

The interplay of local and regional factors in generating temporal changes in the ice phenology of Dickie Lake, south-central Ontario, Canada

Huaxia Yao¹, James A. Rusak¹, Andrew M. Paterson¹, Keith M. Somers¹, Murray Mackay², Robert Girard¹, Ron Ingram¹, and Christopher McConnell¹

¹ *Dorset Environmental Science Centre, Ontario Ministry of Environment, 1026 Bellwood Acres Rd, Dorset, Ontario, Canada P0A 1E0*

² *Climate Research Division, Environment Canada, 4905 Dufferin St, Toronto, Ontario, Canada, M3H 5T4*
Corresponding author email: huaxia.yao@ontario.ca

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Abstract

Ice-on date occurred significantly later over 1975–2009 at Dickie Lake, Ontario, while ice-off date showed no significant trend, differing from many other records in North America. We examined the ice phenology using 3 modelling approaches: a lake-specific regression model to derive a suite of local predictors; a regionally derived regression model to test larger-scale predictors; and a physically based, one-dimensional thermodynamic model. All 3 models were also applied to generate future ice cover scenarios. The local regression revealed air temperature to be an important predictor of ice phenology in our area, as reported elsewhere; however, reductions in wind speed and increases in lake heat storage over the last 35 years also contributed significantly to a delayed ice-on date. Ice-off dates were strongly correlated with the effects of warmer air temperatures but also influenced by increased snowfall and reduced wind speed. Thus, although changes in ice phenology were related to continental-scale changes in air temperature, they were also influenced by more localized climatic variables, and a careful examination of local events was needed for a complete assessment of ice phenology. Predictabilities of the regional regression model, which primarily relied on air temperature to predict phenology, and the physically based model were lower than the lake-specific local regressions, reinforcing the need for inclusion of local variables when greater accuracy is important. Finally, the 3 methods generated similar estimates of reductions in ice cover over the next 90 years, predicting a 40–50 day decrease in ice season length by 2100.

Key words: Dickie Lake, ice-off, ice-on, regression, snowfall, temperature, wind speed

Introduction

Ice cover plays a fundamental role in the biological, chemical, and physical processes of freshwater ecosystems in cold regions. For example, changes in ice dynamics alter lake physical parameters such as water temperature, stratification dynamics, and water budgets (Rouse et al. 2008, Brown and Duguay 2010) that in turn affect chemical and biological conditions (Keller 2007). Earlier ice breakup may increase the exposure of organisms to ultra violet radiation during long spring days as well as

their susceptibility to damage (Keller 2007), decrease the abundance of certain zooplankton species (Preston and Rusak 2010), and alter phytoplankton community structure (Rühland et al. 2008). The long-term dynamics of lake and river ice is also an important regulator of local climatic conditions and an indicator of climate change and variability (Latifovic and Pouliot 2007).

A wide array of studies has examined ice phenology and dynamics in lakes. Many of these have focused on temporal changes in ice dynamics, which can be divided roughly into 3 categories according to the length of the

datasets: long-term (>100 y), medium-term (50–100 y), and short-term (<50 y) records. Most of the long-term studies have revealed a delay in the date of ice formation, an advancement in the date of ice breakup, and thus an increase in the overall duration of the ice-free season. For example, in an examination of a 150 year ice record from 26 rivers and lakes located south of 60°N, Magnuson et al. (2000) reported a mean delay of ice-on of 5.8 d/100 y, and an advancement of ice-off by 6.3 d/100 y. They found that these changes corresponded to an increase in air temperature of 1.2 °C over 100 years. In more northern regions (e.g., Russia, north of 60°N), other studies reported later ice-on and earlier ice-off dates over the period 1893–1985 (Ginzburg et al. 1992, Soldatova 1993). Similar long-term trends have been reported in many other regions (e.g., Yukon River: Jasek 1998; south-central Ontario: Futter 2003; New England: Hodgkins et al. 2002), and collectively these studies identify the large importance of climatic factors in regulating ice dynamics.

These patterns are not universal, however. For example, some rivers in central and eastern Siberia exhibited later dates of ice-breakup, and hence an increase in the duration of ice-cover over time (Soldatova 1993). In central Ontario, relatively shallow Lake Nipissing also showed a weak delay in ice-off dates, based on a long-term record from 1900 to 2000 (Environment Canada and US Environmental Protection Agency 2007). Furthermore, Lake Erie did not show a clear or significant trend in ice cover for the period 1900–2000 (Assel 2004).

Among studies of medium length (50–100 y), a consistent trend has also not been observed in all cases. Ice-off dates for 341 lakes across Canada occurred approximately 1.48 d earlier per decade between 1950 and 2004 (Environment Canada and US Environmental Protection Agency 2007). Similarly, Latifovic and Pouliot (2007) used observed and satellite data for the same period (1950–2004) and confirmed that the majority of lakes examined showed a trend of delayed ice-on and earlier ice-off dates in Canada; however, they also reported the opposite trend in some lakes. These differences were generally attributed to regional differences in air temperature changes and variability in the lengths of data records. Opposing trends in ice dynamics (i.e., earlier freeze-up and later breakup) were also reported for some Russian rivers (Smith 2000).

Results from short-term (<50 y) studies of ice dynamics are similarly variable among geographical regions. Most of the Great Lakes, for example, showed a clear decreasing trend in ice cover from the 1970s to the 2000s (Assel et al. 2003, Assel 2004, 2005). This finding was supported by a study of 81 lakes in southern Canada and the upper-Midwestern United States that revealed a trend of earlier ice-off dates from 1980 to 1994 (Wynne et

al. 1998). Furthermore, ice phenology among 65 waterbodies in the Great Lakes region showed more rapid changes from 1975 to 2004 than during the long-term average from 1846 to 1995 (Jensen et al. 2007). Jensen et al. (2007) also reported substantial spatial variability in ice records, however, which seemed to mirror spatial patterns in temperature, snow depth, and snow day (snowy days in a year) trends. Finally, trends toward earlier ice-off were observed by Duguay et al. (2006) for many Canadian lakes during 1951–2000; however, ice-on dates showed fewer significant trends when compared to ice-off dates.

Although many strong patterns have emerged from the above-mentioned studies, suggesting consistent trends in ice dynamics, there were also notable exceptions regarding the timing of ice formation and ice-off; therefore, there exists a need to examine additional lakes in greater detail across a variety of geographic settings to improve our understanding of the patterns and causes of changing ice cover.

Most studies have explored the relationship between changes in ice phenology and climate, primarily air temperature (Magnuson et al. 2000, Williams and Stefan 2006), and to a lesser extent changing snow conditions (William and Stefan 2006, Jensen et al. 2007). While these are undoubtedly important factors to consider, other site-specific factors may potentially improve our understanding and ability to predict ice dynamics on a more local scale. For example, surface water temperatures during the summer and fall, wind speed, water column transparency, and lake heat storage may all affect the freeze-up date. Similarly, local climatic factors such as snowfall depth and changes in air temperature may influence the timing of breakup. Global climatic indices can also influence and integrate a number of different climate variables and, as such, have been shown to influence ice dynamics (Straile et al. 2003, Livingstone et al. 2010). Further, studies to date have tended to rely on statistical models to examine possible linkages, while far fewer studies have used physically based dynamic models (e.g., Liston and Hall 1995a, 1995b, Flato and Brown 1996, Walsh et al. 1998, Menard et al. 2002, Duguay et al. 2003, Vincent et al. 2008).

To help address these uncertainties, we examined a 35 year dataset from Dickie Lake, south-central Ontario, Canada. Ice data showed that while the date of ice-on was significantly delayed from 1975 to 2009 (a period of warming in south-central Ontario), the date of ice-off had no significant trend over time. Using linear regression techniques and dynamic lake modeling to explore the role that climatic factors play in determining ice dynamics, we examined the relationship between ice-on and ice-off dates and several possible causative factors beyond changes in air temperature (wind speed, snowfall, water

temperature, and global climatic indices). Finally, we used these modelling approaches to predict changes in ice phenology from 2010 to 2100.

Study site

Dickie Lake is a small inland waterbody located in the District Municipality of Muskoka, south-central Ontario, Canada (Fig. 1). The lake ($45^{\circ}8'34''\text{N}$; $79^{\circ}5'41''\text{W}$) has a lake surface area of 0.94 km^2 , a mean depth of 5.0 m , and a water volume of $4.7 \times 10^6 \text{ m}^3$. Regional ice-on and ice-off data from 1975 until the late-1990s were derived from a composite of 8 small ($<100 \text{ ha}$) headwater lakes near Dorset, Ontario (Futter 2003). All data after 1999 are derived from nearby Grandview Lake (Dorset Environmental Science Centre [DESC], unpubl. data), resulting in a dataset of 35 continuous years (1975–2009).

Grandview Lake is centrally located with respect to 8 long-term study lakes monitored by DESC (which include Dickie but not Grandview) and is within 8 km of the study lake Dickie (Fig. 1). Grandview is of similar size, shape, orientation, and fetch to Dickie Lake but has a greater

maximum depth ($28 \text{ vs. } 12 \text{ m}$). The switch in observations from the DESC lakes to Grandview Lake did not bias the results of our trend detection and regression analyses. To confirm, we compared the ice-on (1 y) and ice-off dates (5 y) derived from Hobo Tidbit temperature sensors (logging every 6 h) in the DESC lakes from 2005 to 2010 with the date estimated from visual inspection of Grandview Lake. The ice-off date differed by no more than 1 day over the 5 years, and the ice-on date was 4 days different in the 1 year of comparison (further details are provided in the Supplementary Materials).

Hydrological and meteorological data, required for water balance or energy balance calculations, were also available for Dickie (Yao 2009, Yao et al. 2009) during the same period. Climatic and meteorological data for the period (daily air temperature, humidity, wind speed, solar radiation, precipitation) were provided from a meteorological station near Dickie Lake (Fig. 1). Water temperature and Secchi data were sampled on a biweekly or monthly basis (Ingram et al. 2006). Five inlet streams and outflow of Dickie Lake have been gauged since the late 1970s.

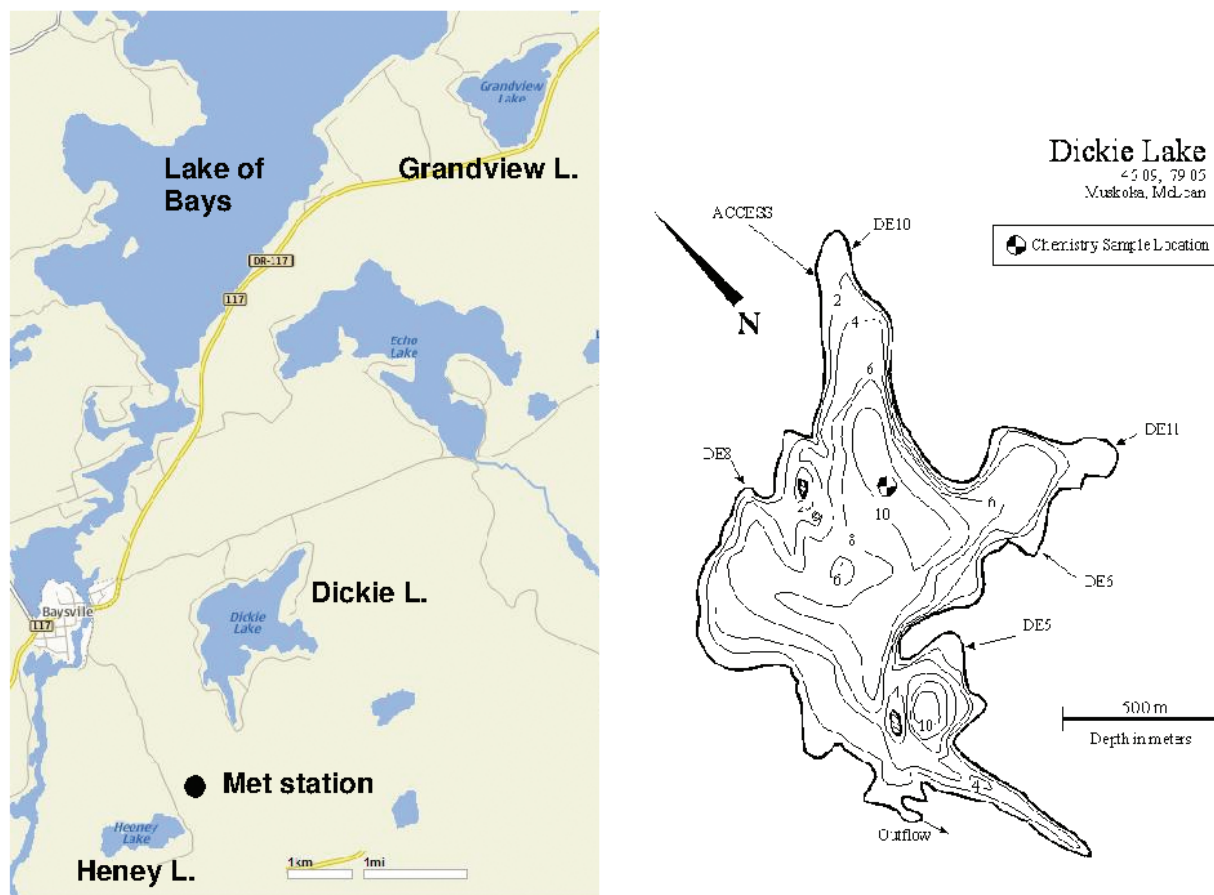


Fig. 1. Study area and location of Dickie Lake.

Methods

When examining lake ice data, 2 main approaches are commonly used by researchers: (1) a statistical or empirical approach that identifies temporal trends in ice phenology data or explores relationships between ice phenology and physical environmental factors using regression techniques; and (2) physically based thermodynamic models that simulate ice formation and decay processes. Detailed reviews of these methodologies have been provided by Assel (1991), Brown and Duguay (2010), and Skinner (1993). Here, we used both approaches to understand the determinants of the somewhat anomalous patterns of ice dynamics at Dickie Lake and compare the ability of different methods to reconstruct past dynamics and predict future trends. Prior to modelling ice dynamics, freeze and thaw dates were regressed against time (year) to verify the significance of temporal trends during the study period.

Local regressions

Multiple regressions, with climate and lake thermal conditions as explanatory variables, were performed to examine relationships with ice phenology (ice-on date and ice-off date). We considered 7 potential predictors for the ice-on date regression. (1) Cold air above the lake surface

is a driving factor in ice formation, and colder temperatures in the months October–November–December play a large role in the timing of lake ice formation. In addition to the obvious effects of air temperature, (2) surface water temperatures during the summer and fall may also be important in delaying ice-on dates. (3) Wind speed (mean value for Oct–Nov–Dec) was also included because it may affect the cooling process of lake water in the fall and early winter, impacting the timing of the fall turnover and initial ice formation. Because water column transparency may also influence a lake's heat budget and affect ice dynamics on a local scale (Snucins and Gunn 2000), we used (4) Secchi depth (ice-free average of fortnightly measurements, a range of 2.1–3.6 m over the years studied) as another potential local determinant of ice dynamics. (5) Lake heat storage provides an integrated measure of the thermal energy that must be dissipated before freezing can occur and, as such, may provide better predictability than variables like temperature and transparency alone. Additional integrated metrics of meteorology can be found in global climatic indices, which also have been shown to influence ice dynamics (Livingstone et al. 2010). Here we used (6) an annual estimate of the El Niño Southern Oscillation (ENSO) Index (6-month [Oct–Mar] mean; Rusak et al. 1999) and (7) the October–December North Atlantic Oscillation (NAO) Index (Hurrell and Deser 2009) as the final 2 independent variables (Table 1).

Table 1. Explanatory variables considered for local regressions and used for regional formulas. Also listed are input variables for the Hostetler model. Note the differences of months used by the variables between ice-on and ice-off dates.

	Ice-on	Ice-off
Local regression	mean air temperature (Oct–Dec) mean lake surface temperature (May–Nov) mean wind speed (Oct–Dec) annual-mean Secchi depth lake heat storage (ice-free season) ENSO (6 months Oct–Mar) NAO (Oct–Dec)	mean air temperature (May–Mar) snowfall (Jan–Apr) mean wind speed (Dec–Apr) annual-mean Secchi depth ENSO (Oct–Mar) NAO (Dec–Mar)
Regional formula	mean air temperature (Sep–Dec) latitude of lake elevation lake area mean depth of lake	mean air temperature (Feb–Jun) latitude elevation mean depth of lake
Hostetler model	daily air temperature vapour pressure wind speed short-wave radiation precipitation inflow discharge outflow discharge	daily air temperature vapour pressure wind speed short-wave radiation precipitation inflow discharge outflow discharge

Similarly, 6 potential climatic factors affecting ice breakup, including air temperature (Oct-to-May mean) were included in this multiple regression analysis. The total snowfall volume during January-to-April (affecting ice thickness and thaw rate), mean December-to-April wind speed (affecting snow accumulation and break-up dynamics), Secchi depth (rate of spring warming), and the same global climatic indices (6-month ENSO and the Dec–Mar NAO) were used in this analysis (Table 1).

Traditional multiple linear regression approaches are often criticized for the differences that arise in variable choice, depending on the order of variable inclusion or selection methodology (e.g., forward vs. backward stepwise selection techniques). Thus, we used the Akaike's Information Criterion (AIC) to determine the final regression model selection (Akaike 1974). AIC values trade off model accuracy with model complexity and are used to derive the most parsimonious solution by selecting models that provide the greatest explanatory power while ensuring the fewest number of variables in the final model. We derived models for all possible combinations of explanatory variables and chose the model having the lowest AIC value as our final solution.

Regional formulas

We compared our local regressions with a regional model established by Williams and Stefan (2006) for 128 lakes in the United States and Canada, which utilized air temperature, geography, and lake bathymetry as predictors (Table 1). The data length differed greatly among the lakes used, falling in the range of 1851 to 1998 with a median duration of 14 years. The ice-on date (IOD) was regionally expressed as:

$$\text{IOD} = 1.719 * T_{\text{SOND}} - 1.672 * \text{Lat} - 0.013 * \text{Ele} + 0.0016 * A + 0.146 * H + 408.8, \quad (1)$$

where T_{SOND} = the mean air temperature (°C) for Sep–Dec, Lat = the latitude of the lake (degrees), Ele = the elevation (m), A = the lake area (km²), and H = the mean depth of the lake (m). The ice-off date (IFD) was expressed as:

$$\text{IFD} = -3.81 * T_{\text{FMAMJ}} + 0.936 * \text{Lat} + 0.018 * \text{Ele} + 0.157 * H + 76.7, \quad (2)$$

where T_{FMAMJ} was the mean temperature for Feb–Jun. These regional models, using geography and bathymetry instead of meteorological and biological variables, provided a useful contrast to the local regression approach employed in the first analysis. By comparing observed ice dates to the predicted dates from both local and regional

regressions, we determined which technique best predicted historical ice dynamics.

Physical model

In addition to the regression techniques described above, we used a one-dimensional thermal-dynamic model proposed by Hostetler and Bartlein (1990). The model simulates, on a daily timescale, the processes of energy exchange at the lake surface, thermal transfer in the lake's water column, and ice formation and decay, with outputs of temperature profiles and ice thickness. The modelled ice-on and ice-off dates were then determined from the ice thickness results (i.e., IOD when thickness >0; IFD when thickness = 0). The required meteorological input (Table 1; daily air temperature, vapour pressure, wind speed, short-wave radiation, precipitation, inflow discharge, outflow discharge) and lake bathymetric data were available for Dickie Lake. A root-mean-square deviation (RMSD) was calculated for the modelled IODs and corresponding observed dates. We used the RMSD calculated for each method to compare accuracy among the 3 techniques.

Predictions of future ice cover

Future ice dynamics under a changing climate were also predicted using each of these methods. Monthly and daily time series of all required climatic inputs for years 2010–2100 were obtained from the Canadian Regional Climate Model (CRCM V4.2 data: aev run). This series was generated and supplied by the Ouranos Climate Simulation Team via the Canadian Centre for Climate Modelling and Analysis data distribution webpage (Music and Caya 2007). IODs and IFDs of each year during the 90 years were calculated separately by 3 methods (local regression, regional regression, and Hostetler model) to obtain the length of ice season (days).

Results

Trends in ice phenology

The IOD varied between day-of-year 315 and 362 and showed a clear increasing trend toward later IODs over the 35 years (Fig. 2a; 4.86 d/decade). The variation explained by this significant linear trend ($p = 0.0001$) was 36%. The IFD varied between days 91 and 126 and did not show a significant trend ($R^2 = 0.033$, $p = 0.296$). The annual duration of ice-cover and ice-free periods (Fig. 2b) showed a strong negative trend in ice-cover duration (decreasing by 6.86 d/decade) and a positive trend in ice-free duration.

Local regressions

Ice-on date (IOD): A multiple regression of IOD and our 7 climatic or physical factors yielded the most parsimonious solution (as determined by lowest AIC values) with air temperature (T_a , °C), wind speed (Sw , $m\ s^{-1}$), and heat storage (Sh , $10^6\ J\ m^{-3}$) in the final equation, where

$$IOD = 311 + 3.93T_a - 6.35Sw + 0.582Sh \quad (3)$$

(Table 2). The other 4 potential factors (lake surface temperature, transparency, ENSO, and NAO) did not contribute sufficient explanatory power to warrant their inclusion. Thus, delayed IODs were related to higher fall air temperatures, lower wind speeds, and higher values of stored heat (Fig. 3).

The predicted IODs using equation 3 captured the main pattern of variation observed in the long-term record (Fig. 4), with an $R^2 = 0.627$ and an RMSD of 6.1 d. By comparing the trend line with the one-to-one line (Fig. 4), the regression tended to overestimate earlier IODs (occurring primarily between 1975 and the 1980s) and underestimate later IODs (occurring between 1990 and the 2000s), but worked best for more moderate IODs.

Ice-off date (IFD): A multiple regression of IFD and our 6 climatic or physical factors yielded the most parsimonious solution (as determined by lowest AIC values) with air temperature (T_a) alone, where

$$IFD = 108 - 3.70T_a, \quad (4)$$

and the other 5 factors were omitted (Table 2). The predictions generally matched the observed pattern in ice-off variation (Fig. 5), with an RMSD of 5.7 d. An obvious bias was observed in some years, however, with large mismatches between modelled and observed IFDs that generated an overall poorer model fit ($R^2 = 0.33$).

Although not included in the most parsimonious regression solution for IFD, we examined the roles of snowfall (because of its appearance in other models; e.g., Jensen et al. 2007) and wind speed (because of its predictive capacity for IOD in Dickie Lake). When the air temperature of October–May increased and tended to advance IFD, the total snowfall in January–April also increased and could have delayed IFD (Fig. 6). The roles played by snow in ice growth and melt can be complicated (e.g., Williams and Stefan 2006). For example, snow cover on the ice could act as an insulator that reduces ice growth or creates slush, which can refreeze into gray ice (a common occurrence in our study area) and increases ice thickness that delays ice melt. The contribution of decreasing wind speed to ice-off was also not significant, but it might help maintain a longer snow cover by

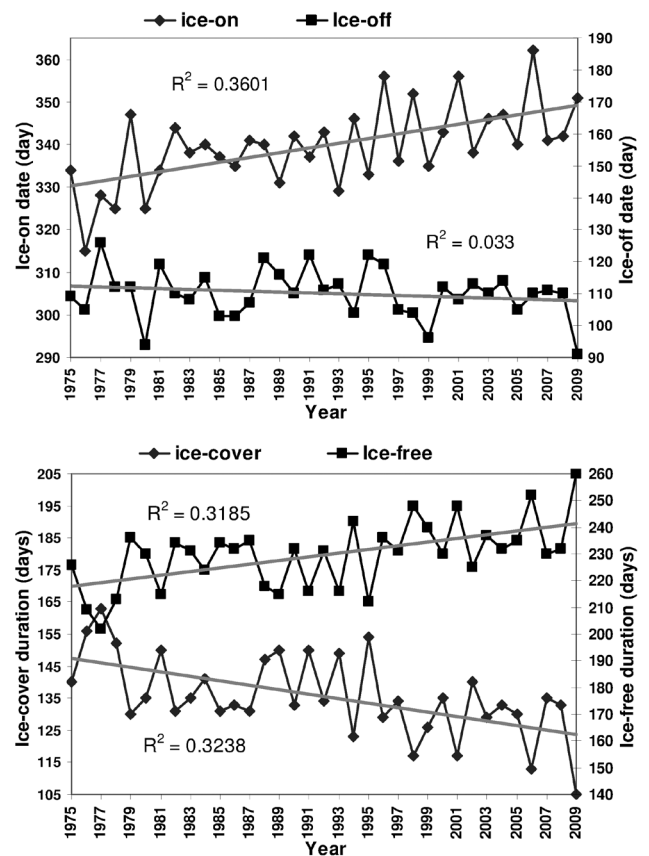


Fig. 2. Annual time series of ice-on date, ice-off date (Julian day) and its temporal trend line (upper graph); annual time series of ice-cover duration, ice-free duration and its temporal trend line (lower graph).

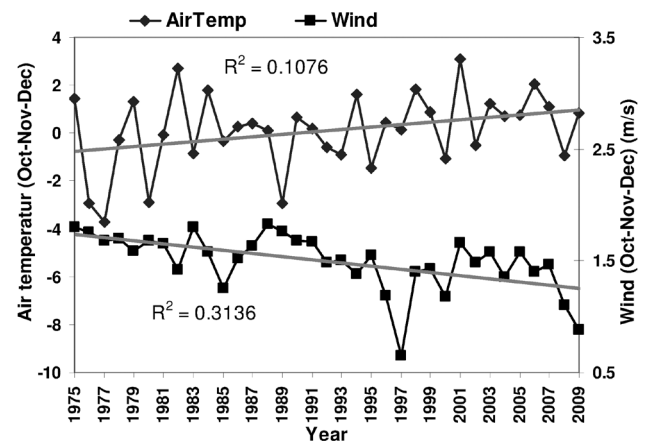


Fig. 3. Annual time series of air temperature, wind speed, and their trends.

maintaining snow depth and reducing snow and ice evaporation. The conflicting and offsetting effects from changes in temperature, snowfall, and wind may all contribute to the lack of a significant trend observed in IFDs.

Table 2. Most parsimonious regression statistics for multiple regressions minimizing AIC values for ice-on and ice-off (dependent variables), shortened from global climatic indices, local meteorology and lake-specific Secchi depth (as explanatory variables).

Dependent Variable	Variables remaining in AIC solution	Adjusted R ²	p-value
Ice-on (doy)	Mean Air Temperature (Oct–Dec), Mean Wind Speed (Oct–Dec), Mean Heat Storage (ice-free season) of Whole Lake	0.627	<0.0001
Ice-off (doy)	Mean Air Temperature (Oct–May)	0.33	0.0003

Table 3. Root mean squared deviation (RMSD) for the 3 methods: local regression, regional formula, and Hostetler model.

Method	Ice-on	Ranking	Ice-off	Ranking
Local regression	6.1	1	5.7	1
Regional formula	8.9	3	9.8	2
Hostetler model	8.2	2	12.3	3

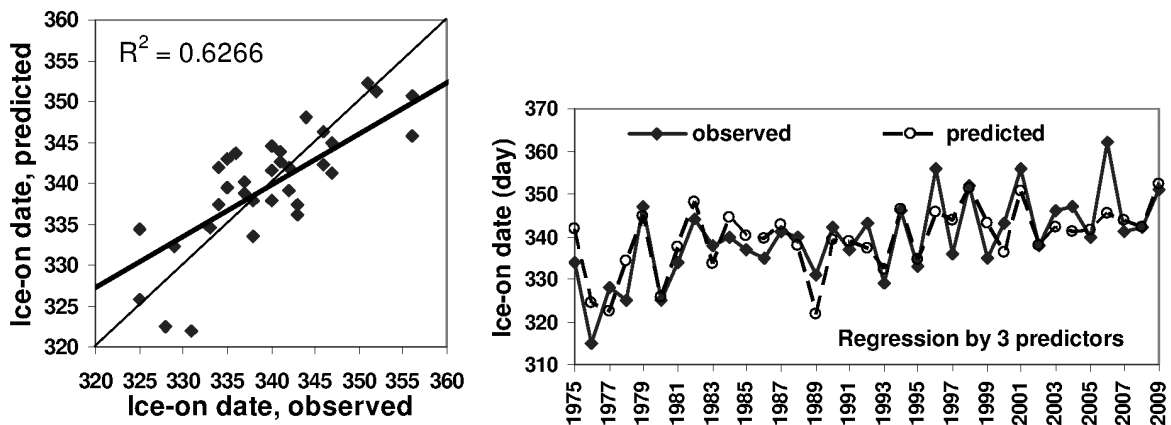


Fig. 4. Comparison of ice-on date predicted by local regression with the observed date.

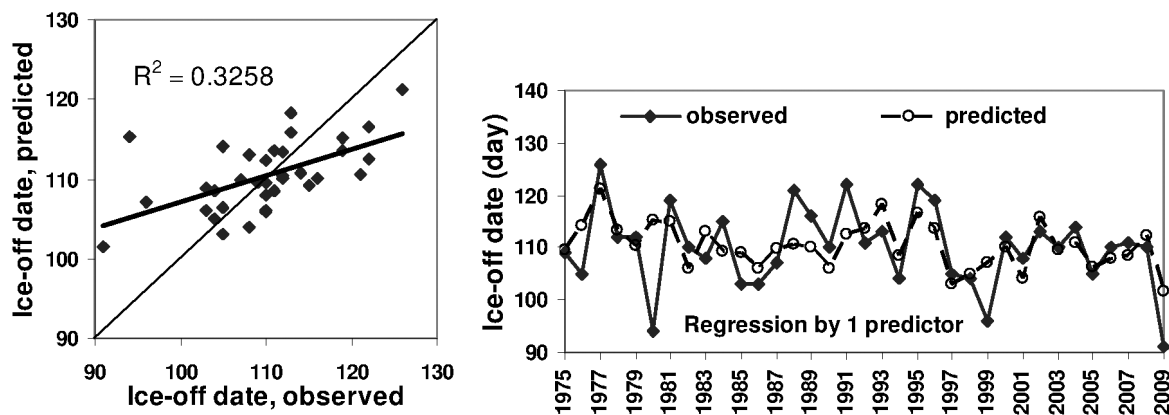


Fig. 5. Comparison of ice-off dates predicted by local regression with the observed date.

Regional regression model

The regionally based regression model for North America (Williams and Stefan 2006; equation 1) proved capable of capturing some of the variation in ice dates from Dickie Lake. Predictions of IODs for the 35 years (Fig. 7; $R^2 = 0.538$ between predicted and observed) showed larger deviations from observed data than those predictions using the local regression formula (Fig. 4). The regional formula produced a larger RMSD of 8.9 d, nearly 3 days longer than the 6.1 d produced by equation 4 (Table 3). The regionally predicted ice-on time series clearly underestimated conditions in the most recent 20 years and did not reflect any trend over time. Its predicted interannual variations were also much smaller than the actual observations. The predicted IFDs were severely underestimated ($R^2 = 0.212$, RMSD = 9.8 d). This greater bias from observed ice-on values may be caused by a number of factors: first, the formulas were developed using a dataset prior to 1998, not including some of the warmest years on record post-1998; second, the regionally based formula was not sensitive enough to air temperature changes occurring at a single location; and third, the formula only considered one climatic factor (i.e., air temperature), excluding others like wind speed. Although developed to be generically applied to North American lakes, particularly in a spatial context, caution is strongly recommended when using it to make long-term predictions for a single lake.

Hostetler model

Lake ice thickness was modelled using the Hostetler model for each year from 1978 to 2009. There were no monitored ice thickness data for directly testing this model; therefore, lake water temperature data and ice phenology records were used to evaluate the model's applicability. Modelled daily lake surface temperatures did fit well with the observed temperature (Fig. 8), and temperature distributions along a lake depth profile were also well-modelled (results not shown here). By comparing the modelled IODs or IFDs to the observed data (Fig. 9), the modelled results yielded a greater RMSD than obtained by the local regression (Table 3) but were slightly smaller than the error generated from the regional formula. For IFDs, the Hostetler model yielded a much larger RMSD than the local regression or the regional model (Table 3). The patterns of interannual variations were also poorly reproduced. The local regression model outperformed the regional formulas or the dynamic model in estimation of both IODs and IFDs in Dickie Lake (Table 3). Between the regional and dynamic models, the

regional model predicted more accurate ice-off predictions but performed more poorly in predicting IODs.

Predictions of future ice cover

The predicted IODs differ substantially among the 3 methods: local regressions show the fastest increase, the Hostetler model generated a more moderate increase, and the regional formula generated only a slight delaying of dates. The predicted IFDs have similar patterns among the 3 methods, although the interannual variations are very different (Fig. 10). As for the ice-season length, despite the obvious differences in annual values or interannual changes, all 3 methods produced a roughly similar long-term trend (i.e., a continued reduction in the length of ice season) roughly from 130 d in 2010 to 80 d in 2100. The maximum ice thickness in a year, as calculated by Hostetler model, was also predicted to decrease from about 50 to 25 cm in 90 years.

Caution should be exercised when applying any future predictions generated by these methods because the uncertainties can be large. None of the methods reproduced ice-on or ice-off records over the past 35 years exceedingly well, and the Hostetler model was not specifically tested against ice thickness observations for Dickie Lake. There are, of course, uncertainties when making future predictions of ice dynamics, but the results suggest just how much change we can expect in ice phenology over the next several decades.

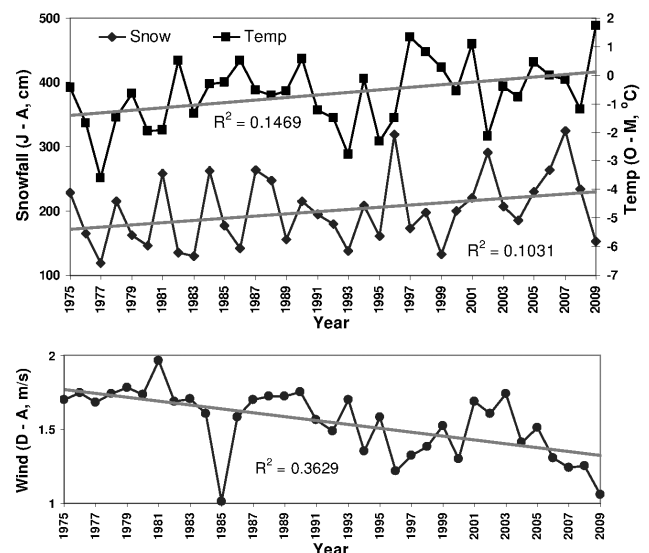


Fig. 6. Time series of mean air temperature (Oct–May), total snowfall (Jan–Apr), mean wind speed (Dec–Apr), and their temporal trends.

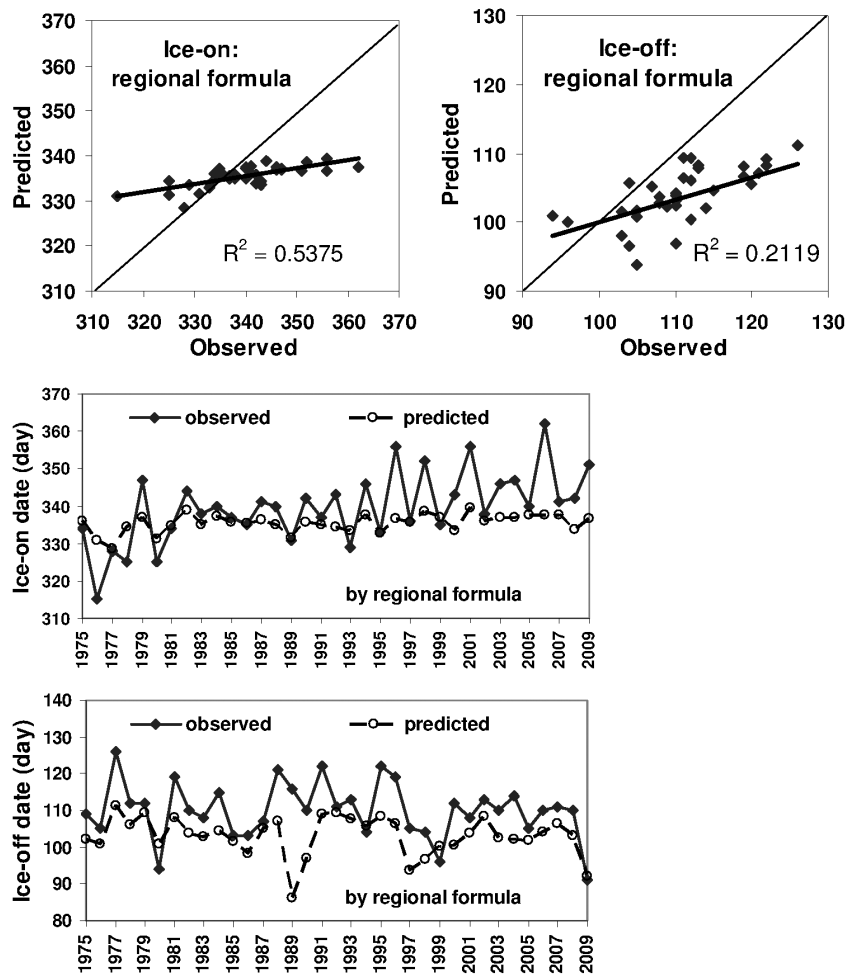


Fig. 7. Comparison of predicted and observed values obtained using the regional model equations for ice phenology.

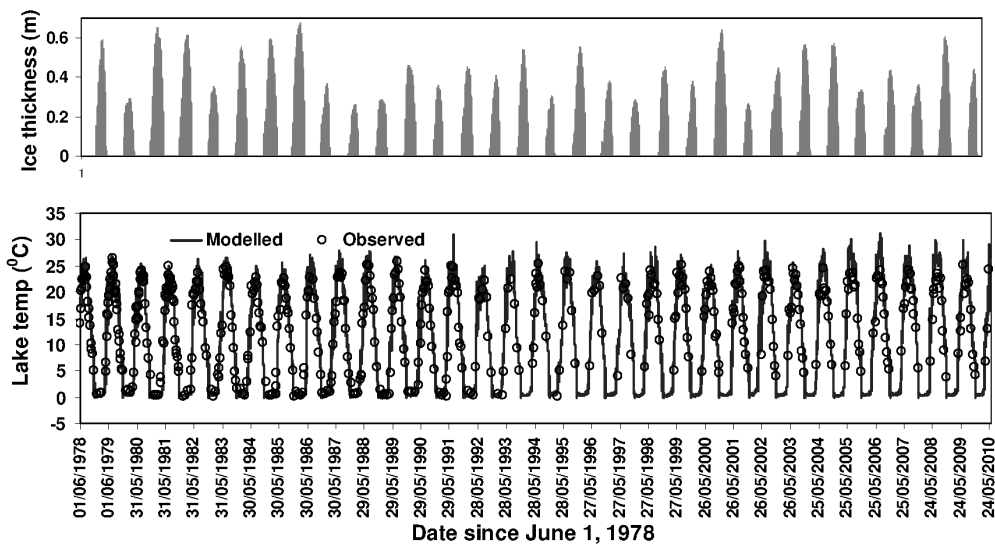


Fig. 8. Modelled ice thickness (upper), modelled lake surface temperature (lower), and observed lake temperature.

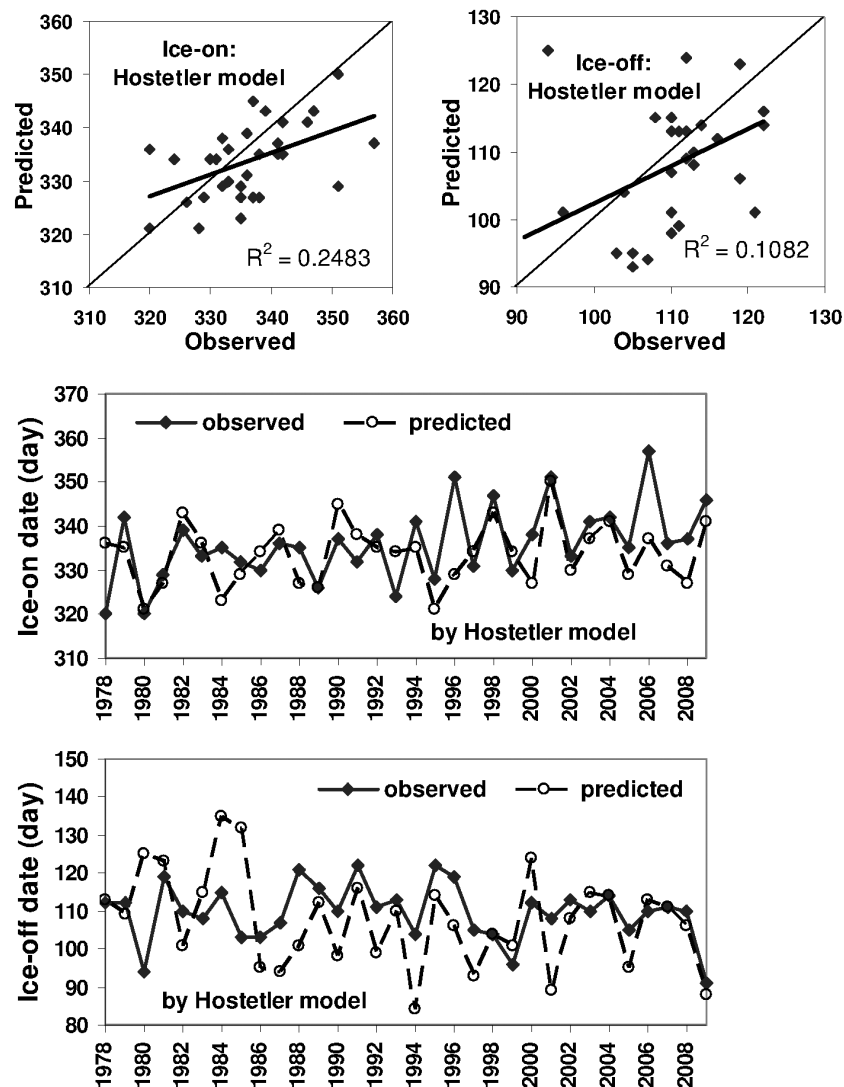


Fig. 9. Predictions by Hostetler model.

Discussion

The ice phenology trends and relationships documented for Dickie Lake both resemble and differ from those presented in the literature. For example, the direction and magnitude of changes in IOD from our study agreed with other results presented for the Northern Hemisphere (e.g., North America, Northern Europe). On average, IOD was delayed by approximately 4.9 d/decade over 1975–2009 at Dickie Lake, which was comparable to the 3.3 d/decade reported for 65 lakes across the Great Lakes region during a similar period 1975–2004 (Jensen et al. 2007). The mean delay for 341 Canadian lakes was 1.5 d/decade over the slightly longer period of 1950–2004 (Environment Canada and US Environmental Protection Agency 2007), while the mean

delay over 150 years in Northern Hemisphere lakes (Magnuson et al. 2000) was smaller still at 0.58 d/decade. In contrast, IFDs at Dickie Lake did not show a clear temporal trend, and the slight advancement of 1.1 d/decade was much smaller than the 2.1 d/decade recorded for 65 lakes within the Great Lakes region during 1975–2004.

Similar to other studies, we found that the most important factor driving changes in ice dynamics is air temperature. Although wind speed and heat storage were also important terms in our local regressions, they are rarely mentioned or examined in other statistical studies of changes in ice phenology (see exceptions in Williams and Stefan 2006, Keller 2007, Brown and Duguay 2010). The accuracy of predictions from our ice-on regression model that included air temperature, wind speed, and heat

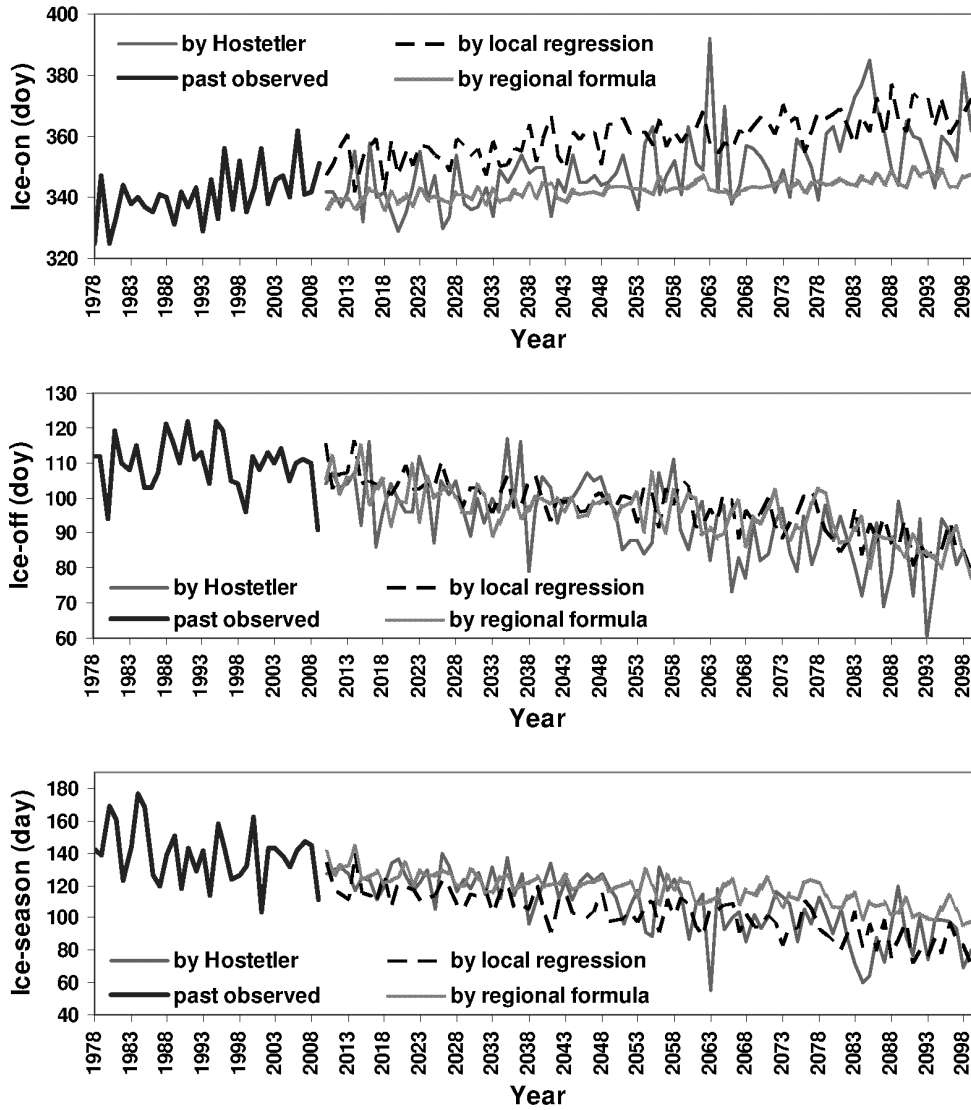


Fig. 10. Future variations of ice-on, ice-off, and ice season length in 2010–2100 as predicted by 3 methods.

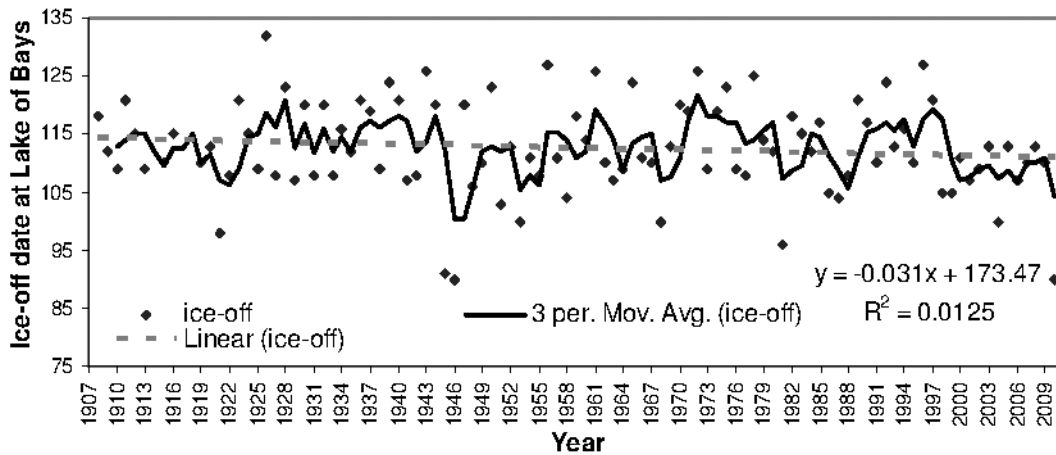


Fig. 11. Longer record of ice-off dates at Lake of Bays (dots represent annual ice-off date, solid line a 3-year moving average, and dashed line a linear trend).

storage was comparable to other models. For example, the model proposed by Assel (1991), using a freezing degree-day parameter, found a root mean square error of 17%, while our regression model improved this error to 10%. Even when factors such as snow depth and wind speed were not significant predictors of ice conditions, as was the case with IFDs, an examination of their influence demonstrated that they could have important and sometimes opposing effects on ice conditions at different times in the historical record. This result highlights the important role that local conditions play in determining the response of ice phenology to a changing climate.

Despite evidence that surface water temperatures are strongly correlated to air temperature in many lakes (Keller 2007), surface water temperature was not an important predictor of ice dynamics in Dickie Lake at an annual scale. In part, this may be due to the complex interactions between wind, water chemistry, and whole-lake water temperatures. For example, in a lake near Sudbury, Ontario, Canada, Tanentzap et al. (2008) documented a 28 year record of whole-lake cooling in Clearwater Lake, in contrast to a regional warming in air temperature. This was attributed to a large reduction in local wind speeds (driven by forest regrowth and changes in atmospheric circulations; Vautard et al. 2010) and increased vertical light attenuation with rising dissolved organic carbon concentrations during recovery from lake acidification. Collectively, these factors altered the thermal regime of the lake and acted as modifiers to create a cooler lake overall. Clearly, wind speed can play a substantial role in influencing lake thermal conditions locally and may regulate the relationship between air and lake temperatures.

The differences in the predictability of the local regression solutions were instructive. About 60% of the adjusted variation in IOD was predicted by the most parsimonious multiple regression equation (54% with all variables), while only 30% of the adjusted variation (24% using all variables) was captured for IFD. This result reinforced the difficulty in providing reliable IFD predictions, particularly at the local scale in our region.

Although the nonsignificant trend in IFD differed from many published results, it was supported by several studies in Eastern Canada (Smith 2000, Assel 2004, Environment Canada and US Environmental Protection Agency 2007). The mechanisms underlying this phenomenon are not yet fully understood, but this study offers a plausible cause: increased air temperature may be off-set by the effects of increased snowfall and reduced wind locally, resulting in no net change in IFD. A similar ice record was noted in the nearby, albeit larger, Lake of Bays, just north of Dickie Lake (Fig. 1). A continuous record of ice breakup since 1908 also showed no significant decline over time (Fig. 11; B. Tapley, Lake of

Bays Association, July 2011, pers. comm.) and only a minor decrease of 3.1 d in 100 years, on average. Furthermore, a dataset of 1213 lakes indicated that the timing of IOD and IFD was not equally pronounced over the entire Northern Hemisphere (Weyhenmeyer et al. 2011). Our results further indicate that ice phenology can be localized and site-specific, and the effects of climate on ice-off and ice duration, at least in the short term, are difficult to predict when competing processes are at work.

Our comparison of statistical versus dynamic modelling approaches highlighted some important similarities and differences among techniques. The local and regional regressions attempt to find simple linear relationships between ice phenology and its predictors. Because of the linearity of the changes in air temperature and other variables, they can perform reasonably well when applied to ice dynamics. As for the performance of these 2 regression methods, the local regressions produces a better prediction of ice phenology for Dickie Lake because other predictors are important in reconstructing temporal variation in ice phenology, while the regional regressions are less accurate because they capture temporal variation using only air temperature and spatial variables, which do not seem to be as important at a local scale. Alternatively, the dynamic Hostetler model is much more complex and depends on many more factors and processes. The model is designed to simulate lake thermal dynamics, lake evaporation, water budget, and ice processes, the latter ice module being just one part of the model. For a more sophisticated model, its mediocre performance (as measured by model RMSD) when compared with the simpler regression approaches may be related primarily to 2 factors. First, its one-dimensional nature includes certain assumptions of physical processes that may be best simulated in 2 or 3 dimensions; and second, the model has not been specifically calibrated to long-term ice thickness data. Although the predicted ice thickness compares well with the range of conditions present in this region, annual ice thickness data would have improved model predictability.

Among the 8 lakes intensively monitored by DESC, Dickie Lake is unique in its proximity and physical similarity to Grandview Lake, from which a portion of the ice record is derived. A comparison with another DESC lake could be instructive in increasing the generality of these results. Harp Lake, 26 km north of Dickie Lake, was chosen for this comparison. The local regression analysis and regional predictions, using data from Harp Lake, produced results similar to those from Dickie (see Supplementary Materials). Although outside of the scope of our present study, this comparison bodes well for the application of the locally important variables in a more regional context.

Future predictions of changes in ice phenology highlight just how dramatic the upcoming changes for

lakes in this region might be and what effects they could have on the local economy. The Muskoka region has a strong tourism-based economy, and winter visitors come for recreational activities that require safe ice conditions (e.g., ice fishing, snowmobiling). Changes to both the duration and thickness of ice will impact the length of the season available for winter recreation with potential large effects on the local economy. Despite the obvious uncertainties in model performance and future predictions, the 3 models yielded roughly similar future predictions of decreases in ice duration. Overall, the physically based model may be more reliable for predicting future trends (although it performed worse than the local regressions) because of its more mechanistic basis and the fact that the regressions rely exclusively on past records that may not apply to the future conditions.

Conclusions

Our study at Dickie Lake indicated that a full understanding of ice phenology can be complicated and is strongly influenced by local conditions. Accurately determining the critical variables influencing ice dynamics depends on the nature of their specific interactions. Further, despite the significance of 3 models tested in our study, there is still considerable unexplained variation in these results and their predictive capacity. Given that ice conditions play a key role in determining the physical, biological, and socio-economic attributes of lakes in north-temperate regions, and the large changes that will occur due to climate warming over the next century, continued studies to improve the predictability of ice dynamics are necessary.

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