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ANALYSIS OF GREAT LAKES ICE COVER CLIMATOLOGY: WINTERS 2006-2011

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Analysis of Great Lakes Ice Cover Climatology: Winters 2006-2011

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ABSTRACT

A 33-winter ice concentration climatology (Assel 2003a, Assel 2005a) was recently updated for winters 2006-2011 (Wang et al. 2012a). This report provides an analysis of the 2006-2011 ice cycles within the context of: dates of first (last) ice, ice duration, ice cover distribution, ice cover anomalies, and seasonal progression of lake-averaged ice cover. Analysis data are available as ASCII and graphic files.

1. 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). The information presented here updates analysis products given in Assel (2003a, 2005a) 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 (2005a). 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.

2. DATA

The ice cycle analysis presented here is based on 389 digitized ice charts: 46 (2006), 46 (2007), 55 (2008), 45 (2009), 46 (2010), and 151 (2011). In general, ice charts began in early December and ended in early May. Wang et al. (2012a) provides details of the distribution of dates of ice charts for each winter season. The original ASCII ice chart files were produced by the National Ice Center (NIC) and the Canadian Ice Service (CIS). The data consists of grids of over-water cells embedded in a land mask (a 510 x 516 matrix at a nominal spatial resolution of 2.55 km for winter 2006, and a 1024 x 1024 matrix at a nominal spatial resolution of 1.275 km at approximately 45^0N for winters 2007-2011). 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 CoastWatch land mask (http://coastwatch.glerl.noaa.gov/ftp/masks/new/), and ice concentration codes, consistent with Assel (2003a, 2005a). Fixed formatted ASCII and ARC/INFO shape files: names, structure, and ice concentration codes, are available in Wang et al. (2012a) for those interested in these data.

3. ANALYSIS METHODS

An analysis for threshold ice concentration values of dates of first (last) ice each winter and ice duration (the difference between these dates) was made for each winter season. The original ice charts had ice concentration recorded to the nearest 10%. The analysis was made on nine overlapping threshold ice concentration values in 10% increments starting from ice concentration ≥10%, and ending at ice concentrations ≥90% (i.e., ≥10%, ≥20%, ≥30%, ≥40%, ≥50%, ≥60%, ≥70%, ≥80%, ≥90%). A grid search of over-water cells, cell by cell, was made on the original ice chart grids for each winter to determine the first (last) observed date for each of the nine threshold values of ice concentration at each grid cell. *These dates of observed first (last) ice may not be the* ***actual*** *date that ice* ***first formed*** *and* ***actual last date*** *of ice because this analysis is limited by the dates of the first and last ice charts of each winter and the fact that daily observations were not made.* However, it is likely that for most of the Great Lakes surface, the actual date of first ice occurred somewhere between the date of the first ice chart, and the ice chart that has the observed threshold value of ice concentration. This is true because on the date of the first ice chart, most of the Great Lakes are usually open water or ice free. A similar comment is true for the date of last ice cover. Additional information and details on dates of first (last) ice and ice duration for the 30-winter base period (1973-2002) are given in Assel (2003b).

Spatial lake-averaged ice cover is calculated for each Great Lake and for the Great Lakes as a whole for each ice chart given in Wang et al. (2012a) for each winter season. A grid encoding the grid cells for each lake was used to calculate the lake-averaged ice cover for each lake. That grid, given as a fixed formatted mask text file (GLmask2.txt for the 510 x 516 land mask and CW1024a.txt for the 1024 x 1024 land mask) is documented and available in Appendix A-3 of Wang et al. (2012a). All grid cell ice concentrations for a given lake for a given date are summed and a lake average is then calculated by dividing the sum by the total number of grid cells for that lake. Line plots of lake-averaged ice cover for a given lake and winter season represent general linear trends in the daily lake averaged time series. *It should be cautioned that the true lake-averaged ice cover trend may vary from those given by the line plots as weather conditions can affect ice cover greatly between consecutive observed ice charts.*

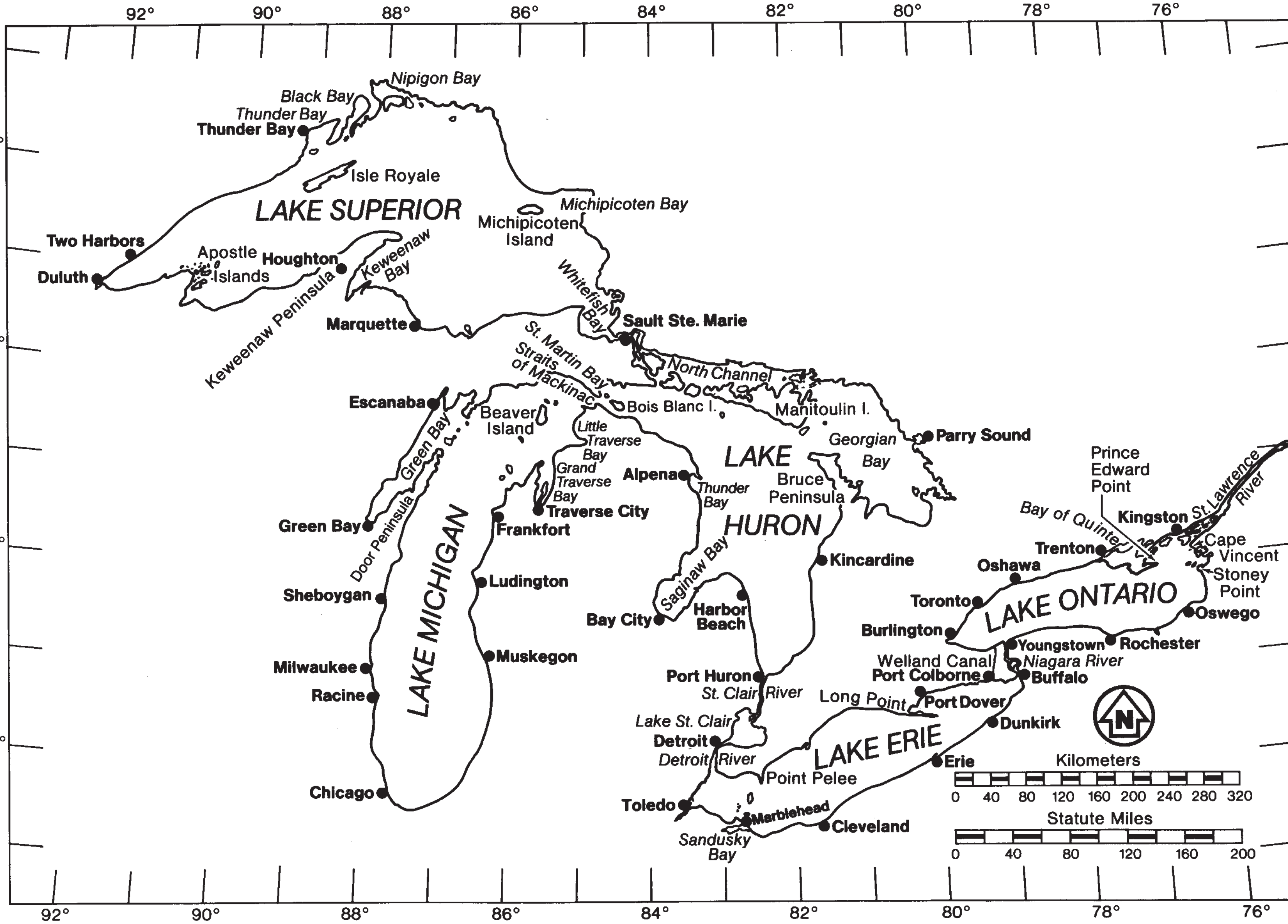
Assel (2005a,b) produced ice anomaly charts for each winter from 1973 to 2005. Ice anomaly charts were produced for each ice chart of the winter by calculating the difference (for each over water grid cell) between the 30-winter (1973-2002) weekly median ice concentration grid and the ice concentration grid for a date that corresponds to the mid-week day of the weekly median (e.g., the 30-winter weekly median ice chart for January 12-18 would be used to calculate the ice anomaly chart for an ice chart dated January 15). In a similar manner, ice anomaly charts were produced from the ice charts given in Wang et al. (2012a) for the six winters of the update period. Ice anomaly charts provide a metric of the trends in ice cover over any date in a given winter season relative to the 30-winter base period. Positive (negative) differences occur when the ice chart for a given winter has ice cover concentration greater (less) then the 30-winter median.

4. PRODUCTS AND DISCUSSION

Analysis products are summarized in a series of line plots (for lake averaged ice cover) and charts for: 1) dates of first (last) ice and ice duration, 2) daily ice concentration, and 3) daily ice concentration anomalies. ASCII text files containing integer codes for ice are also produced for all the data given in the graphic plot file products. Data and file documentation for: 1) the dates of first (last) ice and ice duration are given in Appendix 1; plots and tables of daily lake-averages are given in Appendix 2; daily ice cover anomaly plots and ASCII grids are given in Appendix 3. Seasonal and spatial trends are discussed below using selected data from these appendices. Many of the geographic locations cited in the remainder of this report are given in the Great Lakes place name chart for the reader's convenience.

5. DATES OF FIRST (LAST) ICE AND ICE DURATION

Ice concentration ≥ 10% (the boundary between ice and open water) for dates of first (last) ice and ice duration, respectively are portrayed in Figures 1-3, and trends are summarized.


92°
90°
88°
86°
84°
82°
80°
78°
76°
48°
46°
44°
42°
Nipigon Bay
Black Bay
Thunder Bay
Thunder Bay
Isle Royale
LAKE SUPERIOR
Michipicoten Bay
Michipicoten Island
Two Harbors
Apostle Islands
Houghton
Duluth
Keweenaw Bay
Keweenaw Peninsula
Marquette
Whitefish Bay
Sault Ste. Marie
St. Martin Bay
Straits of Mackinac
North Channel
Bois Blanc I.
Manitoulin I.
Escanaba
Beaver Island
Little Traverse Bay
Grand Traverse Bay
Green Bay
Georgian Bay
Parry Sound
LAKE HURON
Bruce Peninsula
Alpena
Thunder Bay
Traverse City
Frankfort
Green Bay
Door Peninsula
LAKE MICHIGAN
Prince Edward Point
Bay of Quinte
Kingston
St. Lawrence River
Trenton
Cape Vincent
Kincardine
Saginaw Bay
Oshawa
Stoney Point
Ludington
Sheboygan
Toronto
LAKE ONTARIO
Oswego
Bay City
Harbor Beach
Burlington
Youngstown
Rochester
Muskegon
Welland Canal
Niagara River
Milwaukee
Port Huron
Port Colborne
Buffalo
St. Clair River
Long Point
Port Dover
Racine
Lake St. Clair
Dunkirk
Detroit
LAKE ERIE
Detroit River
Erie
Point Pelee
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0 40 80 120 160 200
Sandusky Bay
N

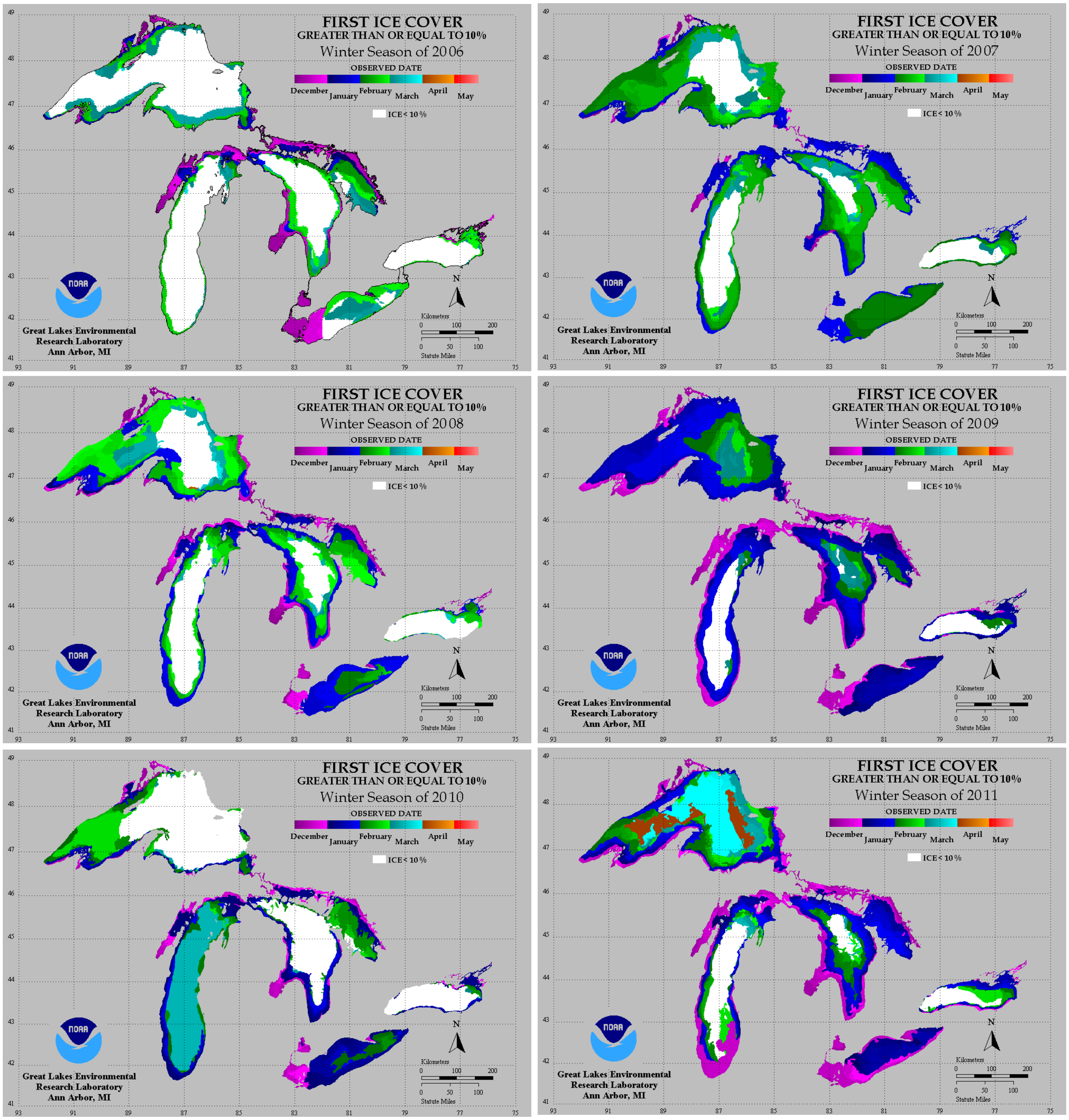

Figure 1. Dates of first reported ice ≥ 10%.

In general, shallow nearshore areas formed ice in December and January; deeper shore areas and most mid-lake areas formed ice in February and March, (Figure 1), April (2011) at some mid-lake areas of Lake Superior. December in winters 2009 (December 2008) and 2011 (December 2010) had largest shore and nearshore areas ice cover. Earliest most extensive mid-lake ice formed January 2009. Largest areas of open water (≤ 10% ice) occurred in winter 2006 (all lakes) and in winter 2010 (Lakes Superior and Huron).

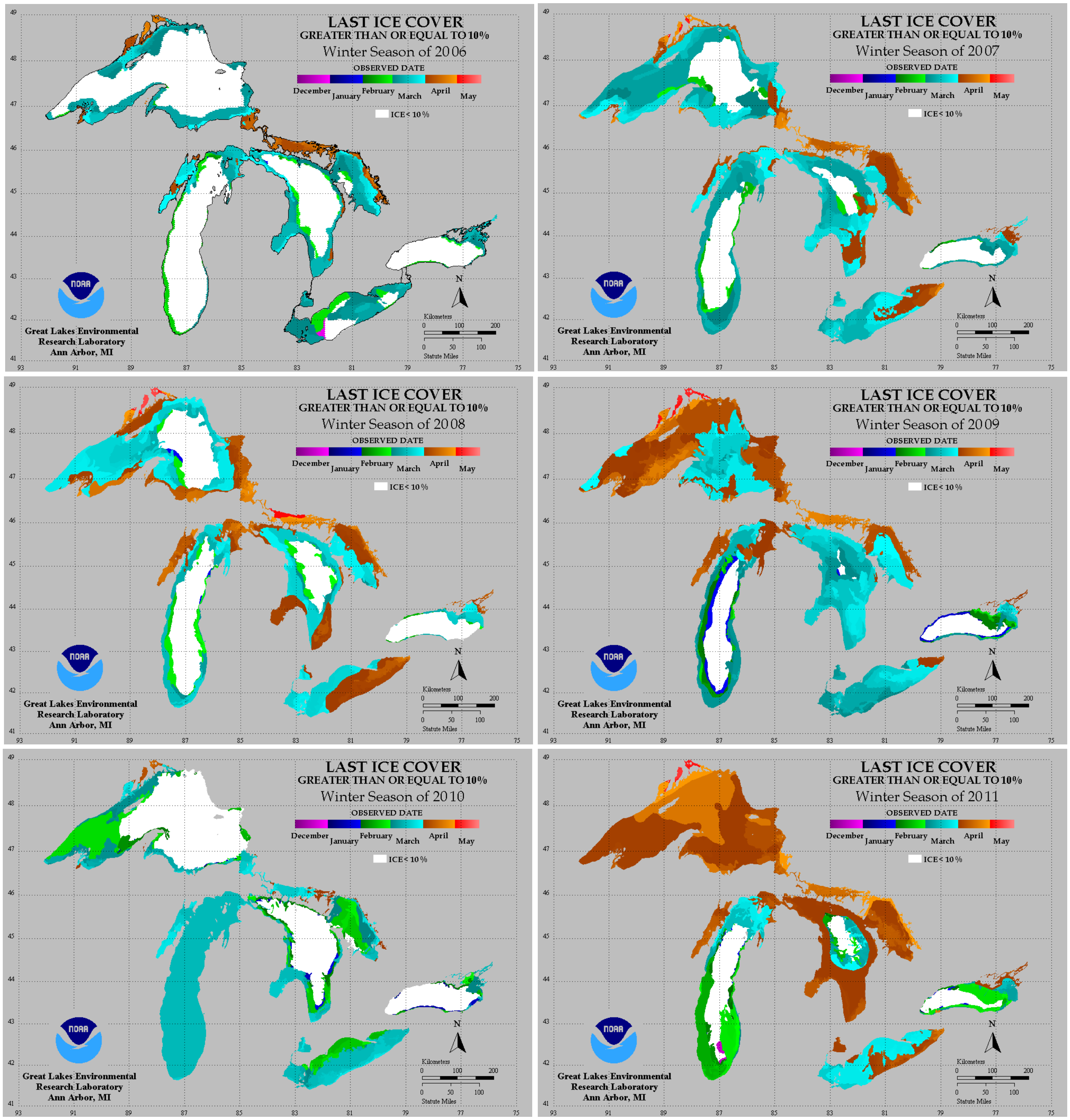

Figure 2. Dates of last reported ice ≥ 10%

Last reports of mid-lake ice cover ≥ 10% occurred in March over much of the Great Lakes (Figure 2), with last dates in February in western Lake Superior (2010), southern half of Lake Michigan (2011), north-central shore of Lake Erie (2010), and lake-ward of northeast shore of Lake Ontario (2009, 2011). Last reports of ice cover in April were most prevalent over Lake Superior (2011, 2009), Huron (2011), and western Lake Erie (2008). Bay ice lasted into May in northern Lake Superior (2007, 2008, 2009, and 2011) and North Channel of Lake Huron (2008).

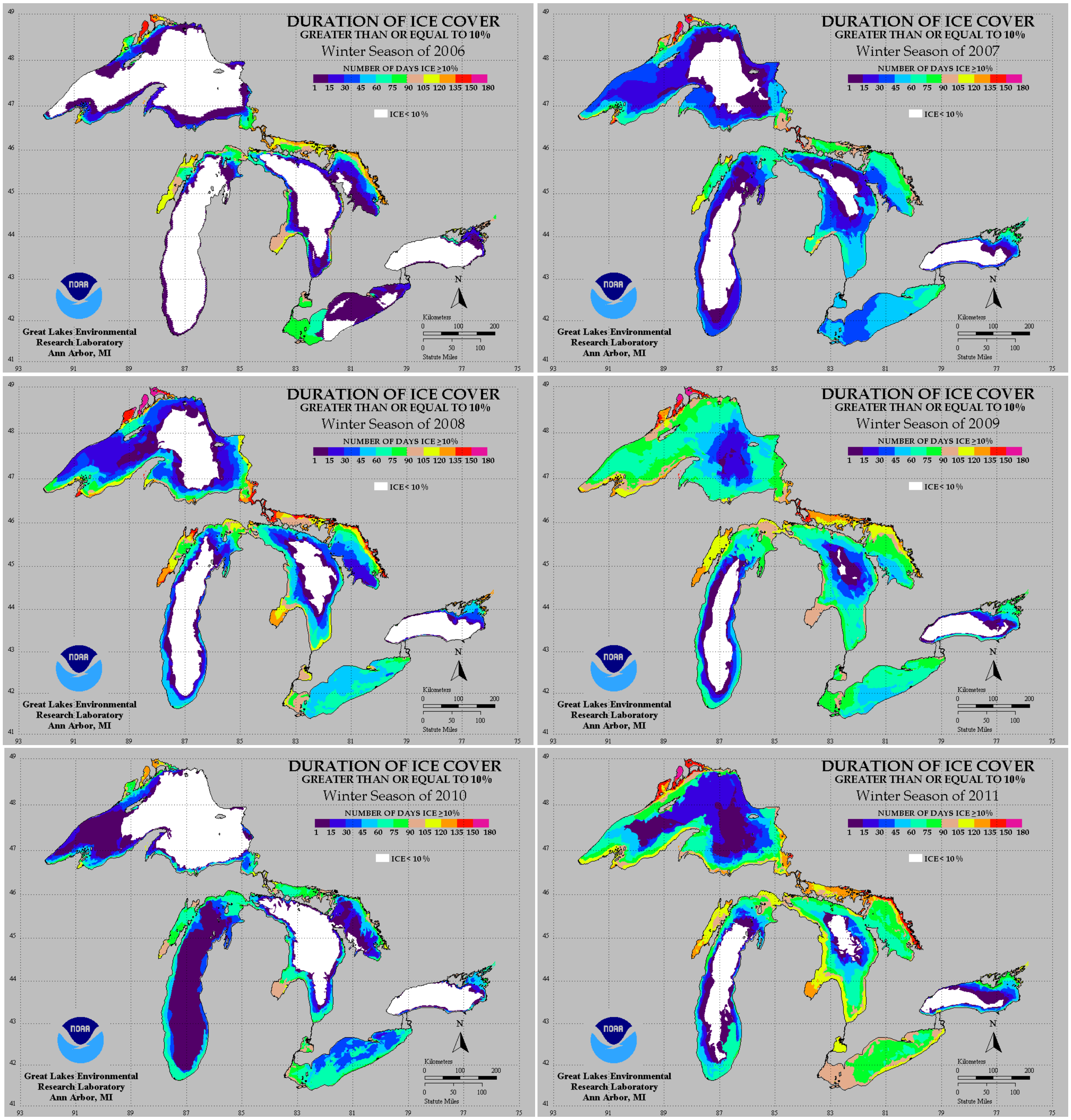

Figure 3. Duration of ice cover ≥ 10%.

Winter 2006 had the smallest area of ice cover duration for ice cover concentration ≥ 10%, and winter 2009 had the largest for the Great Lakes (Figure 3). Shallow shore areas of the Great Lakes had higher ice cover duration (> 90 days) compared to more exposed mid-lake areas (< 60 days most winters). The highest ice cover durations occurred in portions of Thunder, Black, Nipigon, and Whitefish Bays (Lake Superior, exceeded 150 days some winters), Green Bay (Lake Michigan exceeded 120 days some winters), St. Marys River (exceeded 135 days some winters), North Channel, Georgian Bay, and Saginaw Bay of Lake Huron (exceeded 120 days some winters), Lake St. Clair (exceeded 105 days some winters) the western basin of Lake Erie (exceeded 90 days some winters), and the southern Lake Erie shore (exceeded 105 days one winter).

6. SEASONAL PROGRESSION OF ICE COVER

The daily lake–averaged ice cover portrays the seasonal progression of the ice cycles. Charts of ice cover and charts of ice cover anomaly portray ice cover near the time of maximum ice cover for the Great Lakes as a whole are presented below. Detailed data are made available in Appendix 2 and Appendix 3.

6.1 The 2006 Great Lakes Ice Cycle

Ice cover was limited primarily to areas along the shores and in large bay of the Great Lakes in winter 2006 (Figure 4). Ice cover extent was near its seasonal maximum value in early March (Figure 5, Table 1). The seasonal maximum value ranked as the third (Great Lakes, Lake Erie) fourth (Lakes Superior, Michigan, Huron), and eighth (Lake Ontario) lowest over the 39 winters from 1973 to 2011. 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. Along the north shore, it extended lake-ward from the three large bays along the north shore to Isle Royale and covered Whitefish Bay in the east. Lake Michigan's Green Bay and the Straits to Bois Blanc Island had extensive ice cover; ice lined the perimeter of Lake Huron with high concentrations in the North Channel, the eastern half of Georgian Bay, and Saginaw Bay. Ice cover was extensive on Lake St. Clair. Lake Erie had disjointed ice cover in the western and central lake basins, and Lake Ontario had substantial ice cover in the north-eastern portion of that lake. Large negative ice cover anomalies extended over all of Lake Superior (with the exception of the mid-lake area of the eastern basin), over the western half of Georgian Bay and southern portions of the southern end of Lake Huron, and again over virtually all of Lake Erie. Lake Ontario had positive ice cover anomalies in the north-eastern quadrant of that lake in early March. Most of the Great Lakes ice had dissipated by the end of March (Figure 2). Ice in some bay areas lasted into April.

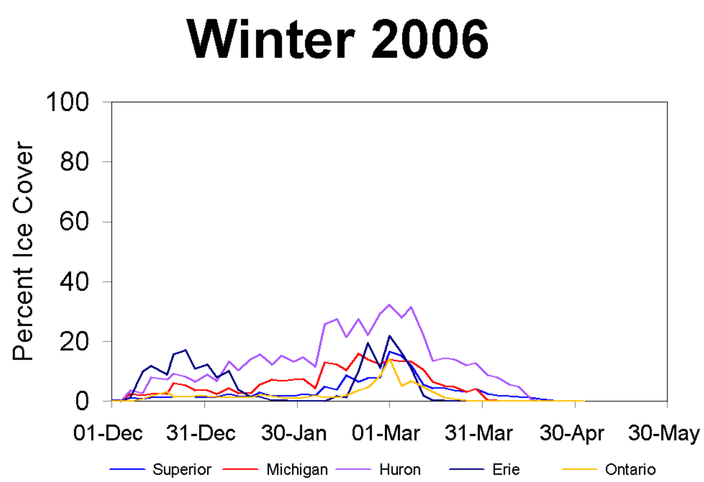

Figure 4. Daily lake-averaged ice cover winter 2006.

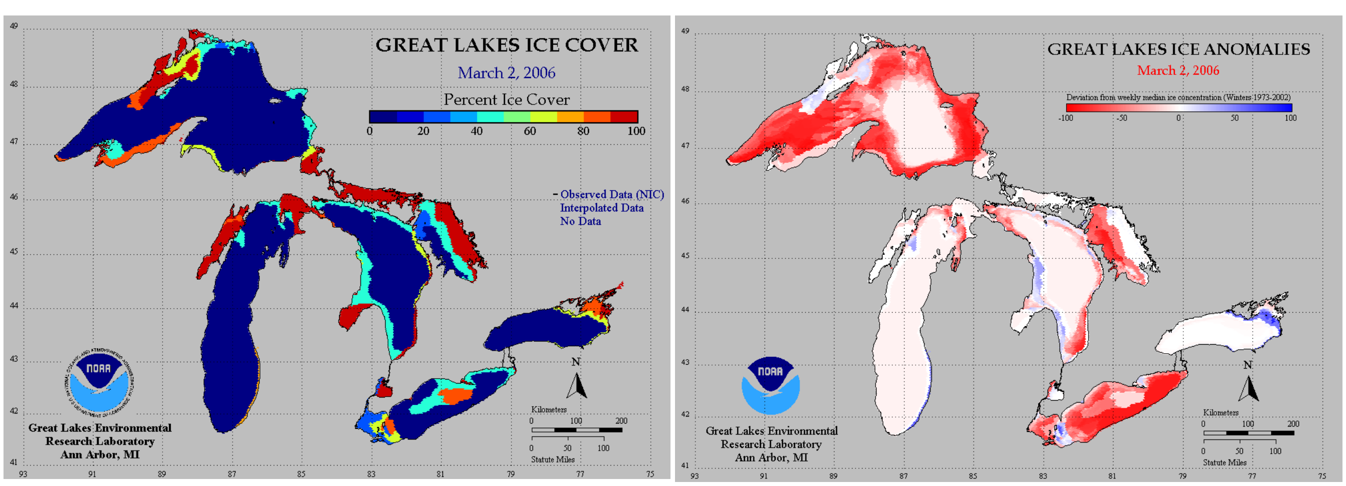

Figure 5. Maximum ice cover and ice anomaly charts winter 2006.

6.2 The 2007 Great Lakes Ice Cycle

Ice cover was more extensive in winter 2007 (Figure 6) relative to the previous year (Figure 4). Ice cover was confined primarily to shore and near shore in January. A large increase in ice occurred in February to reach near Annual Maximum Ice Cover (AMIC) values. Large decreases occurred in the last week of that month and early March. Lower air temperatures late in the first week of March resulted in the Great Lakes being at or near their AMIC near the beginning of the second week of March (Figure 7). The AMIC of the Great Lakes (55.2%) ranked 18th out of 39 winters and so can be thought of as typical, i.e., not extreme (Table 1). At that time, extensive ice covers were located in (1) the west basin and lake ward of the shore of the east basin of Lake Superior, (2) Green Bay, (3) much of the lake north of the north end of Grand Traverse Bay and the perimeter of the south shore in Lake Michigan, (4) much of Lake Huron with the exception of the deeper mid-lake area between Alpena, Michigan and the Bruce Peninsula to the east, (5) all of Lake Erie, and (6) the northeast end of Lake Ontario. This ice cover had positive anomalies for much of the north shore of Lake Superior and the perimeters of the remaining Great Lakes and a negative anomaly lake-ward of the eastern basin and west of the Keweenaw Peninsula to the Apostle Islands in Lake Superior. The ice cover was short lived as warmer air temperatures brought a dramatic reduction in ice cover for Lake Superior and the northern third of Lakes Michigan and Huron by March 12. By mid-March, the ice dissipation period was well under way over the entire Great Lakes, and by the end of the March, the bulk of the ice was located in the three large bays along the north shore and Whitefish Bay in Lake Superior, and the North Channel and the southern portion of Georgian Bay in Lake Huron; ice of lower concentration remained in the southern end of Lake Huron and in the eastern half of Lake Erie.

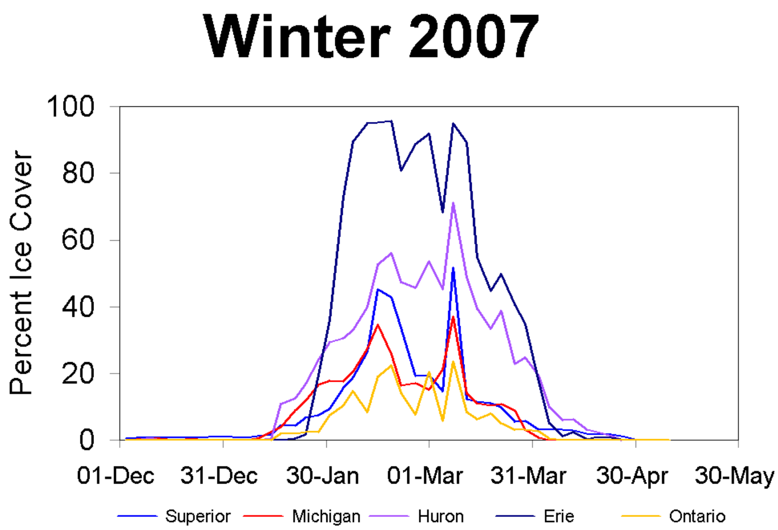

Figure 6. Daily lake-averaged ice cover winter 2007.

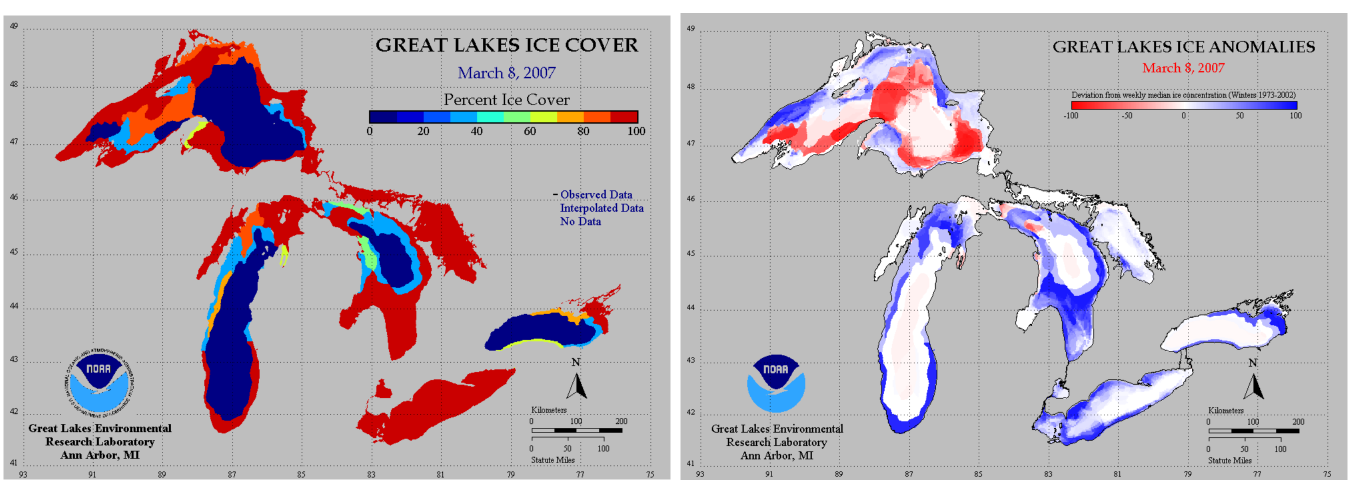

Figure 7. Maximum ice cover and ice anomaly charts winter 2007.

6.3 The 2008 Great Lakes Ice Cycle

Winter 2008 was similar to winter 2007. Ice formed in the shore areas and the west basin of Lake Erie in December and became more extensive in January (Figure 1). Mid-lake ice formations began in February. The maximum ice cover for the individual Great Lakes occurred on February 21 (Lake Michigan), March 10 (Lakes Superior, Erie, Ontario), and March 17 (Lake Huron). The seasonal maximum ice cover for the Great Lakes as a whole occurred on March 10 (Figure 8, Figure 9). The AMIC, 53.7%, ranked 17th from the lowest and was similar to winter 2007 (Table 1). At the time of maximum ice cover for the Great Lakes as a unit, not for individual Great Lakes, Lake Erie was over 90% ice covered, Lake Superior was 62% ice covered -- the mid-lake east basin of Lake Superior had open water, Lake Huron was 57% ice covered -- ice extended out from the entire lake perimeter and covered the North Channel and Georgian Bay, Lake Michigan was 31% ice covered -- with mid-lake ice limited primarily north of Traverse City and shore ice more extensive along the west shore, Lake Ontario had 14% ice cover with the ice limited primarily to the northeastern end of the lake and much more limited ice along the lake's perimeter. At the time of maximum ice extent, the largest areas of positive ice cover anomalies were located in the western basin of Lake Superior, along much of the perimeter of Lake Huron, most of the west basin and extending to the north shore west of Long Point in Lake Erie, and in the extreme northeast end of Lake Ontario. Ice cover dissipated over the next month, by April 10, the bulk of the ice cover was located in the large bays of Lakes Superior and the northern bays in Lakes Huron and Michigan.

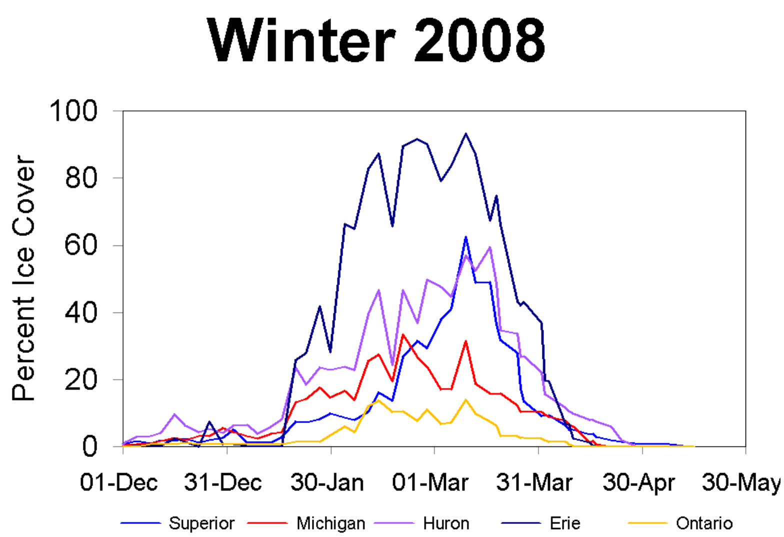

Figure 8. Daily lake-averaged ice cover winter 2008.

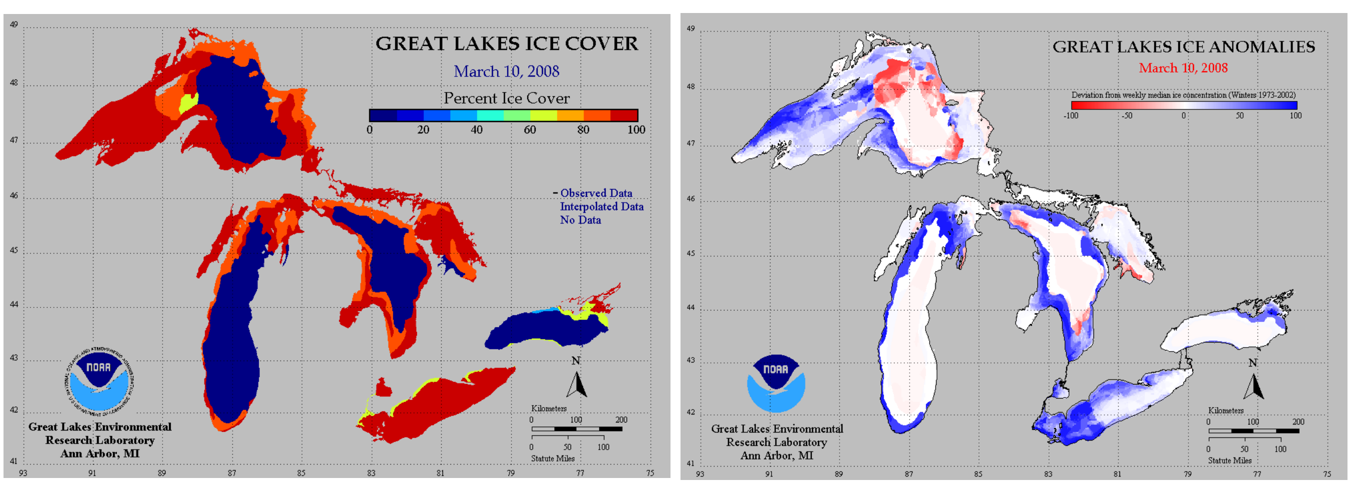

Figure 9. Maximum ice cover and ice anomaly charts winter 2008.

6.4 The 2009 Great Lakes Ice Cycle

Early winter ice cover was anomalously high in winter 2009. Ice formed in the mid-lake areas in January (Figure 1, Figure 10). Lake Erie was over 90% ice covered by mid month, and anomalies continued to be positive through the last week of January, e.g. Figure 11. Lake-averaged ice covers were at or near seasonal maximums on four of the Great Lakes from January 29 to February 2: January 29 (Lake Michigan, 52.3%), February 2 (Lake Huron 73%, [not maximum], Lake Erie 95.5%, and Ontario 25.9%). The seasonal maximum ice cover for the Great Lakes as a whole took place about one month later, March 2 (73.9%), and was ranked 31st from the lowest ice cover or the 9th from the highest ice cover over the 39 winters under study (Table 1). On March 2, lake-averaged ice cover on the individual Great Lakes was 93.6% on Lake Superior, 42.1% on Lake Michigan, 85.1% on Lake Huron, 95.0% on Lake Erie, and 8.4% on Lake Ontario. Ice cover anomalies on March 2 were positive and most extensive in the east basin of Lake Superior, the main body of Lake Huron, and portions of the north end and the south shores of Lake Michigan (Figure 12). Ice covers dissipated over mid-lake areas during March. Ice lasted to early April in western Lake Superior. By April 27, the only significant ice cover was in three bays along Lake Superior's north shore.

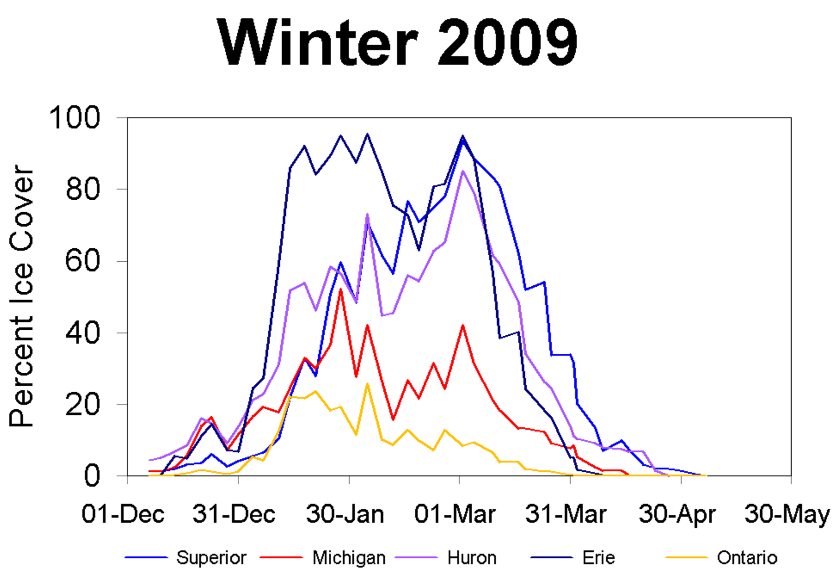

Figure 10. Daily lake-averaged ice cover winter 2009.

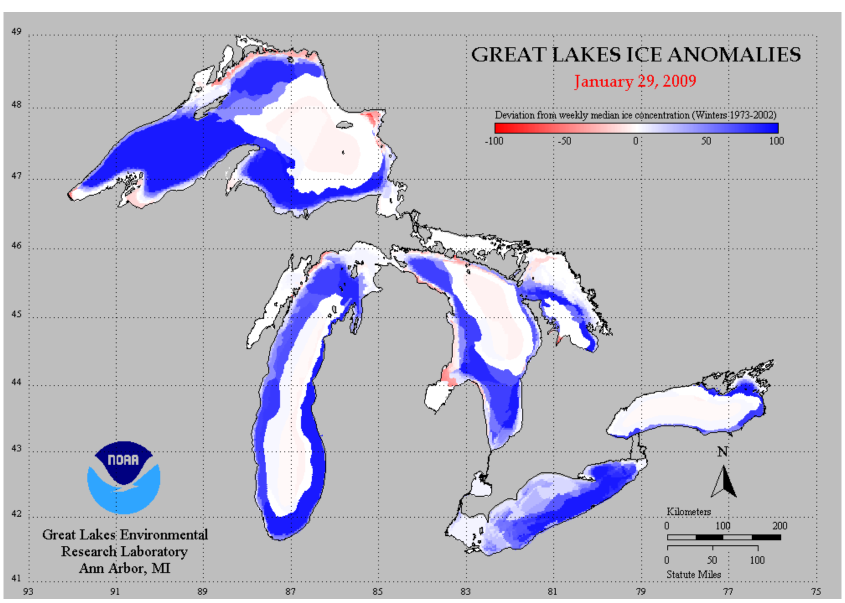

Figure 11. January 29, 2009 ice cover anomalies.

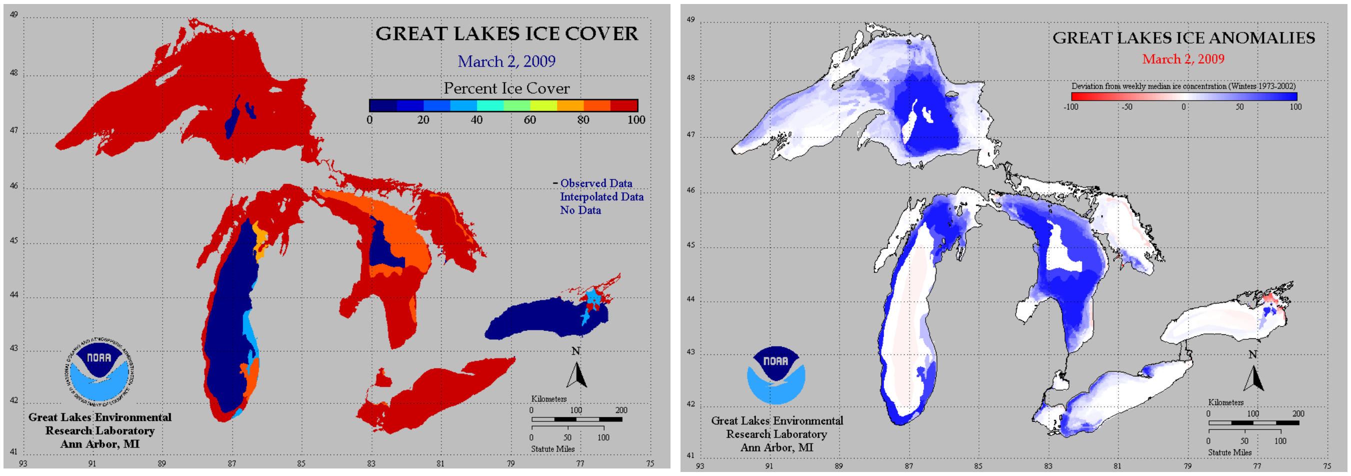

Figure 12. Maximum ice cover and ice anomaly charts winter 2009.

6.5 The 2010 Great Lakes Ice Cycle

The 2010 ice cycle was mild, the mid-lake areas of the Great Lakes remained open water most of the winter. Ice formed in the western basin of Lake Erie and the shore regions of large bays of the Great Lakes in December, in deeper areas of large bays and in general along the perimeter of the Great Lakes and the central basin of Lake Erie in January, in the mid-lake west basin of Lake Superior, most of Georgian Bay, and deeper areas of central and east Lake Erie in February, and much of Lake Michigan in March (Figure 1). The Great Lakes AMIC (27.4%) ranked as the 7th from the lowest over the 39 winters 1973-2011 (Figure 13, Figure 14, Table 1) and occurred on February 8. Lakes Michigan (23.5%), Huron (34.6%), Erie (93.1%) and Ontario (13.1%) were at or near their seasonal maximum value on February 8. Lake Superior was at its seasonal maximum value (27.3%) two weeks later on February 22. At the time of maximum ice extent of the entire Great Lakes (Figure 14) ice cover was limited primarily to the perimeter of the Great Lakes, with the exception of Lake Erie. The nearshore regions of Lake Superior and northern Lake Huron had negative ice cover anomalies, while the southern shore region of Lake Michigan had positive ice cover anomalies (Figure 14). Ice cover declined over the Great Lakes during the remainder of February and into March. A dramatic loss of ice cover occurred on Lake Erie on March 14 (Figure 13) due to an intense low pressure system passing in the southern Great Lakes region that brought warmer temperatures and high winds, see Appendix 4 for surface temperature, wind and pressure fields March 13-14. By the end of March, the Great Lakes were ice free with the exception of very limited amounts of ice in the shore areas and bays of Lake Superior and the North Channel and Georgian Bay in Lake Huron.

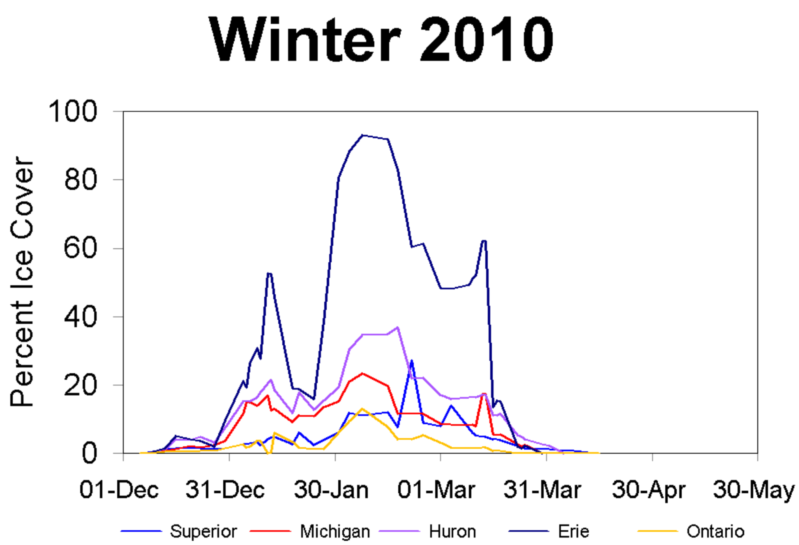

Figure 13. Daily lake-averaged ice cover winter 2010.

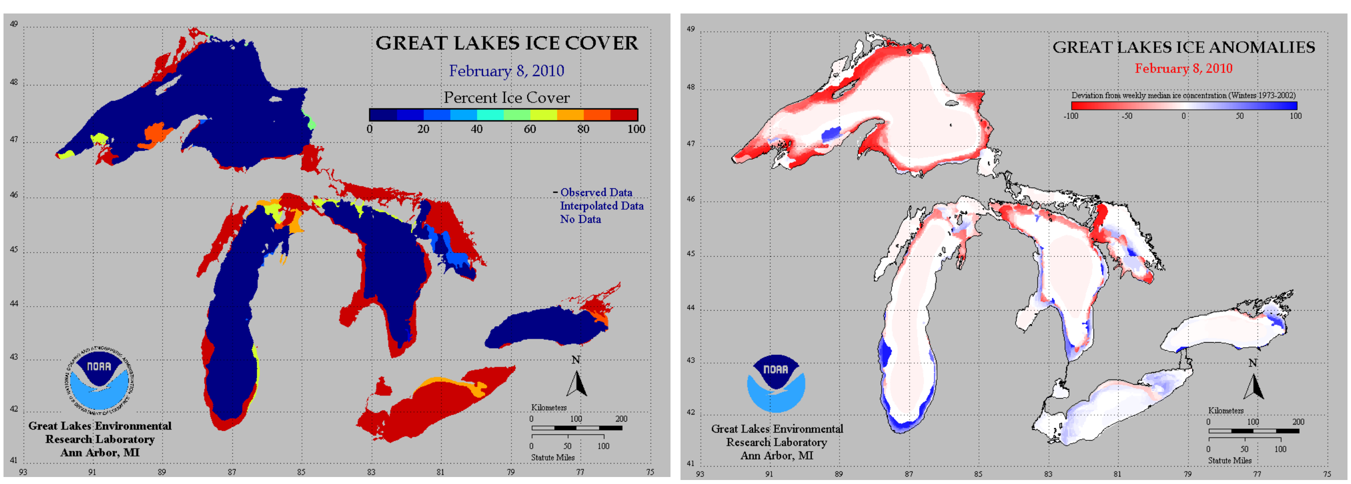

Figure 14. Maximum ice cover and ice anomaly charts winter 2010.

6.6 The 2011 Great Lakes Ice Cycle

The temporal variability of daily lake averaged ice cover is better defined in 2011 (Figure 15) relative to the other five winters (Figures 4, 6, 8, 10, 13) because of the greater number of observations that winter (151). Large areas of initial ice formation occurred in December and were unusually extensive for the southern end of Lake Michigan and southern shore of Lake Erie relative to the other winters (Figure 1). Lake Erie was near 70% ice covered by mid-January and at its maximum ice cover by February 1. The Great Lakes as a whole and Lake Michigan reached maximum ice cover (40.1%, 29.4% respectively) on February 11, this was the 11th from the lowest maximum ice cover (Table 1); Lake Superior had 26% ice cover that date. At maximum ice cover negative ice anomalies occurred in the Great Lakes (Figure 16) primarily in: Lake Superior, northern Lake Michigan, Lake Huron (Georgian Bay); notable positive ice anomalies occurred: north of the Apostle Islands in Lake Superior, along the south half of the west shore, and along the south shore Lake Michigan (south of 44th parallel), lake-ward of the west shore of Lake Huron, and along the south shore of Lake Ontario. A large decline in ice cover occurred on the Great Lakes in mid February (Figure 15) due to the passage of a strong low pressure system February 13-14, see Appendix 4. Ice cover increased after that time and maximum ice covers for Lakes Huron (63.8%) and Ontario (31.1%) occurred on February 24, Lake Superior was at 29.2% (March 8) but did not reach it seasonal maximum of 33.6% until April 2 due to extensive short lived new ice formation in late March-early April. In general ice covers declined during March; by mid April the Great Lakes were virtually ice free except for the three large north shore bays of Lake Superior, where it lasted until May 10.

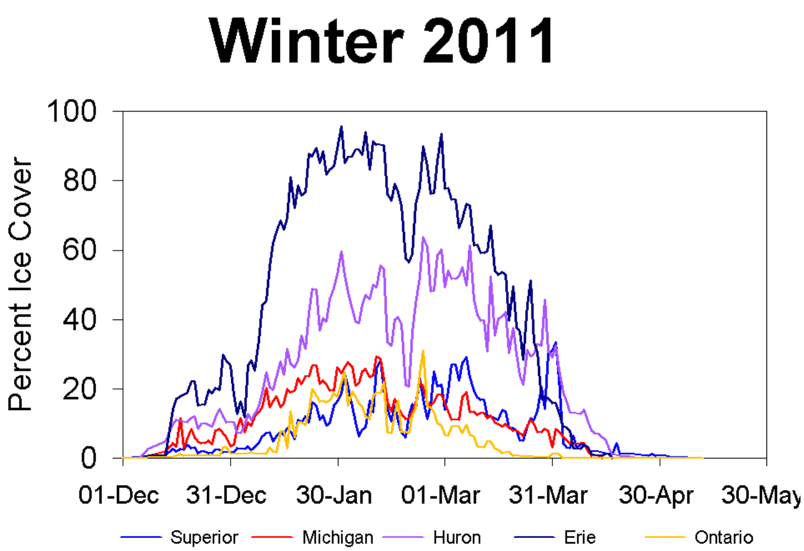

Figure 15. Daily lake averaged ice cover, winter 2011.

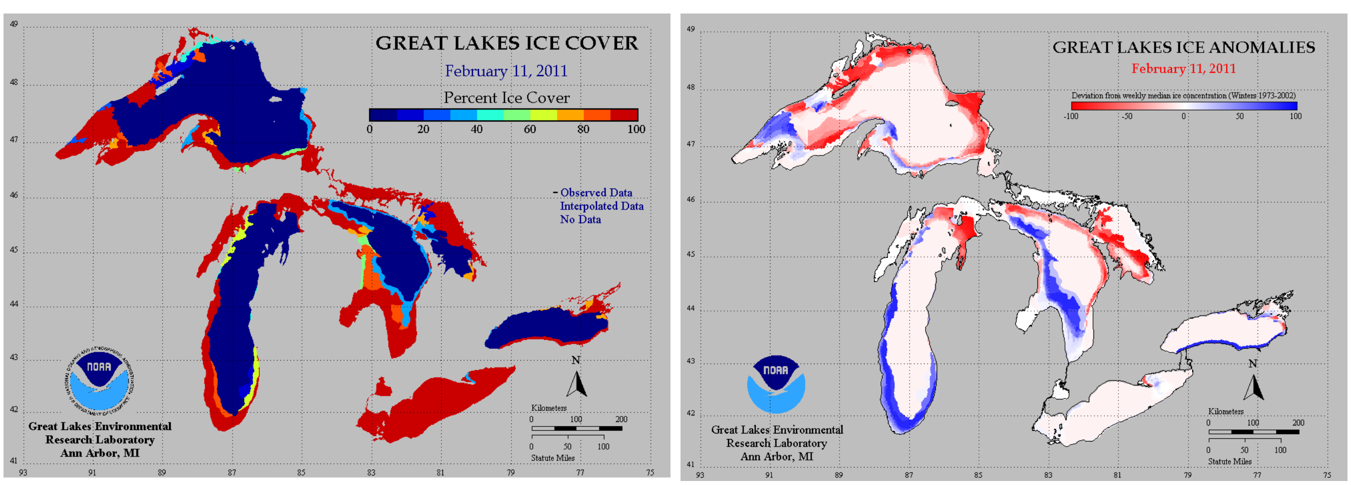

Figure 16. Maximum ice cover and ice anomaly charts winter 2011.

Table 1. Annual Maximum Ice Cover (AMIC) Lowest to Highest Winters 1973 - 2011

	Great Lakes		Lake Superior		Lake Michigan		Lake Huron		Lake Erie		Lake Ontario		
Rank	Year	AMIC	Year	AMIC	Year	AMIC	Year	AMIC	Year	AMIC	Year	AMIC	Rank
1	2002	11.8	2002	10.3	1973	33.0	2002	26.1	1998	5.4	2002	4.0	1
2	1998	14	1998	11.1	2002	12.4	1998	28.6	2002	14.4	1998	6.2	2
3	2006	20	1987	14.5	1998	15.1	1983	31.8	2006	21.9	1987	8.4	3
4	1983	22.1	2006	16.6	2006	15.8	2006	31.9	1983	40.8	1983	12.5	4
5	1999	26.2	1999	18.3	1987	20.0	1999	36.0	1991	44.4	2010	13.1	5
6	1987	27.3	1983	20.2	1999	23.0	2010	36.9	1999	74.8	1991	13.6	6
7	2010	27.4	2010	27.3	2010	23.5	2000	41.9	1975	80.1	2008	14	7
8	2001	34.4	2000	33.5	1983	23.6	1987	43.5	1990	85.5	2006	14.1	8
9	2000	34.8	2011	33.6	1995	23.7	2001	45.7	1987	88.0	1975	14.9	9
10	1976	39.9	1995	43.9	1991	25.8	1991	50.5	1974	88.5	1976	15.2	10
11	2011	40.1	2001	46.7	2000	27.2	1976	52.5	2000	90.7	1989	17.7	11
12	2005	43.3	1976	49.9	1975	28.1	1975	55.1	1988	91.5	1999	17.9	12
13	1995	46.4	2007	51.8	2011	29.4	2005	58.9	2005	93.0	2001	17.9	13
14	1975	50.2	2004	52.2	2005	29.4	2008	59.5	2010	93.1	1992	21.1	14
15	2004	51.7	2005	54.5	2001	29.5	1995	59.7	2008	93.4	1988	21.1	15
16	1988	53.6	2008	62.7	1976	29.5	1988	60.1	1980	93.4	1995	21.7	16
17	2008	53.7	1975	64.9	1988	32.7	1974	61.4	2001	94.0	2000	22.3	17
18	2007	55.2	1988	67.3	2008	33.5	2011	63.8	1992	94.1	2007	23.8	18
19	1991	56.5	1973	69.8	1989	36.3	2004	64.5	1989	95	1974	24.5	19
20	1997	58.4	1974	73.8	2004	36.4	1997	65.3	1993	95.2	1997	25.6	20
21	1974	58.7	1980	77.2	1993	36.4	1973	66.7	2004	95.4	2009	25.9	21
22	1973	60.6	1993	80.3	2007	37.2	1980	70.3	1976	95.4	1980	30.6	22
23	1980	62.8	1992	80.8	1997	37.8	2007	71.4	1986	95.5	2011	31.1	23
24	1984	65.2	1990	81.7	1980	38.6	1986	73.5	2009	95.5	1993	34.3	24
25	1992	67.8	1985	81.9	1974	39.4	1990	75.3	1973	95.7	1990	35.1	25
26	1993	68.2	1981	84.7	1985	41.3	1992	76	2003	95.7	2005	37.8	26
27	1990	69.2	1982	85.3	1992	42.2	1984	77.6	1984	95.7	1985	38.2	27
28	1985	69.8	1989	87.5	1984	43.3	1993	79.4	1995	95.8	2004	38.5	28
29	1989	71.2	1984	88.2	1990	46.9	2009	85.1	2007	95.8	1984	40.7	29
30	1981	71.3	1997	89.0	2003	48.0	1989	86.3	2011	95.8	1986	43.7	30
31	2009	73.9	1986	90.7	2009	52.3	1985	87.4	1985	96.0	1996	45.1	31
32	1982	74.8	1991	91.3	1981	53.8	1982	93.3	1981	96.0	1977	46.7	32
33	1986	76.4	1978	92.5	1982	60.2	1981	93.8	1982	99.1	1981	47.6	33
34	2003	79.1	2009	93.6	1978	66.6	1977	95.0	1997	99.6	2003	49.6	34
35	1996	81.7	2003	95.5	1986	66.8	1978	95.8	1977	99.8	1982	50.7	35
36	1978	83	1977	96.0	1996	75.0	2003	96.2	1994	99.8	1978	57.7	36
37	1977	89.9	1994	96.7	1994	90.6	1979	96.4	1979	100.0	1973	62.6	37
38	1979	94.7	1979	97.1	1979	92.3	1996	98.2	1996	100.0	1994	79.7	38
39	1994	94.8	1996	100.0	1977	93.1	1994	98.5	1978	100.0	1979	86.2	39

The sources of AMIC are lake averages from Assel (2003a), Assel (2005a), and calculated from original ice charts from Wang et al. (2012a). AMIC values between 1989 and 1995 in Assel (2003a) were previously calculated by averaging CIS and NIC daily lake-averaged data. Here we used the original ice charts to calculate AMIC.

7. CONCLUSIONS

The description of the dates of first (last) ice, ice duration, and ice cycles given above is only a small portion of the detailed data available in the appendices and provides a very limited look at the annual ice cycle for each winter and a comparison with a the 30-winter climatology.

The differences in the timing of first (last) ice and ice duration for the relatively mild 2006 winter compared to the relatively severe 2009 ice cycle suggests that there may be corresponding signals in the biological, geochemical, or physical process in the winter and early spring lake ecosystem that relate to the differences in ice cover during these two winters. Schwab et al. (2006) and Eadie et al. (1996) provide evidence that the date of ice cover loss in late winter - early spring affects sediment resuspension and the timing of the spring coastal plume in southern Lake Michigan.

Recent research by Bai et al. (2010, 2012) and Wang et al. (2012b) provide evidence that these data are useful in the analysis of the inter-annual ice cover variability relative to teleconnection patterns in the ocean and 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, 2005b,c, 2004, 2003b, 1998), Assel et al. (2004, 2003), Assel and Norton (2001), Assel and Rodionov (1998), and Rodionov et al. (2001).

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APPENDIX 1. DATES OF FIRST ICE, LAST ICE, AND ICE DURATION

File names for the date of first reported ice (FST), last reported ice (LST), and ice duration (DUR) are listed below. Download Appendix 1.

COMPRESSED	UNCOMPRESSED Names	No. files
FSTYYGRID.ZIP	FSTYYMM.DAT	9
FSTYYPLOT.ZIP	FSTYYMM.GIF	9
LSTYYGRID.ZIP	LSTYYMM.DAT	9
LSTYYPLOT.ZIP	LSTYYMM.GIF	9
DURYYGRID.ZIP	DURYYMM.DAT	9
DURYYPLOT.ZIP	DURYYMM.GIF	9

Where: FST (LST) = first (last) reported ice file, DUR= ice cover duration in days. GRID = ASCII data file, PLOT = ice chart plot file, YY = year (06, 07, 08, 09, 10, 11), MM = threshold, for first (last) reported date and ice duration.

First Ice Cover Plots (ice concentration ≥: 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, 90%)
Last Ice Cover Plots (ice concentration ≥: 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, 90%)
Ice Duration Plots (ice concentration ≥: 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, 90%)

GRID File Structure

Winter 2006: There are 510 records; each record has 516 “cells” in an I3 format, where I3 = an integer.
Winters 2007-2011: There are 1024 records; each record has 1024 “cells” in an I3 format, where I3 = an integer.

GRID Data Codes

Code = -1 (land), code = 0 (ice cover concentration is less than the threshold value), code = 1 to 182 (date that the ice cover concentration threshold value was first (or last) observed, or for ice duration, this is the number of days between first and last reported ice cover. If the first and last date are the same, the duration is 1, if there was no ice cover for the given ice concentration value, the duration is 0. For example, if the date code for a single grid cell on a file of “first date ice cover greater or equal to 90%” was 63, that corresponds to a date of February 1; if the date code for a single grid cell on a file of “last date ice cover greater or equal to 90%” was 122, that corresponds to a date of April 1. See Table 1 below for a complete list of the first / last date codes and associated dates.

Table A1. Summary of the first ice and lst ice date codes and associated calendar dates*											
Day Code		Day Code		Day Code		Day Code		Day Code		Day Code	
001	Dec 1	032	Jan 1	063	Feb 1	091	Mar 1	122	Apr 1	152	May 1
002	Dec 2	033	Jan 2	064	Feb 2	092	Mar 2	123	Apr 2	153	May 2
003	Dec 3	034	Jan 3	065	Feb 3	093	Mar 3	124	Apr 3	154	May 3
004	Dec 4	035	Jan 4	066	Feb 4	094	Mar 4	125	Apr 4	155	May 4
005	Dec 5	036	Jan 5	067	Feb 5	095	Mar 5	126	Apr 5	156	May 5
006	Dec 6	037	Jan 6	068	Feb 6	096	Mar 6	127	Apr 6	157	May 6
007	Dec 7	038	Jan 7	069	Feb 7	097	Mar 7	128	Apr 7	158	May 7
008	Dec	039	Jan 8	070	Feb 8	098	Mar 8	129	Apr 8	159	May 8
009	Dec 9	040	Jan 9	071	Feb 9	099	Mar 9	130	Apr 9	160	May 9
010	Dec 10	041	Jan 10	072	Feb 10	100	Mar 10	131	Apr 10	161	May 10
011	Dec 11	042	Jan 11	073	Feb 11	101	Mar 11	132	Apr 11	162	May 11
012	Dec 12	043	Jan 12	074	Feb 12	102	Mar 12	133	Apr 12	163	May 12
013	Dec 13	044	Jan 13	075	Feb 13	103	Mar 13	134	Apr 13	164	May 13
014	Dec 14	045	Jan 14	076	Feb 14	104	Mar 14	135	Apr 14	165	May 14
015	Dec 15	046	Jan 15	077	Feb 15	105	Mar 15	136	Apr 15	166	May 15
016	Dec 16	047	Jan 16	078	Feb 16	106	Mar 16	137	Apr 16	167	May 16
017	Dec 17	048	Jan 17	079	Feb 17	107	Mar 17	138	Apr 17	168	May 17
018	Dec 18	049	Jan 18	080	Feb 18	108	Mar 18	139	Apr 18	169	May 18
019	Dec 19	050	Jan 19	081	Feb 19	109	Mar 19	140	Apr 19	170	May 19
020	Dec 20	051	Jan 20	082	Feb 20	110	Mar 20	141	Apr 20	171	May 20
021	Dec 21	052	Jan 21	083	Feb 21	111	Mar 21	142	Apr 21	172	May 21
022	Dec 22	053	Jan 22	084	Feb 22	112	Mar 22	143	Apr 22	173	May 22
023	Dec 23	054	Jan 23	085	Feb 23	113	Mar 23	144	Apr 23	174	May 23
024	Dec 24	055	Jan 24	086	Feb 24	114	Mar 24	145	Apr 24	175	May 24
025	Dec 25	056	Jan 25	087	Feb 25	115	Mar 25	146	Apr 25	176	May 25
026	Dec 26	057	Jan 26	088	Feb 26	116	Mar 26	147	Apr 26	177	May 26
027	Dec 27	058	Jan 27	089	Feb 27	117	Mar 27	148	Apr 27	178	May 27
028	Dec 28	059	Jan 28	090	Feb 28	118	Mar 28	149	Apr 28	179	May 28
029	Dec 29	060	Jan 29			119	Mar 29	150	Apr 29	180	May 29
030	Dec 30	061	Jan 30			120	Mar 30	151	Apr 30	181	May 30
031	Dec 31	062	Jan 31			121	Mar 31				May 31
* Note: For leap years, code 91 = Feb 29, code 92 = Mar 1 and so on.											

APPENDIX 2. LAKE AVERAGED ICE COVER TIME SERIES

Lake-averaged ice covers were calculated for each Great Lake each winter season for data given in Wang et al. (2012a). The time series for each winter begins on the date of the first ice chart and ends on the date of the last ice chart. Dates of first and last ice chart are summarized below for each winter season from Wang et al. (2012a).

Table 1. Summary of Ice Charts Date Statistics

Winter Season	Number of Charts	Date of First Ice Chart	Date of Last Ice Chart	Days Between First and Last Ice Chart	Average Number of Days Between Ice Charts
2006	46	28-Nov	04-May	157	3.43
2007	46	04-Dec	10-May	158	3.46
2008	55	26-Nov	15-May	171	3.13
2009	45	08-Dec	07-May	151	3.38
2010	46	07-Dec	15-Apr	130	2.85
2011	151	02-Dec	13-May	162	1.08

Lake Averages - spatial averages of ice cover for each Great Lake.

Composite line plots of lake averaged ice cover for all five Great Lakes (Superior, Michigan, Huron, Erie, and Ontario) for each winter are named **seaYY.BMP,** where YY is 06, 07, 08, 09, 10, and 11 for winters of 2006, 2007, 2008, 2009, 2010, and 2011 respectively. Note line plots of Lake St. Clair and the entire Great Lakes as a whole are not included in the composite plot each winter for the sake of clarity, these data are however given in text files.

Six text files (**avgYY.txt),** where YY is as defined above, are fixed formatted ASCII files of lake-averaged ice cover. The first record is a column heading listing the dates and lakes, the remaining records are the lake-averaged ice cover for each of the five Great Lakes, Lake St. Clair, and the Great Lakes taken as a whole. The appropriate data is under each of the header records. The header records for each winter season are:

Year Mo Da Jd Sup Mic Hur Stc Eri Ont GL

Where *Year* is the year, *Mo* is the month, *Da* is the day of the month, *Jd* is the Julian date, and *Sup Mic, Hur, Eri, Stc, Ont, and GLs,* are Lakes Superior, Michigan, Huron, Erie, St. Clair, Ontario, and the entire Great Lakes, respectively.

The number of over water grid cells used to calculate the lake-averaged ice cover for each great lake is summarized below for the 510 x 516 and the 1024 x 1024 grid masks given in Wang et al. (2012a).

	510 x 516	1024 x 1024
Superior	13850	54278
Michigan	8545	33510
Huron	9161	35402
St. Clair	157	575
Erie	3574	13897
Ontario	2801	10754
Great Lakes	38088	148416

APPENDIX 3. ICE COVER AND ICE COVER ANOMALY ICE CHARTS

Introduction

Ice charts showing the distribution pattern of ice cover concentration over the Great Lakes are provided below in a different format (color code) then given in Wang et al. (2012a). Also the daily median ice charts given in Assel (2005b) are used to calculate anomaly ice charts for the 2006-2011 winters as described in the report text. Click on the blue text below to download ice charts and anomaly ice chart.

Ice Charts

Ice charts are in compressed files organized by winter season.

Compressed Image File Names: YYYYgif.zip, where YYYY is the winter (2006…, 2011), "gif" defines the image format.

Image File Names: **YYYddd2.GIF**, where "YYY" = winter season, yyy=106 for 2006, 107 for 2007…111 for 2011; ddd = day of the winter season (101=Dec 1, ...132=Jan 1, …282=May 31), 2 is an indicator for observed ice chart.

Please note that one ice chart for winter 2006 and two ice charts for winter 2008 were not included because they occurred in November when very little ice was observed on the Great Lakes. These charts are, however, available in Wang et al. (2012a).

Anomaly Ice Charts

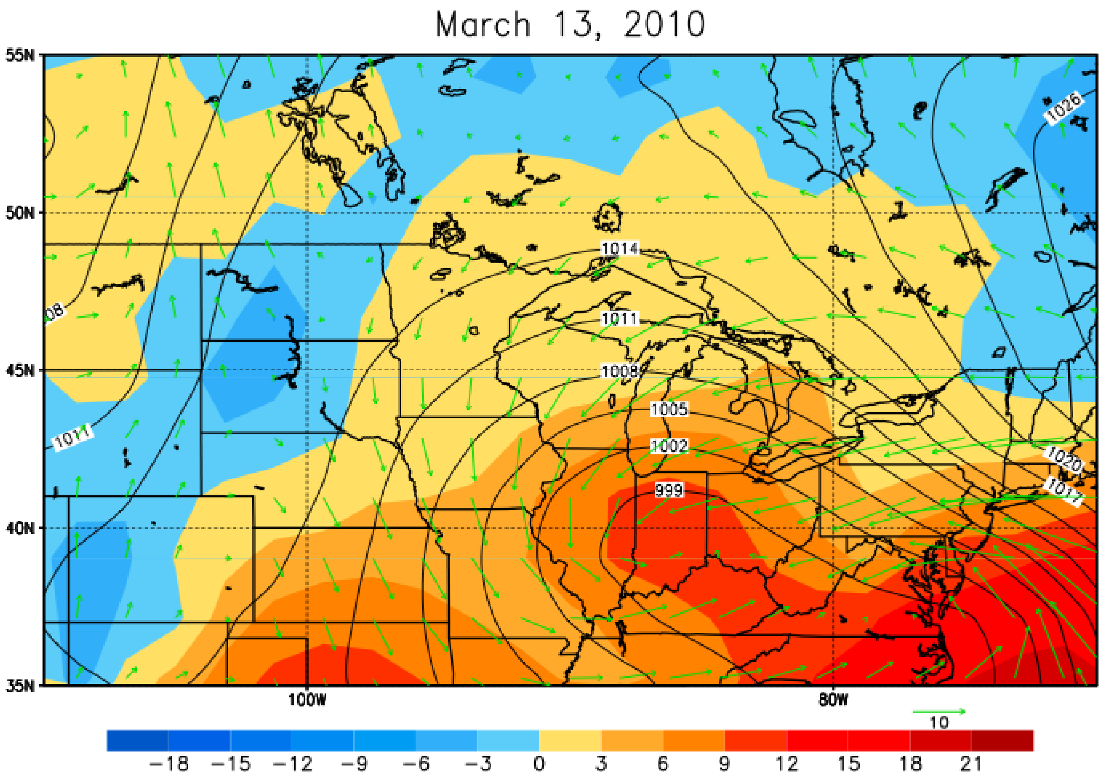
Charts that portray the spatial distribution patterns of ice concentration anomalies over the Great Lakes for a given date of a given winter. Anomaly ice charts are arranged by winter season in compressed files.

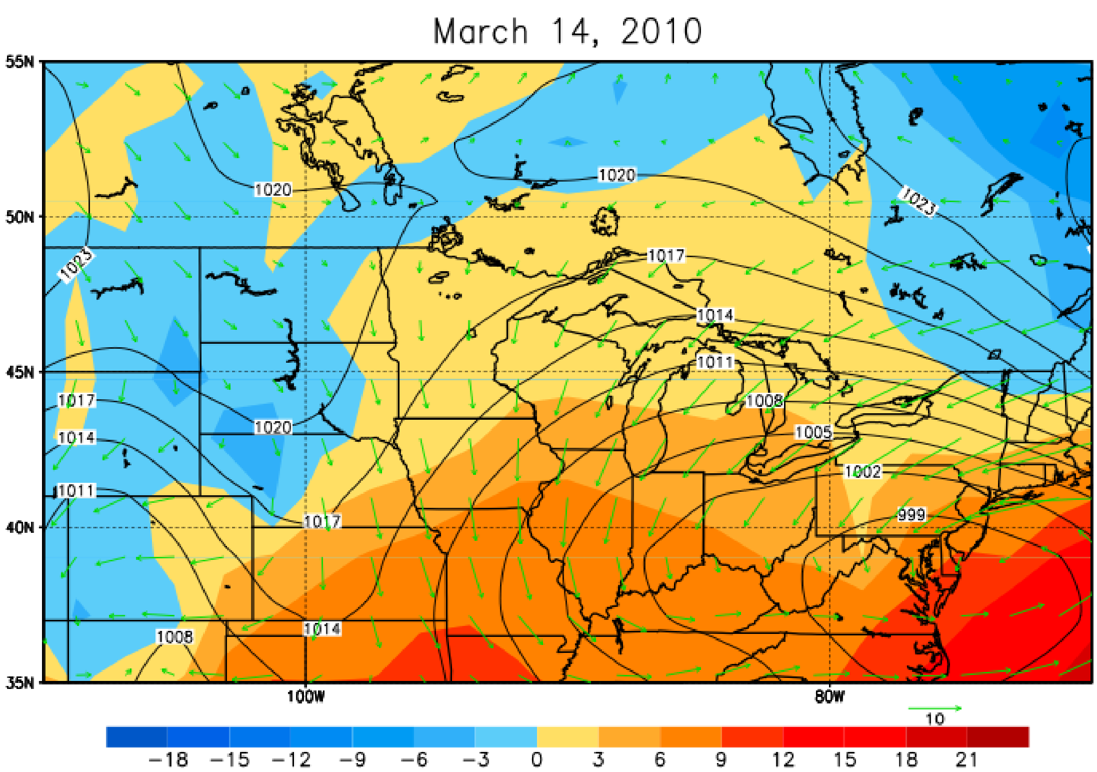
Compressed Image File Names: YYYYanogif.zip, where YYYY is the winter (2006…, 2011), "ano" is an indicator for ice anomaly image data, and "gif" defines the image format.

Image File Names: YYYddd.GIF, where "YYY" and "ddd" are as defined above.

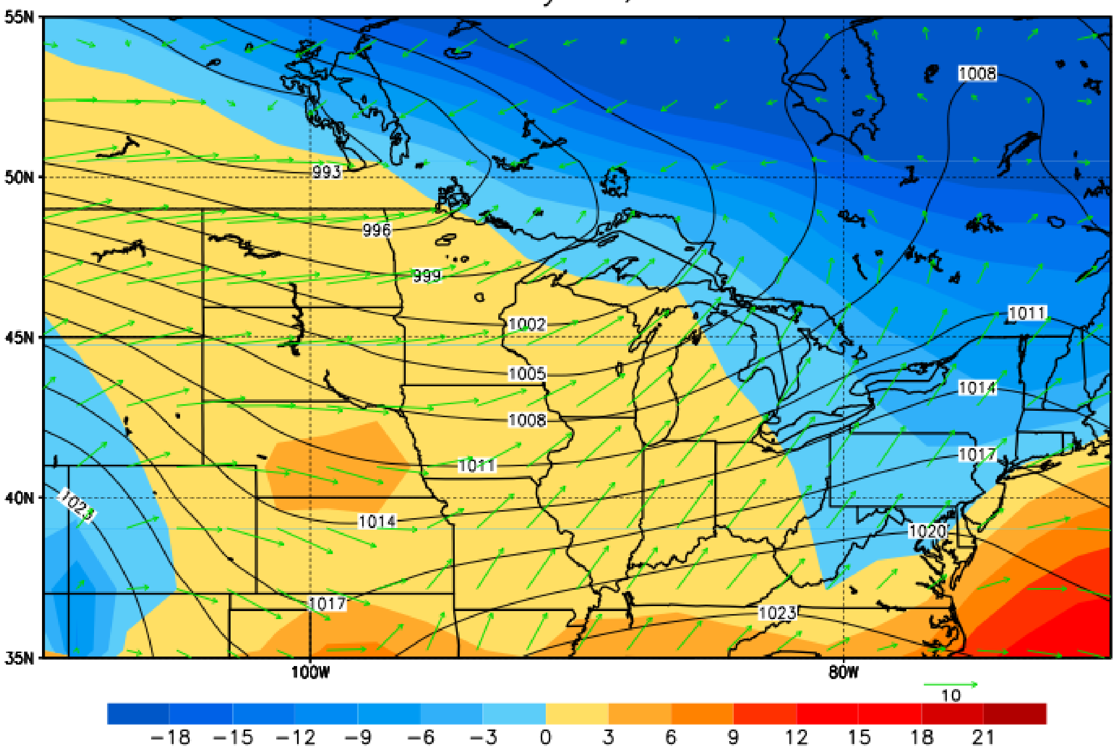
APPENDIX 4. SURFACE ANALYSIS MARCH 13-14, 2010, FEBRUARY 13-14, 2011

Figure 1. Air temperature (shaded, C), surface winds (vectors, m/s) and sea level pressure (contours, hPa) on March 13-14, 2010, and February 13-14 showing the passage of a cyclone from west to east. The data are from NCEP2. (www.cpc.ncep.noaa.gov/products/wesley/reanalysis2/)





February 13, 2011



February 14, 2011