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

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

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 $\geq 10\%$
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](image)

![Figure 5. Maximum Ice Cover and Ice Anomaly Charts for the 2012 Winter Season](image)
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 southern shore and nearshore areas of Lake Ontario. Ice dissipated over the middle regions of Lake Michigan and Lake Ontario in March; the majority 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](image1)

**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](image2)

**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](image)

**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](image)

**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)

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The annual maximum ice cover values are lake averages calculated from the original ice charts.
CONCLUSIONS
In previous ice climatology analysis, the analysis products 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 average 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).


ACKNOWLEDGMENTS:
We appreciate support from the Cooperative Institute of Great Lakes Research (CIGLR) 2017 Summer Fellows program. This is GLERL Contribution No. 1871 and CIGLR Contribution No. 1120.

REFERENCES


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

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

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

\begin{verbatim}
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 1:31){
    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)))
    }
  }
}
\end{verbatim}
#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>
<thead>
<tr>
<th>Winter Season</th>
<th>Number of Ice Charts</th>
<th>Date of First Ice Chart</th>
<th>Date of Last Ice Chart</th>
</tr>
</thead>
<tbody>
<tr>
<td>2012</td>
<td>136</td>
<td>November 29th</td>
<td>April 13th</td>
</tr>
<tr>
<td>2013</td>
<td>177</td>
<td>November 29th</td>
<td>May 28th</td>
</tr>
<tr>
<td>2014</td>
<td>192</td>
<td>November 24th</td>
<td>June 5th</td>
</tr>
<tr>
<td>2015</td>
<td>195</td>
<td>November 14th</td>
<td>May 29th</td>
</tr>
<tr>
<td>2016</td>
<td>160</td>
<td>November 27th</td>
<td>May 5th</td>
</tr>
<tr>
<td>2017</td>
<td>136</td>
<td>December 11th</td>
<td>April 26th</td>
</tr>
</tbody>
</table>

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

```r
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(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))
    }
  }
}
```
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.

\textbf{R Software Code}

Below is the \textit{R} code for determining the ice cover anomalies for a given winter season.

\begin{verbatim}
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[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)
    }
  }
}
\end{verbatim}
data<-t(interleave(t(data),t(data)))
interp<-matrix(-1,1024,1024)
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