# Historical Trend in Ice Thickness on the Piscataquis River in Central Maine

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**ABSTRACT**

We analyzed a long-term record of ice thickness on the Piscataquis River in central Maine to determine whether there were temporal trends that were associated with climate warming. Trends in ice thickness were compared and correlated with regional time series of winter air temperature, heating degree days (HDD) , date of river ice-out, seasonal center-of-volume date (SCVD) (date on which half of the stream runoff volume during the period 1 Jan and 31 May has occurred), water temperature, and lake ice-out date. All of these variables except lake ice-out date showed significant temporal trends during the 20th century. Average ice thickness around 28 Feb. decreased by about 23 cm from 1912 to 2001. Over the period 1900 to 1999, winter air temperature increased by 1.7 ˚C and HDD decreased by about 7.5%. Final ice-out date on the Piscataquis River occurred earlier (advanced), by 0.23 days $yr^{-1}$ over the period 1931 to 2002. The SCVD advanced by 0.11 days $yr^{-1}$ over the period 1903 to 2001. Ice thickness was significantly correlated with winter air temperature, HDD, river ice-out, and SCVD ($P$-value < 0.01). These systematic temporal trends in multiple hydrologic indicator variables indicate a coherent response to climate forcing.

Keywords: climate change, hydrologic indicators, river ice thickness

**INTRODUCTION**

Hydrologic variables that are sensitive to incremental changes in temperature regime can serve as indicators of systematic changes in climate, providing evidence for physical responses to these changes in spite of large interannual variability. Coherence among several indicators within a region may be the most compelling evidence for change. Recent studies have shown that average dates of lake ice-out (Magnuson et al., 2000), river ice-out (Beltaos, 1999; Magnuson et al., 2000), and timing of the spring peak river discharge (Burn, 1994; Cayan et al., 2001) advanced in North America during the 20th century. Both April snow water equivalent in North America and snow cover extent in April over the northern hemisphere have decreased in the 20th century (Brown, 2000). Systematic thinning of arctic sea ice (Rothrock and Maykut, 1999), the Greenland ice sheet (Patterson and Reeh, 2001), and seasonal decreases in sea-ice extent (Parkinson et al., 1999) have been reported. Fang and Stefan (1998) examined potential trends in lake ice thickness associated with a doubling of atmospheric $CO_2$ in the U.S., but there have not been any reports indicating systematic trends in river ice thickness.

The growing season has lengthened based on historical records of killing frosts (Baron and Smith, 1996) and temperature records (Cooter and LeDuc, 1995). There are several indicators that show an advance in spring for various biological indicators. Lilac and honeysuckle first-bloom dates have occurred earlier in recent years (Schwartz and Reiter, 2000; Cayan et al. 2001).

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Remotely sensed spectral reflectance data (normalized difference vegetation index (NDVI) is consistent with an earlier onset of greenness and a concordant earlier drawdown in atmospheric $CO_2$ concentration (Myneni et al., 1997). The date of nesting of the tree swallow (*Tachycineta bicolor*) advanced by up to 9 days over the period 1959–1991 throughout North America (Dunn and Winkler, 1999). The photoperiodic response of the pitcher plant mosquito (*Wyeomyia smithii*) in Maine has shifted towards shorter, more southern day lengths as growing seasons have become longer, which is correlated with increasing mean annual temperatures in Maine (Bradshaw and Holzapfel, 2001). These responses are all consistent with observed trends in increasing springtime and mean annual air temperature (MAT) over the region during the 20$^{th}$ century (Houghton et al., 2001). The objective of this analysis was to test the hypothesis that late winter river ice thickness would show systematic thinning that was consistent with other hydroclimatic and biological indicators of warmer climate and advancing spring.

**METHODS**

The U.S. Geological Survey has historical records of river discharge measurements in wintertime when rivers were covered with ice. These measurements have been made approximately every four to six weeks. Occasionally the measurements are made more frequently (as often as every two weeks). For hydroclimatological study it is essential to minimize the potential for influences other than climate. It is therefore critical to select an unregulated river because flow regulation can affect ice formation, breakup, and presumably ice thickness. The Piscataquis River near Dover–Foxcroft, [U.S. Geological Survey streamflow gaging station No. 01031500] in central Maine meets the criteria for a streamflow dataset that is free from any significant confounding influence that could affect flow, including consumptive use, impoundment and release, or changes in land use (Slack and Landwehr, 1992; Stewart et al., 2001).

Another consideration in river selection is that slush and frazil ice should not be present under the solid ice because this ice will confound the estimation of ice thickness. In addition, the site should be one in which measurements are made in the same cross section each year. On some rivers, winter discharge measurements are made above or below the continuous streamflow gaging site to facilitate getting on solid ice for safety considerations. Slush or frazil ice does not usually form at this location and the measurements are routinely made in the same cross section.

For some rivers there are periods of time when these discharge measurements included records of both ice thickness and the distance from the water surface to the bottom of the ice (WSBI). If slush or frazil ice is present it is included in the WSBI measurement: therefore, if the discharge measurement notes indicate slush ice, ice thickness measurements from such records should be not be used. WSBI measurements are standard measurements used to estimate the effective depth of water for calculation of discharge under ice conditions and they were made by a consistent set of standard methods throughout the period of record (Barrows and Horton, 1907; Corbett, 1943; Buchanan and Somers, 1969). The period of record for which ice measurements are available on the Piscataquis River near Dover–Foxcroft is from 1912 to 2001; this is one of the longest records available for an unregulated river in Maine. At this site, WSBI measurements were recorded at 12 to 20 locations along a cross section that was established immediately upstream of the streamgage site.

The frequency of measurements made during a given year was variable over the period of record. Measurements were less frequent in the earlier part of the period of record. For a climatological time-series analysis, it is important that the ice thickness measurements be made at the same time each year because there is a systematic change in ice thickness over time (Vavrus, 1996). Because this was not the original intent of the measurements, they were not made on the same day of the year. However, a specific data-collection program on the Piscataquis River involved measurements within a few days of 28 Feb. from 1940 to 1974. In most other years during the period of record, measurements were recorded within three weeks of 28 Feb. For the entire period of record, 67% of all measurements used in this analysis were made on 28 Feb. +/– 1 week; 94% +/– 2 weeks; 100% +/– 3 weeks (Figure 1). There was no temporal bias with regard to proximity to 28 Feb, except between 1940 to 1974 when all measurements were recorded on 28 Feb. +/– 1 week; however, there was substantially more variability in this date prior to 1940 and after 1974 than during the period from1940 to 1974 (Figure 1).

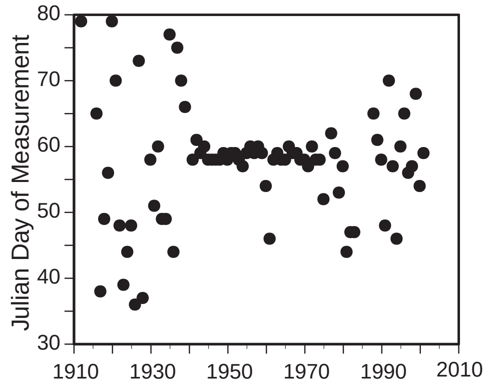


Figure 1. Julian day of discharge measurement when water surface to bottom of ice (WSBI) was recorded at station 40, Piscataquis River near Dover Foxcroft, Maine.

It is also important that measurements be made at the same locations each year because there is variation in ice thickness both across the cross section (perpendicular to flow) and along a given reach (parallel to flow) at a given distance from the bank. These differences are a result of different water velocities, water depths, and distances from water inflows from groundwater or tributaries. During the special data-collection program on the Piscataquis River from 1940 to 1974 ice thickness measurements were made 40 feet from the left edge of water facing downstream (station 40). In 90% of all other years, ice thickness and WSBI measurements were made at station 40 or within five feet to either side of this point. In the other years, measurements were made within 10 feet of either side of this point. In all cases where measurements were not made at station 40, we interpolated between measurements to estimate thickness at station 40.

There was no ice present during the measurement window for 15 of the years in the period of record. Ice-free years were treated in two separate ways for trend analysis and correlation tests. In one series of tests, ice thickness was assigned zero for ice-free years and in the other tests, it was assigned a value of 12.6 cm, which was one cm less than the lowest measured ice thickness. The latter treatment is similar to recommended statistical treatment for censored data (Helsel and Hirsch, 1992). In 12 of the years between 1912 and 2001, no data were recorded because there were no site visits during the Feb. 28 +/– 3 weeks window. Seven of the years in which no data were collected occurred in the first half of the record and the remaining 5 years in which no data were collected occurred in the second half of the record.

The following rules were applied when there were no measurement dates within the period Feb. 28 +/– 7 days. If there were no measurements made within the period Feb. 28 +/– 21 days, no data were recorded. If there was only one measurement made within the period Feb. 28 +/– 21 days, data for this measurement date were recorded. If there was more than one measurement made within the period Feb. 28 +/– 21 days, then values were interpolated between the two measurements closest to and on either side of Feb. 28 to approximate values on Feb. 28. In some years data were not collected at station 40 but were collected within 5 feet on either side of this location. In these years measurements at station 40 were interpolated using the measurements on either side, or if there was only one measurement within 5 feet on either side, that measurement was used.

Air temperature time series were obtained from the U.S. Historical Climatology Network (USHCN) dataset (Karl et al., 1990). Data were retrieved as monthly averaged mean temperature. All USHCN stations in Maine having continuous temperature data for the period 1900–1999 were used in the analysis. The seven stations that met this criteria were Portland, Lewiston, Houlton, Eastport, Acadia, Orono, and Farmington. The data have been subjected to quality control and homogeneity testing and adjustment procedures for bias originating from changes in time-of-observation (Karl, et al. 1986), instrumentation (Quayle, et al. 1991), station moves (Karl and Williams, 1987), and urban warming (Karl, et al., 1988).

Mean monthly air temperature data from the seven long-term USHCN sites in Maine were used to develop aggregate regional average annual and winter (1 Dec. through 28 Feb.) temperature anomaly time series. The averages were computed as the arithmetic mean of the seven sites. Annual heating degree days (HDD) were calculated by multiplying the number of days per month by the difference (18.33˚C—average monthly temperature in ˚C) and summing all months. Annual HDD were calculated for the year ending 28 Feb (or 29 Feb in a leap year). HDD are a measure of how cold the winter was and as such are likely to be related to late winter ice thickness.

A time series was developed for the Julian date of final ice-out on the Piscataquis River near Dover–Foxcroft using U.S. Geological Survey records for the period 1931 through 2002. Ice-out records are derived from analysis of river stage hydrographs that contain distinct features that indicate ice effects on river stage. These features are identified on the basis of past experience, judgement, and local knowledge (Buchanan and Somers, 1969). In contrast to lake ice-out records that have been questioned because of observer subjectivity and lack of standard protocols (Houghton et al., 2001), river ice-out records are based on physical measurements following rigorous standard protocols. When it is determined that ice has affected stage, it is noted for each day of ice effect. Under low flow conditions, river stage on the Piscataquis River near Dover–Foxcroft is affected by the regulation of impoundments used by paper mills. The frequency of flow regulation has decreased over the period of record as the number of mills operating in the river basin has declined. Flow regulation can affect river stage enough to affect ice breakup although it is unknown whether these flow regulations actually have affected river ice-out dates. A decreasing frequency of flow regulation would suggest a decreasing frequency of mid-winter ice breakups and would be associated with a trend towards increasing ice thickness over time.

Another time series was developed for mean May water temperature at the Wild River near Gilead, Maine. The Wild River site was selected for water temperature because it has the longest and most complete temperature record for any river in Maine. May water temperature was recorded continuously at the Wild River site for 26 out of 36 years from 1966 through 2001. The month of May has the most complete monthly temperature record. The water-temperature probe was placed 3 cm from the stream bottom and was never exposed to the air. The location, type of instrumentation, and riparian vegetation have not changed in any way that would introduce bias into the temperature measurement.

A time series was also developed to assess the timing of the seasonal center-of-volume date (SCVD) for the Piscataquis River near Dover–Foxcroft. The SCVD statistic was defined as the Julian date on which half of the stream runoff volume during the period 1 Jan and 31 May has occurred. This statistic is sensitive to the timing of snowmelt but relatively insensitive to individual hydrologic events that occur with random frequency. As such, this indicator is thought to be responsive to the timing of spring warming in hydrologic systems that normally experience a large seasonal snowmelt episode (Court, 1962). A similar statistic was used for New England rivers to assess the influence of snowfall amount and temperature on timing of runoff (Hartley and Dingman, 1993).

Time series data were also obtained from the Maine Atlantic Salmon Commission (ASC) on the timing of salmon migration on the Penobscot River (Ken Beland, ASC, written communication). Time series data on the timing of adult alewife (herring) migration on the Androscoggin River.were obtained from the Maine Department of Marine Resources (DMR) annual Brunswick Fishway Reports. Both the ASC and DMR maintain fish traps at Veazie and Brunswick, Maine respectively, at where adult fish are counted as they return from salt water to freshwater. From daily count data the Julian date of median capture (50% of total returning fish captured as of this date) was determined. The period of record for this data is from 1983 through 2001 alewives and 1986–2001 for salmon. The timing of returning migration is influenced by water temperature and the amount of streamflow.

An ordinary least-squares regression between WSBI and ice thickness was developed using the period from1912 to 1975 (n=46) for measurements recorded at station 40 on the Piscataquis River. Years with no ice present were not included in this regression. Standard tests for analysis of residuals were applied to assess the validity of the regression model (Helsel and Hisrch, 1992). The Durban–Watson statistic was used to test for serial correlation. The regression model was then used to estimate ice thickness for the entire period of record (1912–2001) using WSBI measurements for all measurements during the 28 Feb. +/– 3 weeks window.

Hydroclimatological time series were plotted for their periods of record and a Locally Weighted Scatterplot Smooth (LOWESS) (Helsel and Hirsch, 1992) curve was plotted through the data for graphical interpretation of the trend. For these plots, zero ice thickness was used for years in which no ice was present. Temporal trend tests for ice thickness, winter air temperature, HDD, Julian date of river ice-out, SCVD, water temperature, and salmon migration date were conducted with a nonparametric test for monotonic trend based on Kendall's tau statistic (Helsel and Hirsch, 1992). Using this test, no assumptions of normality of the distribution are required, but serial correlation is assumed to be negligible. The Durban–Watson statistic was calculated to test for serial correlation. Trend analysis using Kendall's tau statistic requires that there are few missing values and their distribution through time is relatively constant. Where trends were significant (P-value<0.05), the slopes were estimated using the nonparametric Kendall–Theil/Sen estimation (median of all possible pair-wise slopes) (Helsel and Hirsch, 1992). The nonparametric Kendall Rank Correlation tau statistic was used to test the significance of correlations between ice thickness and winter air temperature anomaly, HDD, lake ice-out date, river ice-out date, water temperature, and the SCVD. The slopes of these relationships were estimated using the Kendall–Theil/Sen estimator. For trend tests and slope estimation involving ice thickness, the results were reported for both treatments of ice-free conditions (using zero ice thickness or ice-thickness set to 12.6 cm).

## RESULTS

### WSBI versus Ice Thickness Regression

WSBI and ice thickness were strongly correlated ($r^2$=0.91) and the regression relation was highly significant (P-value <0.0001) over the period from1912 to1975 (n=45) for the Piscataquis River near Dover–Foxcroft (Figure 2). An analysis of residuals indicated a valid regression model and no serial correlation was detected. The regression equation is: Ice thickness (cm) = 1.75 + 1.015[WSBI (cm)]. There was no relation between the year and the frequency of occurrence of ice-free conditions during the Feb. 28 +/– 3 weeks window (Figure 3). WSBI was usually equal to or slightly less than ice thickness except in rare cases where water was flowing over the surface of the ice.

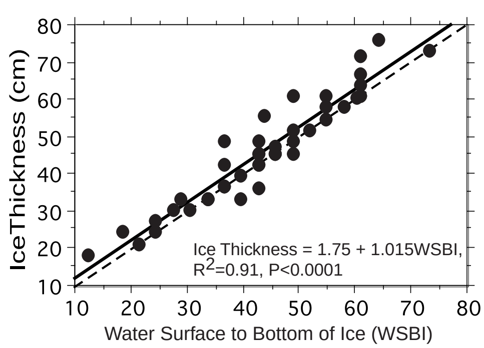


Figure 2. Ordinary least squares regression of ice thickness as a function of water surface to bottom of ice (WSBI). Solid line is the regression line and dashed line is the 1:1 line.

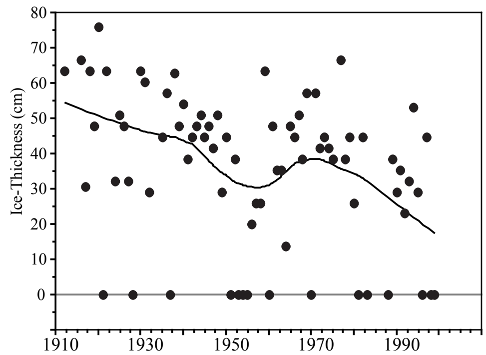


Figure 3. Ice thickness around 28 Feb on the Piscataquis River, near Dover Foxcroft versus time. Plotted line is LOWESS curve (tension = 45 years).

**Temporal Trends**

Although there was substantial interannual variation, there was a distinct overall trend towards thinning of river ice (Figure 3). The LOWESS curve revealed a short-term trend reversal over the period from about1950 to1975. This trend reversal is consistent with regional cooling during the 3rd quarter of the 20th century (Houghton et al., 2001, Hansen et al., 1998). Hansen et al. (1999) speculated that the cause of the cooling could be associated with an unusually strong cool phase of the North Atlantic Oscillation, a reduction in heat transport, or tropospheric response to anthropogenic greenhouse gas-induced stratospheric cooling. Cicerone et al. (2001) suggested that the cause of the 1946 to1975 cooling could have been sulfate aerosols, and that oceanic circulation could also be involved. In addition, Cicerone et al. (2001) noted that changes in solar luminosity and volcanic eruptions could not be excluded.

Where zero ice thickness was used for years of ice-free conditions, there was a significant relation (P-value=0.0021) between ice thickness and time (Table 1) with average ice thickness decreasing about 23 cm from 1912 to 2001 (Figure 3). The slope (the rate of ice thinning) was estimated to be –0.26 cm $yr^{-1}$, using the non-parametric Kendall–Theil slope estimation (Table 1). This change in ice thickness was equivalent to a decrease of nearly 50% over the time period. When years of ice-free conditions were censored and assigned a value of 12.6 cm (1 cm less than the minimum measured ice thickness), the estimated slope decreased slightly to –0.25 cm $yr^{-1}$ (Table 1). Systematic decreases in thickness of river ice have not been previously reported so the rate for the Piscataquis River cannot be compared to other rivers. Fang and Stefan (1998) projected a decrease in lake ice thickness of 30 cm associated with a projected ~6 ˚C increase in mean annual temperature (5 cm/ ˚C) for a doubling in atmospheric $CO_2$ over central Maine. The rate of thinning of Arctic sea-ice over the last 40 years (Rothrock et al., 1999) is an order of magnitude greater than what we observed for river ice, but rates of change for climate indicators tend to be substantially amplified at extreme northern latitudes (Houghton et al., 2001).

The aggregate winter air temperature anomaly from1900 to1999 indicated both a systematic increase in air temperature over time and cooling during the 3rd quarter of the 20th century (Figure 4, Table 1). The increasing temperature trend was significant (P-value<0.01) and the slope of the trend was 0.017 ˚C $yr^{-1}$ (Table 1). The aggregate mean annual air temperature anomaly also increased significantly with a similar slope of 0.019 ˚C $yr^{-1}$ (Table 1). These warming trends are similar to those reported for the larger regional area (Houghton et al., 2001). Ice thickness on 28 Feb was more highly correlated with winter air temperature than with mean annual air temperature so winter temperature was used for subsequent correlation tests and slope estimates.

The number of HDD for the year ending 28 Feb of the year in which ice thickness was measured or estimated from WSBI decreased over time (Figure 5). This time series also showed a cooling trend during the 3rd quarter of the 20th century, indicating cooler winters (increasing HDD) (Figure 5). The decreasing HDD trend was significant (P-value<0.0001) and the slope of the trend was –3.1 HDD $yr^{-1}$ (Table 1). This trend is equivalent to a decrease of about 7.5% in HDD from 1900 to 1999.

**Table 1. Statistical tests for significance of temporal trends and correlations between ice thickness (cm) on the Piscataquis River near Dover–Foxcroft and other indicator variables.**

| Y | X | Kendall's tau | P-value | Thiel/Sen Slope[1] |
|---|---|---|---|---|
| MAT Anomaly | Year (1900–1999) | 0.29 | 0.000018 | 0.019 ˚C $yr^{-1}$ |
| Winter Temp | Year (1900–1999) | 0.20 | 0.0041 | 0.017 ˚C $yr^{-1}$ |
| HDD | Year (1900–1999) | –0.27 | 0.000066 | –3.1 HDD $yr^{-1}$ |
| Ice Thickness | Year (1912–2001) | –0.23 | 0.0021 | –0.26 to –0.25 cm $yr^{-1}$ |
| River Ice-Out | Year (1931–2002) | –0.24 | 0.003 | –0.23 day $yr^{-1}$ |
| SCVD[2] | Year (1903–2000) | –0.22 | 0.0016 | –0.11 day $yr^{-1}$ |
| Water Temp.[3] | Year (1966–2001) | 0.43 | 0.0019 | 0.09 ˚C $yr^{-1}$ |
| Salmon Migration | Year (1986–2001) | –0.45 | 0.015 | –1.3 day $yr^{-1}$ |
| Alewife Migration | Year (1983–2001) | –0.35 | 0.039 | –1.2 day $yr^{-1}$ |
| Ice Thickness | Winter Temp (˚C) | –0.45 | <0.00001 | –8.2 to –6.9 cm ˚$C^{-1}$ |
| Ice Thickness | HDD | 0.34 | 0.00007 | 0.040 to 0.036 cm $HDD^{-1}$ |
| Ice Thickness | River Ice-Out | 0.27 | 0.001 | 0.59 to 0.54 cm $day^{-1}$ |
| Ice Thickness | SCVD[2] | 0.23 | 0.0025 | 0.78 to 0.69 cm $day^{-1}$ |
| Ice Thickness | Water Temp.[3] (˚C) | –0.21 | 0.15 | –2.32 to –2.32 cm ˚$C^{-1}$ |
| Ice Thickness | Lake Ice-Out[4] | 0.15 | 0.053 | 0.39 to 0.33 cm $day^{-1}$ |
| SCVD[2] | River Ice-Out | 0.39 | <0.00001 | 0.48 day $day^{-1}$ |
| River Ice-Out | Winter Temp (˚C) | –0.26 | 0.0030 | –2.78 day ˚$C^{-1}$ |

[1]First element of range for Thiel/Sen slope estimator uses ice thickness set to 0.0 for ice-free conditions, second element of range uses ice thickness set to 12.6 cm for ice-free conditions.

[2]SCVD is the Julian date on which half of the runoff volume during the period between 1 Jan and 31 May had flowed past the gage.

[3]Mean May water temperature at Wild River near Gilead, Maine

[4]Moosehead Lake

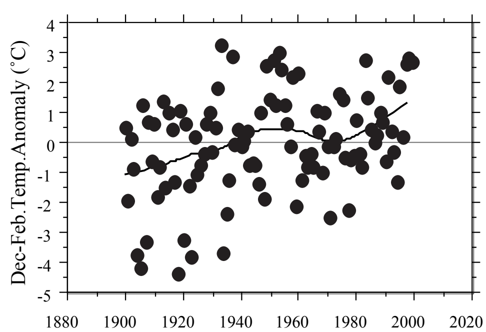


Figure 4. Aggregate winter (December through February) air temperature anomaly (˚C) for seven USHCN stations in Maine with LOWESS curve (tension=45 years).

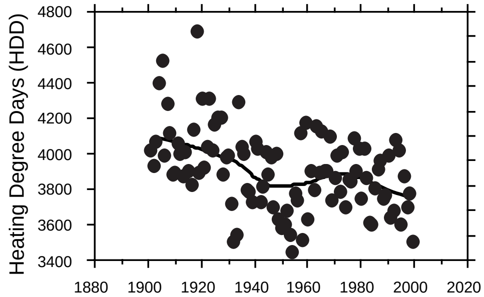


Figure 5. Average annual heating degree days (HDD) for seven USHCN stations in Maine with LOWESS curve (tension=45 years).

The time series for the Julian date of final ice-out on the Piscataquis River near Dover–Foxcroft indicated a trend towards earlier ice-out over the period of record (Figure 6). The trend was significant (P-value=0.003) with a slope of –0.23 day $yr^{-1}$ (Table 1). The temporal pattern in river ice-out date does not exhibit an acceleration during the period 1970 to 2001 compared with the overall long-term trend as is apparent in the winter air temperature and ice thickness trends. The reasons for the differences in decade-scale patterns of hydrologic time series may relate to differences in responses to several variables including temperature, snowfall, rainfall, albedo, cloudiness, and wind speed. The rate of advance in ice-out date on the Piscataquis River (–0.23 day $yr^{-1}$) is similar to that published for other rivers in the northern hemisphere (Magnuson et al., 2000; Beltaos, 1999). We also examined the temporal trend in the date of first ice-on at this site and determined that there was no significant change in this timing.

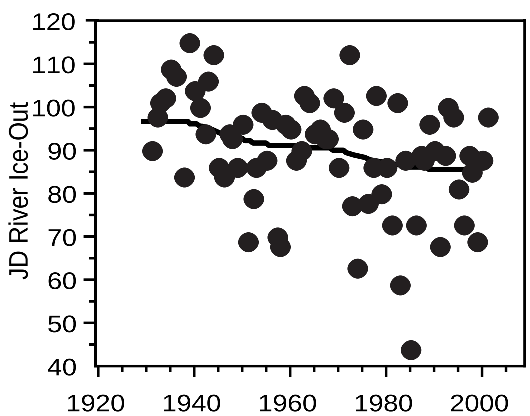


Figure 6. Julian date of final river ice-out for the Piscataquis River near Dover–Foxcroft. Plotted line is LOWESS curve (tension=45).

The SCVD advanced significantly (P-value <0.01) over time (1903–2000) (Table 1). This hydrologic time series did not show a trend reversal during the 3rd quarter of the 20th century. The SCVD was relatively constant at about Julian date 111 (April 21, or April 20 in leap years) until about 1970 when it began advancing rapidly (Figure 7). The slope of the relation over the period of record was –0.11 days $yr^{-1}$, which was very similar to the rate of change in advance in ice-out date for this river (Table 1). This advance in the SCVD is also consistent with the finding that, on average, maximum flows occurred earlier in basins with higher average temperatures (approximately 5.4 days earlier per ˚C) in Vermont, New Hampshire, and Massachusetts (Hartley and Dingman, 1993). The temporal pattern in SCVD suggests that spring snowmelt could be a threshold-like response in which there is little observed change until a threshold is reached and then the response is large and rapid. One possible mechanism that could explain this response is that snowmelt involves a ripening of the snowpack through warming and absorption of rainfall. To initiate snowmelt-driven runoff, the snowpack requires a threshold amount of energy (warmer spring temperatures) and rainfall. For the Piscataquis River Basin, this threshold may have been reached around 1970 so that the accumulated winter snowpack began to melt earlier.

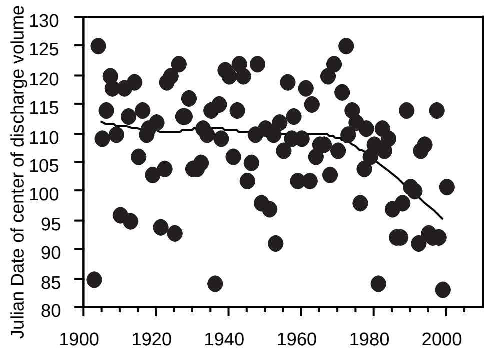


Figure 7. Julian date of center of discharge volume during the period 1 Jan through 31 May for the Piscataquis River near Dover–Foxcroft. Plotted line is LOWESS curve (tension=45).

Mean May water temperature in the Wild River near Gilead increased significantly (P-value=0.0019) over the period of record (1966–2001) (Table 1, Figure 8). This increase in monthly water temperature was consistent with increasing winter air temperature and with decreasing HDD over the time period (Figures 4 and 5). The increase in May water temperature is also consistent with earlier snowmelt in the region as inferred from the trend in SCVD on the Piscataquis River, and with earlier ice-out dates on the Piscataquis River. Water temperatures probably remain quite low, within a few degrees of zero, until the majority of snow in the basin has melted and run off. The slope of the trend in May water temperature plotted against time was 0.09 $^{\circ}C\ yr^{-1}$, which is substantially greater than the rate of winter air temperature increase over this period (Table 1). The higher rate of increase in water temperature compared with MAT suggests a higher proportion of the annual warming occurring during the spring and the importance of the changes in timing of snowmelt and river ice-out date. In contrast, the Houghton et al. (2001) found the smallest increase in temperature for March through May compared with other quarters for 1976–2000 for this region. These differences may result from contrasts between the local and regional seasonal warming patterns and the different groups of years considered.

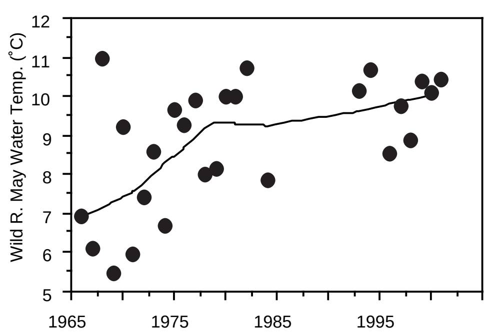


Figure 8. Mean May water temperature at the WIld River near Gilead, Maine. Plotted line is LOWESS curve (tension = 45).

The date of ice-out on Moosehead Lake, immediately northwest of the Piscataquis River Basin, advanced significantly over the period 1847 to 1995 (Magnuson et al., 2000). However, this trend was not statistically significant for the period 1912 through 2000 (data not shown). In a recent analysis it was shown that ice-out advanced significantly (P-value < 0.1) in only 4 out of 13 lakes in New England with100 years or less of records; however, ice-out advanced significantly (P-value < 0.05) at 14 out of 16 lakes having >100 years of record (Hodgkins et al., In Press). These results suggest that river ice-out and river ice thickness have been more responsive than lake ice-out to warming temperatures in the 20th century.

**Correlations Between Ice Thickness and Other Hydroclimatological Variables**

Ice thickness (when ice-free years were included as zero ice thickness) was significantly correlated with winter air temperature, HDD, and date of river ice-out (P-value < 0.0001) (Figure 9, Table 1). The plots of ice thickness versus winter air temperature and HDD show that the years having ice-free conditions cluster in warmer-than-average winters (lower HDD) and colder-than-average winter air temperature anomaly years as would be expected if presence of winter ice were related to aggregate winter coldness. Ice thickness was also significantly correlated with the SCVD (P-value = 0.0025) (Figure 9, Table 1). We expected to see this correlation because earlier stream runoff is consistent with earlier spring warming and snowmelt. In central Maine, substantially more runoff occurs during the period of snowmelt than during other times of year (Dudley and Nielsen, 2000; Nielsen, 1999) so SCVD during this period is likely to be sensitive to the timing of snowmelt.

Correlations between ice thickness and other climate and hydrologic variables were also computed after censoring the data and assigning a value of 12.6 cm for ice thickness for ice-free conditions. These correlations resulted generally in slightly lower slopes. There were no observations of ice thickness between 12.6 cm and zero thickness. Using zero ice thickness for ice-free conditions may overestimate the effect of incremental warming beyond a certain temperature threshold because ice thinner than 12.6 cm may be unstable under normal variations in flow. However, we believe that excluding ice-free years from the analysis is not justified and the true slopes of the relations probably lie between the ranges shown for zero and 12.6 cm ice thickness for ice-free conditions.

Other factors besides air temperature are important in the regulation of ice thickness on rivers. Based on observations and modeling studies on Wisconsin lakes, it is likely that snow accumulation, surface albedo, and heat flux between the river and the ice all influence ice thickness (Vavrus et al., 1996). In rivers, hydraulic factors such as the velocity and depth of water beneath the ice would influence heat flux and therefore ice thickness. Winter rainfall or melting and runoff associated with mid-winter thaws could influence water level and velocity and surface albedo.

On many rivers in Maine, including the Piscataquis River near Dover–Foxcroft, the presence of ice during the winter can be intermittent. Episodes of mid-winter ice break-up are usually associated with rising stream levels following rainfall. The frequency of mid-winter ice break-up events has increased from an average of 0.67 $yr^{-1}$ prior to 1950 to 1.9 $yr^{-1}$ from 1950 to 2001. The increasing frequency of mid-winter ice breakups likely contributes to the observed decrease in ice thickness. However, both ice thickness and the frequency of mid-winter ice breakups are likely to be affected directly by warming and indirectly by increases in winter rainfall amount and intensity if river stage is affected. Rainfall, snow accumulation, surface albedo, cloudiness, and heat flux between the river and the ice probably explain the variation in the simplistic relation between ice thickness and winter air temperature. It is unlikely that flow regulation has influenced ice thickness because flow regulation has decreased over time while mid-winter ice breakup frequency has increased and ice thickness has decreased.

The correlations between ice thickness and water temperature and ice thickness and lake ice-out date indicated substantially weaker trends (P-values 0.15 and 0.05 respectively) than we observed with other variables (Table 1). The water temperature time series may not be long enough to show a significant trend with ice thickness and ice-out. River ice-out also occurs before 1 May and May water temperatures may not always be influenced by winter and early spring temperatures. The lake ice-out data do not show a strong temporal trend over the period of record for ice thickness so the weakness of the correlation between lake ice-out and ice thickness is not surprising. Also, river ice-out date, water temperature, and ice thickness are more likely to be influenced by mid-winter rainfall and resultant increases in flow than is lake ice-out date.

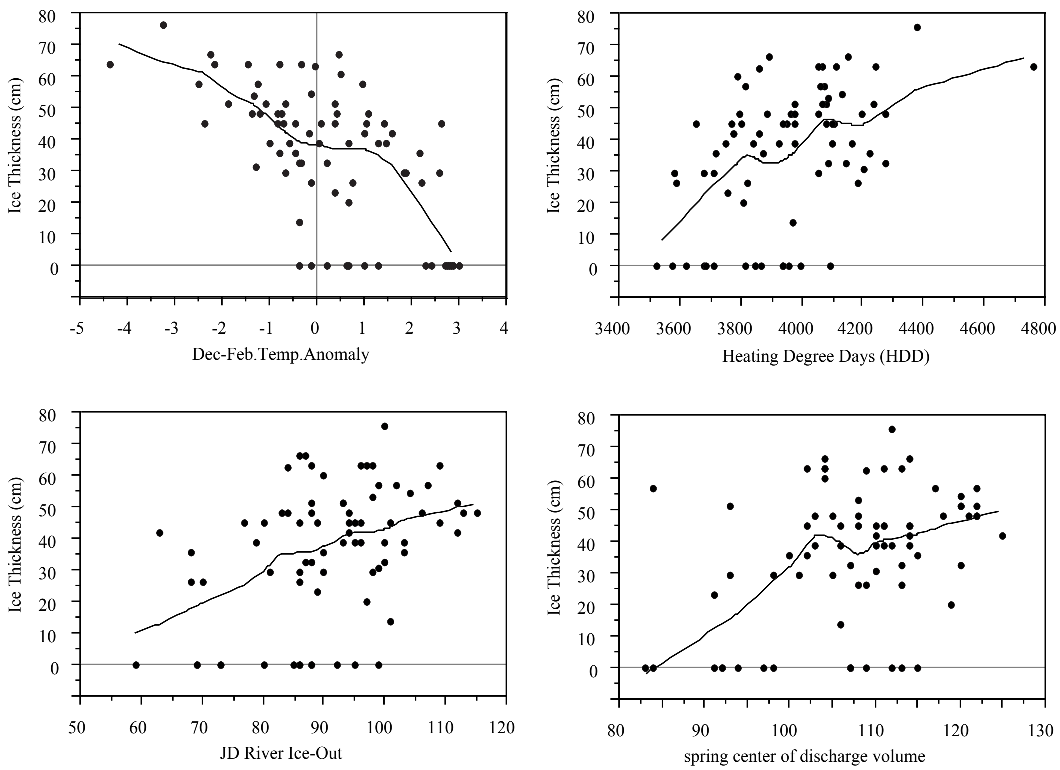


Figure 9. Correlations between ice thickness around 28 Feb. on the Piscataquis River near Dover–Foxcroft and other hydrolclimatological variables. Plotted lines are LOWESS curves (tension=45%)

The SCVD was significantly correlated (P-value<0.00001) with the date of river ice-out (Table 1) which is consistent with the timing of both being related to the timing of spring warming and snowmelt. Similarly, the date of river ice-out was significantly correlated (P-value=0.003) with winter air temperature anomaly, which is consistent with earlier spring warming and snowmelt.

Decreases in ice thickness, advance in the timing of river and lake ice-out, and advance in timing of SCVD are likely to have consequences for aquatic biota that are sensitive to ice phenology and hydrologic regime (Schindler 2001; Beltaos and Prowse, 2001; Porter et al., 1996). Schindler (2001) provides an extensive list of potential effects of warming-induced changes in stream habitats in Canada. Schindler's list includes effects on the distribution, abundance, and productivity of algae, zooplankton, and invertebrates, and changes in dissolved organic carbon concentrations and UV light penetration. Beltaos and Prowse (2001) discuss impacts of altered ice break-up and flow regimes on fluvial geomorphology and aquatic ecology. They emphasize changes in scouring, sediment and nutrient fluxes, and impacts on delta ecosystems. Advance in timing of river ice-out and SCVD are consistent with earlier recession to summer base flow and reductions in growing season runoff that may accompany warming trends depending upon future trends in precipitation (Poff, 1992; McCarty et al., 2001).

Changes in stream temperature regime will affect sensitive fish species (Schindler, 2001; Eaton and Scheller, 1996). Changing stream thermal regimes will also likely affect the timing of migration, spawning, and adaptation to saltwater in anadromous Atlantic salmon, based on the sensitivity of these processes to water temperature in related species (Welch, 1998; Welch and Ishida, 1998; Beamish, 1995). The median capture date for returning adult salmon at the Veazie Fishway Trap on the Penobscot River, in Maine, has advanced significantly (P-value=0.015) over the period 1986 to 2001 (Table 1, Figure 10) in a likely response to warming. Similarly the median capture date for returning adult alewives (herring) has advanced at the Brunswick Fishway on the Androscoggin River in Maine has advanced significantly (P-value=0.015) over the period 1986 to 2001 (Table 1, Figure 10). An advance in the timing of lake ice-out is likely to impact lake oxygenation, species composition and abundance, phytoplankton production, and productivity at various trophic levels (Livingstone, 1997; Assel and Robertson, 1995).

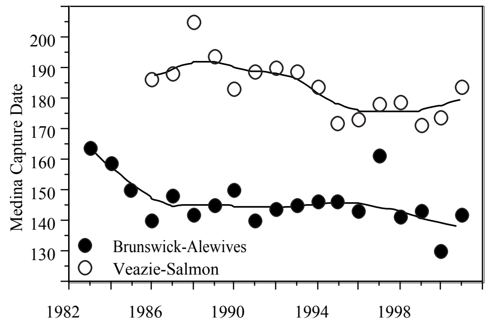


Figure 10. Median capture date for returning adult Atlantic Salmon at the Veazie Fishway Trap on the Penobscott River in Maine and for returning alewives (herring) at the Brunswick Fishway on the Androscoggin River. Plotted lines are LOWESS curves (tension=10 years).

## CONCLUSIONS

The coherence among ice thickness, date of river ice out, seasonal center of volume date, and air temperature records over time, including the response to cooling in the 3rd quarter of the 20th century and the significant correlations between ice thickness and other variables suggest a mutual sensitivity to regional climate forcing. The temporal trends in ice thickness, other hydrologic variables, and plant and animal phenologies are all consistent with air temperature trends that show earlier spring warming. Coherence among multiple time series associated with regional warming provides evidence that hydrologic variables are sensitive indicators to small systematic changes in average climatic conditions. Collection of long-term hydrologic data is essential for understanding the response of natural systems to climate forcing. The data series are also important for the development of predictive models necessary to provide resource managers with tools for informed decision making. Sensitive aquatic ecosystems are likely to be responding to these ongoing changes in river-ice phenology and to changes in hydrologic and thermal regimes in streams.

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