CHANGES IN THE NUMBER AND TIMING OF DAYS OF ICE-AFFECTED FLOW ON NORTHERN NEW ENGLAND RIVERS, 1930–2000*

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Abstract. Historical dates of ice-affected flows for 16 rural, unregulated rivers in northern New England, USA were analyzed. The total annual days of ice-affected flow decreased significantly ($p < 0.1$) over the 20th century at 12 of the 16 rivers. On average, for the nine longest-record rivers, the total annual days of ice-affected flow decreased by 20 days from 1936 to 2000, with most of the decrease occurring from the 1960s to 2000. Four of the 16 rivers had significantly later first dates of ice-affected flow in the fall. Twelve of the 16 rivers had significantly earlier last dates of ice-affected flow in the spring. On average, the last dates became earlier by 11 days from 1936 to 2000 with most of the change occurring from the 1960s to 2000. The total annual days of ice-affected flow were significantly correlated with November through April air temperatures ($r = -0.70$) and with November through April precipitation ($r = -0.52$). The last spring dates were significantly correlated with March through April air temperatures ($r = -0.73$) and with January through April precipitation ($r = -0.37$). March mean river flows increased significantly at 13 of the 16 rivers in this study.

1. Introduction

It is important to document changes, or lack of changes, in long-term hydrologic data series in New England (the six states in the far northeastern USA). In addition to having many rural, unregulated rivers with more than 50 years of continuous flow data, it is a mid-latitude region with a large climatic gradient. The median total seasonal snowfall ranges from less than 40 inches in southern New England to more than 100 inches in northern New England (Cember and Wilks, 1993). The near-freezing temperatures present in the late fall, winter, and early spring make New England rivers sensitive to small changes in temperature. The relative amount of precipitation falling as rain or snow directly affects river flow and river ice in these seasons. The annual dates of ice-affected river flow for the six New England states have not been documented or analyzed, with the exception of five rivers in coastal Maine (Dudley and Hodgkins, 2002). New England has been the focus of climatological studies covering various topics though, including: temperature and precipitation (Bradbury et al., 2002a; Wettstein and Mearns, 2002; Keim et al.,

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2003), evaporation and evapotranspiration (Fennessey and Kirshen, 1994), frost dates (Cooter and Leduc, 1995; Baron and Smith, 1996), river flows (Hartley and Dingman, 1993; Bradbury et al., 2002b; Hodgkins et al., 2003a; Huntington, 2003), lake ice-out dates (Hodgkins et al., 2002), birds (Valiela and Bowen, 2003), and freshwater ecosystems (Moore et al., 1997).

Previous researchers have analyzed trends over time in river-ice data in North America, northern Europe, and northern Asia. Studies that analyzed two or more rivers include: Wing (1943), unknown number of rivers in Minnesota, Wisconsin, and Michigan, USA; Ginzburg et al. (1992) and Soldatova (1993), unknown number of rivers in the former Soviet Union; Smith (2000), nine rivers in Arctic and subarctic Russia; Magnuson et al. (2000), five rivers (total) in Canada, Finland, and eastern Russia; Kuusisto and Elo (2000), two rivers, one in Latvia and one in Finland; Zhang et al. (2001), approximately 20 rivers across Canada with 50 years of data (more rivers with shorter record lengths); Burn and Hag Elnur (2002), 22 rivers across Canada with 48 years of record (more rivers with shorter record lengths); and Dudley and Hodgkins (2002), five rivers in coastal Maine, USA. These researchers looked at the first day of ice in the fall, the last day of ice in the spring, the total number of ice days in the winter, or some combination of these data. All of these studies were based on human observations of river ice, except for Wing (1943), Zhang et al. (2001), Burn and Hag Elnur (2002), and Dudley and Hodgkins (2002), which were based on continuous river-flow records. This paper presents an analysis of trends over time in northern New England river-ice data based on continuous river-flow records, and an analysis of the correlation of the river-ice data with air temperature and precipitation data.

In addition to being a climatic indicator, river ice is important because it can cause major damage to human structures and it affects various aspects of river geomorphology and ecology. Ice-jam induced flooding has been documented in the United States, Canada, Norway, Sweden, Finland, Iceland, and Russia (Prowse and Beltaos, 2002). Ice jams contributed to the extensive flooding in New England in 1936 (Grover, 1937). River ice is responsible for the creation of numerous erosional and depositional features within river channels and on channel floodplains. Physical disturbances associated with ice break-up scouring and flooding are important to nutrient and organic matter dynamics, water chemistry, and the abundance and diversity of river biota. The succession of riparian vegetation is directly linked to the scouring effects of ice (Prowse and Beltaos, 2002). River ice break-up is likely to have important effects on primary producers, consumers, and food-web dynamics of river biota, although detailed information describing the magnitude of their effects is scarce (Scrimgeour et al., 1994). Mortality, emigration, or displacement of fishes of all life stages are often the result of severe ice conditions, through the action of damming, scouring, associated flooding or direct freezing (Power et al., 1993). Anchor ice (described in the next section) can have serious effects on fish eggs and embryos developing within gravel beds (Prowse, 1994).

1.1. EFFECT OF ICE ON THE COMPUTATION OF RIVER FLOWS

Some rivers in New England have been gaged by the U.S. Geological Survey (USGS) for more than 100 years. The primary product of USGS gaging efforts has been the computation and publication of daily mean river flows. Flows, however, are not typically measured continuously. Instead, the river height (or stage) is measured continuously (actually once every 15–60 min) and the flows computed with a river height/flow relation, usually called a rating curve. The presence of ice in a river channel affects the relation between river height and flow (Rantz et al., 1982); therefore, the presence of ice in rivers has been historically determined and recorded. The following general discussion of river ice and its effect on the computation of river flow is taken from Rantz et al. (1982). Additional details on river ice processes are available in Ashton (1986), Beltaos (1995), and Kerr et al. (2002).

The formation of ice in river channels, in particular on hydraulic control sections (typically, the riffles downstream of a gaging station that control the river height at the station at low to medium flows), affects the river height/flow relation by causing backwater (a higher-than-normal river height for a given flow). This backwater varies with the quantity and nature of the ice, as well as with the flow. Backwater at a gaging station can be caused by anchor ice or by surface ice. Anchor ice is an accumulation of spongy ice or slush adhering to the rocks of a river bed. It may build up on the river bed and (or) the hydraulic control section to the extent that backwater occurs. The river-height rise usually starts in late evening or early morning when the ice begins to form and adhere to the rocks. By late morning, the sun typically warms the river bed sufficiently to release the ice and the river height starts to fall.

The second type of ice that causes backwater at a gaging station is surface ice. Surface ice normally forms first along the edges of a river. The ice sheet then builds out from the shore and eventually forms an ice sheet across the entire river. Surface ice, where it is in contact with the river, increases the frictional resistance to the river flow and the river height will increase for a given flow.

Rises in river height due to anchor ice are clearly recognizable from continuous river-height records (for example, Figure 1: Fish River, Royal River). Rises in river height due to surface ice are often recognizable from continuous river-height records (Figure 1: Fish River, Diamond River). River-height records are supplemented by visual observations of river ice conditions, river flow measurements, daily temperature and precipitation records, and flows from nearby gages to determine days of ice-affected flow. River height rises, particularly rises that lack the smoothness of ones caused by an increase in flow, combined with very cold temperatures and a lack of precipitation are indicative of ice-affected river flow.

The first ice-affected river flows in New England each fall are caused by the first substantial presence of anchor ice and (or) surface ice. The breakup of river ice in the spring, at rivers with complete or nearly complete ice cover, typically is a dramatic event in which the ice cover is picked up and transported by medium

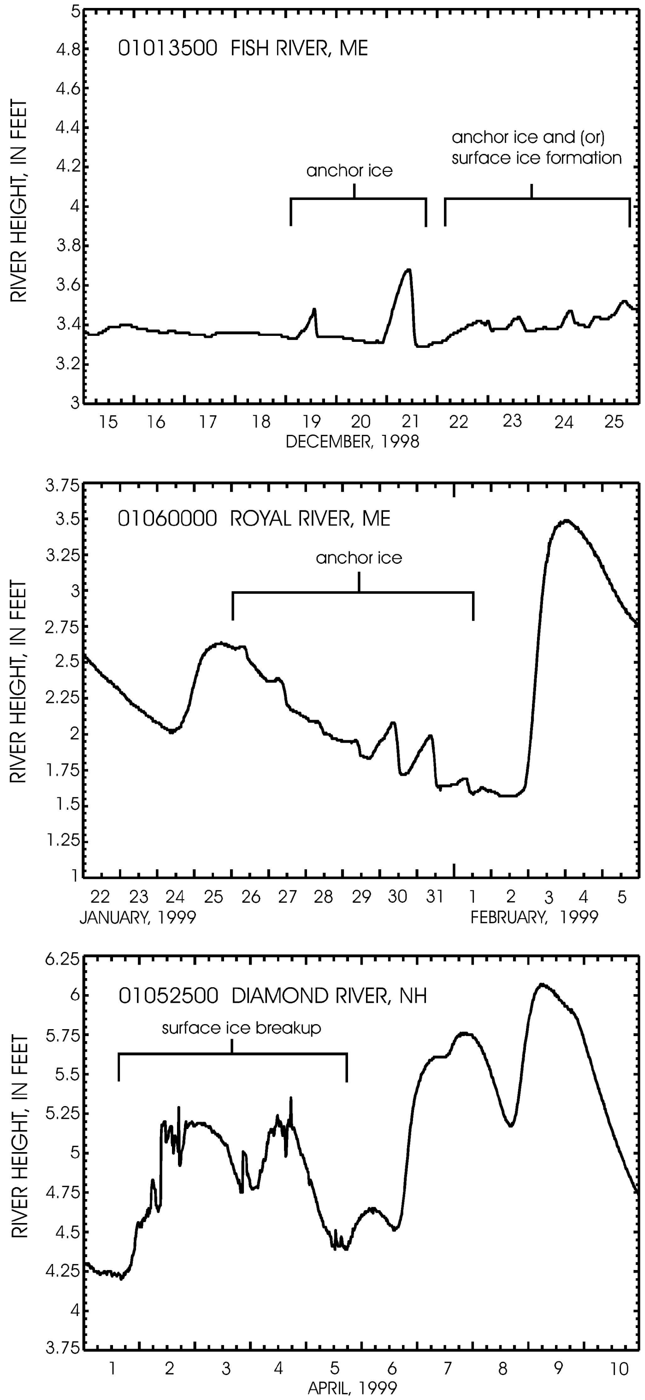


Figure 1. Examples of river ice affecting river height at three U.S. Geological Survey streamflow gaging stations in New England.

or high river flows (Figure 1: Diamond River). Dynamic river-ice breakup can also occur in the winter. Days of ice-affected flow each winter, in general, range from continuous or nearly continuous in far northern New England to intermittent days of ice-affected flow in southern and coastal New England.

2. Data

Records from all gaging stations on rivers in the six New England states (Connecticut, Maine, Massachusetts, New Hampshire, Rhode Island, and Vermont) were searched for long-term, usable records of ice-affected flow. Long-term records were defined as those from a gaging station that was operated for at least 50 years with records through water year 2000. (A water year begins October 1 of the previous calendar year and ends September 30 of the current calendar year. For example, water year 2000 begins October 1, 1999 and ends September 30, 2000). Usable records are defined as those from a gaging station whose hydraulic control section location did not change during the period of record and whose flows were not subject to substantial regulation or urbanization.

Ice conditions can be very different in different locations, even a short distance upstream or downstream from any given location. For this reason, rivers where the control section location changed over their period of record were not used. Substantial regulation is defined as regulation that could affect the formation and (or) stability of ice at the station. This required that a river at a gaging station had either no known flow regulation over time or only low-flow regulation, of an amount that was judged to be insignificant. Rivers with substantial amounts of regulation were eliminated from this study. The USGS lists all known regulation that may affect the computation of river flows in its annual published data reports. There were six sites retained for this study that had some low-flow regulation for all or part of their period of record (Table I), typically from upstream mills. With the exception of the Allagash River, regulation has decreased over time at these rivers. A decrease in regulation, all other things being equal, is expected to increase the number of ice-affected flow days at a site. That said, the regulation at the six mentioned rivers is believed to be insufficient to affect the number of days of ice-affected flow in these rivers.

All of the rivers used in this study are in rural areas. Rivers in northern Maine, northern New Hampshire, and northern Vermont generally drain remote, undeveloped forests. Rivers in southern Maine and southern New Hampshire generally drain rural areas with forests, small towns, some pasture land, and some low-density residential development. It is unlikely that any activities occurred on or near the rivers in this study or on their tributaries, such as warm-water discharges, that would affect the trends in ice-affected river flows 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%

TABLE I

Attained significance levels (p-values) for Mann-Kendall trend tests of ice-affected flow days over time

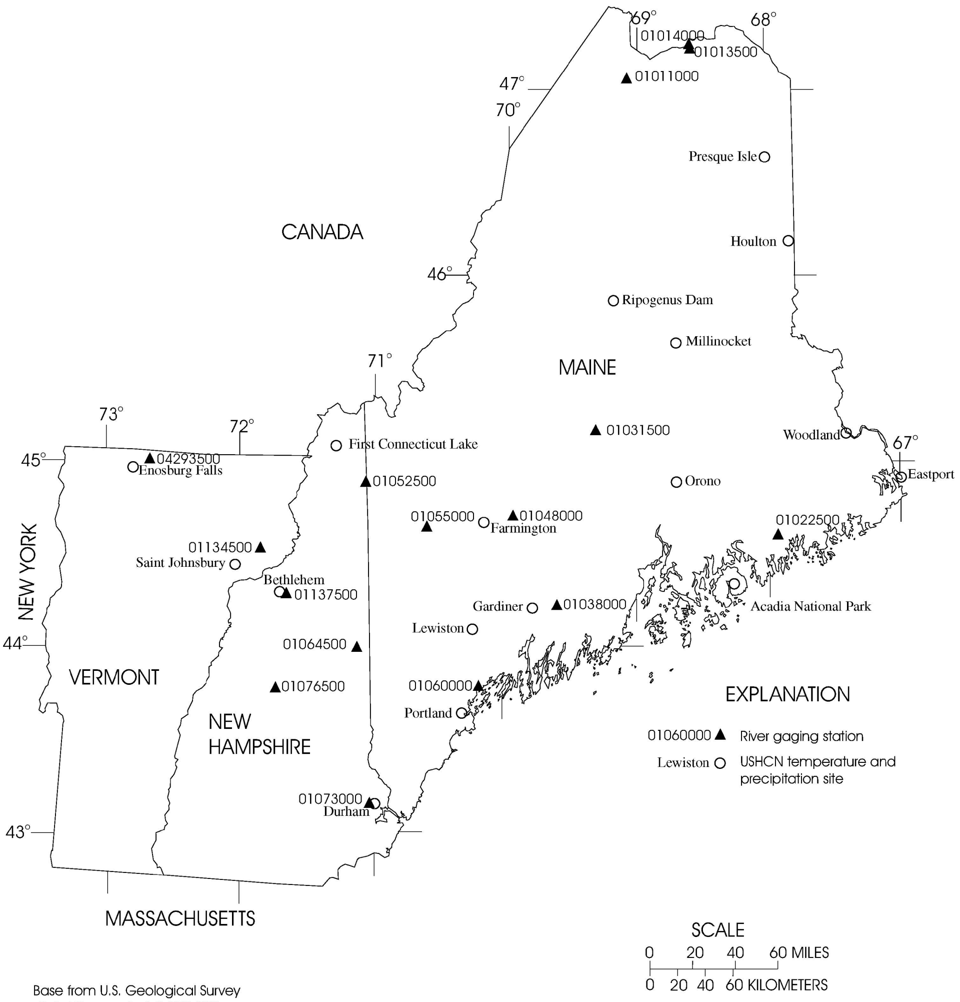
USGS station number	River name and state	Period of record	Total days of ice-affected flow		First fall day of ice-affected flow		Last spring day of ice-affected flow	
01011000	[a]Allagash, ME	1932–2000	**0.046**	(−)	0.69	(−)	**0.076**	(−)
01013500	Fish, ME	1930–2000	**0.0016**	(−)	0.11	(+)	**0.038**	(−)
01014000	St. John, ME	1934–2000	**0.086**	(−)	0.59	(−)	**0.098**	(−)
01022500	Narraguagus, ME	1949–2000	**0.044**	(−)	0.82	(−)	**0.046**	(−)
01031500	[a]Piscataquis, ME	1931–2000	**0.052**	(−)	0.50	(−)	**0.010**	(−)
01038000	[a]Sheepscot, ME	1939–2000	0.21	(−)	**0.074**	(+)	**0.023**	(−)
01048000	Sandy, ME	1929–1979, 1988–2000	**0.029**	(−)	0.72	(+)	0.21	(−)
01052500	Diamond, NH	1942–2000	**0.099**	(−)	0.69	(−)	**0.016**	(−)
01055000	Swift, ME	1931–2000	**0.0001**	(−)	0.56	(−)	**0.018**	(−)
01060000	[a]Royal, ME	1950–2000	0.11	(−)	0.32	(+)	0.12	(−)
01064500	Saco, NH	1930–2000	0.47	(−)	0.35	(−)	0.27	(−)
01073000	Oyster, NH	1936–2000	0.11	(−)	0.48	(+)	**0.020**	(−)
01076500	[a]Pemigewasset, NH	1941–2000	**0.025**	(−)	0.11	(+)	0.12	(−)
01134500	Moose, VT	1948–2000	**0.014**	(−)	**0.0004**	(+)	**0.018**	(−)
01137500	Ammonoosuc, NH	1940–2000	**<0.0001**	(−)	**0.0017**	(+)	**0.0010**	(−)
04293500	[a]Missisquoi, VT	1934–2000	**0.0002**	(−)	**0.030**	(+)	**0.019**	(−)

[a] River known to have some low-flow regulation over all or part of it's period of record.

forested in 1880 and 70–80% forested in 1995. Counties in northern Maine were 85–90% forested in 1880 and 90–95% forested in 1995 (Irland, 1998). The potential effects of reforestation on ice-affected river flows in New England are unknown. The possible influence of land-use change and flow regulation on historical ice-affected flow days are discussed further in the results section.

Sixteen gaging stations on rivers in New England (all in northern New England) met the criteria of this study (Hodgkins et al., 2003b; Figure 2). Data collection from two of the 18 rivers in Hodgkins et al. ended in the 1970s and the data were not used in this study. The long-term dates of ice-affected flow in Hodgkins et al. were compiled from U.S. Geological Survey (USGS) historical flow and ice records from data reports (the annual Water-Data Reports and their predecessor Water-Supply Papers, for states in New England) and USGS files.

The presence of ice in rivers has been determined by the USGS using the same methods from 1913 (and probably before this for several years) to the present (Hoyt, 1913; Rantz et al., 1982), with one known exception. The earliest river-height records in New England typically were collected daily by an observer, rather than by a continuous recorder, until the 1930s. The presence of ice that affected the river



Base from U.S. Geological Survey
digital files, scale 1:2,000,000
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Figure 2. USGS river gaging stations with historical ice-affected flow data and USHCN temperature and precipitation sites in northern New England used for this study.

height/flow relation, especially anchor ice, may have been interpreted differently using these two methods of data collection. Therefore for this report, dates of ice-affected flow are analyzed only for those years when continuous recorders were used at each gaging station.

The determination of days of ice-affected flow that occur during periods of missing river-height record at a gaging station can be less accurate than if the river-height record was not missing. This is because estimates during periods of missing river-height records are based on flows from nearby rivers and on daily temperature and precipitation records. Individual years of record at gaging stations with missing winter river-height record were censored if there was any question about the accuracy of the ice-affected flow records. In general, the only acceptable ice-affected flow data in years with missing river-height record were short amounts of missing river-height record at sites with long, continuous periods of ice-affected flow in that season. In these cases, the missing river-height record was not near the beginning or end of the days of ice-affected flow for the winter and there were no substantial peak flows during the period of missing record. On average, four years were censored over the period of record at each of the 16 river gaging stations. The length of record presented for the 16 rivers in this report ranges from 51 to 71 years, with an average of 63 years.

Each of three coastal river gaging stations had one year (a different year for each site) with no days of ice-affected flow. These three years had complete river-height records. For the purpose of trend testing, the first date of ice-affected flow in the fall was considered to be one day later than the latest first date of ice that was recorded over the period of record at that site. Likewise, the last date of ice-affected flow in the spring was considered to be one day earlier than the earliest last date at that site.

The location of the 16 gaging stations are shown in Figure 2. A majority of these rivers are in Maine, with some in New Hampshire and Vermont. No long-term records from Massachusetts, Connecticut, or Rhode Island were analyzed because no rivers in these states met the criteria of this study.

In addition to analyzing days of ice-affected flow, this study analyzed historical air temperature and precipitation data. The U.S. Climate Division meteorological data set may not be appropriate for decadal to century scale climate studies (Keim et al., 2003). Monthly air-temperature and precipitation (total liquid equivalent) time series were therefore obtained from the U.S. Historical Climatology Network (USHCN) data set that was developed and is maintained at the National Climatic Data Center (Karl et al., 1990). The USHCN data have been subjected to quality control and homogeneity testing. Temperature data have been adjusted for bias originating from changes in observation time (Karl et al., 1986), instrumentation (Quayle et al., 1991), station location and other station changes (Karl and Williams, 1987), and urban heat-island effects (Karl et al., 1988). Precipitation data have been adjusted for bias originating from changes in station location and other station changes (Karl and Williams, 1987). The location of the 17 USHCN temperature and precipitation sites used in this study are shown in Figure 2.

3. Methods of Analysis

Temporal trends in the annual number and timing of days of ice-affected river flow were evaluated using the non-parametric Mann-Kendall test (Helsel and Hirsch, 1992) because changes over time did not appear to be linear (Figures 3–5). 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.

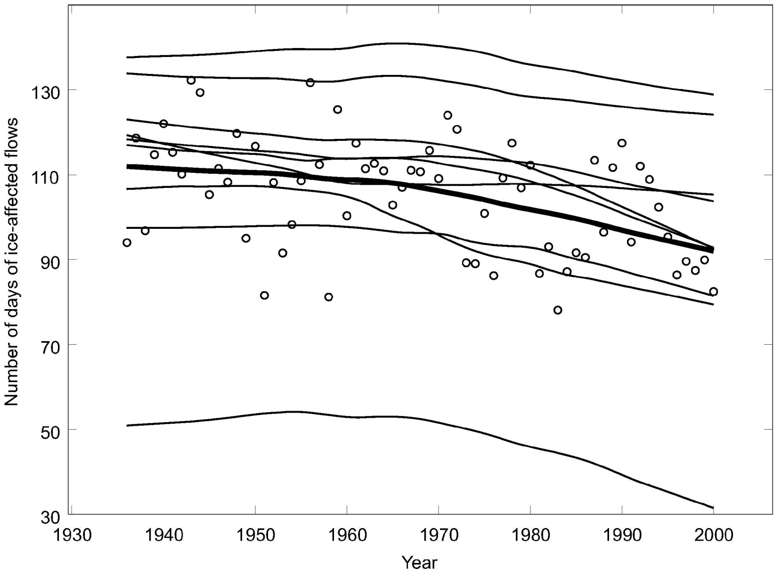

Figure 3. Smooths of the total annual days of ice-affected flow, over time, for the nine longest-record river gages in northern New England used in this study. Circles represent the annual values for the average of the nine sites. The thick line is the smooth of the average annual values.

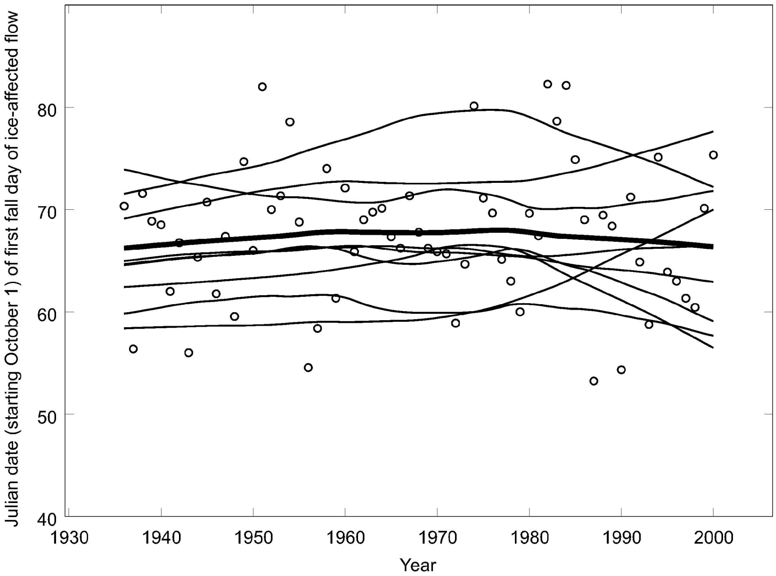

Figure 4. Smooths of first dates of ice-affected flow in the fall, over time, for the nine longest-record river gages in northern New England used in this study. Circles represent the annual values for the average of the nine sites. The thick line is the smooth of the average annual values.

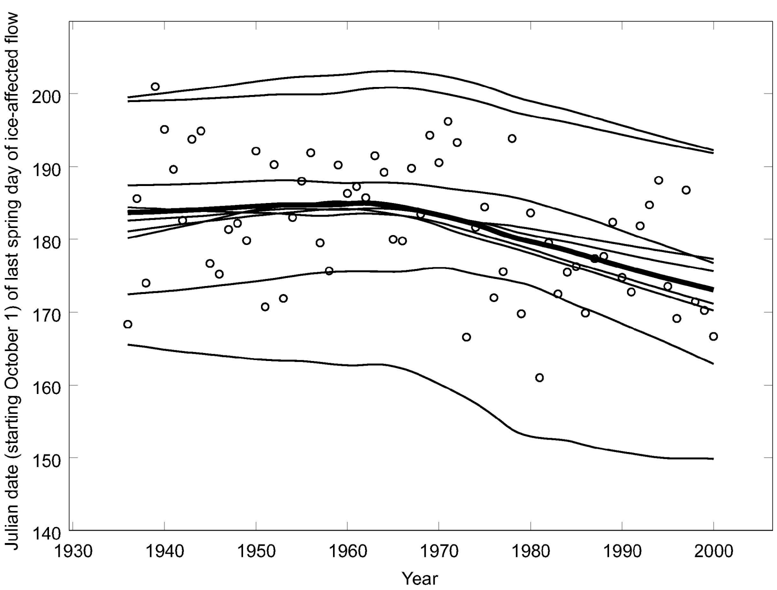

Figure 5. Smooths of last dates of ice-affected flow in the spring, over time, for the nine longest-record river gages in northern New England used in this study. Circles represent the annual values for the average of the nine sites. The thick line is the smooth of the average annual values.

LOESS smooths are determined solely by the data, without assuming the form of the relation (linear, etc.) between the variables (Helsel and Hirsch, 1992). Julian date, or a sequential numbering of days, starting October 1 (instead of the usual January 1 starting date), was used in the Mann-Kendall tests and LOESS smooths for all dates in this paper. This was done to keep fall and spring ice-affected flow dates in the same year. Pearson's r was used as the measure of correlation in this paper.

There must be no serial correlation for the Mann-Kendall test p-values to be correct. Serial correlations were analyzed by computing the Durbin-Watson statistic on the residuals of the LOESS smooths for each river that had a significant temporal trend ($p < 0.1$) in any of the three categories in Table I. Three of the 28 data series in Table I with significant temporal trends had significant serial correlation ($p < 0.1$), all with p-values between 0.01 and 0.1. The values of the Durbin-Watson statistics for these three sites were between 1.5 and 1.6. Serial correlation was not considered to be a problem with the data analyzed in this paper.

For this paper, we were primarily interested in significant changes over time at individual rivers (local significance), rather than whether the region as a whole was changing (global or field significance). We generally find the geographic pattern of local significance more instructive than the global significance of a region. We did, however, look at the region as a whole to compute an average magnitude of change in the river-ice data over time and to correlate river-ice data with average meteorological data. To make global statements of significance for a region, global tests must be computed. This has been done for environmental data using different methods, including binomial probability tests with corrections for spatial correlation (Livezy and Chen, 1983; Lettenmaier et al., 1994), regional sums or averages (Dettinger and Cayan, 1995; Lindstrom and Bergstrom, 2004), the Bonferroni inequality (Cooter and Leduc, 1995), and a regional average Kendall's S trend test (Douglas et al., 2000). In this paper, when testing the region as a whole, we averaged the longest-record river-ice and meteorological data, for each year, for sites across the region. Because we used regional-average data for some tests, we also tested for temporal trends in the average river-ice data with the Mann-Kendall test.

4. Results

4.1. TEMPORAL TREND TESTS

The total annual days of ice-affected flow decreased significantly over time during the 20th century in northern New England at 12 out of 16 of the rivers analyzed with $p < 0.1$ (Table I), and at 14 out of 16 rivers with $p \leq 0.11$. The remaining two rivers had insignificantly decreasing days of ice-affected flows. There is strong evidence of fewer ice-affected flow days on rivers in northern New England since the first half of the 20th century.

Four of 16 rivers had significantly later first dates of ice-affected flow in the fall with $p < 0.1$ (Table I) and 6 out of the 16 rivers had significantly later first dates with $p \leq 0.11$. Four of these six rivers were located in northern Vermont or New Hampshire. Three of the remaining 10 rivers in northern New England had insignificant trends toward later dates while 7 had insignificant trends toward earlier dates. There is weak evidence of a shift in the timing of the first dates of ice-affected flow in the fall in northern New England, except for parts of northern New Hampshire and northern Vermont where there is stronger evidence. Zhang et al. (2001) found significant trends toward earlier fall dates of ice-affected flow from 1947 to 1996 at four rivers in Canada to the northeast of New England which differs from the results of this study. Like this study, Zhang et al. found insignificant trends at two sites to the northwest of New England.

Twelve out of 16 rivers in northern New England had significant trends toward earlier last dates of ice-affected flow in the spring with $p < 0.1$ (Table I), and 14 of 16 rivers had significant trends toward earlier last dates with $p \leq 0.12$. The two remaining rivers had insignificant trends toward earlier last dates. There is strong evidence of a shift in the timing of the last dates of ice-affected flow in the spring in northern New England since the first half of the 20th century. The trends in northern New England may be caused, at least in part, by earlier spring snowmelt runoff. The ice-breakup in the spring is often caused by the dynamic forces of high river flows. Hodgkins et al. (2003a) found significant trends toward earlier spring high flows at all 11 rivers in northern New England with the greatest amount of seasonal snowpack. The earlier high spring river flows are probably caused by earlier snowmelt runoff (Hodgkins et al., 2003a; Dudley and Hodgkins, 2002).

Zhang et al. (2001) found significant trends toward earlier spring ice-out dates at two rivers, a significant trend toward later dates at one river, and insignificant trends at three rivers, in areas of Canada to the northwest and northeast of New England from 1947 to 1996. The difference in temporal trend results between northern New England rivers and rivers in adjacent areas of Canada may indicate that the mechanisms controlling the timing of Canadian flows did not change in the same way as New England mechanisms, that the Canadian measure of river ice is not as sensitive as the USGS measure, or that the additional years of data used in this study strengthen the trend test results.

It is difficult to compare the trends in ice-affected flows in this study (first dates of ice-affected flow in the fall, total annual days of ice-affected flow, and last dates of ice-affected flow in the spring) to the limited number of studies from other parts of the world (see Section 1 for a list of studies). This is due to differences in the type of data analyzed (which in several cases is not well defined) and differences in the time periods studied.

Six of the rivers in this study had some low-flow regulation over all or part of their period of record. The amount of regulation at these sites is not expected to affect the results of this study. The six slightly regulated rivers show temporal trends similar to the unregulated rivers. If regulation affected the number of ice-affected flow days at any of the six rivers other than the Allagash River, it should have caused rivers to have more days of ice-affected flow in recent years. This runs counter to all the significant temporal trends which show fewer ice-affected flow days in recent years.

It is unlikely that the documented changes in ice-affected flow days in this study were substantially impacted by changes in land use over time. The most significant land-use change in the drainage basins of the rivers in this study has been the conversion of farmland to forest, particularly in the more southern basins. This change, however, was gradual over the 20th century (Irland, 1998) whereas most of the change in ice-affected flow days occurred in the last 30–40 years.

4.2. MAGNITUDE OF CHANGES

LOESS smooths of the total annual days of ice-affected flow, over time, for the nine longest-record river gages in northern New England used in this study (01011000, 01013500, 01014000, 01031500, 01048000, 01055000, 01064500, 01073000, 04293500; Figure 2, Table I) are shown in Figure 3. Also in Figure 3 are the annual total days of ice-affected flow for the average of the nine sites and the smooth of the average annual values. To compute an average magnitude of change in northern New England, averaging nine rivers from 1936 to 2000 was judged to be the best balance between maximizing the number of sites used and maximizing the period of record covered. The smooths for individual sites, in general, are consistent with the average smooth. Using the nine-river average, the total days of ice-affected flow decreased significantly over time (Mann-Kendall test, $p = 0.0013$). On the basis of the average LOESS smooth, the total number of ice-affected flow days decreased by 20 days (18%) from 1936 to 2000. Most of this change occurred from the 1960s to 2000.

LOESS smooths of the first dates of ice-affected flow in the fall, again for the nine longest-record river gages in New England (Figure 4) vary considerably from the average smooth. For the average smooth, however, there was no substantial change from 1936 to 2000.

LOESS smooths of the last dates of ice-affected flow in the spring, for the nine longest-record sites (Figure 5), like the smooths for total annual days of ice-affected flow, are generally consistent with the average smooth. Using the nine-river average, the last dates of ice-affected flow became significantly earlier over time (Mann-Kendall test, $p = 0.0037$). On the basis of the average smooth, the last dates of ice-affected flow in the spring became earlier by 11 days from 1936 to 2000. Like the total number of ice-affected flow days, most of the change occurred from the 1960s to 2000.

The changes in the average beginning and ending dates from 1936 to 2000 do not add up to the average change in the total days of ice-affected flow for the same time period. This implies that in addition to earlier last dates of ice-affected flow in the spring, the number of ice-affected flow days in the winter between the beginning and ending dates have declined. To test this idea, ice-affected flow days, by month, for November to April, were examined. The total number of ice-affected flow days for the nine longest-record sites in northern New England were averaged for each month from 1936 to 2000. Trends over time were then tested for significance and the magnitude of change computed by LOESS smooths. The total number of ice-affected flow days decreased significantly ($p < 0.1$) from 1936 to 2000; in January, February, March, and April (Table II). Trends over time were not significant for November and December (same winter season, previous calendar year). The magnitude of the decrease was two to three times greater in March and April than in January and February (Table II).

4.3. CORRELATIONS WITH AIR TEMPERATURES AND PRECIPITATION

The annual total ice-affected flow days and the last dates of ice-affected flow in the spring were tested for correlation with monthly air temperature and precipitation data. Individual months and aggregated months were used. The aggregated months were computed as arithmetic averages of the individual months. The average annual total ice-affected flow days for the nine longest-record rivers in northern New England were tested against average monthly temperatures for the 17 USHCN

TABLE II

Attained significance levels (p-values) for Mann-Kendall trend tests and magnitude of changes, based on LOESS smooths, for total number of ice-affected flow days over time, by month, for nine-river average, 1936 to 2000

Month	Mann-Kendall p-value	Magnitude of change (days)	Average number of days in 1936
November	0.89	0	2
December	0.35	−4	22
January	**0.096**	−2	29
February	**0.0087**	−2	27
March	**0.0013**	−6	25
April	**0.028**	−4	7

Numbers in bold indicate $p < 0.1$.

TABLE III

Correlation coefficients (r-values) between annual total number of ice-affected flow days (nine-river average) and monthly temperatures and precipitation (17-site average)

Month(s)	Temperature correlation coefficient	p-value of correlation	Precipitation correlation coefficient	p-value of correlation
November	−0.28	0.027	−0.21	0.091
December	−0.49	<0.0001	−0.27	0.032
January	−0.05	0.69	−0.31	0.012
February	−0.39	0.0015	−0.16	0.21
March	−0.43	0.0003	−0.16	0.20
April	−0.46	0.0001	−0.34	0.0055
March–April	−0.52	<0.0001	−0.33	0.0075
February–April	−0.61	<0.0001	−0.37	0.0021
January–April	−0.56	<0.0001	−0.45	0.0002
December–April	**−0.69**	<0.0001	**−0.48**	0.0001
November–April	**−0.70**	<0.0001	**−0.52**	<0.0001

Numbers in bold are the highest correlations.

temperature stations in the same area as the nine rivers (Figure 2), for 1936–2000 (Table III). The highest correlations with the annual total ice-affected flow days and air temperatures were with November through April temperatures ($r = -0.70$, $p < 0.0001$) and December through April temperatures ($r = -0.69$, $p < 0.0001$). The November through April temperatures explain about half ($r^2 = 0.49$) of the variability in the annual total number of days of ice-affected flow. All individual months, except for January, were significantly correlated with the total days of ice-affected flow.

TABLE IV

Correlation coefficients (r-values) between monthly total number of ice-affected flow days (nine-river average) and average monthly temperatures and precipitation (17-site average)

Month	Temperature correlation coefficient	p-value of correlation	Precipitation correlation coefficient	p-value of correlation
November	−0.49	<0.0001	−0.25	0.045
December	**−0.72**	<0.0001	**−0.53**	<0.0001
January	−0.38	0.0016	**−0.33**	0.0072
February	−0.48	<0.0001	−0.28	0.025
March	−0.54	<0.0001	−0.21	0.10
April	**−0.64**	<0.0001	−0.22	0.084

Numbers in bold are the highest correlations.

It is curious that the annual total number of days of ice-affected flow were not significantly correlated with January air temperatures. To further investigate this, average monthly air temperatures (for the same 17 temperature sites discussed earlier) were tested for correlation with average monthly total number of days of ice-affected flow (for the nine longest-record river gages in this study, as discussed earlier) (Table IV). For example, average November air temperatures were tested against average November total days of ice-affected flow. Total ice-affected flow days were significantly correlated ($p < 0.1$) with air temperatures for each month from November to April. January, however, had the lowest correlation coefficient ($r = -0.38$) and February had the second lowest (−0.48). The highest correlation coefficients were near the ends of the ice season, in December (−0.72), March (−0.54), and April (−0.64). An air temperature change in January probably has less effect on the number of days of ice-affected flow than an equal change closer to the ends of the ice season because a change in January is less likely to rise above the freezing point.

Monthly precipitation values were averaged for the same 17 sites discussed previously and correlated with total days of ice-affected flow for the nine longest-record river gages (Table III). November through April precipitation had the highest correlation ($r = -0.52$, $p < 0.0001$) and December through April had the second highest correlation ($r = -0.48$, $p = 0.0001$). These two combinations of months also had the highest correlations with monthly air temperatures, though the temperature correlations were higher ($r = -0.70$ and −0.69, respectively). The best correlation with temperature explains 49% of the variability in the total days of ice-affected flow while the best correlation with precipitation explains 27% of the variability.

Correlations between average monthly total days of ice-affected flow and average monthly precipitation also were tested (Table IV). Correlations were significant ($p \leq 0.1$) for all months. The highest correlations were with December ($r = -0.53$) and January ($r = -0.33$). Unlike the monthly correlations with temperature, the correlations did not increase in March and April. Temperature-driven snowmelt runoff may be more important to March and April days of ice-affected flow than precipitation in these months.

Since total days of ice-affected flow are highly correlated to November through April air temperatures and precipitation, both could impact the total days of ice-affected flow. Increased winter temperatures could result in more liquid winter precipitation which in turn could affect river ice directly and by causing increased winter flow. Increased winter precipitation could also affect river ice and river flows. Both temperature and precipitation (November through April) were tested for changes over time. Neither had a significant change from 1936 to 2000 ($p =$ 0.25 and 0.18, respectively). Since there are multiple significant changes over time (Table I) in the total days of ice-affected flow, this could indicate that the total days of ice-affected flow is a more sensitive climatic indicator than either temperature or precipitation.

Because both November through April air temperatures and precipitation had significant correlations with total days of ice-affected flow, we also tested for correlation between temperature and precipitation. There was a significant correlation between November through April temperature and precipitation ($r = 0.42$, $p = 0.0006$). Higher air temperatures were associated with higher amounts of precipitation.

Since increased winter flows may be important to the total number of days of ice-affected flow and since neither temperatures or precipitation had significant changes from 1936 to 2000, we tested for significant changes over time in monthly mean flows for all rivers in this study, for their complete period of flow records through 2000 (Table V). There were significant ($p < 0.1$) increases in November, December, January, and April mean monthly flows at two to four rivers for each month. There was a significant decrease in flow at one river in April. Monthly mean flows increased significantly at nine rivers in February and at 13 rivers in March. The trends in monthly ice-affected flow days over time with the lowest p-values were also in February and March (Table II). This lends support to the idea that increased river flows are driving a decrease in days of ice-affected flow in the late winter.

The annual last dates of ice-affected flow in the spring for the nine longest-record rivers in northern New England were correlated with average monthly temperatures and precipitation (Table VI) for 17 USHCN temperature sites in the same area as the nine rivers (Figure 2), for 1936–2000. The highest correlations with temperature were with March through April temperatures ($r = -0.73$, $p < 0.0001$) and February through April temperatures ($r = -0.71$, $p < 0.0001$). The highest correlations with precipitation were with January ($r = -0.36$, $p = 0.0030$) and January through April ($r = -0.37$, $p = 0.0027$) precipitation. The best air temperature correlation explains 53% of the variability in the annual last dates of ice-affected flow in the spring while the best precipitation correlation explains 14%. The last dates of ice-affected flow are more sensitive to changes in temperature than changes in precipitation. River ice breakup has been found to be related to spring air

TABLE V
Attained significance levels (p-values) for Mann-Kendall trend tests of mean monthly river flows over time

USGS station number	River name and state	November		December		January		February		March		April	
01011000	Allagash, ME	0.25	(+)	0.21	(+)	**0.046**	(+)	**0.0048**	(+)	**0.0006**	(+)	**0.0050**	(+)
01013500	Fish, ME	0.15	(+)	**0.026**	(+)	**0.018**	(+)	**0.0003**	(+)	**0.0003**	(+)	**0.0021**	(+)
01014000	St. John, ME	0.94	(−)	0.31	(+)	0.14	(+)	**0.0075**	(+)	**0.0003**	(+)	**0.0041**	(+)
01022500	Narraguagus, ME	0.28	(−)	0.10	(−)	0.62	(−)	0.66	(+)	**0.050**	(+)	0.42	(−)
01031500	Piscataquis, ME	**0.084**	(+)	0.21	(+)	0.41	(+)	**0.015**	(+)	**0.036**	(+)	0.15	(+)
01038000	Sheepscot, ME	0.92	(+)	0.74	(+)	0.51	(+)	0.27	(+)	**0.057**	(+)	0.73	(−)
01048000	Sandy, ME	0.26	(+)	0.34	(+)	0.37	(+)	**0.033**	(+)	**0.0098**	(+)	0.75	(−)
01052500	Diamond, NH	0.73	(+)	0.41	(+)	**0.083**	(+)	**0.0081**	(+)	**0.014**	(+)	0.45	(+)
01055000	Swift, ME	0.11	(+)	0.21	(+)	0.44	(+)	**0.026**	(+)	**0.0006**	(+)	0.48	(+)
01060000	Royal, ME	0.50	(−)	0.25	(−)	0.79	(−)	0.99	(−)	0.37	(+)	**0.045**	(−)
01064500	Saco, NH	**0.0059**	(+)	**0.055**	(+)	0.48	(+)	0.15	(+)	**0.049**	(+)	0.62	(+)
01073000	Oyster, NH	0.17	(+)	0.61	(+)	0.86	(−)	0.37	(+)	0.71	(−)	0.68	(−)
01076500	Pemigewasset, NH	**0.0065**	(+)	0.12	(+)	0.64	(+)	**0.037**	(+)	0.97	(−)	0.74	(−)
01134500	Moose, VT	0.13	(+)	0.42	(+)	**0.063**	(+)	0.16	(+)	**0.015**	(+)	0.42	(−)
01137500	Ammonoosuc, NH	0.37	(+)	0.69	(+)	0.10	(+)	0.14	(+)	**0.017**	(+)	0.97	(−)
04293500	Missisquoi, VT	**0.093**	(+)	0.26	(+)	0.39	(+)	**0.0071**	(+)	**0.070**	(+)	0.10	(−)

Numbers in bold indicate $p < 0.1$. Positive or negative signs after the numbers indicate the sign of Kendall's Tau for each Mann-Kendall test.

TABLE VI

Correlation coefficients (r-values) between annual last dates of ice-affected flow in the spring (nine-river average) and monthly temperatures and precipitation (17-site average)

Month(s)	Temperature correlation coefficient	p-value of correlation	Precipitation correlation coefficient	p-value of correlation
November	−0.09	0.47	−0.08	0.55
December	−0.08	0.52	0.08	0.52
January	−0.06	0.64	**−0.36**	0.0030
February	−0.28	0.024	0.00	1.00
March	−0.68	<0.0001	−0.11	0.385
April	−0.54	<0.0001	−0.27	0.028
March–April	**−0.73**	<0.0001	−0.25	0.044
February–April	**−0.71**	<0.0001	−0.23	0.071
January–April	−0.64	<0.0001	**−0.37**	0.0027
December–April	−0.56	<0.0001	−0.22	0.083
November–April	−0.54	<0.0001	−0.23	0.069

Numbers in bold are the highest correlations.

temperatures at rivers in the former Soviet Union, Finland, and Canada (Prowse and Beltaos, 2002).

5. Summary and Discussion

For 12 of the 16 rivers analyzed in this study, the total annual days of ice-affected flow decreased significantly ($p < 0.1$) over their period of record. On average, for the nine longest-record rivers in northern New England, the total days of ice-affected flow decreased significantly ($p = 0.0013$) from 1936 to 2000. Most of the 20-day change in the total days of ice-affected flow occurred from the 1960s to 2000. This study also found significant changes in the nine-river average, over time, toward fewer ice-affected flow days in the individual months of January, February, March, and April. The magnitude of change was two to three times greater in March and April than in January and February. Mean monthly flows increased significantly ($p < 0.1$) at 9 of 16 rivers in February and 13 of 16 rivers in March. The annual total number of days of ice-affected flow were significantly correlated with November through April air temperatures ($r = -0.70$) and with November through April precipitation ($r = -0.52$).

In the only other known study of winter geophysical or biological changes in northern New England, Huntington et al. (2003) found a significant decrease over time ($p = 0.0021$) in average ice thickness around February 28 on the Piscataquis River in central Maine (same site as in this paper). The ice thinned by about 23 cm (45%) from 1912 to 2001. The annual ice-thickness values were significantly correlated ($r = -0.62$, $p < 0.0001$) with December through February air temperatures. Thinner late-winter river ice thickness over time is consistent the results of this study which show fewer total days of ice-affected flow over time at the Piscataquis River and fewer days of ice-affected flow in January and February for the nine-river average. In southern New England, there was a northward shift in winter ranges of bird species on Cape Cod, Massachusetts from 1930 to 2001 (Valiela and Bowen, 2003). The northward shift was positively correlated with local winter air temperatures ($r = 0.81$ to 0.91).

Four of 16 rivers in this study had significantly later ($p < 0.1$) first fall days of ice-affected flow. Three of the four rivers were located in northern New Hampshire or northern Vermont. To date there has been only weak evidence of fall temperature-related changes in New England hydrology. Hodgkins et al. (2003a) and Dudley and Hodgkins (2002) found few significant changes in the timing of fall high flows. No other studies of New England fall biological or geophysical changes are known. Globally, there is much less information available on autumn phenology for both plants and animals than for spring phenology (Sparks and Menzel, 2002).

Twelve of the 16 rivers in this study had significantly earlier ($p < 0.1$) last dates of ice-affected flow in the spring. On average, for the nine longest-record rivers in northern New England, the last dates became significantly earlier ($p = 0.0037$) from 1936 to 2000. Most of the 11-day change in the last date of ice-affected flow occurred from the 1960s to 2000. The average dates were significantly correlated with March through April air temperatures ($r = -0.73$) and January through April precipitation ($r = -0.37$). Biological and geophysical changes in spring in New England are consistent with observations of earlier last dates of ice-affected flow. The annual date of the last hard spring freeze (Cooter and Leduc, 1995) and lilac bloom dates at four stations (Schwartz and Reiter, 2000) became significantly earlier in New England from 1961 to 1990 and from 1959 to 1993, respectively. The last-frost date became earlier by 11 days while three of the four lilac bloom dates became earlier by more than 10 days. Much of the significant change toward earlier lake ice-out dates in New England since the 1800s occurred from approximately 1968 to 2000 after dates became later from approximately 1945 to 1968 (Hodgkins et al., 2002). Ice-out dates from 1968 to 2000 became earlier by approximately 5 days in northern and mountainous areas of Maine and New Hampshire and approximately 13 days in more southerly areas of these states. Winter/spring high flows became significantly earlier in northern and mountainous sections of Maine and New Hampshire over the 20th century, with most of the one to two week change occurring in the last 30 years (Hodgkins et al., 2003a). Spring lake ice-out dates, winter/spring river high-flow dates, and last dates of spring ice-affected river flow were significantly correlated with March through April air temperatures, all with a correlation coefficient of about 0.70 (Hodgkins et al., 2002; Hodgkins et al., 2003a; this study).

Overall, there is strong and consistent evidence of biological and geophysical changes, all consistent with warming temperatures, in the late-winter and spring in

New England in the last 30–40 years. There is some evidence of recent geophysical changes in mid-winter that are consistent with warming temperatures, and little evidence of changes in the fall.

The documented reduction in the number of days of ice-affected flow from January to April could have important ecological effects. One potential effect involves more frequent formation of anchor ice. Anchor ice does not form when surface ice is present. With fewer ice-affected flow days in the winter, there may be less continuous surface-ice cover and more frequent opportunities for anchor ice to form. Anchor ice typically forms on very cold, clear winter nights. These conditions could still be present in winters that are generally warmer. Anchor ice can restrict or even eliminate substrate flow. This has serious effects on stream biota sensitive to subfreezing conditions and (or) dissolved oxygen in the substrate water, particularly fish eggs and embryos developing within gravel beds (Prowse, 1994).

The documented changes in the last dates of ice-affected flow in the spring could also have important effects on river ecology, including effects on primary producers, consumers, and trophic dynamics. Despite the potential importance of river ice break-up to community structure and function, detailed information describing the magnitude of their effects and underlying causal mechanisms is scarce (Scrimgeour et al., 1994).

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