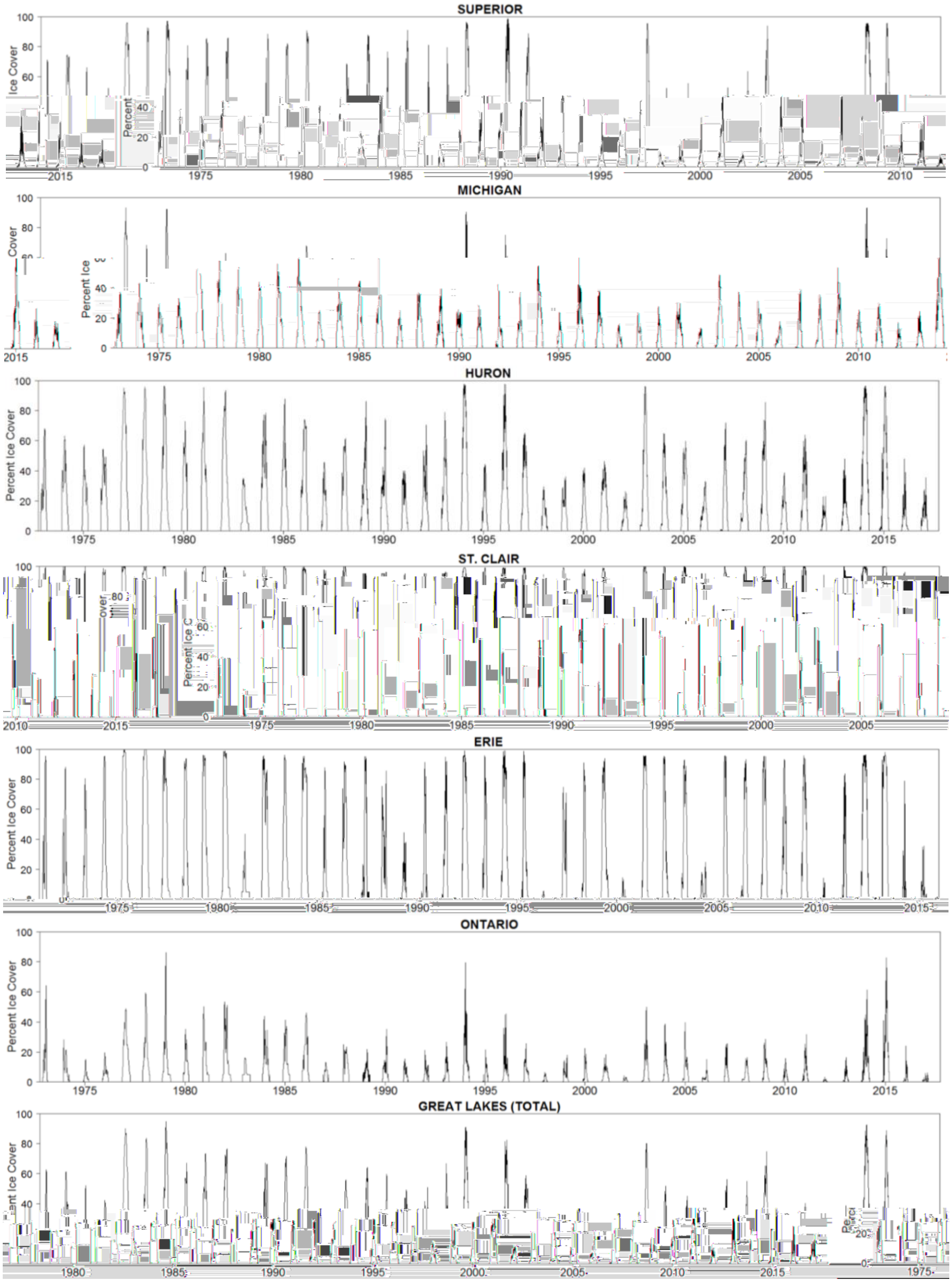


Figure 5. Time Series of Ice Cover in the Great Lakes, 1973-2017

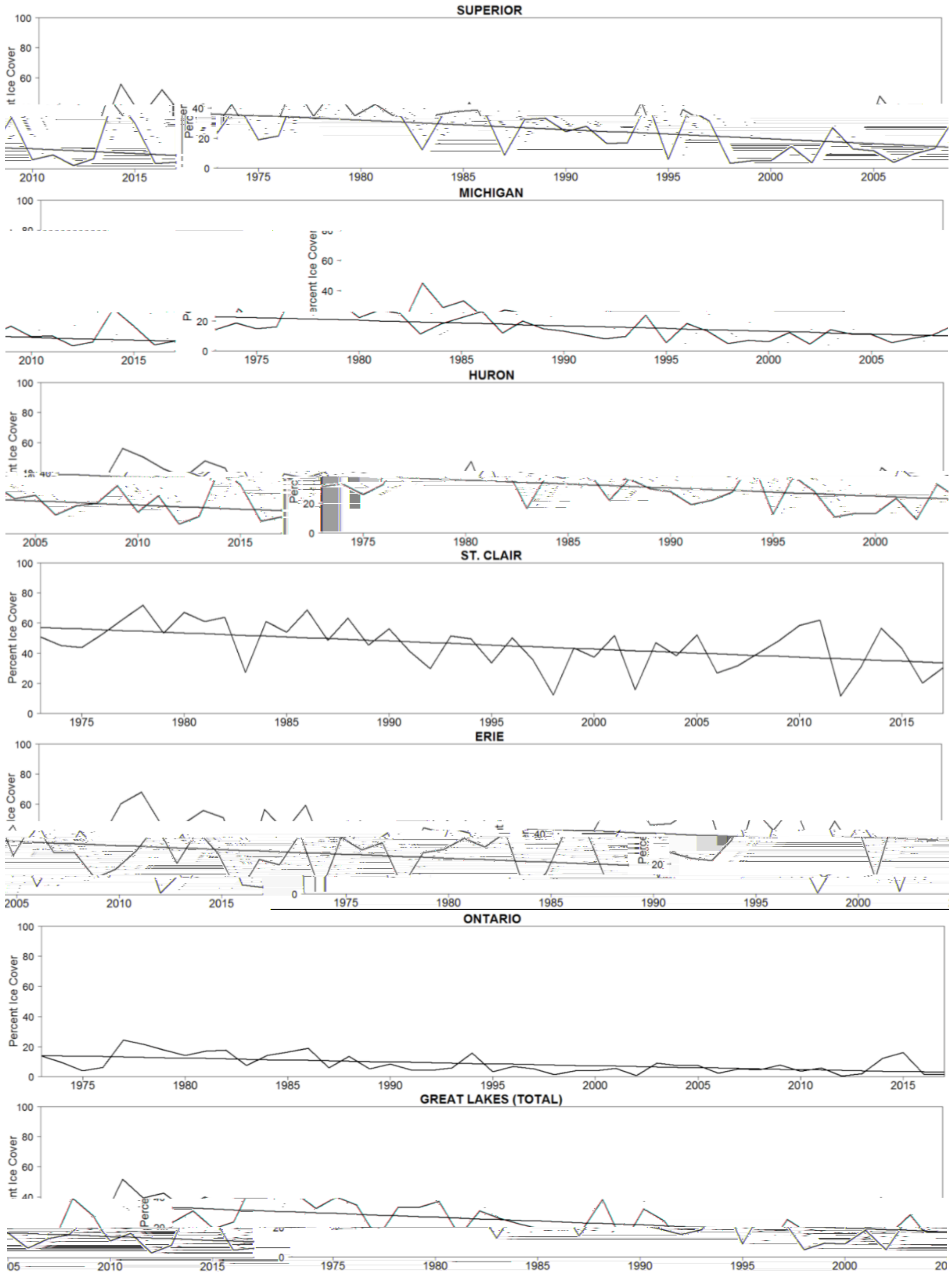


Figure 6. Annual Mean Ice Cover (AAIC) and Trend in the Great Lakes, 1973-2017.

Long-term Trends

The linear regressions in Figure 5 are the long-term trends of annual Great Lakes ice coverage (winters 1973 to 2017) determined from the least squares fit method. In all of the Great Lakes, the linear regressions show a negative, long-term trend in ice cover since 1973. This function is in the following form:

$$y = a + bt$$

where a is the y-intercept corresponding to the percent ice cover value in 1973, b is the slope of the linear function, i.e. the rate of change of percent ice cover with time in years t.

Annual mean ice cover in all of the lakes show a significant negative trend since the 1970s. The rate of decrease from lake to lake ranges from 0.25 to 0.62 (% per year). Lake Superior has the largest negative trend (-0.62% per year), Lake Huron and Lake St. Clair place second (-0.54% per year), followed by Erie (-0.53% per year), Michigan (-0.36% per year) and Ontario (-0.25% per year), respectively. Over the entire 45-winter period, total loss of annual lake ice coverage ranges from 42% in Lake St. Clair to 81% in Lake Ontario. Total ice cover loss across the Great Lakes during the 45-winter period is 69%.

Table 3. Trends in Great Lakes Annual Mean Ice Cover Averaged from December 1 to April 30.

	Superior	**Michigan**	**Huron**	**St. Clair**	**Erie**	**Ontario**	**Great Lakes (Total)**
a, intercept	36	23	39	57	43	14	33
b, slope	-0.62	-0.36	-0.54	-0.54	-0.53	-0.25	-0.51
b/a [%]	-1.71	-1.57	-1.38	-0.94	-1.23	-1.81	-1.53
Total Loss [%]	-22	-16	-23	-23	-23	-11	-22

Table 3 gives the characteristic values of each linear function. Variable '*a*' is the y-axis intercept constant for the linear function, i.e. the percent ice cover value for 1973; variable '*b*' is the slope of the function (the rate of change in percent ice cover with time *t*).

Table 4. Statistical means and standard deviations of annual average ice cover (AAIC) in individual lakes and entire Great Lakes (basin), averaged from December 1 to April 30, for the period 1973-2017.

Avg. Dec-Apr	**Superior**	**Michigan**	**Huron**	**Erie**	**Ontario**	**Basin**
Mean	22	14	26	32	6	21
Std	16	9	13	18	5	13
Std/Mean	0.72	0.64	0.50	0.56	0.83	0.62

Table 4 shows the statistics of mean, standard deviation, and the ratio of standard deviation to the mean for AAIC. Lakes Huron and Erie have the smallest ratio, while Lakes Ontario has the largest ratio, indicating that predictability of annual mean ice cover in Huron and Erie is higher than that in Ontario.

Since annual mean ice cover averaged from December 1 to April 30 is not a realization of ice cover (Wang et al. 2012b), the commonly-used variable is the annual maximum ice cover (AMIC), a realization that can be measured in a day of a winter season. Therefore, the following analysis provide the statistics of AMIC.

Similar to Table 4, Table 5 shows the statistics of mean, standard deviation, and the ratio of Std to the mean for AMIC. Lakes Huron and Erie have the smallest ratio, while Lakes Ontario has the largest ratio, indicating that predictability of AMIC in Huron and Erie is higher than that in Ontario.

Table 5. Statistical means and standard deviations of annual maximum ice cover (AMIC) in individual lakes and entire Great Lakes (basin) at one day during December 1 to April 30, for the period 1973-2017.

AMIC	Superior	Michigan	Huron	Erie	Ontario	Basin
Mean	63	42	65	84	32	55
Std	30	22	23	25	21	24
Std/Mean	0.48	0.52	0.35	0.30	0.66	0.44

Table 6. Regression linear trend of AMIC for the period 1973-2015, $x=a+bt$ in percentage (t in years starting with 0 at 1973, a is constant, and b is the trend/slope).

	a	b (annual trend)	Decadal trend	Total loss up to 2015
Superior	77.00	-0.90	-9.0	-38.70
Michigan	39.04	-0.39	-3.9	-16.77
Huron	66.87	-0.51	-5.1	-21.93
Erie	90.86	-0.48	-4.8	-20.64
Ontario	26.00	-0.36	-3.6	-15.48
Basin	62.00	-0.60	-6.0	-25.80

Table 7. The same as Table 6 (for the period 1973-2013), except excluding 2014 and 2015 ice seasons.

	a	b (annual trend)	Decadal trend	Total loss up to 2013
Superior	79.73	-1.09	-10.9	-44.69
Michigan	50.57	-0.61	-6.1	-25.01
Huron	80.92	-0.66	-6.6	-27.06
Erie	97.82	-0.56	-5.6	-22.96
Ontario	43.80	-0.50	-5.0	-20.50
Basin	62.43	-0.79	-7.9	-32.39

Table 6 shows the regression analysis results of AMIC for five individual lakes and the entire basin. The trend was provided (column 4), and the total loss of lake ice at 2015, relative to 1973, is also provided (column 5). Lake Superior has the highest total loss among the lakes at -39%, partially due to the warming caused by the ice/water albedo feedback (Wang et al. 2005; Austin and Colman 2007). The basin-wide loss of ice cover from 1973 to 2015 is -26%.

Since the Great Lakes experienced extremely cold winters with severe ice cover in 2014 and 2015 (93% during 2013/14 (Clites et al. 2014) and 89% during 2014/15), it is obvious that these two winters will significantly change the trend. Table 7 shows the results, similar to Table 6, excluding these two winters. As expected, the trends of each lake for the period 1973-2013 (Table 7) are larger than those for the period 1973-2015 (Table 6).

Therefore, we must use trends cautiously when interpreting ice cover change. Again, the trend calculated within a specific period of time such as 1973-2015 (Table 6) can only be applicable to the same period, and cannot be extrapolated to the future and back to the past. It should not be interpolated to a period shorter than the time series of the data from which the trends are derived (e.g. Table 7), since there are decadal and multi-decadal changes in lake ice cover.

Decadal Variability

With the last seven years (2011-2017) of data added to the previous time series (Wang et al. 2012a), decadal variability further stands out, as does the interannual variability (Fig. 7). The decadal variability in small lakes was investigated by previous studies (Magnuson et al. 2000; Ghanbari et al. 2009; Weyhenmeyer et al. 2011). During this 45-year period, three high ice bands stand out: 1977-79, 1994, and

2014-15, with separation periods of 17 years and 21 years, respectively. Similarly three low ice bands also stand out: 1983, 1998-2002, and 2010-2013, separated by around 18 and 12 years, respectively. The longest low ice band started in 1998 and lasted to 2013. The 1997/98 El Niño was the largest El Niño event of the century (Van Cleave et al. 2014), which may be associated with a regime shift in lake ice cover and other environmental components. This is part of the remarkable downward trend observed during 1973-2013 (Table 7 vs. Table 6), which can be attributed to a combination of multi-decadal variability and human-caused secular climate warming. The 5-year running mean indicates that this multi-decadal variability has a large peak in 1980 and a small peak in 1995.

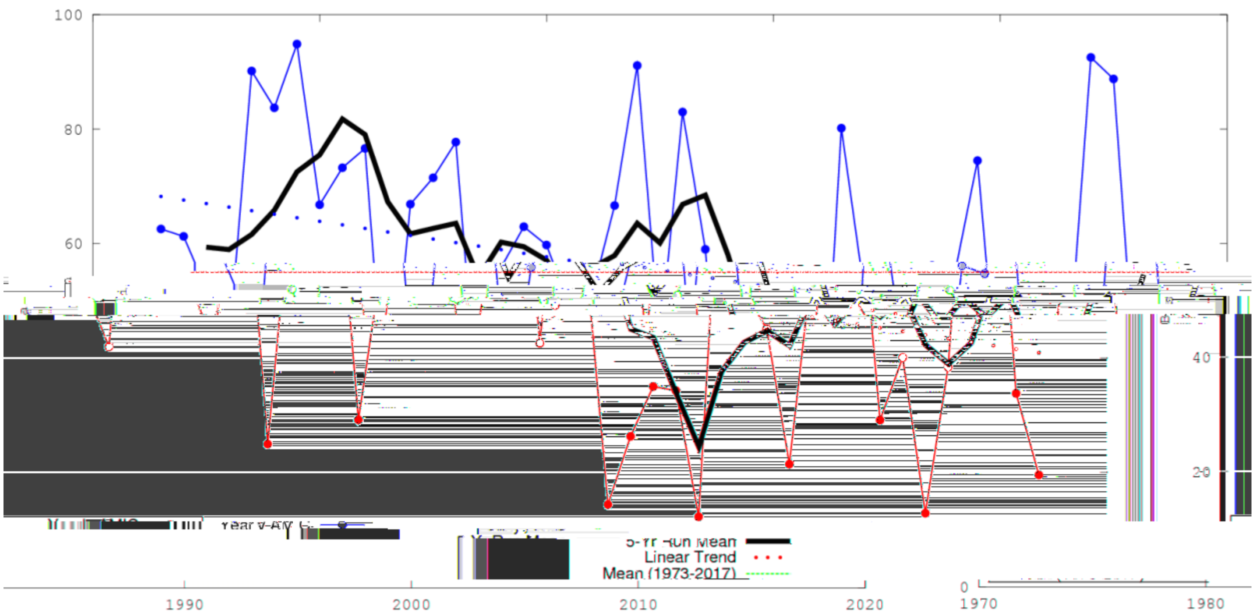


Figure 7. Time series of AMIC during 1973-2017. The thick line is the 5-year running mean, indicating the decadal signal. The dashed red line is the climatological mean of 55%, and the blue dashed line indicates the long-term trend.

CONCLUSIONS

Growth of ice cover during the seasonal cycle in the Great Lakes is quite similar across all of the lakes. Some timing differences of ice onset and offset are observed between shallow and deep water lakes. Given the same atmospheric conditions, shallow lakes begin forming ice and reach maximum ice cover earlier than deep lakes.

Weekly standard deviations of lake ice cover are recognized to have comparable magnitude (and sometimes greater magnitude) with their corresponding climatological means. This suggests overall poor predictability of long-term ice conditions due to the effects of large, interannual variability. In the lake ice cover time series for each of the six lakes, two significant periods of about 8 (before 1998) and 4 (after 1998) years are observed. This strong interannual variability is possibly due to the effects of climate forcing on the Great Lakes, especially within more recent years (the past two decades).

Lake ice cover shows a long-term, declining trend (winter seasons of 1973 to 2017). The greatest negative trends are in Lakes Superior, Huron, St. Clair and Erie. In total, a 69% loss in all Great Lakes annual average ice cover is observed over the entire 45-winter period.

With the last six years of data (2012-2017) added to the analysis, in addition to large variability on interannual time scales, decadal variability in Great Lakes ice cover stands out. Lake ice trends should be interpreted with caution, because the decadal variability in lake ice cover often contributes to the downward or upward trend.

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