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Seasonal, Interannual, and Decadal Variability and Long-Term Trend of Ice Cover in Whitefish Bay and the Apostle Islands National Lakeshore of Lake Superior, 1973-2022

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SEASONAL, INTERANNUAL, AND DECADAL VARIABILITY AND LONG-TERM TREND OF ICE COVER IN WHITEFISH BAY AND THE APOSTLE ISLANDS NATIONAL LAKESHORE IN THE GREAT LAKES, 1973-2022

Jia Wang, Shaun Laurinaitis, and David Cannon

1. INTRODUCTION

The 50-year winter ice cover data set consists of 7435 ice charts of total ice concentration for both Whitefish Bay and the Apostle Islands National Lakeshore. This report updates the ice climatology dataset for Whitefish Bay and the Apostle Islands from GLERL's previous 45-winter (1973 – 2017) report covering all of the Laurentian Great Lakes. The Apostle Islands are defined as the region of Lake Superior bounded by 47.1°N, 46.56°N, -90.35°W, and -91.0°W. The original ice chart data was 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 occurs 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, total winter ice cover in Lake Erie reached 98.3% and 98.7% in 2018 and 2019, respectively, while ice cover in 2020 only reached 64%, followed by 85.7% in 2021. 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 increasing trends in global surface temperature 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 Whitefish Bay and the Apostle Islands National Lakeshore 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 Whitefish Bay or the Apostle Islands ice data for planning purposes. Ice cover trends and climatology are useful and important to the operation of the locks in the St. Mary's River during the late fall and early spring as well as over-winter shipping in Whitefish Bay. As for the Apostle Islands, this data is useful for tourism purposes as many tourists travel to the region in the winter to see ice formations and "ice caves". This report also contributes valuable data and analysis to extend previous research on ice modelling in the Apostle Islands (Ji et al. 2019). Another motivation of this report is to provide lake ice conditions at a larger effort to investigate winter limnology and ecosystem function in the Laurentian 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 2022 range from 100 to 197; the dates of first ice charts of the season range from the middle of November to the beginning of January, and the last ice charts of the season 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 of the season refers to the date that NIC began recording ice cover for the season; similarly, the date of the last ice chart of the season is the last date where NIC recorded ice cover data. These charts are the same for all regions of the Great Lakes including Whitefish Bay and the Apostle Islands National Lakeshore.

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
2022	178	26-Nov	22-May

3. ANALYSIS OF LAKE ICE COVER FOR WHITEFISH BAY AND THE APOSTLE ISLANDS: 1973-2022

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, Whitefish Bay and the Apostle Islands National Lakeshore, are enlarged for clarity. The daily climatology of ice cover in the Great Lakes was also produced for Whitefish Bay and the Apostle Islands (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, followed by an ice offset. Whitefish Bay and the Apostle Islands show similar annual ice cover trends, with ice onset in early December, ice cover maxima in mid-February, and ice offset in late May. The Apostle Islands region gains ice cover about 3-5 days earlier than Whitefish Bay, which may be due to the Apostle Islands being located closer to the enclosed plains of North America where many of the cold air outbreaks and polar air masses originate from. Whitefish Bay, on the other hand, is located on the opposite side of the lake, situated such that incoming cool air is warmed as it passes over Lake Superior. As such, Whitefish Bay is warmer than the more open waters of the Apostle Islands in the early winter growing period (December – January). Following the early ice growth season, Whitefish Bay exhibits a higher percent of ice cover than the Apostle Islands. In general, ice melts completely during mid-May.

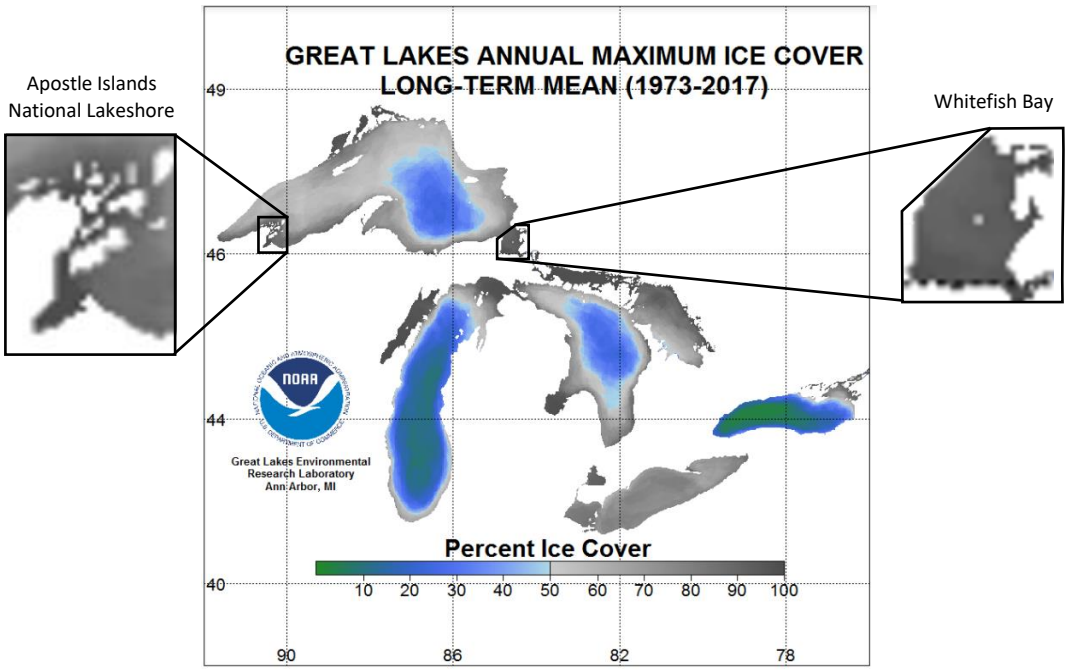


Figure 1. Long-term mean of annual maximum ice cover (AMIC) in the Laurentian Great Lakes from 1973-2017. The boxes show the study regions: Whitefish Bay and the Apostle Islands National Lakeshore.

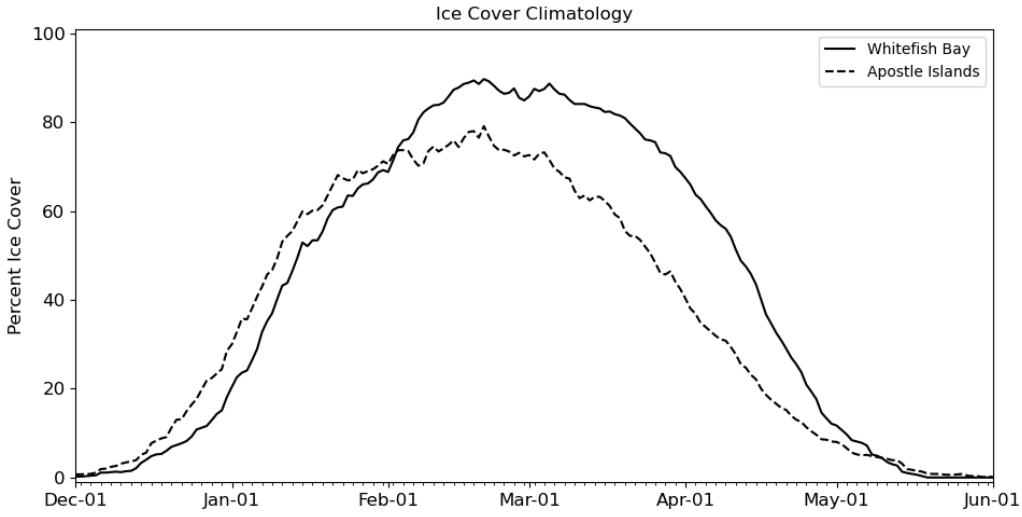


Figure 2. Average ice cover concentration of Whitefish Bay and the Apostle Islands (1973-2022)

3.1 SEASONAL VARIATIONS

To begin analyzing interannual variations in ice cover in Whitefish Bay and the Apostle Islands, the mean daily lake ice cover for every measured date in the winter season is determined across the 50-winter period (1973 - 2022; Figure 3). On average, ice forms on Whitefish Bay in week 51 and in the Apostle Islands in week 50 (Table 2). The growing period of ice cover is 8 weeks for Whitefish Bay and 9 weeks for the Apostle Islands. Whitefish Bay and the Apostle Islands both reach their seasonal maximum ice cover area during week 7. On average, the ice cover has completely melted by approximately week 20 in both regions.

Table 2. Statistics of seasonal cycle dates (week number)

	Whitefish Bay	Apostle Islands
Onset	51	50
Maximum	7	7
Offset	20	20

The corresponding weekly variability of annual ice cover, defined by standard deviations, indicate that Whitefish Bay has the lower ratio of standard deviations to the mean, and the Apostle Islands 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 the Apostle Islands (41%) than Whitefish Bay (35%), indicating that year-to-year change in ice cover is slightly larger in the Apostle Islands than Whitefish Bay. The ratio is inversely proportional to predictability. This implies that ice cover in Whitefish Bay has higher predictability, while ice cover in the Apostle Islands has lower predictability.

Ice cover (concentration) alone cannot be used to detect changes in winter climate conditions in both Whitefish Bay and the Apostle Islands because standard deviations (i.e., year-to-year variability) are comparably high from January 1 to May 1 for both regions (Fig.3) . Ice thickness is a reliable parameter that should be used, whenever available, to investigate the response of ice cover to the changing climate.

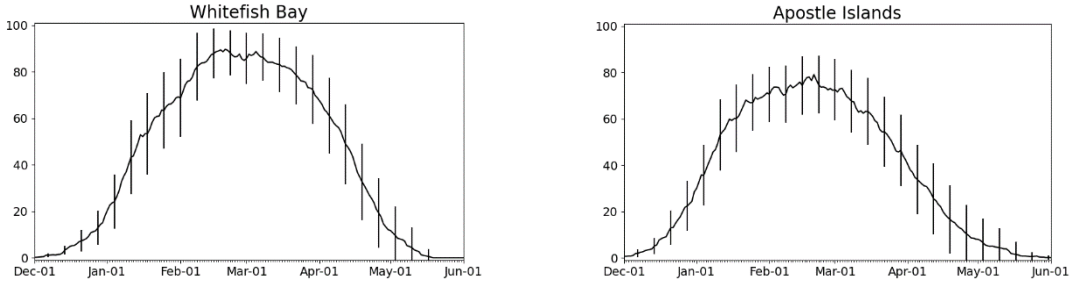


Figure 3. Seasonal variation of weekly ice coverage with one standard deviation above and below the mean.

3.2 INTERANNUAL VARIABILITY, FIRST AND LAST ICE COVER

Time series of daily ice cover areas for Whitefish Bay and the Apostle Islands have been constructed based on the ice concentration data for the winters of 1973 to 2022 (Figure 4). Both regions have differing depths due to unique bathymetry features (Figure 5), and neither area reaches 100% ice cover every season. For Whitefish Bay, only 45 seasons achieved ice cover above 95% while the Apostle Islands achieved ice cover of 95% or higher for 34 of the 50 seasons.

This demonstrated that only considering maximum lake ice cover may not be sufficient in detecting possible climate signals in shallow or deep-water regions that are constrained by their bathymetry (Wang et al., 2012a). The Apostle Islands are observed to have high interannual variability of ice cover while Whitefish Bay is observed to be slightly less variable.

Whitefish Bay 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 2012 was the second lowest year, although a La Nina event was occurring at the time (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.

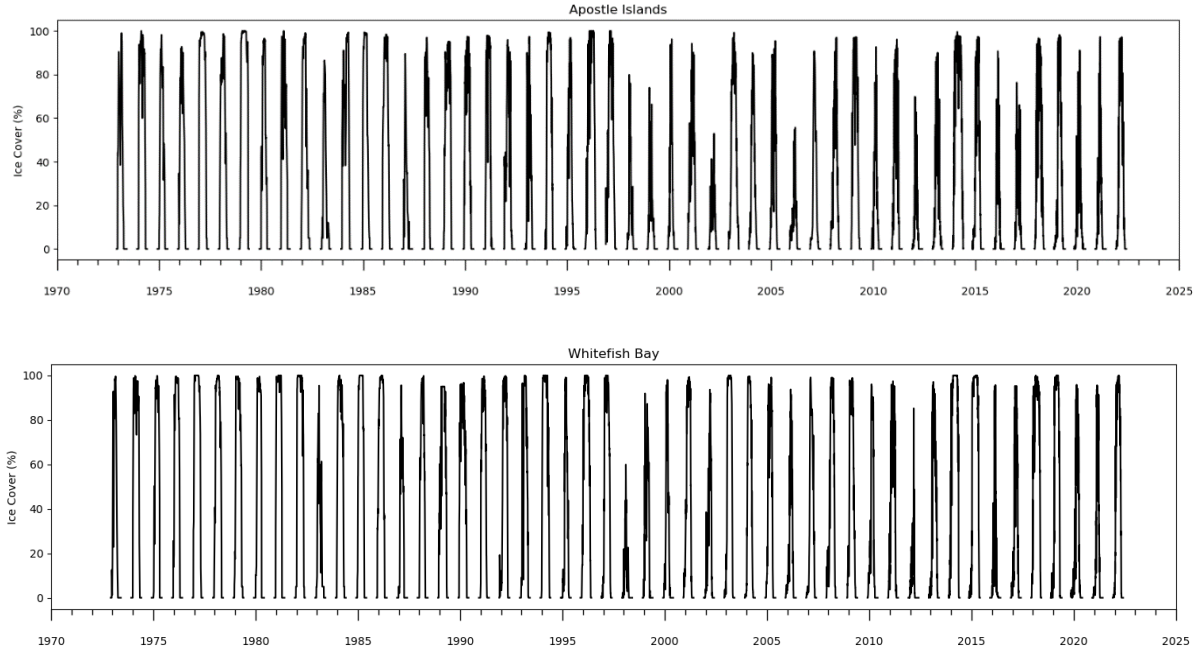


Figure 4. Daily time series of ice cover in the Apostle Islands National Lakeshore and Whitefish Bay, 1973-2022

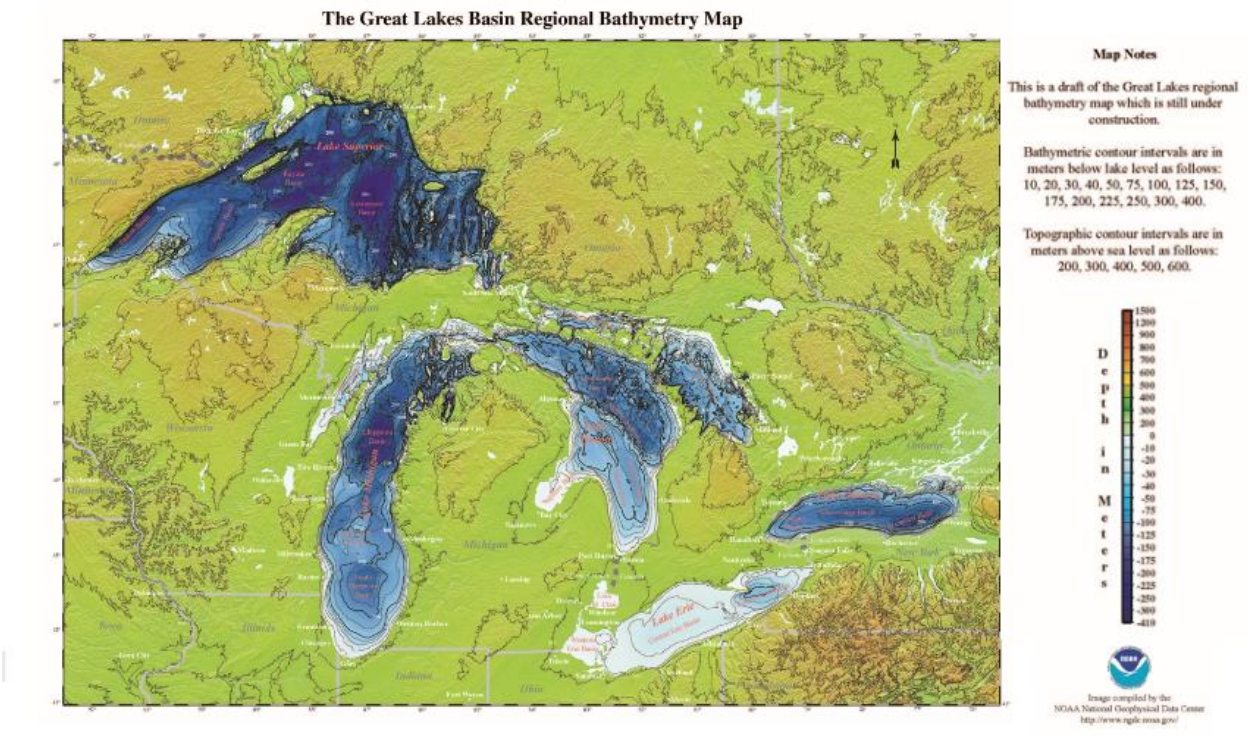


Figure 5. Laurentian Great Lakes basin bathymetry map. Figure reproduced from NCEI's "Great Lakes Bathymetry" website. Bathymetry contour intervals are in meters below lake level and are as follows: 10, 20, 30, 40, 50, 75, 100, 125, 150, 175, 200, 225, 250, 300, and 400 meters.

Both regions include unique topography and bathymetry that may influence interannual ice cover variability. The Apostle Islands (average depth: 7–8m) region consists of smaller islands and shallow waters that may make it easier for ice to form, as well as deeper portions of water to the south and east of the islands that may take longer to freeze (Fig. 5). Whitefish Bay (average depth: ~15m) is a relatively enclosed body of water, with a small entrance to the bay and overall shallower waters allowing for more ice cover to form during the winter (Fig. 5). It is also important to note that the predominant synoptic wind direction across the Great Lakes during the winter season is from the west or northwest. Ice would also be more difficult to be moved out of the region by winds and currents due to its enclosed nature, meanwhile the Apostle Islands is surrounded by more open waters that the ice can be moved into and out of. This helps to explain why we see a greater number of years with 100% ice cover in Whitefish Bay than in the Apostle Islands.

Time series plots for the first and last day of ice cover (≥ 10%) in the 50-year period were produced for Whitefish Bay and the Apostle Islands (Figure 6). The first day of ice cover for Whitefish Bay and the Apostle Islands were similar, averaging around late December. The average last day of ice cover for Whitefish Bay was around mid-April, with the Apostle Island's last day of ice cover averaging around mid to late April. For Whitefish Bay, the first day of ice cover is increasing by 0.7 days/decade and the last day of ice cover is decreasing by -1.0 days/decade. This means that the ice cover is occurring later in and is melting earlier in the season. Since the first day of ice cover is increasing and the last day is decreasing, the total duration is decreasing by -1.7

days/decade (Figure 7). For the Apostle Islands, the first day of ice cover is increasing by 0.4 days/decade while the last day of ice cover is decreasing by -2.7 days/decade. This means that the first and last days of ice cover are converging and therefore the duration of ice cover is decreasing by -3.1 days/decade (Figure 7).

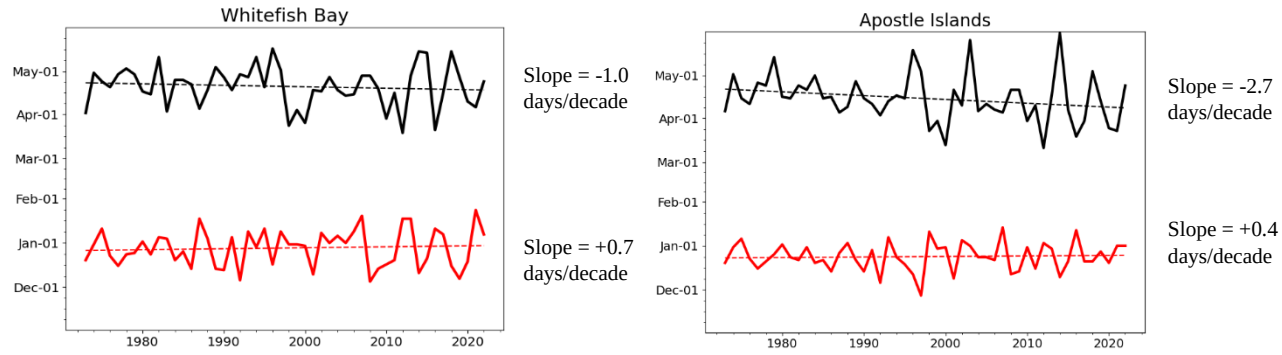


Figure 6. Time series of the first and last day of ice cover for each year from 1973-2022. The solid, bold black line represents the last day of ice cover for each year, and the dotted black line represents the trend. The solid, bold red line represents the first day of ice cover for each year, and the dotted red line represents the trend. The trend is in Julian days/decade.

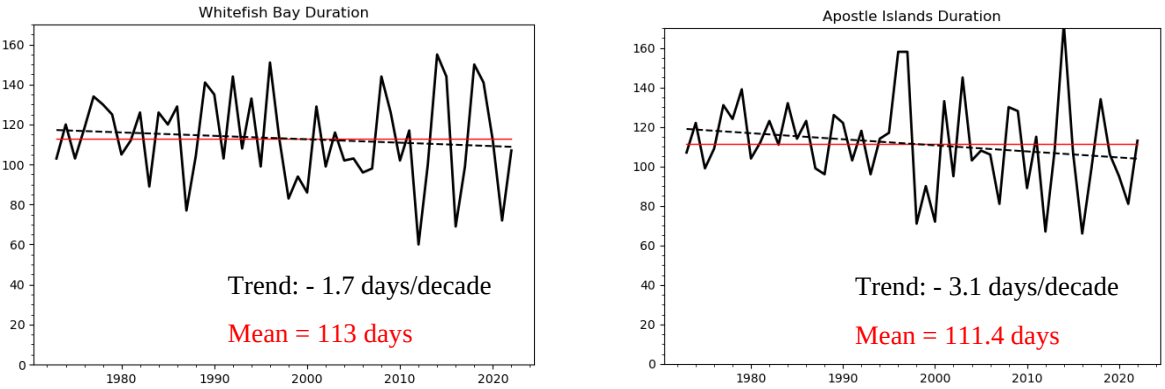


Figure 7. Time series of the duration of ice cover in the number of days for each year from 1973-2022. The dashed line represents the trendline, in units of Julian days/decade.

Time series plots for the annual average ice cover (AAIC), defined as the ice cover averaged between December 1 and April 30, in Whitefish Bay and the Apostle Islands are produced for each region (Figure 8). Each region is observed to have relatively large interannual variability. This may imply a uniform, major response of lake ice to atmospheric interannual variability of teleconnection patterns such as the North Atlantic Oscillation, the El Niño-Southern Oscillation (Bai et al. 2012), the Atlantic Multidecadal Oscillation, and the Pacific Decadal Oscillation (Wang et al. 2018). Additionally, both regions show a negative trend, with annual mean ice cover decreasing by 0.41% per year in Whitefish Bay and 0.55% per year in the Apostle Islands between 1973 and 2022.

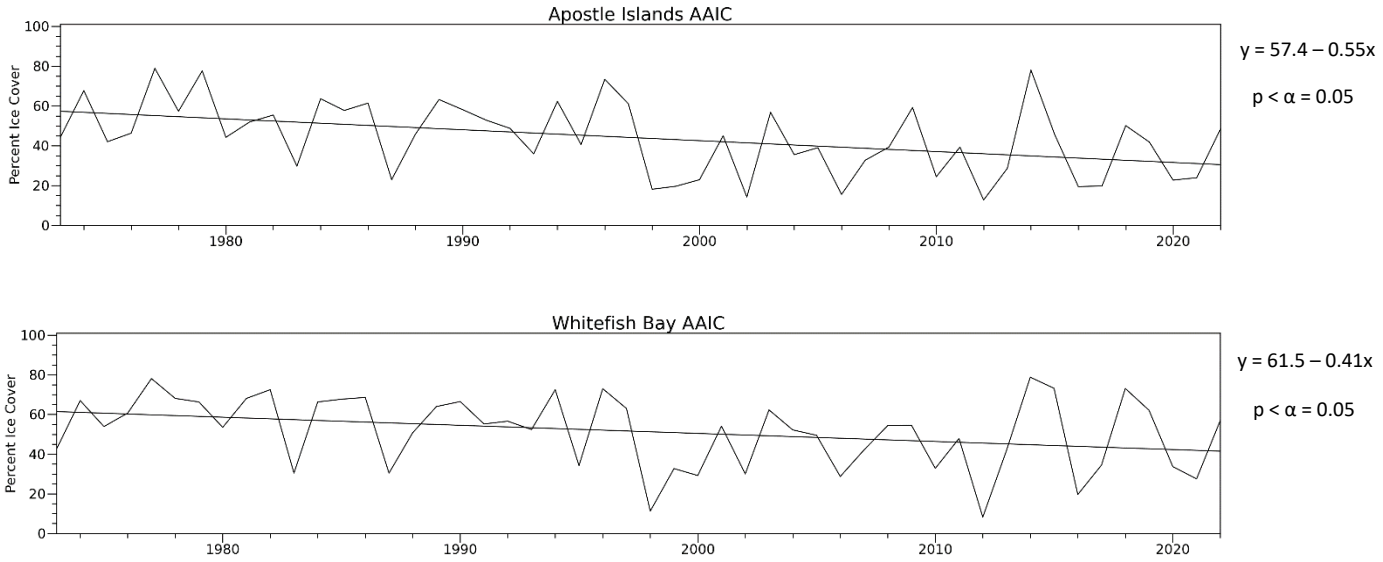


Figure 8. Annual average ice cover (AAIC) in the Laurentian Great Lakes, 1973-2022 with trendline. *x* in the regression equations denotes the time starting from 0, 1, …50, corresponding to 1973, 1974, … 2022.

3.3 LONG-TERM TRENDS

The linear regressions in Figure 8 are the long-term trends of annual average ice cover in Whitefish Bay and the Apostle Islands (winters 1973 to 2022) 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 and *b* is the slope of the linear function, defined as the rate of change of percent ice cover with time in years since 1973 (*t*). The best-fit characteristic values of the linear function fit to annual average ice cover are included in Table 3.

Annual average ice cover in both regions shows a significant negative trend since the 1970s. The rate of decrease in Whitefish Bay is 0.41% per year. The rate of decrease in the Apostle Islands is 0.55% per year. This is consistent with previous research on ice cover trends over the entire Great Lakes region (Mason et al. 2016). Over the entire 50-winter period, total loss of annual lake ice coverage is 20.5% in Whitefish Bay and 27.5% in the Apostle Islands.

Table 3. Trends in Whitefish Bay and the Apostle Islands annual average ice cover (AAIC) averaged from December 1 to April 30.

	Whitefish Bay	Apostle Islands
a, intercept	61.5	57.4
b, slope [%/yr]	-0.41	-0.55
b/a [%]	-0.67	-0.96
Total Loss [%]	20.5%	27.5%

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

	Whitefish Bay	Apostle Islands
Mean	51.5	43.9
Std	17.8	17.9
Std/Mean	0.35	0.41

Table 4 shows statistics of the mean, standard deviation, and standard deviation to mean ratio for AAIC. Whitefish Bay has a smaller ratio than the Apostle Islands (0.35 vs. 0.41, respectively), indicating that predictability of annual mean ice cover in Whitefish Bay is higher than that in the Apostle Islands.

Annual average ice cover (AAIC), which is integrated over an entire ice season, is an important parameter for tracking changes in ice cover (Wang et al. 2012b), especially when compared to the more commonly used annual maximum ice cover (AMIC) indicator, which is only measured over a single day of the winter season. AAIC implicitly includes the total ice cover duration, which is an important parameter for tracking overall changes in ice season characteristics. While AMIC cannot provide any information on the duration of ice cover, it remains a convenient single-day indicator for tracking climate change. Therefore, the following analysis provides the statistics of both AAIC and AMIC for comparison.

Similar to Table 4, Table 5 includes statistics of the mean, standard deviation, and standard deviation to mean ratio for AMIC. Whitefish Bay has a smaller ratio (std/mean: 0.06) than the Apostle Islands (std/mean: 0.11). This indicates that the variability of AMIC (6%) in Whitefish Bay is much lower than the variability of AAIC (35%). Similarly, the variability of AAIC (41%) is more than three times larger than the variability of AMIC (11%) in the Apostle Islands. The lower variability of AMIC makes it more difficult to identify long-term trends in ice cover, suggesting that AAIC is a better, perhaps more physically sound, parameter for detecting climate change.

Table 6 shows the AMIC regression analysis results for Whitefish Bay and the Apostle Islands. The Apostle Islands have a higher total maximum ice cover loss over the 50-year sample record than Whitefish Bay, with losses of 9.5% and 3.0%, respectively. The trend in ice cover loss per year in the Apostle Islands (-0.19% /year) is also nearly 3 times as high as the trend observed in Whitefish Bay (-0.06% /year).

Table 5. Statistical means and standard deviations of annual maximum ice cover (AMIC) in Whitefish Bay and the Apostle Islands, 1973-2022.

	Whitefish Bay	Apostle Islands
Mean	97	93
Std	6	10
Std/Mean	0.06	0.11

Table 6. Trends in annual maximum ice cover (AMIC) in Whitefish Bay and the Apostle Islands

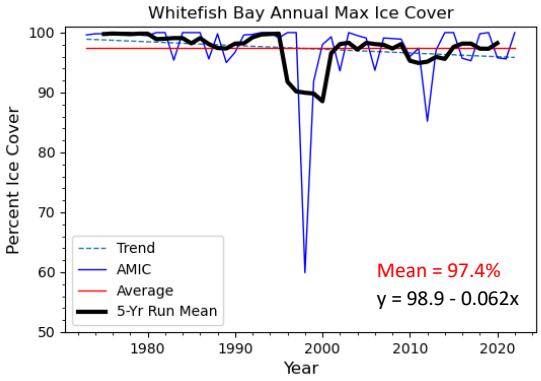
	Whitefish Bay	Apostle Islands
a, intercept	98.9	97.55
b, slope [%/yr]	-0.06	-0.19
b/a [%]	-0.06	-0.19
Total Loss [%]	3	9.5

Comparing Table 6 with Table 3 and Table 5 with Table 4, it is found that AAIC captures larger variability than AMIC. This is likely because AAIC includes ice duration implicitly, while AMIC uses only one value (realization) collected on a single day to represent the ice season, although the correlation between the two is very high (0.94; see Bai et al. 2015). In summary, AAIC is more physically 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 50-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 five low ice bands also stand out: 1983, 1987, 1998-2002, 2010-2013, and 2020-2021 separated by around 4, 11, 8, and 7 years, respectively. The longest low ice band started in 1998 and lasted until 2013. Using the 5-yr running mean (Figure 9), we can see a sharp drop in the longer term mean of AMIC in both Whitefish Bay and the Apostle Islands around 1996-1998. However, AMIC in Whitefish Bay seems to bounce back from this drop, while in the Apostle Islands it is much slower to rebound.

A sharp decline in ice-cover can also be seen in the timeseries of AAIC (Figure 10), with local minima occurring around 1998. Unlike the AMIC, the AAIC running mean in both regions struggles to rebound, staying below the 50-yr AAIC mean value for nearly all of the post 1998 period. 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 1973-2022, which can be attributed to a combination of multi-decadal variability and human-caused secular climate warming.



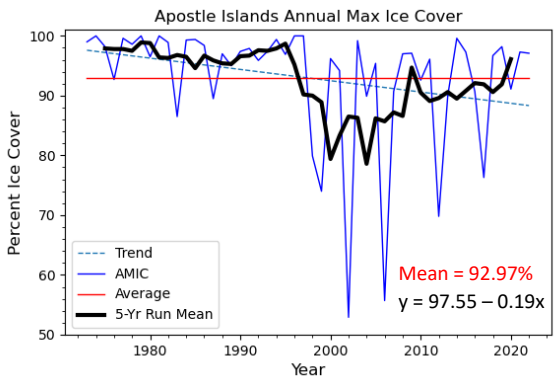


Figure 9. Time series of AMIC during 1973-2022. The blue solid line is the AMIC, the red line is the climatological mean of each region, the blue dashed line indicates the long-term trend, and the black line is the 5-year running average of the AMIC.

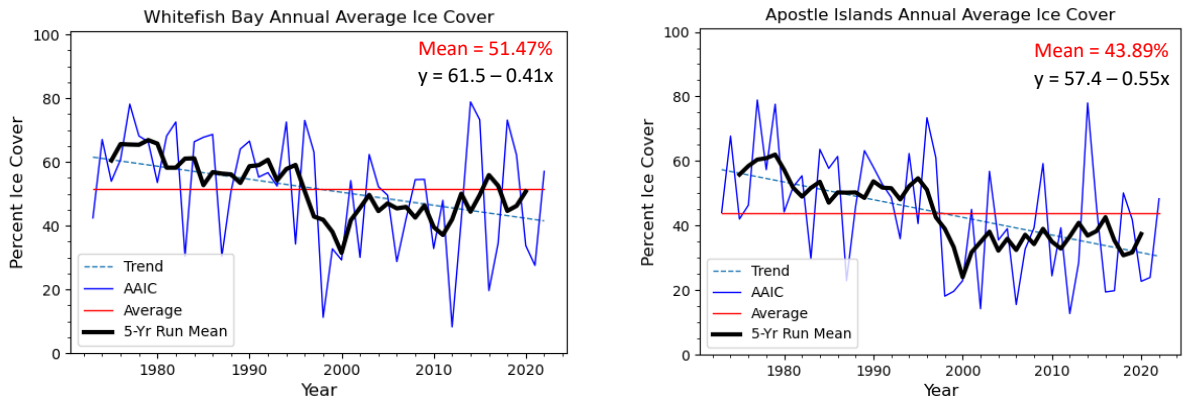


Figure 10. Time series of AAIC during 1973-2022. The blue solid line is the AAIC, the red line is the climatological mean of each region, the blue dashed line indicates the long-term trend, and the black line is the 5-year running average of the AAIC. The pre-1998 AAIC average for Whitefish Bay is 59.3% and the post-1998 average is 43.7%. For the Apostle Islands, the pre-1998 average is 53.7% and the post-1998 average is 34.1%.

3.5 SUMMARY

Growth of ice cover during the seasonal cycle is comparable between Whitefish Bay and the Apostle Islands due to their similar bathymetry as well as latitude. Some timing differences of ice onset and offset are attributed to shallow and deep water regions, as well as to the geographical location of each region. Given the same atmospheric conditions, shallow, lower latitude areas begin forming ice and reach maximum ice cover earlier than deep, higher latitude areas.

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 (e.g. the past two decades; Lin et al. 2021).

Lake ice cover shows a long-term, declining trend (winter seasons of 1973 to 2022). Decreasing trends are more severe in the Apostle Islands than in Whitefish Bay.

AAIC, which is averaged over the entire ice season, is an important physical variable because it implicitly includes the ice duration, while AMIC only records a single daily maximum value for an entire ice season. We recommend that in addition to AMIC, AAIC be used to reflect ice variability and long-term trends in response to climate change. Research into ice thickness is also recommended, as it is another indicator to reflect ice variability. Ice thickness is important as it

could change and vary while ice cover maxima remains at or near 100%. It is also useful for winter recreation such as ice fishing and those traversing the lake ice.

4. ANALYSIS OF ANNUAL AVERAGE ICE COVER TRENDS FOR WHITEFISH BAY AND THE APOSTLE ISLANDS USING CLIMATOLOGICALLY FILLED DATA: 1973-2022

The current ice cover record contains some discrepancies that may affect the results of the analysis procedures, specifically with the annual average ice cover (AAIC) parameter. Many years have varying amounts of non-recorded daily ice data., presumably due to changes in technology, the reliability of data collection, and natural barriers such as cloud cover. This is more prevalent within the earlier years of our dataset, with missing observations extending well into the annual analysis period (December 1st to April 30th). In our original analysis, these values were filled in with zeros, assuming that there was no ice cover outside the recorded observations. However, initial ice cover records often started above 10%, creating a physically unrealistic ice onset date and growth period. In order to more accurately represent the missing ice cover, the created climatology for each region was used to fill in missing observations and evaluate changes in estimated trends. It is important to note that if accurate observations were used to replace missing values, which are especially prevalent in the earlier part of the 50-year period, it is likely that the negative ice cover duration and ice onset date trends in both regions would become more dramatic. Similarly, the negative AAIC trends over the period found previously would also become more dramatic.

4.1 DATA

The data used in this analysis is the same as used previously in Section 3, however missing data that were originally replaced with zeros are now replaced with the respective daily ice cover value for the climatology of that region. This climatology is shown in Figures 2 and 3 in the previous section. Climatology time series were constructed by averaging the ice cover values for a specific day across all 50 years for all dates between December 1st and June 1st.

4.2 INTERANNUAL VARIABILITY

As in Section 3, daily ice cover time series (Figure 11) were created in order to see the interannual variability in the climatologically filled data. It is important to then compare this new time series to those analyzed previously to see what differences there are and if any significant changes exist. Since the climatology is only used for the dataset on days early and late in each winter season, no significant changes are made to the peaks of the annual ice covers. What has changed are the tails of the ice cover seasons, including both the onset and offset of ice cover, which are now more smoothed and gradual in nature. As such, only the average annual ice cover value for each year is particularly impacted, with interannual variability and annual maximum ice covers remaining the same. Overall, this gives us a more accurate and realistic time series of daily ice cover over the 50-yr period.

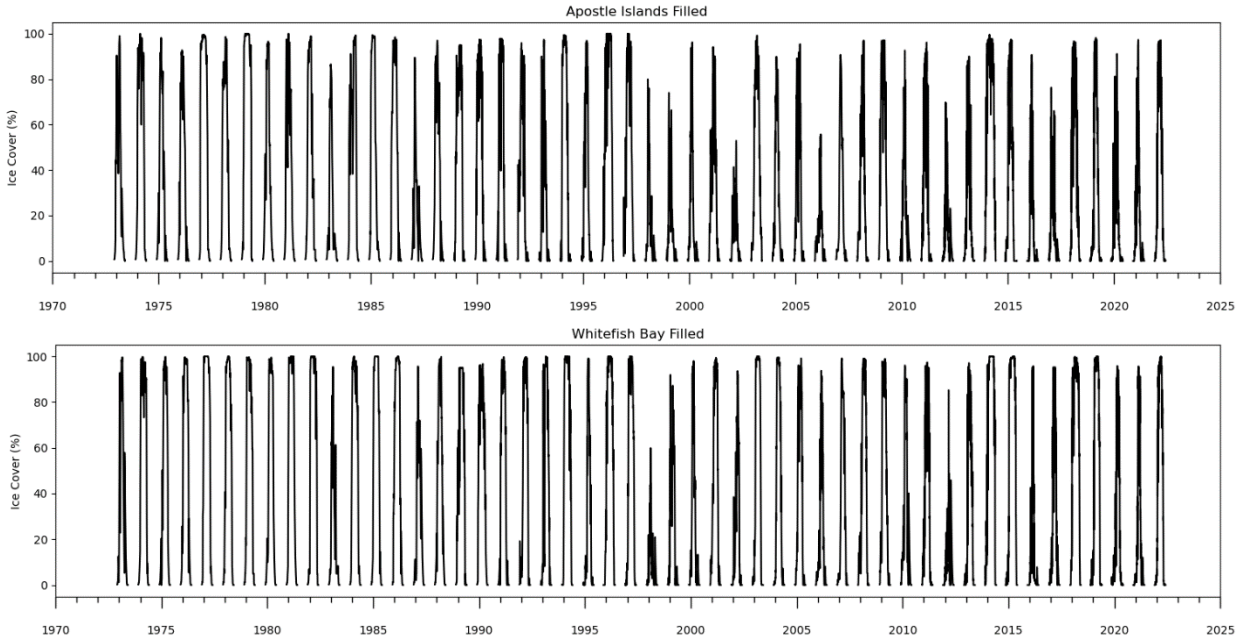


Figure 11. Daily Climatologically Filled Time Series of Ice Cover in the Apostle Islands National Lakeshore and Whitefish Bay, 1973-2022

4.3 LONG-TERM TRENDS

As in section 3.3, the linear regressions in Figure 12 are the long-term trends of annual average ice cover in Whitefish Bay and the Apostle Islands between 1973 to 2022, now computed using the new climatologically filled data. This regression is again determined from the least squares fit method. As before, the linear regressions show a negative, long-term trend in ice cover since 1973 for both regions.

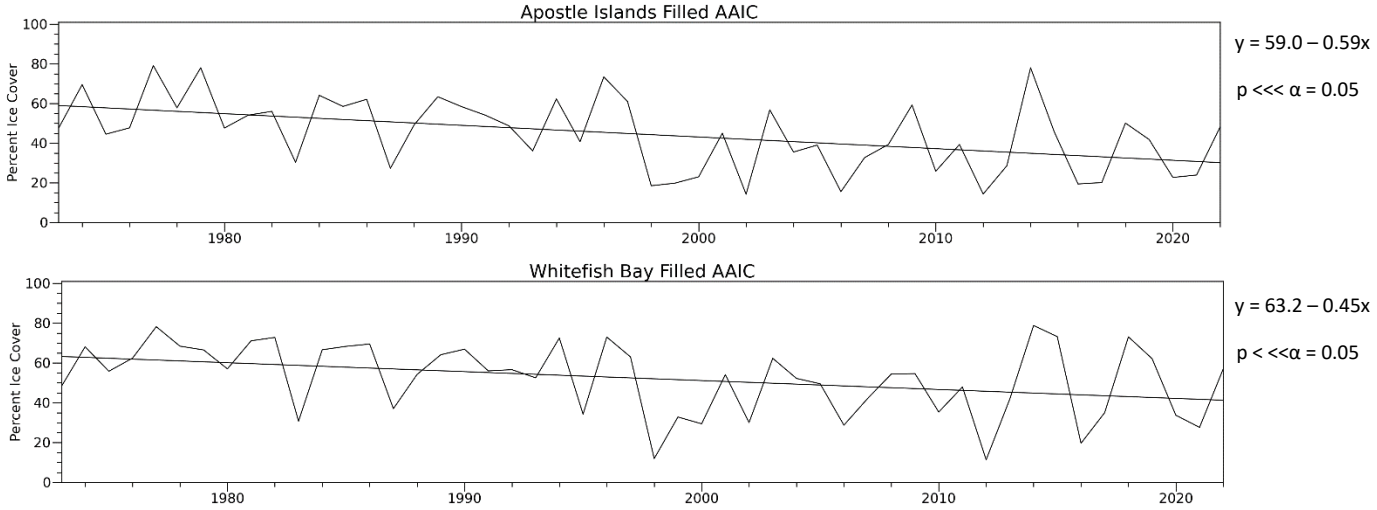


Figure 12. Climatologically filled annual average ice cover (AAIC) in the Great Lakes, 1973-2022 with trendline. *x* in the regression equations denotes the time starting from 0, 1, …50, corresponding to 1973, 1974, … 2022.

The yearly mean ice cover trends estimated using climatology filled time series show significant negative trends. However, these trends have become slightly more dramatic, with the slope of both regression lines increasing in magnitude by 0.04%/year compared to the trends discussed previously (Figure 8). With this new data, the rate of decrease in Whitefish Bay is 0.45% per year (previously 0.41%). The rate of decrease in the Apostle Islands is 0.59% per year (previously 0.55%). Over the entire 50-winter period, total loss of annual lake ice coverage is 22.5% in Whitefish Bay and 29.5% in the Apostle Islands.

Table 7 gives the characteristic values of each linear function for the climatologically filled in data. Table 8 shows statistics for the mean, standard deviation, and standard deviation to mean ratio for the filled AAIC time series. Whitefish Bay again has the smaller ratio (std/mean: 0.33) and the Apostle Islands (std/mean: 0.40) has the larger ratio, indicating that predictability of annual mean ice cover in Whitefish Bay is higher than that in the Apostle Islands. Both have slightly smaller ratios with the filled in data, indicating that AAIC is slightly more predictable with climatological data included, and that values do not deviate from the mean AAIC value as much as they did previously.

Table 7. Trends in the filled Whitefish Bay and the Apostle Islands Annual Average Ice Cover (AAIC) averaged from December 1 to April 30.

	Whitefish Bay	Apostle Islands
a, intercept	63.2	59.0
b, slope [%/yr]	-0.45	-0.59
b/a [%]	-0.71	-1.0
Total Loss [%]	22.5%	29.5%

Table 8. Statistical means and standard deviations of the filled annual average ice cover (AAIC; %) in Whitefish Bay and the Apostle Islands, averaged from December 1 to April 30, for the period 1973-2022.

	Whitefish Bay	Apostle Islands
Mean	52.2	44.6
Std	17.5	17.9
Std/Mean	0.33	0.40

4.4 SUMMARY

Using climatological data to fill in missing observations improves the accuracy of long-term trend analyses. Once again, lake ice-cover shows a long term and declining trend from 1973 to 2022. The greatest negative trend is still found in the Apostle Islands National Lakeshore, but substituting in representative values for ice cover instead of only zeros increases this negative trend in both regions. It is important to reiterate that AAIC is an important physical variable to use as it inherently includes ice duration, which better reflects annual ice variability and trends in response to climate change.

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., 2021). The information presented below updates analysis products previously completed by Assel et al. (2013), Wang et al. (2017a,b), and Wang et al. (2021), 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 created during the 2022 winter season by the NIC. Ice charts generally span between late November and early May. The data in these 1024x1024 pixel grids contains the entire Great Lakes region (Fig. 12) 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 winter 2022). The resolutions vary with latitude; see Wang et al., (2012a) and Yang et al. (2020) for details. Ice charts were downloaded from National Ice Center and quality control was conducted for location of over-water grid cells, to be consistent with NOAA GLERL the CoastWatch land mask, 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.

5.2 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.

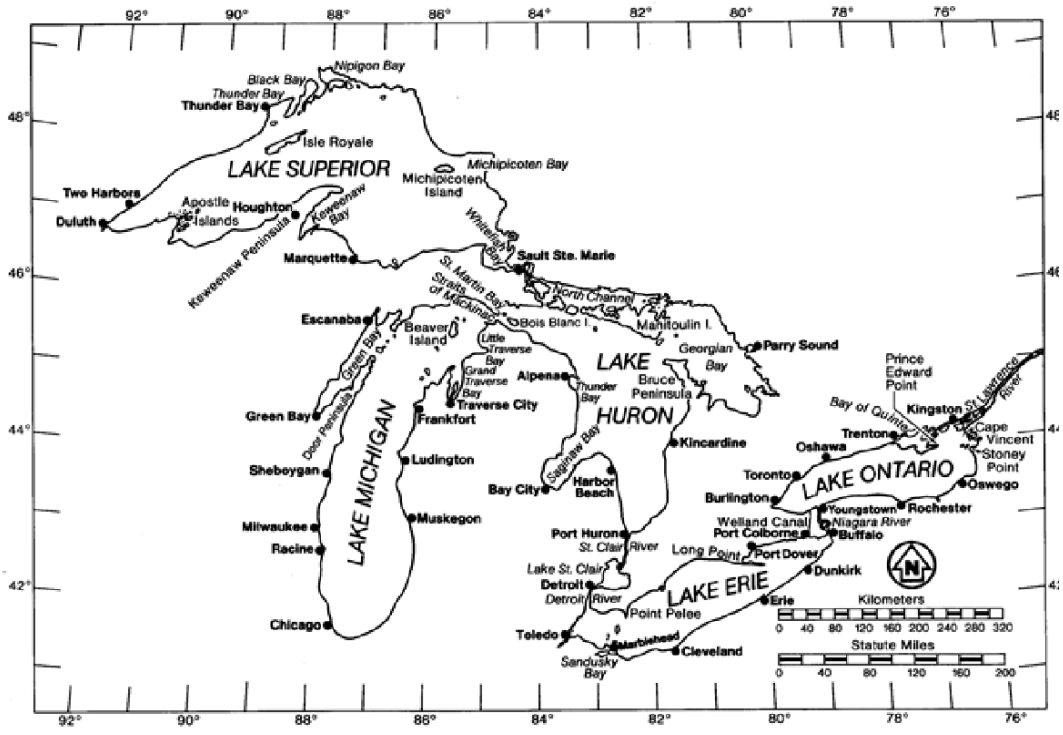


Figure 13. Named locations in the Laurentian Great Lakes (Assel 2005a)

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 Figures 14-16.

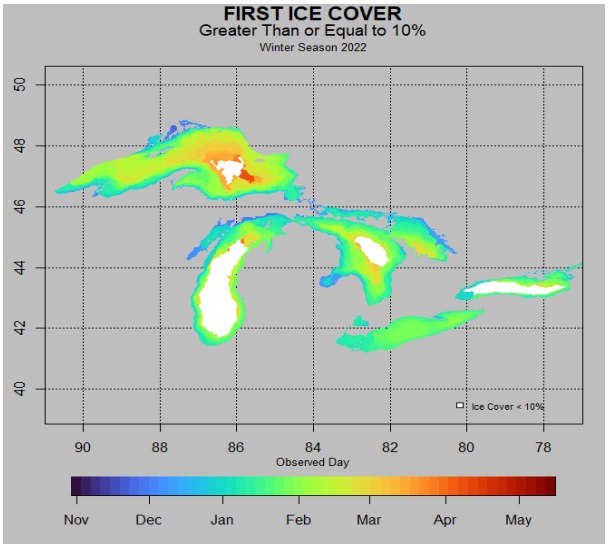


Figure 14. Dates of first reported ice cover ≥ 10% for Winter 2022

Figure 14 shows that ice is generally observed to form in shallow, nearshore areas between November and January and in deeper offshore areas between February and March. Ice covered the entirety of Lake Erie, as well as much of Lake Superior and Lake Huron. The largest areas of open water, where ice concentrations were less than 10%, were found in Lake Michigan and Lake Ontario.

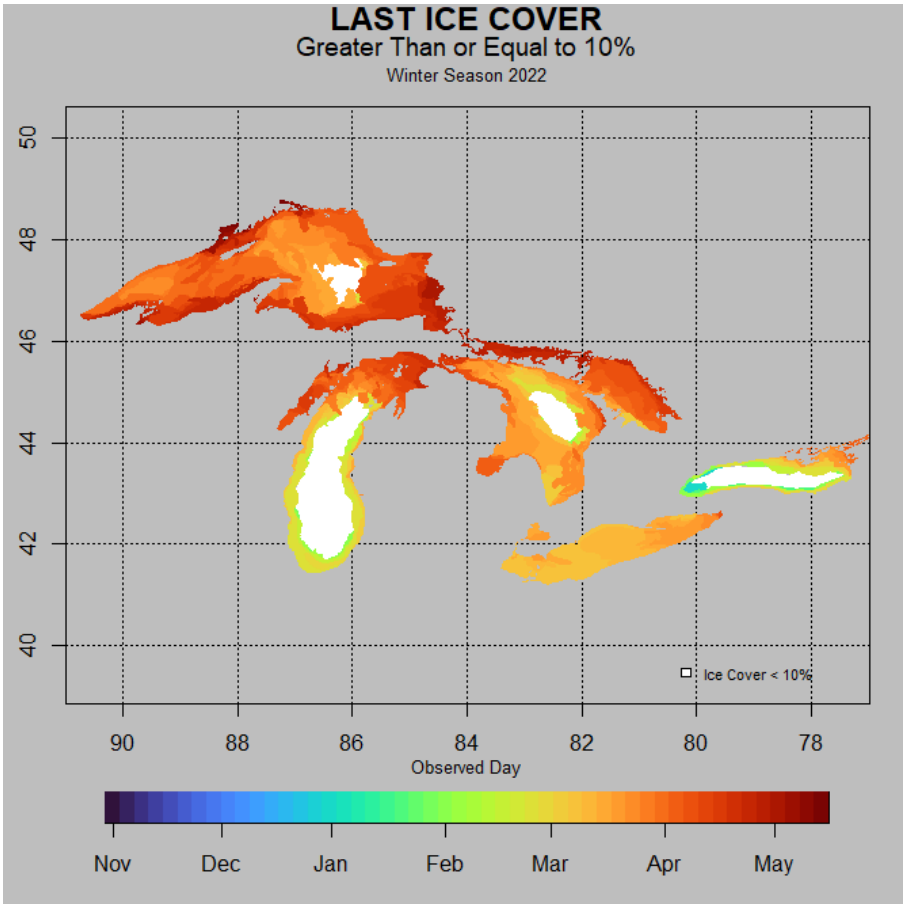


Figure 15. Last recorded day of ice cover ≥ 10% for Winter 2022

Figure 15 shows that last reports of offshore ice cover greater than 10% occurred during March and early April in the majority of the Laurentian Great Lakes. Lake Superior offshore 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, especially in the higher latitude areas of the lakes. The latest ice cover greater than 10% occurred in the northern nearshore areas of Lake Superior, with ice remaining until mid-May.

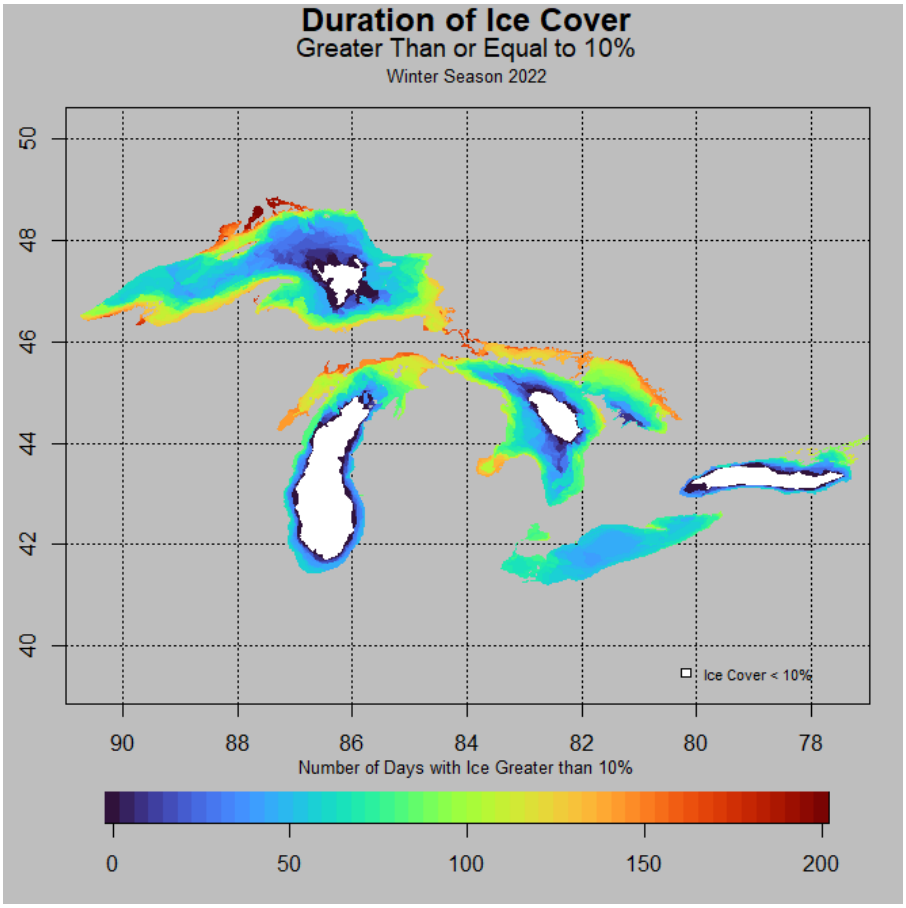


Figure 16. Total duration of ice cover ≥ 10% for Winter 2022.

Figure 16 indicates that nearshore areas of the Laurentian Great Lakes generally endured the longest duration of ice cover, while the deeper offshore areas of the lakes either had no ice cover or shorter durations of ice cover greater than 10%. In the 2022 winter season, some nearshore areas and semi enclosed waters experienced between 150-200 days of ice cover. Much of Lake Erie's ice cover was only present for around 50 days on average. The same was generally true for the moderately deep waters of Lake Superior. Lake Ontario had the smallest duration of ice cover on average (for areas that did contain ice cover), however ice cover in the northeastern part of the lake near the entrance to the St. Lawrence River lasted for upwards to 100 days.

5.4 SEASONAL PROGRESSION OF ICE COVER

The daily average lake ice cover line plots (Figure 17) 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.

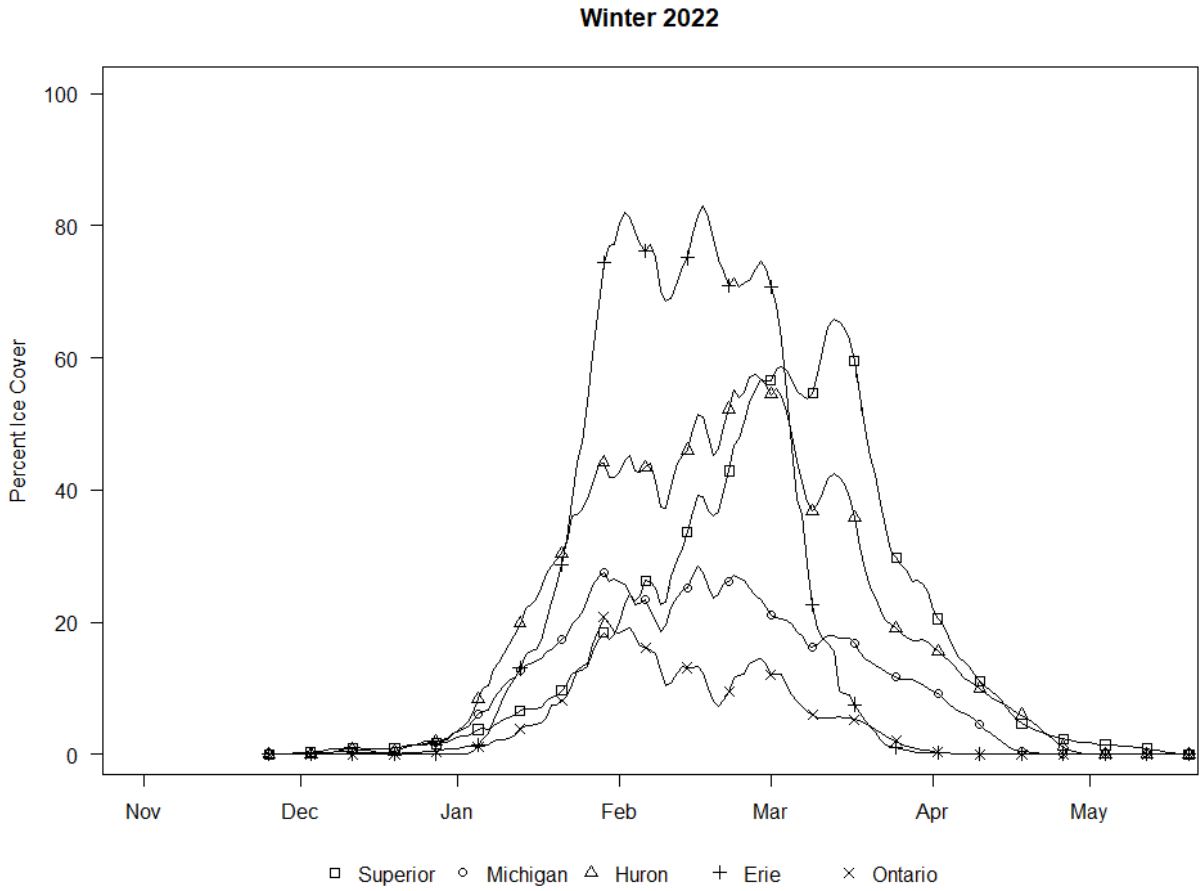


Figure 17. Daily lake average ice cover for the 2022 Winter season

In the 2022 winter season, ice cover generally began in late November and lasted until early to mid-May on the fringes of some of the upper Great Lakes, such as Lake Superior. Lake Erie had the highest average ice cover maximum of the season, reaching around 80% ice cover in late January and mid-February. Lake Superior reached a maximum average ice cover of just above 60% in mid-March, about a month later than Lake Erie's peak. Lake Huron's peak was around 60% in late February, and Lake Michigan and Ontario both peaked around 20% in late January. Many of the lakes had different times in which their ice cover peaks were reached, with the shallow Lake Erie reaching its peak the earliest. Lake Erie and Ontario had the shortest durations of average lake ice cover over 10%.

Although Lake Huron had a peak ice cover of nearly 60%, the average ice cover for the lake was below 40% for much of the season. A similar finding is present for Lake Erie, where a fast onset and offset of ice cover growth led to high average ice cover for around 90 days. Other than this period however, average ice cover for the lake was generally around 20% or lower for the rest of the season. Therefore, AMIC cannot fully reflect the amount and duration of the ice cover, and AAIC remains a more physically sound variable for describing seasonal ice conditions.

Besides annual climatological and sub-seasonal forcings, the synoptic scale forcings on daily ice cover can be seen in Figure 17. The synoptic time scale is defined as a weather phenomenon lasting anywhere from 3 to 7 days. This means roughly every 3-7 days in a location a synoptic scale disturbance will come through and bring about a weather change. In the realm of ice cover, temperature changes and wind shifts are the two prevalent synoptic scale forcings, both occurring with fronts. This signal can be seen on every lake throughout the season, as every 3-7 days a peak or a dip in ice cover occurs. This is likely due to a frontal passage bringing either colder (warmer) temperatures allowing for rapid ice creation (melting) or a wind shift bringing a more favorable or unfavorable wind direction for the ice to either stay in or move away from its formation region.

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 better defined temporal variability of daily lake average ice cover.

The 2022 winter season was characterized by differing timing in the peaks of maximum ice cover across the Great Lakes. The duration of the season was relatively long with ice cover beginning in late November and lasting until early to mid-May. Maximum average ice cover was high on some of the Laurentian Great Lakes, including Lake Superior, Lake Huron, and Lake Erie, but it was significantly lower on Lakes Michigan and Ontario.

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 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 Laurentian 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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APPENDIX

A time series of all 50-years of daily ice cover was created as well. This was done to compare how the climatology compared to certain years such as those with the highest or lowest AAIC value. From this we can also see the envelope and the upper or lower bounds of where ice cover has been analyzed for each region over the past 50 years. The time series were constructed with any NA values from missing ice cover being filled in with zeros as done in the Section 3 analysis.

In Whitefish Bay (Figure 18), 2014 had the largest AAIC value (78.8%) and had a larger duration of ice cover than average. Ice cover also remained near 100% from early February to late April. The 2012 winter season had the smallest AAIC value (8.2%) and had a very short duration of ice cover, with ice completely melting by late March. A lot of variability in daily ice cover is also apparent, especially in early March.

In the Apostle Islands National Lakeshore (Figure 19), 1977 had the largest AAIC value (78.9%) and had a slightly larger duration than the average. Ice cover never reached 100% but hovered in the high 90s from January until mid-March. It is important to note that the sharp drop-offs in ice cover on each end of the time series are due to the missing data being filled in with zeros, with is especially prevalent in earlier years such as 1977. It is likely that with accurate data these drop-offs would disappear and the daily ice cover would become more variable, as well as the AAIC value for this year being lower than it currently is. The 2012 winter season again had the smallest AAIC value (12.7%) with an earlier peak in ice cover than Whitefish Bay's 2012 season. Daily ice cover was once again very variable with a shorter duration than the average.

The 2022 winter season was also plotted separately to compare its ice cover time series with that of other years and the mean for both regions. For Whitefish Bay (Figure 20), a later onset and earlier offset of ice cover compared to the mean can be seen. The duration of ice cover was overall below average, but for much of the season daily ice cover values were above that in the climatology. For the Apostle Islands (Figure 21), ice cover duration and the daily ice cover values were closer to that of the climatology. Much more daily variability in ice cover than in Whitefish Bay can also be seen, especially apparent in the period from February to mid-March.

Overall, the 2022 season had ice cover slightly above average for both regions. In all years, a large amount of daily variability can be seen which may be attributed to more synoptic scale forcing as mentioned previously. Every 3-7 days a sharp rise or drop is present, caused likely by the passage of a weather system or front that had brought a sharp change in air temperatures or wind directions and speed.

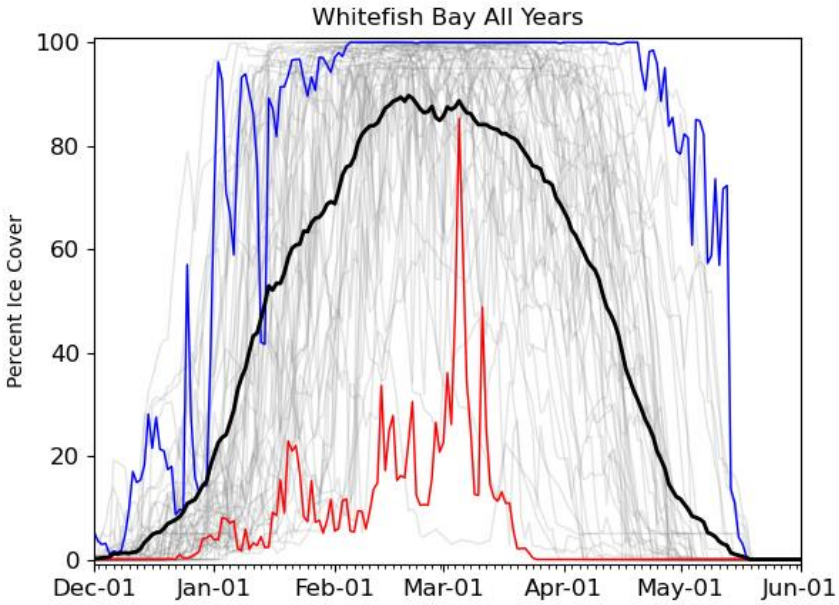


Figure 18. Time series of daily ice cover for all 50 years in Whitefish Bay. The blue line represents the year with the maximum AAIC value (2014) and the red line represents the year with the minimum AAIC value (2012). The thick black line represents the daily ice cover average of all years.

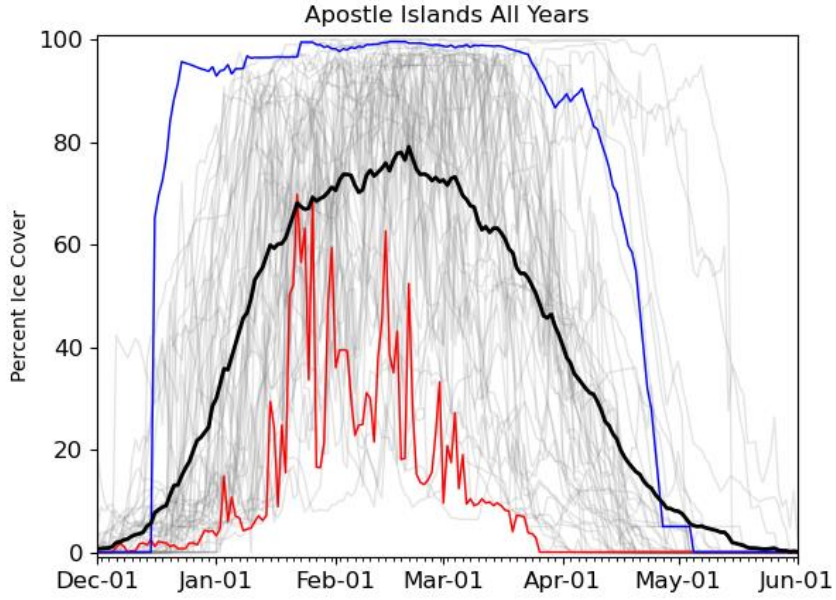


Figure 19. Time series of daily ice cover for all 50 years in the Apostle Islands. The blue line represents the year with the maximum AAIC value (1977) and the red line represents the year with the minimum AAIC value (2012). The thick black line represents the daily ice cover average of all years.

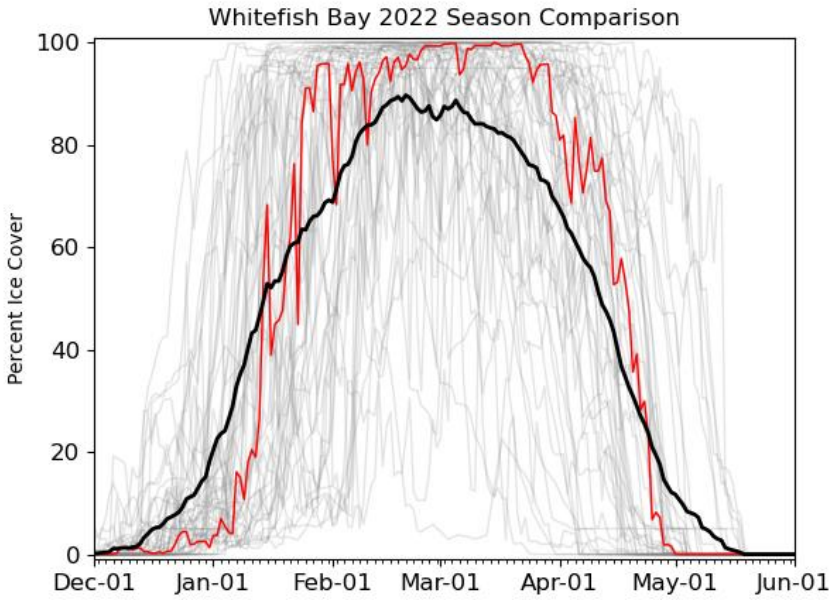


Figure 20. Whitefish Bay 2022 winter season comparison. The red line represents the 2022 winter season. The thick black line represents the daily ice cover average of all years.

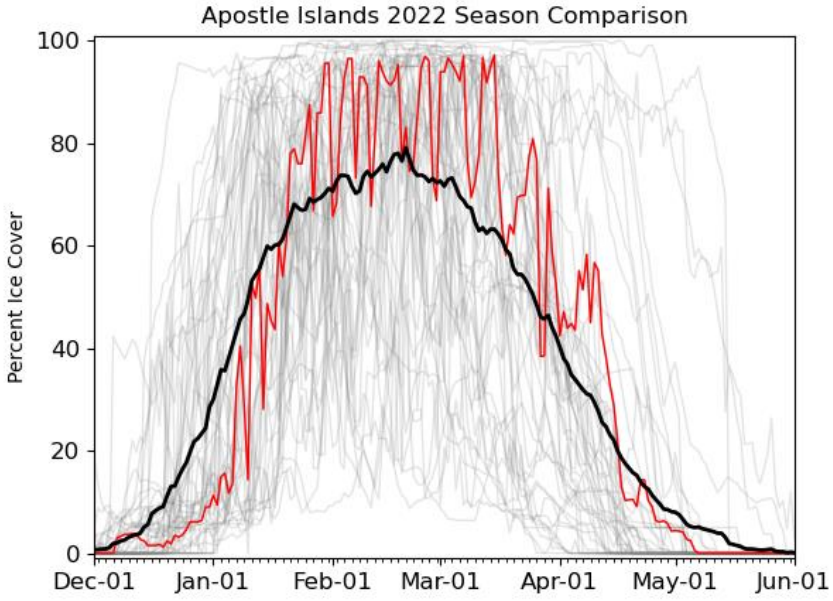


Figure 21. The Apostle Islands 2022 winter season comparison. The red line represents the 2022 winter season. The thick black line represents the daily ice cover average of all years.