Article

Limnological measures related to climate change in the Hubbard Brook Valley, USA

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Abstract

Long-term monitoring within the Hubbard Brook Valley revealed changes in many climate and limnological variables known to affect the structure and function of aquatic ecosystems. The Hubbard Brook Valley is located in the White Mountains of New Hampshire, USA, and is the site of integrated, long-term ecological, biogeochemical, and hydrological studies. Mean annual temperatures in 2 headwater streams on south-facing slopes of the Hubbard Brook Valley declined ~2 °C from 1966 to 1983 and then showed a small (~1 °C) and variable increase thereafter. No significant change in temperature was observed in 3 north-facing, headwater streams. Reliable records of ice-in and ice-out have been maintained since 1968 for Mirror Lake at the base of the Hubbard Brook Valley. The duration of ice cover on Mirror Lake has declined since 1968 at a significant rate of about −0.475 d/yr as a result of earlier ice-out (0.203 d/yr) rather than later ice-in dates. Since about 1996 the duration of ice cover has become much more variable with a nonsignificant change in ice cover duration. Evaluating how various temperature-sensitive components of aquatic ecosystems in the Hubbard Brook Valley change (amount and timing) in the future will be important to developing a better understanding of limnological responses to climate change.

Key words: air temperature, Hubbard Brook Experimental Forest, lake ice cover, Mirror Lake, solar radiation, stream temperatures

Introduction

Climate change has impacted aquatic ecosystems worldwide and is likely to have profound and complicated effects on the ecology, biogeochemistry, and hydrology of these ecosystems in upcoming decades (e.g., Meyer et al. 1999, Journal of American Water Resources Association 1999, Rühland et al. 2008, Wilby et al. 2010). Moreover, lakes and rivers often provide among the clearest and earliest indicators of climate change, including floods and droughts, changes in temperature (heat budgets), and biotic diversity.

Despite the potentially large effects of climate change on aquatic ecosystems, there is relatively little long-term information on and/or analysis of the changes occurring. For example, relatively little has been published on long-term temperature changes in streams and rivers (see Kaushal et al. 2010), and in many cases, results are equivocal; and although many long-term records of ice duration on lakes and rivers are available (e.g., Magnuson et al. 2000a, 2000b) opportunities to evaluate specific drivers of long-term change are relatively rare. This paper focuses on changes in temperature of headwater streams and on the timing (onset and loss) and duration of ice cover on Mirror Lake, all within the Hubbard Brook Valley, as well as potential, major drivers of change.

Site description

The Hubbard Brook Valley is located in the White Mountains of central New Hampshire, USA, and has been the site of long-term, integrated hydrological, biogeochemical, and ecological studies since the early 1960s (Likens and Bormann 1995). The Hubbard Brook Valley (43°56′N; 71°45′W) contains the 3160 ha Hubbard Brook Experimental Forest (HBEF) with 9 experimental, hydrologically gauged watershed ecosystems (Likens and Bormann 1995). The HBEF climate is cool-temperate,

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humid-continental with mean July and January temperatures of 18.7 °C and −8.3 °C, respectively, at 450 m elevation (Federer et al. 1990, Bailey et al. 2003). Vegetation is characterized by northern hardwood deciduous trees, with more coniferous species on ridgetops and on north-facing slopes (www.hubbardbrook.org).

Mirror Lake (43°56.5′N; 71°41.5′W) is a small (15 ha; z_{max} 11 m), clearwater lake near the mouth of the Hubbard Brook Valley at an elevation of 213 m. Extensive research has been done on the limnology, hydrology, biogeochemistry, and paleoecology of the lake since 1967 (Likens 1985, Winter and Likens 2009).

Methods

Long-term solar radiation and air temperature were measured at a Class A Weather Station at an elevation of 256 m a.s.l., located 0.5 km from Mirror Lake. Details about the procedures for these measurements and the equipment used are given in Likens (1985, 2000), Federer et al. (1990), and Bailey et al. (2003). Annual air temperatures are arithmetic means of weekly values, reported on a calendar-year basis.

Temperatures in headwater streams were measured weekly (~48 to 50 measurements/yr-stream) with either a Whitney underwater thermometer, an Hg thermometer, or a digital thermometer, all carefully calibrated (see Likens 2000). South-facing streams (Watersheds W6 and W3) were measured at elevations of W6 = 552 ± 3 m a.s.l., W3 = 497 ± 3 m a.s.l., and north-facing streams at W7 = 616 ± 3 m a.s.l., W8 = 600 ± 3 m a.s.l., and W9 = 680 ± 3 m a.s.l. Measurements in headwater streams in W3 and W6 began in 1966, and first full year of measurement for W7, W8, and W9, was in 1996. Reliable records of the timing for ice-in and ice-out exist for Mirror Lake since 1968–1969. The precision of the ice-in date is ±2 d and for ice-out date is ±1 d (see Likens 2000 for details).

Results

Temperature change in headwater streams of the Hubbard Brook Valley

In contrast to some other locations in the northeastern United States (Kaushal et al. 2010), there has been no consistent, long-term increase in water temperature in headwater streams in the Hubbard Brook Valley. In fact, mean annual temperatures in 2 south-facing headwater streams (W3 and W6) of the Valley declined by ~2 °C from 1966 to 1983, then showed small (~1 °C) and variable increase thereafter (Fig. 1). No significant change ($p > 0.10$) was measured in north-facing headwater

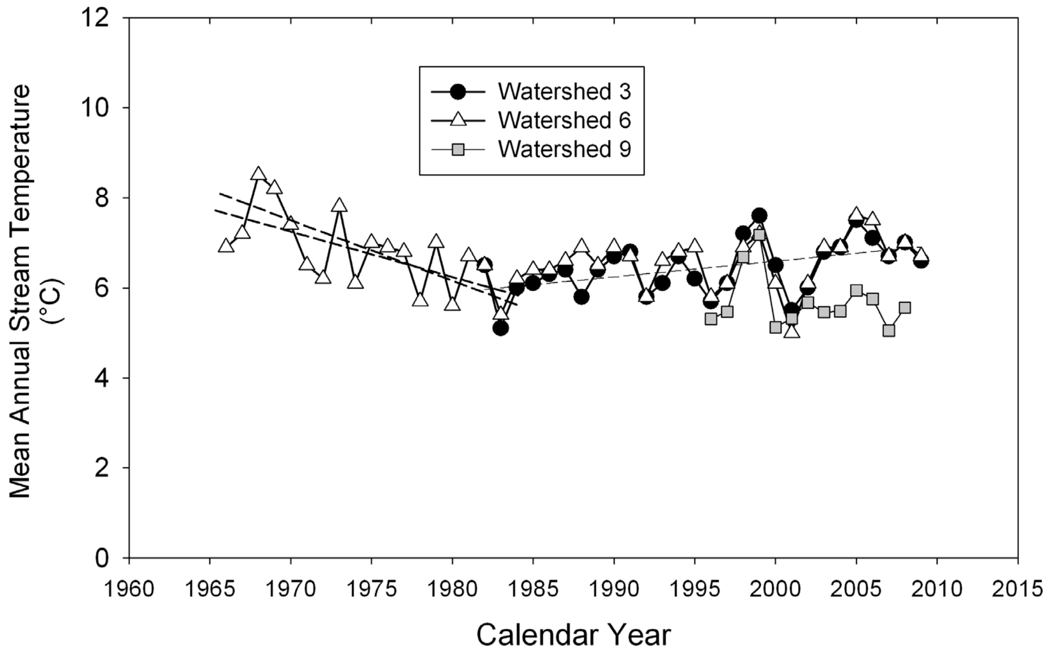

Fig. 1. Trends in mean annual streamwater temperatures derived from weekly measurements in headwater streams of experimental Watersheds 3 (W3), 6 (W6) and 9 (W9) of the Hubbard Brook Valley (W3 and W6 modified and updated from Kaushal et al. 2010). Regression line for W3 (---): 1966 to 1983, $Y = -0.133X + 269.5$, $p = 0.003$, $r^2 = 0.42$; 1983 to 2009, $Y = 0.040X - 72.9$, $p = 0.005$, $r^2 = 0.28$; 1966 to 2009, $p = 0.12$; W6 (—): 1966 to 1983, $Y = -0.099X + 202.4$, $p = 0.005$, $r^2 = 0.39$; 1983 to 2009, $Y = 0.025X - 44.3$, $p = 0.08$, $r^2 = 0.12$; 1966 to 2009, $p = 0.22$. There was no significant trend for W9 (····): 1996 to 2008, $Y = -0.04X - 84.3$, $p = 0.41$, $r^2 = 0.06$.

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streams (W7, W8, and W9). Stream temperatures in north-facing streams tracked those in south-facing streams during 1996 to 2002 but were cooler after 2002 (Fig. 1). Temperatures and patterns were similar in north-facing headwater streams, but only data for W9 are shown (Fig. 1). Maximum temperatures were several degrees Celsius higher than minimum temperatures in the south-facing headwater streams in early spring. March was the only month of the year when this difference was significant (Bernhardt et al. 2005).

Ice cover on Mirror Lake

Other records of ice duration on lakes and rivers may be longer, but both the length, and especially the quality (small uncertainty in the timing of the ice-in and ice-out dates), of the record for Mirror Lake are unusual (Magnuson et al. 2000a, 2000b). The ice-in date currently occurs ~6.5 days later than 1968 (42 yr period), but the long-term trend is not significant at $p < 0.05$; in contrast the ice-out date is ~12 days earlier (43 yr period), and the long-term trend is significant ($r^2 = 0.15$, $p = 0.01$; Fig. 2). The average long-term ice-in date is 7 December, and the average ice-out date is 16 April.

The pattern of ice-cover duration on Mirror Lake reported in 1998 (Likens 1998, 2000) showed a decline in duration at a significant ($p = <0.02$) rate of about −0.54 d/yr; that is, ice-cover duration was about 17 days less in 1998 than in 1967–1968 (Fig. 3) [these values are slightly different than published values because of an error discovered in the earlier data]. The average duration of ice cover for the full 42 yr period is 130.8 days, ranging from 96 days in 2009–2010 to 149 days in 1968–1969.

In the 12 years since 1998 (1998–2009), duration of ice cover has not changed significantly, although ice-out on 18 March 2010 was the earliest on record (30 days earlier than the long-term average; Fig. 2). The duration of ice cover on Mirror Lake has become much more variable since about 1996 (Figs. 3 and 4). The rate of change of ice cover on Mirror Lake for the entire 42 yr period (1968–1969 to 2009–2010) is −0.475 d/yr or ~20 days less in 2009–2010 than in 1968–1969 (Fig. 3). This trend toward an earlier ice-out date and a shorter period of ice cover on Mirror Lake is associated with higher air temperatures in late winter and

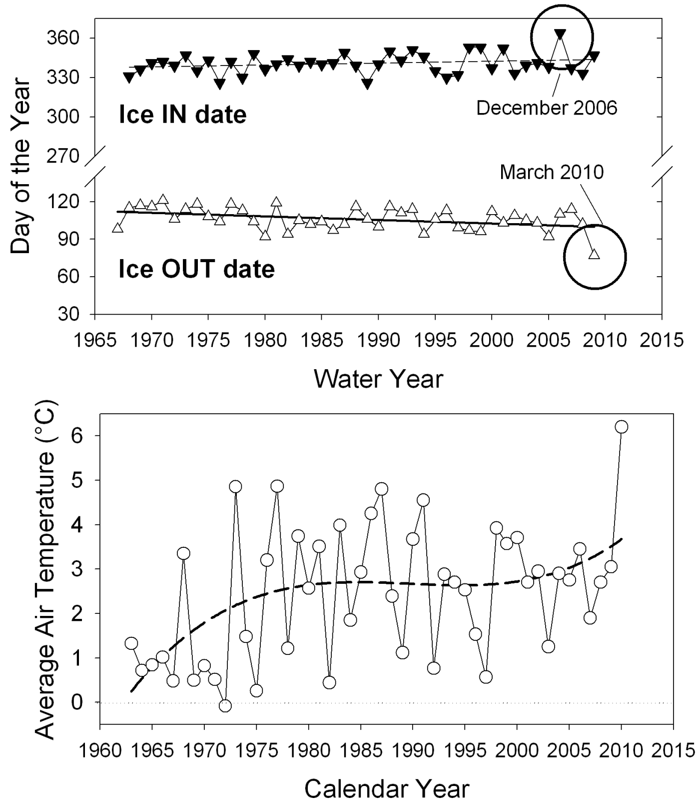

Fig. 2. TOP: Long-term trends in onset of ice cover (ice-in; $p = 0.12$, $r^2 = 0.06$) and loss of ice cover (ice-out; $p = 0.01$, $r^2 = 0.15$) for Mirror Lake; BOTTOM: trend in average air temperature for Mirror Lake during Mar–Apr from 1963 to 2010 ($r^2 = 0.23$, $p = 0.04$, third-order regression).

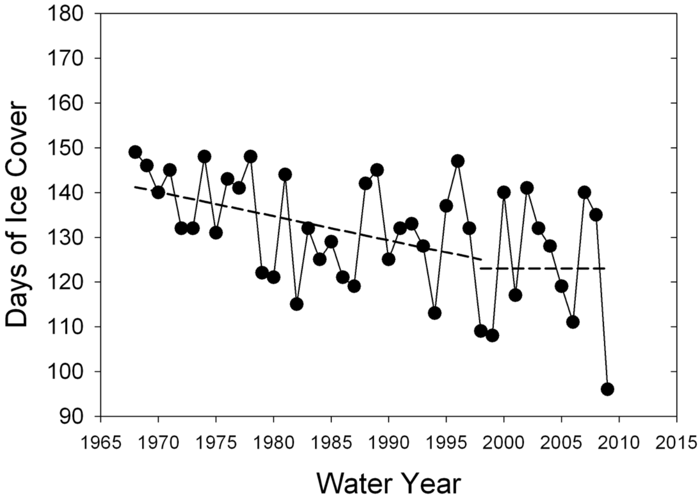

Fig. 3. Trends in the duration of ice cover on Mirror Lake. [1968 to 2009 (42 yrs), $Y = -0.475X + 1075$, $r^2 = 0.21$, $p = 0.003$; 1968 to 1998 (31 yrs), $Y = -0.54 + 1205$, $r^2 = 0.19$, $p = 0.015$; 1998 to 2009 (12 yrs), $Y = 0 + 123$, $r^2 = 0$, $p = 1.0$]. Water-year includes ice-in during year preceding year of ice-out.

early spring (Figs. 2 and 3), and cloudier spring weather at HBEF (Likens 2000, and see below). Based on linear regression, current, mean maximum air temperatures in March and April (when ice-out occurs) are 2 °C and 3.5 °C higher, respectively, than 48 years ago in the Hubbard Brook Valley, and there is a strong and direct relation between duration of ice cover and March–April air temperature ($p = <0.001$, $r^2 = 0.32$). Mean minimum air temperature in April is 1.9 °C warmer today than 48 yrs ago (trend not significant for March). Importantly, mean minimum monthly air temperatures in April have been above 0 °C since 1998 (but not in 2002). All months except October showed an increase in air temperature in the long-term record. The largest increase (0.054 °C/yr) occurred in April, followed in descending order by December, February, August, September, March, and January.

Mean, monthly solar radiation has been declining in all months in the Hubbard Brook Valley since 1963 (A. Bailey, US Forest Service, Jul 2011, pers. comm.) with the largest decline in July (−0.075 MJ/m^2-yr), April (−0.063 MJ/m^2-yr), February (−0.0629 MJ/m^2-yr), May (−0.061 MJ/m^2-yr), and October (−0.053 MJ/m^2-yr). Although no direct measures of cloudiness are available, the decline in surface solar radiation undoubtedly corresponds to an increase in cloudiness. Inexplicably, there is a statistically significant, inverse relation between duration of ice cover and solar radiation during April ($p = 0.001$, $r^2 = 0.23$). There is no statistically significant relationship between ice-out dates and March or April solar radiation.

There is no statistical relation in duration of ice cover on Mirror Lake with the North Atlantic Oscillation Index (NAOI) or El Niño Southern Oscillation (ENSO) Index. The NAOI has varied from about −5 to +5 during the winter months from 1964 to 2010, but there is no statistically significant, long-term trend in the NAOI Index (http://www.cgd.ucar.edu/cas/jhurrell/indices.html) or relation in the spring season (March, April, and May) NAOI or with the winter season (Feb–Mar) NAOI and the March–April air temperature or solar radiation at HBEF. Likewise, no significant ($p < 0.05$) relation was found between the ENSO Index and March–April air temperature or March–April solar radiation at HBEF.

Discussion

Warmer and wetter climate has been predicted for the northeastern United States in upcoming decades, but with enhanced hydrologic extremes, such as more frequent drought and extended low-runoff periods in summer (e.g., Union of Concerned Scientists 2006, Hayhoe et al. 2007, Huntington et al. 2009). Recent modeling, however, has suggested that increases in evapotranspiration will largely offset increases in precipitation, resulting in relatively little change in streamflow (Campbell et al. 2011). Based on ~5 decades of data, there are many examples of climate change within the Hubbard Brook Valley (Likens 2000, Campbell et al. 2007, Likens and LaBaugh 2009). For example, the average annual air temperature has increased ~0.5 °C during the past 50 yr; winter air temperatures have warmed more rapidly than summer temperatures; snow depth and snow cover duration have shown long-term declines (Campbell et al. 2007); and vegetation phenology has changed (Richardson et al. 2006).

Drivers of stream temperature change are numerous and complicated and are not necessarily unidirectional or quantitatively known. For example, water temperature is measured at higher elevations in headwater streams of HBEF and therefore is undoubtedly affected by the temperature of subsurface discharge into the channel, which in turn is affected by soil temperature and moisture, as well as by ambient air temperature, canopy shading, and snow cover in these areas. All these factors are likely to change in the future as a result of climate change. As such, it is rather remarkable to see any long-term, unidirectional changes in stream temperature. Soil temperatures seem to have increased slightly after 1990, but severe soil frost also was observed during winters of 2004–2005, 2005–2006, and 2006–2007 at HBEF (Judd et al. 2011). Soil temperature, which affects subsurface water temperature, is probably a major driver for water temperature in headwater streams, but no long-term data on this relation are available for the HBEF.

Higher maximum streamwater temperatures in spring are driven by solar radiation when the deciduous canopy is leafless, an ecologically important time because (1) the bulk of dissolved inorganic nitrogen losses occur from watersheds on an annual basis via stream water, presumably as the result of increased nitrification (Likens and Bormann 1995); (2) the warmer air and water temperatures around the time of snow melt may increase the strength of a so-called vegetational "vernal dam" reducing nutrient loss in stream water from watershed-ecosystems (Muller and Bormann 1976, Bernhardt et al. 2005); and (3) the capacity of algal and microbial assemblages in stream ecosystems to assimilate, transform, or denitrify nitrogen may be greatly facilitated at this time by these conditions (Bernhardt et al. 2005).

It is now well known that duration of ice cover on lakes and rivers can be used to evaluate changes in climate because it is an important component of the heat balance of a lake or river in the Temperate Zone (e.g., Livingstone 2000, Magnuson et al. 2000a, 2000b, Likens 1985, 1998, 2000, Hodgkins et al. 2002). The sharply increased variability in the length of ice-cover period on Mirror

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Lake after about 1996 (Fig. 4) may be related to increased variability in climate and phenology (affecting albedo) in the region. Less snow cover (Campbell et al. 2007), particularly with earlier and more frequent melt periods in winter, would further exacerbate an earlier loss of ice cover (timing of ice-out) on Mirror Lake by changing the timing of melt-water flowing into the lake and the albedo of land surfaces in the watershed, as well as the albedo of the ice surface itself. Indeed, depth of snow-cover is declining in the HBEF (Fig. 5A) and is empirically related to the duration of ice cover on Mirror Lake (Fig. 5B).

The asymmetry in seasonal drivers affecting ice-out at Mirror Lake is complicated but may be related to the change and variation in albedo and plant phenology, for example spring "green up" affecting atmospheric water vapor and thus re-radiation of infra-red radiation back to the water surface (Schwartz and Karl 1990). Because phenology is changing in the Hubbard Brook Valley (Richardson et al. 2006), it may be one of the important drivers of increased variability in the duration of ice cover (Fig. 4). The change in pattern of ice cover on Mirror Lake from an ever shorter period from 1968 to about the mid-1990s, to an insignificant decline and increased variation in ice-cover duration thereafter, has also been observed in Canadian lakes (e.g., Likens 2000, Rühland et al. 2008). One important value of a long-term record is obvious from these data; if data for ice-cover duration were to exist only from 1968 to 1996 or only for 1996 to 2010 for Mirror Lake, these individual periods, even though relatively long, would have been misleading regarding the longer trend and pattern.

Because of construction of Interstate Highway 93 (I-93) through the Northeast watershed of Mirror Lake in 1969–1970 and the heavy use of NaCl as a deicer on this highway, there has been a significant input of salt into the lake via the Northeast Tributary and in ground water (Rosenberry et al. 1999, Kaushal et al. 2010, Likens and Buso 2010). The increased salt loading to the lake raises a question regarding the lowering of the freezing point of water in the lake and how this might affect the timing and duration of ice cover. Calculations show, however, that NaCl concentrations in Mirror Lake currently are not high enough to have an appreciable effect on the freezing point of the water in Mirror Lake.

Clearly, climate change does not occur in a simple, predictable way, and the various temperature-sensitive components within the Hubbard Brook Valley have not

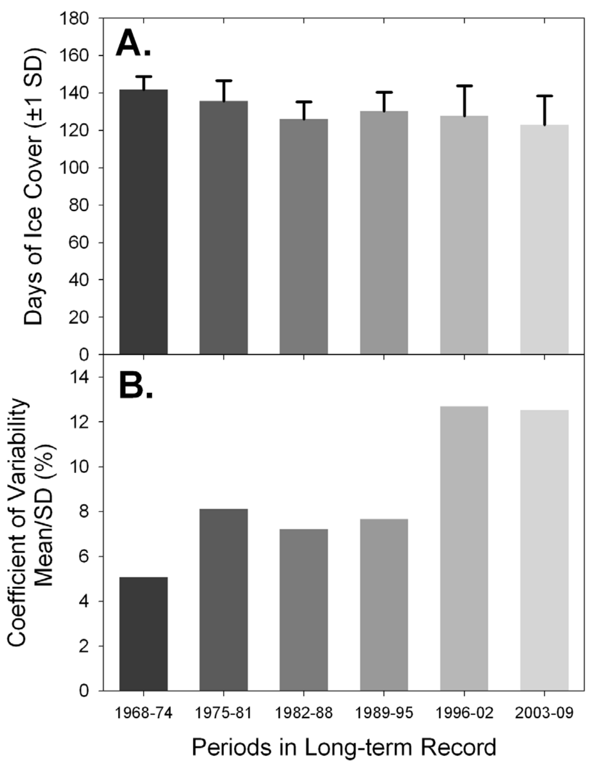

Fig. 4. (A) Average ice-cover duration (days ± 1SD) and (B) relative variation in average ice-cover duration (days) in Mirror Lake for different periods from 1968 to 2009.

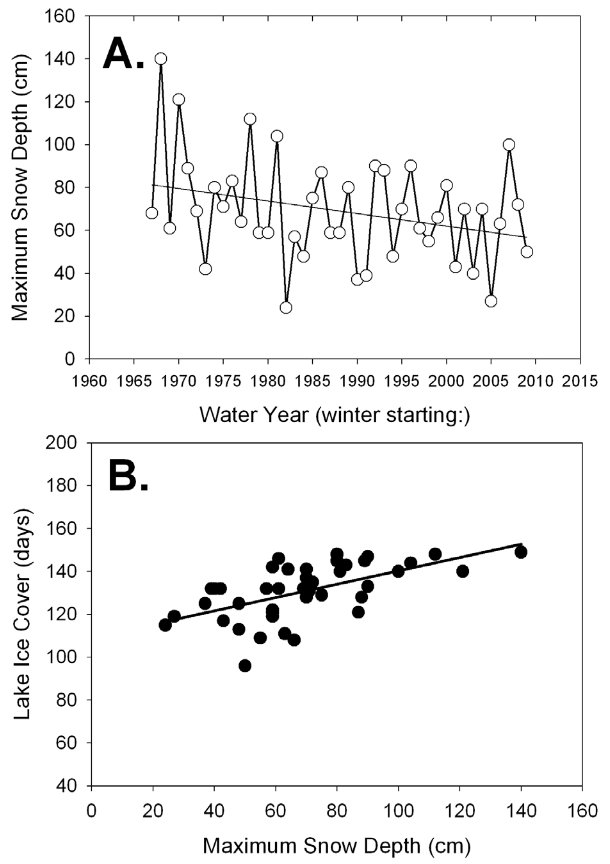

Fig. 5. (A) Depth of snow cover in the HBEF with time (−0.585 cm/yr, $r^2 = 0.09$, p = <0.05, and (B) relation between ice-cover duration on Mirror Lake and snow depth in the HBEF ($r^2 = 0.35$, $p = 0.001$).

shown a simple response either. The effects of changing (timing and magnitude) air temperature, solar radiation, relative humidity, the insulating qualities of different amounts of snow cover and its associated albedo, timing of runoff of meltwater from the catchment and its temperature, and the occurrence of rain versus snow during the winter season, all contribute to an extremely complicated mix of major drivers controlling the onset, loss, and duration of ice cover on a lake. Sorting out how these variables affect the heat balance and temperature trends of Mirror Lake and headwater streams in the Hubbard Brook Valley in the future will be important because these changing and uncertain conditions will undoubtedly alter the ecology and biogeochemistry of these aquatic ecosystems. The opportunity to analyze these complicated and highly variable responses in temperature of headwater streams and in ice cover on Mirror Lake is a clear example of the value of long-term data in limnological–ecological studies (Lindenmayer and Likens 2010). Moreover, the size, location, and long-term protection make the Hubbard Brook Valley an excellent site for studies of this type.

Summary

The changing patterns of ice cover on Mirror Lake have been measured for 42 years and the temperature of headwater streams for up to 47 years in the Hubbard Brook Valley of New Hampshire, USA.

Duration of ice cover on Mirror Lake is about 20 days less than 42 years ago, resulting from earlier ice-out, not later ice-in dates.

The ice-out date on 10 March 2010 was 30 days earlier than the long-term average.

The rate of decline in length of ice cover on Mirror Lake was relatively steep between 1968 and 1998 but was much more variable and not significant from about 1996–1998 to the present.

Temperature in 2 headwater streams on south-facing slopes of the Hubbard Brook Valley declined by ~2 °C from 1963 to 1983 and then increased by ~1 °C from 1983 to the present. No significant change in temperature was measured in 3 north-facing, headwater streams.

Air temperatures in March and April are significantly warmer today than 48 years ago, but solar radiation is consistently less in most months (more cloudy) in the Hubbard Brook Valley.

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