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Analysis of Great Lakes Ice Cover Climatology: Winters 2012-2017

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ABSTRACT

This report analyzes the 2012-2017 ice cycles in the Great Lakes region through dates of first (last) ice, ice duration, ice cover distribution, ice cover anomalies, and ice cover seasonal progression. Line plots and ice charts aid the discussion of seasonal and spatial patterns of ice cover over the Great Lakes during each winter season. The data, which is in the form of digitized ice charts, was produced by the National Ice Center and are available to download from their website as ASCII files, http://www.natice.noaa.gov/products/great_lakes.html.

INTRODUCTION

The annual formation and loss of ice cover on the Great Lakes each winter, i.e. the annual ice cycle, affects the lake's ecosystem, the regional economy of the Great Lakes, and is an index of regional winter climate. A 30-winter (1973-2002) climatology of Great Lakes ice cover (Assel 2003a) was updated for total ice concentration for winters 2003-2005 (Assel, 2005a) and more recently for winters 2006-2011 (Wang et al., 2012a). Assel et al. (2013) updated the ice cover data base for winters 2006-2011, following up the previous ice cover descriptions of Assel (2003) for 1973-2002 and of Assel (2005a) for 2003-2005. The information presented here updates analysis products given in Assel (2003a, 2005a) and Assel et al. (2013) including: dates of first ice, dates of last ice, and ice cover duration. Line plots and ice charts portray the seasonal and spatial patterns and trends of ice cover over each winter season. Analysis methods are the same as in Assel et al. (2013). Analysis products are available as fixed formatted ASCII grid and graphical files described in Appendix 1, Appendix 2, and Appendix 3. This report makes access and use of these data feasible to others interested in such information.

DATA

The data provided for this analysis includes 996 digitized ice charts: 136 (2012), 177 (2013), 192 (2014), 195 (2015), 160 (2016) and 136 (2017). Ice charts generally span between late November and early April. The data in these 1024x1024 pixel grids contains the entire Great Lakes region and consists of over-water cells that are mapped onto a land mask. Each cell contains an ice concentration value recorded to the nearest 10%.

The data consists of grids of over-water cells embedded in a land mask (a 1024x1024 matrix at a nominal spatial resolution 1.275 km at approximately 45°N for winters 2012-2017). The resolutions vary with latitude; see Wang et al., (2012a) for details. Ice charts were downloaded from http://www.natice.noaa.gov/products/great_lakes.html and quality controlled for location of over-water grid cells, to be consistent with NOAA GLERL the CoastWatch land mask (ftp://coastwatch.glerl.noaa.gov/masks/new/), and ice concentration codes, consistent with Assel (2003a, 2005a). Fixed formatted ASCII and ARC/INFO shape file: names, structure, and ice concentration codes, are available in Wang et al., (2012a) for those interested in these data.

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.

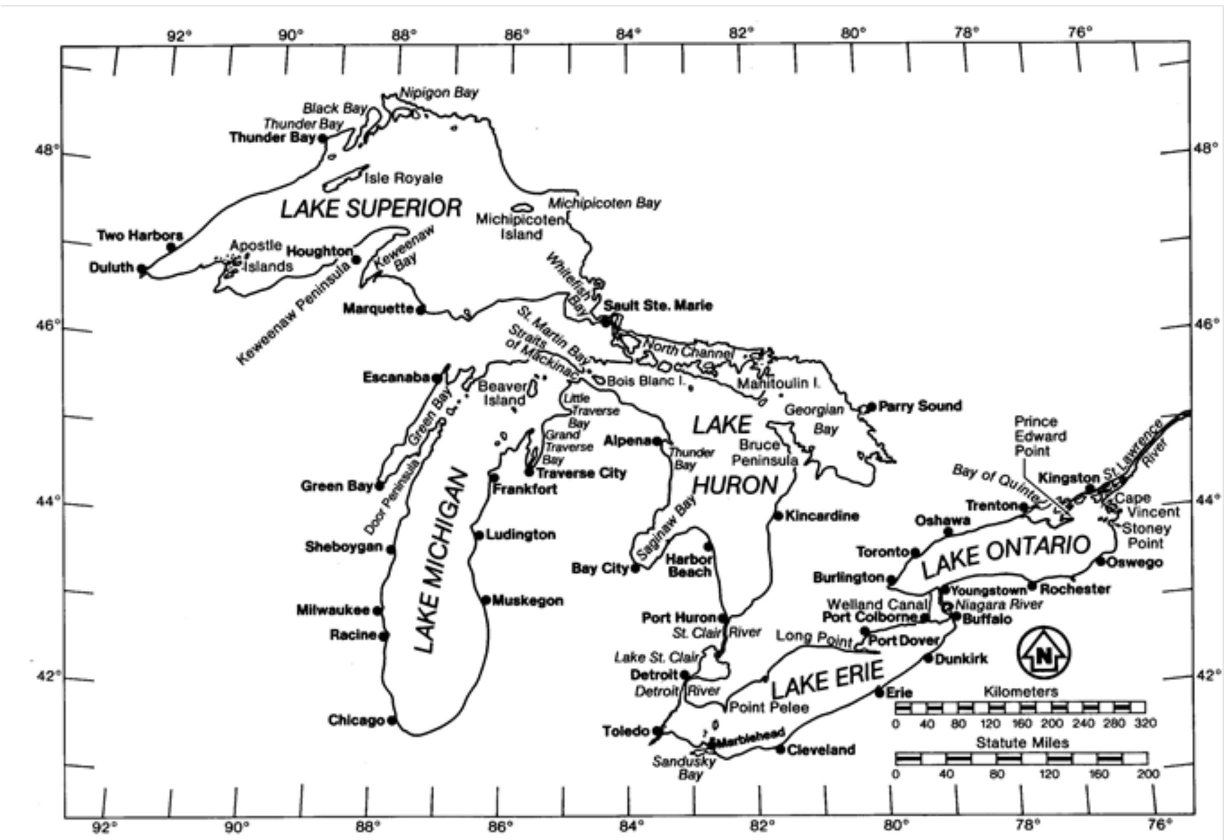
To analyze the seasonal progression of ice cover across the Great Lakes, the daily average lake ice cover is calculated for each of the Great Lakes and winter seasons. Average ice cover is the mean of all ice concentrations recorded in a specific lake for a measured date. Line plots of average lake ice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

Ice anomaly charts are produced for each winter season and provide a metric for the ice cover trends relative to the 39-winter base period (1973-2011). An ice anomaly chart is the difference between the 39-winter weekly median ice concentration grid and the ice concentration grid corresponding to the midweek day of the weekly median. For example, the ice anomaly chart for January 4th, 2012 is calculated by subtracting the 39-winter weekly median ice concentration from January 1st to January 7th. A positive (negative) difference indicates that the ice chart for a given winter has ice cover greater (less) than the 39-winter median.

PRODUCTS AND DISCUSSIONS

The analysis products in this report are summarized as follows: 1) dates of first (last) ice and ice duration, 2) daily ice concentrations and 3) ice concentration anomalies. Further documentation of first (last) ice and ice duration are given in Appendix 1, daily lake average ice concentrations in Appendix 2, and ice concentration anomalies in Appendix 3. *R* software code used to produce each analysis product is included.

GREAT LAKES PLACE NAMES



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 1-3. Trend descriptions are included.

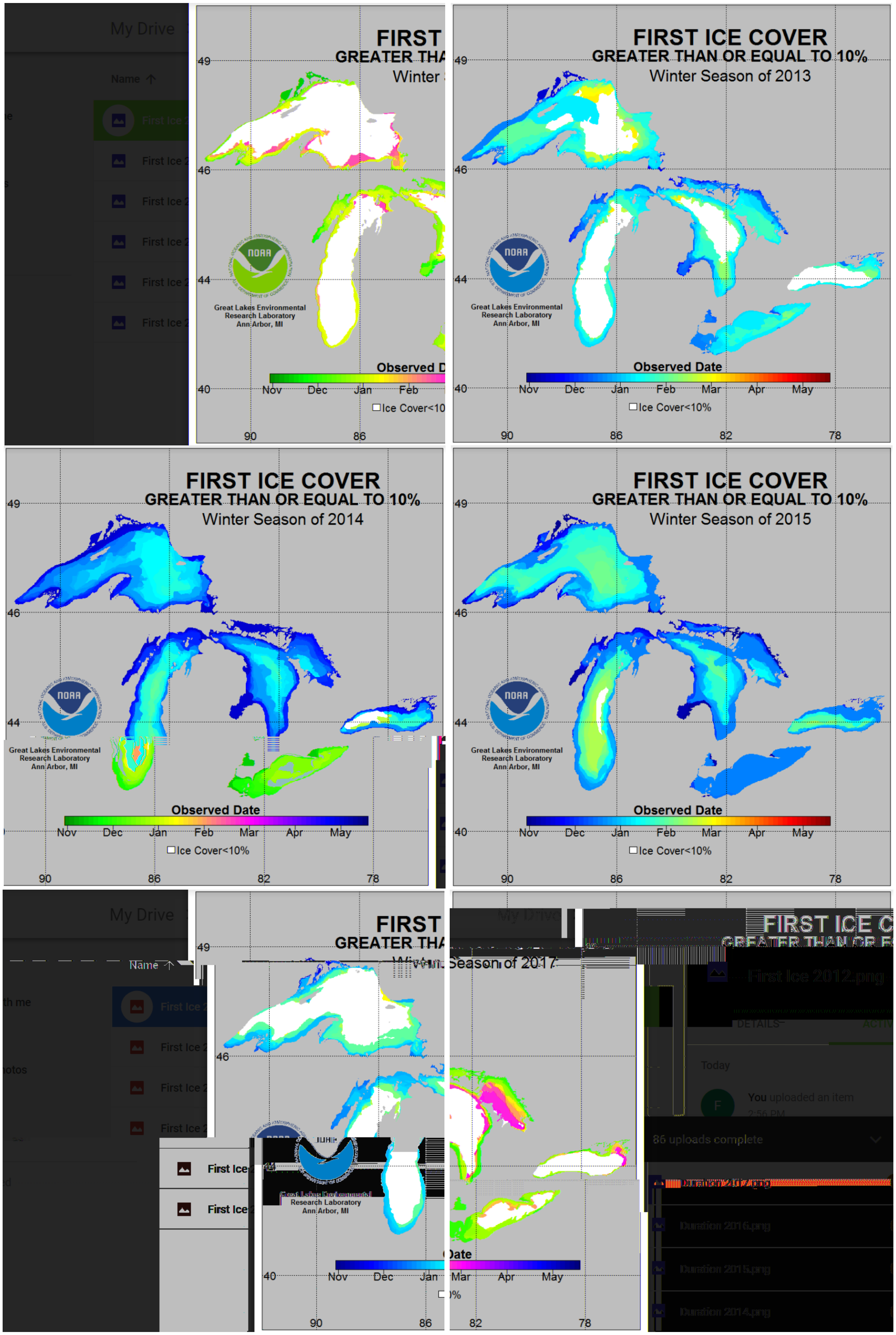


Figure 1. Dates of First Reported Ice ≥ 10%

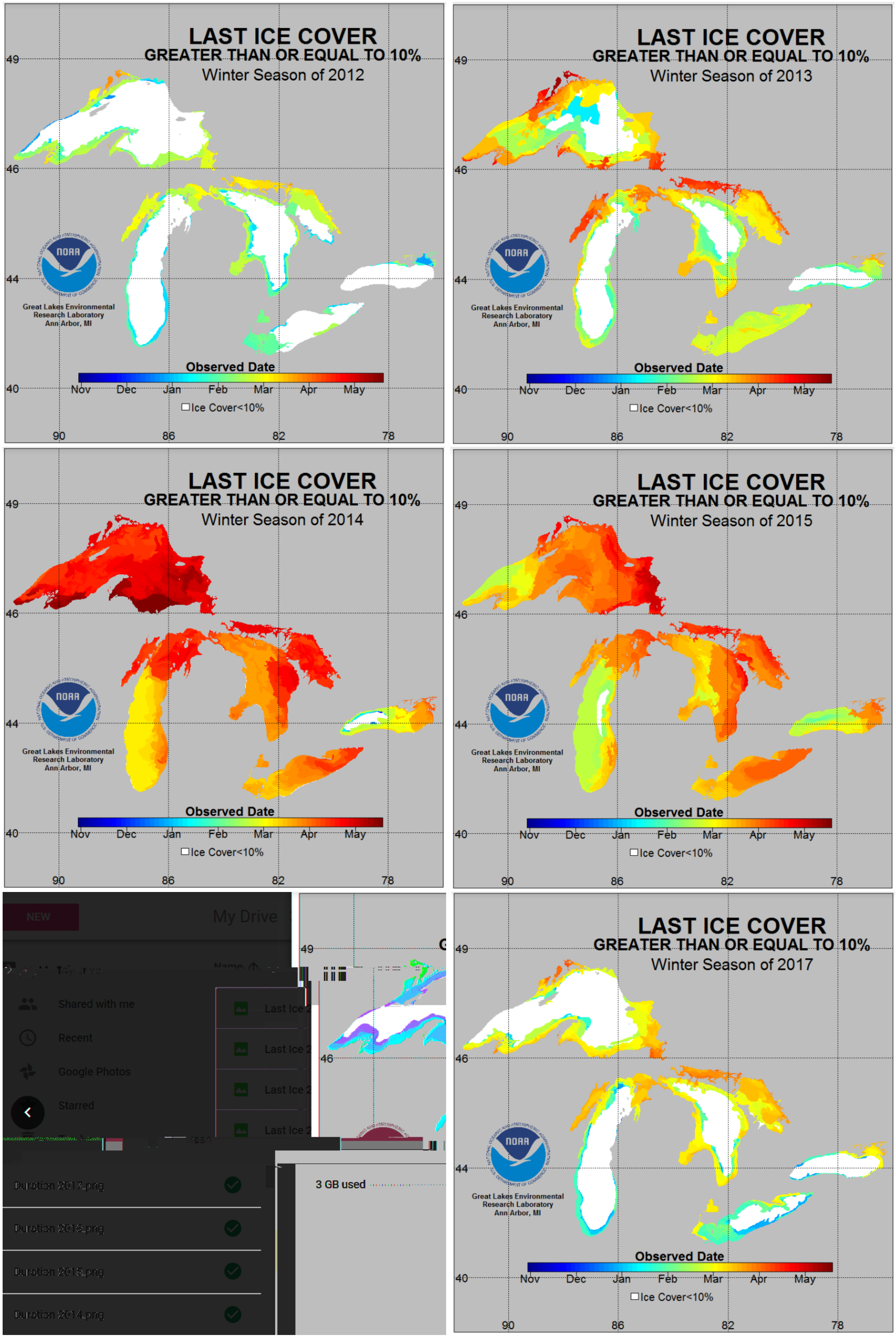


Figure 2. Dates of Last Reported Ice ≥ 10%

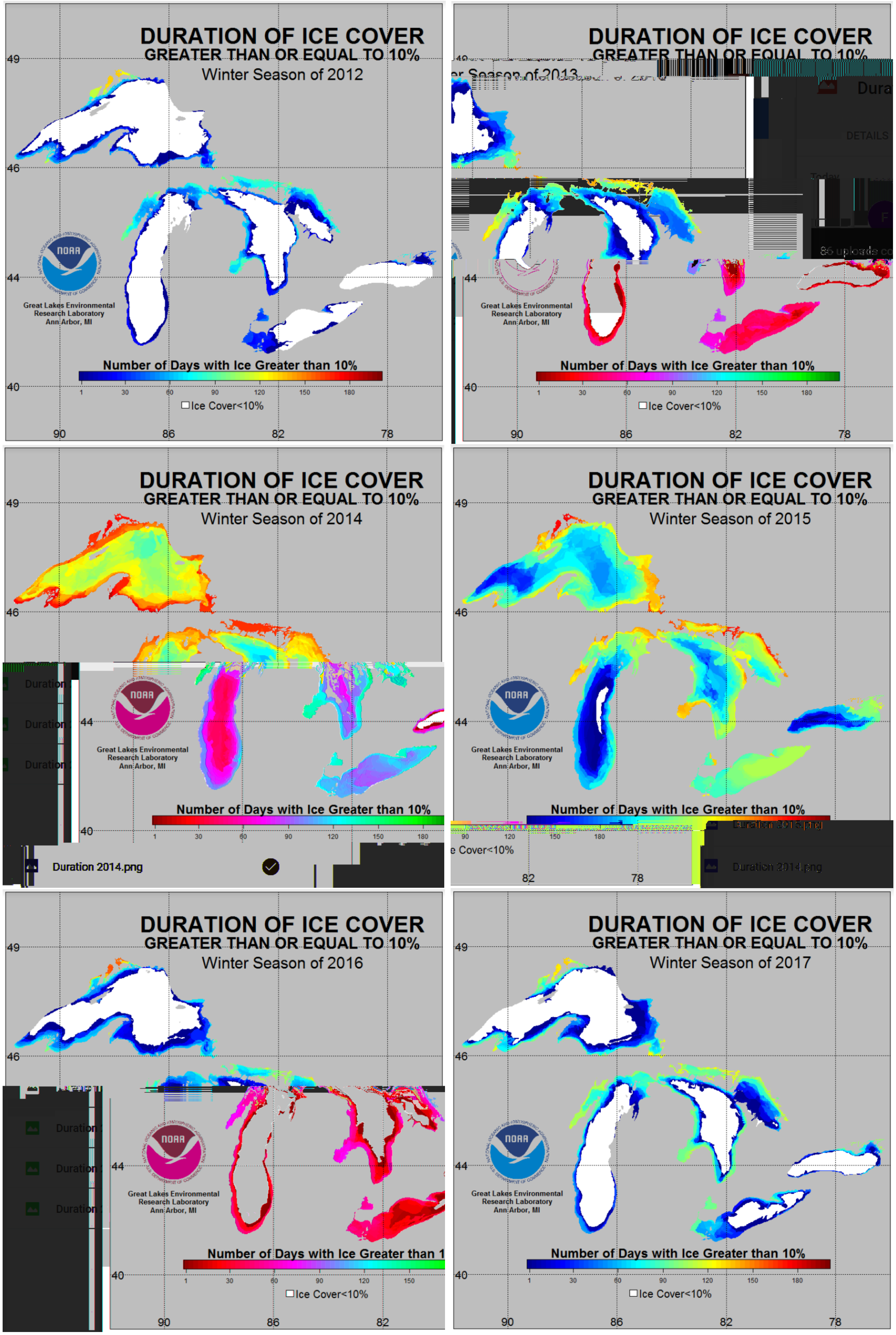


Figure 3. Duration of Ice Cover ≥ 10%

Summary of Figure 1: Ice is generally observed to form in shallow, nearshore areas during November, December, and January and in deeper shore and middle areas during February and March (Figure 1). Ice covered the greatest amount of shore and nearshore area in December 2014. The earliest and most extensive middle area ice formed in January 2014 and February 2015. The largest areas of open water, where ice concentrations were less than 10%, occurred in the 2012 winter season for all of the Great Lakes.

Summary of Figure 2: Last reports of middle lake area ice cover greater than 10% over the majority of the Great Lakes occurred during March (Figure 2). Lakes areas with last dates in February include western Lake Superior in 2010 and 2015, Lake Erie in 2013 and 2016, the northern shore of Lake Ontario in 2015, and the eastern shore of Lake Ontario in 2017. Last reports of ice cover in April and May were most prevalent over Lake Superior, Lake Huron, northern Lake Michigan in 2014, and western Lake Erie in 2015.

Summary of Figure 3: The 2012 winter season had the smallest total area of ice cover duration with concentrations greater than 10%; the 2014 winter season had the largest for the Great Lakes (Figure 3). Shallow shore areas in the Great Lakes generally had higher ice cover duration compared to middle areas. The highest ice cover durations occurred in regions of Thunder, Bay, Black Bay, Nipigon Bay, Whitefish Bay (exceeded 150 days for 2012, 2013, 2014 winter seasons), Green Bay (exceeded 120 days for 2013, 2014, 2015 and 2017 winter seasons), St. Marys River (exceeded 120 days for 2012, 2013, 2014, 2015 winter seasons), and Saginaw Bay (exceeded 120 days for 2014 and 2015 winter seasons).

SEASONAL PROGRESSION OF ICE COVER

The daily average lake ice cover line plots are seasonal progressions of the Great Lakes ice cycle for each winter season. The daily maximum ice cover and ice cover anomalies spatial plots are also shown. Additional documentation on producing the analysis products are in Appendix 2 and Appendix 3.

2012 Great Lakes Ice Cycle

Ice cover was primarily limited to areas along the shores and bays of the Great Lakes in the 2012 winter season. Ice cover extent was near its seasonal maximum in late January, which is relatively early compared to other winter seasons. The seasonal maximum value ranked as the first (Superior, Huron and Ontario), second (Great Lakes and Erie) and third (Michigan) lowest over the 45 winters from 1973 to 2017. Near the time of the annual maximum ice cover, Lake Superior ice cover extended from the Apostle Islands to the western shore of the Keweenaw Peninsula. Ice cover also extended along Thunder, Black and Nipigon Bay in the north shore. Lake Michigan's Green Bay and the Straits to Bois Blanc Island had extensive ice cover. Lake Huron's North Channel and eastern side of Georgian Bay and Saginaw Bay had high ice concentrations. Ice cover was extensive on Lake St. Clair. Lake Erie had ice cover on the western shore. Negative ice cover anomalies extended over Lake Superior's Whitefish Bay, the eastern side of Georgian Bay in Lake Huron, and surrounded the outer shores of Lake Erie. Lake Huron also had positive ice cover anomalies along the Thunder Bay. Essentially all of the Great Lakes ice had dissipated by the end of March.

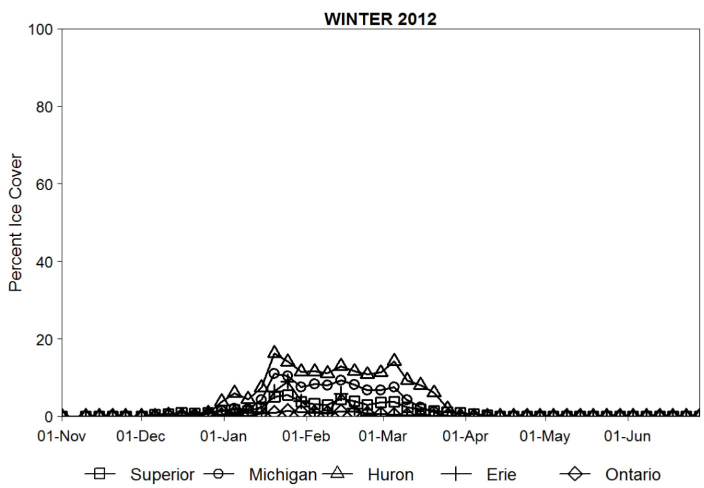


Figure 4. Daily Lake Average Ice Cover for the 2012 Winter Season

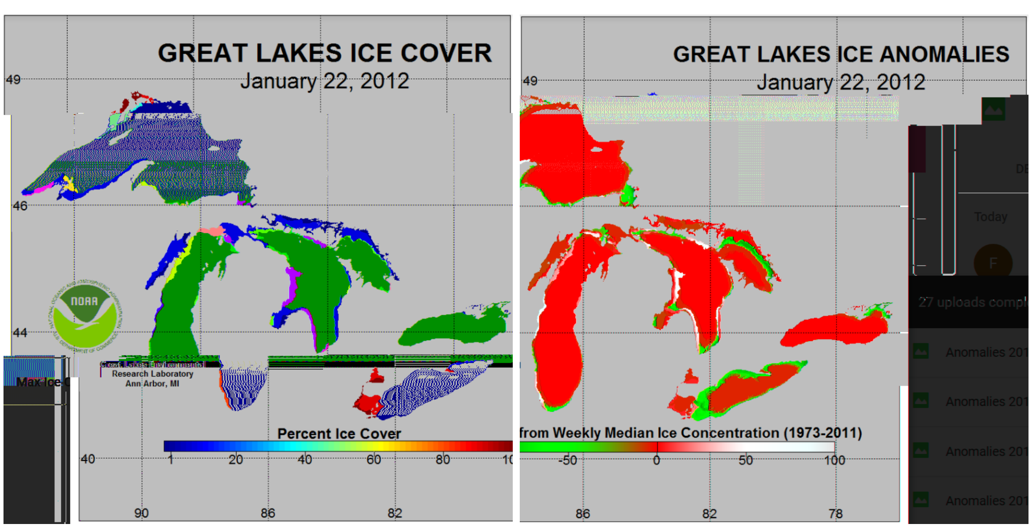


Figure 5. Maximum Ice Cover and Ice Anomaly Charts for the 2012 Winter Season

2013 Great Lakes Ice Cycle
Ice cover was more extensive in the 2013 winter season relative to the previous year. Ice cover was primarily limited to shore and nearshore areas during November and December. A large increase in ice cover formed in January to reach near the near annual maximum ice cover values. The seasonal maximum value ranked as eighth (Michigan) lowest over the 45 winters from 1973 to 2017. The Great Lakes reached maximum ice cover on February 18 where extensive ice cover was located in the west basin of Lake Superior, Green Bay, Grand Traverse Bay, the south shore of Lake Michigan, Saginaw Bay, the eastern side of the Georgian Bay, mostly all of Lake Erie, and the northeastern side of Lake Ontario. Lake Superior had positive anomalies for much of the north shore. Lake Superior had a negative anomaly west of the Keweenaw Peninsula to the Apostle Islands. Most of the Great Lakes ice lasted until the end of April.

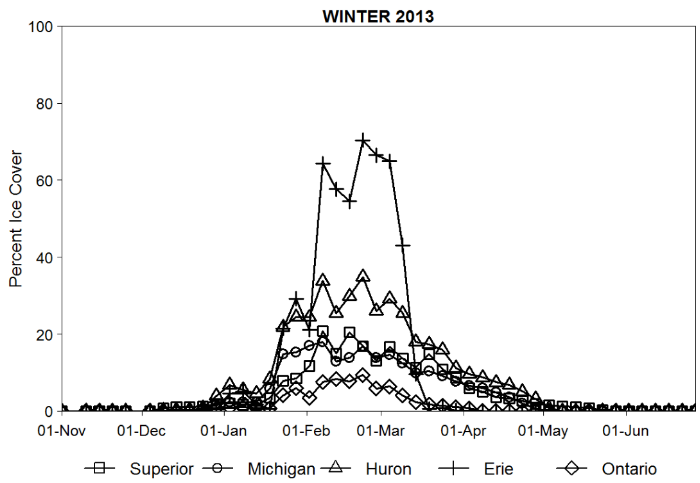


Figure 6. Daily Lake Average Ice Cover for the 2013 Winter Season

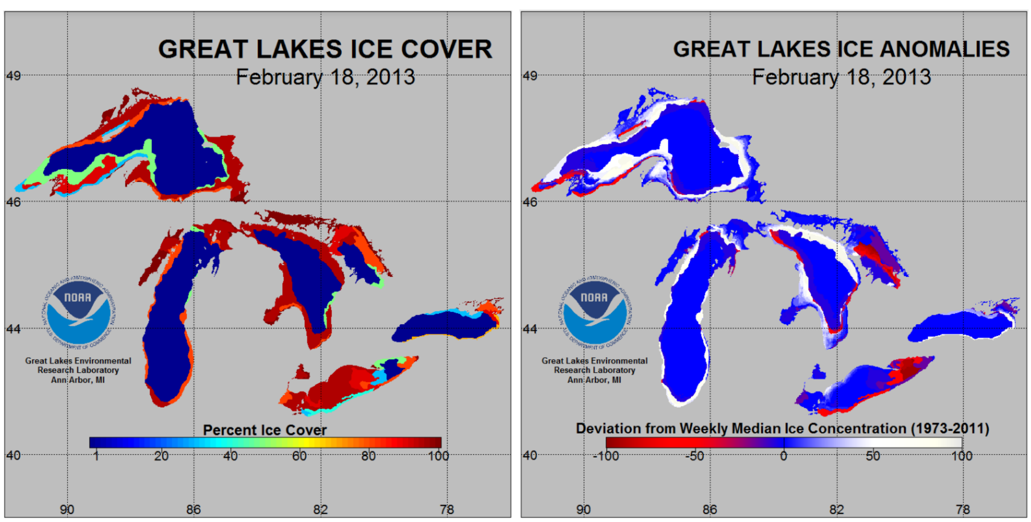


Figure 7. Maximum Ice Cover and Ice Anomaly Charts for the 2013 Winter Season

2014 Great Lakes Ice Cycle

Early ice cover was anomalously high in the 2014 winter season. Ice formed in the middle areas of the lake in January. Lake Erie was over 90% ice covered for majority of the winter season and anomalies continued to be positive through the end of March. Lake average ice cover was at or near seasonal maximums for the Great lakes from the beginning of January to the end of March. The seasonal maximum value ranked as the first (Michigan), second (Great Lakes), third (Huron), fifth (Superior and Ontario) and ninth (Erie) highest over the 44 winters from 1973 to 2017. Ice cover anomalies on March 4th were positive and extended across the main bodies of Lake Superior, Lake Huron and Lake Michigan, and the eastern side of Lake Ontario. Lakes Superior, Huron and Erie maintained average ice cover of over 50% until the middle of April before beginning to significantly dissipate. The longest lasting ice for 2014 was until early May in southern Lake Superior.

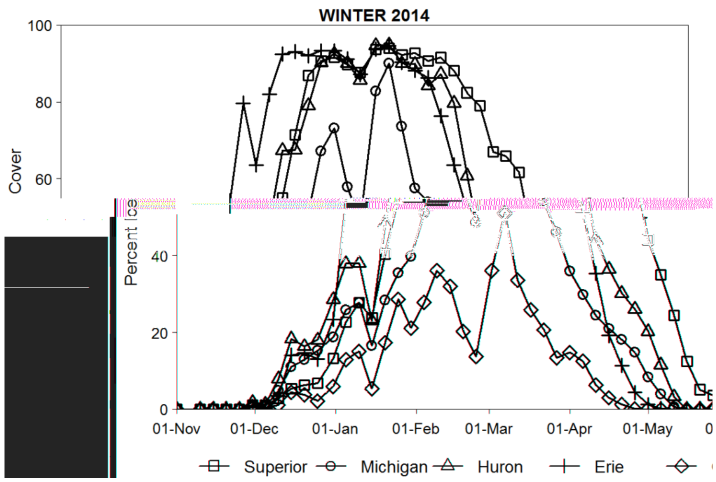


Figure 8. Daily Lake Average Ice Cover for the 2014 Winter Season

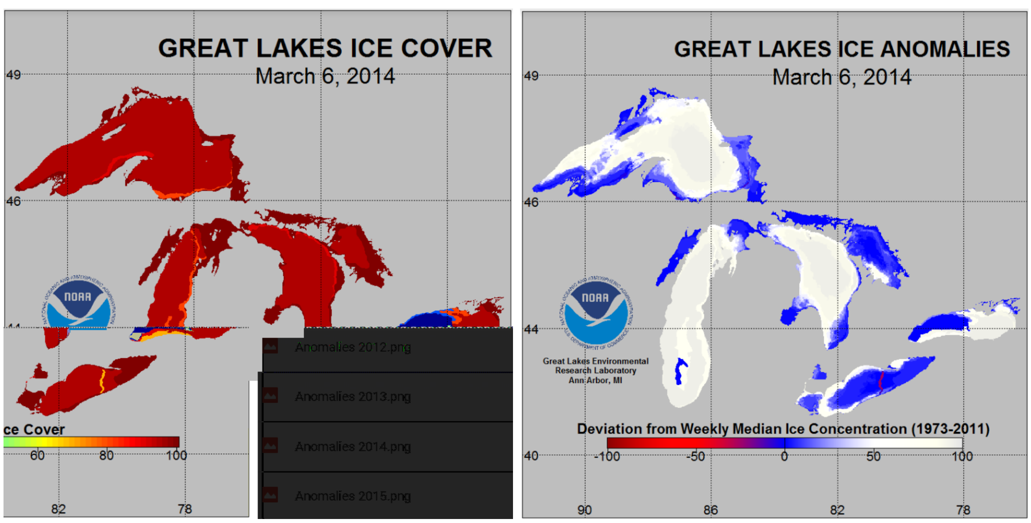


Figure 9. Maximum Ice Cover and Ice Anomaly Charts for the 2014 Winter Season

2015 Great Lakes Ice Cycle

The 2015 winter season was similar to the 2014 season. Ice cover was anomalously high in the middle regions of the Great Lakes in February. Lake Erie was over 90% covered with ice from the beginning of January to the middle of March. The seasonal maximum value ranked as the second (Ontario), fourth (Huron), fifth (Great Lakes), sixth (Superior and Michigan) and eighth (Erie) highest over the 44 winters from 1973 to 2017. Ice cover anomalies on February 28th were positive and extensive in the central areas of Lake Superior, shore and nearshore areas of Lake Michigan, central area of Lake Michigan, and southerm shore and nearshore areas of Lake Ontario. Ice dissipated over the middle regions of Lake Michigan and Lake Ontario in March; the marjority of ice cover in Lake Superior, Lake Huron, and Lake Erie dissipated during April.

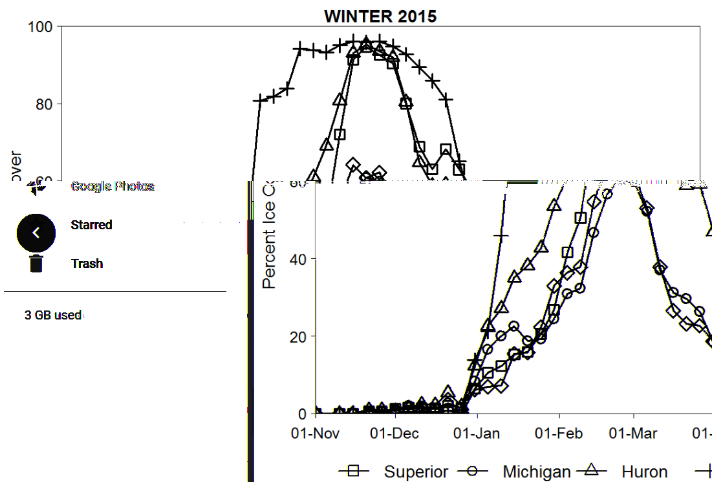


Figure 10. Daily Lake Average Ice Cover for the 2015 Winter Season

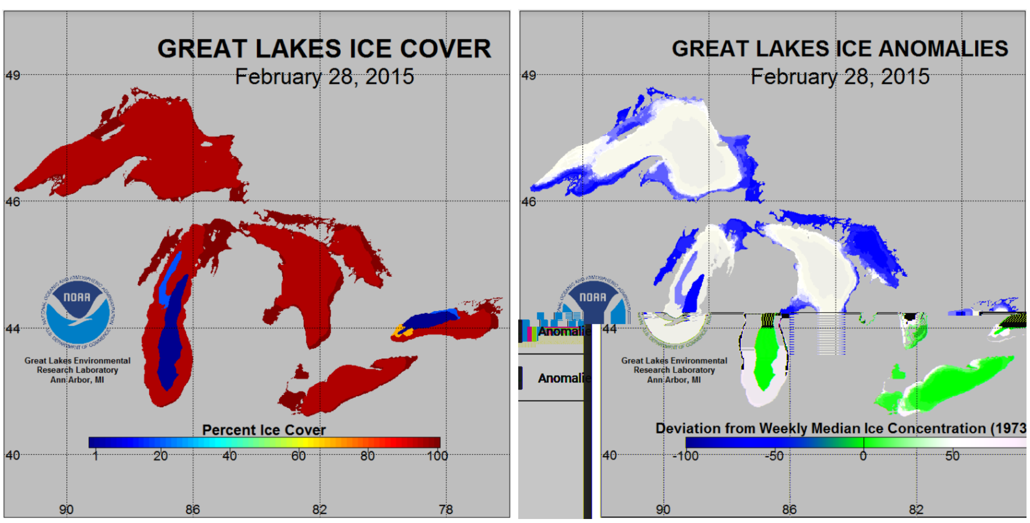


Figure 11. Maximum Ice Cover and Ice Anomaly Charts for the 2015 Winter Season

2016 Great Lakes Ice Cycle

Ice cover was primarily limited to areas along the shores and the bays of the Great Lakes in the 2016 winter season. Ice cover extent was near its seasonal maximum value in the middle of February. The seasonal maximum value ranked as the eighth (Superior), ninth (Erie) and tenth (Great Lakes) lowest over the 44 winters from 1973 to 2017. Near the time of the annual maximum ice cover, Lake Superior ice cover extended from the Apostle Islands to the western shore of the Keweenaw Peninsula. Ice cover extended along the three large bays (Thunder, Black, and Nipigon Bay) in the north shore and covered Whitefish Bay. Erie had negative ice cover anomalies in the central region during the middle of February. Ice break-up began in all of the Great lakes during the beginning of March and most ice dissipated by the end of March.

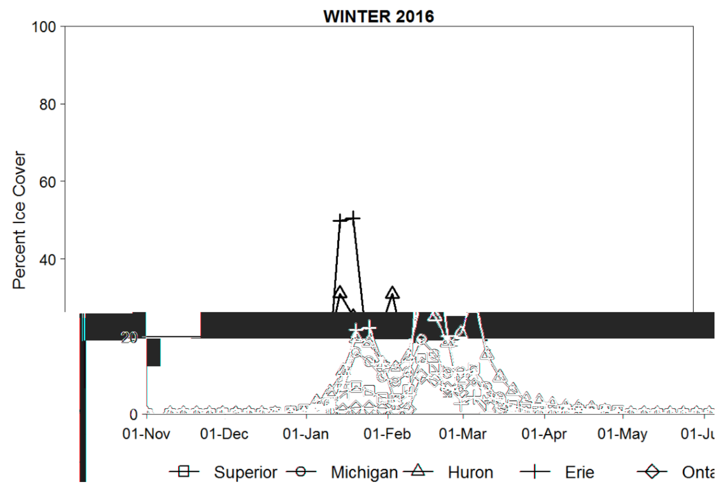


Figure 12. Daily Lake Average Ice Cover for the 2016 Winter Season

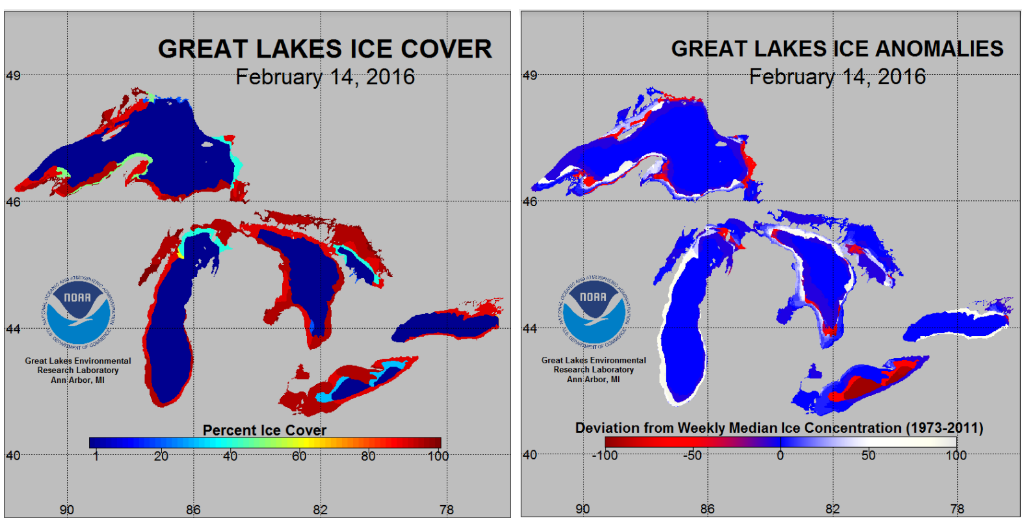


Figure 13. Maximum Ice Cover and Ice Anomaly Charts for the 2016 Winter Season

2017 Great Lakes Ice Cycle

The 2017 winter season in the Great Lakes is characterized by ice cover limited to the shore and bay areas. Unlike previous winter seasons, the ice cycle, i.e. ice onset, peak, break-up, and offset, of 2017 is less clearly defined. The extent of ice cover reached the annual maximum halfway through March. The seasonal maximum value ranked as the third (Ontario), fourth (Great Lakes), fifth (Michigan and Erie), sixth (Huron) and seventh (Superior) lowest over the 44 winters from 1973 to 2017. During the period of annual maximum ice cover in the Great Lakes, Lake Superior contained negative ice cover anomalies extending along the northern shore of Isle Royale and southern shore from the Apostle Islands to the Keweenaw Bay.

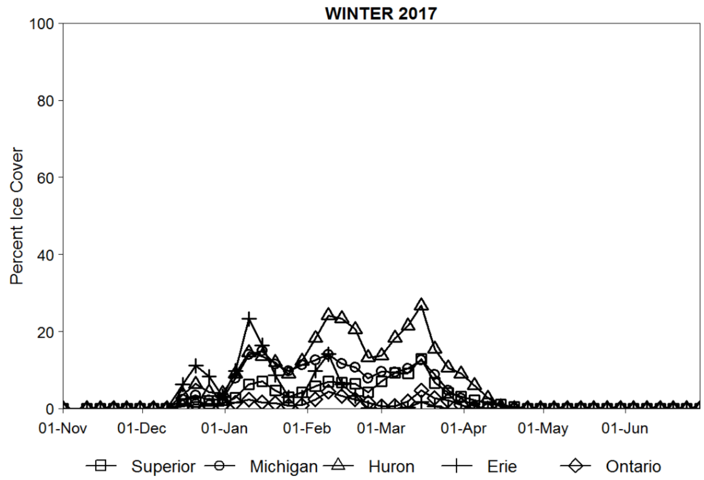


Figure 14. Daily Lake Average Ice Cover for the 2017 Winter Season

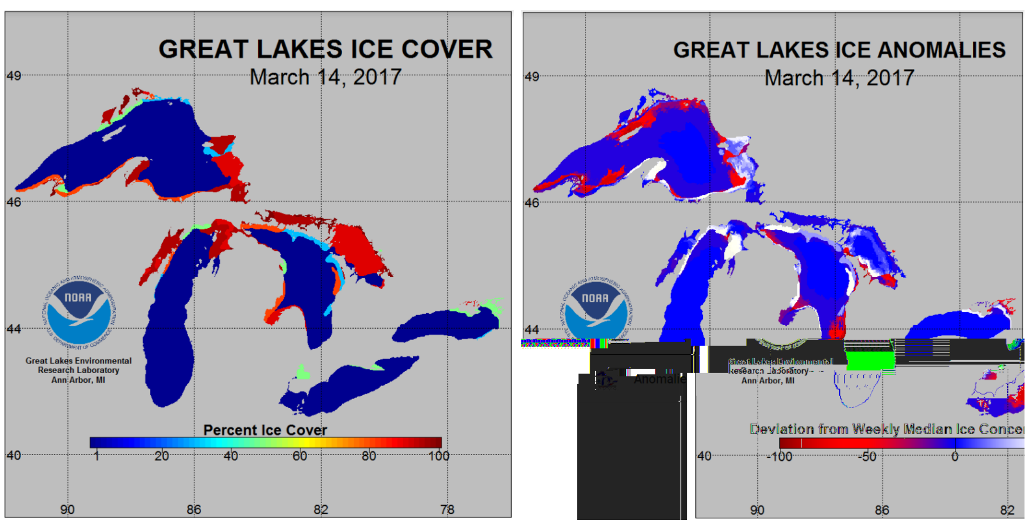


Figure 15. Maximum Ice Cover and Ice Anomaly Charts for the 2017 Winter Season

Table 1. Annual Maximum Ice Cover (AMIC): Lower to Highest Winters (1973-2017)
(Revised: March 26, 2018)

	Great Lakes		Superior		Michigan		Huron		Erie		Ontario		
Rank	Year	AMIC	Year	AMIC	Year	AMIC	Year	AMIC	Year	AMIC	Year	AMIC	Rank
1	2002	11.9	2012	8.5	2002	12.4	2012	22.8	1998	5.4	2012	1.9	1
2	2012	12.9	1998	9.3	1998	15.1	2002	26.1	2012	13.9	2002	4.0	2
3	1998	14.3	2002	10.3	2006	16.2	1998	28.6	2002	14.4	2017	5.6	3
4	2017	19.4	1987	14.5	2017	16.7	1983	31.8	2006	21.9	1998	5.7	4
5	2006	21.5	2006	17.6	2012	16.7	2006	32.2	1991	35.1	1987	8.4	5
6	1999	23.3	2017	18.2	1987	19.3	1999	34.6	2017	35.5	1991	11.6	6
7	1983	25.5	1999	18.3	1999	20.3	2017	35.4	1983	40.8	2010	12.4	7
8	2010	29.2	1983	20.2	1991	21.5	2010	37.0	1990	72.8	1983	12.5	8
9	1987	30.7	2016	22.7	1995	21.6	1995	41.7	1999	74.8	2008	14.0	9
10	2001	31.6	1995	28.8	1975	22.7	2000	42.0	2016	78.7	2006	14.3	10
11	2016	33.8	2010	29.0	2010	23.5	1987	43.5	1975	80.1	1975	14.9	11
12	2000	34.4	1976	31.3	1983	23.6	1991	43.8	2013	83.7	1976	15.2	12
13	1992	38.0	2000	33.5	2013	24.4	2001	45.7	1987	88.0	1989	15.5	13
14	2013	38.4	2013	33.6	2016	26.8	2013	47.8	1974	88.5	2013	15.6	14
15	2011	40.1	2011	33.6	2000	27.2	2016	48.0	1992	89.8	1992	17.5	15
16	1995	41.7	2001	46.2	2011	29.4	1976	52.5	2000	90.7	1999	17.9	16
17	1976	43.2	2004	52.2	2005	29.4	1975	55.1	1988	91.5	2001	17.9	17
18	2005	44.2	2007	52.7	1976	29.5	2005	58.9	1989	91.6	1995	18.8	18
19	1991	46.0	2005	54.5	2001	29.5	2008	59.5	2001	92.5	1988	21.1	19
20	1975	51.4	2008	63.7	1990	30.5	1988	60.1	2005	93.0	2009	22.2	20
21	2004	51.9	1975	64.9	1989	30.9	1974	61.4	2010	93.1	2000	22.3	21
22	2008	54.7	1988	67.3	1993	32.2	2011	63.8	2008	93.4	2016	23.5	22
23	1988	55.5	1973	69.8	1988	32.7	2004	64.5	1980	93.4	2007	23.8	23
24	2007	56.2	1992	73.3	1992	32.8	1997	65.3	1995	93.5	1974	24.5	24
25	1997	57.7	1974	73.6	1973	33.0	1973	66.7	1984	93.6	2011	24.9	25
26	1974	60.4	1980	77.2	2008	33.5	1992	69.9	2011	94.1	1997	25.6	26
27	1973	62.1	1993	77.2	2004	36.4	1980	70.3	1993	94.3	1993	28.8	27
28	1989	62.3	1990	78.1	2007	37.2	2007	71.4	1986	95.0	1990	29.5	28
29	1990	65.1	1997	79.3	1997	37.8	1986	73.5	2009	95.0	1980	30.6	29
30	1980	65.9	1985	81.9	1980	38.6	1990	73.8	1976	95.4	2005	37.8	30
31	1984	66.7	1989	82.3	1974	39.4	1989	76.3	2004	95.4	1985	38.2	31
32	1993	67.4	1981	84.7	1985	41.3	1984	77.6	2003	95.7	2004	38.5	32
33	1985	71.0	1982	85.3	1984	43.3	1993	78.3	1973	95.7	1984	40.7	33
34	1981	72.5	1984	88.2	1981	47.6	2009	85.1	2007	95.8	1986	43.7	34
35	2009	74.5	1991	89.6	2003	48.0	1985	87.4	1981	96.0	1996	45.1	35
36	1982	75.6	1986	90.7	2009	52.3	1982	93.3	1985	96.0	1977	46.7	36
37	1986	77.1	1978	92.5	1982	60.2	1981	93.8	2014	96.1	1981	47.6	37
38	2003	80.2	2009	93.7	1978	66.6	1977	95.0	2015	96.1	2003	49.6	38
39	1996	81.0	2003	95.5	1986	66.8	1978	95.8	1994	96.7	1982	50.7	39
40	1978	83.5	2015	95.7	1996	71.2	2014	96.1	1982	99.1	1994	55.7	40
41	2015	88.8	2014	95.8	2015	72.9	2003	96.2	1997	99.6	1978	57.7	41
42	1994	89.0	1977	96.0	1994	82.7	2015	96.3	1977	99.8	2014	60.8	42
43	1977	90.1	1994	96.1	1979	92.3	1979	96.4	1979	100.0	1973	62.6	43
44	2014	92.5	1979	97.1	1977	93.1	1994	96.9	1978	100.0	2015	82.4	44
45	1979	94.7	1996	100.0	2014	93.1	1996	98.2	1996	100.0	1979	86.2	45
Rank	Year	AMIC	Year	AMIC	Year	AMIC	Year	AMIC	Year	AMIC	Year	AMIC	Rank
	Great Lakes		Superior		Michigan		Huron		Erie		Ontario		

The annual maximum ice cover values are lake averages calculated from the original ice charts.

CONCLUSIONS

In previous ice climatology analysis, the analysis proudcts including dates of first (last) ice, ice duration, and ice cycles provided a limited look at the annual ice cycles for each winter in comparison to a 39-winter climatology. Given the significantly greater amount of data measurements (daily ice charts) taken in recent years, however, temporal variability of daily lake avearge ice cover is better defined for the 2012-2017 seasons.

In general, the ice cycles of 2012-2017 have been found to be significantly anomalous in their annual maximum ice cover (AMIC) values compared to previous years. The 2012, 2013, 2016, and 2017 winter seasons all possess considerably high rankings for lowest AMIC (with the majority ranking from 1st to 15th); both the 2014 and 2015 winter seasons rank from 1st to 9th in highest AMIC across all of the Great lakes (see Table 1).

Ice cover data can be further useful in the analysis of atmospheric and oceanic teleconnection patterns and ice cover trends in the Great Lakes on various time scales (Assel 2013). Recent research Wang et al. (2012b, 2017) and Bai et al (2012) provide evidence these data are useful in the analysis of the inter-annual and decadal ice cover variability in response to teleconnection patterns in the atmosphere and in the analysis of multi-decadal trends in Great Lakes ice cover over the last four 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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REFERENCES

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. Great Lakes ice cover climatology update: Winters 2003, 2004, and 2005. NOAA Technical Memorandum GLERL-135. NOAA, Great Lakes Environmental Research Laboratory, Ann Arbor, MI, 21 pp. (2005a). 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. NOAA, Great Lakes Environmental Research Laboratory, Ann Arbor, MI, 27 pp. (2005b). https://www.glerl.noaa.gov/pubs/tech_reports/glerl-133/

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. 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. 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. NOAA Atlas. An Electronic Atlas of Great Lakes Ice Cover, Winters: 1973-2002. NOAA Great Lakes Environmental Research Lab., Ann Arbor, MI. (2003a). 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., 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

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., 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, J. Wang, A. Clites, and X. Bai. Analysis of Great Lakes ice cover climatology: Winters 2006-2011. NOAA Technical Memorandum GLERL-157. NOAA Great Lakes Environmental Research Laboratory, Ann Arbor, MI, 26 pp. (2013). https://www.glerl.noaa.gov/pubs/tech_reports/glerl-157/tm-157.pdf

Bai, X., J. Wang, C.E. Sellinger, A.H. Clites, and R.A. Assel. Interannual variability of Great Lakes ice cover and its relationship to NAO and ENSO. *Journal of Geophysical Research* 117(C03002):25 pp. (DOI:10.1029/2010JC006932) (2012). http://www.agu.org/pubs/crossref/2012/2010JC006932.shtml

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

Wang, J., R. A. Assel, S. Walterscheid, A.H. Clites, and X. Bai. Great Lakes ice cover climatology update: Winters 2006-2011 description of the digital ice cover data set. NOAA Technical Memorandum GLERL-155, 45 pp (2012a). http://www.glerl.noaa.gov/ftp/publications/tech_reports/glerl-155/tm-155.pdf

Wang, J., X. Bai, H. Hu, A.H. Clites, M.C. Colton, and B.M. Lofgren. Temporal and spatial variability of Great Lakes ice cover, 1973-2010. *Journal of Climate* 25(4):1318-1329 (DOI:10.1175/2011JCLI4066.1) (2012b). http://journals.ametsoc.org/doi/pdf/10.1175/2011JCLI4066.1

Wang, J., J. Kessler, A. Assuncao, X. Bai, Z. Yang, A. Clites, B. Lofgren, J. Bratton, P. Chu, and G. Leshkevich. Decadal variability of Great Lakes ice cover in response to AMO and PDO, 1973-2017 (2017). (submitted to J. Climate)

Appendix 1. Dates of First Ice, Last Ice, and Ice Duration

Grid File Structures
For the winters of 2012-2017, each ice chart grid file consist a 1024x1024 pixel grid of integers that contains the entire Great Lakes region.

Grid Data Codes
Land is assigned a data code of '-1'. Ice cover concentrations that are less than 10% are assigned '0'.

For charts of first (last) ice, data codes '15279' to '17318' are numerical representations of calendar dates given by *R*. See Table A1 for a list of data codes associated with calendar dates of the first day of each month from winter seasons 2012 to 2017.

For ice duration charts, data codes '1' to '200' are the number of days between the first and last reported ice cover. Ice duration is considered 1 day if the first and last date are the same; duration is 0 if the ice cover concentration is less than 10%.

Table A1. Calendar Dates and Corresponding *R* Numerical Data Code

Data Code		Data Code	
November 1, 2011	15279	November 1, 2014	16375
December 1, 2011	15309	December 1, 2014	16405
January 1, 2012	15340	January 1, 2015	16436
February 1, 2012	15371	February 1, 2015	16467
March 1, 2012	15400	March 1, 2015	16495
April 1, 2012	15431	April 1, 2015	16526
May 1, 2012	15461	May 1, 2015	16556
June 1, 2012	15492	June 1, 2015	16587
November 1, 2012	15645	November 1, 2015	16740
December 1, 2012	15675	December 1, 2015	16770
January 1, 2013	15706	January 1, 2016	16801
February 1, 2013	15737	February 1, 2016	16832
March 1, 2013	15765	March 1, 2016	16861
April 1, 2013	15796	April 1, 2016	16892
May 1, 2013	15826	May 1, 2016	16922
June 1, 2013	15857	June 1, 2016	16953
November 1, 2013	16010	November 1, 2016	17106
December 1, 2013	16040	December 1, 2016	17136
January 1, 2014	16071	January 1, 2017	17167
February 1, 2014	16102	February 1, 2017	17198
March 1, 2014	16130	March 1, 2017	17226
April 1, 2014	16161	April 1, 2017	17257
May 1, 2014	16191	May 1, 2017	17287
June 1, 2014	16222	June 1, 2017	17318

R Software Code

Below is the *R* software code for producing charts for the dates of first ice, last ice and ice duration for a given winter season.

```
winter_year<-2017 #USER INPUT
previous<-winter_year-1

#LOCATES FIRST DATED CHART STARTING FROM NOVEMBER 1ST
for (month in 11:12){
  for (day in 1:31){
    x<-file.exists(paste(format(ISOdate(previous,month,day),"%Y%m%d"),'.ct',sep=""))
    if (x==TRUE){
      start<-as.numeric(as.Date(ISOdate(previous,month,day)))
      break
    }
  }
  if (x==TRUE){
    break
  }
}

#LOCATES LAST DATED CHART STARTING FROM JUNE 30TH
for (month in 6:4){
  for (day in 31:1){
    x<-file.exists(paste(format(ISOdate(winter_year,month,day),"%Y%m%d"),'.ct',sep=""))
    if (x==TRUE){
      end<-as.numeric(as.Date(ISOdate(winter_year,month,day)))
      break
    }
  }
  if (x==TRUE){
    break
  }
}

#ASSIGNS FIRST CHART DATE TO VALUES ≥10%
first_ice<-matrix(scan(file=paste(format(as.Date(start,origin="1970-01-01"),"%Y%m%d"),'.ct',sep=""),skip=6))
first_ice[first_ice>=10]<-start



#ITERATION THROUGH CHARTS IN CHRONOLOGICAL ORDER
#ASSIGNS CHART DATE WHERE ICE ≥10% AND VALUES OF FIRST ICE CHART ≤10%
for (month in 11:12){
  for (day in 1:31){
    x<-file.exists(paste(format(ISOdate(previous,month,day),"%Y%m%d"),'.ct',sep=""))
    if (x==TRUE){
      data<-matrix(scan(file=paste(format(ISOdate(previous,month,day),"%Y%m%d"),'.ct',sep=""),skip=6))
      first_ice[first_ice>=0&first_ice<10&data>=10]<-as.numeric(as.Date(ISOdate(previous,month,day)))
    }
  }
}
for (month in 1:6){
  for (day in 1:31){
    x<-file.exists(paste(format(ISOdate(winter_year,month,day),"%Y%m%d"),'.ct',sep=""))
    if (x==TRUE){
      data<-matrix(scan(file=paste(format(ISOdate(winter_year,month,day),"%Y%m%d"),'.ct',sep=""),skip=6))
      first_ice[first_ice>=0&first_ice<10&data>=10]<-as.numeric(as.Date(ISOdate(winter_year,month,day)))
    }
```

```
  }
}

#ASSIGNS LAST CHART DATE TO VALUES ≥10%
last_ice<-matrix(scan(file=paste(format(as.Date(end,origin="1970-01-01"),"%Y%m%d"),'.ct',sep=""),skip=6))
last_ice[last_ice>=10]<-end

#ITERATION THROUGH CHARTS IN REVERSE CHRONOLOGICAL ORDER
#ASSIGNS CHART DATE WHERE ICE≥10% AND VALUES OF LAST ICE CHART ≤10%
for (month in 6:1){
  for (day in 31:1){
    x<-file.exists(paste(format(ISOdate(winter_year,month,day),"%Y%m%d"),'.ct',sep=""))
    if (x==TRUE){
      data<-matrix(scan(file=paste(format(ISOdate(winter_year,month,day),"%Y%m%d"),'.ct',sep=""),skip=6))
      last_ice[last_ice>=0&last_ice<10&data>=10]<-as.numeric(as.Date(ISOdate(winter_year,month,day)))
    }
  }
}
for (month in 12:11){
  for (day in 31:1){
    x<-file.exists(paste(format(ISOdate(previous,month,day),"%Y%m%d"),'.ct',sep=""))
    if (x==TRUE){
      data<-matrix(scan(file=paste(format(ISOdate(previous,month,day),"%Y%m%d"),'.ct',sep=""),skip=6))
      last_ice[last_ice>=0&last_ice<10&data>=10]<-as.numeric(as.Date(ISOdate(previous,month,day)))
    }
  }
}
first_ice[first_ice==-1]<-NA
last_ice[last_ice==-1]<-NA

#ICE DURATION IS DIFFERENCE BETWEEN FIRST AND LAST DATES
dur<-last_ice-first_ice

#ICE DURATION IS 1 WHEN FIRST AND LAST ICE DATES ARE EQUAL
dur[first_ice==last_ice&first_ice>0&last_ice>0]<-1
```

Appendix 2. Daily Lake Average Ice Cover

The daily lake average ice cover time series for each winter season begins with the date of the first ice chart and ends with the date of the last ice chart. Dates of first and last ice are summarized below in Table 2A.

Table 2A. Summary of Ice Charts

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

***R* Software Code**

Below is the *R* software code for graphing the daily lake average ice cover time series for a given winter season.

```
library(zoo)

winter_year<-2011 #USER INPUT
previous<-winter_year-1

date<-vector()
Sup_avg<-vector()
Mch_avg<-vector()
Hrn_avg<-vector()
Er_avg<-vector()
Ont_avg<-vector()

lk_ids<-matrix(scan('1024_lake_ids.txt'))

#CALCULATES MEAN ICE COVER FOR EACH DAILY CHART AND GREAT LAKE
for (month in 11:12){
  for (day in 1:31){
    x<-file.exists(paste(format(ISOdate(previous,month,day),"%Y%m%d"),'.ct',sep=""))
    if (x==TRUE){
      date<-c(date,as.numeric(as.Date(ISOdate(previous,month,day))))
      data<-matrix(scan(file=paste(format(ISOdate(previous,month,day),"%Y%m%d"),'.ct',sep=""),skip=6))

      Sup<-data[lk_ids==1]
      Mch<-data[lk_ids==2]
      Hrn<-data[lk_ids==3]
      Er<-data[lk_ids==4]
      Ont<-data[lk_ids==5]

      Sup_avg<-c(Sup_avg,mean(Sup))
      Mch_avg<-c(Mch_avg,mean(Mch))
      Hrn_avg<-c(Hrn_avg,mean(Hrn))
      Er_avg<-c(Er_avg,mean(Er))
      Ont_avg<-c(Ont_avg,mean(Ont))
    }
  }
}
for (month in 1:6){
  for (day in 1:31){
```

```
    x<-file.exists(paste(format(ISOdate(winter_year,month,day),"%Y%m%d"),'.ct',sep=""))
    if (x==TRUE){
      date<-c(date,as.numeric(as.Date(ISOdate(winter_year,month,day))))
      data<-matrix(scan(file=paste(format(ISOdate(winter_year,month,day),"%Y%m%d"),'.ct',sep=""),skip=6))

      Sup<-data[lk_ids==1]
      Mch<-data[lk_ids==2]
      Hrn<-data[lk_ids==3]
      Er<-data[lk_ids==4]
      Ont<-data[lk_ids==5]

      Sup_avg<-c(Sup_avg,mean(Sup))
      Mch_avg<-c(Mch_avg,mean(Mch))
      Hrn_avg<-c(Hrn_avg,mean(Hrn))
      Er_avg<-c(Er_avg,mean(Er))
      Ont_avg<-c(Ont_avg,mean(Ont))
    }
  }
}

#CALCULATES A WEEKLY ROLLING MEAN FOR EACH LAKE
Sup_avg<-rollmean(Sup_avg,7,fill=0)
Mch_avg<-rollmean(Mch_avg,7,fill=0)
Hrn_avg<-rollmean(Hrn_avg,7,fill=0)
Er_avg<-rollmean(Er_avg,7,fill=0)
Ont_avg<-rollmean(Ont_avg,7,fill=0)
```

Appendix 3. Maximum Ice Cover and Ice Cover Anomaly Charts

The date of annual maximum ice cover (AMIC) in a winter season is determined as the greatest value of total Great Lakes average ice concentration.

The 39-winter (1973-2017) weekly median ice concentration charts are used to calculate the anomaly ice charts for the 2012-2017 winters. The anomaly ice charts represent the spatial distribution patterns over the Great Lakes for a given day in the winter season relative to the 39-winter, long term median.

***R* Software Code**
Below is the *R* code for determining the ice cover anomalies for a given winter season.

```
library(gdata)
library(matrixStats)

max_date<-"03-14-2017" #USER INPUT

max_matrix<-matrix(scan(file=paste(format(as.Date(max_date,"%m-%d-%Y"),"%Y%m%d"),'.ct',sep=""),skip=6))
dim(max_matrix)<-c(1024,1024)
max_matrix<-max_matrix[,ncol(max_matrix):1]

winter_year<-as.numeric(format(as.Date(max_date,"%m-%d-%Y"),"%Y"))
lower<-as.numeric(as.Date(max_date,"%m-%d-%Y"))-3
upper<-as.numeric(as.Date(max_date,"%m-%d-%Y"))+3

#INTERLEAVING METHOD TO APPROXIMATE 510X516 GRID RESOLUTION TO 1024X1024
old<-matrix(scan('510_516_lake_ids.txt'))
dim(old)<-c(516,510)
old<-interleave(old,old)
old<-t(interleave(t(old),t(old)))

fnl<-matrix(0,1024,1024)
fnl[4:1024,10:1024]<-old[1:1021,3:1017]
fnl[fnl>0]<-1

original<-matrix(scan('1024_lake_ids.txt'))
dim(original)<-c(1024,1024)
original[original>0]<-1

#INDICATOR FOR OVER-WATER/LAND DISCREPANCIES BETWEEN 510X516/1024X1024 GRIDS
diff<-original-fnl

counter_1<-0
first<-vector()

lk_ids<-matrix(scan('510_516_lake_ids.txt'))

#APPROXIMATE 510X516 GRID RESOLUTION TO 1024X1024
#APPENDS CHARTS (1973-2006) FOR WEEK CENTERED AROUND MAXIMUM ICE COVER
for (year in 1973:2006){
  for (i in lower:upper){
    i_month<-format(as.Date(i,origin="1970-01-01"),"%m")
    i_day<-format(as.Date(i,origin="1970-01-01"),"%d")
    x<-file.exists(paste(format(ISOdate(year,i_month,i_day),"%Y%m%d"),'.ct',sep=""))
    if (x==TRUE){
      data<-matrix(scan(file=paste(format(ISOdate(year,i_month,i_day),"%Y%m%d"),'.ct',sep=""),skip=6))
      dim(data)<-c(516,510)
      data<-interleave(data,data)
```

```
      data<-t(interleave(t(data),t(data)))
      interp<-matrix(-1,1024,1024)
      interp[4:1024,10:1024]<-data[1:1021,3:1017]
      interp[diff==-1]<--1
      interp[diff==1]<-NA
      first<-c(first,interp)
      counter_1<-counter_1+1
    }
  }
}

counter_2<-0
second<-vector()

lk_ids<-matrix(scan('1024_lake_ids.txt'))


#APPENDS CHARTS (2007-2011)  FOR WEEK CENTERED AROUND MAXIMUM ICE COVER
for (year in 2007:2011){
  for (i in lower:upper){
    i_month<-format(as.Date(i,origin="1970-01-01"),"%m")
    i_day<-format(as.Date(i,origin="1970-01-01"),"%d")
    x<-file.exists(paste(format(ISOdate(year,i_month,i_day),"%Y%m%d"),'.ct',sep=""))
    if (x==TRUE){
      second<-
c(second,matrix(scan(file=paste(format(ISOdate(year,i_month,i_day),"%Y%m%d"),'.ct',sep=""),skip=6)))
      counter_2<-counter_2+1
    }
  }
}

series<-c(first,second)
dim(series)<-c(1048576,counter_1+counter_2)

#LOCATE WEEKLY MEDIAN ICE CONCENTRATIONS
final<-rowMedians(series,na.rm=TRUE)

dim(final)<-c(1024,1024)
final<-final[,ncol(final):1]

#ANOMALY IS DIFFERENCE BETWEEN ANNUAL MAXIMUM AND WEEKLY MEDIAN
anom<-max_matrix-final
```