Great Lakes Ice Cover

Identification

1. Indicator Description

This indicator describes how ice cover concentration and duration in the Great Lakes (Lake Superior, Lake Michigan, Lake Huron, Lake Erie, and Lake Ontario) have changed between 1973 and 2020. Ice cover is a useful indicator of climate change because it can be affected by air and water temperatures (Wang et al., 2018). Reduced ice cover contributes to more evaporation, which can lead to lower water levels in the lakes and more lake-effect precipitation over nearby land (USGCRP, 2018). Ice cover on the Great Lakes also plays an important role in regional tourism and recreation, the shipping industry, and aquatic ecosystems (Mason et al., 2016).

Components of this indicator include:

- Average annual ice cover concentration and duration in the Great Lakes since 1973 (Figure 1).
- Average rate of change of ice cover concentration in the Great Lakes since 1973 (Figure 2).
- Average rate of change of ice duration in the Great Lakes since 1973 (Figure 3).

2. Revision History

April 2021: Indicator published.

Data Sources

3. Data Sources

Great Lakes annual ice cover concentration and duration data were provided to EPA by the National Oceanic and Atmospheric Administration (NOAA) Great Lakes Environmental Research Laboratory (GLERL). GLERL prepared annual results for the period 1973 to 2020 using daily and weekly ice charts available from the Canadian Ice Service (CIS) and the U.S. National Ice Center (NIC) for the winter-spring season (i.e., December to May). Ice charts developed by CIS were used from 1973 to 1988 while ice charts from NIC were used from 1989 to 2020.

4. Data Availability

EPA obtained the annual ice cover concentration and duration results for this indicator from GLERL. The summary statistics used for Figures 1 and 2 are available at: www.glerl.noaa.gov/data/ice/#historical. This link also provides the underlying ice charts that feed into Figure 3 and the summary statistics, though the most recent set of source data for Figure 3 were provided by GLERL staff. The GLERL website combines data from NOAA's Great Lakes Ice Atlas for 1973 to 2005, available at: www.glerl.noaa.gov/data/ice/atlas, and data for 2006 to 2020 that were processed with the same methods (Wang et al., 2012a).

The original NIC ice charts are available starting with the 1996 winter-spring season at: https://usicecenter.gov/Products/GreatLakesCharts. The original CIS ice charts are available at: https://iceweb1.cis.ec.gc.ca/Archive/page1.xhtml?lang=en.

Similar data are available through 2014 from the Great Lakes Aquatic Habitat Framework (GLAHF) at: www.glahf.org/data.

Methodology

5. Data Collection

Data for this indicator were prepared by GLERL using original CIS and NIC ice charts and a similar approach as GLAHF (Mason et al., 2016). The ice cover data are based on data files from CIS for the years 1973 to 1988 and from NIC from 1989 to the present; data from both Canadian and U.S. sources are combined in the NIC data.

Synoptic ice chart observations, usually covering only a portion of one or more of the Great Lakes, began in 1960. Composite ice charts, including observations from various data sources (e.g., ships, shore, aircraft, and satellite) that cover the entire area of the Great Lakes were developed beginning in the 1970s. Data used for this indicator and covering the winter-spring seasons of 1973 to 2006 were collected at a 2.5 kilometer (km) × 2.5 km resolution and include a combination of observed and interpolated data from CIS and NIC (Assel, 2005; Assel et al., 2002; Wang et al., 2012a). For example, the NIC states that their “products are analyzed by sea and freshwater ice experts using multiple sources of near real time satellite data, derived satellite products, buoy data, weather, and analyst interpretation of current sea ice conditions” (https://usicecenter.gov/Products/GreatLakesCharts). Data for the 2007 winter-spring season and onward were resampled at a nominal 1.8 km × 1.8 km resolution and based on similar sources.

Ice charts were produced at a frequency of about two per week starting in 1960; starting with the 2011 winter-spring season, NIC started making daily ice charts available at the request of GLERL. The ice charts that this indicator is based on are composite charts, which include both observed ice conditions and estimated ice conditions based on extrapolation from earlier dates, interpolation, or climatological data (Assel et al., 2002). Ice charts have traditionally covered dates from December to May, although in some recent years there have been ice charts starting in November and extending into June. This does not affect the consistency of EPA’s indicator, because (as noted in Section 6 below) the indicator is restricted to data from December through May. It just means that additional data happened to be available for November and June in some years, but not others.

6. Indicator Derivation

For the purposes of this indicator, a year’s “winter-spring season” is the period of ice cover that starts on December 1 of the previous year and ends on May 31 (May 30 for leap years) of that year (Bai et al., 2012; Wang et al. 2012b). For example, results for 2019 cover the period December 1, 2018, to May 31, 2019. In more recent years, ice charts in some instances started in November and extended to June; however, these were excluded from the analysis for the sake of consistency over time.

A series of digitization efforts at GLERL has converted the NIC and CIS ice chart data (described above) to standardized geospatial files from 1973 to the present. GLERL converted these files into raster layers that cover the entire surface of the Great Lakes and have a standard map projection, land mask, map scale, and symbology. Raster layers for the winter-spring seasons 1973 to 2006 are on a 510 × 516 grid and have a 2.55 km × 2.55 km resolution. Data for subsequent years are on a 1024 × 1024 grid, which has a resolution of 1.8 km × 1.8 km at the equator; due to the map projection used, the actual grid resolution is approximately 1.275 km × 1.275 km at the latitude of the Great Lakes. Norton et al. (2000) and Wang et al. (2012a) describe in more detail the methodology and quality control efforts involved in digitizing the original ice charts.

To develop the yearly seasonal averages (December through May) presented in this indicator and to harmonize the data across the entire period of record, data (Bai et al., 2012; Wang et al., 2012b) from the older raster layers (i.e., 1973 to 2006) were first resampled to the higher-resolution 1024 × 1024 grid, per Mason et al. (2016). As part of this process, the shoreline area for each lake was also filled in to match the 1024 × 1024 grid. Temporal interpolation was then used on consecutive ice chart grids, cell by cell (Wang et al., 2012b), to create daily grids, per Assel (2005). Additional details on processing the resulting ice cover concentration and duration data are provided in Yang et al. (2020) and described below.

Figure 1. Maximum Ice-Covered Area in the Great Lakes, 1973–2020

The graphs in Figure 1 show the maximum percentage of each lake's surface area that froze in a given year. It is based on daily lake-wide ice cover percentages from NOAA GLERL for each lake. The analysis involves simply identifying the day of each year on which the maximum coverage occurred, and plotting that maximum value.

Figure 2. Duration of Ice Cover in the Great Lakes, 1973–2020

The graphs in Figure 2 show the number of days per year in which at least 5 percent of each lake's total surface area was frozen. EPA obtained daily lake-wide ice cover percentages from NOAA GLERL for each lake, then totaled the number of days per year in each lake that had 5 percent ice cover or more. EPA used this 5 percent threshold to be consistent with other published analyses that examined ice cover duration based on lake-wide frozen area (e.g., Van Cleave et al., 2014). For this analysis, "duration" represents the total number of days during the winter-spring season that met the threshold. The days need not all be consecutive or contiguous to be included, although in practice, most of them are (see Figure TD-3).

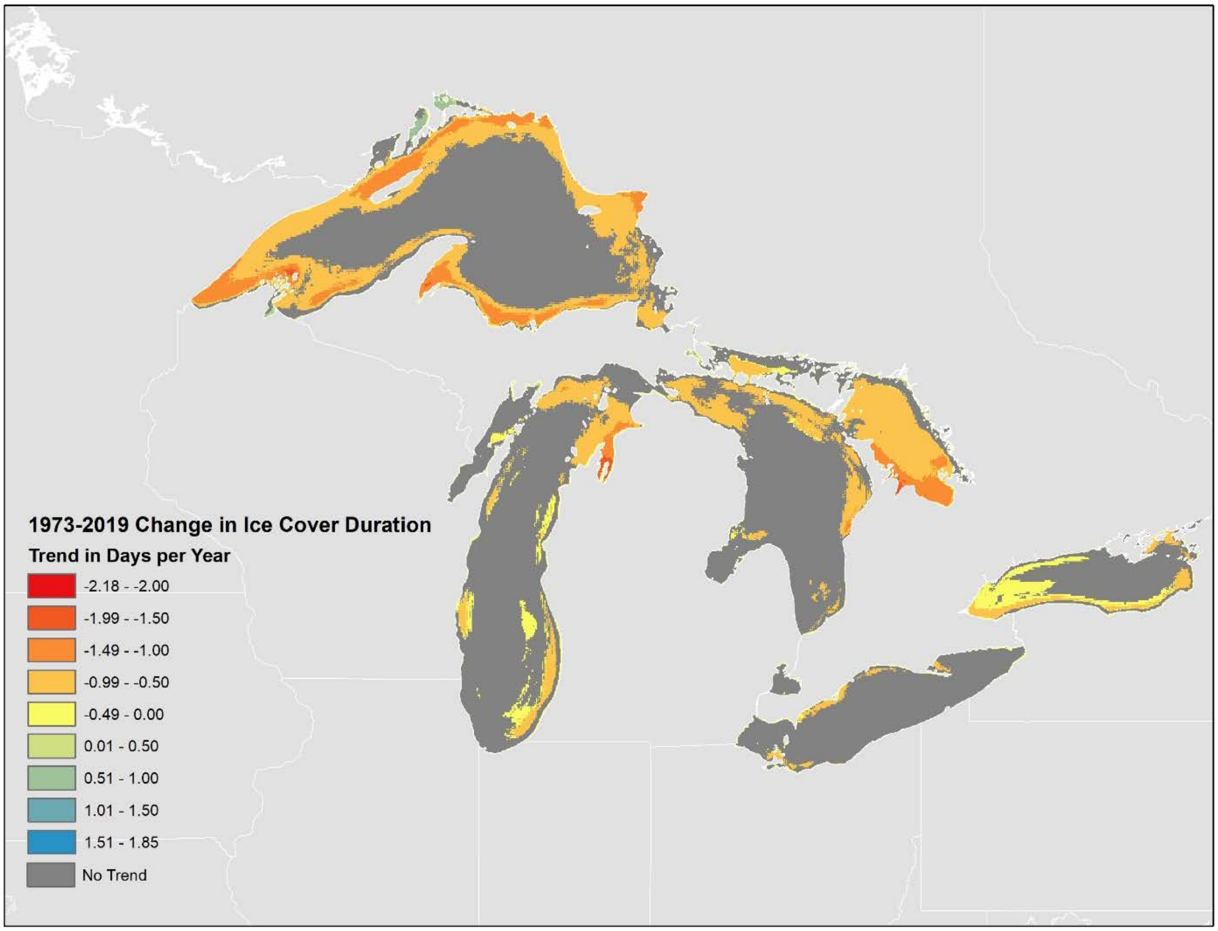
Figure 3: Change in Ice Cover Duration in the Great Lakes, 1973–2019

Figure 3 presents a map showing average rates of change in ice cover duration from 1973 to 2019 for each grid cell. It is based on a geospatial analysis of daily ice charts to determine the number of days per year when each grid cell (or pixel) was frozen. This analysis applies a criterion of 10 percent ice concentration at the individual pixel level, consistent with the mapping methods published by Mason et al. (2016). This means a pixel is counted in the duration metric for each day in which it had an ice concentration (percent of pixel area frozen) of 10 percent or higher. As with Figure 2, "duration" represents the total number of days during the season that met the threshold; the days need not all be consecutive or contiguous. Changes over time were estimated for each grid cell by running ordinary least-squares linear regression models using each grid cell's annual values from 1973 to 2019, per

Mason et al. (2016). Results are presented in units of days per year. Changes in duration for grid cells defined with "no trend" did not exhibit a statistically significant increasing or decreasing trend to the 90 percent level ($p < 0.1$).

EPA used a 90 percent confidence level for determining statistical significance to be consistent with a similar analysis performed in Mason et al. (2016) and the Fourth National Climate Assessment (USGCRP, 2018). For reference, Figure TD-1 displays trends in ice cover duration using a 95 percent confidence level. Using a higher confidence threshold means that fewer grid cells exhibit a statistically significant trend; however, the overall conclusions that can be drawn from this map are similar to the conclusions that can be drawn from the "90 percent" map presented in EPA's indicator.

Figure TD-1. Change in Ice Cover Duration of the Great Lakes, 1973–2019, 95 Percent Confidence Level



Data source: NOAA, 2019

7. Quality Assurance and Quality Control

The digitization of original ice charts by GLERL involved significant quality control measures. The locations of ice coverage and attribute data were examined visually, and the attribute data were checked against the ASCII file attribute data. Slight inconsistencies between NIC and GLERL shoreline boundaries that resulted in missing overwater data were addressed by extrapolating ice concentrations in cells with missing data using adjacent cells. Files with large amounts of missing data were either corrected by NIC or not included for further analysis. When graphic and ASCII files from NIC had inconsistent dates, the date of the graphic file, which was always one day earlier than the ASCII file, was used. More detail on quality control efforts can be found in Norton et al. (2000) and Wang et al. (2012a).

Analysis

8. Comparability Over Time and Space

The digitization of CIS and NIC ice charts involved standardization to allow comparability over time and space. The ice charts were mapped onto a Mercator projection and used a consistent land mask developed for the 1024 × 1024 grid based on the NOAA Great Lakes CoastWatch land mask (Wang et al., 2012a). Additionally, slight inconsistencies in shoreline boundaries were standardized so that the over-water grid cells in the maps would be consistent over time (Wang et al., 2012a). Temporal interpolation was performed to create a consistent daily dataset for calculation of annual averages (Assel, 2005). Where grid cells were missing data, as was the case for some areas near the shore, ice coverage was extrapolated from the nearest cells containing data to ensure comprehensive spatial coverage over water cells in the lakes (Wang et al., 2012a).

9. Data Limitations

Factors that may impact the confidence, application, or conclusions drawn from this indicator are as follows:

1. Compared with climate warming trends, natural year-to-year variability and decadal climate cycles may have a stronger influence on ice cover area and duration (Bai et al., 2012; Wang et al., 2018). With more than four decades of data, though, this indicator clearly shows meaningful long-term trends and variations that relate to the regional climate of the Great Lakes, which is controlled by global atmospheric teleconnection patterns.

2. There are temporal gaps in the daily ice chart record before the 2011 winter-spring season, and there are spatial gaps in the record, especially for shoreline areas and older ice charts. In constructing the source data for this indicator, NOAA addressed these gaps by temporal interpolation and spatial extrapolation using nearby cells.

3. The ice cover area and duration results presented in this indicator are limited by the dates of the winter-spring season (December 1–May 31, or May 30 for leap years). Therefore, the observed date of first and last ice may be inaccurate for some grid cells; there may have been ice cover in some grid cells before the winter-spring season started or after it ended. However, it is likely that for most grid cells, the actual dates of first and last ice occurred somewhere within the range of December to May because the first and last ice charts of this range show most of the Great Lakes with no ice cover in each year (Assel, 2005).

10. Sources of Uncertainty

Uncertainty estimates are not directly available for this indicator. For context, Wang et al. (2012b) shows error bars around monthly averages drawn from an earlier version of this analysis.

Satellite imagery analysis for ice cover can have uncertainties. Issues could include differences between instruments on different satellite missions, instrument drift, gaps due to cloud cover, occasional gaps due to malfunctions or lack of coverage, inaccurate readings due to the appearane or reflectivity of meltwater pooling on the surface of the ice, and other effects. Detailed information about exactly which satellite missions and instruments provided data for the NIC ice charts is not available, which precludes a comprehensive examination of specific uncertaintes. However, all the items noted above are well recognized issues that satellite data processing algorithms are commonly designed to overcome. By relying on processed satellite data products, and by using interpolation and other sources to fill gaps and corroborate the satellite record, the analysis that supports this indicator provides more reliable results than it would if it relied solely on raw satellite observations.

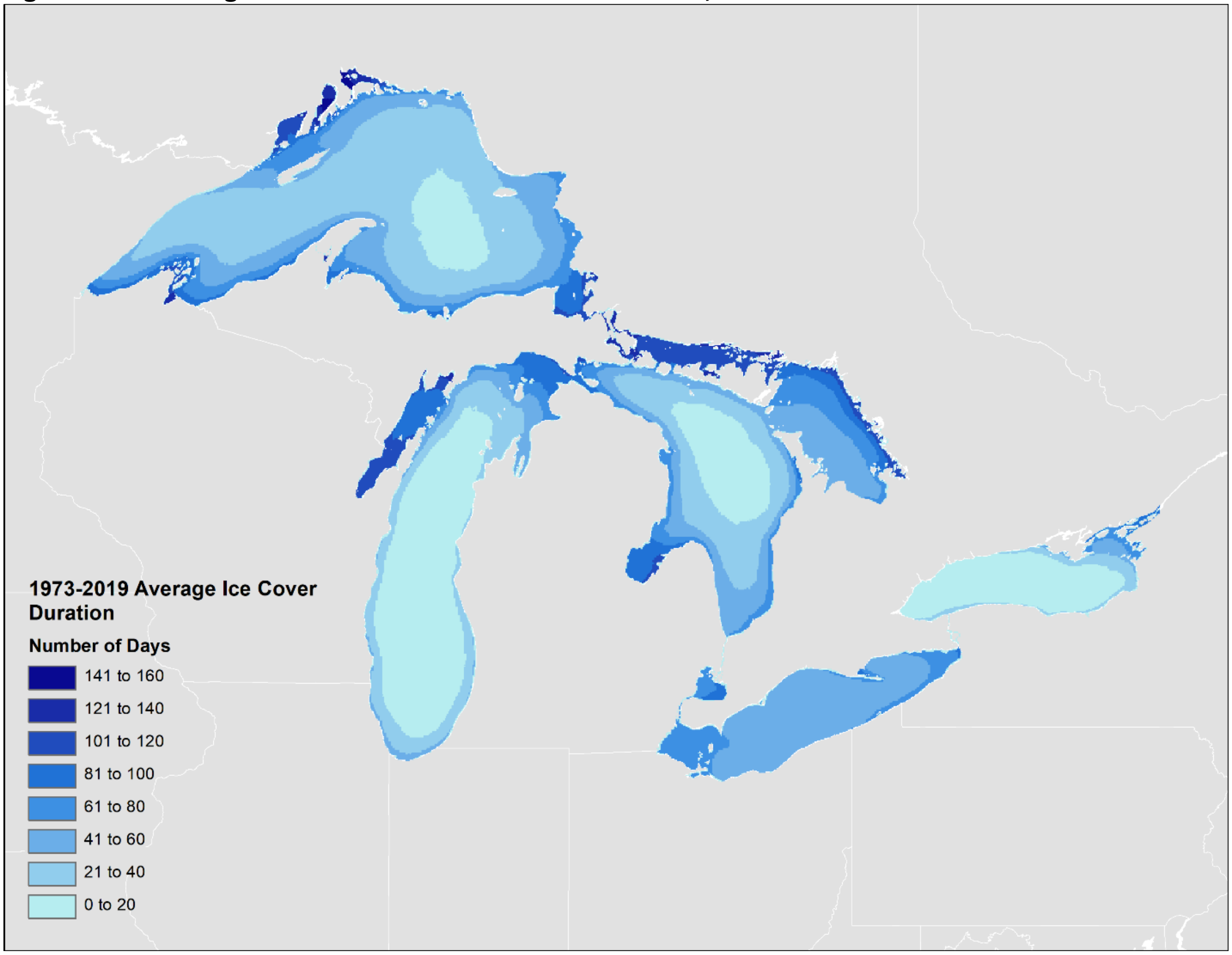
Original ice chart data were collected at a roughly biweekly frequency before the 2011 winter-spring season (December–May) and daily since then (Wang et al., 2012a). Temporal interpolation is used to estimate ice cover for intervening days and may not reflect actual conditions. Additionally, the extrapolation of missing data in over-water cells introduces uncertainty in the affected records. However, because this indicator uses yearly seasonal averages, temporal interpolation and spatial extrapolation of records should not significantly affect the values used in this indicator or the trends exhibited in the results.

11. Sources of Variability

The area and duration of ice cover on the Great Lakes naturally vary from year to year in response to normal variation in weather patterns, multi-year climate cycles such as the El Niño and Southern Oscillation and North Atlantic Oscillation (e.g., Bai et al., 2012), decadal climate patterns such as the Atlantic Multidecadal Oscillation and Pacific Decadal Oscillation (Wang et al., 2018), and other factors (Wang et al., 2017). Overall, though, temporal variability should not impact the conclusions that can be inferred from the multi-decadal time trends shown in this indicator.

Some of the spatial variability depicted in Figure 3 is due to the fact that ice tends to form more at the lake shorelines, with the offshore areas more commonly unfrozen. This happens because areas near the shore are shallower and cool faster than deeper offshore regions. Figure TD-2 below presents a map of the average winter-spring season (December through May) ice cover duration from 1973 to 2019, using the same 10 percent pixel area criterion that was used to generate Figure 3. This map is presented as additional context for the results presented in Figures 2 and 3 of EPA’s indicator. For example, Figure 3 shows an area in the center of Lake Superior with no significant trends over time in ice cover concentration and duration; Figure TD-2 suggests that this observation might relate to the fact that ice rarely forms in that region. Because the number of frozen days tends to be smaller offshore than nearshore (particularly in lakes such as Michigan and Ontario), averages and trends are likely not as reliable offshore as nearshore. Furthermore, the method of determining significance depends on the degrees of freedom, which means less likelihood of significance offshore, where there are fewer days with ice cover.

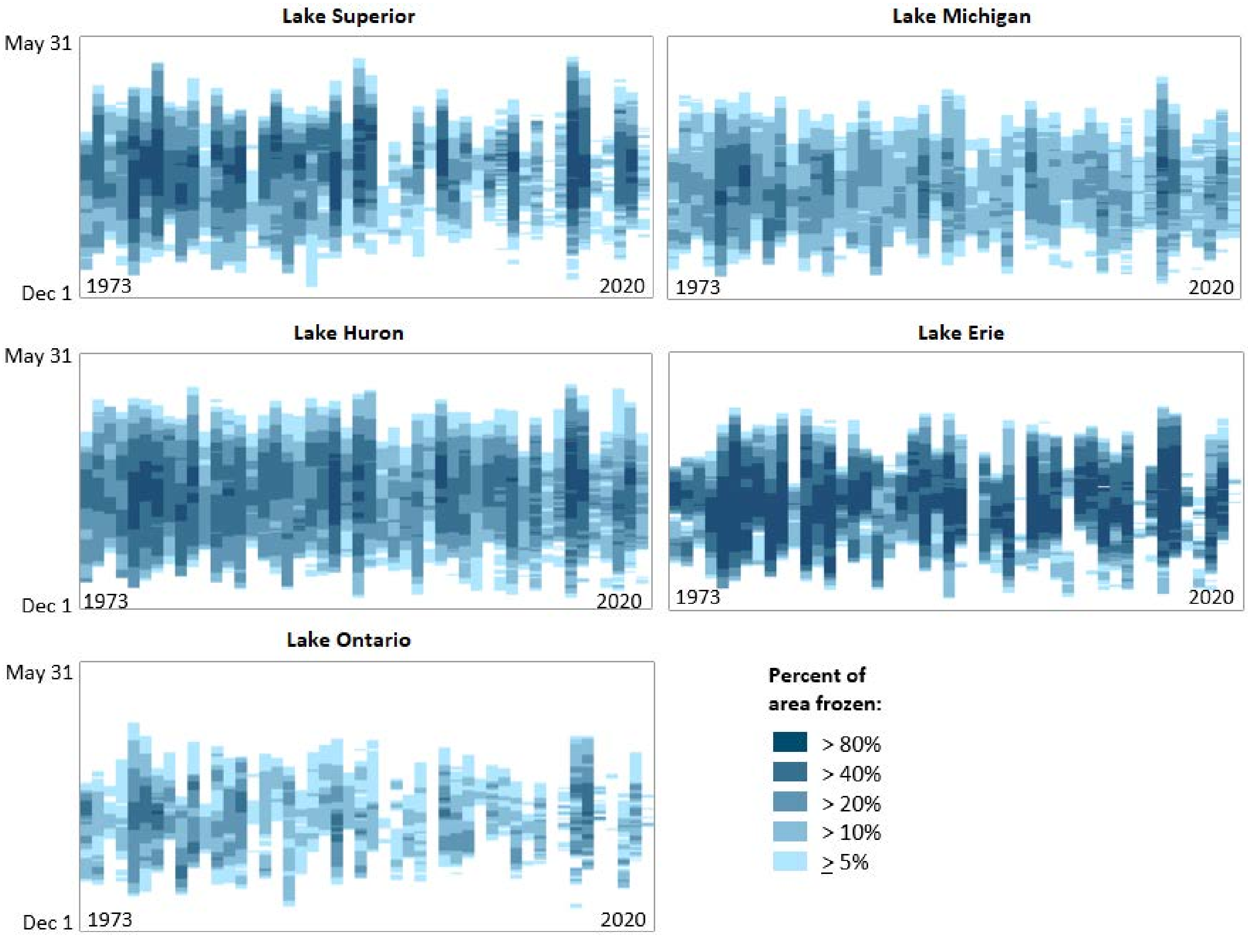
Figure TD-2. Average Ice Cover Duration of the Great Lakes, 1973–2019



Data source: NOAA, 2019.

For additional context, Figure TD-3 shows each lake's annual ice cover duration (column height) and percent frozen area (column shading) on a calendar axis. This figure shows the relationship between ice-covered area and duration and the inherent year-to-year variability in each of these parameters for each lake. This figure is an update to a figure that appeared in Van Cleave et al. (2014), using the same analytical methods, with the exception that Van Cleave et al. used multi-day smoothing while Figure TD-3 presents actual daily values. Per Van Cleave et al. (2014), Figure TD-3 counts any day when lakewide ice cover represented 5 percent or more of the total lake surface area.

Figure TD-3. Daily Ice-Covered Area of the Great Lakes, 1973–2020



Data source: NOAA, 2021

12. Statistical/Trend Analysis

Table TD-1 below shows the slope, p-value, and total change from an ordinary least-squares linear regression of each lake's maximum ice-covered area (as a percentage of total lake area, per Figure 1) and ice cover duration (per Figure 2). Maximum ice-covered area trends are significant to a 95 percent level ($p < 0.05$) for one lake (Superior); duration trends are significant to a 95 percent level for two lakes (Ontario and Superior). As Table TD-1 shows, a few more trends are significant to a 90 percent level ($p < 0.1$).

Table TD-1. Linear Regressions of Annual Ice Cover Data, 1973–2020

Lake	Maximum ice-covered a			Ice cover duration		
	Slope (% area/ year)	P-value	Total change (% area) (slope × 47 years)	Slope (days/ year)	P-value	Total change (days) (slope × 47 years)
Erie	-0.510	0.075	-24.0	-0.548	0.105	-25.8
Huron	-0.369	0.134	-17.3	-0.164	0.408	-7.7
Michigan	-0.285	0.211	-13.4	-0.380	0.078	-17.9
Ontario	-0.313	0.128	-14.7	-0.872	0.0046	-41.0
Superior	-0.714	0.023	-33.6	-0.969	0.0045	-45.5
All lakes	-0.450	0.070	-21.1			

Figure 3 shows the average rate of change in ice cover duration from 1973 to 2019 for each grid cell where the ordinary least-squares linear regression trend is significant to a 90 percent level.

The analyses described above use linear regression as a simple first-order tool for screening and characterizing trends. That said, it is worth noting that previous studies have shown that trends in Great Lakes ice cover can be significantly non-linear, including a step change for Lake Superior in 1997–1998 (e.g., Van Cleave et al., 2014). Non-linear behavior should be taken into consideration when interpreting the presentation of these trends.

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