Hydro-ecological effects of changing Arctic river and lake ice covers: a review

Terry D. Prowse and Kirsten Brown

ABSTRACT

Freshwater ice is an integral part of the hydrologic regimes of cold environments. It controls the ecology of related aquatic systems and is important economically, through the facilitation of winter transport and via generation of extreme hydrologic events. Given projected changes in future climate, concern has been raised about related changes in freshwater ice. This paper reviews the status and trends in records of lake and river ice around the circumpolar North from traditional observations, remote sensing and paleo-sources. The temporal and spatial variability in trends are evaluated with relation to climatic conditions. Rapid changes experienced in freeze-up and break-up timing for high-latitude lakes, compared to those at more southerly locations, are particularly notable. Also considered are the nature and implications of changes in future freshwater-ice regimes that will have cascading effects on cold-region hydrology and a suite of hydro-ecological conditions including UV radiation receipts, habitat quality and availability, fisheries productivity and contaminant pathways. Overall, the duration and event timing of river and lake ice are proving to be useful indicators of climate change. Considering the scope and significance of ice-cover changes on northern hydro-ecology, a recommendation is made to place more emphasis on long-term and spatially diverse monitoring of freshwater ice.

Key words | climate change, floods, hydro-ecology, lake ice, low flows, river ice

Terry D. Prowse (corresponding author)
Kirsten Brown
Water and Climate Impacts Research Centre,
Environment Canada/Department of Geography,
University of Victoria,
PO Box 3060 STN CSC,
Victoria, British Columbia,
Canada V8W 3R4
Tel.: +1 250 363 3067
Fax: +1 250 363 3586
E-mail: *Terry.Prowse@ec.gc.ca*

INTRODUCTION

Ice cover is an important component of northern freshwater ecosystems and influences numerous physical, chemical and biological processes operating in lentic and lotic systems (Walsh *et al.* 2005). Lake ice directly affects many limnological properties and processes including, for example: solar radiation inputs and their spectral signature for photobiological and photochemical processes, ultraviolet radiation, atmosphere–water body gas exchanges, heat budgets of the water column, stratification and under-ice mixing, bio-geochemical dynamics and the entrainment of terrestrial inputs, including contaminants (e.g. see the review by Vincent *et al.* (2008*b*)). Similarly, river ice exerts a broad range of controls on lotic systems including the productivity and diversity of instream and riparian habitat, carbon inputs, dissolved oxygen levels, sediment transport and river morphology, and hydrologic extremes, such as low flows and floods (Prowse 2001*a*,*b*; Prowse & Culp 2003). Within the Arctic, lake and river ice also permit a suite of private and public roads to link northern communities, thereby providing an inexpensive way to resupply remote resource industries and ready access for supporting traditional and subsistence lifestyles, which depend on these lentic and lotic ecosystems (Nuttall *et al.* 2005; Furgal & Prowse 2008; Prowse *et al.* 2009*a*).

The duration of Arctic lake and river ice is determined by the dates of autumn freeze-up and spring break-up, unlike in more southerly latitudes where winter can be characterized by a number of freeze-up and break-up events, not necessarily corresponding to single events in the autumn and spring. In general, rivers experience much

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more dynamic events than those on lakes given that the formation, growth and ablation of lake ice primarily occurs *in situ* while that on rivers is controlled by the hydraulic effects of flowing water. Overall, however, the timing of such events on both systems is strongly controlled by climate (e.g. Walsh *et al.* 1998; Prowse & Beltaos 2002), and numerous attempts over the past half-century have been made to make linkages between lake/river ice phenology and climatic variables, particularly air temperature. However, because of the more complex factors controlling river-ice processes, river ice has rarely been used as an environmental indicator of climate change. Instead, most attention has been focused on lake ice which has a higher sensitivity to a single meteorological variable and a much lower signal/noise ratio (e.g. Barry 1984). The potential effects of climate on lotic systems due to changes in river ice, however, are no less important than those projected to result in lentic systems due to changes in lake ice.

Over approximately the last two decades, climate-induced changes in lake and river ice have been considered by a number of international scientific assessments including the Intergovernmental Panel on Climate Change (IPCC; e.g. Fitzharris *et al.* 1995; Anisimov *et al.* 2001, 2007) and the Arctic Climate Impact Assessment (ACIA; e.g. Walsh *et al.* 2005; Wrona *et al.* 2005). The foci of the various chapters in these assessments has been both on lake and river ice phenology as an indicator of climate change, and how such change might be affecting important aquatic ecosystems. Unfortunately, however, either because of space limitations or differing foci among the chapters, the trend and impact information has never been presented as an integrated product. The upcoming fifth assessment by the IPCC (2013), and two Arctic Council sponsored reports: (a) the Arctic Monitoring and Assessment Program report–Snow Water Ice and Permafrost in the Arctic (2011) and (b) Conservation of Arctic Flora and Fauna report on Arctic Biodiversity (2012), will again be assessing changes related to these two important cryospheric components. In consideration of the above, this paper has a dual objective: (i) to provide an update about historical trends in lake and river ice, including information derived from paleo-records and (ii) to review the full range of hydro-ecological impacts that have resulted, or could result, from changes in freshwater ice.

STATUS AND TRENDS

Records of lake and river ice duration are available for the Arctic from a variety of disparate sources covering various time periods. In terms of the most recent period of record, these include remote sensing and the hydrometric and direct ice-observing programs conducted by the various circumpolar countries, although some differing physical definitions are employed that can make intercomparisons difficult (e.g. Prowse *et al.* 2007*a*). For the longer term, it has been possible to extract information from related historical archives in which lake and river ice cover have been observed anecdotally for religious or cultural reasons (e.g. Magnuson *et al.* 2000; Sagarin & Micheli 2001). The longest-term records have been derived, only in the case of lake ice, from proxy data obtained from sediment cores as part of broader assessments of changes in climate (e.g. Smol *et al.* 2005).

Changes in the taxa buried in lake and pond sediments (i.e. siliceous algal and chitinous invertebrate remains) have been used by many researchers to identify warming trends and the historical presence/absence of ice cover on northern lakes (e.g. Douglas *et al.* 1994; Korhola *et al.* 2002; Sorvari *et al.* 2002; Michelutti *et al.* 2003; Rühland *et al.* 2003; Smol *et al.* 2005). The strength of such inferences is based on the knowledge that changes in ice-cover duration and, hence, longer growing seasons increase primary production and produce taxonomic shifts in algae and invertebrates (e.g. Rouse *et al.* 1997; Douglas & Smol 1999; Keatley *et al.* 2008). In general, such evidence points towards warming temperatures and shorter ice durations since the end of the Little Ice Age around 1850, with greater changes observed in northernmost areas when compared to more temperate locations (Smol *et al.* 2005). Notably, however, not all paleoecology research of northern areas indicates warming conditions. Diatom assemblages from northern Quebec and Labrador, an area which has not experienced as profound a warming as elsewhere in the north, do not show noticeable species changes (Laing *et al.* 2002; Ponader *et al.* 2002; Paterson *et al.* 2003), reinforcing the validity of this paleo-proxy approach. Although the temporal resolution of most paleo-based interpretations of warming and ice-cover trends is fairly coarse and can only indicate very long-term trends, some current research is focused on being able to quantify shorter-term trends (A. Korhola, personal communication, 2010).

Higher temporal resolution trends in Arctic lake and river ice cover can be derived from ground-based observations and remote sensing. Unfortunately, the former is constrained by the spatial coverage of observation sites, the number of which has also been declining over the past two decades in the circumpolar Arctic (e.g. Shiklomanov *et al.* 2002), and the latter by the relatively short period of observational records. Moreover, many of the trend analyses of such records have been carried out as part of broader regional studies, typically conducted at the continental scale and not specifically focused on the Arctic. Although not exhaustive of all work on the subject, the following discusses key temporal trends contained in such reports, focusing on ones that are particularly germane to high-latitude conditions and/or place the northern trend results in a broader regional context.

Covering approximately the same past 1.5 centuries noted by paleo-limnological studies to have likely experienced reduced ice-cover duration, Magnuson *et al.* (2000) found that lake and river freeze-up dates in the northern hemisphere have become later at an average rate of 5.8 d/c (days per century) and break-up dates have become earlier at a rate of 6.5 d/c. Overall, this translates into an average reduction in ice-cover duration of almost two weeks/c. They further observed reductions in cover duration from a small number of records that began as early as the 16th century, although rates of change increased after approximately 1850. Only a few of the sites employed by Magnuson *et al.* (2000) were north of even 60°N and, although these tended to show similar directions of change, strong decade-scale variations make the trends highly sensitive to selected beginning and end dates (Walsh *et al.* 2005). Moreover, most of the sites employed by Magnuson *et al.* (2000) are spatially diverse and hence provide little insight into potential regional trends, especially within the Arctic. To obtain such, it is necessary to evaluate more regional–continental studies that have been undertaken, albeit for shorter periods.

In the case of river ice, some of the most comprehensive regional assessments of trends in freeze-up and break-up dates that include significant areas of the Arctic and subarctic were conducted by Ginzburg *et al.* (1992) and Soldatova (1993) for the former Soviet Union (FSU) using data from ~1893–1985. The most significant regional trend indicated the occurrence of later river-ice freeze-up dates in the European part of the FSU and western Siberia, which also experienced an average advance of break-up by approximately 7–10 d/c. Hence, there was an overall regional reduction in ice duration of up to one month. In contrast, on the opposite side of the FSU (central and western Siberia), there was a weaker but still significant trend towards earlier freeze-up dates and, for some rivers, even later break-ups, thus producing an increase in ice-season duration. Interestingly, a shorter period record analysis (1917–1994; record lengths 54–71 yr) by Smith (2000) of major Arctic and subarctic Russian rivers found trends opposite to those of Ginzburg *et al.* (1992) and Soldatova (1993). Specifically, earlier rather than later freeze-ups were noted for rivers west of the Yenisei, and later freeze-ups in eastern Siberia. Although Smith (2000) did not observe earlier break-up dates, trends towards earlier melt that precedes break-up were identified. The degree to which differences in break-up definition might be responsible for the reported differences in trends amongst these studies is unknown.

Although there appear to be no comparable analyses of lake ice across Russia/FSU, considerable information about ice duration trends exists for Scandinavia. Some of the longest-term records have been reported by Korhonen (2006), who showed significant trends towards earlier break-up at a rate of 6–9 d/c since the early 19th century. Similarly, freeze-up showed delays of 5–8 d/c and, although few of these trends were statistically significant, the overall average reduction of about 2 weeks/c is comparable to that reported in the broader study by Magnuson *et al.* (2000) discussed earlier. Moreover, the trends in lake break-up dates are comparable in magnitude to the long term records for rivers in European and western FSU by Ginzburg *et al.* (1992) and Soldatova (1993). Numerous other studies of lake and river ice have been conducted in the high latitudes of Scandinavia and Russia, and although they have varying lengths of record, the strongest signal is for earlier break-ups and, usually, later freeze-ups, resulting in a reduction in total ice-cover duration (e.g. Zachrisson 1989; Kuussisto & Elo 2000; Vuglinsky 2006).

In the case of North America, numerous trend analyses have been conducted but very few with long-term records, largely because of the later initiation of observing networks (e.g. see reviews by Walsh *et al.* (2005), Prowse *et al.* (2007*a*) and Beltaos & Prowse (2009)). For lake ice, one of the most regionally comprehensive high-latitude assessments was conducted by Duguay *et al.* (2006) of Canadian lakes over the last half-century at four different multi-decade intervals. Concurring with results for Eurasia, they noted trends toward earlier break-ups for most lakes during the intervals that included the most recent period of pronounced warming in the 1990s. Few significant trends were observed for freeze-up dates and a lower degree of spatial coherence when compared with break-up dates. To some degree, such large spatial variability in freeze-up trends are contrary to those of Zhang *et al.* (2001) who reported widespread trends toward earlier freeze-up over comparable periods. Moreover, while Zhang *et al.* (2001) also noted earlier break-up across Canada, there were exceptions in areas of eastern Canada that have been noted to experience cooler conditions and related responses were observed in a number of other cryospheric components (e.g. see the review by Duguay *et al.* (2006)). In contrast, trends towards earlier break-ups are most pronounced in north-western Canada and North America (Alaska) as supported by the results of a number of researchers (e.g. Jasek 1998; Sagarin & Micheli 2001; Lacroix *et al.* 2005; White *et al.* 2007; de Rham *et al.* 2008). Overall, the combined changes in freeze-up and break-up dates would favour a reduction in ice-cover duration because of the typically stronger trends to earlier break-up, although the exact magnitude of the reduction is unclear because of the more variable response of freeze-up dates.

Remote sensing offers one of the most reliable methods of observing and quantifying trends in ice-cover absence/presence, especially when available on a daily basis. Based on AVHRR imagery, for example, Latifovic & Pouliot (2007) extended existing ground-based records for 36 Canadian lakes for the 1950s to 2004, and developed records for 6 high-latitude lakes from 1985–2004 based solely on remote sensing records. Although some of the sites showed statistically significant freeze-up trends, the break-up observations were more robust. The majority of the sites showed both earlier break-up and delayed freeze-up dates for the entire period, averaging 0.18 and 0.12 d/yr, respectively, and thus equating to an average reduction in ice duration of 0.30 d/yr. These rates increased to an average 0.23, 0.16 and hence 0.39 d/yr, respectively, for a more recent 1970–2004 period. Notably, all six of the far northern lakes (primarily on the Canadian Archipelago) exhibited trends to earlier break-ups and later freeze-ups, averaging 0.99 and 0.76 d/yr. This translates into an ice-cover reduction rate of 1.75 d/yr, or approximately 4.5 times that found for the more southerly portions of Canada for the most rapid depletion period of 1970–2004. The degree to which this reflects the effects of more recent, or higher-latitude, warming is unclear.

In many of the above noted trend analyses, there have been various attempts to link changes in the timing of freeze-up and break-up with climatic variables. Although ice events result from a complex set of hydro-meteorological variables, particularly in the case of river ice (e.g. Prowse *et al.* 2007*b*), the primary focus has been on simple air temperature. Specifically, air temperatures 1–3 months preceding the events have been most strongly correlated with their timing (e.g. Magnuson *et al.* 2000; Walsh *et al.* 2005; Duguay *et al.* 2006; Korhonen 2006), although such relationships can exhibit spatial nonlinearities associated with latitude (e.g. Weyhenmeyer *et al.* 2004). Overall, temporal trends in such events are most likely related to the large-scale warming that has affected northern regions, particularly in the case of spring warming (e.g. Serreze & Francis 2006) and the occurrence of break-up. Exemplary of this relationship, Bonsal & Prowse (2003) showed strong correlations between the timing of freeze-up and break-up events, and that of spring and autumn 0° isotherm dates over Canada for various hydro-cryospheric processes in the last century.

CONCERNS FOR THE FUTURE

Given the strong association to climate of lake and river ice freeze-up and break-up timing, as well as winter duration, significant concern has been raised about future changes that might occur in ice-covered systems (Walsh *et al.* 2005; Wrona *et al.* 2005; Anisimov *et al.* 2007). It is generally accepted that, as the climate warms, earlier break-up dates will be seen in northern areas and longer open-water conditions will prevail (Bates *et al.* 2008). Such changes will affect sensitive northern ecosystems as well as human activities. For instance, a reduction or complete loss of the ice-based winter road network, which links northern communities and provides access to remote resource-based industries, will require either the expansion of land-based roads or an increased reliance on air transportation, both much more costly options (Prowse *et al.* 2009*a*). Similarly, it will directly affect traditional and subsistence lifestyles of northern peoples that have relied on lake and river ice covers, such as in the case of fisheries (Nuttall *et al.* 2005; Reist *et al.* 2006).

In addition to simply affecting access to fisheries, ice-induced changes in primary production are expected to affect all trophic levels, the effect on Arctic fisheries being one example. Increased temperature and light availability, from reduced ice duration or changes in composition that affect ice reflectance and absorption, will favour productivity, especially in the oligotrophic High Arctic ponds that are currently frozen for a majority of the year (e.g. Wrona *et al.* 2005; Prowse *et al.* 2006; Vincent *et al.* 2008*a*). Other related changes may, however, produce negative effects. For example, the increased abundance of food available for fish in river systems, and the increased habitat availability with less ice (e.g. lack of freezing to the bed), may cause otherwise anadromous species to remain in rivers year round. Feeding at sea has been linked to larger sizes in fish and larger populations, thus the increased productivity may ultimately lead to decreased fish yields (Reist *et al.* 2006).

The enhanced UV radiation that will also reach aquatic ecosystems as they become clear of highly reflective and attenuating snow and ice may also cause pigmentation changes in both plankton and fish and may render some food sources inedible or less nutritious, and possibly affect their immune systems (Wrona *et al.* 2005). For Arctic lakes that have been perennially ice- and snow-covered, orders-of-magnitude increases in ultraviolet exposure are projected to occur–increases greater than those due to moderate stratospheric ozone depletion (Vincent *et al.* 2007, 2008*a*).

Decreases in ice coverage and warmer summer temperatures will generally increase lake and river temperatures, causing changes in lake mixing regimes and limnological gradients, particularly for lakes that had been ice-covered for multiple years (A Vincent *et al.* 2008). Ice-related changes in the normally stratified conditions that prevail during spring snowmelt, which is typically enriched in various solutes, will significantly modify the biogeochemical dynamics of high-latitude lakes (Vincent *et al.* 2008*b*). This has special importance in the case of contaminants carried in terrestrial runoff, which may begin to mix within the water column as the lakes lose their ice covers and spring water-density stratification (Macdonald *et al.* 2003; Wrona *et al.* 2006).

As ice is lost, some previously unstratified lakes may begin to experience stratified seasons. A longer ice-free season will increase the length of stratification and generally increase the depth of mixing, which may lower oxygen concentrations in the hypolimnion and increase stress on cold-water organisms (Rouse *et al.* 1997). Rapid stratification may lower dissolved oxygen concentrations at depth and a deeper thermocline will reduce the available habitat for cold-water organisms, forcing some fish to seek refuge in deeper areas (Reist *et al.* 2006). Planktonic species, on the other hand, will benefit from the increased light availability and warm epilimnion temperatures associated with lake stratification (Prowse *et al.* 2006). One of the more obvious effects of warming on fish populations is the fact that certain species are very close to their tolerance limits. Some fish living in sub-Arctic environments may move northwards, resulting in competition for native species while for other fish the temperature stresses may prove fatal (Reist *et al.* 2006).

Changes in the duration of river ice is also a reason for concern, particularly as it relates to the dynamics of hydrologic events, such as spring break-up floods. These events are of special importance to the health of riparian ecosystems, especially the major Arctic river deltas and their associated vast array of lakes (Anisimov *et al.* 2007). Reduced ice-cover duration will be accompanied by thinner ice covers; ice thickness being one of the major physical controls on the frequency and severity of ice-jam flooding (e.g. Beltaos *et al.* 2006; Beltaos & Prowse 2009). Particularly if accompanied by other climate-induced changes such as sea-level rise or reduced snowmelt runoff, reduced ice cover and subsequent decline in the frequency of ice-jam flooding is therefore likely to seriously impair the aquatic function of these critical Arctic ecosystems (e.g. Prowse *et al.* 2002; Lesack & Marsh 2007). Moreover, such changes will also affect the traditional practices of the indigenous peoples that rely on such delta ecosystems for subsistence fisheries or harvesting of aquatic mammals (Reist *et al.* 2006; Prowse *et al.* 2009*b*).

The duration and event timing of river and lake ice are proving to be effective indicators of climate change in northern latitudes. Given the broad and serious implications of ice-cover changes on Arctic aquatic systems, it would seem prudent to focus increased efforts on such a critical bio-indicator.

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