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Seasonal, Interannual, and Decadal Variability and Long-Term Trend of Ice Cover in Western Lake Erie and Green Bay in the Great Lakes, 1973-2021

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SEASONAL, INTERANNUAL, AND DECADAL VARIABILITY AND LONG-TERM TREND OF ICE COVER IN WESTERN LAKE ERIE AND GREEN BAY IN THE GREAT LAKES, 1973-2021

Jia Wang, Erika Maneke, and James Kessler

1. INTRODUCTION

The 49-year winter data set consists of 7257 ice charts of total ice concentration for both Green Bay and Western Lake Erie. This report updates the ice climatology dataset for Green Bay and Western Lake Erie from the GLERL's previous 45-winter (1973 – 2017) report covering all of the Great Lakes. Western Lake Erie is defined as the region of Lake Erie west of the longitude 82.5 degrees west. The original ice charts data were produced by the 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 Chapters 2-6 of Wang et al. (2012a) and Yang et al. (2020).

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, the 2018 and 2019 winter ice cover in Lake Erie reached 98.3% and 98.7% total cover, respectively, while ice cover in 2020 only reached 64%. Possible contributors include interannual and interdecadal climate variability, and long-term trends (Assel 1990; Wang et al. 2018), 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).

This report shows variability in ice cover for the regions of both Green Bay and Western Lake Erie on seasonal, interannual, and decadal time scales. This update of the ice dataset should be useful to the research community as well as others who rely on Green Bay or Western Lake Erie ice data for planning purposes. Another motivation of this report on both regions is to provide lake ice conditions to a large effort on investigation of winter limnology and ecosystem in the Great Lakes (Ozersky et al. 2021).

2. DISTRIBUTION OF ICE CHARTS BY WINTER SEASON

The number of ice charts per winter season for the years 1973 to 2021 range from 100 to 197; the dates of first ice charts range from the middle of November to the beginning of January, and the last ice charts range from the beginning of April to the beginning of June (Table 1). Since the winter season of 2011, the NIC has been producing daily charts for each winter season allowing for daily ice chart analysis. The date of the first ice chart refers to the date that NIC began recording ice cover for the season; similarly, the date of last ice cover is the last date where NIC recorded ice cover data. These charts are the same for all regions of the Great Lakes including Green Bay and Western Lake Erie.

Table 1. Summary of Ice Chart Statistics

Winter Season	Number of Ice Charts	Date of First Ice Chart	Date of Last Ice Chart
1973	108	20-Dec	6-Apr
1974	123	31-Dec	2-May
1975	113	2-Jan	24-Apr
1976	120	23-Dec	20-Apr
1977	140	16-Dec	4-May
1978	134	21-Dec	3-May
1979	148	18-Dec	14-May
1980	106	2-Jan	16-Apr
1981	113	24-Dec	15-Apr
1982	148	21-Dec	17-May
1983	134	21-Dec	3-May
1984	136	20-Dec	3-May
1985	127	22-Dec	27-Apr
1986	131	14-Dec	23-Apr
1987	100	27-Dec	5-Apr
1988	106	3-Jan	17-Apr
1989	146	14-Dec	8-May
1990	136	13-Dec	27-Apr
1991	125	28-Dec	1-May
1992	158	6-Dec	11-May
1993	143	14-Dec	5-May
1994	162	3-Dec	13-May
1995	153	9-Dec	10-May
1996	197	18-Nov	31-May
1997	169	26-Nov	13-May
1998	144	2-Dec	24-Apr
1999	141	15-Dec	4-May
2000	148	3-Dec	28-Apr
2001	154	1-Dec	3-May
2002	158	3-Dec	9-May
2003	179	2-Dec	29-May
2004	158	1-Dec	6-May
2005	159	2-Dec	9-May
2006	158	28-Nov	4-May
2007	155	4-Dec	7-May
2008	172	26-Nov	15-May
2009	151	8-Dec	7-May
2010	130	7-Dec	15-Apr
2011	163	2-Dec	13-May
2012	137	29-Nov	13-Apr
2013	181	29-Nov	28-May
2014	194	24-Nov	5-Jun
2015	197	14-Nov	29-May
2016	161	27-Nov	5-May
2017	137	11-Dec	26-Apr
2018	174	29-Nov	21-May
2019	183	15-Nov	16-May
2020	188	10-Nov	15-May
2021	159	22-Nov	29-Apr

3. ANALYSIS OF LAKE ICE COVER FOR GREEN BAY AND WESTERN LAKE ERIE: 1973-2021

The spatial, long-term mean of the annual maximum ice cover (AMIC) in the Great Lakes was constructed based on ice chart data from the winter seasons of 1973 to 2017 (Figure 1). The two areas of interest for this report, Green Bay and Wester Lake Erie, are enlarged for clarity. The daily climatology of ice cover in the Great Lakes was also produced for Green Bay and Western Lake Erie (Figure 2). The seasonal ice cycle in the Great Lakes consists of an ice onset, a growing period in which the annual maximum ice cover area is reached, and then an ice offset. Green Bay and Western Lake Erie show similar ice onset in early December and similar growing periods in which maximum ice cover occurs in mid-February, but Green Bay has a visibly later ice offset than Western Lake Erie. Green Bay also exhibits a higher percent of ice cover than Western Lake Erie after the growing period. In general, ice melts completely during mid-April to early May.

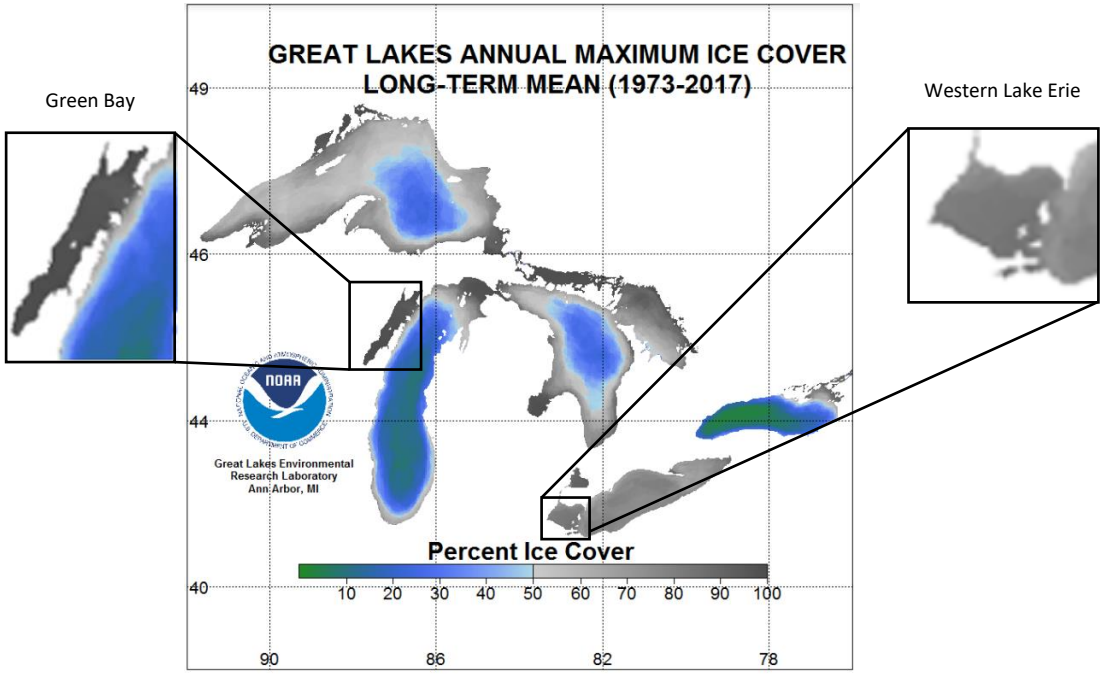


Figure 1. Long-term Mean of Annual Maximum Ice Cover (AMIC) in the Great Lakes from 1973-2017. The boxes show the study regions: Green Bay and Western Lake Erie.

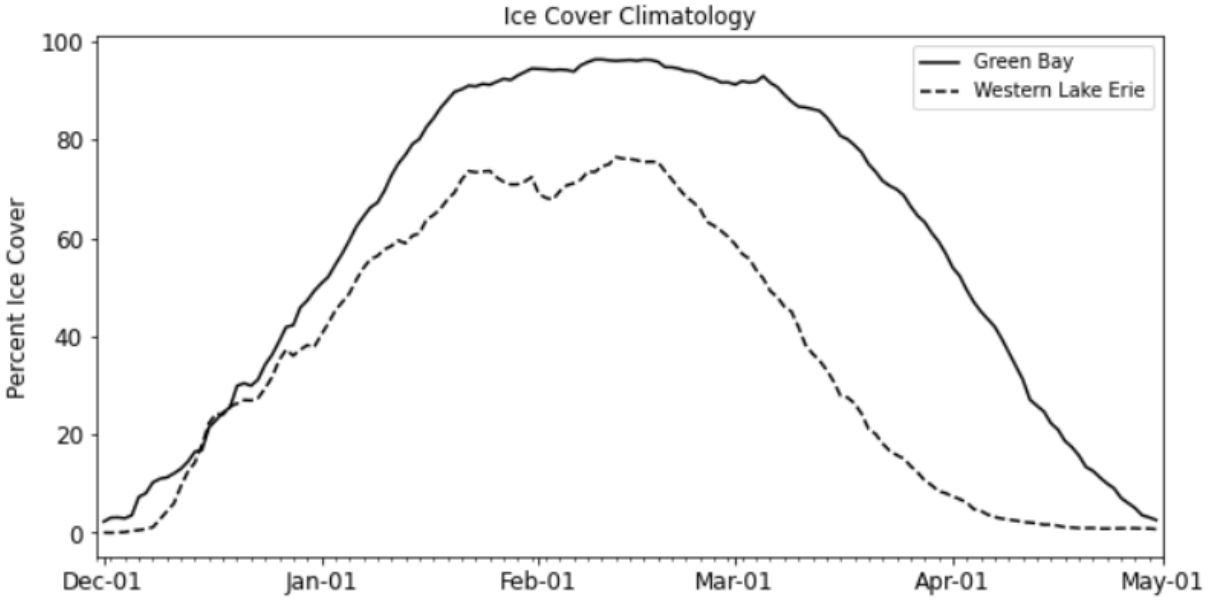


Figure 2. Average ice cover concentration of Green Bay and Western Lake Erie (1973-2021)

3.1 SEASONAL VARIATIONS

To begin analyzing interannual variations in Great Lakes ice cover, the mean daily lake ice cover for every measured date in the winter season is determined across the 49-winter period (Figure 3). On average, ice forms on Green Bay and Western Lake Erie in week 50 (Table 2). The growing period of ice cover is 8 weeks for Green Bay and Western Lake Erie. Green Bay and Western Lake Erie both reach their seasonal maximum ice cover area during week 6. On average, the ice cover has completely melted around week 16 for Green Bay and week 13 for Western Lake Erie.

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

	Green Bay	**Western Lake Erie**
Onset	50	50
Maximum	6	6
Offset	16	13

The corresponding weekly variations defined by standard deviations (i.e., variability) of annual ice cover indicate that Green Bay has the lower ratio of standard deviations to the mean, and Western Lake Erie has the higher ratio of standard deviations to the mean (Fig. 3 and Table 4). The ratio of standard deviation to mean is higher in Western Lake Erie (43%) than Green Bay (16%), indicating that year-to-year change in ice cover is larger in Western Lake Erie than Green Bay. The ratio is inversely proportional to predictability. This implies that ice cover in Green Bay has higher predictability, while ice cover in Western Lake Erie has lower predictability.

Therefore, using ice cover (concentration) only cannot detect the climate change of the winter season in Green Bay due the low variability. Nevertheless, ice cover in the freezing season (December 15 to January 15) and melting season (March 15 to April 15) can be used to monitor the climate change, because the standard deviations are larger than the winter season. Ice thickness is a reliable parameter that should be used, whenever available, to investigate the response of ice cover to the changing climate.

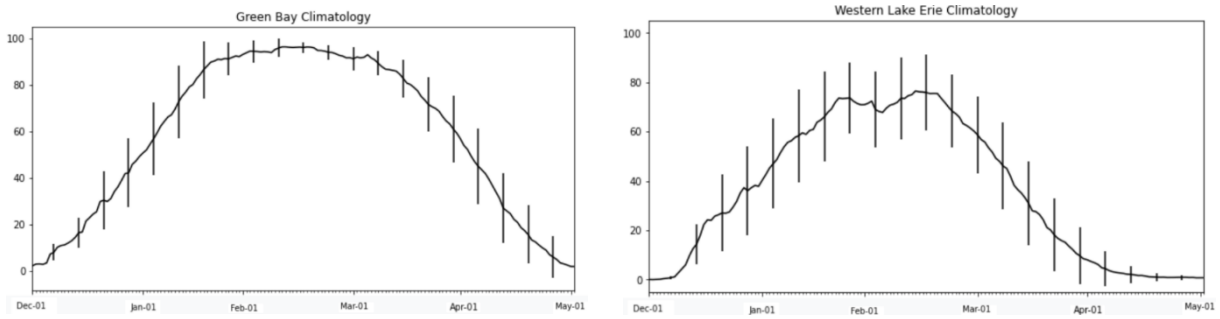


Figure 3. Seasonal Variation of Weekly Ice Coverage with one standard deviation above and below the mean.

3.2 INTERANNUAL VARIABILITY, FIRST AND LAST ICE COVER

Time series of daily ice cover area for Green Bay and Western Lake Erie have been constructed based on the ice concentration data for the winters of 1973 to 2021 (Figure 4). For shallow water lakes like Green Bay and Lake Erie, almost complete ice cover is achieved for most of the 49-winter seasons. For Green Bay, all of the 49 seasons achieved ice cover above 95% while Western Lake Erie achieved ice cover of 95% for 40 of the 49 seasons. This demonstrated that only considering 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). Western Lake Erie is observed to have high interannual variability of ice cover while Green Bay is observed to be less variable.

Lake Erie experienced the least amount of ice cover during the 1998 winter season (Fig. 4), which was the largest El Nino event of the 20th century and led to a large warm temperature anomaly in the Great Lakes region (Van Cleave et al. 2014). Ice cover in 2020 was the second lowest year, also because of a strong El Nino event (Bai et al. 2012). Furthermore, in more 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.

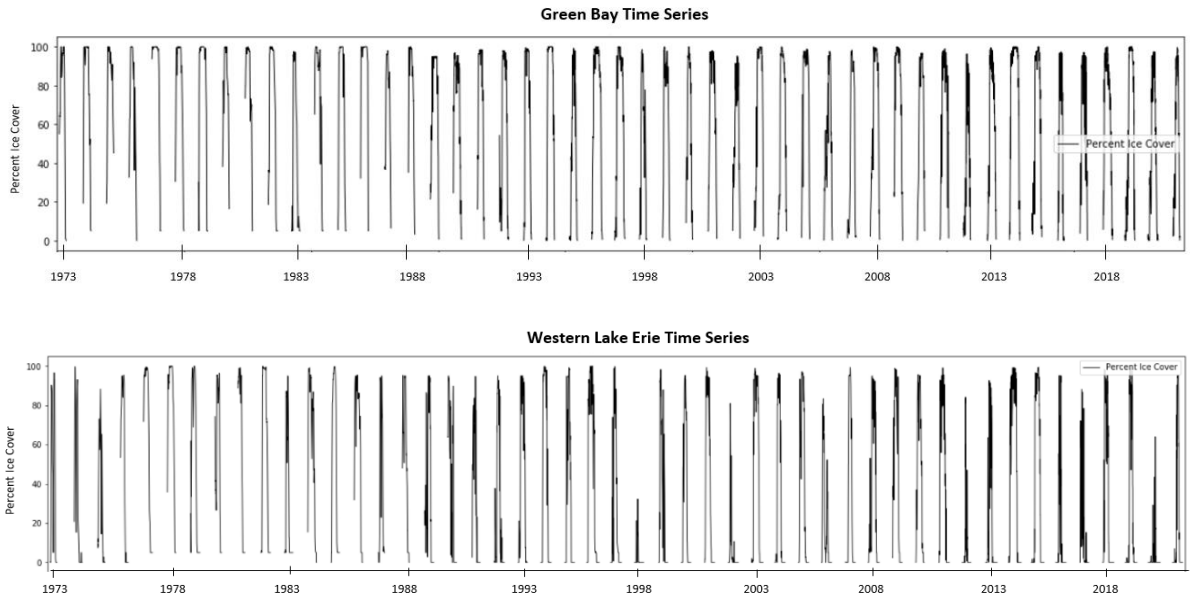


Figure 4. Daily Time Series of Ice Cover in the Green Bay and Western Lake Erie, 1973-2021

Time series plots for the first and last day of ice cover (≥ 10%) in the 49-year period were produced for Green Bay and Western Lake Erie (Figure 5). The first day of ice cover for Green Bay and Western Lake Erie were similar, averaging around mid- to late December. The average last day of ice cover for Green Bay was around mid-April, but Western Lake Erie's last day of ice cover averaged around mid-March. For Green Bay, both the first and last days of ice cover had a negative slope, -3.1 days/decade and -2.2 days/decade, respectively. This means that the ice cover is occurring and melting earlier in the season. But because the first day of ice cover is decreasing more quickly than the last day of ice cover, the duration is slowly increasing by 0.8 days/decade (Figure 6). For Western Lake Erie, the first day of ice cover is increasing by 1.6 days/decade while the last day of ice cover is decreasing by -2.4 days/decade. This means that the first and last days of ice cover are diverging and therefore the duration of ice cover is decreasing by -3.9 days/decade (Figure 6).

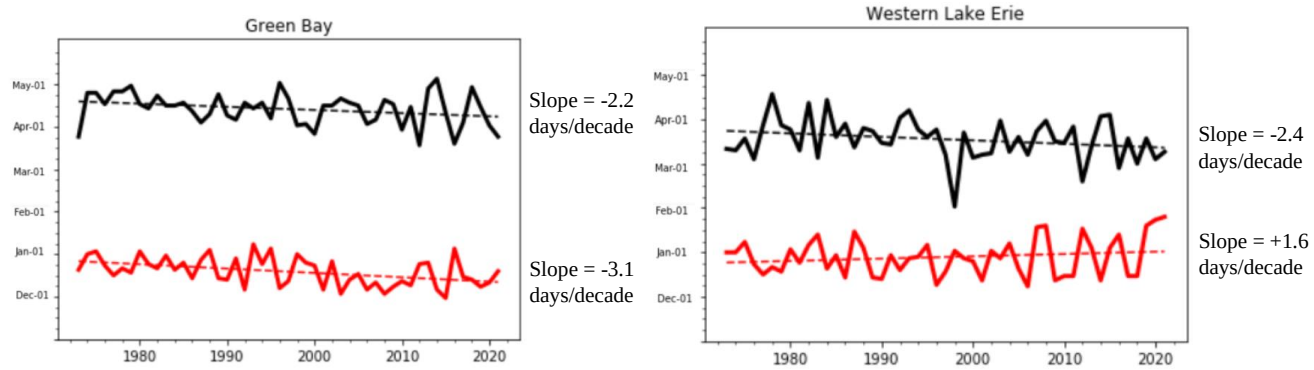


Figure 5. Time series of the first and last day of ice cover for each year from 1973-2021. The solid, bold black line represents the last day of ice cover for each year, and the dotted black line represents the trend. The solid, bold red line represents the first day of ice cover for each year, and the dotted red line represents the trend. The trend is in Julian days.

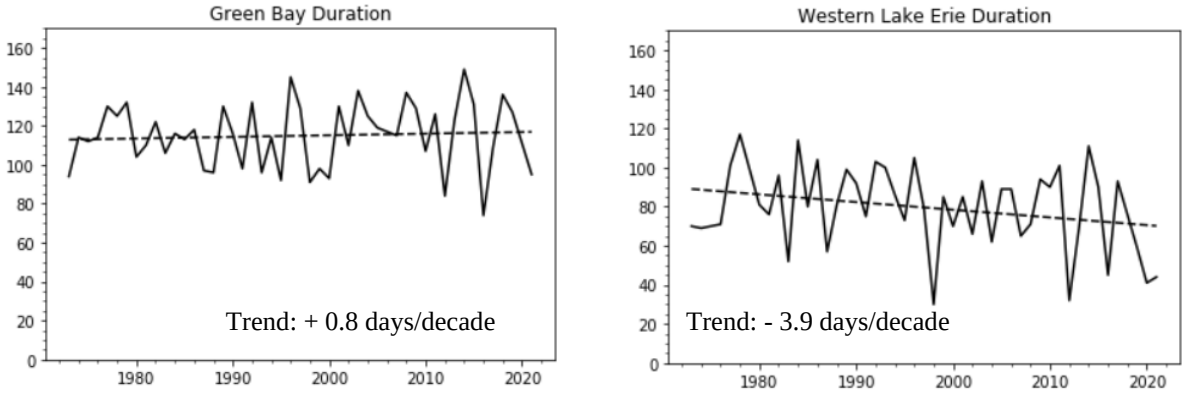


Figure 6. Time series of the duration of ice cover in number of days for each year from 1973-2021. The dashed line represents the trendline.

Time series plots for the annual average ice cover (AAIC), which is defined as the annual mean ice cover averaged from December 1 to April 30, in Green Bay and Western Lake Erie are produced for each lake (Figure 7). 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) and AMO and PDO (Wang et al. 2018). Additionally, both lakes show a negative trend with Green Bay's annual mean ice decreasing by 0.413 percent per year and Western Lake Erie's annual mean ice decreasing by 0.566 percent per year during the 1973-2021 period.

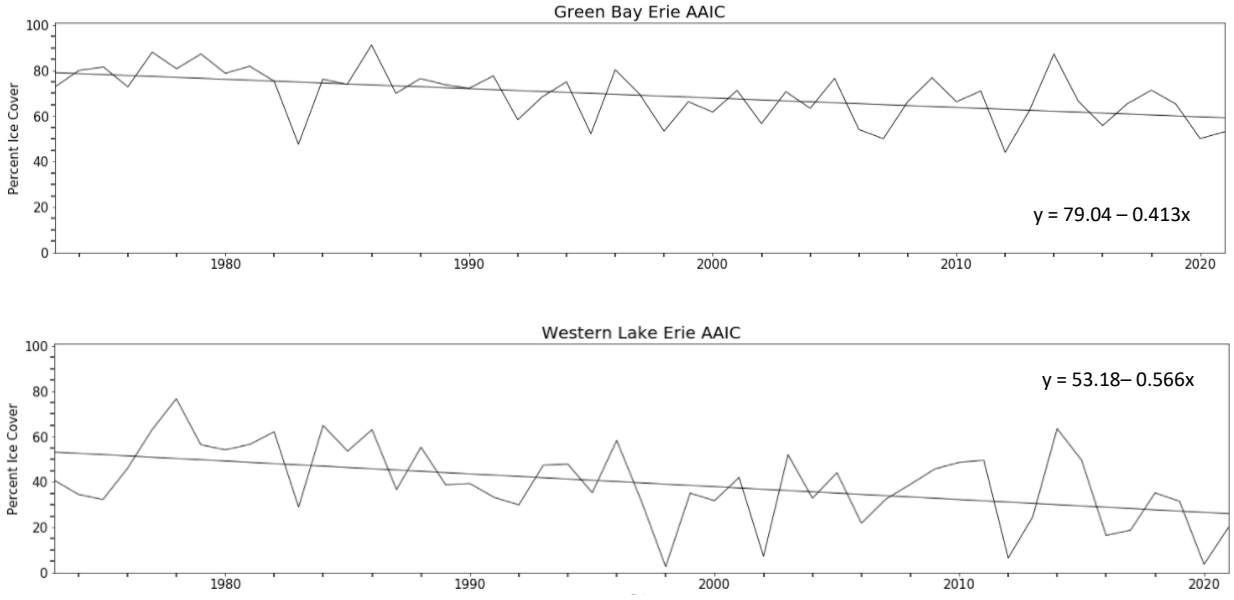


Figure 7. Annual Average Ice Cover (AAIC) in the Great Lakes, 1973-2021 with trendline. *x* in the regression equations denotes the time starting from 0, 1, …49, corrsponding to 1973, 1974, … 2021.

3.3 LONG-TERM TRENDS

The linear regressions in Figure 5 are the long-term trends of annual Green Bay and Western Lake Erie ice coverages (winters 1973 to 2021) determined from the least squares fit method. In both regions, 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 both regions show a significant negative trend since the 1970s. The rate of decrease in Green Bay is 0.41% per year. The rate of decrease in Western Lake Erie is 0.57% per year. Over the entire 49-winter period, total loss of annual lake ice coverage is 20% in Green Bay and 28% in Western Lake Erie.

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 3. Trends in Green Bay and Western Lake Erie Annual Average Ice Cover (AAIC) Averaged from December 1 to April 30.

	Green Bay	Western Lake Erie
a, intercept	79.04	53.17
b, slope [%/yr]	-0.41	-0.57
b/a [%]	-0.52	-1.07
Total Loss [%]	20	28

Table 4. Statistical means and standard deviations of annual average ice cover (AAIC in %) in Green Bay and Western Lake Erie, averaged from December 1 to April 30, for the period 1973-2021.

	Green Bay	Western Lake Erie
Mean	69	40
Std	11	17
Std/Mean	0.16	0.43

Table 4 shows the statistics of mean, standard deviation, and the ratio of the standard deviation to the mean for AAIC. Green Bay has the smaller ratio, while Western Lake Erie has the larger ratio, indicating that predictability of annual mean ice cover in Green Bay is higher than that in Western Lake Erie.

Since annual mean ice cover averaged from December 1 to April 30 is an important parameter of ice cover (Wang et al. 2012b), compared to the commonly-used variable, annual maximum ice

cover (AMIC), an indicator that can be measured in a day of a winter season. The reason is AAIC implicitly includes the ice duration, while AMIC does not, although AMIC is convenient to use because it is a daily measurement. Therefore, the following analysis provides the statistics of both AAIC and AMIC for comparison.

Similar to Table 4, Table 5 shows the statistics of mean, standard deviation, and the ratio of the standard deviation to the mean for AMIC. Green Bay has the smaller ratio of 0.01, while Western Lake Erie has the larger ratio of 0.12. This indicates that the variability of AMIC (1%) in Green Bay is much lower than AAIC (16%). Similarly the variability using AMIC (12%) is more than three times smaller than that using AAIC (43%). Therefore, AAIC as a variable is much more physical sound than AMIC in detecting climate change.

Table 6 shows the regression analysis results of AMIC for Green Bay and Western Lake Erie. Western Lake Erie has the higher total loss among the lakes at 7%. Green Bay lost just 1.5% over the 49-year period.

Table 5. Statistical means and standard deviations of annual maximum ice cover (AMIC) in Green Bay and Western Lake Erie at one day during December 1 to April 30, 1973-2021.

	Green Bay	Western Lake Erie
Mean	99	94
Std	1.37	11
Std/Mean	0.01	0.12

Table 6. Trends in Green Bay and Western Lake Erie using Annual Maximum Ice Cover.

	Green Bay	Western Lake Erie
a, intercept	99.6	97.4
b, slope [%/yr]	-0.03	-0.14
b/a [%]	-0.03	-0.14
Total Loss [%]	1.5	7

Comparing Table 6 with Table 3 and Table 5 with Table 4, it is found that AAIC captures larger variability than AMIC, because AAIC implicitly includes ice duration, while AMIC just takes a maximum value (realization) of a single day over the ice season, although the correlation between the two is very high (0.94; see Bai et al. 2015). In short, AAIC is more physical sound than AMIC in studying the response of lake ice to climate change.

3.4 DECADAL VARIABILITY

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 49-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 four low ice bands also stand out: 1983, 1998-2002, 2010-2013, and 2020 separated by around 18, 12, and 7 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

atmospheric forcing (Lin et al. 2021). This is part of the remarkable downward trend observed during 1973-2021, which can be attributed to a combination of multi-decadal variability and human-caused secular climate warming.

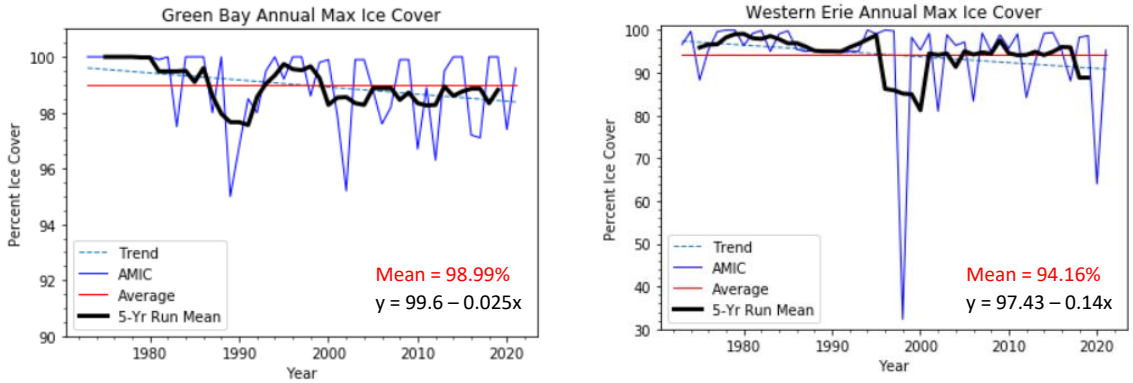


Figure 8. Time series of AMIC during 1973-2021. The blue solid line is the AMIC, the red line is the climatological mean of each region, the blue dashed line indicates the long-term trend, and the black line is the 5-year running average of the AMIC.

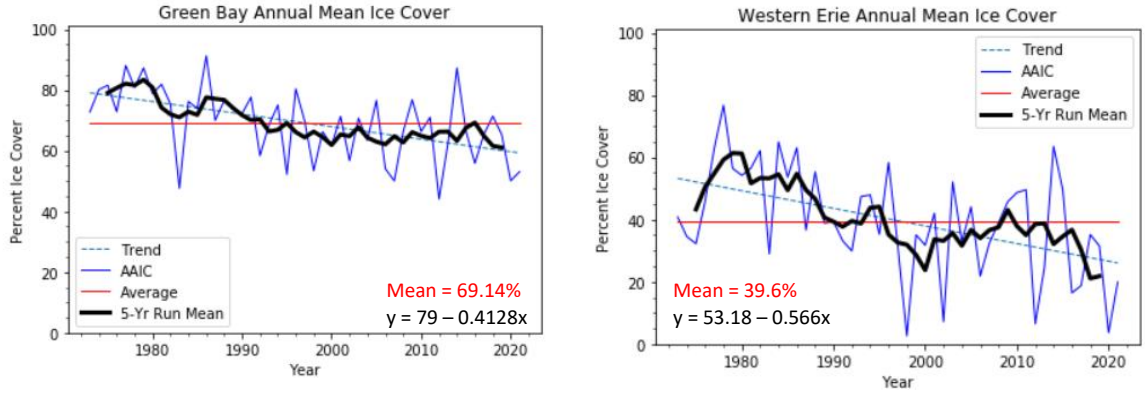


Figure 9. Time series of AAIC during 1973-2021. The blue solid line is the AAIC, the red line is the climatological mean of each region, the blue dashed line indicates the long-term trend, and the black line is the 5 year running average of the AAIC.

3.5 SUMMARY

Growth of ice cover during the seasonal cycle is comparable between Green Bay and Western Lake Erie due to their similar bathymetry. Some timing differences of ice onset and offset are observed between shallow and deep water lakes as well as the latitude of the lakes. Given the same atmospheric conditions, shallow, lower latitude lakes begin forming ice and reach maximum ice cover earlier than deep, higher latitude lakes.

Weekly standard deviations of lake ice cover are recognized to have comparable magnitude with their corresponding climatological means. This suggests overall high year-to-year variability and poor predictability of long-term ice conditions due to the effects of large, interannual variability. In the lake ice cover time series for both regions, two significant periods of about 8 (before 1998)

and 4 (after 1998) years are observed. This strong interannual variability is due to the effects of climate forcing on the Great Lakes (Bai et al. 2012; Wang et al. 2018), especially within more recent years (the past two decades) (Lin et al. 2021).

Lake ice cover shows a long-term, declining trend (winter seasons of 1973 to 2021). The greatest negative trend between Green Bay and Western Lake Erie is observed in Western Lake Erie.

AAIC is an important physical variable, an average over a whole ice season, because physically it contains ice duration, while AMIC just records a daily maximum value over an ice season. We recommend that in addition to AMIC, AAIC be used to reflect ice variability and trend in response to climate change, because AMIC ignores the ice duration.

4. ANALYSIS OF GREAT LAKES ICE COVER CLIMATOLOGY: WINTERS 2018-2021

The annual formation and melt of ice cover on the Great Lakes each winter, i.e. the annual ice cycle, affects the lake's ecosystem, the regional economy of the Great Lakes, and is an index of regional winter climate. A 30-winter (1973-2002) climatology of Great Lakes ice cover (Assel 2003a) was updated for total ice concentration for winters 2003-2005 (Assel, 2005a). Assel et al. (2013) updated the ice cover data base for winters 2006-2011, following up the previous ice cover descriptions of Assel (2003) for 1973-2002 and of Assel (2005a) for 2003-2005. The climatology was more recently updated for winters 2006-2011 (Wang et al., 2012a) and again for 2012-2017 (Wang et al., 2017). The information presented here updates analysis products previously done by Assel et al. (2013) and Wang et al. (2017a,b) including: dates of first ice, dates of last ice, ice cover duration (Wang et al. 2020), and line plots which portray the seasonal and spatial patterns and trends of ice cover over each winter season.

4.1 DATA

The data provided for this analysis includes 704 digitized ice charts: 174 (2018), 183 (2019), 188 (2020), and 159 (2021). Ice charts generally span between late November and early May. The data in these 1024x1024 pixel grids contains the entire Great Lakes region (Fig. 10) and consists of over-water cells that are mapped onto a land mask. Each cell contains an ice concentration value recorded to the nearest 10%.

The data consists of grids of over-water cells embedded in a land mask (a 1024x1024 matrix at a nominal spatial resolution 1.275 km at approximately 45°N for winters 2018-2021). The resolutions vary with latitude; see Wang et al., (2012a) and Yang et al. (2020) for details. Ice charts were downloaded from http://www.natice.noaa.gov/products/great_lakes.html and quality control was conducted for location of over-water grid cells, to be consistent with NOAA GLERL the CoastWatch land mask (ftp://coastwatch.glerl.noaa.gov/masks/new/), and ice concentration codes, consistent with Assel (2003a, 2005a). Fixed formatted ASCII and ARC/INFO shape file: names, structure, and ice concentration codes, are available in Wang et al., (2012a) for those interested in these data.

4.2 ANALYSIS METHODS

Ice charts for first (last) ice and ice duration, which is the difference between these dates, are produced for each winter season. The original ice charts contain ice concentration values recorded to the nearest 10%. For each winter season, an iterative search across all of the over-water cells in the original ice charts is performed to determine the first (last) observed date of ice concentration *greater than or equal to 10%* for each grid cell.

To analyze the seasonal progression of ice cover across the Great Lakes, the daily average lake ice cover is calculated for each of the Great Lakes and winter seasons. Average ice cover is the mean of all ice concentrations recorded in a specific lake for a measured date. Line plots of average lake ice cover represent the seasonal progression of ice cover over a winter season.

GREAT LAKES PLACE NAMES

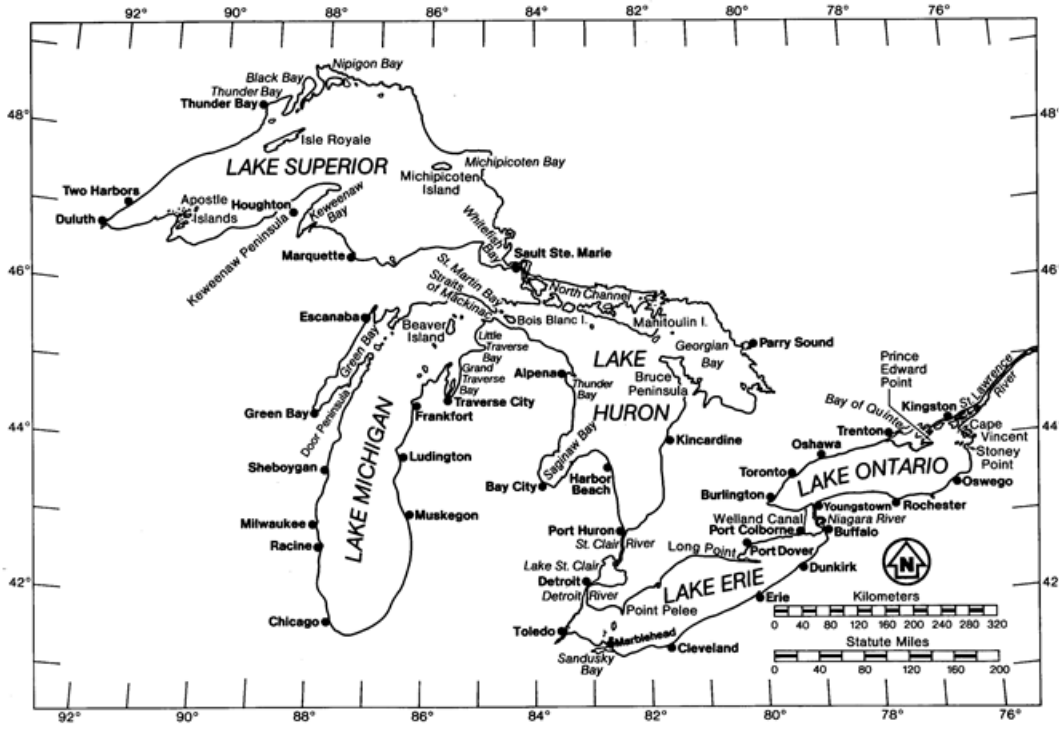


Figure 10. Great Lakes Place Names (Assel 2005a)

4.3 DATES OF FIRST (LAST) ICE AND ICE DURATION

Ice concentrations greater than 10% for dates of first (last) ice and ice duration are plotted on spatial grids in Figures 11-13. Trend descriptions are included.

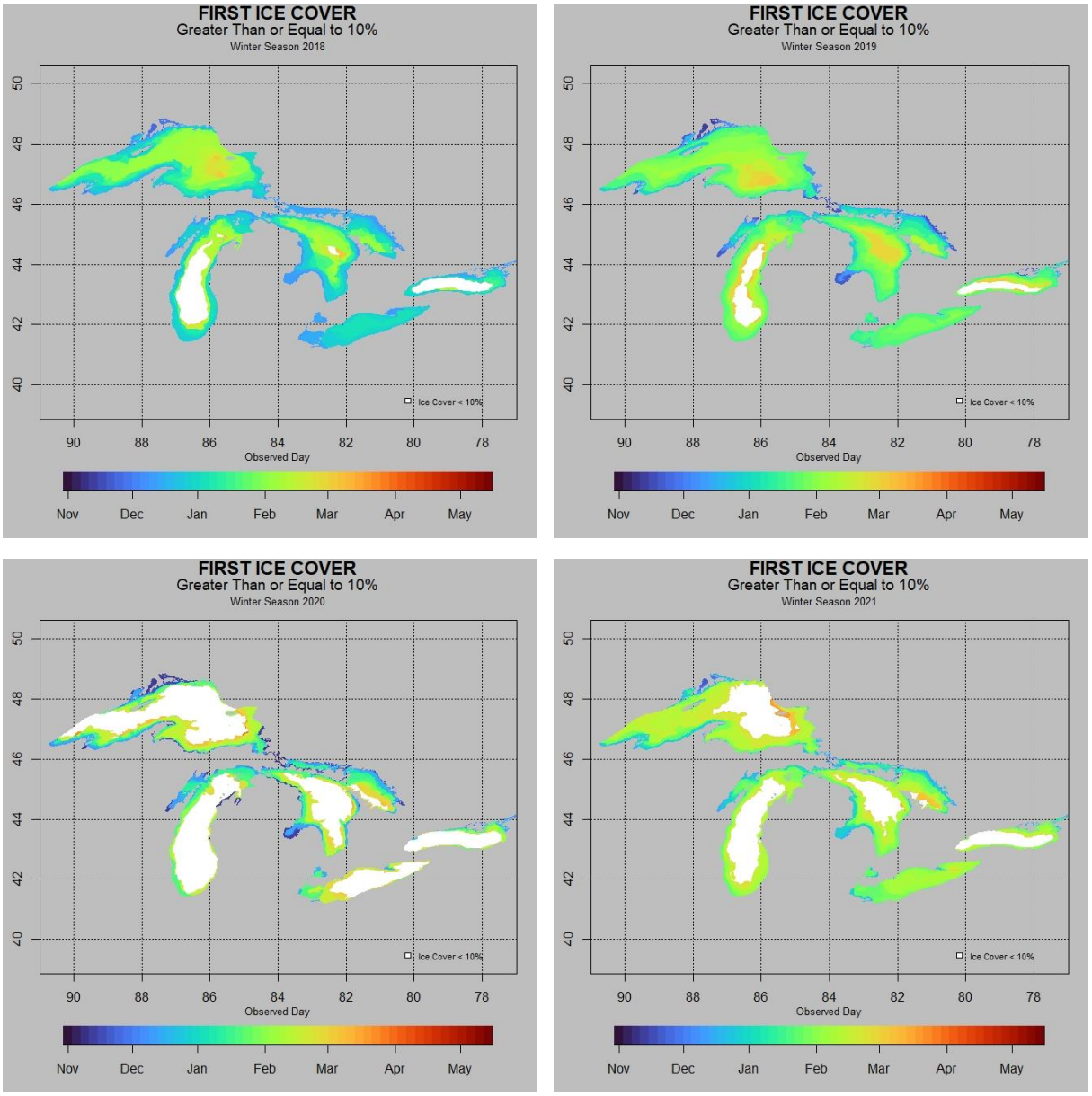


Figure 11. Dates of First Reported Ice ≥ 10%

Figure 11 shows that ice is generally observed to form in shallow, nearshore areas during November, December, and January and in deeper shore and middle areas during February and March. Ice covered the greatest amount of open water in the 2019 winter season. The largest areas of open water, where ice concentrations were less than 10%, occurred in the 2020 winter season for all of the Great Lakes.

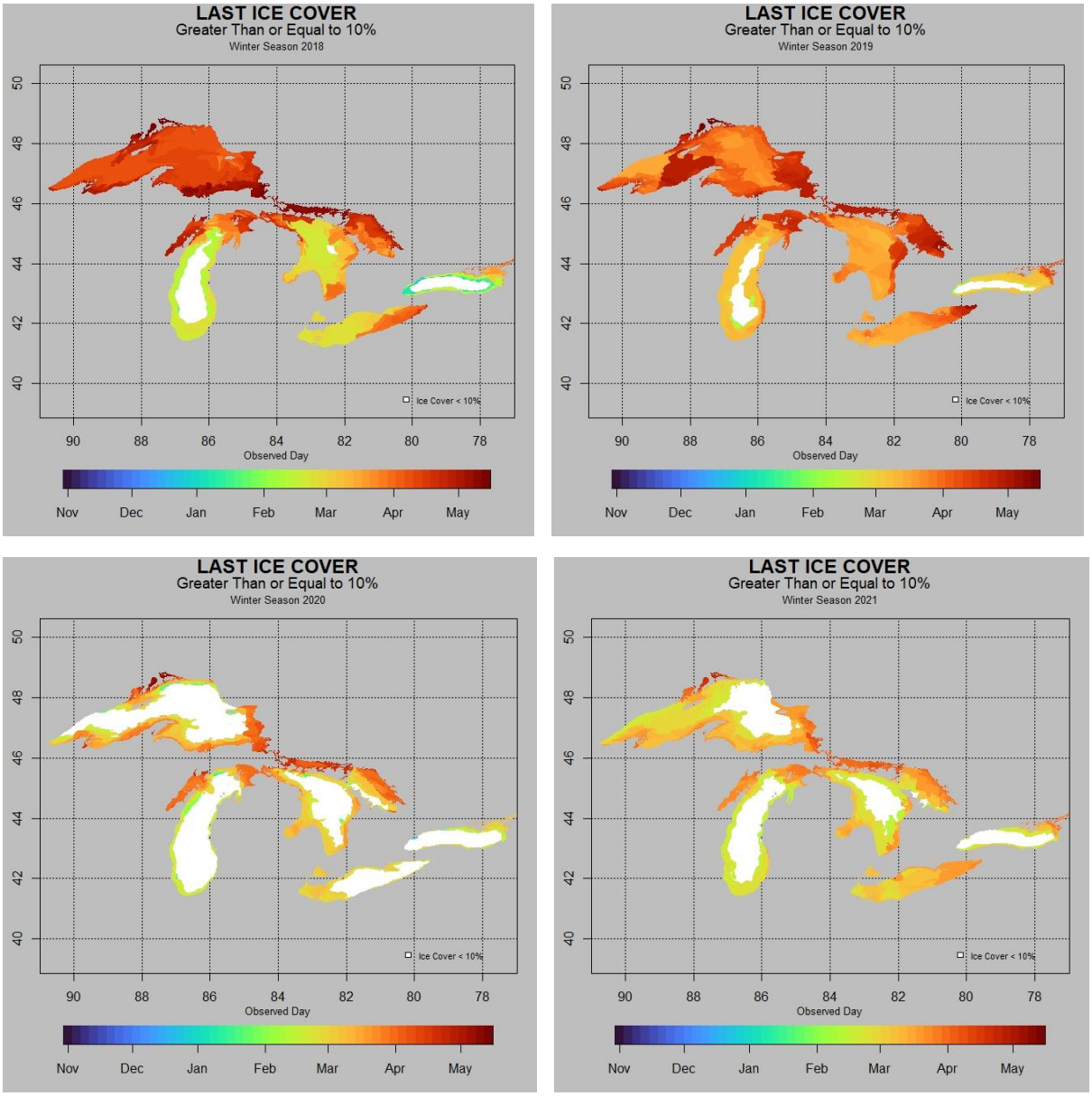


Figure 12. Dates of Last Reported Ice ≥ 10%

Figure 12 shows that last reports of middle lake area ice cover greater than 10% over the majority of
the Great Lakes occurred during February and March. Lake Superior's middle lake ice cover lasted the longest, through April, while Lake Huron and Lake Erie lasted until March. Nearshore ice cover greater than 10% persisted until late April and May. The 2018 winter season saw the latest last ice cover for Lake Superior, and the 2019 winter season saw the latest last ice cover for Lakes Michigan, Huron, Erie, and Ontario.

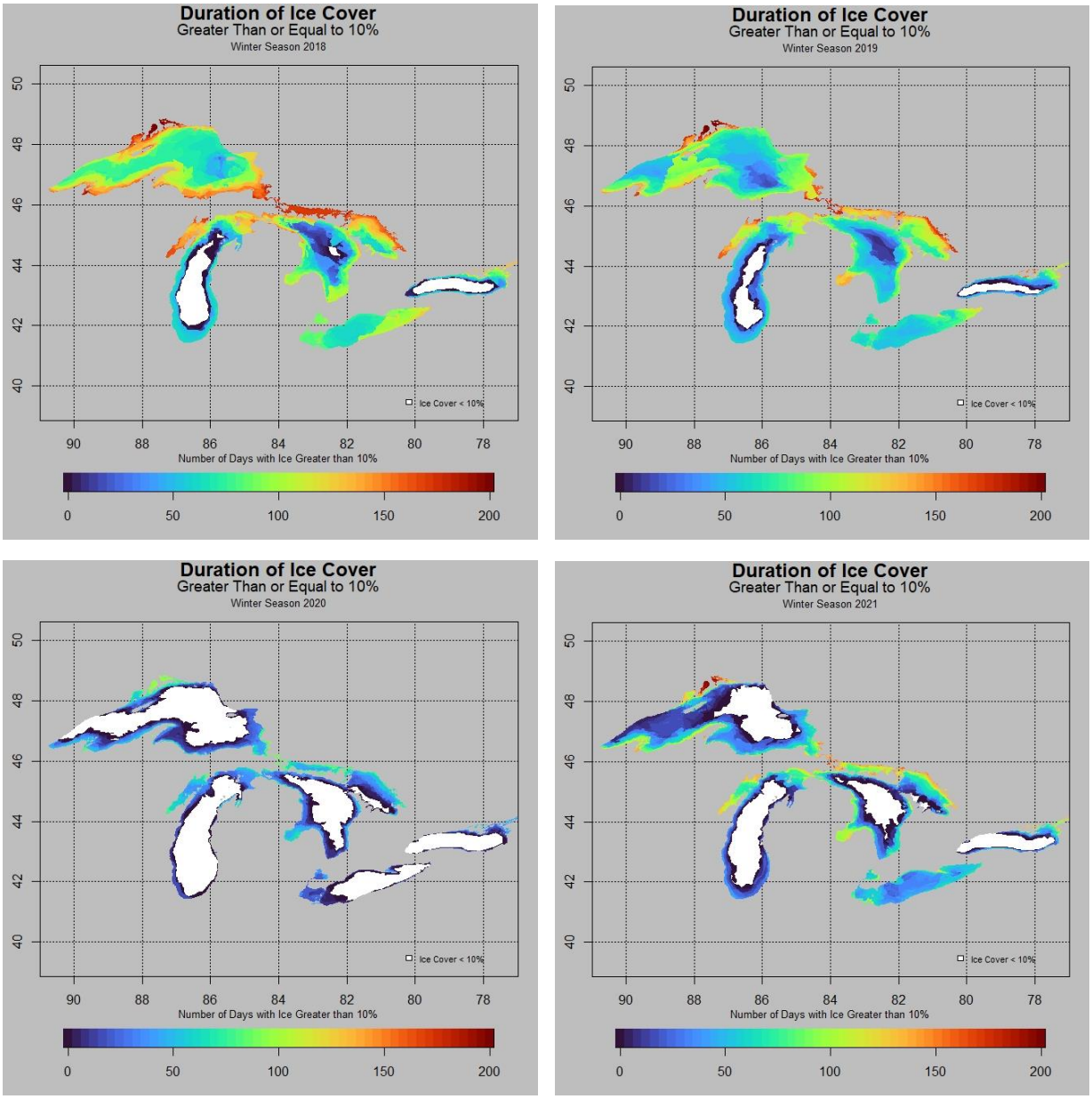


Figure 13. Duration of Ice Cover ≥ 10%

Figure 13 indicates that nearshore areas of the Great Lakes generally showed the longest duration of ice cover, while the deeper middle areas of the lakes either had no ice cover or shorter durations of ice cover greater than 10%. The 2018 and 2019 winter seasons showed longer durations of ice cover with areas of Lake Superior, Green Bay, and the Georgian Bay experiencing more than 100 days of ice cover, while Lake Huron and Lake Erie had areas with 50-100 days of ice cover. The 2020 winter season saw the shortest duration of ice cover between 2018 and 2021. Most areas saw no ice cover greater than 10% or had a duration of less than 50 days. The 2021 winter season saw some areas like the Nipigon Bay and Black Bay with a duration over 100 days, but large parts of Lake Michigan, Lake Superior, Lake Huron, and Lake Ontario saw no days with ice greater than 10% or a duration of 50 days or less.

4.4 SEASONAL PROGRESSION OF ICE COVER

The daily average lake ice cover line plots are seasonal progressions of the Great Lakes ice cycle for each winter season. A 7-day rolling mean of the daily average lake ice cover is plotted and acts to smooth the line and show a better representation of the progression of ice cover.

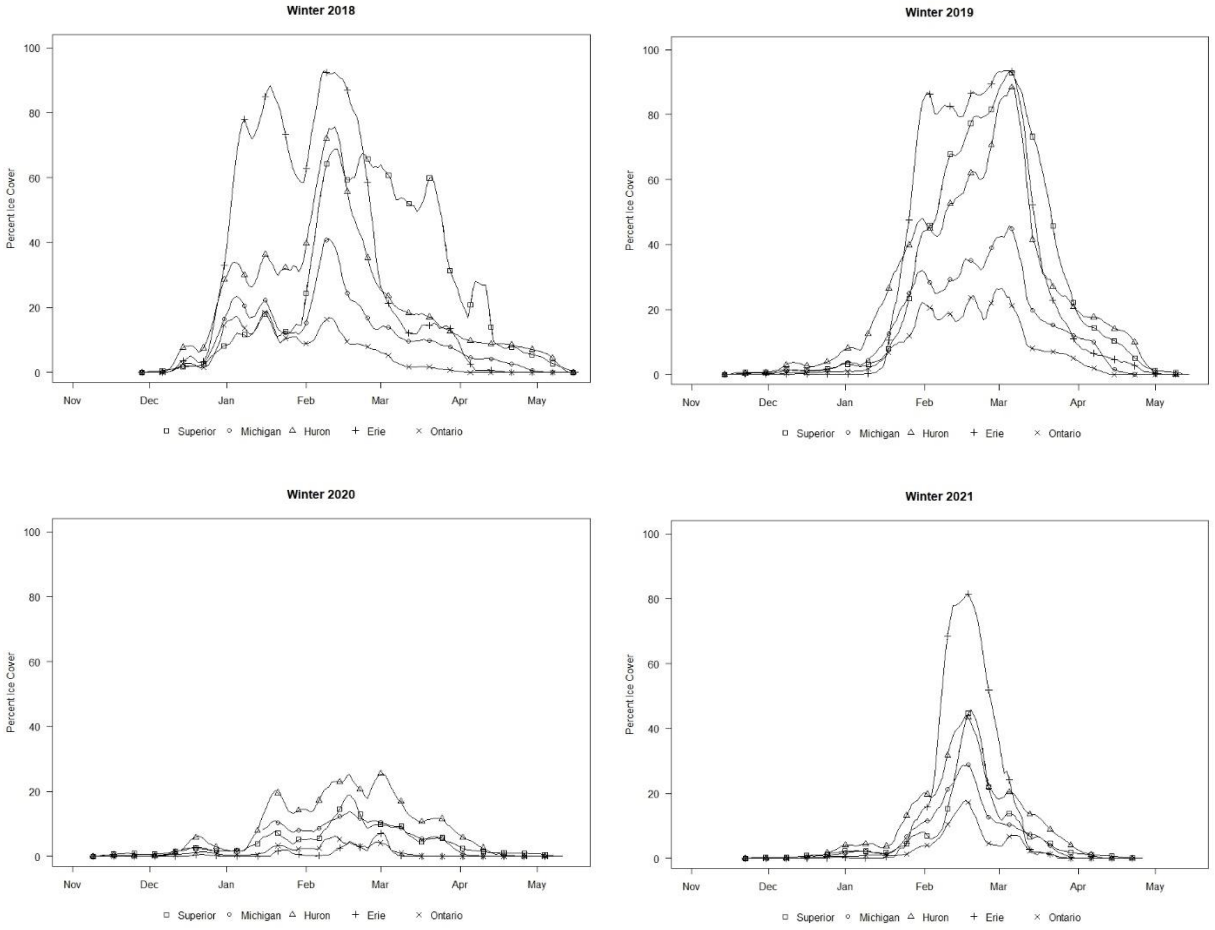


Figure 14. Daily Lake Average Ice Cover for the 2018-2021 Winter Seasons

In the 2018 winter season, ice cover began in early December and lasted until the middle of May. Lake Erie experienced the largest maximum ice cover within the lakes with over 90% ice cover in February. All of the lakes experienced maximum ice cover greater than 40% with the exception of Lake Ontario, which reached approximately 20% ice cover. Maximum ice cover generally occurred in early February.

In the 2019 winter season, ice cover began in early January for most lakes and lasted through April. Lake Superior, Lake Huron, and Lake Erie all experienced maximum ice cover above 80% while Lake Ontario experienced the lowest maximum ice cover around 30%. Maximum ice cover for each lake occurred in early March.

The 2020 winter season was much different due to a strong El Nino year (Bai et al. 2012) and other possible climate forcings such as AMO and PDO (Wang et al. 2018). None of the five lakes exceeded 40% ice cover. The ice generally occurred between January and early April.

In the 2021 winter season, ice cover began in January and lasted until April. Lake Erie experienced the largest maximum ice cover of approximately 80% in mid-February. Lake Superior and Lake Huron saw the next largest maximum ice cover at over 40% each.

Overall, the four plots show the daily average ice cover for the 2018-2021 winter seasons and illustrate the seasonal variability that occurs in the Great Lakes. The first day of ice cover varied from early December to mid-January while the last day of ice cover varied from the beginning of April to late May. The date of maximum ice cover varied between February and March. The 2018 and 2019 winter seasons were relatively long with high concentrations of ice cover. The 2020 winter season had very low concentrations of ice cover. The 2021 winter season was the shortest of the 2018-2021 winter seasons but saw higher ice cover concentrations than the 2020 winter season with shortest duration. Therefore, AMIC cannot fully reflect the amount and duration of the ice cover, and AAIC should be physical sound variable to use.

4.5 SUMMARY

This section updates the products from 2018 to 2021, following the products from 1973-2017, previously done by Assel et al. (2013) and Wang et al. (2017a,b) including: dates of first ice, dates of last ice, ice cover duration (Wang et al. 2020), and seasonal cycle of ice cover in all five lakes, which portray the seasonal and spatial patterns and trends of ice cover over each winter season.

First (last) ice cover dates and ice duration provide an important but limited look at the annual ice cycles for each winter. In recent years, significantly greater amounts of data measurements, in the form of daily ice charts spanning the entirety of the winter season, have led to better defined temporal variability of daily lake average ice cover.

The 2018 and 2019 winter seasons were relatively long with high maximum ice cover concentrations while the 2020 winter season saw a comparatively short season with very low maximum ice cover concentrations. The 2021 winter season was also short compared to the 2018 and 2019 winter seasons yet saw higher maximum ice cover concentrations compared to the 2020 winter season.

Ice cover data can be further useful in the analysis of atmospheric and oceanic teleconnection patterns and ice cover trends in the Great Lakes on various time scales (Assel 2013). Recent research Wang et al. (2012b, 2018) and Bai et al (2012) provide evidence these data are useful in the analysis of the interannual and decadal ice cover variability in response to the atmospheric teleconnection patterns and in the analysis of multi-decadal trends in Great Lakes ice cover over the last five decades. These studies augment earlier work by Assel (2009, 2005c, 2004, 1998, and 1997), Assel et al (2004, 2003, 2002), Assel and Norton (2001), Assel and Rodionov (1998), and Rodionov and Assel (2001).

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