NOAA Technical Memorandum GLERL-183

Seasonal, Interannual, and Decadal Variability and Long-Term Trend of Ice Cover in Saginaw Bay and Georgian Bay in the Great Lakes between 1973-2022

Jia Wang[1], Marissa Osterloh[3,4], and David Cannon[2]

[1] NOAA Great Lakes Environmental Research Laboratory

[2] Cooperative Institute for Great Lake Lakes Research, University of Michigan

[3] William M. Lapenta NOAA Student Internship Program

[4] Department of Geological and Atmospheric Sciences, Iowa State University, Ames, Iowa

Great Lakes Environmental Research Laboratory
4840 S. State Road, Ann Arbor, Michigan

UNITED STATES
DEPARTMENT OF COMMERCE

Howard Lutnick
Secretary

NATIONAL OCEANIC AND
ATMOSPHERIC ADMINISTRATION

Neil Jacobs, Ph.D.
Administrator

NOTICE

Mention of a commercial company or product does not constitute an endorsement by the NOAA. Use of information from this publication concerning proprietary products or the tests of such products for publicity or advertising purposes is not authorized.

This publication is available as a PDF file and can be downloaded from GLERL's web site: www.glerl.noaa.gov. Hard copies can be requested from GLERL, Information Services, 4840 S. State Road, Ann Arbor, Michigan 48108 pubs.glerl@noaa.gov.

TABLE OF CONTENTS

1. INTRODUCTION……..…….5
2. DISTRIBUTION OF ICE CHARTS BY WINTER SEASON…….…...6
3. ANALYSIS OF LAKE ICE COVER FOR GREEN BAY AND WESTERN LAKE ERIE: 1973-2022……..7
3.1 SEASONAL VARIATIONS.……...…….…9
3.2 INTERANNUAL VARIABILITY, FIRST AND LAST ICE COVER ……..11
3.3 LONG-TERM TRENDS ……..……...……15
3.4 DECADAL VARIABILITY …….……17
3.5 SUMMARY……...……...……..…….18
4. ANALYSIS OF THE ADDITION OF CLIMATOLOGY TO CURRENT DATASETS ……...…….…….19
5. ANALYSIS OF GREAT LAKES ICE COVER CLIMATOLOGY: WINTERS 2018-2022…….……..….24
5.1 DATA…….…24
5.2 ANALYSIS METHODS …….…….…..24
5.3 DATES OF FIRST (LAST) ICE AND ICE DURATION……...25
5.4 SEASONAL PROGRESSION OF ICE COVER……27
5.5 SUMMARY……..……..……28
6. OVERALL CONCLUSIONS ON ICE CLIMATOLOGY FOR SAGINAW BAY AND GEORGIAN BAY……..….29

ACKNOWLEDGEMENTS……..……..31
REFERENCES ……..……..…31

LIST OF FIGURES

Figure 1. Long-term Mean of Annual Maximum Ice Cover (AMIC) in the Great Lakes from 1973-2017. The boxes show the study regions: Saginaw Bay and Georgian Bay ……...8
Figure 2. Bathymetry Map of the Great Lakes ……....9
Figure 3. Average daily ice coverage in Saginaw Bay and Georgian Bay over the course of the 1973-2022 winter seasons.……10
Figure 4. Seasonal Variation of Weekly Ice Coverage for Saginaw Bay and Georgian Bay ...…...11
Figure 5. Daily Time Series of Ice Cover in Saginaw Bay and Georgian Bay, 1973-2022 …….....12
Figure 6. Time Series of First and Last Day of Ice Cover for Saginaw Bay and Georgian Bay, 1973-2022……...13
Figure 7. Time Series of Ice Cover Duration…….14
Figure 8. Annual Average Ice Cover (AAIC) in the Great Lakes, 1973-2022 with trendline …. 15
Figure 9. Time series of AMIC for Saginaw Bay and Georgian Bay, 1973-2022 ...……....18
Figure 10. Time series of AAIC for Saginaw Bay and Georgian Bay, 1973-2022 ...…...……...…18
Figure 11. Daily Time Series of Ice Cover in Saginaw Bay and Georgian Bay with Climatology values added to days of zero ice cover from December 1st to April 30th, 1973-2022 ……20
Figure 12. Average Annual Ice Cover (AAIC) in the Great Lakes with Added Climatology for the regions Saginaw Bay and Georgian Bay, 1973-2022……21
Figure 13. Time series of AAIC during 1973-2022. The solid blue 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 ……...……22
Figure 14. Named locations in the Great Lakes ……....25
Figure 15. Dates of First Reported Ice ≥ 10%.....25
Figure 16. Dates of Last Reported Ice ≥10%.....26
Figure 17. Dates of Duration of Reported Ice ≥ 10%.....27
Figure 18. Daily Lake Average Ice Cover for the 2022 Winter Season……..28

LIST OF TABLES

Table 1. Summary of Ice Chart Statistics ……....7
Table 2. Statistics of Seasonal Cycle Dates (Week Number) ……10
Table 3. Trends in Saginaw Bay and Georgian Bay Annual Average Ice Cover (AAIC) Averaged from December 1 to April 30 ……16
Table 4. Statistical means and standard deviations of annual average ice cover (AAIC) in Saginaw Bay and Georgian Bay, averaged from December 1 to April 30, for the period 1973-2022 ……16
Table 5. Statistical means and standard deviations of annual maximum ice cover (AMIC) in Saginaw Bay and Georgian Bay from December 1st to April 30th, 1973-2022 ……17
Table 6. Trends in Saginaw Bay and Georgian Bay Annual Maximum Ice Cover ……17
Table 7. Trends in Saginaw Bay and Georgian Bay using Annual Maximum Ice Cover ……23
Table 8. Statistical means and standard deviations of annual average ice cover (AAIC in %) in Saginaw Bay and Georgian Bay, averaged from December 1st to April 30th, for the period in 1973-2022 ……..23

1. INTRODUCTION

The 50-year winter ice cover dataset available from the U.S. National Ice Center (USNIC) consists of 7,435 ice charts covering the Laurentian Great Lakes. This report aims to update the ice climatology dataset for Saginaw Bay and Georgian Bay (Lake Huron), which was previously described in GLERL's 45-winter (1973-2017) Great Lakes ice report (Wang et al. 2017a,b). Saginaw Bay is located in Lake Huron in northeast Michigan, with given coordinates 43. 85°N, 83.68°W, whereas Georgian Bay is located in northeastern Lake Huron, bordered by south-central Ontario, Canada (45.41°N, 81.11°W). Ice chart data was originally produced by USNIC as ASCII files, and a mask was used to select the regions listed above. Details regarding data format, quality control, ArcGIS processing, and data availability are similar to those discussed in chapters 2 - 6 of Wang et al. (2012a) and Yang et al. (2020).

A driving factor in investigating variability in ice cover for the Laurentian Great Lakes is that different lakes (or regions) may experience spatial and temporal variability related to lake orientation, depth (i.e., water heat storage), and turbidity (i.e., albedo due to sedimentation; Wang 2012). Furthermore, Great Lake ice cover is a sensitive indicator of regional climate change (Assel et al.,1995; Assel and Robertson, 1995; Magnuson et al.,1997,2000). Although seasonal ice cover occurs annually, there is high interannual variability. For example, the maximum ice cover over the Laurentian Great Lakes was 95% in 1979 and only 11% in 2002 (Bai et al. 2012). In 2018 and 2019, Lake Huron had an annual mean ice cover of 81.4% and 95.7%, respectively. But in 2020, Lake Huron had a large dip in annual mean ice cover, falling to only 32.1%. In 2021 and 2022, ice cover partially rebounded but remained low with means of 48.3% and 67.2%, respectively. Possible explanations for this interannual variability include both multidecadal trends and long-term global climate warming.

This report highlights variability in ice cover for two bays in Lake Huron (i.e. Saginaw Bay, and Georgian Bay) on seasonal, interannual, and decadal time scales. This update on the ice dataset will be a useful tool for the research community, providing information relevant to winter limnology, ecosystem function, and community management in Lake Huron.

For this study, we chose to analyze two locations within Lake Huron: Saginaw Bay and Georgian Bay. We chose Saginaw Bay to look at due to the Bay supporting the largest commercial walleye fishery in Lake Huron and therefore it is vital to know the ice climatology for the region due to its economic benefits. Secondly, we chose to investigate Georgian Bay due to the bay's large commercial shipping port.

2. DISTRIBUTION OF ICE CHARTS BY WINTER SEASON

The number of ice charts available from USNIC for each winter season from 1973 to 2022 ranges from 100 to 197. Ice charts produced by USNIC cover the entire Great Lakes region, including Saginaw Bay and Georgian Bay. The first date of ice chart publication for each season ranged from November 14th to January 3rd, with end dates ranging from April 5th to June 5th (Table 1). Since the 2011 winter season, USNIC has produced daily ice charts, although the first date of chart issuance does not necessarily correspond with the first date of ice cover on the lakes.

Table 1. Summary of statistics for ice charts available from USNIC

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
2022	178	26-Nov	22-May

3. ANALYSIS OF LAKE ICE COVER FOR SAGINAW BAY AND GEORGIAN BAY: 1973-2022

The spatial, long-term mean of the annual maximum ice cover (AMIC) in the Great Lakes was constructed using USNIC ice chart data from the winter seasons of 1973 to 2017 (Figure 1). The two areas of interest for this report, Saginaw Bay, and Georgian Bay are enlarged for clarity. A bathymetry map for The Great Lakes is provided to give insight into the depths of the different lakes **(**Figure 2**)**. The map shows that Georgian Bay (average depth: 59m) is significantly deeper than Saginaw Bay (average depth: 10m).

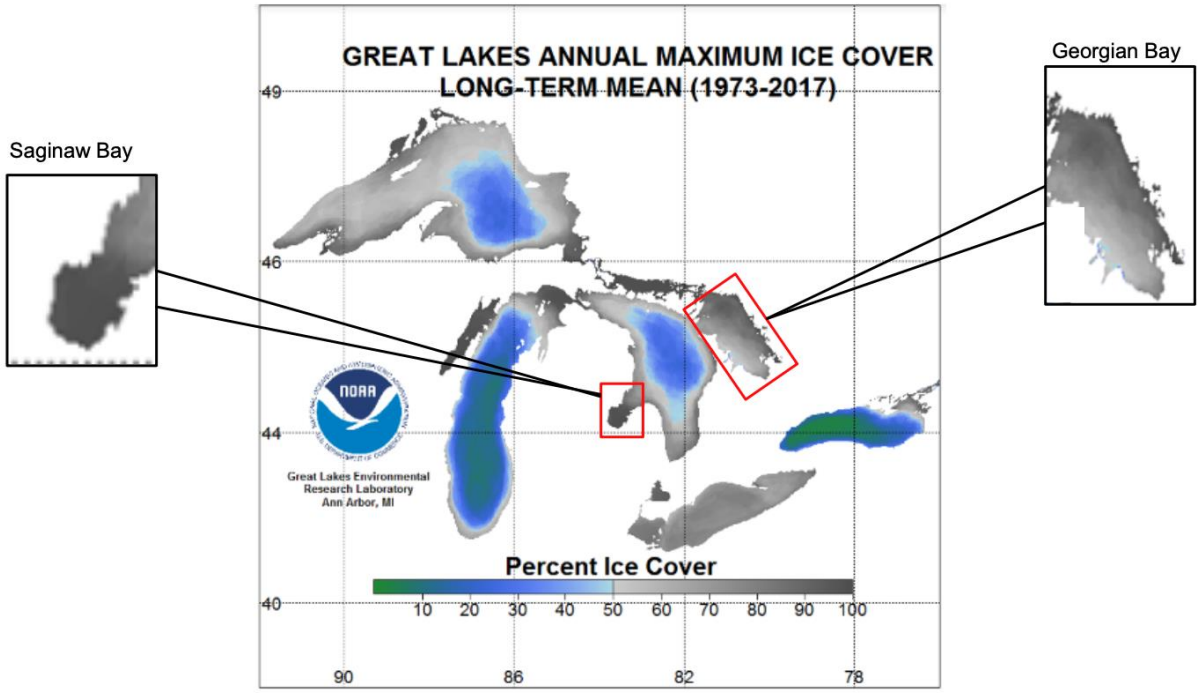


Figure 1. Long-term mean of annual maximum ice cover (AMIC) in the Great Lakes from 1973-2017. The boxes show the study regions: Saginaw Bay and Georgian Bay and the colormap indicates the percent ice cover.

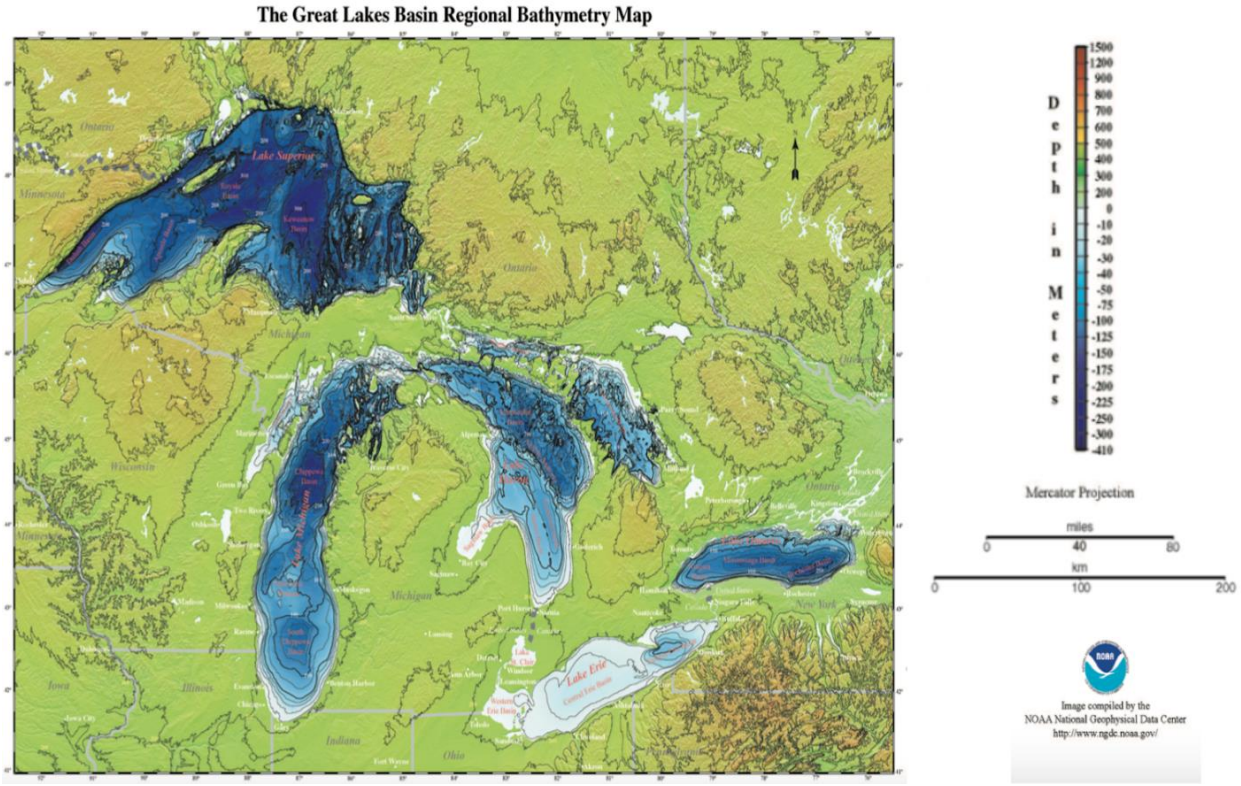


Figure 2. Bathymetry map for the Laurentian Great Lakes.

3.1 SEASONAL VARIATIONS

The mean daily ice cover for Georgian Bay and Saginaw Bay is shown in Figure 3. Daily averages were computed using all historical daily data available over the 50 year record. Average ice climatologies for each region show a general ice growth season from December through February and an ice melt season from March until May, with peak ice concentrations around 65% and 85% for Georgian Bay and Saginaw Bay, respectively. An analysis of the start date of ice cover (or ice-on date), the growing period in which a maximum occurs, and the offset (or ice-off date) are shown in Table 2. Ice-on and ice-off dates are estimated as the first and last day at which ice cover exceeds 10%. On average the first recorded ice cover date occurs in week 50 and week 51 (late December) for Saginaw Bay and Georgian Bay, respectively., while the maximum is reached in weeks 7 and 9, respectively. The day of the last recorded ice cover for Saginaw Bay occurs during week 14, whereas Georgian Bay's date of last ice cover occurred two weeks later, in week 16.

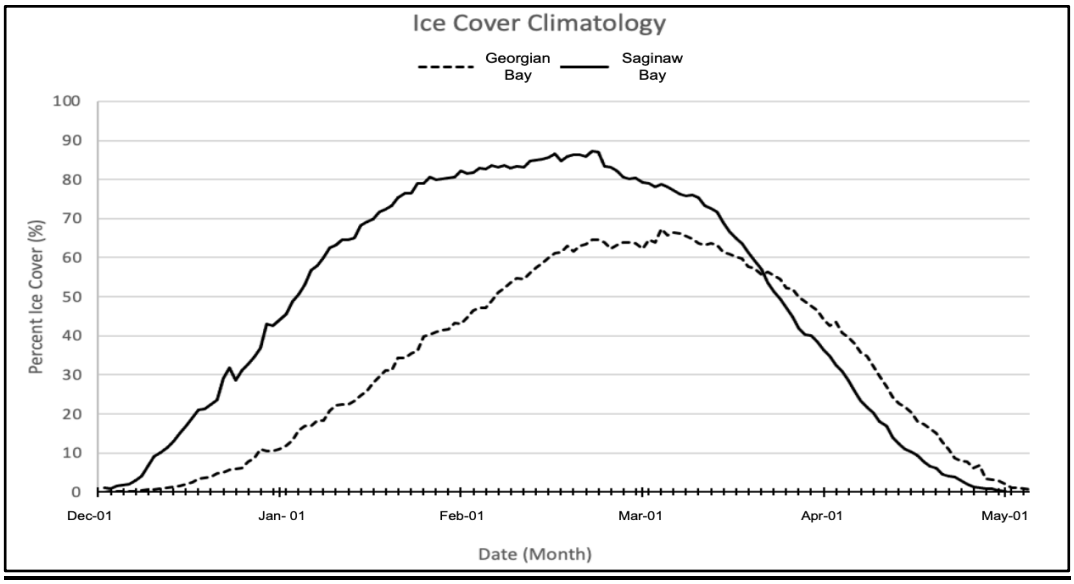


Figure 3. Average ice cover concentration of Georgian Bay and Saginaw Bay (1973-2022)

Table 2. Statistics of average seasonal ice climatology dates (week number). The Onset and Offset weeks are the first and last weeks of ice cover >10%, respectively, and the Maximum is the week in which the maximum ice cover occurs.

	Saginaw Bay	Georgian Bay
Onset	50	51
Maximum	7	9
Offset	14	16

Variability in ice cover is defined by the standard deviation as computed for each week of observations collected over the entire 50-year data record (Table 2 and Figure 4). Saginaw Bay has a lower average standard deviation to mean ratio (0.24) than Georgian Bay (0.48). The ratio is inversely proportional to predictability. This implies that, in general, the ice cover in Saginaw Bay is more predictable that the ice cover in Georgian Bay, where the year-to-year variability in ice cover is larger. While the low variability in ice cover in Saginaw Bay suggests that climate warming is producing only minor changes in ice concentration, standard deviation ratios alone may produce an incomplete picture of changing ice climatologies. For example, ice cover in the freezing (December 15 to January 15) and melting seasons (March 15 to April 15) have higher standard deviation ratios (values?) than those observed during the peak ice season (January 15 to March 15), highlighting potentially shifting ice-on and ice-off dates (discussed below). Ice

thickness is likely also changing in both bays, and should be used, whenever available, to investigate the response of ice cover to the changing climate.

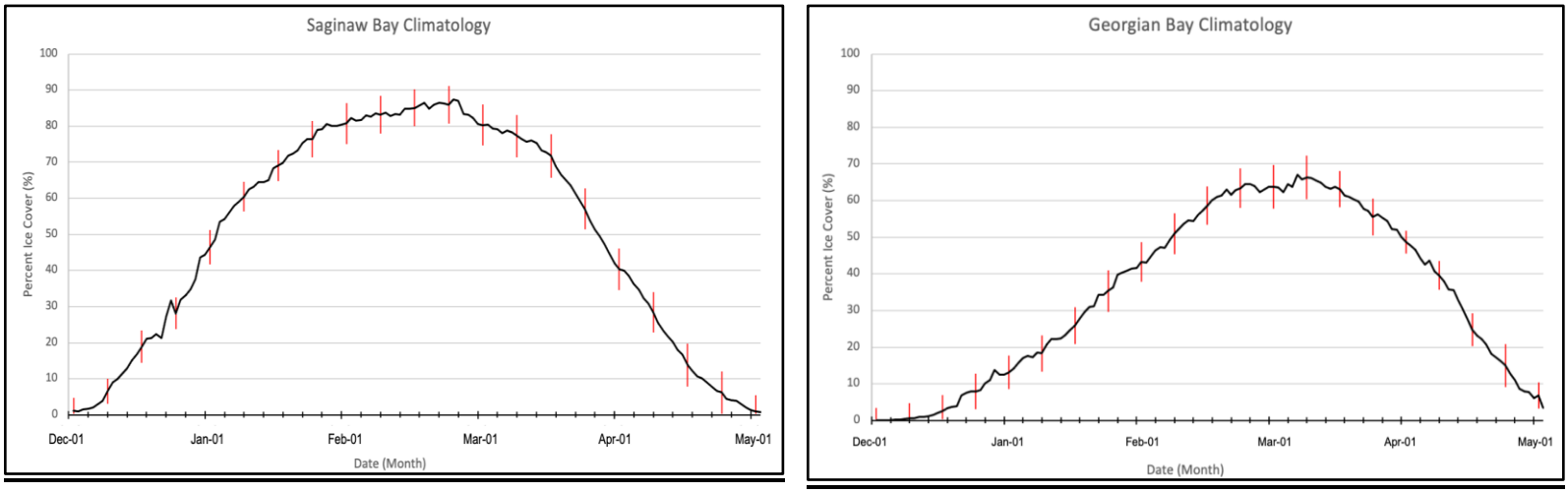


Figure 4. Seasonal variation of weekly ice coverage (black) with one standard deviation above and below and the mean (red).

3.2 **INTERANNUAL VARIABILITY, FIRST AND LAST ICE COVER**

Time series of daily ice cover area for Saginaw Bay and Georgian Bay have been constructed based on the ice concentration data for the winters of 1973 to 2022 (Figure 5). For this analysis, we assume that ice cover is absent (0%) when there is no observational data available during the ice season (Dec. 1st to Apr. 30th). However, the missing data are replaced by the climatological daily data, as shown in Fig. 4. In general, maximum ice cover in Saginaw Bay is higher than that observed in Georgian Bay, despite its position at lower, warmer latitudes (Figure 1). Differences in ice cover are likely linked to variable bathymetries (Figure 2), with the shallower waters of Saginaw Bay requiring less extreme cold snaps to initiate ice formation. The lower volume of Saginaw Bay may also explain differences in interannual variability, with higher variability in mean and peak annual ice-cover in Georgian Bay compared to the shallower Saginaw Bay.

Georgian Bay and Saginaw Bay experienced especially low ice cover during the 1998 winter season (Figure 5), with maximum ice concentrations of 37% and 88%, respectively. Previous studies have linked this low-ice season to the largest El Niño event of the 20th century, which led to a large temperature anomaly in the Laurentian Great Lakes region (e.g. Van Cleave et al., 2014).

An El Niño event also caused an anomalously low ice season in 2002 (see Fig. 2 of Bai et al. 2012), when both bays experienced their lowest ice cover maxima on record (Saginaw Bay: 80%; Georgian Bay: 30%). In more recent years, beginning in 1998, lower levels of ice cover have consistently occurred every 3 - 4 years. This may imply that interannual climate variability is higher in the last two decades compared to the previously recorded winters.

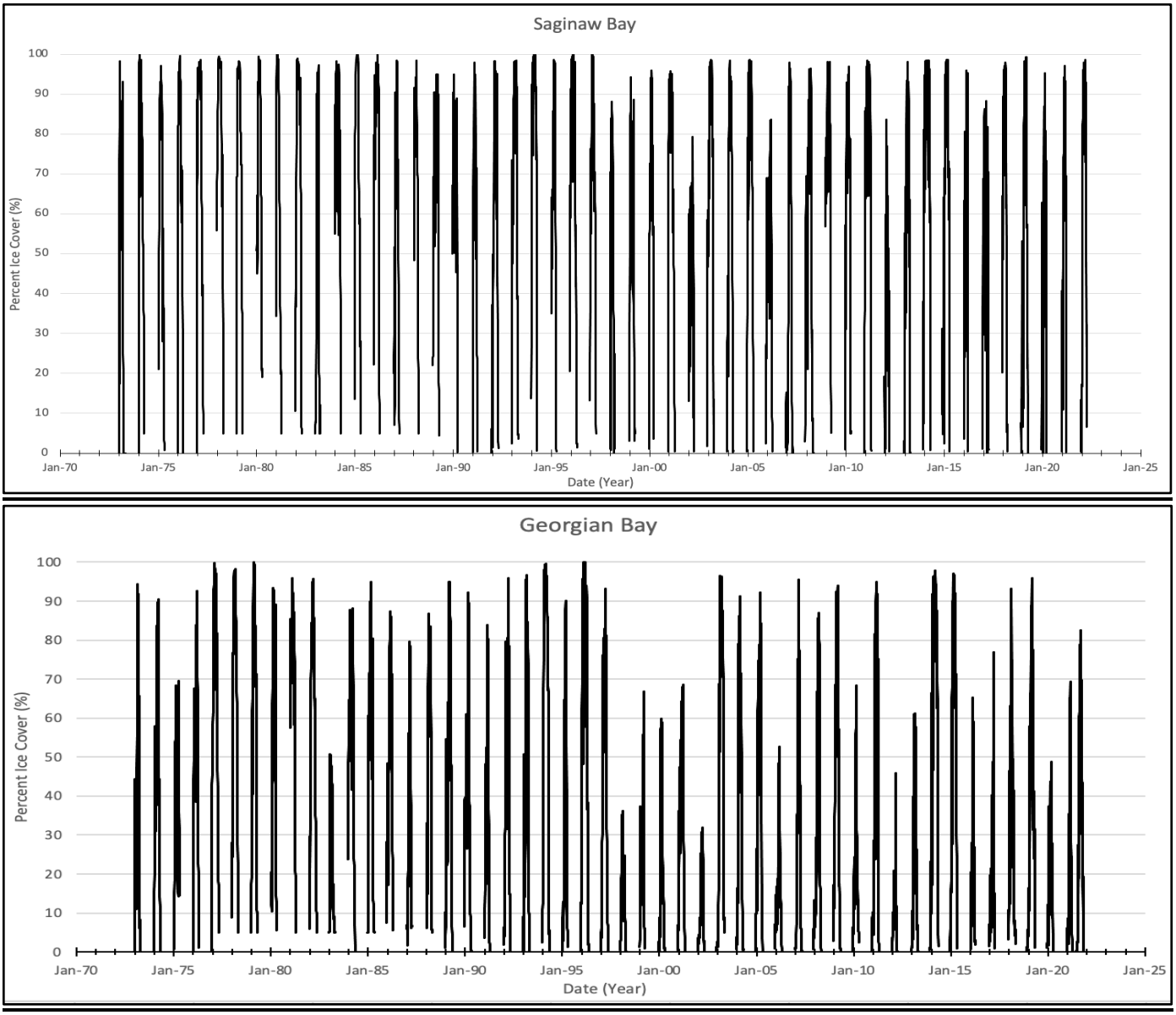


Figure 5. Daily time series of ice cover in Saginaw Bay and Georgian Bay, 1973-2022.

Time series plots for the first (ice-on) and last (ice-off) day of ice cover (≥10%) in Saginaw Bay and Georgian Bay are shown in Figure 6. The first (-3.0 days/decade) and last (-4.1 days/decade)

day of ice cover in Saginaw Bay show decreasing trends, suggesting that the ice-on and ice-off dates are occurring earlier in the season in recent years. Although both dates are occurring earlier, the ice-off date is changing more rapidly, resulting in a net shortening of the ice cover duration (Figure 7; -1.0 days/decade). In Georgian Bay, the first day of ice cover is occurring later in the season (0.8 days/decade) and the last day of ice cover is occurring earlier in the season (-1.0 days/decade). As with Saginaw Bay, changes in the ice-on and ice-off dates are leading to a net decrease in the total duration of ice cover is Georgian Bay (-1.0 days/decade).

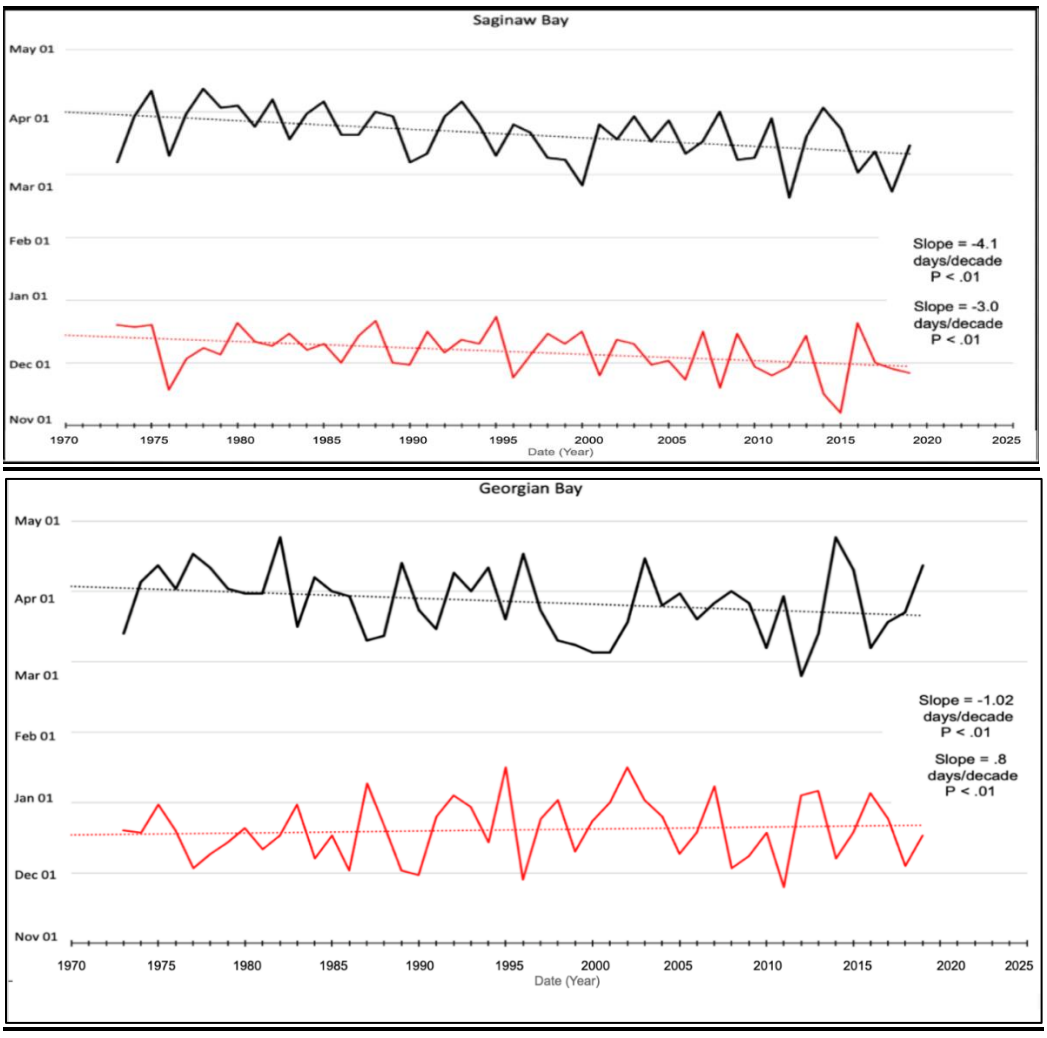


Figure 6. Time series of the first and last day of ice cover for each year from 1973-2022. The solid, bold black line represents the last day of ice cover for each year, and the dotted black line represents the trend. The solid red line represents the first day of ice cover for each year, and the dotted red line represents the trend. Trend slopes and p-values are included for reference.

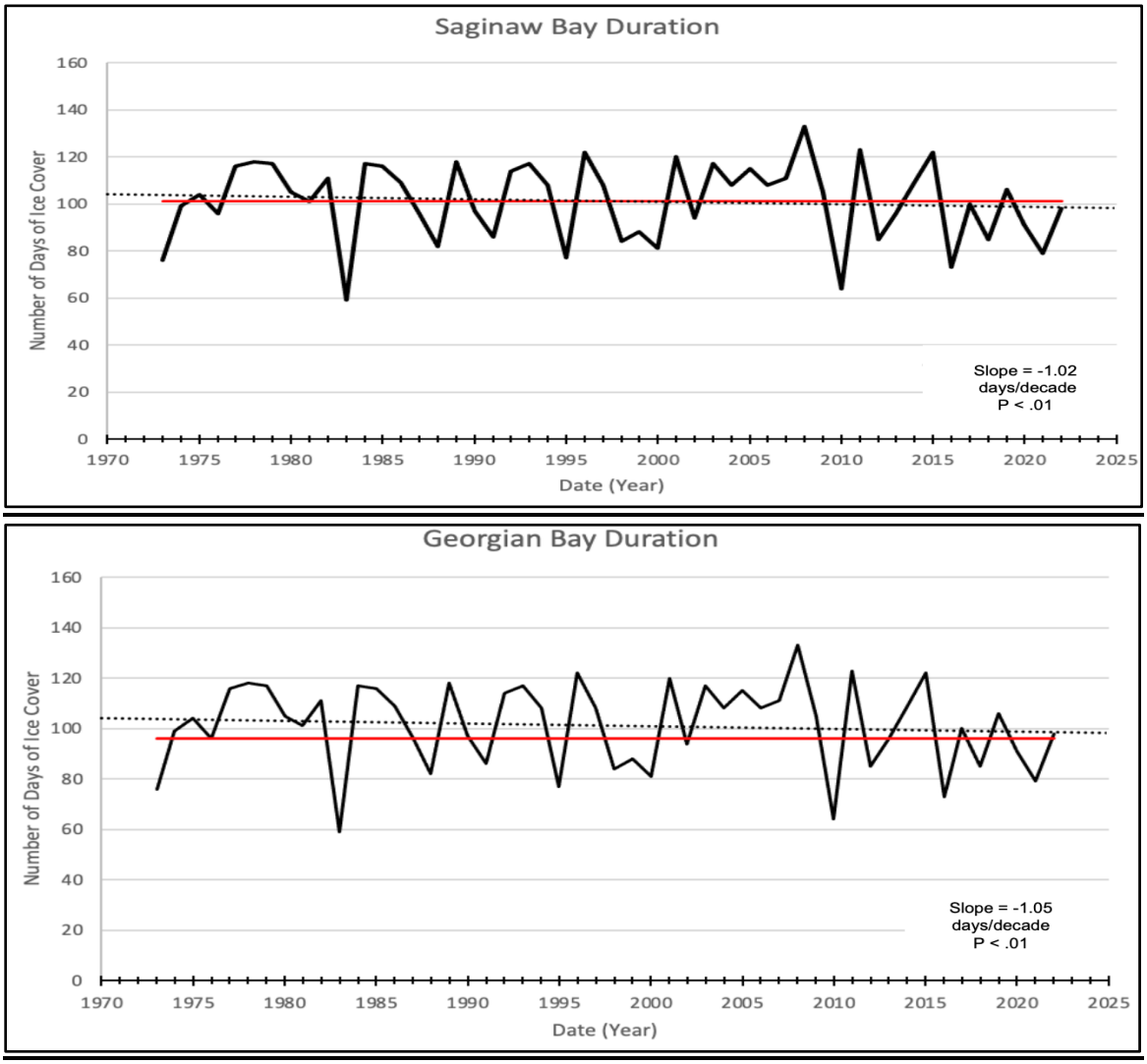


Figure 7. Time series of the duration of ice cover in number of days for each year from 1973-2022. The dashed line represents the trendline, and the red line is the mean. Trend slopes and p-values are included for reference.

Time series plots for the annual average ice cover (AAIC) in Saginaw Bay and Georgian Bay, defined as the annual mean ice cover averaged from December 1 to April 30th, are shown in Figure 8 and Figure 10. Both regions show a negative trend, with Saginaw Bay decreasing by 0.19 %/year and Georgian Bay decreasing by 0.32 %/year between 1973 and 2022. The greater trend in Georgian Bay suggests that the bay is changing more rapidly and may be more strongly affected by warming climate conditions.

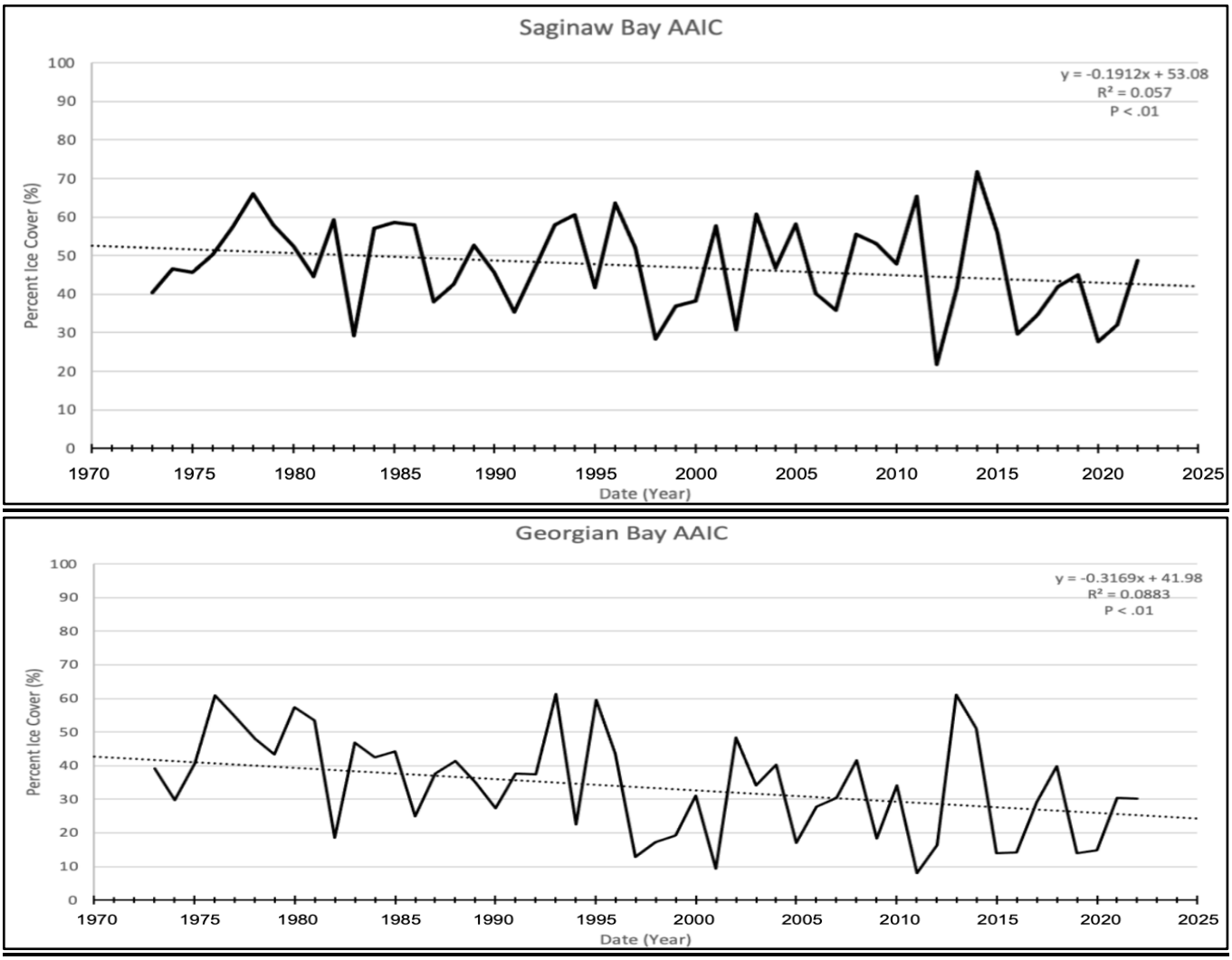


Figure 8. Average annual ice cover (AAIC) in Saginaw Bay and Georgian Bay between 1973-2022. Dashed lines indicated best-fit linear trends, with trend equations, correlations of determination (R^2), and p-values for the slope included for reference.

3.3 LONG-TERM TRENDS

In both Saginaw Bay and Georgian Bay, annual average ice cover (AAIC) and annual maximum ice cover (AMIC) observations show a strong negative long-term trend in ice cover since 1973. Best-fit linear functions take the form:

$$y = bt + a,$$

where a is the y-intercept corresponding to the percent ice cover value in 1973, and b is the slope of the linear function, equal to the rate of change of the percent ice cover with time in years since 1973, t. The characteristic values of each linear function are shown in Table 3. Annual mean ice

cover in both regions shows a significant negative trend since the 1970s. With a rate of decrease of 0.19 %/year in Saginaw Bay and 0.32 %/year in Georgian Bay, annual average ice coverage has decreased by a total of 10% and 16%, respectively, over the entire 50-year record.

Table 3. Trends in Saginaw Bay and Georgian Bay annual average ice cover (AAIC) averaged from December 1st to April 30th.

	Saginaw Bay	**Georgian Bay**
a, intercept	53.08	41.98
b, slope [%/yr]	-0.19	-0.32
b/a [%]	-0.36	-0.8
Total Loss [%]	10	16

Table 4. Statistical means and standard deviations of annual average ice cover (AAIC in %) in Saginaw Bay and Georgian Bay, averaged from December 1st to April 30th, for the period in 1973-2022.

	Saginaw Bay	**Georgian Bay**
Mean	47.74	33.04
Std	11.67	15.93
Std/Mean	0.24	0.48

Table 4 shows statistics for the annual average ice cover (AAIC) in Saginaw Bay and Georgian Bay, including the mean, the standard deviation, and the ratio of the standard deviation to the mean. AAIC is generally larger and less variable in Saginaw Bay (mean: 47.7%; std: 11.7%) than in Georgian Bay (mean: 33.0%; std: 15.9%). As with the standard deviation ratios computed for weekly climatology, the standard deviation-to-mean ratios for AAIC are larger in Georgian Bay (0.48) than Saginaw Bay (0.24), suggesting that AAIC is more predictable year-over-year in Saginaw Bay than in Georgian Bay.

Annual mean ice cover (AAIC), which is averaged over the entire winter season (i.e. December 1 to April 30) is a more meaningful climate change indicator than the annual maximum ice cover (AMIC), which represents only a single day of the winter season (Wang et al. 2012b). Estimates of the AAIC implicitly include the total ice cover duration, an important indicator of changes in ice climatology, while estimates of the AMIC do not, although AMIC remains convenient as a daily measurement that does not require temporal integration. Therefore, the following analysis provides the statistics of both AAIC and AMIC for comparison.

Table 5 includes the statistics for mean, standard deviation, and standard deviation to mean ratio for the annual maximum ice cover in Saginaw Bay and Georgian Bay. While Georgian Bay has a lower average AMIC than Saginaw Bay (83% vs. 88%), variability in ice cover maxima is substantially higher in the deeper bay (Georgian Bay: 18.2%; Saginaw Bay: 13.2%). Standard deviation to mean ratios for AMIC are lowest in Saginaw Bay (0.15), with a ratio of 0.22 in Georgian Bay. The variability of AMIC (0.15 – 0.22) is much lower than that of AAIC (0.24 – 0.48) in both bays, suggesting that AAIC is a more useful (and physically sound) variable for detecting changes in ice climatology than the AMIC, especially in the Laurentian Great Lakes.

Table 5. Statistical means and standard deviations of annual maximum ice cover (AMIC) in Saginaw Bay and Georgian Bay as estimated between December 1st and April 30th, 1973-2022.

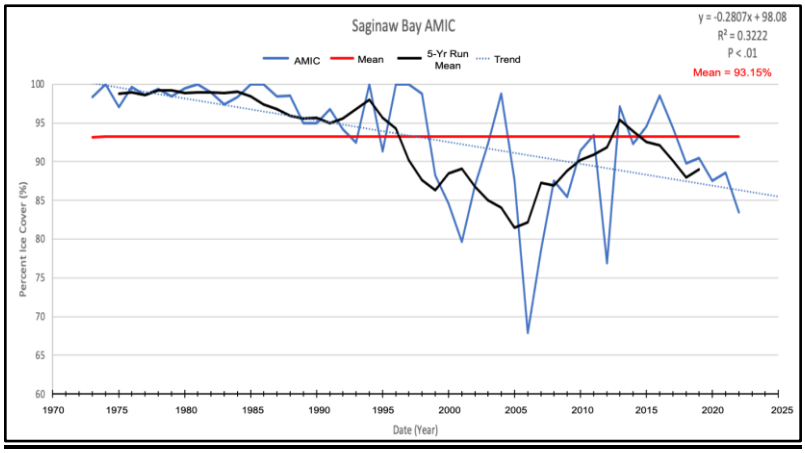
	Saginaw Bay	**Georgian Bay**
Mean	88	83
Std	13.15	18.19
Std/Mean	0.15	0.22

Table 6. Trends in annual maximum ice cover (AMIC) in Saginaw Bay and Georgian Bay

	Saginaw Bay	**Georgian Bay**
a, intercept	98	41.98
b, slope [%/yr]	-0.51	-0.32
b/a [%]	-0.52	-0.16
Total Loss [%]	25	7

Decadal variability, which describes long-term changes in climatic conditions, is a significant area of research in both small and large lakes (Magnuson et al., 2000; Ghanbari et al., 2009; Weyhenmeyer et al., 2011). For each of the fifty years investigated in the current study (1973 – 2022), we calculated the annual maximum ice cover (AMIC) for Saginaw Bay and Georgian Bay to describe the decadal variability of local ice climatology (Figure 9). Annual maximum ice cover in Saginaw Bay (mean: 93%) was less variable than AMIC in Georgian Bay (mean: 83%). The lowest AMIC in Saginaw Bay occurred in 2006 when ice cover never exceeded 67%. The lowest AMIC in Georgian Bay occurred in 2002 at 31%. Each of these low ice cover years (i.e. 2002 and 2006) correspond with El Niño events, which have been shown to have a strong effect on climate conditions in the Laurentian Great Lakes. Between 1973 and 2022, AMIC in Saginaw Bay decreased at a rate of 0.28% per year, whereas AMIC in Georgian Bay decreased at a rate of 0.13%

per year. These trends can be attributed to multi-decadal variability and human-induced secular climate warming.



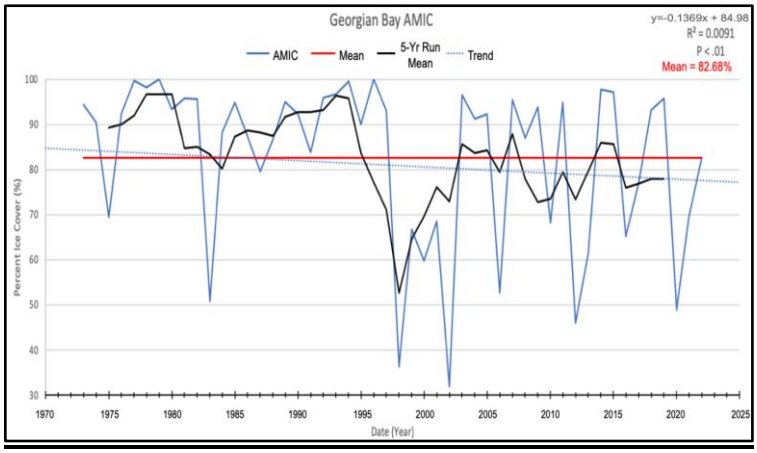
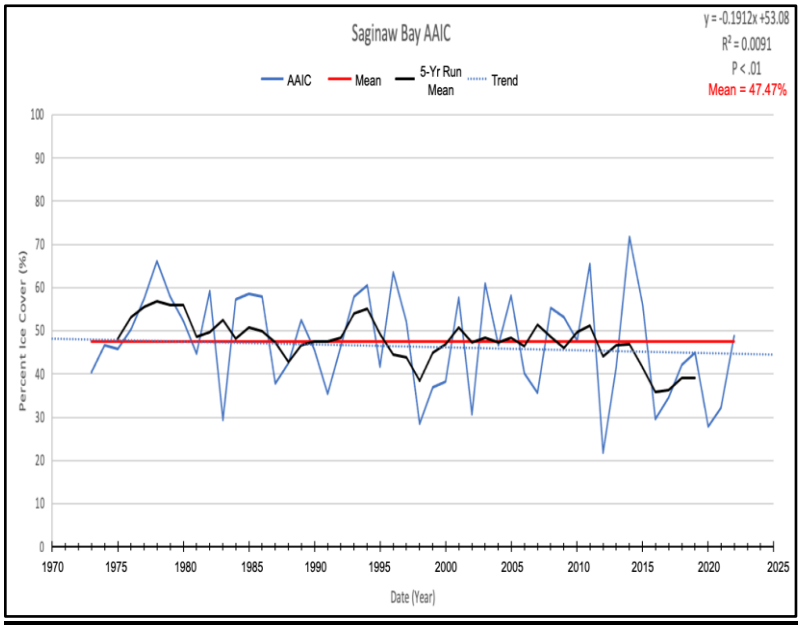


Figure 9. Time series of AMIC during 1973-2022. The solid blue line is the AMIC, the red line is the climatological mean of each region, the blue dashed line indicates the long-term trend, and the black line is the 5-year running average of the AMIC.



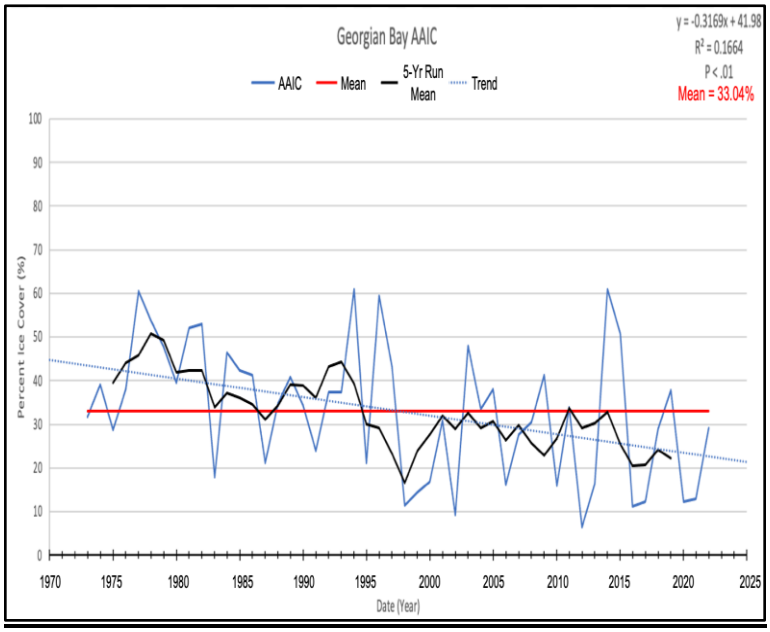


Figure 10. Time series of AAIC during 1973-2022. The solid blue line is the AAIC, the red line is the climatological mean of each region, the blue dashed line indicates the long-term trend, and the black line is the 5-year running average of the AAIC.

3.5 SUMMARY

Seasonal ice cover growth in Saginaw Bay and Georgian Bay were notably different, likely due to differences in bathymetry (i.e. water depth and volume) and latitude in each bay. Using historical

observations available through the U.S. National Ice Center, we observed differences in the first and last day of ice cover, the AAIC, and the annual AMIC. Both lakes show a decrease in ice duration and AAIC, with both parameters decreasing fastest in Georgian Bay. This could be due to the larger depth and volume of Georgian Bay, which creates a larger thermal mass to cool before ice formation. With warmer winters due to climate change, deeper waters will take longer to freeze than shallow waters. On the other hand, AMIC is decreasing faster in Saginaw Bay than in Georgian Bay. While Saginaw Bay often reached 100% ice cover in the past, maximum ice cover in the bay has rarely exceeded 90% since the major El Niño event in 1998, driving a large downward trend between 1973 - 2022. This is in contrast to Georgian Bay, where AMIC quickly rebounded to decadal averages post-1998, resulting in weaker long-term trends. It is possible that AMIC is more sensitive to annual minimum air temperatures, with lower temperatures retaining high AMIC levels at upper latitudes, even if those high AMIC levels occur for shorter periods of time. This highlights the importance of AAIC, which is averaged over the entire whole ice season rather than collected on a single day, as a climate change indicator. As such, 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 THE ADDITION OF CLIMATOLOGY TO CURRENT DATASETS

In the earlier part of the period (primarily before 1985), there is a significant amount of missing data at the beginning of the ice season. Before 1985, at the beginning of each winter period, the first ice chart produced by USNIC would often begin well above 10% average ice cover. This may reflect changes in technology (e.g. increases in satellite coverage) or image analysis at USNIC. This missing data has a significant impact on the perceived first day of ice cover, ice cover duration, and annual average ice cover, since AAIC is estimated over the entire ice season. To adjust for missing ice cover at the beginning of the season, we substituted missing values between December 1st and April 30th with the average ice climatology for each sample region (Figure 11). Below, we discuss changes in variable statistics and trends associated with these substitutions.

Substituted time series are shown in Figure 11. In comparison to the original data (Figure 5), we can see that there are noticeable differences at the beginning of each year. In Figure 5, there are

numerous days in which the first day of ice cover begins well above 10%, whereas, with the climatology data added in, this all ice seasons begin with days at (or close to) 0% ice cover.

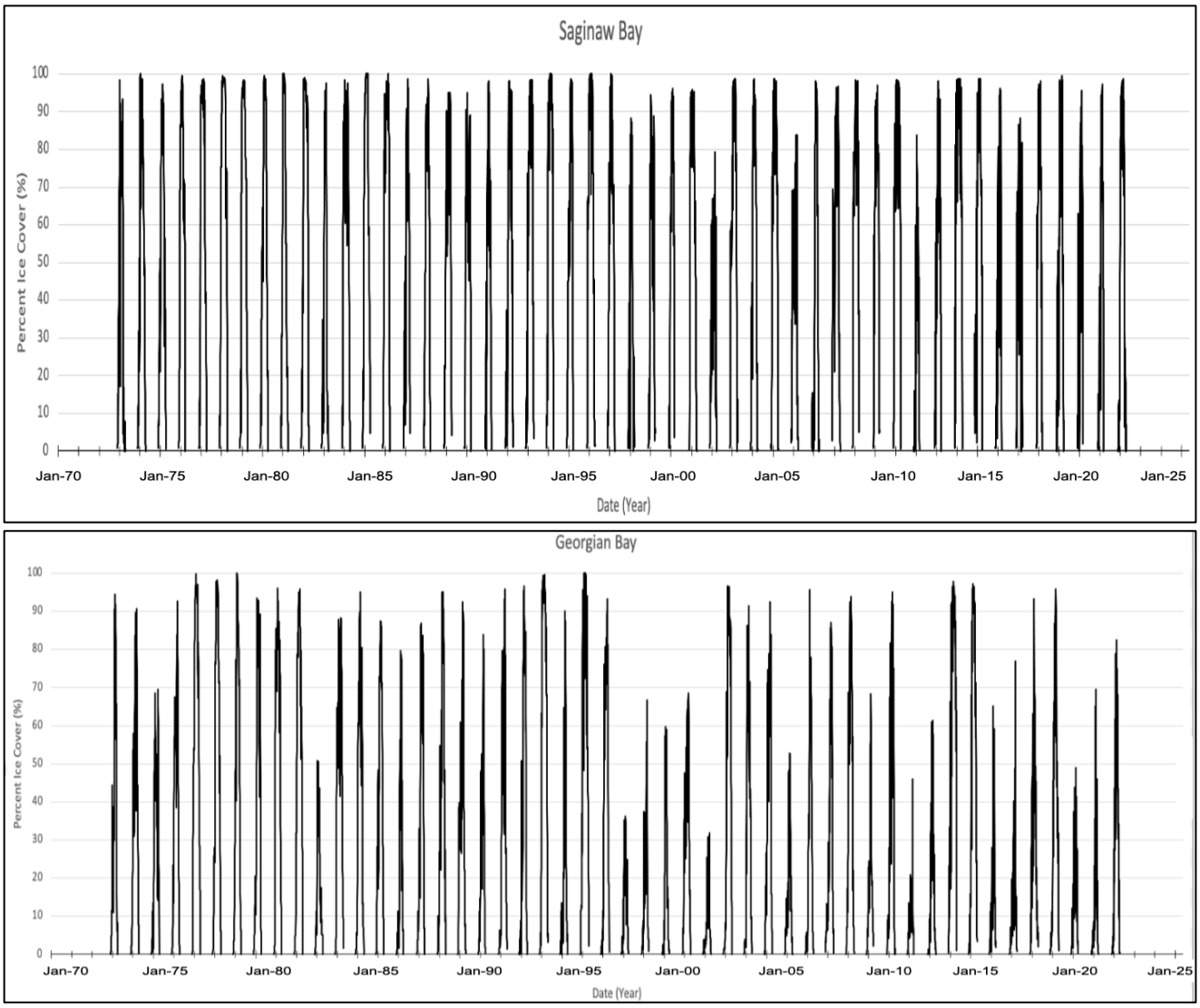


Figure 11. Daily time series of ice cover in Saginaw Bay and Georgian Bay with climatology values added to days of zero ice cover from December 1st to April 30th, 1973-2022.

AAIC was recalculated for each region using the new climatology substituted time series (Figure 12, Figure 13). AAIC trends were substantially different when calculated using the edited time series. In Saginaw Bay, trends changed from -0.19 %/year to -0.20 %/year. In Georgian Bay, trends changed from -0.32 %/year to -0.42 %/year. This shows that accurate representations of ice cover at the beginning of each winter season are important for detecting long-term trends, and improved time series representations may result in more significant warming trends than previously thought.

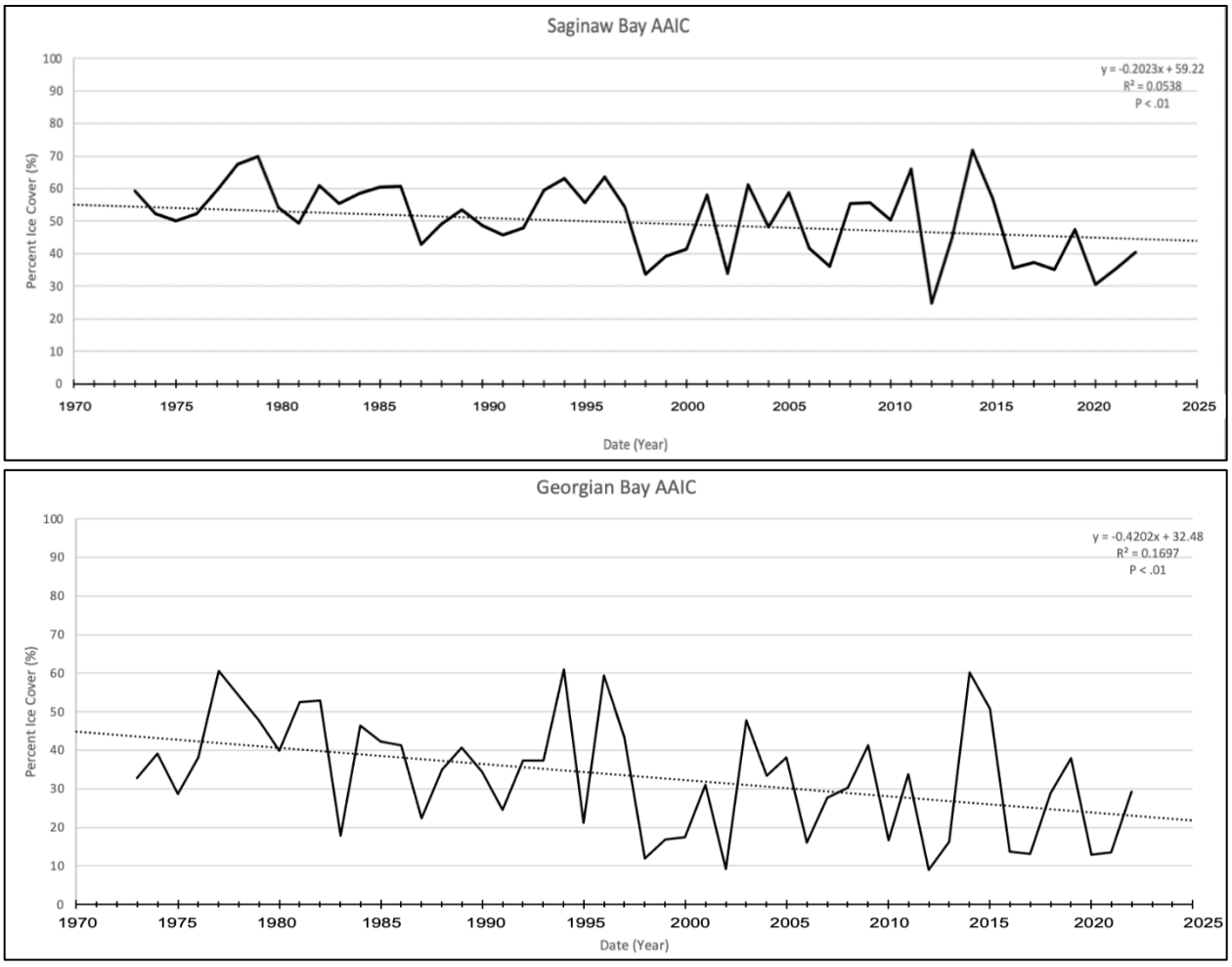


Figure 12. Average annual ice cover (AAIC) in Saginaw Bay and Georgian Bay with added climatology, 1973-2022.

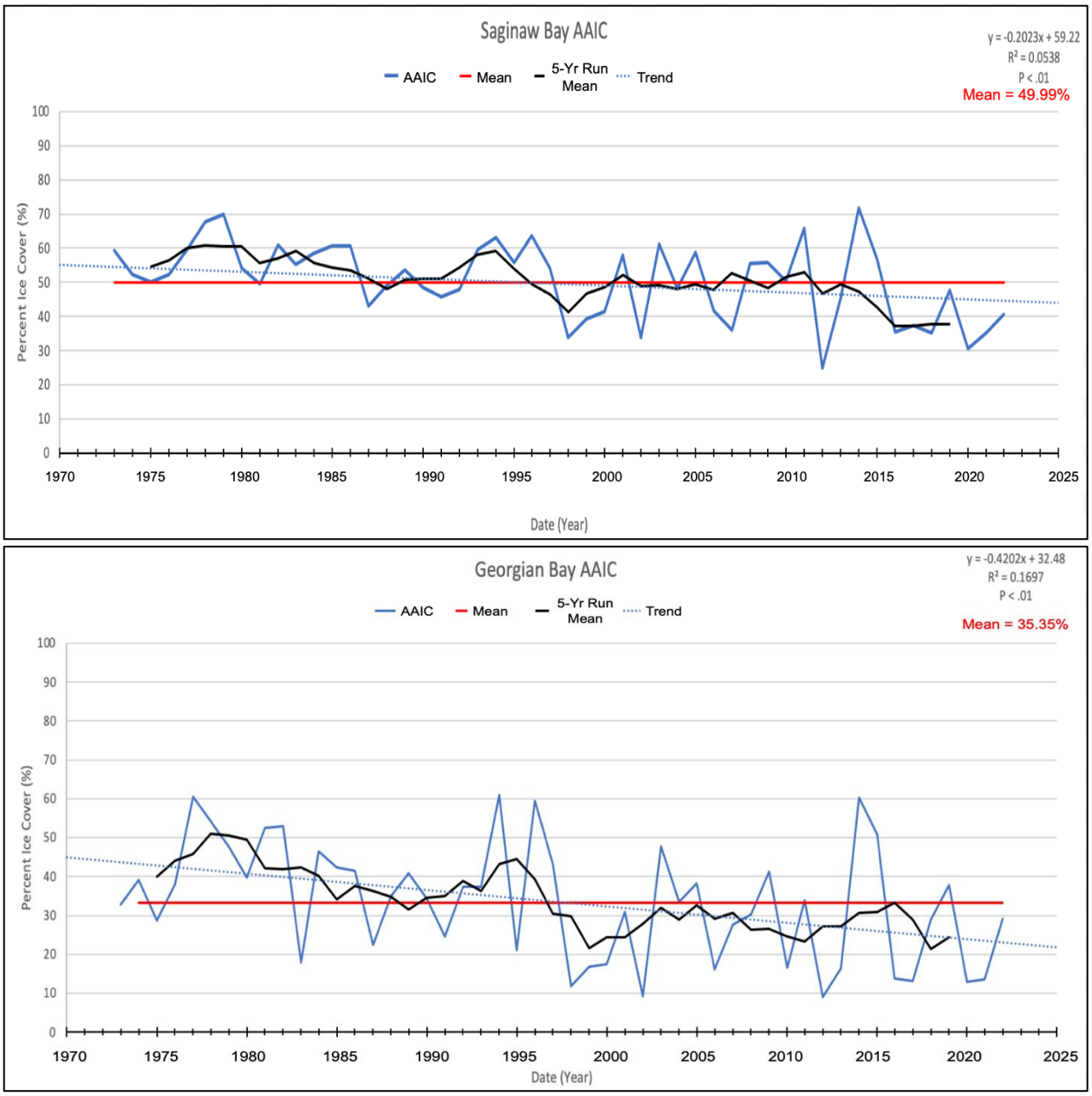


Figure 13. Time series of AAIC during 1973-2022. The solid blue line is the AAIC, the red line is the climatological mean of each region, the blue dashed line indicates the long-term trend, and the black line is the 5-year running average of the AAIC.

Table 7 and Table 8 show the trend parameters, mean, and standard deviation for AAIC estimated using climatology-filled ice cover time series. Trend intercepts calculated for Saginaw Bay and Georgian Bay both decrease with added climatology, meaning that the entire line shifted downward, indicating less ice cover. Furthermore, the mean for both locations stayed relatively

the same. This shows that although the addition of climatology causes a more negative slope, the variability on a year-to-year basis allows for the mean value to remain neutral.

Table 7. Long-term trends in annual average ice cover (AAIC) in Saginaw Bay and Georgian Bay computed using climatology-filled data.

	Saginaw Bay	**Georgian Bay**
a, intercept	59.22	32.48
b, slope [%/yr]	-0.20	-0.42
b/a [%]	-0.34	-1.2
Total Loss [%]	10	20

Table 8. Statistical means and standard deviations of annual average ice cover (AAIC in %) in Saginaw Bay and Georgian Bay, averaged from December 1st to April 30th, for the period 1973-2022. Statistics were computed using climatology-filled data.

	Saginaw Bay	**Georgian Bay**
Mean	50	35
Std	11.41	15.25
Std/Mean	.23	0.44

The duration plots cannot be resolved by climatology. With the addition of climatology, we can better understand the trend of the beginning of the winter period, but we are still unable to know when exactly ice cover begins. We hypothesize that with the correct knowledge of when ice cover correctly begins, the duration at the beginning of our 50-year period would actually lengthen, making the trend more extreme in Figure 7.

The addition of the climatology helps us to understand some of the errors in the ASCII files produced by the NIC. We found that, with the climatology, the AAIC produces a more negative trend meaning that ice cover is actually decreasing more than expected. Other things were left unchanged with the addition of the climatology, such as the mean of the AAIC and the AMIC for both bays. Adding climatology still does not give scientists an accurate representation of when ice cover begins in both locations, so there is likely some error with the ice onset dates and ice durations discussed in this report.

5. ANALYSIS OF GREAT LAKES ICE COVER CLIMATOLOGY: WINTER 2022

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 was initially published by Assel (2003a). Climatology reports were subsequently updated for 2003 - 2005 (Assel, 2005a), 2006 - 2011 (Wang et al., 2012a; Assel et al., 2013), 2012 – 2017 (Wang et al., 2017), and 2017 – 2021 (Wang et al., 2026). The information presented below updates analysis products previously completed by Assel et al. (2013), Wang et al. (2017a,b), and Wang et al. (2022), 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.

5.1 DATA

The data provided for this analysis includes 178 digitized ice charts from 2022. For the year 2022, ice charts were provided daily from November 26 to May 22. The data is in 1024x1024 pixel grids and contains the entire Great Lakes region (Figure 14). 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 of 1.275 km at approximately 45°N for winter 2022). The resolutions vary with latitude; see Wang et al. (2012a) and Yang et al. (2020) for details.

5.2 ANALYSIS METHOD

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.



Figure 14. Named locations in the Laurentian Great Lakes (Wang et al. 2026)

5.3 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 Figure 15. Trend descriptions are included.

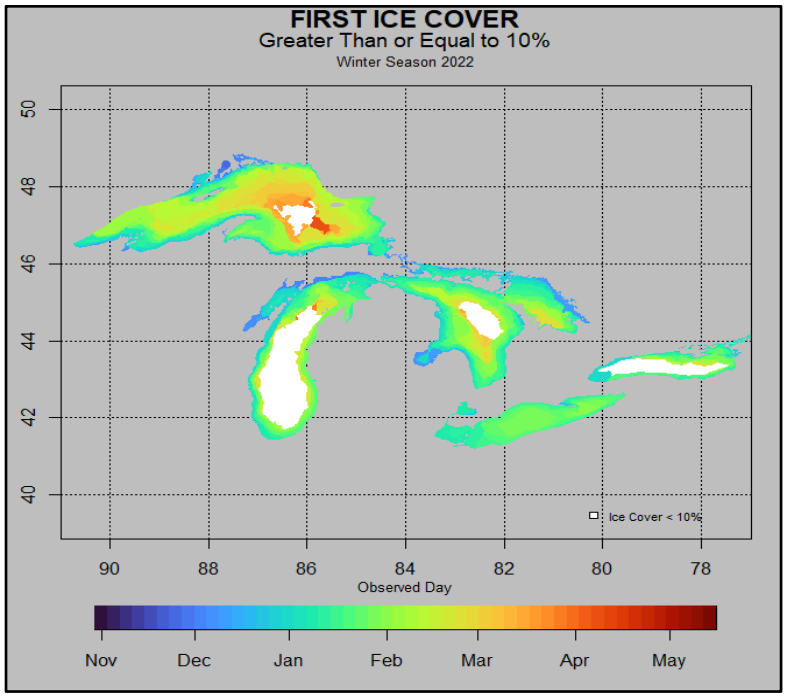


Figure 15. Dates of first reported ice cover ≥ 10% for Winter 2022

Figure 15 shows that ice forms earlier in the year closer to the shore in more shallow regions whereas deeper regions occur later in the winter season. As shown in Figure 15, the majority of Lake Michigan does not have ice cover greater than 10 percent for the 2022 season while the remainder of the Laurentian Great Lakes are largely covered with ice.

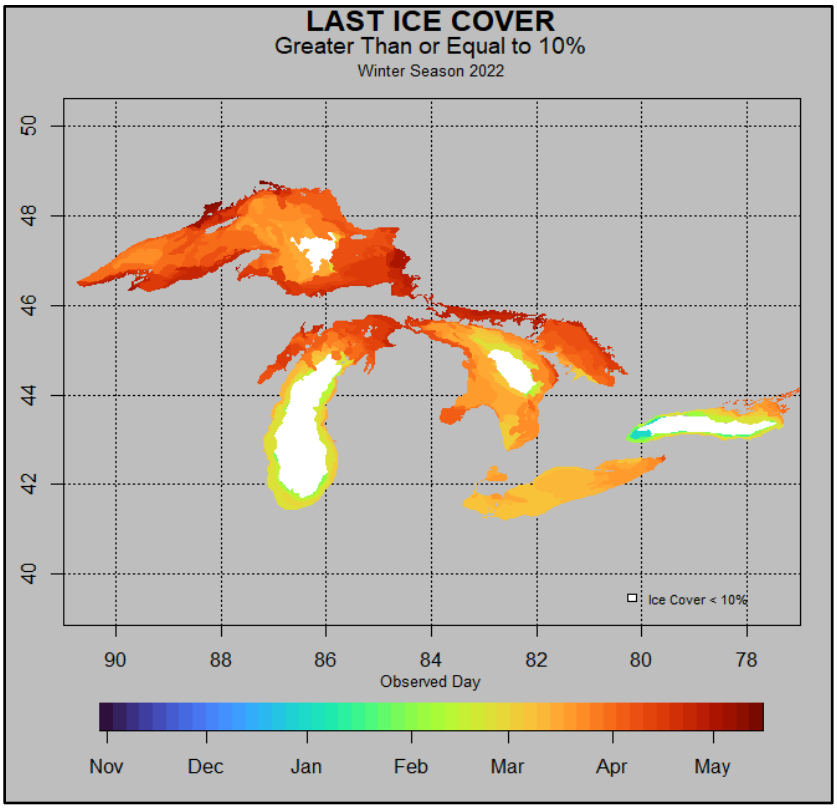


Figure 16. Last recorded day of ice cover ≥ 10% for Winter 2022

Figure 16 shows the last recorded day of ice cover that is ≥ 10% for the Great Lakes in 2022. The figure shows that, in general, ice cover in the deeper areas of the lakes ends earlier in the season whereas the shallow areas have ice cover longer into the season. For Lake Erie, the entire lake is without ice sometime in late March. Comparatively, the southern shore of Lake Michigan and Lake Ontario is without ice by the end of February. On the other hand, Lake Superior and Lake Huron have ice cover until April and May. Due to the latitude and longitude of Lake Superior and Lake Huron being further north, ice cover is expected to remain longer for these lakes as depicted in the figure.

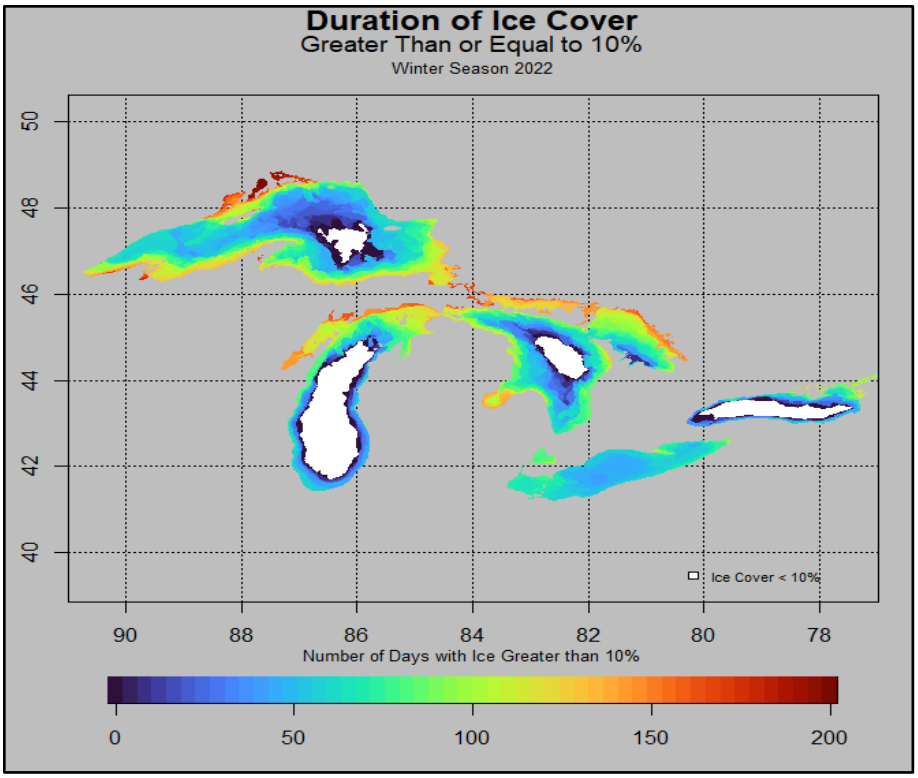


Figure 17. Duration of ice cover ≥ 10% for Winter 2022

Figure 17 depicts the duration of ice cover for all of the Laurentian Great Lakes for the winter 2022 season. Most notably, Lake Huron and Lake Superior have the largest number of days of ice cover greater than 10 percent, approximately 100 days, for the season. Geographically this aligns with our hypothesis that the more northern lakes will have more ice cover. Furthermore, it is also seen that shallow parts of the lakes have a longer duration than the deeper parts.

5.4 SEASONAL PROGRESSION OF ICE COVER

The daily average lake ice cover line plots are seasonal progressions of the Great Lakes ice cycle for winter 2022. 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.

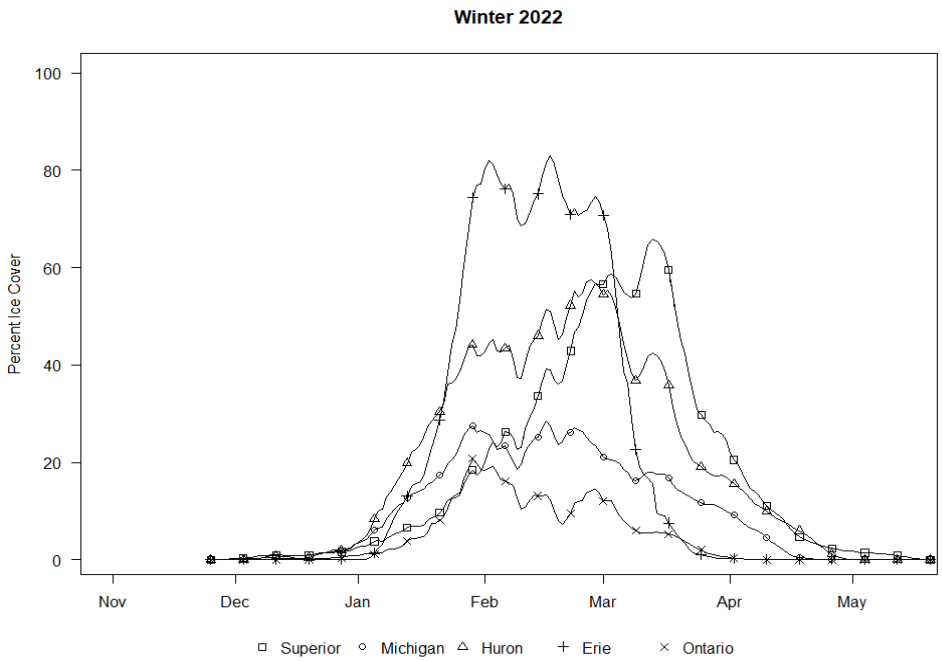


Figure 18. Daily lake average ice cover for the 2022 Winter season.

As seen in the figure, Lake Erie has the largest peak for percent ice cover as well as the earliest peak in terms of date. This could be due to the inherent bathymetry of Lake Erie, which is the is the shallowest of the Laurentian Great Lakes and therefore has the lowest thermal mass. Although it is the shallowest body of water in the Great Lake region, it still only had a maximum of approximately 80 percent. The other lakes have maximums of less than 65 percent. This is compared to the findings of the 2021 winter season by Wang et. al (2026). Lake Ontario experienced the lowest amount of ice cover for the 2022 season (max: 22%). Lake Ontario has the second largest depth, succeeded by Lake Superior, which had the second highest amount of ice cover in 2022. These results lead us to conclude that both bathymetry and lake location in terms of latitude and longitude should both be considered in the evaluation of ice cover.

5.5 SUMMARY

This section serves to continue the evaluation of 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 for the winter season of 2022. This updates the evaluation of winter seasons 1973-2017, previously done by Assel et al. (2013) and Wang et al. (2017a,b).

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 the better-defined temporal variability of daily lake average ice cover.

Bathymetry of a Great Lake can provide insight into how icing conditions may occur for that lake. But other meteorological forcings, such as wind patterns, extreme weather events, and ENSO patterns can also play a large role in icing conditions for the Great Lakes and therefore should also be considered when looking at ice climatology. Furthermore, the latitude and longitude of the lake should also be considered when looking at ice climatology and ice forecasting.

Ice cover data can also be 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 from 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).

6. OVERALL CONCLUSIONS ON ICE CLIMATOLOGY FOR SAGINAW BAY AND GEORGIAN BAY

One of the largest differences between the two bays are their bathymetry. Saginaw Bay is found to be much more shallow than Georgian Bay, which led to significant differences in ice cover characteristics. First, we found that the ice cover in Saginaw Bay has higher predictability, while the ice cover in Georgian Bay has lower predictability. We were able to conclude this due to the standard deviation to mean ratio, which highlights normalized variability in each bay. We found that Georgian Bay is more volatile whereas Saginaw Bay averages nearly the same ice cover per year. This has led us to conclude that future predictions of ice cover in Saginaw Bay may be easier,

and more accurate, than predictions for Georgian Bay. This result is likely linked to the bathymetry of each bay. Since Georgian Bay is much deeper than Saginaw Bay, it is much more susceptible to climate forcings and therefore leads to higher interannual variability.

In addition to Georgian Bay being highly volatile, we also found that ice cover in Georgian Bay has a smaller duration than Saginaw Bay and is also decreasing faster. This result shows that ice cover in Georgian Bay is quickly disappearing and shipping over the bay will be able persist longer in the coming decades.

Throughout this report we also looked at differences between average annual ice cover (AAIC) and average maximum ice cover (AMIC). It is found that AAIC in Georgian Bay is decreasing at a faster rate than Saginaw Bay, but Saginaw Bay's AMIC is decreasing faster than Georgian Bay. This is a probable result of the larger depth (~59m) of Georgian Bay. With warmer winters due to climate change, a deeper lake will take longer to freeze than a shallow lake like Saginaw Bay resulting in a lower AAIC. On the other hand, Saginaw Bay's AMIC is decreasing at a faster rate than that of Georgian Bay. This means that although there is more ice cover over Saginaw Bay, the maximum ice cover for the season decreases faster than that of Georgian Bay. This may mean that there are not as many cold snaps happening in at the lower latitudes of Saginaw Bay, restricting the bay from reaching high ice cover maxima. This can also be seen in an analysis of United States temperature climatology.

In this report we added climatology values into the existing dataset for dates where there was zero ice cover from December 1st to April 30th. The addition of the climatology helps us to understand some of the errors in the ASCII files produced by the NIC. We found that, with the climatology, the AAIC produces a more negative trend meaning that ice cover is actually decreasing more than expected. Other things were left unchanged with the addition of the climatology, such as the mean of the AAIC and the AMIC for both Bays. Adding climatology still does not give scientists an accurate representation of when ice cover begins in both locations, so there may be errors in the ice duration and ice onset date estimates presented in this analysis, especially those estimated before 1985.

In conclusion we have found that the consideration of both bay bathymetry and geographic location are important factors to consider when analyzing ice cover. Overall, we found that deeper, more northern regions are more susceptible to climate forcings, whereas shallow, more southern regions will still freeze, but may not have a high of maximum ice cover. Lastly, ice cover data may also be useful in the analysis of atmospheric and oceanic teleconnection patterns and ice cover trends in the Laurentian Great Lakes on various time scales.

ACKNOWLEDGMENTS:

Marissa Osterloh appreciates the support from the 2022 NOAA William M. Lapenta Summer Internship and thank James Kessler and Lacey Mason for the dataset. This is the GLERL contribution No. 183.

REFERENCES

Assel, R.A., J.Wang, A.H. Clites and X. Bai. Analysis of Great Lakes Ice Cover Climatology: Winters 2006-2011. NOAA Technical Memorandum GLERL-157, Great Lakes Environmental Research Laboratory, Ann Arbor, MI. (2013). https://www.glerl.noaa.gov/pubs/tech_reports/glerl-157/tm-157.pdf

Assel, R.A., and S. Rodionov. Atmospheric teleconnections for annual maximum ice cover on the Laurentian Great Lakes. *International Journal of Climatology* 18:425-442 (1998). http://www.glerl.noaa.gov/pubs/fulltext/1998/19980001.pdf

Assel, R.A., and D.M. Robertson. Changes in winter air temperatures near Lake Michigan, 1851-1993, as determined from regional lake-ice records. *Limnology and Oceanography* 40(1):165-176 (1995).

Assel, R. A. Classification of annual Great Lakes ice cycles: Winters of 1973-2002. *Journal of Climate* 18:4895-4905 (2005c). http://www.glerl.noaa.gov/pubs/fulltext/2005/20050028.pdf

Assel, R.A**.** Contemporary Lake Superior ice cover climatology. In *State of Lake Superior*. M. Munawar and I.F. Munawar (eds.). Aquatic Ecosystem Health and Management Society, Ecovision World Monograph Series, Canada, 51-66 (2009). http://www.glerl.noaa.gov/pubs/fulltext/2009/20090048.pdf

Assel, R.A. An Electronic Atlas of Great Lakes Ice Cover. NOAA Great Lakes Ice Atlas, Great Lakes Environmental Research Laboratory, Ann Arbor, Michigan 48105 (2003). http://www.glerl.noaa.gov/data/ice/atlas/

Assel, R.A. Great Lakes Ice Cover, First Ice, Last Ice, and Ice Duration: Winters 1973-2002. NOAA TM ERL GLERL-125, NOAA Great Lakes Environmental Research Laboratory, Ann Arbor, MI. (2003b). https://www.glerl.noaa.gov/ftp/publications/tech_reports/glerl-125

Assel, R.A. Great Lakes Ice Cover Climatology Update: Winters 2003, 2004, and 2005. NOAA Technical Memorandum GLERL-135, Great Lakes Environmental Research Laboratory, Ann Arbor, MI. (2005b). https://www.glerl.noaa.gov/pubs/tech_reports/glerl-135/tm-135.pdf

Assel, R.A. Great Lakes Weekly Ice Cover Statistics. NOAA Technical Memorandum GLERL-133, Great Lakes Environmental Research Laboratory, Ann Arbor, MI. (2005a). https://www.glerl.noaa.gov/pubs/tech_reports/glerl-133/tm-133.pdf

Assel, R.A. An ice-cover climatology for Lake Erie and Lake Superior for the winter seasons 1897-1898 to 1982-1983. *International Journal of Climatology* 10:731-748 (1990).

http://www.glerl.noaa.gov/pubs/fulltext/1990/19900009.pdf
Assel, R. A., S. Drobot, and T. E. Croley, II. Improving 30-day Great Lakes ice cover outlooks. *Journal of Hydrometeorology* 5(4):713-717 (2004). http://www.glerl.noaa.gov/pubs/fulltext/2004/20040016.pdf
Assel, R. A. Lake Erie ice cover climatology -- basin averaged ice cover: winters 1898-2002. NOAA Technical Memorandum GLERL-128. NOAA, Great Lakes Environmental Research Laboratory, Ann Arbor, MI, 15 pp. (2004). https://www.glerl.noaa.gov/pubs/tech_reports/glerl-128
Assel, R. The 1997 ENSO Event and Implications for North American Laurentian Great Lakes Winter Severity and Ice Cover. *Geophysical Research Letters* 25(7):1031-1033 (1998). http://www.glerl.noaa.gov/pubs/fulltext/1998/19980016.pdf
Assel, R. A., K. Cronk and D. C. Norton. Recent trends in Laurentian Great Lakes ice cover. *Climatic Change* 57:185-204 (2003). http://www.glerl.noaa.gov/pubs/fulltext/2003/20030001.pdf
Assel, R.A. and D. C. Norton. Visualization of Great Lakes Ice Cycles. *EOS Transactions* 82(7):83 (2001). http://www.agu.org/eos_elec/00259e.html
Bai, X., J. Wang, C. Sellinger, A. Clites and R. Assel. Interannual variability of Great Lakes ice cover and its relationship to NAO and ENSO. *Journal of Geophysical Research*, Vol. 117, C03002 (March 2012). http://onlinelibrary.wiley.com/doi/10.1029/2010JC006932/full
Bai, X., J. Wang, J. Austin, D. Schwab, R. Assel, A. Clites, J. Bratton, M. Colton, J. Lenters, B. Lofgren, T. Wohlleben, S. Helfrich, H. Vanderploeg, L. Luo, and G. Leshkevich, 2015. A record breaking low ice cover over the Great Lakes during winter 2011/2012, *Clim. Dyn.* 44, 5: 1187-1213.11
Ghanbari, R.N., H.R. Bravo, J.J. Magnuson, W.G. Hyzer, Barbara J. Benson, 2009, Coherence between lake ice cover, local climate and teleconnections (Lake Mendota, Wisconsin), J. of Hydrology, 374 (2009) 282–293
Lin, Y-C, A. Fujisaki-Manome, and J. Wang, 2022. Recently Amplified Interannual Variability of Great Lakes ice cover and its Connection to Sea Ice over the Bering and Chukchi Seas, J. Climate (in press)
Magnuson, J.J., D.M. Robertson, B.J. Benson, R.H. Wynne, D.M. Livingstone, T. Arai, R.A. Assel, R.G. Barry, V. Card, E. Kuusisto, N.G. Granin, T.D. Prowse, K.M. Stewart, and V.S. Vuglinski. Historical trends in lake and river ice cover in the Northern Hemisphere. *Science* 289:1743-1746 (2000).
Magnuson, J.J., K.E. Webster, R.A. ASSEL, C.J. Bowser, P.J. Dillon, J.G. Eaton, H.E. Evans, E.J. Fee, R.I. Hall, L.R. Mortsch, D.W. Schindler, and F.H. Quinn. Potential effects of climatic changes on aquatic systems: Laurentian Great Lakes and Precambrian Shield region. *Hydrological Processes* 11:825-871 (1997). 24
National Geophysical Data Center (NGDC). *The Great Lakes Batymetry Map*. National Oceanic and Atmospheric Administration (NOAA). https://www.ncei.noaa.gov/sites/default/files/2021-09/greatlakesbasin.jpg
Ozersky, T., A.J. Bramburger, A.K. Elgin, H.A. Vanderploeg, J. Wang, J.A. Austin, H.J. Carrick, L. Chavarie, D.C. Depew, A.T. Fisk, S.E. Hampton, E.K. Hinchey, R.L. North, M.G. Wells, M.A. Xenopoulos, M.L. Coleman, M.B. Duhaime, A. Fujisaki-Manome, R.M. McKay, G.A. Meadows, M.D. Rowe, S. Sharma, M.R. Twiss, and A. Zastepa, 2021. ***The Changing Face of Winter: Lessons and Questions from the Laurentian Great Lakes***, *J. Geophys Res. Biogeosciences*, 126, e2021JG006247. https://doi.org/10.1029/2021JG006247
Rodionov, S., R. A. Assel, and L. R. Herche. Tree-structured modeling of the relationship between Great Lakes ice cover and atmospheric circulation patterns. *Journal of Great Lakes Research* 27(4):486-502 (2001). . http://www.glerl.noaa.gov/pubs/fulltext/2001/20010011.pdf
Van Cleave, K, J.D. Lenters, and J. Wang, E.M. Verhamme, 2014. A regime shift in Lake Superior ice cover, evaporation, and water temperature following the warm El Niño winter of 1997-98, Limnology and Oceanography, 59(6), 1889–1898. doi:10.4319/lo.2014.59.6.1889
Wang, J., J. Kessler, F. Hang, H. Hu, A.H. Clites, and P. Chu, 2017a. Great Lakes Ice

Climatology Update of Winters 2012-2017: Seasonal Cycle, Interannual Variability, Decadal Variability, and Trend for the period 1973-2017, NOAA Technical Memorandum GLERL-170, 25 pp. 2017.

Wang, J., J. Kessler, F. Hang, H. Hu, A.H. Clites, and P. Chu, 2017b. Analysis of Great Lakes Ice Cover Climatology: Winters 2012-2017, NOAA Technical Memorandum GLERL-171, 15 pp. 2017.

Wang, J., R.A. Assel, S. Walterscheid, A. H. Clites and X. Bai. Great Lakes Ice Climatology Update: Winter 2006-2011. 2012a, Description of the Digital Ice Cover Dataset. NOAA Technical Memorandum GLERL-155, Great Lakes Environmental Research Laboratory, Ann Arbor, MI. (2012). https://www.glerl.noaa.gov/pubs/tech_reports/glerl-155/tm-155.pdf

Wang, J., X. Bai, H. Hu, A. H. Clites, M. C. Colton and B. M. Lofgren. 2012b, Temporal and Spatial Variability of Great Lakes Ice Cover, 1973-2010. *Journal of Climate* (2012). http://journals.ametsoc.org/doi/abs/10.1175/2011JCLI4066.1

Wang, J., J. Kessler, X. Bai, A. Assuncao, A. Clites, B. Lofgren, J. Bratton, P. Chu, and G. Leshkevich, 2018. Decadal variability of Great Lakes ice cover in response to AMO and PDO, 1963-2017, *J. Climate*, DOI: 10.1175/JCLI-D-17-0283.1

Wang, J., T-Y Yang, J. Kessler, H. Hu, and P. Chu, 2020. Great Lakes ice duration, winter severity index, accumulative freezing degree days, and atmospheric teleconnection patterns, 1973–2018, NOAA Technical Memorandum GLERL-174, 90 pp.

Wang, J., E. Maneke, and J. Kessler, 2026. 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, NOAA Technical Memorandum GLERL-185, 24pp.

Weyhenmeyer, G.A., D.M. Livingstone, M. Meili, O. Jensen, B. Benson, and J.J. Magnuson, 2011. Large geographical differences in the sensitivity of ice-covered lakes and rivers in the Northern Hemisphere to temperature changes, Global Change Biology (2011)17, 268–275, doi: 10.1111/j.1365-2486.2010.02249.x

Yang, T-Y, J. Kessler, L. Mason, P.Y. Chu and J. Wang, 2020. Data descriptor: A consistent Great Lakes ice cover digital data set for winters 1973-2019. *Scientific Data, 7:259 | https://doi.org/10.1038/s41597-020-00603-1*