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HISTORICAL CHANGES IN LAKE ICE-OUT DATES AS INDICATORS OF CLIMATE CHANGE IN NEW ENGLAND, 1850–2000

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ABSTRACT

Various studies have shown that changes over time in spring ice-out dates can be used as indicators of climate change. Ice-out dates from 29 lakes in New England (USA) with 64 to 163 years of record were assembled and analysed for this study. Ice-out dates have become significantly earlier in New England since the 1800s. Changes in ice-out dates between 1850 and 2000 were 9 days and 16 days in the northern/mountainous and southern regions of New England respectively. The changes in the ice-out data over time were very consistent within each of the two regions of New England, and more consistent than four air-temperature records in each region. The ice-out dates of the two regions had a different response to changes in air temperature. The inferred late winter–early spring air-temperature warming in both regions of New England since 1850, based on linear regression analysis, was about 1.5 °C. Published in 2002 by John Wiley & Sons, Ltd.

KEY WORDS: lake ice-out dates; lake ice break-up; New England; trend analysis; temperature; climate change; Mann–Kendall; LOESS

1. INTRODUCTION

Lake ice-out dates, or the dates of ice break-up, are the annual dates in spring when winter ice cover leaves a lake. Ice-out dates correlate most strongly with air temperatures in the month or two before ice-out (Tramoni *et al*., 1985; Palecki and Barry, 1986; Robertson *et al*., 1992; Livingstone, 1997). Many studies in the last 15 years have used Northern Hemisphere lake ice-out dates as climatic indicators (Tramoni *et al*., 1985; Palecki and Barry, 1986; Rousteenoja, 1986; Robertson *et al*., 1992; Assel and Robertson, 1995; Anderson *et al*., 1996; Livingstone, 1997; Magnuson *et al*., 2000). In Northern Hemisphere mid-latitude areas such as New England, ice-out dates can serve as useful indicators of late winter and early spring climate change. Changes over time in lake ice-out dates can have important effects on aspects of lake ecology, such as the rate of summer oxygen depletion (Stewart, 1976), and the productivity and abundance of phytoplankton (Maeda and Ichimura, 1973) and organisms at higher trophic levels (Porter *et al*., 1996).

2. DATA AND METHODOLOGY

A remarkable amount of lake ice-out data have been recorded and saved in New England over the past two centuries. For some lakes in New England, such as Moosehead Lake (lake 4 in Figure 1), ice-out dates were important for local steamship transportation. Data from other lakes, for example Richardson Lake (lake 9), were important for annual log drives. Individuals have collected and saved extensive data because of general

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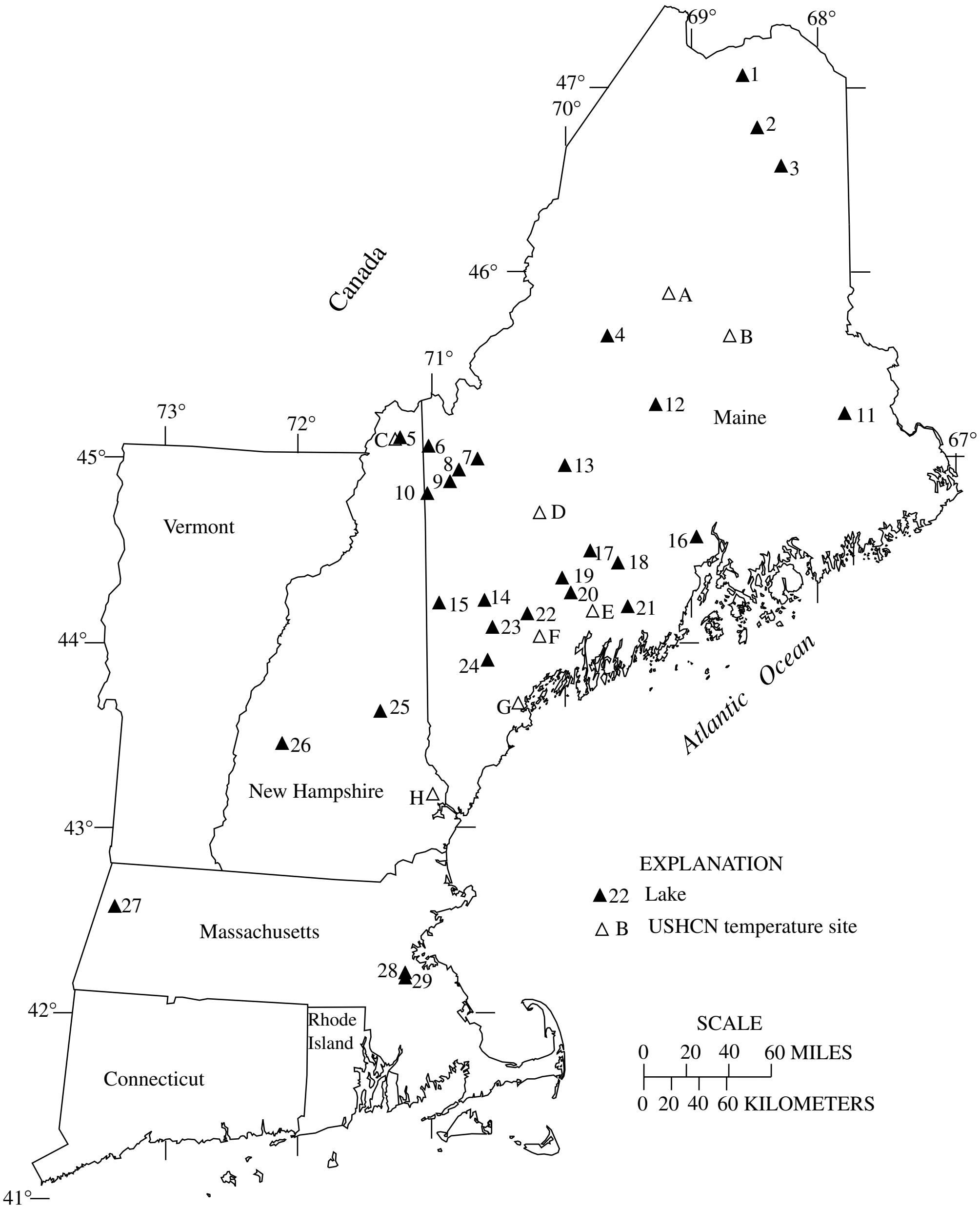

Figure 1. Location of lakes and US Historical Climatology Network (USHCN) temperature observation sites in New England. Lake names are shown in Table I

curiosity and community interest. For Damariscotta (lake 21) and West Grand (lake 11) Lakes, the same family has been collecting ice-out data for three generations. Lake ice-out dates for 29 lakes in New England were assembled (Hodgkins and James, 2002) and analysed in this study (Figure 1, Table I). Five lakes had more than 150 years of data and 16 had more than 100 years of data. More long-term data (greater than 100 years of record) were available for New England than has been previously reported for all of North America (Magnuson *et al.*, 2000). Long-term lake ice-out data for many lakes in New England represent a

Table I. Mann–Kendall trend tests for New England lakes. Locations are shown in Figure 1

Lake number	Lake name	Period of record	Years of record	p value
1	Eagle	1922–2000	67	0.74
2	Portage	1925–2000	75	0.067
3	Squa Pan	1930–99	64	0.84
4	Moosehead	1848–2000	153	<0.0001
5	First Connecticut	1920–2000	81	0.42
6	Aziscohos	1913–2000	86	0.93
7	Rangeley	1880–2000	121	0.016
8	Mooselookmeguntic	1884–2000	99	0.20
9	Richardson	1880–2000	119	0.028
10	Umbagog	1880–2000	110	0.021
11	West Grand	1878–2000	123	0.0012
12	Sebec	1879–2000	120	0.060
13	Embden	1925–2000	76	0.38
14	Pennesseewassee	1874–1999	125	0.0011
15	Kezar	1901–99	99	0.90
16	Swan	1891–2000	110	0.011
17	Messalonskee	1909–2000	67	0.12
18	China	1874–2000	74	0.0040
19	Maranacook	1925–2000	76	0.023
20	Cobbosseecontee	1840–2000	159	<0.0001
21	Damariscotta	1837–2000	163	<0.0001
22	Auburn	1836–2000	158	<0.0001
23	Thompson	1902–2000	99	0.092
24	Sebago	1807–2000	160	<0.0001
25	Winnipesaukee	1887–2000	114	0.11
26	Sunapee	1869–2000	132	<0.0001
27	Pontoosuc	1925–98	74	0.51
28	Houghtons	1886–2000	115	0.0001
29	Ponkapoag	1886–2000	115	<0.0001

unique hydroclimatic data set that is useful for regional climate modelling and continued monitoring of the geophysical response to regional climate change.

Most of the lakes in this study are located in rural areas. Lakes in northern Maine and northern New Hampshire generally drain remote, undeveloped forests. Lakes in southern Maine and southern New Hampshire generally drain rural areas with forests, some low-density residential development, and small towns. Auburn (lake 22), Houghtons (lake 28), Ponkapoag (lake 29), and Pontoosuc (lake 27) Lakes are in or near urban areas. The ice-out dates for these lakes may be affected by urban heat island temperature effects. It is unlikely that any activities occurred on the rural lakes in this study or on their inlet streams, such as warm-water discharges, that would affect the trends in ice-out dates over time. Large amounts of forest have replaced farmland in southern Maine and southern New Hampshire over the last 120 years. Counties in southern Maine were 35–50% forested in 1880, whereas in 1995 they were 70–80% forested. Counties in northern Maine were 85–90% forested in 1880 (Irland, 1998). The effects of reforestation on lake ice-out dates are unknown.

It is unlikely that ice-out trends in the lakes in this study were affected by anthropogenic changes in lake morphometry. The lakes in this study have probably had some water-level changes over the last 150 years. However, most lakes in northern New England existed as natural lakes prior to being dammed for commercial activities (typically mills on outlet streams and log driving). Wynne *et al*. (1996), in their study of Canadian and American lakes, found a lack of importance of any measures of lake morphometry, including depth and surface area, on the temporal coherence of ice-out dates.

Ice-out definitions for individual lakes can vary over time and between observers. Some 20 years or more of overlapping data from independent observers were available for six lakes. The mean difference in reported ice-out dates for all years of overlapping record for each of 11 observer pairs was computed at these lakes. The three lakes with relatively round shapes (Auburn, lake 22; First Connecticut, lake 5; and Sebago, lake 24) had mean differences between 0 and 1 day. Two long, narrow lakes with north–south axes (Damariscotta, lake 21; Maranacook, lake 19) had mean differences of 3–4 days. In both cases, the observer on the lake with later ice-out dates was located at the northern end of the lakes, whereas the observer with earlier ice-out dates was located at the southern end of the lakes. Another long north–south lake, Cobbosseecontee (lake 20), had mean differences of 0–2 days, depending on the observer pair. Based on this limited data set, observer biases of more than 1 day are unlikely on relatively round lakes. Conversely, 3–4 day biases appear likely on long, narrow lakes if the observation locations are at different ends of the lake. These biases could cause large biases in temporal ice-out trends at individual lakes. At a large number of lakes, however, it is unlikely that observer-location biases would tend to bias the temporal trend test results in any one direction. For example, there is no reason to expect that (for a large number of lakes) people observed older ice-outs at the southern end of lakes and observed more recent ice-outs at the northern end of lakes.

Julian date of ice-out (including the extra day in leap years) was used for all analyses in this paper. A small bias is introduced by using a calendar date rather than using timing relative to the vernal equinox. The maximum bias is 0.8 days (Sagarin, 2001), for sites with ice-out dates from 1900 to 2000.

For lakes with overlapping data, we used the data that were judged to be most consistent over time with data from earlier and later time periods for that lake. We did not estimate missing years of ice-out dates and made no adjustments to lake-ice observations, with the following exceptions. Some 19 years of data at Damariscotta Lake (1959, 1962–68, 1970–78, 1997–98) and 2 years at Cobbosseecontee Lake (1974, 1994) were filled in from a secondary observer on each lake and adjusted by the average difference in the dates between the primary and secondary observers. One year of data at China (1901), Damariscotta (1927), Portage (1958), and Sebec (1904) Lakes and 2 years at Messalonskee Lake (1916, 1945) were not reasonable based on comparisons with other lakes in New England and were dropped from the data set. The data for these years appear to be in error by 1 month, probably because of recording errors. Sebago Lake did not freeze over completely in 9 years in the 1900s. Ice-out dates for these years were entered as 1 day earlier than the earliest recorded ice-out date.

Air-temperature time series were obtained from the USHCN data set that was developed and is maintained at the National Climatic Data Center (Karl *et al.*, 1990). The data have been subjected to quality control and homogeneity testing, and adjustment procedures for bias originating from changes in observation time (Karl *et al.*, 1986), instrumentation (Karl and Williams, 1987; Quayle *et al.*, 1991), station location (Karl and Williams, 1987), and urban heat-island effects (Karl *et al.*, 1988).

Pearson's r was used as the measure of correlation in this paper. Regression analyses were done with ordinary least-squares regression. Monotonic trends in the annual ice-out dates over time were evaluated using the non-parametric Mann–Kendall test, because changes over time did not appear to be linear. The data were smoothed for graphical presentation and serial correlation testing by use of locally weighted regression (LOESS; Cleveland and Devlin, 1988) with locally linear fitting, a robustness feature, and a weighting function of 45 years. Serial correlations in the trend tests were analysed by computing the Durbin–Watson statistic on the residuals of the LOESS smooths for each lake. One of 29 lakes (Squa Pan) had a value (1.36) that would indicate serial correlation.

3. RESULTS

Lake ice-out dates have become earlier ($p < 0.0001$) at all five lakes in New England with more than 150 years of data (Table I). Ice-out dates have become earlier ($p < 0.1$) at 10 of 11 lakes with 101–150 years of data. These results are consistent with other lakes across the Northern Hemisphere (Magnuson *et al.*, 2000). Ice-out dates have become earlier ($p < 0.1$) at 4 of 13 lakes with 100 years or less of data. The only lake (First

Connecticut) that indicated later ice-out dates had an insignificant trend ($p = 0.42$). A significant signal of earlier ice-out dates generally emerged from the noise of interannual variability when data prior to 1900 were available. The interannual variability of ice-out dates for Moosehead (lake 4 in Figure 1) and Damariscotta (lake 21) Lakes is shown in Figure 2. The effects of reforestation on the temporal trends in lake ice-out dates are unknown. Any effects, however, would be more gradual than the changes that have occurred in the ice-out dates in the last 50 years (Figure 3).

The data used to create the eight LOESS smooths in Figure 3 are from the four longest-record lakes in northern and mountainous areas of New England and the four longest in more southerly locations. The smooths from these eight lakes were similar to smooths from the other lakes in their respective regions. There were some differences in the smooths because of periods of missing record and different start dates for ice-out records. The four smooths within each region are similar in steepness of slope and in the timing of changes of slope. The timing of changes in slope were similar among all eight sites. Slopes in the southern region generally were steeper than slopes in the northern/mountainous region.

To describe changes over time in ice-out dates, Moosehead Lake was used as an indicator lake for the northern/mountainous region and Damariscotta Lake was used for the southern region. Based on the LOESS smooths, Moosehead Lake ice-out dates became earlier by 9 days from 1850 to 2000. Most of this change toward earlier ice-out dates occurred in two approximate periods: 1875–1900 and 1968–2000. Damariscotta Lake ice-out dates became earlier by 16 days in this same period, with most of the change occurring in the approximate periods 1875–1945 and 1968–2000. Other geophysical and biological responses to earlier spring warming in New England are consistent with observations of earlier ice-out. April snow water equivalent in North America decreased significantly in the 1900s (Brown, 2000), and the annual date of the last hard spring

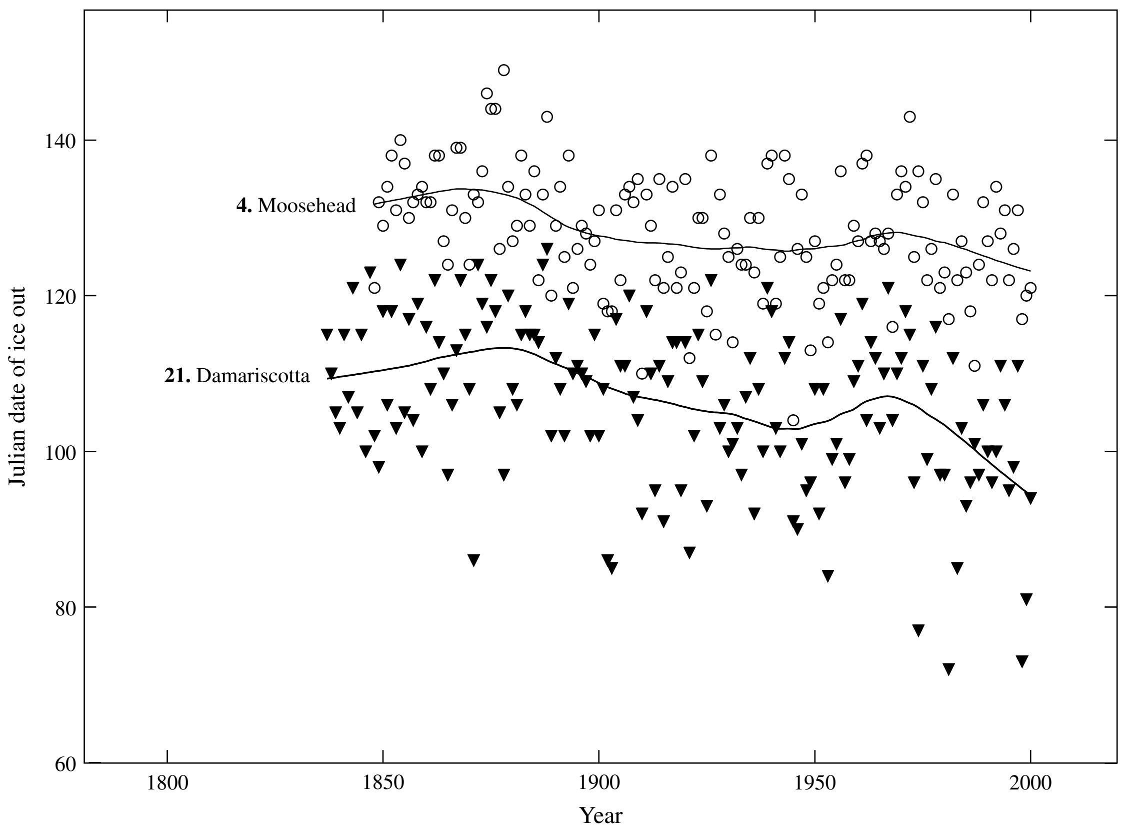

Figure 2. Ice-out dates over time for Moosehead and Damariscotta Lakes. Data smoothed by locally weighted regression. Locations are shown in Figure 1

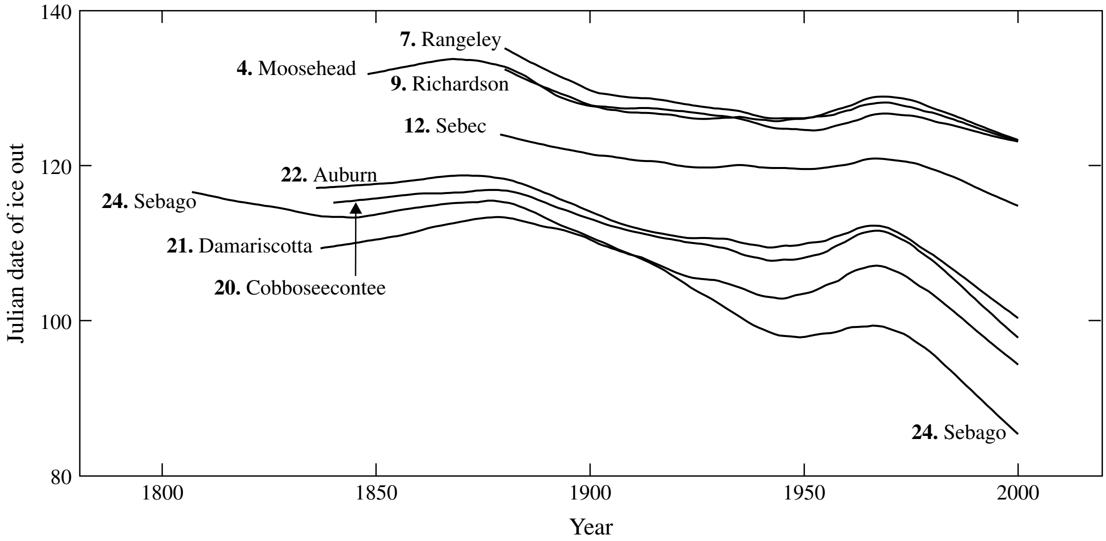

Figure 3. Ice-out dates over time for eight selected lakes in New England. Data smoothed by locally weighted regression. Locations are shown in Figure 1

freeze (Cooter and Leduc, 1995) and lilac bloom dates at four stations (Schwartz and Reiter, 2000) became significantly earlier in New England in the last few decades.

Air temperature is considered to be the most important variable in determining the annual ice-out date for lakes, although snow cover, cloudiness, and wind also may be important factors (Fobes, 1945; Tramoni *et al.*, 1985; Palecki and Barry, 1986; Reycraft and Skinner, 1993). Various aggregates of monthly mean temperatures (March, April, March–April, February–April, January–April, November–April, May–April) for the closest USHCN temperature sites (Figure 1) to Moosehead Lake (Ripogenus Dam) and Damariscotta Lake (Gardiner) were correlated to annual ice-out dates for 1925–99. Data at Ripogenus Dam were not available prior to 1925. For consistency, this same time period was used at other USHCN sites. The highest correlation for Moosehead Lake ($r = 0.77$) was April mean temperature. March–April mean temperature was a close second ($r = 0.73$). The highest correlation for Damariscotta Lake ($r = 0.71$) was March–April mean temperature, with February–April as a close second ($r = 0.69$). The correlations for both lakes became progressively lower as more months of temperature data were aggregated prior to ice-out. Because March–April air temperatures were strongly related to ice-out dates in both the northern/mountainous and southern regions of New England, changes in ice-out dates were used to infer changes in late winter–early spring air temperatures.

The slope of the regression line for 1925–99 between Moosehead Lake ice-out dates (independent variable) and March–April mean temperatures at Ripogenus Dam (dependent variable) was 0.16 °C day^{-1}. The slope for Damariscotta Lake ice-out dates versus March–April mean temperatures at Gardiner was 0.09 °C day^{-1}. Using the second closest temperature observation site for each of the two lakes (Millinocket and Lewiston) resulted in slope changes of 6.2% and 1.5% respectively. First Connecticut Lake is the only USHCN site that is located next to one of the eight lakes shown in Figure 3. The 75 year slope for First Connecticut Lake ice-out dates versus March–April mean temperatures at First Connecticut Lake was 4.3% different than the Moosehead/Ripogenus Dam slope. The 75 year slope in the Damariscotta/Gardiner regression was 7.4% different than the slope using all available data (115 years). No additional data were available for the Moosehead/Ripogenus Dam regression. The 75 year slopes are assumed to be representative of the slopes between 1850 and 2000. Based on the advance in ice-out dates described earlier for Moosehead and Damariscotta Lakes, the northern/mountainous region and southern region in New England became warmer in March–April by 1.4 °C and 1.5 °C respectively between 1850 and 2000.

It is difficult to verify the inferred temperature change discussed above with available air-temperature records. The smoothed historical March–April mean temperature data from the eight USHCN sites nearest to the eight lakes in Figure 3 are plotted in Figure 4. The changes in temperature data were not as consistent within the two regions as were the changes in lake ice-out data. The decreasing temperatures at Portland in the past 30 years, which are quite different from the warming at the other seven sites, may be caused by an ocean effect not present at the other sites. The USHCN bias adjustments at some of the eight sites may not be optimal. Gardiner and Lewiston temperatures have similar patterns from 1950 to the present, but very different patterns prior to 1950. These two sites are about 25 miles apart and a similar distance from the coast. The smoothed temperature records, although less consistent than the smoothed lake ice-out records, generally mirror the timing and direction of changes in the ice-out dates.

The different patterns over time in ice-out dates between the northern/mountainous region and the southern region appear to be caused by differences in their responses to temperature changes. The slope of the regressions between March–April air temperatures and ice-out dates varied between regions. Ice-out dates were less sensitive to changes in air temperature in the northern/mountainous region than in the southern region. This may be caused by the greater amount of snow on lakes in late winter in the northern/mountainous region. The median seasonal maximum snow depth in this region is about 50% greater than in the southern region (Cember and Wilks, 1993). Increased snowfall causes lake ice-out dates to become later, except when snowfall is near zero, due to enhanced creation of grey ice, the added mass of snow, and the higher albedo of snow cover (Vavrus *et al*., 1996).

Changes in lake ice-out dates in New England generally mirror the timing and direction of changes in annual Northern Hemisphere surface temperatures since 1861 (Houghton *et al*., 2001: figure 2.7). Warming, as inferred from earlier ice-out dates (Figure 3), however, begins near 1875, about 35 years earlier than warming in Northern Hemisphere temperatures. This may be caused by differences between regional and hemispheric temperatures. Regional temperature trends over a few decades can be strongly affected by regional variability in the climate system that may be related to various phases of atmospheric–ocean oscillations (Houghton *et al*., 2001).

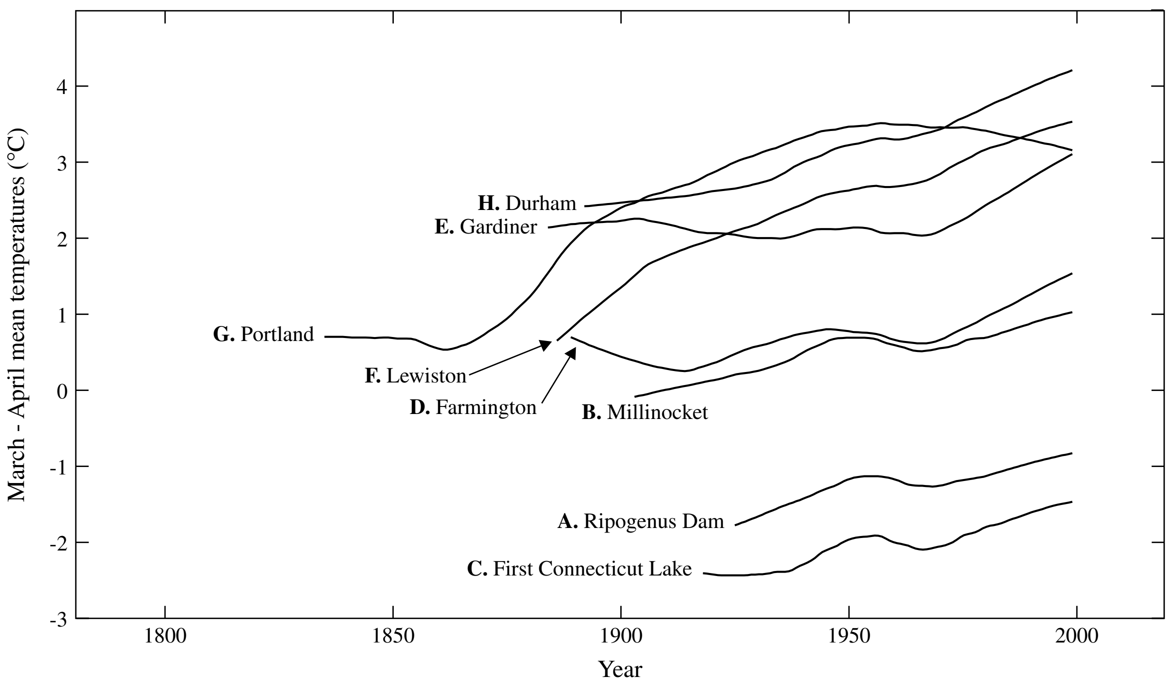

Figure 4. March–April mean temperatures over time for eight selected USHCN temperature sites in New England. Data smoothed by locally weighted regression. Locations are shown in Figure 1

4. SUMMARY

Ice-out dates from 29 lakes in New England with 64 to 163 years of record were assembled and analysed for this study. Ice-out dates have become significantly earlier ($p < 0.0001$) at all five lakes with more than 150 years of data. Ice-out dates have become significantly earlier ($p < 0.1$) at 10 of 11 lakes with 101 to 150 years of data and at 4 out of 13 ($p < 0.1$) lakes with 100 or less years of data. Changes in ice-out dates between 1850 and 2000 were 9 days and 16 days in the northern/mountainous and southern regions of New England respectively. The changes in the ice-out data over time were very consistent within each of the two regions of New England, and more consistent than four temperature records in each region.

Ice-out dates in the two regions of New England were both highly correlated with March–April air temperatures ($r = 0.7$). Ice-out dates were less sensitive to changes in air temperature in the northern/mountainous region than in the southern region. This may be caused by the greater amount of snow on lakes in late winter in the northern/mountainous region. The inferred late winter–early spring air-temperature warming in both regions of New England since 1850 was about 1.5 °C.

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REFERENCES

Anderson WL, Robertson DM, Magnuson JJ. 1996. Evidence of recent warming and El Nino-related variations in ice breakup of Wisconsin lakes. *Limnology and Oceanography* **41**: 815–821.

Assel RA, Robertson DM. 1995. Changes in winter air temperatures near Lake Michigan, 1851–1993, as determined from regional lake-ice records. *Limnology and Oceanography* **40**: 165–176.

Brown RD. 2000. Northern Hemisphere snow cover variability and change, 1915–1997. *Journal of Climate* **13**: 2339–2355.

Cember RP, Wilks DS. 1993. Climatological atlas of snowfall and snow depth for the northeastern United States and southeastern Canada. *Northeast Regional Climate Center Research Series Publication No. RR 93-1*. Ithaca, New York.

Cleveland WS, Devlin SJ. 1988. Locally-weighted regression: an approach to regression analysis by local fitting. *Journal of the American Statistical Association* **83**: 596–610.

Cooter EJ, Leduc SK. 1995. Recent frost date trends in the north-eastern USA. *International Journal of Climatology* **15**: 65–75.

Fobes CB. 1945. The ice clearing dates of the Maine lakes. *Bulletin of the American Meteorological Society* **26**: 331–333.

Hodgkins GA, James IC II. 2002. Historical ice-out dates for 29 lakes in New England. *US Geological Survey Open-File Report 02-34*. Augusta, ME.

Houghton JT, Ding Y, Griggs DJ, Nogues M, van der Linden PJ, Dai X, Maskell K, Johnson CA (eds). 2001. *Climate Change 2001: The Scientific Basis*. Cambridge University Press: Cambridge.

Irland LC. 1998. Maine's forest area, 1600–1995: review of available estimates. *Maine Agricultural and Forest Experiment Station Miscellaneous Publication 736*, University of Maine, Orono, ME.

Karl TR, Williams CN. 1987. An approach to adjusting climatological time series for discontinuous inhomogeneities. *Journal of Climate and Applied Meteorology* **26**: 1744–1763.

Karl TR, Williams CN Jr, Young PJ. 1986. A model to estimate the time of observation bias associated with monthly mean maximum, minimum, and mean temperatures for the United States. *Journal of Climate and Applied Meteorology* **25**: 145–160.

Karl TR, Diaz H, Kukla G. 1988. Urbanization: its detection in the climate record. *Journal of Climate* **1**: 1099–1123.

Karl TR, Williams CN Jr, Quinlan FT, Boden TA. 1990. United States historical climatology network (HCN) serial temperature and precipitation data. *Publication No. 3404*. Carbon Dioxide Information and Analysis Center, Oak Ridge National Laboratory, Oak Ridge, Tennessee.

Livingstone DM. 1997. Break-up dates of alpine lakes as proxy data for local and regional mean surface air temperatures. *Climatic Change* **37**: 407–439.

Maeda O, Ichimura SE. 1973. On the high density of a phytoplankton population found in a lake under ice. *Internationale Revue der Gesamten Hydrobiologie* **58**: 673–685.

Magnuson JJ, Robertson DM, Benson BJ, Wynne RH, Livingstone DM, Arai T, Assel RA, Barry RG, Card V, Kuusisto E, Granin NG, Prowse TD, Stewart KM, Vuglinski VS. 2000. Historical trends in lake and river ice cover in the Northern Hemisphere. *Science* **289**: 1743–1746.

Palecki MA, Barry RG. 1986. Freeze-up and break-up of lakes as an index of temperature changes during the transition seasons: a case study for Finland. *Journal of Climate and Applied Meteorology* **25**: 893–902.

Porter KG, Saunders PA, Haberyan KA, Macubbin AE, Jacobsen TR, Hodson RE. 1996. Annual cycle of autotrophic and heterotrophic production in a small, monomictic Piedmont Lake (Lake Oglethorpe): analog for the effects of climatic warming on dimictic lakes. *Limnology and Oceanography* **41**: 1041–1051.

Quayle RG, Easterling DR, Karl TR, Hughes PY. 1991. Effects of recent thermometer changes in the cooperative station network. *Bulletin of the American Meteorological Society* **72**: 1718–1723.

Reycraft J, Skinner W. 1993. Canadian lake ice conditions: an indicator of climate variability. *Climatic Perspectives* **15**: 9–15.

Robertson DM, Ragotzkie RA, Magnuson JJ. 1992. Lake ice records used to detect historical and future climate changes. *Climatic Change* **21**: 407–427.

Rousteenoja K. 1986. The date of break-up of lake ice as a climatic index. *Geophysica* **22**: 89–99.

Sagarin R. 2001. False estimates of the advance of spring. *Nature* **414**: 600.

Schwartz MD, Reiter BE. 2000. Changes in North American spring. *International Journal of Climatology* **20**: 929–932.

Stewart KM. 1976. Oxygen deficits, clarity and eutrophication in some Madison lakes. *International Revue der Gesamten Hydrobiologic* **61**: 563–579.

Tramoni F, Barry RG, Key J. 1985. Lake ice cover as a temperature index for monitoring climate perturbations. *Zeitschift für Gletscherkdunde und Glazialgeologie* **21**: 43–49.

Vavrus SJ, Wynne RH, Foley JA. 1996. Measuring the sensitivity of southern Wisconsin lake ice to climate variations and lake depth using a numerical model. *Limnology and Oceanography* **41**: 822–831.

Wynne RH, Magnuson JJ, Clayton MK, Lillesand TM, Rodman DC. 1996. Determinants of temporal coherence in the satellite-derived 1987–1994 ice breakup dates of lakes on the Laurentian Shield. *Limnology and Oceanography* **41**: 832–838.