Lake Ice

Identification

1. Indicator Description

This indicator tracks when a set of lakes in the United States froze and thawed each year between approximately 1840 and 2019. The formation of ice cover on lakes in the winter and its disappearance the following spring depends on climate factors such as air temperature, cloud cover, and wind. Conditions such as heavy rains or snowmelt in locations upstream or elsewhere in the watershed also affect the length of time a lake is frozen. Thus, ice formation and breakup dates are relevant indicators of climate change. If lakes remain frozen for longer periods, it can signify that the climate is cooling. Conversely, shorter periods of ice cover suggest a warming climate.

Components of this indicator include:

- First freeze dates of selected U.S. lakes since 1850 (Figure 1).
- Ice breakup dates of selected U.S. lakes since 1840 (Figure 2).
- Trends in ice breakup dates of selected U.S. lakes since 1905 (Figure 3).

2. Revision History

April 2010:	Indicator published.
June 2015:	Updated indicator with data through winter 2014–2015. Added seven lakes and removed one due to discontinued data (Lake Michigan at Traverse City). Removed the original Figure 1, which showed duration, and added Figure 3, a map showing long-term rates of change in thaw dates.
August 2016:	Updated indicator with data through winter 2015–2016.
April 2021:	Updated indicator with data through winter 2019–2020.

Data Sources

3. Data Sources

This indicator is mainly based on data from the Global Lake and River Ice Phenology Database, which was compiled by the North Temperate Lakes Long Term Ecological Research program at the Center for Limnology at the University of Wisconsin–Madison from data submitted by participants in the Lake Ice Analysis Group (LIAG). The database is hosted on the web by the National Snow and Ice Data Center (NSIDC), and it currently contains ice cover data for more than 850 lakes and rivers throughout the world, some with records covering more than 150 years.

Data for many of the selected lakes have not been submitted to the Global Lake and River Ice Phenology Database since 2005. Thus, the most recent data points were obtained from the organizations that originally collected or compiled the observations.

4. Data Availability

Most of the lake ice observations used for this indicator are publicly available from the sources listed below. All of the years listed below and elsewhere in this indicator are presented as base years. Base year 2004 (for example) refers to the winter that begins in 2004, even though the freeze date sometimes occurs in the following year (2005) and the thaw date always occurs in the following year.

The NSIDC's Global Lake and River Ice Phenology Database provides data through 2004 for most lakes, 2005 for Lakes Osakis and Detroit, 2011 for Lake Superior at Bayfield, and 2012 for Lakes Mendota and Monona. Users can access the NSIDC database at: http://nsidc.org/data/lake_river_ice. Database documentation can be found at: https://nsidc.org/data/g01377?qt-data_set_tabs=2#qt-data_set_tabs.

Users can also view descriptive information about each lake or river in the Global Lake and River Ice Phenology Database. This database contains the following fields, although many records are incomplete:

- Lake or river name
- Lake or river code
- Whether it is a lake or a river
- Continent
- Country
- State
- Latitude (decimal degrees)
- Longitude (decimal degrees)
- Elevation (meters)
- Mean depth (meters)
- Maximum depth (meters)
- Median depth (meters)
- Surface area (square kilometers)
- Shoreline length (kilometers)
- Largest city population
- Power plant discharge (yes or no)
- Area drained (square kilometers)
- Land use code (urban, agriculture, forest, grassland, other)
- Conductivity (microsiemens per centimeter)
- Secchi depth (Secchi disk depth in meters)
- Contributor
- Inlet stream (yes or no)

Access to the Global Lake and River Ice Phenology Database is unrestricted, but users are encouraged to register so they can receive notification of changes to the database in the future.

Data for years beyond those included in the Global Lake and River Ice Phenology Database come from the following sources:

- Cobbosseecontee Lake, Damariscotta Lake, Moosehead Lake, and Sebago Lake: U.S. Geological Survey (USGS). Data through 2008 come from Hodgkins (2010), and data from 2009 through 2019 were provided by USGS staff.

- Detroit Lake: Minnesota Department of Natural Resources at: www.dnr.state.mn.us/lakefind/ice.html?id=03038100.

- Geneva Lake: data from 2005–2015 from Geneva Lake Environmental Agency Newsletters at: www.genevalakemanagement.com. These data were compiled from archived newsletters that were previously available and last accessed in 2016, although those newsletters are no longer publicly available. Data for 2016 from the Lake Geneva Regional News at: www.lakegenevanews.net and freeze data for 2018 from the Geneva Lake Environmental Agency Quarterly Publication at: https://1be5091b-f177-405b-8cd1-465d92736d06.filesusr.com/ugd/456c61_a175eeadb0eb41aa8d3682c2a8b99809.pdf.

- Lake George: published by the Lake George Association and collected by the Darrin Freshwater Institute. These data are available online at: www.lakegeorgeassociation.org/wp-content/uploads/2019/11/20191105LakeGeorge-Ice-in-Ice-Out-2019.pdf.

- Lake Mendota and Lake Monona: Wisconsin State Climatology Office at: www.aos.wisc.edu/~sco/lakes/msnicesum.html.

- Lake Osakis: Minnesota Department of Natural Resources at: www.dnr.state.mn.us/lakefind/ice.html?id=77021500.

- Mirror Lake: Ausable River Association at: www.ausableriver.org/watershed/lakes/mirror-lake/mirror-lake-ice-record.

- Otsego Lake: the State University of New York Oneonta Biological Field Station. Data from 2005–2018 are available in the annual reports at: https://suny.oneonta.edu/biological-field-station/publications.

- Shell Lake: provided by the Washburn County Clerk.

This indicator has been updated through base year 2019 for as many lakes as possible. Some lakes, however, have continued to lag behind in publication of freeze dates, thaw dates, or both.

Methodology

5. Data Collection

This indicator examines two parameters related to ice cover on lakes:

- The annual "ice-on" or freeze date, defined as the first date on which the water body was observed to be completely covered by ice.
- The annual "ice-off," "ice-out," thaw, or breakup date, defined as the date of the last breakup observed before the summer open water phase.

Observers have gathered data on lake ice throughout the United States for many years—in some cases, more than 150 years. The types of observers can vary from one location to another. For example, some observations might have been gathered and published by a local newspaper editor; others compiled by a local resident. Some lakes have benefited from multiple observers, such as residents on both sides of the lake who can compare notes to determine when the lake is completely frozen or thawed. At some locations, observers have kept records of both parameters of interest ("ice-on" and "ice-off"); others might have tracked only one of these parameters.

To ensure sound spatial and temporal coverage, EPA limited this indicator to U.S. water bodies with the longest and most complete historical records. After downloading data for all lakes and rivers within the United States, EPA sorted the data and analyzed each water body to determine data availability for the two parameters of interest. As a result of this analysis, EPA identified 14 water bodies—all lakes—with particularly long and rich records. Special emphasis was placed on identifying water bodies with many consecutive years of data, which can support moving averages and other trend analyses. EPA selected the following 14 lakes for trend analysis:

- Cobbosseecontee Lake, Maine
- Damariscotta Lake, Maine
- Detroit Lake, Minnesota
- Geneva Lake, Wisconsin
- Lake George, New York
- Lake Mendota, Wisconsin
- Lake Monona, Wisconsin
- Lake Osakis, Minnesota
- Lake Superior at Bayfield, Wisconsin
- Mirror Lake, New York
- Moosehead Lake, Maine
- Otsego Lake, New York
- Sebago Lake, Maine
- Shell Lake, Wisconsin

Together, these lakes span parts of the Upper Midwest and the Northeast. The four Maine lakes and Lake Osakis have data for only ice-off, not ice-on, so they do not appear in Figure 1 (first freeze date).

6. Indicator Derivation

Figures 1 and 2. Dates of First Freeze and Ice Thaw for Selected U.S. Lakes, 1850/1840–2019

To smooth out some of the variability in the annual data and to make it easier to see long-term trends in the display, EPA did not plot annual time series but instead calculated nine-year moving averages (arithmetic means) for each of the parameters. EPA chose a nine-year period because it is consistent with other indicators and comparable to the 10-year moving averages used in a similar analysis by Magnuson et al. (2000). Average values are plotted at the center of each nine-year window. For example, the average from 1990 to 1998 is plotted at year 1994. EPA did calculate averages over periods that were missing a few data points. Early years sometimes had sparse data, and the earliest averages were calculated only around the time when many consecutive records started to appear in the record for a given lake.

EPA used endpoint padding to extend the nine-year smoothed lines all the way to the end of the analysis period for each lake. For example, if annual data were available through 2019, EPA calculated nine-year smoothed values centered at 2016, 2017, 2018, and 2019 by inserting the 2015–2019 average into the equation in place of the as-yet-unreported annual data points for 2020 and beyond. EPA used an equivalent approach at the beginning of each time series.

As discussed in Section 4, all data points in Figures 1 and 2 are plotted at the base year, which is the year the winter season began. For the winter of 2018 to 2019, for example, the base year would be 2018, even if a particular lake did not freeze until early 2019.

EPA did not interpolate missing data points or integrate ice-free winters into the calculation of the nine-year moving average. This indicator also does not attempt to portray data beyond the time periods of observation—other than the endpoint padding for the nine-year moving averages—or extrapolate beyond the specific lakes that were selected for the analysis.

Magnuson et al. (2000) and Jensen et al. (2007) describe methods of processing lake ice observations for use in calculating long-term trends.

Figure 3. Change in Ice Thaw Dates for Selected U.S. Lakes, 1905–2019

Long-term trends in ice-off (thaw date) over time were calculated using the Sen's slope method as described in Hodgkins (2013). For this calculation, years in which a lake did not freeze were given a thaw date one day earlier than the earliest date on record, to avoid biasing the trend by treating the year as missing data. Five lakes had years in which they did not freeze: Geneva, George, Otsego, Sebago, and Superior. Figure 3 shows the total change, which was determined by multiplying the slope of the trend line by the total number of years in the period of record.

EPA chose to focus this map on thaw dates, not freeze dates, because several of the target lakes have data for only ice-off, not ice-on. EPA started the Sen's slope analysis at 1905 to achieve maximum coverage over a consistent period of record. Choosing an earlier start date would have limited the map to a smaller number of lakes, as several lakes do not have data prior to 1905.

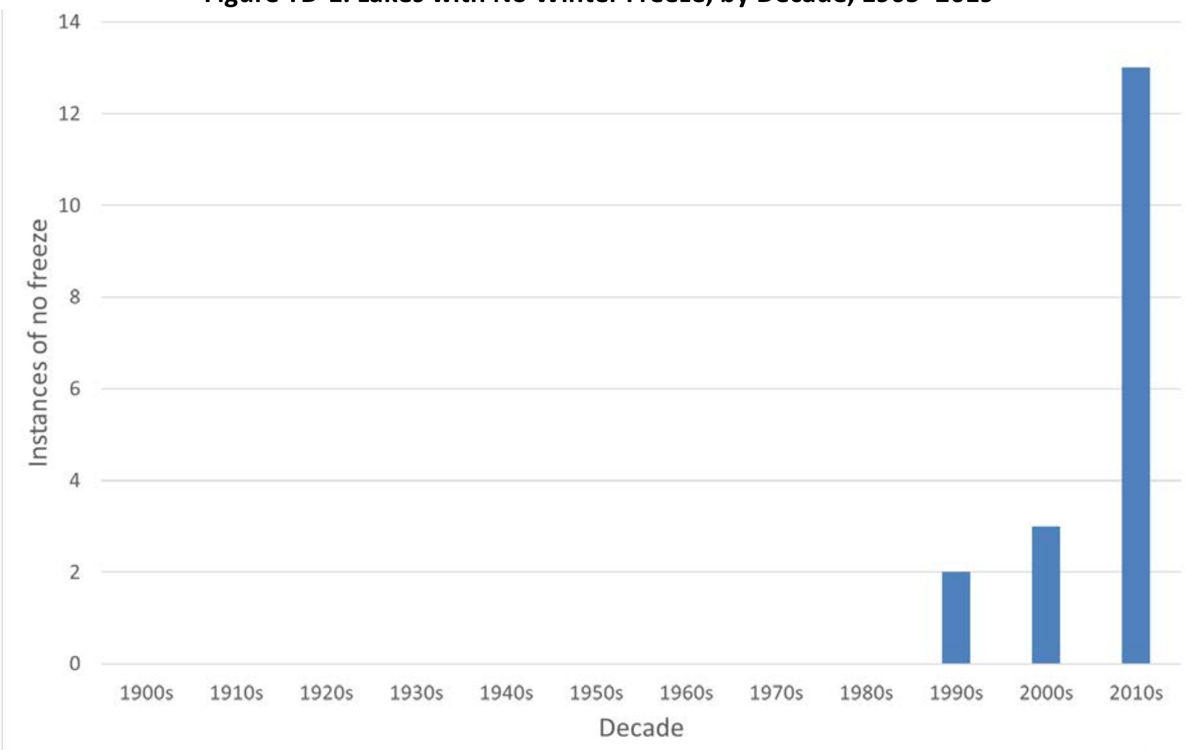
Indicator Development

The version of this indicator that appeared in EPA's *Climate Change Indicators in the United States, 2012* covered eight lakes, and it presented an additional graph that showed the duration of ice cover at the same set of lakes. For the 2014 edition, EPA enhanced this indicator by adding data for seven additional lakes and adding a map with a more rigorous analysis of trends over time. To make room for the map, EPA removed the duration graph, as it essentially just showed the difference between the freeze and thaw dates, which are already shown in other graphs. In fact, in many cases, the data providers determined the duration of ice cover by simply subtracting the freeze date from the thaw date, regardless of whether the lake might have thawed and refrozen during the interim. Starting with the 2015 update to this indicator, EPA also removed one lake (Grand Traverse Bay, Lake Michigan) from the indicator because data for it are no longer routinely collected.

Recent updates to this indicator suggest an increased prevalence of lakes that were ice free during the winter. Due to the strong bias a value of "0" would cause in both the nine-year moving average and the

Sen's slope trend calculations, such years are handled differently. However, years without ice do reflect a significant aspect of the winter ice conditions at the lakes presented in this indicator. To date, EPA has not incorporated ice-free winters into the moving averages shown in Figures 1 and 2, and only included an adjusted value for ice-free years to facilitate trend calculation for Figure 3. Figure TD-1 presents the total number of ice-free lake-years by decade for the set of 14 lakes covered by this indicator. That is, a decadal value of 10 in Figure TD-1 could indicate that 10 lakes each had one ice-free year, or one lake had 10 ice-free years, or some combination thereof. Only years that were documented or inferred as being ice-free were included. Inferred years might include, for example, a news report citing 2015 as the "fourth winter with a freeze since 2005," thereby affirming the six years of missing data were indeed ice-free years. Years that were documented as having no data yet available were not included in Figure TD-1.

Figure TD-1. Lakes with No Winter Freeze, by Decade, 1905–2019



7. Quality Assurance and Quality Control

The LIAG performed some basic quality control checks on data that were contributed to the database, making corrections in some cases. Additional corrections continue to be made as a result of user comments. For a description of some recent corrections, see the database documentation at: https://nsidc.org/data/g01377?qt-data_set_tabs=2#qt-data_set_tabs.

Ice observations rely on human judgment. Definitions of "ice-on" and "ice-off" vary, and the definitions used by any given observer are not necessarily documented alongside the corresponding data. Where possible, the scientists who developed the database have attempted to use sources that appear to be consistent from year to year, such as a local resident with a long observation record.

Analysis

8. Comparability Over Time and Space

Historical observations have not been made systematically or according to a standard protocol. Rather, the Global Lake and River Ice Phenology Database—the main source of data for this indicator—represents a systematic effort to compile data from a variety of original sources.

Both parameters were determined by human observations that incorporate some degree of personal judgment. Definitions of these parameters can also vary over time and from one location to another. Human observations provide an advantage, however, in that they enable trend analysis over a much longer time period than can be afforded by more modern techniques such as satellite imagery. Overall, human observations provide the best available record of seasonal ice formation and breakup, and the breadth of available data allows analysis of broad spatial patterns as well as long-term temporal patterns.

9. Data Limitations

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

1. Although the Global Lake and River Ice Phenology Database provides a lengthy historical record of freeze and thaw dates for a much larger set of lakes and rivers, some records are incomplete, ranging from brief lapses to large gaps in data. Thus, this indicator is limited to 14 lakes with relatively complete historical records. Geographic coverage is limited to sites in four states (Maine, Minnesota, New York, and Wisconsin).

2. Data used in this indicator are all based on visual observations. Records based on visual observations by individuals are open to some interpretation and can reflect different definitions and methods.

3. Historical observations for lakes have typically been made from the shore, which might not be representative of lakes as a whole or comparable to satellite-based observations.

10. Sources of Uncertainty

Ice observations rely on human judgment, and definitions of "ice-on" and "ice-off" vary, which could lead to some uncertainty in the data. For example, some observers might consider a lake to have thawed once they can no longer walk on it, while others might wait until the ice has entirely melted. Observations also depend on one's vantage point along the lake, particularly a larger lake—for example, if some parts of the lake have thawed while others remain frozen. In addition, the definitions used by any given observer are not necessarily documented alongside the corresponding data. Therefore, it is not possible to ensure that all variables have been measured consistently from one lake to another—or even at a single lake over time—and it is also not possible to quantify the true level of uncertainty or correct for such inconsistencies.

Accordingly, the Global Lake and River Ice Phenology Database does not provide error estimates for historical ice observations. Where possible, however, the scientists who developed the database have attempted to use sources that appear to be consistent from year to year, such as a local resident who collects data over a long period. Overall, the Global Lake and River Ice Phenology Database represents the best available data set for lake ice observations, and limiting the indicator to 14 lakes with the longest and most complete records should lead to results in which users can have confidence. Consistent patterns of change over time for multiple lakes also provide confidence in the lake ice data.

11. Sources of Variability

For a general idea of the variability inherent in these types of time series, see Magnuson et al. (2000) and Jensen et al. (2007)—two papers that discuss variability and statistical significance for a broader set of lakes and rivers, including some of the lakes in this indicator. Magnuson et al. (2005) discuss variability between lakes, considering the extent to which observed variability reflects factors such as climate patterns, lake morphometry (shape), and lake trophic status. The timing of freeze-up and break-up of ice appears to be more sensitive to air temperature changes at lower latitudes (Livingstone et al., 2010), but despite this, lakes at higher latitudes appear to be experiencing the most rapid reductions in duration of ice cover (Latifovic and Pouliot, 2007).

To smooth out some of the interannual variability and to make it easier to see long-term trends in the display, EPA did not plot annual time series but instead calculated nine-year moving averages (arithmetic means) for each of the parameters, following an approach recommended by Magnuson et al. (2000).

12. Statistical/Trend Analysis

Figure 1 shows data for the nine individual lakes with freeze date data. Figures 2 and 3 show ice thaw date data for all 14 individual lakes. No attempt was made to aggregate the data for multiple lakes.

EPA calculated trends in freeze dates (Figure 1) by computing Sen's slope and the corresponding Mann-Kendall p-values. EPA performed this regression on the annual values for the entire period of record for each lake, not the smoothed values displayed in Figure 1. As Table TD-1 shows, eight of the nine lakes have trends toward later freezing that are significant to a 95 percent level ($p < 0.05$).

EPA also calculated 1905–2019 trends in thaw dates (Figures 2 and 3) by computing Sen's slope and the corresponding Mann-Kendall p-values. EPA performed this regression on the annual values, not the smoothed values displayed in Figure 2. For years in which a lake did not freeze, EPA inserted a thaw date one day earlier than the earliest date on record. EPA used this approach to be consistent with the thaw date analysis published by Hodgkins (2013) and others. Table TD-2 provides the results of this statistical testing, which can be summarized as follows:

- Seven lakes (Cobbosseecontee, Damariscotta, George, Mirror, Monona, Sebago, and Superior) have trends toward earlier thaw that are significant to a 95 percent level (Mann-Kendall p-value < 0.05).
- Seven lakes (Detroit, Geneva, Mendota, Moosehead, Osakis, Otsego, and Shell) have trends toward earlier thaw that are not significant to a 95 percent level (Mann-Kendall p-value > 0.05).

Table TD-1. Sen's Slope Regression of Freeze Dates

Lake	Period of analysis	Slope (days/year)	P-value
Detroit	1908–2018	0.101	< 0.001
Geneva	1862–2018	0.107	< 0.001
George	1911–2018	0.042	0.355
Mendota	1855–2019	0.094	< 0.001
Mirror	1903–2019	0.094	< 0.001
Monona	1855–2019	0.092	< 0.001
Otsego	1849–2018	0.068	0.003
Shell	1905–2015	0.066	0.017
Superior	1857–2011	0.140	< 0.001

Table TD-2. Sen's Slope Linear Regression of Thaw Dates, 1905–2019

Lake	Slope (days/year)	P-value
Cobbosseecontee	-0.083	0.002
Damariscotta	-0.085	0.010
Detroit	0*	0.816
Geneva	-0.044	0.211
George	-0.061	0.031
Mendota	-0.059	0.053
Mirror	-0.056	0.034
Monona	-0.074	0.015
Moosehead	-0.046	0.052
Osakis	0*	0.605
Otsego	-0.029	0.320
Sebago	-0.140	< 0.001
Shell	-0.052	0.073
Superior	-0.214	< 0.001

**Many statistical software programs, including the one used for this analysis, will report a value of "0" when they identify an infinitesimally small slope.*

These results align with conclusions from the literature. For example, Magnuson et al. (2000) and Jensen et al. (2007) found that long-term trends in freeze and breakup dates for many lakes were statistically significant ($p < 0.05$).

References

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