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Local climatic drivers of changes in phenology at a boreal-temperate ecotone in eastern North America

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Abstract Ecosystems in biogeographical transition zones, or ecotones, tend to be highly sensitive to climate and can provide early indications of future change. To evaluate recent climatic changes and their impacts in a boreal-temperate ecotone in eastern North America, we analyzed ice phenology records (1975–2007) for five lakes in the Adirondack Mountains of northern New York State. We observed rapidly decreasing trends of up to 21 days less ice cover, mostly due to later freeze-up and partially due to earlier break-up. To evaluate the local drivers of these lake ice changes, we modeled ice phenology based on local climate data, derived climatic predictors from the models, and evaluated trends in those predictors to determine which were responsible for observed changes in lake ice. November and December temperature and snow depth consistently predicted ice-in, and recent trends of warming and decreasing snow during these months were consistent with later ice formation. March and April temperature and snow depth consistently predicted ice-out, but the absence of trends in snow depth during these months, despite concurrent warming, resulted in much weaker trends for ice-out. Recent rates of warming in the Adirondacks are among the highest regionally, although with a different seasonality of changes (early winter > late winter) that is consistent with other lake ice records in the surrounding area. Projected future declines in snow cover could create positive feedbacks and accelerate current rates of ice loss due to warming. Climate sensitivity was greatest for the larger lakes in our study, including Wolf Lake, considered one of the most ecologically intact 'wilderness lakes' in eastern North America. Our study provides further evidence of climate sensitivity of the boreal-temperate

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ecotone of eastern North America and points to emergent conservation challenges posed by climate change in legally protected yet vulnerable landscapes like the Adirondack Park.

1 Introduction

Scientific understanding of global climate change has largely outpaced knowledge of climate influences on ecosystems and human communities at the local and regional scales. Local studies of climate change impacts on ecosystem functions and services are needed for informing management, conservation and adaptation efforts (McCarty 2002; Latifovic and Pouliot 2007), as well as fostering public awareness of the nature of climate change and its consequences for human well-being (McMichael et al. 2003; Rosenzweig et al. 2007). From the ecological perspective, monitoring can be especially informative in areas that encompass two or more biomes and their transitional zones (or ecotones), because this is often where the earliest and strongest indications of climate change have been observed (Neilson 1993; Kupfer and Cairns 1996; Allen and Breshears 1998; McCarty 2002; Parmesan and Yohe 2002; Parmesan et al. 2005; Beckage et al. 2008).

To translate the phenomenon of global change to local scales, the study of phenology (the timing of natural events) has played a vital role in providing evidence of ecological and physical changes due to climate forcing (Bradley et al. 1999; Parmesan and Yohe 2002; Huntington et al. 2009). Lake ice phenology – the timing of lake freeze-up (closure) and break-up (opening) – and duration of ice cover are widely used as local-scale indicators of climatic variability and change (Robertson et al. 1992; Vavrus et al. 1996; Maguson et al. 2000; Williams et al. 2004; Weyhenmeyer et al. 2004; Latifovic and Pouliot 2007). In some cases, lake ice can be a better measure of local climate than instrumental records subject to measurement error and bias caused by inappropriate instrument siting (Assel and Robertson 1995; Livingstone 1997; Pielke et al. 2002; Mahmood et al. 2006). Analyses of long-term records of lake ice phenology across the northern US and Canada have provided some of the most compelling evidence of regional and sub-continental warming during the latter half of the 20th century (Robertson et al. 1992; Maguson et al. 2000; Hodgkins et al. 2002; Jensen et al. 2007; Adrian et al. 2009).

Although recent climate change research has focused on ecosystem responses (including lake ice) across broad geographical regions containing climatic or ecological transitions, relatively little work has been done globally that has utilized lake ice records to understand local climate forcing and its potential impacts in very sensitive ecotones. Such monitoring and analysis of lake ice dynamics within ecotones should provide valuable climate insights, especially in montane and/or rural regions where weather station records tend to be sparse and topographical influences on local climate may be complex and poorly understood (Jensen et al. 2007; Latifovic and Pouliot 2007). Changes in these sensitive ecosystems can serve as 'sentinels' of future ecosystem dynamics with a changing climate (Beckage et al. 2008; Adrian et al. 2009; Huntington et al. 2009).

In this study, we evaluated the climatic forcing of lake ice dynamics in an ecotone between northern hardwood and boreal forests in the Adirondack Mountains of northern New York (Fig. 1), based on five unpublished long-term ice records from montane lakes (>450 m elevation) and a local instrumental climate record. Within the US Northeast region, which has experienced rapid warming in recent decades (Hayhoe et al. 2007a; Frumhoff et al. 2007), the Adirondacks broadly encompass a boreal-temperate transitional zone that includes southern range limits of boreal species and forest types, and northern range limits of several temperate species (Jenkins and Keal 2004). Along elevational gradients in the

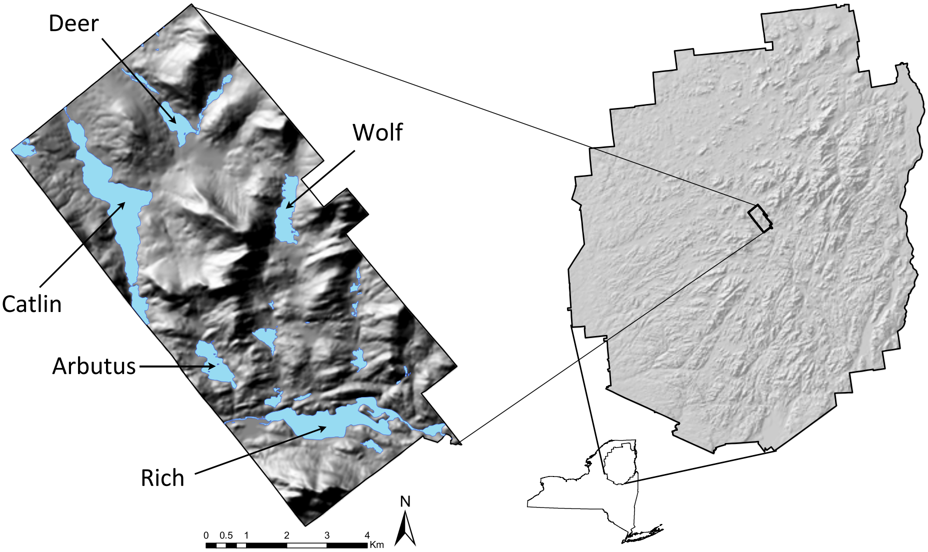

Fig. 1 Study lakes on Huntington Wildlife Forest within the Adirondack Mountains of northern New York State

Adirondacks, transitions between forest types reflect several local ecotones, from low elevation spruce-fir to upland northern hardwoods, and from upland hardwoods to high elevation spruce-fir (Leopold et al. 1988). In the nearby Green Mountains of Vermont, Beckage et al. (2008) found that these forest ecotones have been highly sensitive to recent warming. Adirondack ecotones are likely as sensitive, yet little is known about local climate changes and their roles as drivers of ecological change in the region (Stager et al. 2009).

To assess this sensitivity, we first evaluated trends in the long-term ice phenology records for five montane lakes, varying in morphology, elevation and catchment area, over a period of 33 years (1975–2007). Next, we modeled ice phenology and duration based on a high-quality local climate record (within 5 km of lakes), using an information-theoretic approach. Based on the climate–lake ice models, we identified a group of climatic predictors of lake ice, and evaluated trends in those predictors to identify the factors responsible for changes in ice phenology and duration – hereafter referred to as 'climate drivers' of lake ice changes. This novel approach provided an in-depth understanding of recent climate changes, their role as drivers of ecological change, and the ecosystem vulnerability to those changes, within a sensitive ecotone. Several aspects of observed changes in this ecotone, including the magnitude and seasonality of recent trends, are compared with other studies in the region. Our analysis also provided mechanistic insights on how projected climate changes may affect montane lake ecosystems in the future. Finally, we discuss the local implications of our results for the Adirondacks, which illustrate the emergent challenges of conservation and ecosystem stewardship in a rapidly changing climate.

2 Methods

2.1 Lake ice phenology and weather records

Monitoring of lake ice phenology – the day of year of ice-in (freeze-up) and ice-out (break-up) – has been done intermittently since 1873 and continuously since 1975 at Huntington

Wildlife Forest (HWF), a research facility of the SUNY College of Environmental Science and Forestry (Syracuse, NY). The five lakes monitored range in surface area from 36 to 217 ha and in maximum depth from 3.0 to 18.3 m (Table 1). A small number of missing observations during this period yielded slightly different totals of annual records for each variable (ice-in, ice-out, and ice duration) among lakes. Ice duration was calculated as the difference (in days) between ice-out and ice-in dates; if one of these observations was missing, we did not calculate ice duration for that year. Lake ice observations prior to 1975 (Table 2), including records from the 1870s, 1890s and 1930s, suggest longer ice durations relative to our analysis period of 1975–2007 (Figure A-1; Appendix 1), but we did not analyze these data for the sake of time-series continuity.

Monthly climate indices calculated from the HWF daily weather record were used in our analysis. Continuous daily weather measurements (daily minimum and maximum temperatures) have been collected at HWF since January 1933. In 1949, weather monitoring at HWF became part of the U.S. Weather Bureau network (*Newcomb 4 WNW* – 43 °59” N, 74°14” W). This weather record was corrected and gap-filled by utilizing daily data from NOAA/NWS *Newcomb 3 E* station (approximately 12 km from the A/M site at HWF), and correcting obvious instrumental/data entry errors (e.g., higher minimum temperature than maximum), also using the *Newcomb 3 E* station record (Campbell et al. 2006). This corrected daily HWF record has been utilized in several studies (Mitchell et al. 1996; Park et al. 2003; Campbell et al. 2006). The HWF station was relocated in 1970, and in 1983 it

Table 1 Summary of lake characteristics and ice phenology trends for high-elevation lakes on Huntington Wildlife Forest (43°19′ N, 74°14′ W), in the central Adirondack Mountains, Essex Co., New York. The Mann-Kendall test statistic (τ) was used to determine significance (p) of trends. For trends, the estimated rate (days decade^{-1}) is given, followed by the estimated absolute change in days (in parentheses), based on both the Sen and linear regression estimators

	Arbutus	Catlin	Deer	Rich	Wolf
Area (km^2)	0.46	2.17	0.36	1.55	0.62
Maximum Depth (m)	8.2	16.8	3.0	18.3	14.6
Elevation (m)	514	486	509	477	556
Volume (m^3)	1.39×10^6	1.51×10^7	7.61×10^5	1.44×10^7	3.38×10^6
Catchment Area (ha)	369	5,748	1,738	16,437	840
Ice In					
n	30	33	33	33	28
Mann-Kendall τ (p)	0.24 (0.049)	0.26 (0.042)	0.03 (0.828)	0.19 (0.132)	0.29 (0.031)
Sen rate (absolute)	4.7 (14.0)	3.6 (12.0)	0.6 (1.9)	2.8 (9.2)	5.1 (14.2)
Linear rate (absolute)	4.3 (12.8)	4.2 (14.0)	0.7 (2.2)	3.5 (11.7)	5.6 (15.7)
Ice Out					
n	34	34	30	35	34
Mann-Kendall τ (p)	-0.02 (0.894)	-0.05 (0.710)	-0.01 (0.943)	-0.03 (0.787)	-0.14 (0.258)
Sen rate (absolute)	0 (0)	-0.6 (-2.1)	0 (0)	0 (0)	-1.6 (-5.4)
Linear rate (absolute)	-0.7 (-2.3)	-0.9 (-3.2)	-0.6 (-1.8)	-0.6 (-2.0)	-1.7 (-5.7)
Ice Duration					
n	29	32	29	33	28
Mann-Kendall τ (p)	-0.14 (0.293)	-0.33 (0.010)	-0.16 (0.244)	-0.28 (0.027)	-0.31 (0.023)
Sen rate (absolute)	-2.6 (-7.6)	-5.3 (-17.1)	-2.5 (-7.3)	-4.3 (-14.2)	-7.6 (-21.4)
Linear rate (absolute)	-2.6 (-7.5)	-5.6 (-17.9)	-2.9 (-8.4)	-4.6 (-15.1)	-6.5 (-18.1)

Table 2 Decadal summary of the complete historical lake ice record at Huntington Wildlife Forest (43°19′ N, 74°14′ W), located in the central Adirondack Mountains, Essex Co., New York. Lake names are abbreviated as follows: Rich (R), Catlin (C), Arbutus (A), Deer (D) and Wolf (W)

Decade	n (lakes)	Lakes	Ice In		Ice Out		Ice Duration	
			Median Date	n (obs)	Median Date	n (obs)	Median Days	n (obs)
1870 s	1	R	24-Nov	2	16-May	2	179	1
1890 s	1	R	4-Dec	2	28-Apr	1	149	1
1930s	3	R,C,A	27-Nov	4	30-Apr	12	143	5
1960s	4	R,C,D,W	3-Dec	8	25-Apr	6	146	5
1970s	5	All	28-Nov	22	28-Apr	32	149	20
1980s	5	All	30-Nov	46	20-Apr	46	142	43
1990s	5	All	6-Dec	49	24-Apr	49	139	48
2000s	5	All	9-Dec	40	23-Apr	40	136	40

was moved 0.25 km to the Atmospheric/Meteorological Monitoring Site (A/M) at HWF. Snow depth measurements at HWF have been conducted in the same location approximately 0.5 km south of the A/M site since 1973. There is no evidence that the change in station location in 1983 created anomalies in the daily temperature or precipitation data, or had any long-term influence on the HWF weather record.

2.2 Analysis

2.2.1 Trends in lake ice phenology

We estimated changes in ice phenology on the five study lakes from 1975–2007 based on three metrics: ice-in (day-of-year), ice-out (day-of-year) and ice duration (days). First, Mann-Kendall tests (Mann 1945) were used to estimate the direction and significance of trends. The value of the Mann-Kendall τ statistic between -1.0 and 1.0 indicates the strength of the trend, the sign of τ indicates the direction of the trend, and significance of the trend is provided as a probability (p). Because we analyzed day-of-year, a positive τ for ice-in date indicates a trend of later ice-in, and a negative τ for ice-out dates indicates a trend of earlier ice-out. We estimated trend magnitude (in days) using two methods: non-parametric Sen slopes (Sen 1968) and linear regression slopes. The slope coefficients were multiplied by ten (10) for decadal rates (days decade^{-1}) and by n (observations) to estimate the absolute change (days) during the period of record. All trend rates presented in the text are based on the Sen estimators, as these are more robust for time-series data (Wilcox 2001). Linear regression-based estimates are also provided in tables for reference to other studies using this method. Lastly, we used Kendall's τ rank correlation method (Kendall 1938) to evaluate the year-to-year relationships among lakes in ice phenology and duration. All trend and correlation analyses were conducted using R 2.8 (R Development Core Team 2008).

2.2.2 Climate–lake ice modeling

Using the daily HWF weather record, monthly statistics were estimated for T_{max} and T_{min} (mean, maximum, minimum and standard deviation), precipitation (total monthly and standard deviation) and snow depth (mean and standard deviation). These variables were tested for correlations with ice phenology variables (ice-in date, ice-out date, ice duration) using Kendall's τ in JMP 8.0 (SAS Institute, Cary, NC). This nonparametric test was used to avoid issues with temporal autocorrelation that are common in monthly climate data. All variables with significant Kendall's τ at $p<0.05$ were considered potential climatic predictors, and this group of predictors was used in model formulation and comparison.

We evaluated a group of climate-lake ice models for each lake using an information-theoretic approach based on Akaike's Information Criterion corrected for small sample sizes (AICc). This method ranks models by their log-likelihood and number of terms, creating a penalty for models with more terms, and resulting in the most informative and parsimonious models being ranked highest (Burnham and Anderson 2002). For each lake and phenological metric (ice-in date, ice-out date and duration), we constructed a group of multiple regression models using single variables, all possible combinations of all screened climatic predictors, and a null model. From these, we selected the top-ranked model and all models within two units of AICc, as these models are considered roughly equivalent (see Appendix 2). For brevity, in the results we focus only on the top-ranked models based on AIC. Because lake ice may be a non-linear function of temperature (Weyhenmeyer et al. 2004), we evaluated the goodness of fit of model residuals (predicted – observed) for each of the top-ranked (lowest AIC) models to a group of probability distribution functions (e.g., normal, lognormal, Weibull, Gamma, Johnson, GLog). We also examined variance inflation factors in the top-ranked models to evaluate multicollinearity among parameters. Modeling was conducted using the *Fit Model* platform in JMP 8.0 (SAS Institute, Cary, NC).

For several reasons we did not perform detrending on the climate or lake ice data prior to analysis. Detrending techniques are typically used to remove patterns or trends in time series that are unrelated to the phenomena of interest – such as the removal of the 'geometric bias' often found in tree-ring series (Fritts 1971) – but we could not think of any trends in these time-series that were not directly pertinent to our analysis. Moreover, among the wide variety of detrending techniques available, many which can introduce significant artifacts to subsequent analysis, our choice of technique would have been arbitrary without knowledge of the factors driving the patterns to be removed from the time-series. Lastly, we note that our analysis identified several climate predictors of lake ice that experienced weak or insignificant trends, such as April snow depth and May temperature, as well as strong trends in climatic variables that were uncorrelated with lake ice phenology, such as September warming rates above 2C decade^{-1}. Therefore we are confident that trends in the raw data did not significantly bias our modeling results.

2.2.3 Trends in climatic predictors of lake ice

Monthly climate variables compiled from the daily HWF weather records were evaluated for trends, from 1975–2007, using Mann-Kendall τ, Theil-Sen slopes and linear regression slopes. As above, all trends given as rates (decade^{-1}) in the text are based on Theil-Sen estimators. We analyzed those climate variables that were included as parameters in the top-ranked climate-lake ice models to focus on which trends were potential drivers of observed changes in lake ice. All climate trend analyses were done using R 2.8 (R Development Core Team 2008).

3 Results

3.1 Changes in lake ice phenology

From 1975–2007, changes in ice duration on the lakes at Huntington Wildlife Forest have been due largely to later ice formation, relative to earlier ice breakup (Table 1; Fig. 2). Ice-in has occurred consistently later for all five lakes, at rates between 0.6 (Deer) and 5.1 (Wolf) days per decade. Absolute changes in ice-in dates during the period of record were between 1.9 d (Deer) and 14.2 d (Wolf) later and the trends for Wolf, Catlin and Arbutus were significant at $p<0.05$ (Table 1). The median ice-in date of all five lakes has shifted from Nov 28 to Dec 9 (Table 2). Although ice-out dates became earlier for Catlin (-2.1 d) and Wolf (-5.4 d), none of the ice-out trends based on Mann-Kendall tests were significant at $p<0.05$ (Table 1). Median ice-out date has shifted from Apr 28 to Apr 23 (Table 2). Ice duration decreased for all lakes, and significantly so for Wolf (-21.4 d), Catlin (-17.1 d) and Rich (-14.2 d). Interannual variation in ice phenology and duration was highly synchronous among lakes (based on pairwise correlations), most strongly for the ice-out date (Table 3).

3.2 Climate–lake ice models

Correlation screening identified a candidate set of climatic predictors of lake ice phenology that were largely consistent among the study lakes. Overall, temperatures during early winter (Nov and Dec) were the strongest predictors of ice-in date, indicating that a later ice-in date was associated with warmer air temperatures during the period of ice formation. Snow depth during these months was negatively correlated with ice-in date; i.e., years with more snow typically had earlier ice-in. For ice-out date, the strongest correlations were for those conditions prior to and during ice-out: Mar and Apr temperatures and snow depth. For ice duration, the group of potential climatic predictors included the variables noted above as well as May temperatures. Monthly precipitation (rainfall) variables were mostly not correlated with ice phenology, and those correlations that were significant (at $p<0.05$) were relatively weak ($\tau<0.25$).

Parameter estimates from the multiple regression models, and model rankings based on Akaike weights (w_i), are summarized in Appendix 2. These include several equally

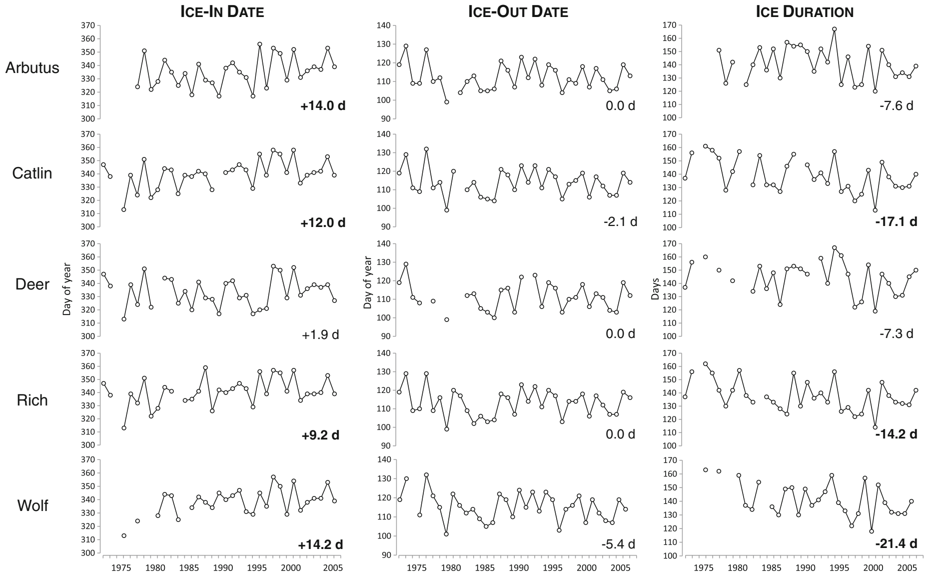

Fig. 2 Trends and variability in lake ice phenology at Huntington Wildlife Forest since 1973. Values inset on each plot are absolute changes (in days) estimated by the Theil-Sen method, and statistically significant trends (based on Mann-Kendall τ at $p<0.05$) are in bold

Table 3 Non-parametric correlations (Kendall's τ) of ice phenology (ice-in date, ice-out date and ice duration in days) among five high-elevation lakes in the Adirondack Mountains, New York. The five lakes are located within Huntington Wildlife Forest (43°19′ N, 74°14′ W), Essex Co., NY.

	Arbutus	Catlin	Deer	Rich	
Ice In					
Arbutus	–				
Catlin	0.72	–			Mean τ=0.67
Deer	0.76	0.60	–		All p<0.0005
Rich	0.55	0.88	0.47	–	
Wolf	0.61	0.85	0.55	0.69	–
Ice Out					
Arbutus	–				
Catlin	0.89	–			Mean τ=0.83
Deer	0.86	0.85	–		All p<0.0001
Rich	0.76	0.87	0.77	–	
Wolf	0.78	0.90	0.79	0.83	–
Ice Duration					
Arbutus	–				
Catlin	0.77	–			Mean τ=0.66
Deer	0.71	0.63	–		All p<0.005
Rich	0.49	0.85	0.46	–	
Wolf	0.55	0.83	0.61	0.70	–

informative alternative models (i.e., within two units of ΔAICc) for ice-in and ice duration; the best models for ice-out were substantially better than alternatives, resulting in only 2–3 alternative models. Below we describe the top-ranked models for each lake and ice variable (Tables 4, 5 and 6).

For ice-in, the top-ranked models were parsimonious (2–4 terms) and explained between 57 % (Wolf) to 74 % (Rich) of the observed variability in ice-in date based on adjusted r^2 values. Multicollinearity among parameters was minimal based on variance inflation factors (Table 4). Among all lakes, Nov T_{min}, Dec T_{min} and Dec T_{max} were the most consistent predictors in the top-ranked models (Table 7).

For ice-out, the top-ranked models contained 2–3 parameters each and explained from 60 % (Rich) to 69 % (Wolf) of annual variation (Table 5). Multicollinearity among parameters was minimal and parameters from the best models were consistent across lakes. All five top-ranked models included Apr T_{max} and Apr snow depth, and four of the top five included Mar T_{min} (Table 7).

The top ranked ice duration models contained 3–5 parameters and explained 54 % (Deer) to 75 % (Catlin) of variability in ice duration (Table 6). Among lakes, parameters varied more than in the ice-in and ice-out models, but Dec T_{min} and Apr snow depth were in all five models, and May T_{min}, Apr T_{max} and Dec snow depth were included in three top-ranked models (Table 7).

Trends and interannual variability in ice phenology and climatic predictors are shown in 'chronology' figures for ice-in (Fig. 3) and ice-out (Fig. 4). For ice-in, the three earliest median ice-in dates (1976, 1980, 1989) corresponded with relatively large negative

Table 4 Multiple regression models of ice-in (freeze-up) date based on local climate variables for five lakes in the central Adirondacks, New York. Best models presented here were selected from a group of candidate models using AICc (see Appendix 2); adjusted r^2 values are given as a relative measure of model explanatory power. Variance inflation factors (VIF) estimate the degree of multicollinearity among parameters in a model (VIF < 4 indicates no significant collinearity). SI units are given for temperature (C) and snow depth (cm) parameter estimates

Lake	Parameter	Estimate	p	VIF	model r^2 adjusted
Arbutus	May max Tmin	0.54	0.0066	1.15	0.61
	Dec max Tmin	0.51	0.0055	1.20	
	Nov mean snow depth	-8.89	0.0132	1.37	
Catlin	Nov mean Tmin	0.75	0.0033	1.31	0.58
	Dec mean Tmax	0.58	0.0009	1.31	
Deer	Nov mean Tmin	0.65	0.0195	1.58	0.60
	Dec max Tmin	0.33	0.0872	1.72	
	Nov mean snow depth	-10.26	0.0042	1.28	
Rich	Nov mean Tmin	0.72	0.0005	1.33	0.74
	Dec mean Tmin	0.21	0.0407	1.55	
	Dec max Tmax	0.22	0.058	2.17	
	Dec mean snow depth	-1.47	0.0575	1.62	
Wolf	Nov mean Tmin	0.36	0.0211	1.48	0.57
	Dec mean Tmax	0.53	0.0037	1.48	

temperature anomalies (cooler than average) in May, Nov and Dec (Fig. 3). The three latest median ice-in dates (1996, 1998, 2001) corresponded with warm anomalies in May, Nov and Dec and trace (< 1 cm) snow depth for 1998 and 2001. For ice-out, the three earliest lake

Table 5 Multiple regression models of ice-out (break-up) date based on local climate variables for five lakes in the central Adirondacks, New York. For details, see caption of Table 4

Lake	Parameter	Estimate	p	VIF	model r^2 adjusted
Arbutus	Mar mean Tmin	-0.42	0.0018	1.18	0.68
	Apr mean Tmax	-0.30	0.007	1.14	
	Apr mean snow depth	1.71	0.0001	1.13	
Catlin	Mar mean Tmin	-0.31	0.0399	1.23	0.62
	Apr mean Tmax	-0.39	0.0038	1.24	
	Apr mean snow depth	1.53	0.0006	1.15	
Deer	Mar mean Tmin	-0.37	0.0262	1.18	0.63
	Apr mean Tmax	-0.30	0.0302	1.18	
	Apr mean snow depth	1.90	0.0002	1.14	
Rich	Apr mean Tmax	-0.52	0.0001	1.09	0.60
	Apr mean snow depth	0.36	0.0003	1.09	
Wolf	Mar mean Tmin	-0.26	0.0469	1.18	0.69
	Apr mean Tmax	-0.51	<.0001	1.16	
	Apr mean snow depth	1.38	0.0007	1.15	

Table 6 Multiple regression models of ice duration (days) based on local climate variables for five lakes in the central Adirondacks, New York. For details, see caption of Table 4

Lake	Parameter	Estimate	p	VIF	model r^2 adjusted
Arbutus	Dec max Tmin	-0.66	0.0029	1.22	0.56
	May max Tmin	-0.43	0.0622	1.23	
	Nov mean snow depth	8.87	0.0339	1.39	
	Apr mean snow depth	1.73	0.0523	1.08	
Catlin	Dec max Tmin	-0.82	<.0001	1.45	0.75
	May max Tmin	-0.33	0.0413	1.16	
	Dec mean snow depth	1.90	0.0378	1.53	
	Apr mean Tmax	-0.69	0.0001	1.09	
	Apr mean snow depth	1.75	0.0034	1.15	
Deer	Dec max Tmin	-0.66	0.003	1.20	0.54
	Nov mean snow depth	10.27	0.0215	1.19	
	Apr mean snow depth	2.53	0.0031	1.01	
Rich	Dec mean Tmin	-0.31	0.0199	1.57	0.66
	Dec max Tmax	-0.27	0.065	2.25	
	Dec mean snow depth	1.92	0.0592	1.76	
	Apr mean Tmax	-0.40	0.0268	1.23	
	Apr mean snow depth	1.68	0.0066	1.08	
Wolf	Dec max Tmin	-0.61	0.0022	1.75	0.73
	May max Tmin	-0.30	0.0864	1.16	
	Dec mean snow depth	2.52	0.0484	1.95	
	Apr mean Tmax	-0.98	<.0001	1.16	
	Apr mean snow depth	1.89	0.005	1.06	

openings (1981, 1988, 1998) corresponded with very low snow depth (<10 cm) and warmer Mar and Apr temperatures (Fig. 4). Years with a mean Apr snow depth of 20 cm or more, including 1975, 1978 and 1994, were among the latest median ice-out dates.

Analysis of the average error (model residuals) for the top-ranked ice duration models (Fig. 5) indicated that model prediction was slightly better during the period of 1995–2007, compared to the two decades prior (1975–1995). Within the former time period, the models consistently over-estimated ice duration. Comparison of the time-series of average residuals with average ice duration (across all five lakes) shows that models were typically under-estimating duration for years with greater than average duration, and vice-versa. Model residuals always fit the normal or lognormal distribution best, based on negative log-likelihood, among the group of distribution functions tested (see *Methods*).

3.3 Trends in climatic predictors of lake ice

The monthly climate variables that were included as parameters in the top-ranked climate–lake ice models (i.e., climate predictors of lake ice) are summarized in Table 7. As noted above, the ice-out models had the most consistent group of parameters (Apr T_{max}, Apr snow depth and Mar T_{min}) across all lakes, relative to the ice-in and ice duration models that had more variety in parameters. Trends in

Table 7 Frequency of monthly climate variables in the best lake ice models (ice-in date, ice-out date and ice duration) for five lakes in the central Adirondacks, New York. Model parameters included statistical moments (mean, min, max, standard deviation) but are grouped in table. The data indicates how often a group of parameters was represented among the five best models (one per lake) for ice-in, ice-out and ice duration; i.e., the consistency of climate predictors among lakes

Ice In Models		**Ice Duration Models**	
May Tmin	1	May Tmin	3
Nov Tmin	4	Apr Tmax	3
Nov snow	2	Apr snow	5
Dec Tmin	3	Nov snow	2
Dec Tmax	3	Dec Tmin	5
Dec snow	1	Dec Tmax	1
Ice Out Models		Dec snow	3
Mar Tmin	4		
Apr Tmax	5		
Apr snow	5		

these parameters are summarized in Table 8. Based on Sen estimators, most of these temperature parameters have experienced warming trends from 1975–2007. Snow depth in Nov and Dec has decreased slightly, while Apr snow depth has marginally increased. Overall, Dec T_{max} has increased the most, with mean T_{max} warming by 0.83 °C decade^{-1} and minimum T_{max} (i.e., the lowest maximum daily temperature observed during Dec) warming by 2.0 °C decade^{-1}. Only the Dec T_{max} trends were significant at $p<0.05$, indicating the relatively strong (upward) directionality in these time series. Despite the lack of significance for other trends, temperature and snow depth changes during these months have also contributed to changes in lake ice phenology and duration.

4 Discussion

Our analysis of climate drivers of lake ice changes on Adirondack mountain lakes provides further evidence of rapid warming and the sensitivity of ecosystems in the boreal-temperate ecotone of the eastern North America. For the three lakes most sensitive to warming in this study, the loss of 14–21 days of ice cover are the largest decreases observed for any published lake ice dataset from the Adirondack region (Jensen et al. 2007; Stager et al. 2009), including Lake Placid (566 m) and Mirror Lake (565 m), which are located at slightly higher elevation and latitude. Regionally, the rates of ice duration loss on these Adirondack lakes are in the upper 10 % of those reported for lakes in the U.S. and Canada (Robertson et al. 1992; Maguson et al. 2000; Hodgkins et al. 2002; Jensen et al. 2007; Latifovic and Pouliot 2007), although there are caveats to such comparisons, including differences in temporal duration of the analysis and lake characteristics. Compared to the studies above, the lake ice records in this study more fully encompass a period of rapid warming in the US Northeast that began in the 1970s (Frumhoff et al. 2007; Hayhoe et al. 2007a). Also, while they are typical in size for higher-elevation mountain lakes, our study lakes are among the smallest analyzed in the North American lake ice literature. Evidence from larger, lower-elevation lakes in the region – such as Lake Champlain that no longer freezes over on a regular basis – suggests that equally large changes in ice duration have occurred, but over longer time periods (Stager et al. 2009).

Unlike most lakes and rivers in northeastern North America, Adirondack lakes have experienced stronger changes in ice-in phenology and relatively little change in ice-out phenology. As result, the duration of ice cover is decreasing mostly because of later closures, while openings are now only slightly earlier. We note, however, that these results are consistent with

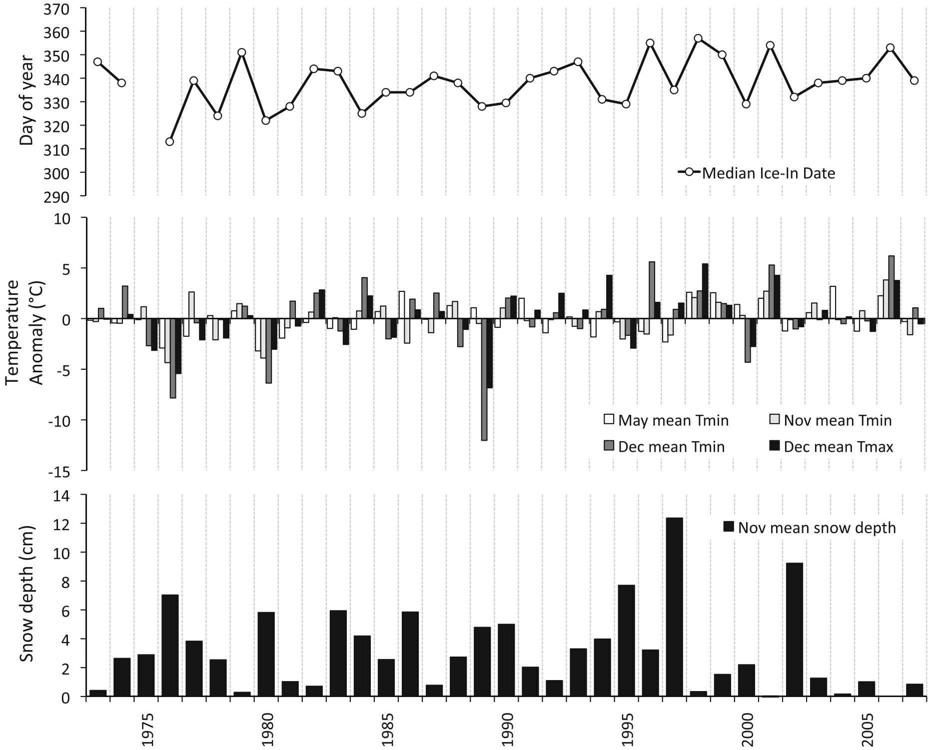

Fig. 3 Chronology of ice-in (freeze-up) date and its climate drivers, for five lakes in the central Adirondacks, New York. Climate predictors were chosen based on their frequency among the five best ice-in models (one per lake; see Table 5). Ice-in dates are median values from all lakes with records in a given year. Temperature anomalies are based on the 1975–2007 mean for each variable

recent lake ice trends reported by Jensen et al. (2007) in the broader region extending from central New York into western Vermont, which includes the Adirondacks. Based on the lake ice data alone, this suggests that recent autumn (SON) and winter (DJF) warming in this area of the US Northeast has been more significant than spring (MAM) warming. In examining climatic drivers of Adirondack lake ice, we found that early winter warming has generally been of greater magnitude than spring warming, which is consistent with the seasonality of lake ice changes. But our analysis also indicated why the spring warming that has occurred locally has not driven significantly earlier lake openings, as seen elsewhere throughout the US Northeast region.

4.1 Local climate drivers of lake ice changes

Our analysis went beyond prior studies by identifying the climate variables that both predicted lake ice phenology and have experienced trends that were consistent with observed changes in lake ice. We constructed climate–lake ice models were both predictive and parsimonious, explaining between 50 and 75 % of variability in the phenology and duration of ice cover with between 2 and 5 terms. Although not robustly parameterized for prediction at this stage, the models are useful for rough forecasting; for example, December warming of between 1 and 3 °C by 2050 (Hayhoe et al. 2007b) could delay the ice-in date by approximately 2–6 days, in the absence of any other changes (i.e., all other parameters held

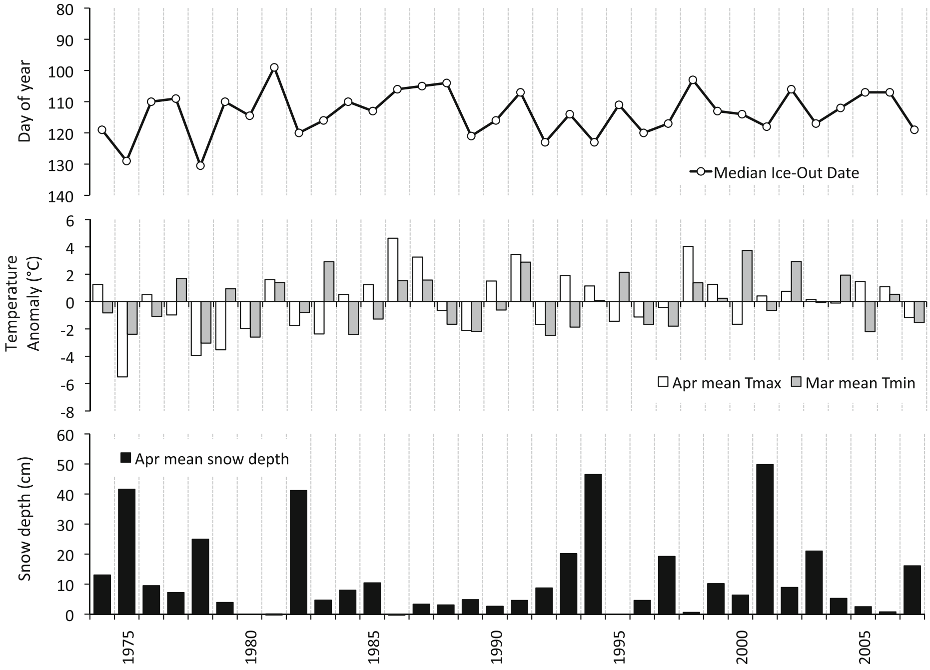

Fig. 4 Chronology of ice-out (break-up) date and its climate drivers, for five lakes in the central Adirondacks, New York. Climate predictors were chosen based on their frequency among the five best ice-in models (one per lake; see Table 5). Ice-out dates (plotted on an inverted scale) are median values from all lakes with records in a given year. Temperature anomalies are based on the 1975–2007 mean for each variable

constant). Overall, the ice-out models performed best and were most consistent among lakes with respect to parameters. Linear models had normal or log-normal distributions of residuals, although non-linear relationships between ice phenology and temperature may exist (Weyhenmeyer et al. 2004).

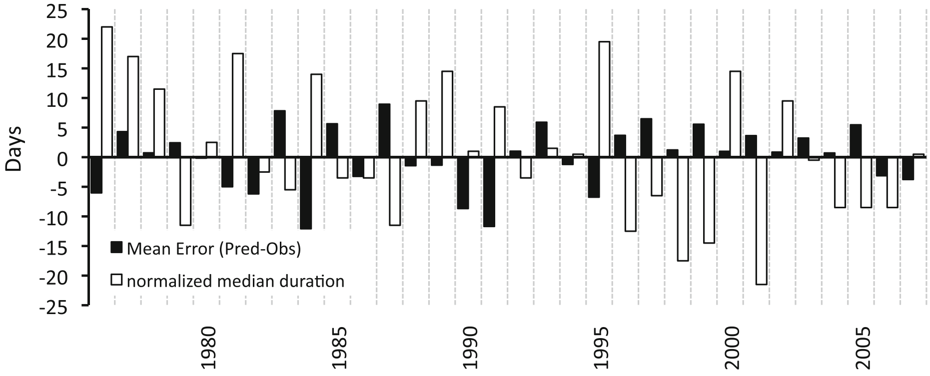

Fig. 5 Average climate-lake ice model error and median ice duration for five lakes in the central Adirondacks, New York. Model error was based on averaging the residuals (predicted – observed) of the five best ice duration models (one per lake). Median ice duration among the five lakes was normalized using the subtraction method

Table 8 Trends in climatic predictors of lake ice phenology based on weather data collected at Huntington Wildlife Forest from 1975–2007. Variables were selected based on their occurrence in the best climate-lake ice models (see Table 7). In addition to Mann-Kendall t and p values, trend magnitudes are given as decadal rates, based on both the Sen and linear regression estimators

	Mann-Kendall τ	p	Sen rate (°C or cm decade^{-1})	Linear rate (°C or cm decade^{-1})
Mar Tmin				
max	-0.01	0.9430	0.00	0.06
mean	0.08	0.5136	0.25	0.08
min	0.05	0.7009	0.44	0.11
Apr Tmax				
max	0.13	0.2989	0.93	0.74
mean	0.16	0.1728	0.49	0.58
min	0.14	0.2664	0.60	0.45
May Tmin				
max	0.22	0.0749	0.88	0.74
mean	0.21	0.0758	0.58	0.58
min	0.18	0.1518	0.28	0.31
Nov Tmin				
max	0.14	0.2434	0.91	0.69
mean	0.16	0.1865	0.40	0.47
min	0.00	0.9886	0.00	-0.07
Dec Tmin				
max	0.09	0.4748	0.23	0.51
mean	0.11	0.3633	0.59	0.77
min	0.11	0.3781	0.85	1.06
Dec Tmax				
max	0.25	0.0389	1.11	1.25
mean	0.24	0.0468	0.83	0.94
min	0.40	0.0010	2.01	2.07
Apr snow				
mean	0.02	0.8647	0.25	-0.02
SD	0.02	0.8983	0.39	0.63
Nov snow				
mean	-0.15	0.2012	-0.50	-0.25
SD	-0.12	0.3342	-0.46	-0.44
Dec snow				
mean	-0.02	0.9095	-0.22	-0.23
SD	-0.12	0.3342	-0.67	-0.66

Modeling of the climate drivers of local phenology changes provides an improved understanding of climate change impacts and helps to better forecast the implications of future climate. For example, we found that warming of December temperatures has been a primary driver of decreasing ice duration on Adirondack mountain lakes. Warming of November minimum and May minimum temperatures drove decreasing ice duration as well. The influence of November and December warming is logical because, during the first 10–15 years of the lake ice record, ice-in occurred in late November but shifted steadily thereafter towards December (Table 2). May warming likely causes the earlier warming of lake water (following ice-out), which influences thermal stratification and the timing of ice formation in the following winter (Stefan and Fang 1997; Williams et al. 2004). November and December snow depth also were related to ice-in timing and have experienced marginal decreases since 1975. Interactions among these drivers can create negative feedbacks that minimize change or positive feedbacks that result in magnified changes. For example, earlier warming of lake water due to higher May temperatures could be counteracted by lower November and December temperatures (negative feedback) or exacerbated by warmer temperatures during these months (positive feedback). The strongest positive feedbacks were evident when warm anomalies in December, November and May coincided with very low snow cover in the same year (Fig. 4); these conditions resulted in the latest ice-in dates observed in the long-term record.

Our analysis also provided an explanation for why ice-in trends have been much greater than ice-out trends in the Adirondacks, despite warming drivers during both times of year. Warming of April T_{max} at the rate of 0.5 °C decade^{-1} would likely have been a stronger driver of earlier ice-out, if not for the influence of snow cover, which was strongly correlated with ice-out dates for all five lakes (i.e., more snow, later ice-out), but had a weakly increasing trend during 1975–2007. Snow cover inhibits heat transfer between atmosphere and lake water, slowing ice growth or decay, and because of its higher albedo (reflectivity), snow reduces the exposure to solar radiation (Vavrus et al. 1996; Winder and Schindler 2004). If snow cover on lakes buffers against warm anomalies in spring (i.e., a negative feedback; see Fig. 5) and delays the ice-out date, this explains the weakness of ice-out trends despite concurrent warming during the same period. We recognize that our snow depth data – collected at the HWF monitoring site and not directly on the lakes – was at best a proxy of snow depth on each lake. Yet because snow was consistently an important parameter in our lake ice models, future projections of decreasing snow cover across the US Northeast (Frumhoff et al. 2007; Huntington et al. 2009) could lead to further decreases in ice duration. It is notable, however, that these projections depict the Adirondacks as one of the few areas in the US Northeast that will have persistent snow pack throughout the winter by 2050 (Frumhoff et al. 2007).

The largest and deepest lakes at HWF exhibited the strongest climate 'signals', or sensitivity to warming, based on greater decreases in ice cover in response to the same local climate drivers. Although a qualitative observation, it indicates that lake volume affects the sensitivity of ice dynamics to ambient warming, potentially because smaller and shallower lakes are more sensitive to short-term variability than larger lakes (Fang and Stefan 1998), resulting in a low 'signal-to-noise' ratio. In addition to morphology, differences in hydrology (i.e., drainage vs. seepage), catchment area and geographic location (i.e., elevation, latitude) can influence lake ice processes and their sensitivity to climate forcing (Williams et al. 2004). Among our study lakes, however, these factors either did not appear to explain differences in sensitivity to warming, or we were unable to sufficiently account for them due to a small sample size.

4.2 Climate vulnerability of a wilderness lake

The most rapid decreases in ice duration that we observed and have yet been observed in the US Northeast have occurred on Wolf Lake, which is considered a 'Heritage Lake' (Stager and Sanger 2003) and one of the most pristine freshwater bodies in the US Northeast (Charles et al. 1990; Sullivan et al. 1999). Wolf Lake at Huntington Wildlife Forest has not experienced significant acidification due to NO_3 and SO_4 deposition (acid rain), nor have invasive or introduced fish, plant or invertebrate species been found in surveys. It is carefully managed by HWF staff to prevent species introductions and is located directly adjacent to the High Peaks Wilderness Area of the NY State Forest Preserve. Although considered one of the most ecologically intact and best-protected lakes in the region, recent warming has driven an estimated loss of three weeks (21 days) of ice cover since 1975. Preliminary studies of lake sediments in Wolf Lake have found shifts in algal communities that are indicative of changing thermal regimes due to decreased ice cover (A. Fenton, *unpublished data*). Reductions in dissolved oxygen as well as increasing suitability for warmer-water invasive fish may threaten brook trout (*Salvelinus fontinalis*) and other endemic fish species in the lake (Stager and Sanger 2003). Therefore, despite stewardship and landscape conservation in the Adirondacks, the region's many lakes – many which have been impacted by acidification and invasive species, but also those like Wolf Lake that have not – may be highly vulnerable to climate change. Because of the ecological, economic and cultural importance of lakes in the Adirondacks, and the long-term monitoring programs of regional efforts like the Adirondack Lake Survey Corporation (http://www.adirondacklakessurvey.org/), the potential for understanding and adapting to recent and future changes in this region is relatively high. More broadly, we suggest that the example of Wolf Lake illustrates the stewardship challenges posed by climate change in places like the Adirondack Park, in which vulnerabilities can emerge in relatively intact ecosystems, despite comprehensive long-term monitoring and landscape-scale conservation efforts.

4.3 Ecological significance of changing lake ice

Changes in lake ice are significant both because of their direct ecological impacts and their value as proxies (indicators) of climate change within biogeographic zones. In the lake ecosystem itself, loss of ice cover may cause shifts in water chemistry (Koinig et al. 1998), thermal strata (Vincent 2009), biotic communities (Smol et al. 2005) and a variety of related ecosystem processes (Blenckner et al. 2002). A shorter ice-covered season leading to an earlier onset of thermal stratification (Keller 2007; Vincent 2009) may result in stress for native fish species, changes in plankton successional dynamics, the decoupling of interactions between trophic groups, and changes in competitive interactions within trophic levels (Stefan et al. 2001; Winder and Schindler 2004; Adrian et al. 2006; Rühland et al. 2008). Several lakes in Ontario, Canada have seen rapid increases in chrysophyte algae due in part to thermal changes attributed to warming (Paterson et al. 2004, 2008). Similar chrysophyte increases have been observed in several montane Adirondack lakes (Arseneau et al. 2011; A. Fenton, *unpublished data*; C. Cummings, *unpublished data*), including two of the lakes analyzed in this study (Arbutus and Wolf), indicating that the effects of warming may already be occurring in these ecosystems.

Lastly, as proxies of change, the phenology of Adirondack lakes provides evidence of rapid warming in the biogeographic zone where they are located – the boreal-temperate ecotone of northeastern North America. Upland forests and wetlands in this ecotone are likely as sensitive to this driver of change as the nearby lakes (Huntington et al. 2009). In addition to rapid changes within the boreal-temperate forest ecotone itself (Beckage et al. 2008), shifts in forest composition and species distributions may be expected based on climate envelope models (Iverson and Prasad 2002) as well as recent field studies (Treyger and Nowak 2011). As the climate warms, longer growing seasons that affect vegetation communities may also significantly reduce runoff from forest watersheds in the region (Huntington 2003). Warming has also been implicated in forest health problems, including the decline of red spruce at high elevations (Hamburg and Cogbill 1988) and the potential spread of forest pests such as the hemlock wooly adelgid into areas where (historically) cooler climates inhibited overwintering (Paradis et al. 2007). Climate also shapes the biogeochemical cycles of northern forest watersheds and their responses to perturbation including nitrate and sulfate deposition (Mitchell et al. 1996), land use change (Aber and Driscoll 1997) and CO_2 fertilization (Ollinger et al. 2007). Overall, if vulnerability is a function of exposure to and sensitivity to drivers of change, these transitional ecosystems, both aquatic and terrestrial, may be among the most vulnerable in North America. An in-depth understanding of both the drivers and outcomes of this vulnerability is essential for future efforts at climate adaptation.

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