

Volume 2, Issue 2

Research Article

Date of Submission: 29 Jan, 2026

Date of Acceptance: 20 Feb, 2026

Date of Publication: 21 May, 2026

## “Is not January Pure Winter?” Ice Duration on Northeastern US Lakes, 1816-2021

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**Citation:** Irland, L. C., Maass, D. I. (2026). “Is not January Pure Winter?” Ice Duration on Northeastern US Lakes, 1816-2021. *Int J Evol Sus Renew Energy Sol*, 2(2), 01-16.

### Abstract

Data were assembled on ice durations for 22 lakes in the Northeast US, spanning the region from Minnesota to Maine. The records began in the 19<sup>th</sup> century for ten of them, second half of the 19<sup>th</sup> century for 7, and post 1950 for 6. Only a few were complete; several had major gaps. These were analyzed for long-term trends, for variability, and comparisons were made for the most recent 60 years, for which the largest number of records were available. By non-parametric tests, the longest series showed significant reductions in ice duration. The periods 1961-1990 and 1991-2022 showed mixed results. High variability characterized the long-term trends across lakes. Since these records are not an actual sample of all lakes in the region, general conclusions from these results should be drawn with care.

### Introduction

An expanding literature deals with the analysis of trends in ice phenology worldwide as well as in local regions and individual water bodies. This literature employs extensive datasets, tests important hypotheses, and uncovers important relationships, such as the role of teleconnections. Many investigators have used ice out dates as proxies for the integrated effects of winter weather on lakes and thus as proxies for climate change [1,2].

In the Northeast USA, records on ice out dates have been preserved and compiled for many lakes and rivers. Yet, few of the oldest records include both ice in and ice out dates. In the region studied here, across the northern US from Minnesota to Maine, we can discover only 21 records, some of them with significant gaps, that provide long-term trends in ice duration. Lake Champlain offers a record of ice in only, which permits identifying years that failed to freeze. Records for several other lakes whose records identify no freeze years are noted. Ten of the records studied here begin early in the 19<sup>th</sup> century, though 2 have significant gaps. Legacy navigation dates for a few ports have been compiled. The oldest of these records – earliest in 1785 -- far predate the oldest known continuous instrumental weather records. But the cited records end by the 1930s in most cases. These are shown here to prompt interest in the use of commercial information on ice phenologies, as historians have often done. A premise of this study is that studying in detail a series of lakes in regions such as this can add to the insights developed from data intensive studies of numerous lakes across the northern Hemisphere, as well as complement the studies of individual lakes.

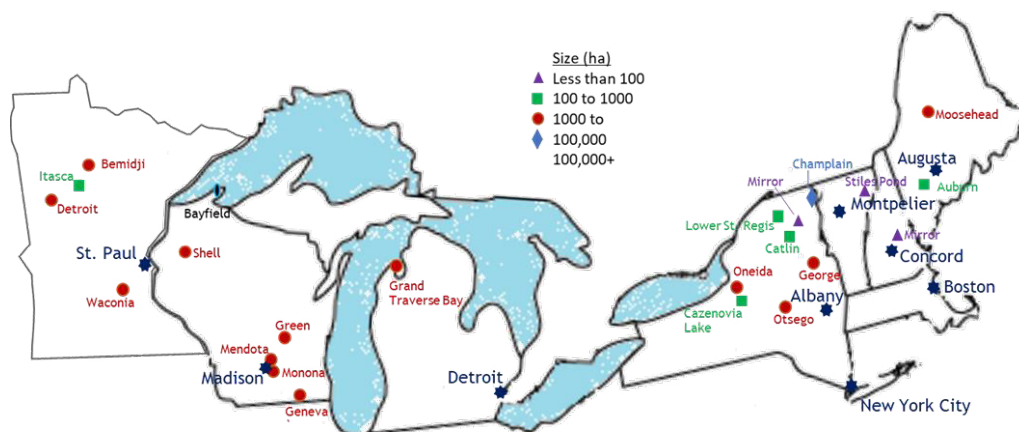


Figure 1: Lake Morey ( Vermont) and Walden and Houlton's (Mass) .

## Literature Review

Scientists have studied 2,499 lakes across 15 nations (43). For a small study like ours, statistical analysis methods are descriptive only and not inferential. Some of the lakes with longest records are reservoirs built by private firms or owned by utilities. Those lakes have had facilities modernized, and they no longer have human damtenders who record ice outs. Those lakes should be taken up by some other agency. Scientists have widened and deepened research on this topic [3]. Recent literature supplies extensive reviews of the regional and global literature on ice phenology in northern hemisphere lakes. See especially and and Imrit and Sharma (2021) and who cite a large body of literature [4-6]. Much of the work has been on connections to climate change [7].

In the Northeast, interest by meteorologists in ice phenology goes back at least as far as Fobes' 1949 paper which treated several Maine lakes. Hodgkin's et al. (2002) documented the historical ice-out on 29 New England Lakes, following up with a series of papers. More recent work has included compilations of data and extensive analyses by Ellis and Greene, 2019; Beyene and Jain 2015; Hodgkins et al, 2010; Hodgkin's, 2013 [8-11].

Intensive case studies of individual lakes have developed insights into relationships between ice formation and melting and local weather (several lakes at Huntingdon Forest, NY); Bruesewitz, et al. 2015 Lake Sunapee, NH; Beyene and Jain, 2020 (L. Auburn, Maine) and the classic work at Oneida Lake, NY; Tan et al. 2018 (Harp Lake, Ontario and 1996, Ontario lakes), (Mirror Lake NH), (Lake Mendota, Fish Lake, and Lake Wingra, southern Wisconsin) [9,12-17].

Other recent work has sketched out the importance of thresholds, nonlinearities, breakpoints, and extreme events in weather drivers of ice regimes. Due to the limited availability of long-term datasets on ice-in dates, little of this work has been able to assess long-term trends in ice duration [18-20]. An early effort was Assel and Herche, 1998, who studied 8 lakes, of which 6 were in North America; of which two were arms of larger lakes. Warne, et al. 2020 reviewed connections between geography and morphology for northern hemisphere lakes [21].

Improving databases on teleconnections such as the NAO and ENSO – southern Oscillation has been incorporated into many models, demonstrating echoes of these remote events in northern hemisphere lake ice regimes [9,22,]. Due to availability of ice and weather records, many of these studies necessarily focused on the post 1950 period. Using a sample of 19 lakes on 3 continents, Yang et al (2020) have shown the effect of windiness on delaying ice-on dates.

Very long histories of cultural eutrophication, vegetation change, and hydrological conditions have been conducted in the Northeast by several groups, including Pedersen, et al 2005; Stager et al. 2021. Authors have occasionally mused about the possible influence of the waning "Little Ice Age" (LIA) in the transition from mid-19th century to 20th century ice regimes (Grove, J.M., 1988), but definitions of the Little Ice Age (LIA) itself have proven elusive. One historian dates the very end of the LIA at 1850. Brief cooling episodes caused by dramatic volcano explosions render the 19th century timing somewhat murky. Forecasts of grim outlooks for northern hemisphere winter ice have been made by several researchers, including Sharma et al., 2020. Finally, closely related work has outlined the importance of changing seasons for landscape and aquatic ecology generally (summarizing 3 LTER sites in the Northeast, Harvard Forest (Massachusetts), northern temperate lakes (N. Wisconsin), and Hubbard Brook Experimental Forest (New Hampshire) [6,23-29].

Hodgkins, 2013 examined late summer hypolimnion dissolved oxygen in three Maine lakes, finding a consistent moderately strong correlation between earlier ice outs and lower dissolved oxygen concentrations [11]. Dunlap and Cook (2004), found effects of early ice out dates on hypolimnion O<sub>2</sub> levels in Green Lake, Maine. Dugan (2021) found varying echoes of "ecological memory" of ice out dates for dissolved oxygen and carbon budgets in 8 northern hemisphere lakes. An international assessment by found widespread evidence of declining DO concentrations in temperate lakes [30]. Connections between this change and ice duration are likely. Blagrove and others (2021) reviewed trends in variability of ice phenology for northern hemisphere lakes.

As Anderson et al, 2021, note: "a shortened winter season results in higher subsurface temperatures and earlier onset of summer stratification. Shifts in the thermal regimes of large lakes will have profound impacts on the ecosystems of the world's surface freshwater." Jane et al, concluded: "Our results suggest that climate change and declining water clarity have altered the physical and chemical environment of lakes. Declines in dissolved oxygen in freshwater are 2.75 to 9.3 times greater than observed in the world's oceans and could threaten essential lake ecosystem services" (Jane, 2021). Cavaliere et al (2022) offer a conceptual analysis of how winter ice phenologies affect an array of biophysical variables in lakes. Effects of changes in ice phenology on fish populations are being studied. Prominent in this region include Magee et al. 2019, on northern cisco in Lake Mendota, showing that populations at the southern end of their range have been extirpated; Looby, 2023; Watz, 2016 [31-35].

## Geographic Setting

The lakes studied here span a wide region. Looking from east to west, two lakes are in Maine; one each in New Hampshire and Vermont; seven are in New York; one in Michigan; six in Wisconsin; and four in Minnesota. Lake Champlain for which we have just ice-in data lies on the border between Vermont and New York. Several Minnesota and Wisconsin lakes are at the prairie margins near the heart of the continent. These are almost 1,900 km from the

east coast while Lake Auburn is only 37 km. Four of the northeastern lakes are less than 100 km from the coast, the farthest from saltwater is Lower St. Regis at 329 km. The lakes occupy a narrow band of latitude, from roughly 42 to 46 degrees latitude, and cross 19 degrees of longitude. From the mid Continent to less than 40 km from the Gulf of Maine, it straddles the Great Lakes. While the latitudinal range is small, it contains 7 states and many different National Climate Data Center climate zones. This study focuses in detail on a set of lakes giving a set of time series and cross section analyses of ice durations, and correlations with available weather observations. The lakes studied here are not in high elevations, for which a growing literature is emerging [36].

While their altitudinal range is limited, the diversity in elevations is considerable for the Northeastern US. The lowest is Lake Champlain (30 m) and the highest not, as one might expect, in the Adirondacks -- it is Mirror Lake NH in the foothills of the White Mountains. The range in size is very large, from 15 ha for Mirror Lake NH, to 133,142 ha for Lake Champlain.

The region spans a range of distinct climates. In the Midwest, the lakes are strongly influenced by continental climate and winter incursions of subarctic storm systems—the famous “Alberta Clippers”. Grand Traverse Bay and several of the New York lakes lie in well-known lake effect zones, as does Stiles Pond, VT. The northern New York, Vermont, and New Hampshire lakes are also affected by winter weather from the north. Finally, Lake Auburn is strongly influenced by coastal weather systems, especially as it is in the middle of the coastal “rain-snow belt”. The higher elevation northeastern lakes lie in a zone where timberlines stand at roughly 4,000 – 4,500 feet, in contrast to the Rockies where timberlines are twice as high.

This region is a broad transition between the mesophytic forests of the south, and the true boreal forests to the north. This why it is useful to look at this broad region alone. The typical trees of this region include white pine, balsam fir, sugar maple, and beech.

### Lakes Studied

For studying ice durations, it would be ideal to have a statistically sound sample of lakes drawn from a population representing a range of sizes, depths, shapes, and hydrographic traits such as turnover rates and artificial dams. The available records, offer nothing like this, however. With 3 lakes smaller than 100 ha, and 3 exceeding 20,000 Ha (not including Champlain which is not analyzed for duration) the range in sizes is very wide (Figure 2). Second largest is Grand Traverse Bay, an arm of Lake Michigan, which is included due to its unusually long record. Details are in Appendix Table 1. Data sources are listed in Appendix Table 2. The lakes vary in surface area by a factor of a thousand, in depth by a factor of ten or more. The lakes vary widely in shape, a few being long, narrow, and ragged; only a few are close to round (Appendix Table 1). Orientation to prevailing seasonal winds is clearly a factor in ice phenology. Gathering data on local winds is challenging and out of scope for this study.

### Data Sources

The records assembled for this work can be grouped into time domains by their length (Table 1). The very oldest is Lake Champlain starting at 1816, though only for ice-in observations. For ten lakes, duration records began in the 19<sup>th</sup> century, six records began in the first half of the 20<sup>th</sup> century, and six in the second half. Hydrographic details are in Appendix Table 2. Details of sources are given in Appendix Table 3.

Period of Earliest		State	Begin	End	Span	Percent Complete
Observations						<b>Complete</b>
2d half 20th	Catlin	NY	1973	2019	46	88%
1950-2021	Stiles	VT	1971	2020	49	100%
	Mirror, NH	NH	1968	2020	52	100%
	Bemidji	MN	1958	2021	63	95%
	Green	WI	1952	2021	69	99%
	Auburn	ME	1953	2020	67	100%
1st half 20th	George	NY	1908	2020	112	87%
1900-1949	Lower St R. Duration	NY	1985	2020	35	100%
	Lower St Regis ice out	NY	1909	2020	111	89%
	Mirror NY	NY	1903	2020	117	97%
	Shell	WI	1905	2021	116	98%
	Itasca	MN	1930	2021	91	74%
	Waconia	MN	1940	2021	81	99%
	Detroit Lakes	MN	1899	2021	122	92%
19th century	Cazenovia	NY	1842	2021	179	85%

1816-1899	Moosehead ice out only	ME	1842	2021	179	100%
	Moosehead Duration	ME	1848	1941	94	100%
	Oneida	NY	1866	2020	155	52%
	Bayfield (Superior)	WI	1864	2018	154	98%
	Mendota	WI	1856	2020	166	100%
	Geneva	WI	1862	2019	157	96%
	Monona	WI	1856	2021	166	95%
	Otsego	NY	1850	2020	172	98%
	Grand Traverse Bay	MI	1852	2020	170	73%
	Champlain (ice in only)	VT/ NY	1816	2021	205	n.a.

**Table 1: Ice Duration Records of Study Lakes**

Several important traits of these records affect the choices of statistical methods for analysis. The subdiscipline concerned with evaluating such data is time series analysis.

- For many lakes the volatility of ice phenology dates has increased noticeably in recent decades. Changing volatility over time, otherwise known as “heteroskedasticity” can bias slope estimates from traditional regression analysis (ordinary least squares or OLS). This requires care in statistically testing for significance between adjacent time periods.
- Most of the records display a modest degree of serial correlation, which can bias OLS estimates of slopes.
- Viewed over long time periods, few if any of the records (charts below) exhibit strong deviations from overall linear trends, though in some instances breakpoints are suggested visually though difficult to confirm statistically.
- Unlike many other hydrological time series, such as rainfall, true extreme values are rare, by any customary measure .
- The time series usually exhibit some level of “persistence”, or tendencies to display runs of years that lie above or below trend. These rarely form regular cycles, however.
- Handling missing data is not a trivial question with these records (Table 1 above). Further, how to properly treat the years that did not freeze (DNF) is a quandary. This is a problem when seeking to compare averages between time periods, but not when using time as an independent variable. For this analysis, years that did not freeze are treated as missing data, but where they are important, they are discussed and charted separately, with several examples are given below.

This list of lakes, as noted above, is not a “sample” of the region’s population of lakes. Conclusions apply only to this list of lakes.

The records vary considerably in completeness and length. For sources, see Appendix Table 1. The longest is 205 years for Lake Champlain (ice in only), though it has significant gaps. Several exceed 150 years (Table 1 above) . The shortest record for duration is Lower St Regis Lake with only 30 years.

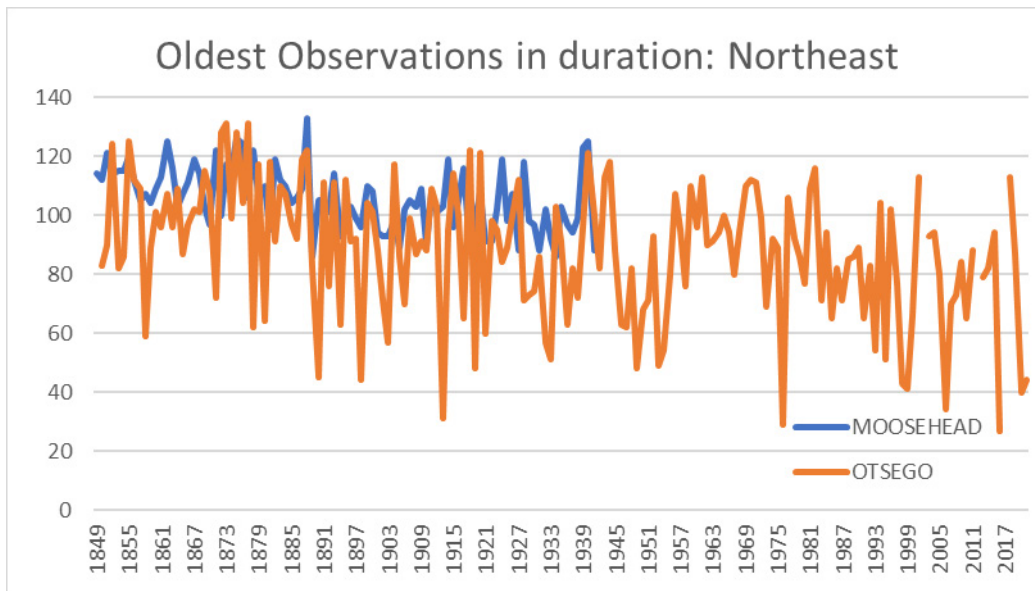
### Statistical Methods

For the eight lakes with the longest records, we used a smoothing function in R. For most of the Lakes we used the loess function, Sen’s slope and the Mann-Kendall statistic are used to analyze trends in the time series. These two methods are non-parametric and, unlike linear regression, do not assume specific data distributions. Linear regression assumes that residuals are independent of each other, while time series are often autocorrelated. We used the Durbin-Watson statistic to examine autocorrelation. The linear regression is shown for illustrative purposes (red line in the graphs). In this paper, we have graphed the records to illustrate trends. Further we examined differences in ice-in and ice-out, frequency of no freeze years, freezing and summarize the detailed ice cover data on The Great Lakes. For 21 lakes, we examine two periods to examine whether the probability density for recent 30-year periods of ice duration are significantly different. Probability density curves compare the two periods.

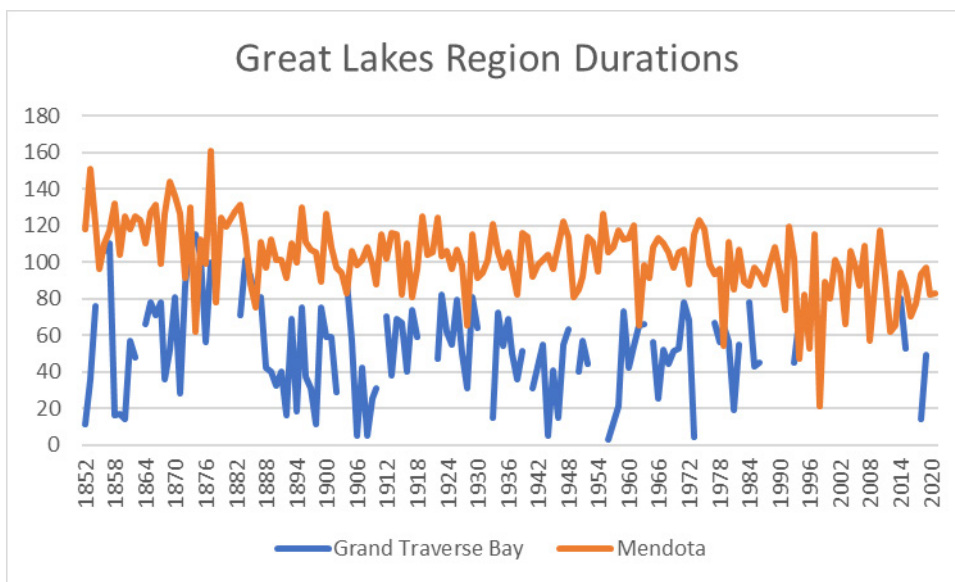
### Results

#### Long-term results for Eight Lakes, 1849-2021

Charting the longest records, we observe shorter ice duration counted in days, shorter episodes of persistence, and gaps in the records are all evident. It seems there was a period of moderate volatility in the middle years and then an increase. Charts of several lakes with the longest records, shown separately for the Northeast and Midwest, illustrate the above-mentioned points on statistical traits and exhibit broad patterns of change (Figures 2, 3).

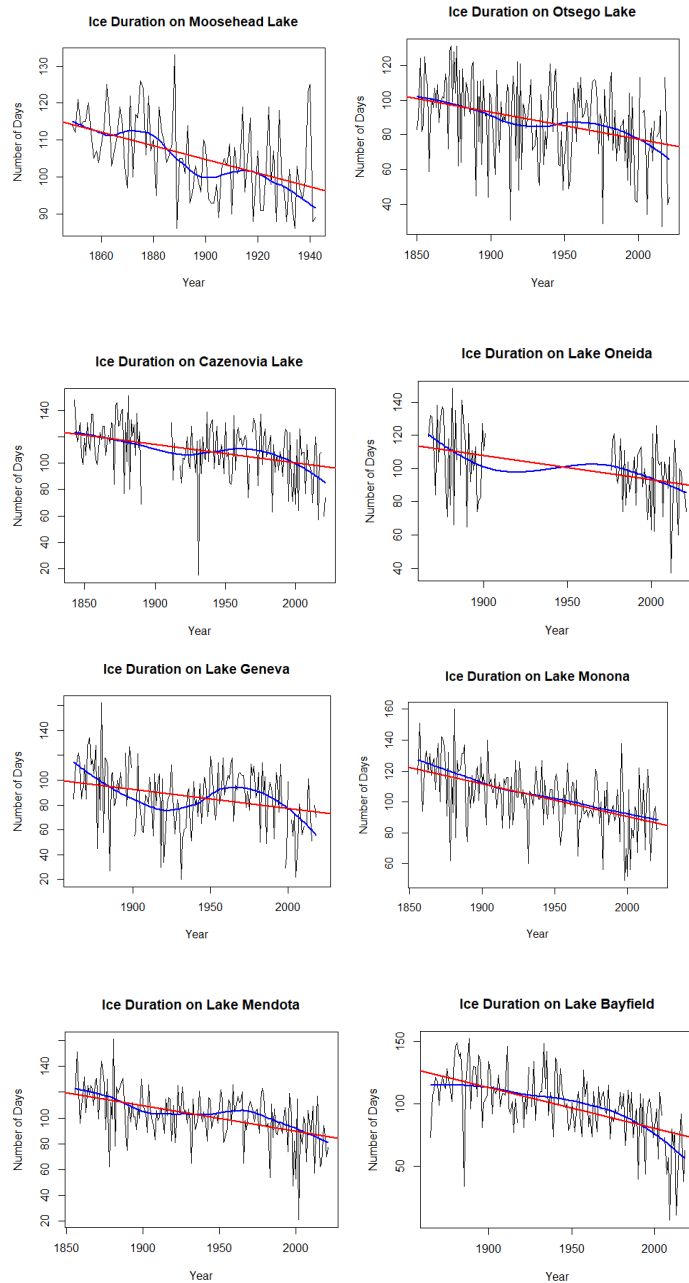


**Figure 2: Two Northeastern Lakes with Data from 19th Century**



**Figure 3 Four Midwestern Lakes with Data from 19th Century**

Interestingly, in the annual data, the smoothed curves show an increase after an initial falling for six of the eight lakes. (Lake Monona and Bayfield are the exceptions.) The Kendall-Mann statistic calculated on the ice duration days show a moderately strong to a strongly negative trend. All the statistics were significant at the  $\alpha=0.05$ , meaning that these are not random. A Durbin-Watson statistic near zero as it is for these lakes suggests that our current model using only consecutive years as an independent variable does not adequately account for the time-dependent structure in the data. For the listed lakes the Durbin-Watson statistic was also significant at least a probability of  $\alpha=0.05$ .



**Figure 4: Smoothed Trends for Eight Lakes.**

Lake name	Regression	Adjust. r2	Kendall- Mann	Sen's slope	Durbin-Watson
Moosehead	458.40- 0.181*(Year)	0.211	-0.357	-0.207	0.016
Otsego	386.06- 0.154*(Year)	0.106	-0.222	-0.149	0.177
Cazenovia	384.493- 0.142*(Year)	0.142	-0.216	-0.131	0.066
Oneida	385.321- 0.146*(Year)	0.133	-0.291	-0.183	0.058
Geneva	380.778- 0.151*(Year)	0.070	-0.182	-0.148	0.125
Mendota	482.19- 0.197*(Year)	0.227	-0.324	-0.178	0.058
Monona	511.054- 0.210*(Year)	0.256	-0.369	-0.214	0.057
Bayfield	733.709- 0.327*(Year)	0.327	-0.427	-0.303	0.075

**Table 2: Regression, Adjusted r2, Kendall-Mann, Sen's Slope and Durbin-Watson Statistics for 8 Lakes.**

Based on regression estimates, changes in ice duration varied widely across the 21 lakes (Table 3). In part, this is due to different lengths of record available. Average changes per decade, estimated by regression, range from less than 1 day (3 lakes) to more than 4 days per decade (5 lakes)

<b>21 Lakes: Change in duration per decade and No of Decades of Record</b>		
<b>Duration</b>	<b>Decline /Decade</b>	<b>No. Decades</b>
L Auburn, ME	4.7	6
Mirror Lk, NH	4.4	5
Stiles Pond, VT	5.8	5
Otsego Lake NY	1.9	17
Catlin Lake NY	3.4	4
Lake George NY	0.3	12
Lower St Regis Lake NY	5.2	3
Mirror Lk NY	4.1	12
Oneida Lake, NY	1.3	11
Cazenovia Lake NY	1.6	18
Grand Traverse Bay MI	1.2	15
Lake Mendota, WI	2	17
Monona WI	1.9	16
Green WI	0.4	7
Geneva WI	0.8	16
Shell WI	1	12
Bayfield WI	3.3	17
Detroit MN	1.2	12
Bemidji MN	2.1	6
Itasca MN	1	9
Waconia MN	0.1	8

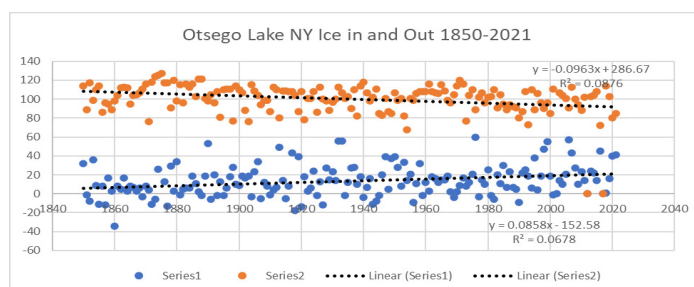
**Table 3: 21 Lakes Change Per Decade Over Period of Record, Ols Estimates**

The longest records available are for 7 lakes across the region; the changes in ice duration since the second half of the 19<sup>th</sup> century are impressive: as long as 34 days. Three of these are in New York, one in Michigan, and three in Wisconsin

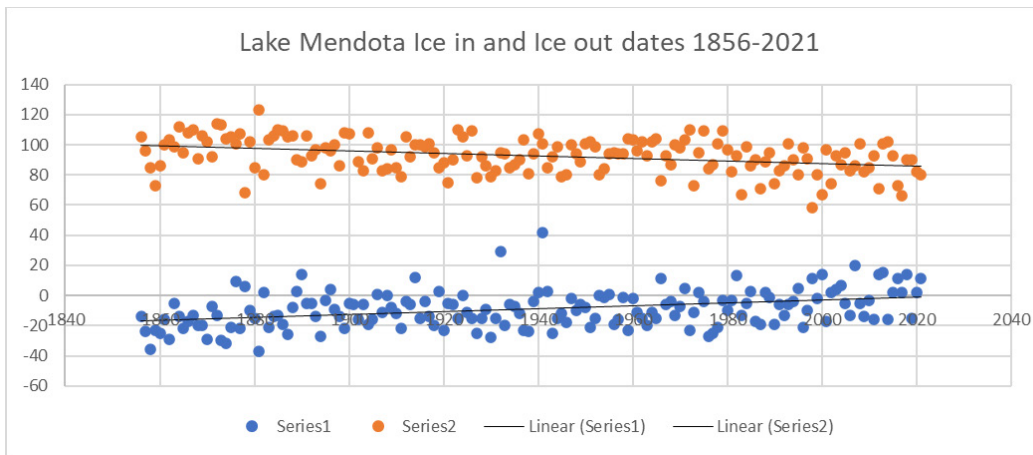
In previous unpublished research on Maine lakes, 11 of 22 lakes showed no statistically significant in changes in ice out dates for last 30 yr. versus the previous 30 year (t-test with allowance for different variances, MS in author possession) [37]. That work and this regional study of durations fit with Magnuson’s conclusions: “Importantly, for ice freeze time series, 20 and 50 years of data were insufficient to detect climate change while longer records did; large-scale climate drivers like El Niño, the North Atlantic Oscillation, as well as local weather influenced inter-year dynamics of lake ice seasonality; inter-year dynamics between lakes were coherent locally and persisted regionally at lower values; extreme ice dates changed in the direction of a warming climate; and changes in lake ice already have affected people negatively”.

**Later Freeze, or Earlier Thaw?**

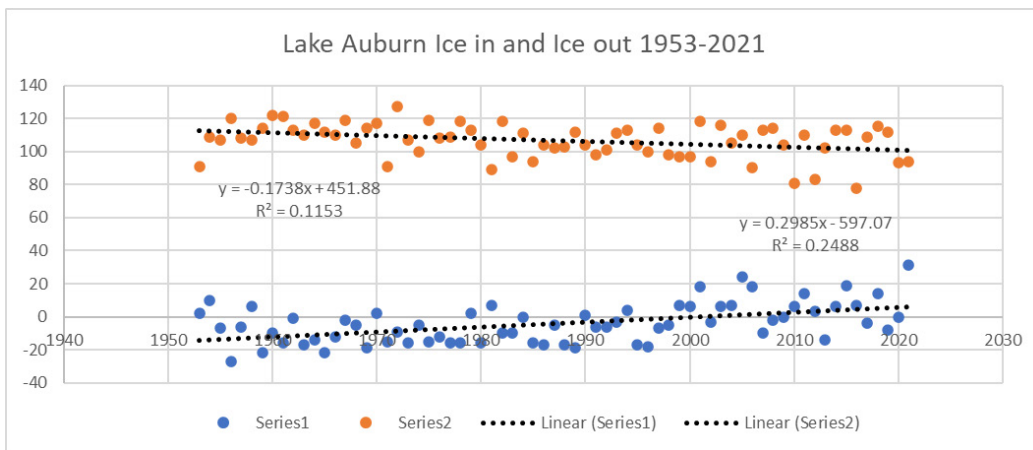
A natural question to bring to this data is this one: which season most influences duration—is it the onset of winter, or the spring melt? The long records for Otsego Lake, Lake Mendota, and Lake Auburn illustrate the typical pattern -- both seasons matter (Figures 5-7) [2].



**Figure 5: Otsego Lake ice-in and ice out. 1858 -2021**



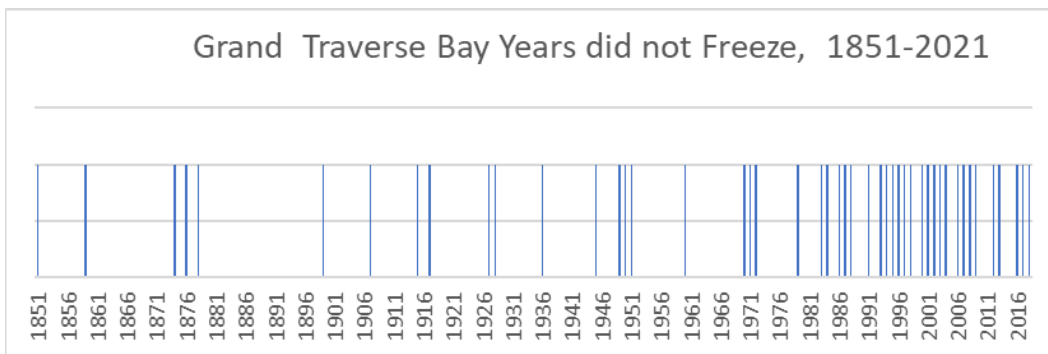
**Figure 6: Lake Mendota ice in and ice out 1856- 2021**



**Figure 7: Lake Auburn ice in and ice out, 1953-2021**

**Increasing Frequency of No Freeze Years**

For some lakes, the balance between freezing influences, and those preventing freezing, mostly temperature and wind, has long been fragile. Several show increased frequencies of no freeze years. At Grand Traverse Bay, in the later 19<sup>th</sup> century the interval between no freeze years was as long as 18 years. After 1997, it only froze 6 times out of 24 years (Figure 9). Otsego Lake recorded no DNF years until 2002; since 2001 it has failed to freeze 3 times.



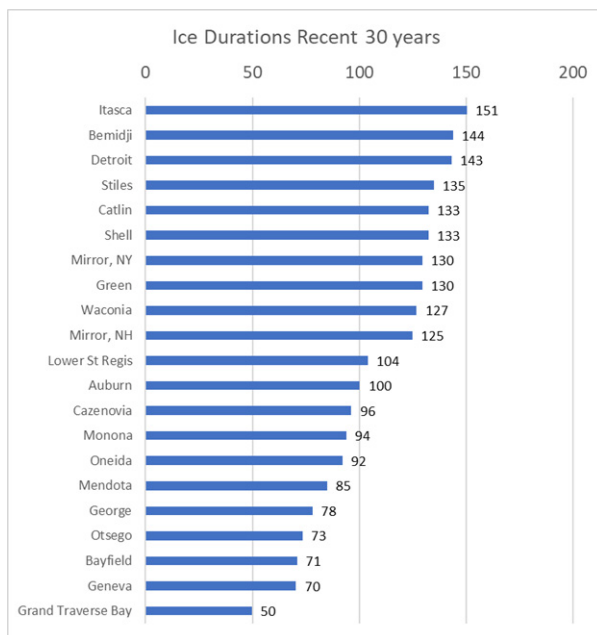
**Figure 8: Years that Grand Traverse Bay did not freeze**

Though the Lake Champlain record only shows ice in dates, this indicates failure to freeze years. From 1900 to 1929, it did not freeze on one occasion; from 1940-1969, 9 times, and from 1980 to 2021, 27 times, or more than half of the years. Lake George (record beginning 1908) only failed to freeze once before 1988 (in 1919), and since has failed to freeze 12 times. Since the mid 80's, Grand Traverse Bay has remained at least partially open more often than not (Figure 8).

Sebago, a large lake near the Gulf of Maine in southern Maine, has an exceptionally long record of ice-out dates, but it enables us to track DNF years. This lake is large and consists of several very large bays which can freeze even when others do not. The record is complete from 1871 but for only 2 missing individual years. The earliest DNF noted was in 1937. This was followed by a series of 5 DNFs from 1947 to 1961. Recently, from 2010 to 2022, it DNF 9 times, and froze only 2 days in 2023.

### Are Recent Shifts in Duration Statistically Significant?

For the last 30 years, ice durations varied across a wide range, from 50 days (Grand Traverse Bay), to 151 days (Itasca) (Figure 12)



**Figure 9 : Ice durations across the lakes for 30 years.**

In this section, we examine changes in ice duration for 30-year periods from 1962 to 1991, compared to 1992 to 2021. The periods were selected for the lakes with the most complete data sets, and because 30-year means are in common use in meteorology. If we were to compare the most current period to an older period, we believe that the comparisons would be more dramatic.

Table 4 lists the counts, means, medians and variances of ice duration for the two periods. For every lake, the mean of ice duration for Period 1 is smaller than for Period 2. Similarly, for every lake, the variation is smaller for Period 1 than for Period 2. This means that ice duration was lower in the second period than they were for the previous period, as well as more variable. Yet, only 10 of the 21 lakes showed statistically significant differences in the means by these analyses. Very large increase in variances are one reason for this.

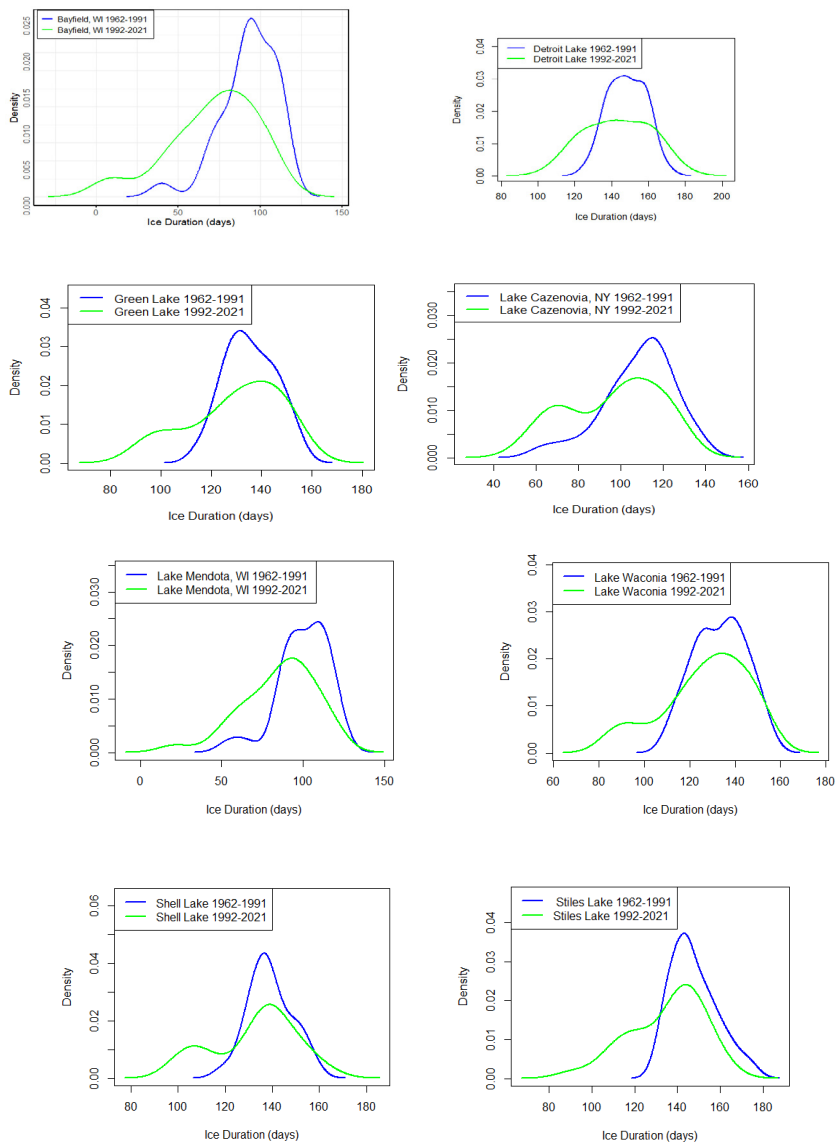
This is well illustrated by the graphs (Figure 10). We calculated and graphed the probability density function for the ice duration data for each periods for each lake. Then we used either the Bartlett or Fligner test to determine whether the variation is significantly different between the two time periods.

Lake	Count		Mean		Change in	Variation		
	1962-1991	1992-2021	1962-1991	1992-2021	Means	1962-1991	1992-2021	
<b>Statistically Significant Change</b>								
Cazenovia.NY	29	29	109.1	96.1	13.0	280.6	459.1	
Mendota.WI	30	30	100.6	85.1	15.5	234.8	497.2	
Bayfield.WI	30	26	92.6	72.7	20.0	269.7	692.6	
Detroit	30	23	147.9	143.8	4.1	100.3	313.2	
Shell	28	29	138.5	133.3	5.3	81.4	304.9	
Waconia	29	30	132.7	127.7	5.0	124.6	340.2	
Stiles	20	30	148.4	135.0	13.5	109.6	289.5	
Green	30	28	135.4	129.8	5.7	98.4	323.8	
<b>Nonsignificant</b>								
Catlin	14	28	142.5	133.1	9.5	127.6	194.5	
Otsego.NY	30	27	89.1	73.1	16.0	310.3	576.4	
Oneida.NY	16	30	99.5	91.7	7.7	200.5	399.2	
Geneva.WI	30	23	93.9	69.7	24.2	332.9	538.2	
Monona.WI	30	22	96.1	93.6	2.5	188.7	451.4	
George	29	19	86.6	78.2	8.4	268.3	493.3	
Mirror NY	30	20	140.0	129.2	10.8	156.1	323.0	
Itasca	18	21	155.5	151.1	4.4	100.8	216.4	
Auburn	30	30	118.7	100.4	18.2	149.3	260.8	
Mirror NH	23	30	135.0	124.8	10.2	113.1	251.7	
Bemidji	26	30	149.4	145.0	4.4	190.4	231.7	

**Table 4: Counts, means, medians and variances for the two periods for 19 lakes with the best recent data. (Yellow highlights indicate significant difference between periods  $\alpha=0.05$ )**

To look further than the bare statistics, Figure 10 plots the probability density functions for the two periods for the 8 lakes. It should also be remembered that the increased frequency of DNF days for some lakes has inflated the variances. Eight of the lakes showed significant differences in variability at a probability  $\alpha = 0.05\%$ . Looking at the graphs for those eight lakes, we can see that the tails for curves for the second period extend well beyond the tails for the first period. For the remainder, variances were not Statistically significant.

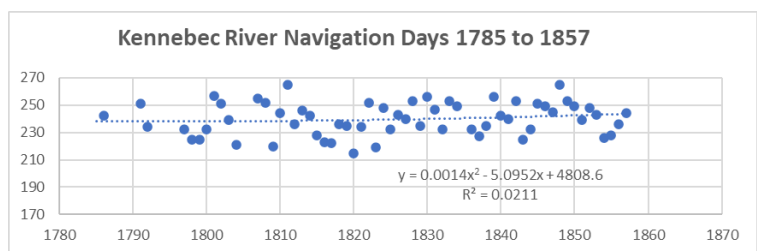
Chart 10. Graphs of Probability Density Function for those lakes whose variation is significantly different from Period 1: 1962 to 1991 (blue) and Period 2: 1992 to 2021 (green).



**Figure 10: Plots of Annual probability density functions for 8 lakes.**

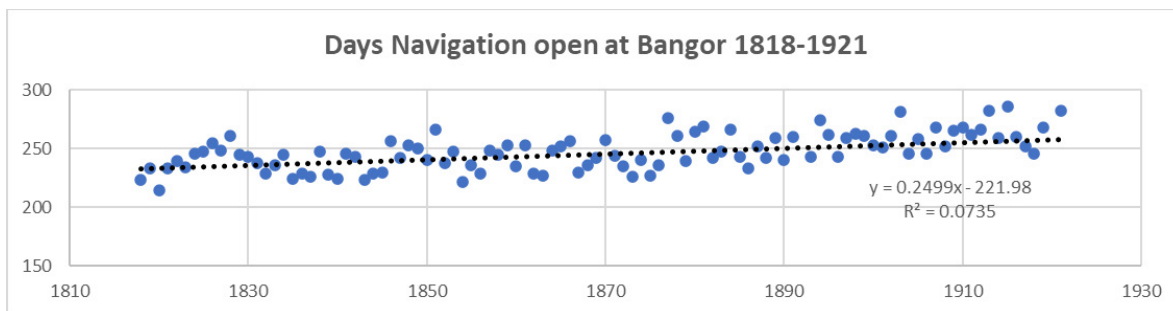
### Legacy Navigation Data for the Northeast

In the quest for long records on ice conditions, commercial records are not often used by science. These records the advantage of being kept by motivated individuals and organizations whose offices stood right at the waterfront. They were often publicly reported in local newspapers. Here we review three examples from Maine. The earliest dates to just before year the US Constitution was ratified. On the Kennebec, from 1785 to 1857, navigation days increased by 2 tenths of a day per decade, a negligible trend considering the interannual variability (Figure 14). During this period the river was active in international trade from ports as far upstream as Hallowell.



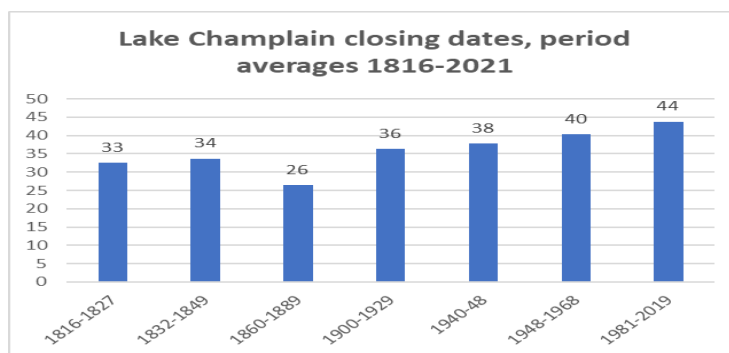
**Figure 11: Days of navigation at Hallowell, Maine 1785-1857.**

Ice conditions at Bangor are available from 1818, 2 years before statehood, until 1921, a century of records. In Thoreau's time, Bangor shipping served destinations around the world in addition to a busy coastwise trade. Waterborne trade declined in Bangor after the early 20<sup>th</sup> century, likely explaining the cessation of this record. Navigation days increased by 0.7 days per decade (Figure 12).



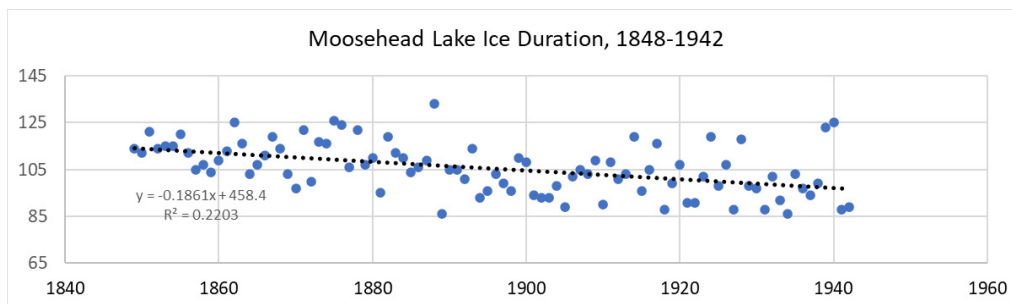
**Figure 12: Days of navigation at Bangor, Maine 1818-1921.**

Ice records on closures were originally based on a ferry service between Plattsburg, New York and Grand Isle, Vermont. Records on ice out dates, however, have not been preserved. Since the series has many gaps, so 20-year averages are shown here. Since the 1820's, closing dates have moved later by 11 days (Figure 16). Further, the frequency of years where no freezing occurs has increased notably (see previous section).



**Figure 13: Averages, closing dates on Lake Champlain 1816-2021**

Moosehead Lake is the largest in Maine, and has been dammed since the mid-1830s. Ice-in observations unfortunately end in 1940, when a local ferry service ceased operations (Figure 17). Still, the record preserves a century's record for a period when other observations are scarce, and in a part of Maine totaling lacking other recorded observations. Here, duration changed rapidly compared to the above rivers, losing 2.2 days per decade over this near-century.

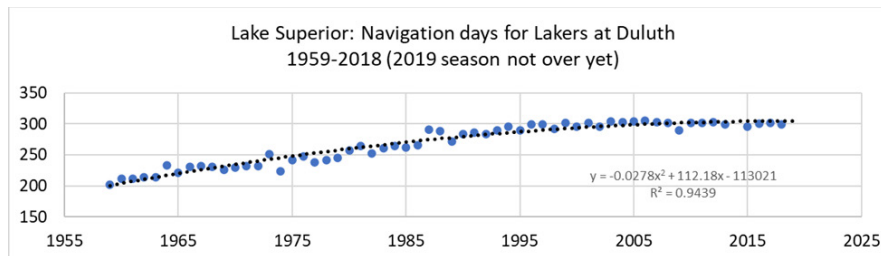


**Figure 14: Moosehead Lake Ice durations 1848-1942.**

Over the periods shown, ice conditions could have been affected by construction of upstream dams, changing conditions in watersheds due to timber cutting and damming of headwater streams, changes in vessels and their ability to navigate icy conditions, commercial ice harvesting, and possibly other factors. Hopefully making these available will stimulate historical research to uncover other proxy records of this early period, which may encompass the waning decades of the Little Ice Age.

**Current Navigation Data**

Navigation dates and other data on commerce can be useful proxy indicators of ice phenology, though subject to many limitations. On Lake Superior, navigation dates for "Lakers" (ships confined to the Lakes by their size) increased by 78 days between the 60's and 2009-2018. Note that presumably due to icebreaking, the navigation days are not sensitive to the large fluctuations in ice cover from year to year.



**Figure 15: Navigation days at Duluth, Minnesota 1959-2018.**

For the ferry to Madeline Island at Bayfield, records from 1857 to 2007 showed that ice cover declined by 45 days, or 3 days per decade. The change was most rapid since 1975 [38]. These are substantial changes, although they may have been affected by changes in ships and icebreaking technology and policies. Records on river ice jams are widely studied in Canada, as are navigation conditions on the St Lawrence Seaway. We believe data sources of this kind have been underexplored as proxy records of climate change.

## Discussion

Ice conditions are important for local businesses and property owners, as well as recreationists. Some states publish ice out dates on the Web to advise boaters and warn ice anglers of unsafe conditions [4]. Studies have documented the increased frequency of loss of life due to falling through ice [6]. A classic record, kept by Thoreau at Walden Pond in the 1840s, was read recently but were unable to determine if this record is currently being updated [39]. Primack's comparison of 1845-1860 with his own observations for 1995-2009 showed ice outs earlier by 15 days, or one day per decade.

Changes in lake ice affect social functions in lakeside communities, including ice fishing derbies. They have made news as they have affected menus of fish fry events [40]. Some lake groups and communities hold lotteries for guessing ice out dates, often with amusing ways to mark the date and time to choose winners. Unfortunately, records are not always kept. Some important records are kept by lake associations and local towns. Regional and temporal patterns described in this study may have more to do with where interested scientists and recordkeepers were located and when they started keeping records than any strong, generalizable scientific relationships. While they show individually weak associations, the cross section geographic comparisons may be of interest.

Records are often incomplete. In past unpublished research on a list of 36 Maine and New Brunswick lakes, there was no year in which more than 31 of them had observations [37]. That number fell to 20 lakes in 2012, and returned to 25 by 2020. The reasons were missing data. In a few instances, on large lakes with very long records, observations had ceased being taken at all. The result was that in Maine, there were only 20 lakes with long enough records to compare the time periods 1990-2020 and 1960 to 1989. Also, in a few instances, observers recorded situations when a lake froze, and opened again after windy weather before finally freezing. In those cases, latest freeze dates were chosen. Observers on more lakes are recording ice observations today, and some include ice-on observations, but these are ones with short records. An example is Acadia National Park where ice in and ice outs are being recorded on several small lakes since 2010.

In New England, there are gaps in geographic coverage. We have no observations for the northwestern forests along the Allagash and St John in Maine. Eastern Maine has only a few sites and they may not be representative. Vermont and New Hampshire offer few very long records, as does Michigan. Southerly margins of the region have none that are readily available south of Maine's Sebago Lake. Observations in southern New England would be valuable, as well as northern Ohio, Pennsylvania, Indiana, and Illinois. In those areas, ice harvesting was a significant local industry in Thoreau's time; it was not eliminated by climate changes but by pollution and the early stages of refrigeration [41]. devotes a chapter to the social side of the ice industry along the Kennebec, which by his time had passed into history [42]. Commercial records from this industry that may survive in business papers could be revealing.

In aggregate analysis of large samples of time series, size distributions of lakes may play a larger part in results without intense data comparisons, especially paying attention to the differing lengths of record. This threatens statistical significance of any comparisons with long weather cycles.

It is likely that hand-kept records have been preserved in unlikely places, such as sporting camps, lake associations, resorts, and records of dam owners and log driving companies, as well as records of ice breaking activities on navigable waterways. Pursuing these would be a fruitful field for historical research.

## Conclusions

Ice out dates have long been used as climate change proxies. For many regions in the Northeast, they span far longer periods than do instrumental records of temperatures. But in the Northeast, the dataset is sparse for tracking long-term trends and variability in ice durations. This is especially true for records starting in the mid to late 19<sup>th</sup> century. Yet a few observations seem warranted. On some large lakes in the Northeast, January is no longer "pure winter"... several

are now ice free all winter in almost every year. Data gathering is now deteriorating, and science is losing long-term records as observations fail to be taken or recorded, or are not made generally available.

Comparisons of the longest available records for eight lakes across the Northeast show a remarkable consistency in linearity of the long-term trends. Sen slopes are all significant. Yet, notable periods of persistence appear as well. When expressed in terms of average change per decade, the longest records showed declines in duration ranging from 0.3 days to 4.1 days per decade. This region, then would be fruitful area for further exploration of possible influences causing these differences.

Over the past 60 years, comparisons can be made for 19 lakes. For ten of these, the mean ice durations were significantly shorter for ten of them, when comparing the first 30 and more recent 30-year periods. In addition, all of the lakes showed higher variances between these two periods, which were statistically significant for 8 of them. Finally, there is good reason to encourage further searches for well documented records in other sources, including those produced by navigational and commercial records such as those presented here.

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**Foot Notes:**

<sup>1</sup> HD Thoreau, Journal Feb 9, 1854

<sup>2</sup> One such measure is existence of observations exceeding 3X the standard deviation.

**Appendices**

**Appendix Table 1**

Lakes	Ice In data	Ice Out data	Town (s)	Dist from coast (km)	Elev of MWL (metres)	Water Area (ha)	Latitude	Longitude	Max depth (metres)	Mean depth (metres)	NCDC Climate Division
L Auburn, ME		X	Auburn	37	88	921	44.1	-70.3	36	11	3
Moosehead Lake, ME	Partial	X	Greenville	90	314	30,542	45.7	-69.7	75	17	1
Mirror Lk, NH	X	X	Woodstock	74	213	15	43.9	-71.7	11	6	2
Stiles Pond, VT	X	X	Town of Waterford	160	267	24	44.4	-71.9	8	4	1
Otsego Lake NY	X	X	Cooperstown	241	364	1,637	42.8	-74.9	51	25	2
Lake Champlain, NY and VT	Partial	none	New York and Vermont	267	30	133,142	44.6	-73.4	122	20	Vermont 2
Catlin Lake NY	X	X	Huntington Forest Newcomb	296	486	217	43.2	-74.1	17	9	3
Lake George NY	X	X	6 towns; Lake George	262	98	11,655	43.6	-73.6	60	21	5
Lower St Regis Lake NY	partial	X	Brighton	329	494	142	44.4	-74.2	12	5	3
Mirror Lk NY	X	X	Lake Placid	298	566	49	44.3	-73.9	18	4	3
Oneida Lake, NY	partial	X	Oneida and Oswego Counties	320	112	20,670	43.1	-75.6	27	7	6
Cazenovia Lake NY	partial	X	same	321	363	471	42.9	-75.9	14	8	6
Grand Traverse Bay, W. Arm, MI	X	X	Traverse City	1,108	177	71,773	44.9	-85.6	190	101	3
Lake Mendota, WI	X	X	Madison	1,308	259	3,958	43.1	-89.4	25	13	8
Lake Monona, WI	X	X	Madison	1,299	256	1,325	43.1	-89.3	22	8	8
Green Lake, WI	Partial	Partial	Ripon	1,282	245	2,973	43.8	-88.9	72	30	6
Lake Geneva, WI	X	X	Lake Geneva	1,221	268	2,186	42.5	-88.4	41	16	9
Shell Lake, WI	X	X	Shell Lake	1,556	380	1,017	45.7	-91.8	10	11	1
Detroit Lakes, MN	Partial	X	Detroit	1,878	417	1,455	46.8	-95.8	27	5	4
Bemidji Lake, MN	Partial	Partial	Bemidji	1,828	406	2,848	47.4	-94.8	23	10	2
Waconia Lake, MN	X	X	Victoria	1,679	294	1,294	44.8	-93.7	11	6	5
Lake Itasca, MN	Partial	X	Lake Itasca	1,845	450	466	47.2	-95.2	12	6 to 10	2
Bayfield Wisconsin	Partial	Partial	Bayfield	1,658	180	n/a	46.8	-90.8	n/a	n/a	1

**Table 5:**

**Appendix Table 2**

Table	Data Sources	Locations are the offices not the sites themselves
<b>Lake</b>	<b>Source</b>	<b>Location</b>
Catlin Lake	SUNY CESF, Huntington Forest	New comb, NY
Stiles Pond	Fairbanks Museum	St. Johnsbury VT
Mirror Lake, NH	Hubbard Brook Experimental Forest	Durham NH
Lake Auburn	Auburn Water and Sewer District	Auburn ME
Lake George	Lake George Association	Lake George NY
Lower St Regis Lake	Paul Smiths College	Paul Smiths NY
Mirror Lake, NY	Au Sable River Assn	Wilmington NY
Cazenovia Lake	Cornell Biological Station	Shackelton Pt, NY
Moosehead Lake	Maine Bureau of Parks and Lands	Augusta, Maine
Oneida Lake	Cornell Biological Station	Shackelton Pt, NY
Lake Mendota	University of Wisconsin	Madison
Otsego Lake	SUNY Oneonta Lake Campus	Cooperstown, NY
Grand Traverse Bay	The Watershed Center	Traverse City MI
Lake Champlain	National Weather Service field office	Burlington VT
Waconia	<a href="https://www.dnr.state.mn.us/ice_out/index.html?year=1940">https://www.dnr.state.mn.us/ice_out/index.html?year=1940</a>	visited 8.25.22
Bemidji	same	""
Itasca	same	""
Detroit	same	"
Green	Shama et al. 2022	internet
Geneva	Shama et al. 2023	internet
Shell	Shama et al. 2024	internet
Monona	Shama et al. 2025	internet
Bayfield (Superior)	Howk, 2009	internet

**Table 6:**

**Appendix Table 3**

<b>Appendix Table Shapes and Setting of Lakes Studied</b>					
<b>Lake</b>	<b>Dam</b>	<b>Shape</b>	<b>Shoreline Development</b>	<b>Landscape</b>	<b>Topography</b>
L Auburn, ME	Y	roundish with arm	mun. WS, 15%	suburban	moderate
Moosehead Lake	Y	complex; islands	pockets of dvlpmt	Private forest	rugged
Mirror Lk, NH	Y	oval; slight bend	10%	nat forest	rugged
Stiles Pond, VT	Y	oblong	0	forest (road 1 shore)	moderate
Otsego Lake NY		elongated	40%	forest farm	moderate
Lake Champlain, NY and VT		elongated	90%	forest or farm	moderate
Catlin Lake NY		elongated; chain	0	forest pres	moderate
Lake George NY	Y	elongated	30% -- pockets	forest or farm	moderate
Lower St Regis Lake NY		roundish; chain	10%	forest pres.	moderate
Mirror Lk NY		oval to long	100%	urban or forest	moderate
Oneida Lake, NY		oblong	90%	woods & farms	
Cazenovia Lake NY		elong; tapered	100% but for bogs	farms woods	flat
Grand Traverse Bay MI		elong. Bay; 2 arms	90%	farms orchards	moderate to flat
Lake Mendota, WI	Y	Roundish	95%	urban farms	flat
Lake Monona, WI		Oval; chain	90%+	suburban	flat
Green Lake, WI	Y	Elongated	80%+	Camps; suburban	flat
Lake Geneva, WI		Oblong	100%	camps, suburban	low rolling
Shell Lake, WI		Round, peninsulas	95%	camps	flat
Detroit Lakes, MN		round w peninsula		camps	flat
Bemidji Lake, MN		Oblong	90%	urban, camps	flat
Waconia Lake, MN		Round	60% but 100% roads	suburbs camps	flat
Lake Itasca, MN		Irregular	5%	wooded; state park	moderate
Bayfield Wisconsin		Channel to island	High	Wooded	moderate

**Table 7:**