Historical trends in river-ice break-up: a review*

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Abstract Over most northern regions, break-up is primarily a spring event. Historical evidence, however, has shown that the timing of river-ice break-up has been shifting in many areas of the Northern Hemisphere and these shifts were associated with observed air temperatures during the break-up period. This paper reviews past trends in break-up from the Eurasian and North American circumpolar regions and synthesizes them into a regional and temporal context. It also evaluates various hydro-climatic explanations for these trends including associations with winter/spring air temperature variations and relationships to large-scale circulation patterns. Even more dramatic changes to break-up timing and magnitude are forecast to occur as the result of climate change. Insights toward future break-up conditions are discussed for two broad-scale regions: the North, a region forecast to experience the most pronounced warming, and the southern limit of the cold regions, a zone of particular cryospheric sensitivity to warming.

Keywords Air temperature trends; climate change; cryosphere; Northern Hemisphere; river ice; teleconnections

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Introduction

River ice plays a fundamental role in the biological, chemical and physical processes of freshwater in cold regions (e.g. Scrimgeour *et al.* 1994; Prowse 2001a,b; Prowse and Culp 2003). For example, it exerts significant control on the timing and magnitude of extreme hydrologic events, such as low flows (Prowse and Carter 2002) and floods (Beltaos and Prowse 2001). Many of these extremes are the result of in-channel ice effects as opposed to landscape runoff processes (Gerard 1990; Prowse 1994). Of particular importance is river-ice break-up, which is an important modifier of biological, chemical and physical processes (e.g. Prowse and Culp 2003), and capable of causing extensive and costly damage to the built environment (Beltaos 1995). Though break-up is primarily a spring event, it is occasionally triggered by mid-winter thaws that are common to more temperate regions of the Northern Hemisphere. Due to the mechanical strength of the ice, mid-winter break-ups can be especially destructive, causing serious damage to infrastructure and property and producing major ecological disturbances to riverine habitats (Cunjak *et al.* 1998; Beltaos *et al.* 2003).

Recent evidence has shown significant changes in break-up timing over several regions of the Northern Hemisphere. Furthermore, in response to the increasing recognition of the ecological and economic significance of river ice, scientific concern has been expressed regarding climate change impacts on future river-ice regimes (e.g. Anisimov *et al.* 2001). Knowledge of past changes in river-ice break-up, however, is rather limited compared to other cryospheric variables such as snowcover, glaciers and lake ice. Nonetheless, there have been a few investigations that examined past trends and variability in break-up over various regions of the Northern Hemisphere for available periods of record. Although fragmented in both time and space, these studies serve as important climate indicators with long-term

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records of ice-related variables acting as useful climate proxies. They also provide insight into future break-up changes given the prospect of climate change.

This paper reviews documented historical trends in river-ice break-up over circumpolar regions of the Northern Hemisphere and synthesizes them on a regional and temporal basis. Since many of these trends are closely linked to the corresponding climate, trends and variations in the associated winter and spring air temperatures and large-scale circulation patterns are also evaluated. Inferences into future break-up scenarios over high latitude and temperate regions of North America are then provided and recommendations are made regarding future research priorities.

Historical trends in river-ice break-up

While numerous time series analyses of freeze-up and break-up dates have been conducted for the Northern Hemisphere, long-period records are relatively scarce. Examination of the longest records of ice break-up (lakes and rivers) showed that the most dramatic changes have occurred over the last 150 years during which break-up advanced (i.e. became earlier) by an average 6 d/100 yr (Magnuson *et al.* 2000). It was also determined that interannual variability has increased since 1950. They further observed from the few available longer time series that a trend toward shorter ice cover durations began as early as the 16th century (only three sites had records beginning prior to 1800): however, the rates increased after approximately 1850. Unfortunately, due to data availability, most of the very long-term stations analyzed by Magnuson *et al.* (2000) were relatively widespread and gave little insight into regional patterns in these trends.

To obtain an appreciation of broad-scale geographic trends, it is necessary to analyze shorter-term records. A number of additional analyses have been conducted on time series of approximately 100 years, the most detailed regional evaluation existing for the Former Soviet Union (FSU; Soldatova 1993) in which near century-long data (~1893–1985) were analyzed for homogenous hydrologic regions. Although appreciable inter-decadal variability was found, significant long-term spatial patterns and temporal trends of river ice-cover dates were identified for the almost 100-year period. Specifically, break-up on major rivers in the European FSU (e.g. Upper Volga, Oka and Don) and western Siberia (Upper Ob and Irtysh) were found to have advanced by an average 7–10 d/100 yr, although some rivers in central and eastern Siberia (e.g. middle to lower Yenisey and Upper Lena) exhibited an opposing trend (i.e. later break-up dates).

A study of shorter-term records from nine major Russian Arctic/sub-Arctic rivers has been conducted by Smith (2000). Possibly because of the shorter record length (i.e. 54–71 yr) or differences resulting from site-specific versus regional foci, some different trends were found compared to those for the longer-term and broad regional studies of Soldatova (1993). In particular, several opposing temporal trends were found for river-ice freeze-up. In the case of break-up timing, trend analysis failed to identify any statistically significant shifts. However, a few significant advances were determined for a related observation regarding the "timing of melt onset". This was reasoned as a trend toward a longer period of pre-break-up melt which, according to break-up theory, favours "thermal" break-ups which are less-intense events that are less likely to produce floods and related disturbances (e.g. Gray and Prowse 1993). Similar analyses that focus directly on break-up characteristics beyond simple timing have not been conducted elsewhere.

In accordance with the results of Soldatova (1993) for the western rivers of the FSU, an advance in long-term (~100+ yr) break-up dates has been documented for rivers in northern Sweden/Finland (Tornelven and Tornio) and the eastern Baltic Sea/Scandinavian region (Daugava) (Zachrisson 1989; Kuusisto and Elo 2000). Williams (1970) also noted that break-up of the Saint John River in eastern Canada and the Neva River in the FSU was advanced by approximately an equivalent amount over the same 1870–1950 period. Even though the Saint John River is more representative of a temperate-maritime climate, Rannie (1983) has found similar results for the Red River, located in a colder continental portion of North America. The average duration of the Red River ice season has been shortened by approximately three weeks during the 20th century. This includes median dates of freeze-up occurring 12 days earlier and break-up 10 days later in the late 19th century compared to the end of the 20th century. Significantly earlier break-up over approximately the same period has also been observed for a few rivers in north-western North America. Studies of the Tanana River in Alaska (1917–2000; Sagarin and Micheli 2001) and the Yukon River in north-western Canada (1896–1998; Jasek 1999) indicated that the average date of break-up has advanced by approximately five days per century. As with the FSU, these trends in north-western North America also exhibited a number of inter-decadal cycles.

Within North America, the most extensive analysis has been conducted for Canada by Zhang *et al.* (2001). Unfortunately, this work had to rely on records less than 50 years long and of varying length. Despite this, a major spatial distinction was observed between western and eastern regions of the country, with the former showing trends towards earlier break-up. A similar distinction was not evident between northern and southern sites. The break-up signal at southern locations can be complicated due to the compounding effects of thinner ice covers and the potential for mid-winter break-ups (Prowse and Beltaos 2002).

As evidenced from the preceding review, the majority of river-ice break-up records over the Northern Hemisphere revealed trends toward earlier dates: however, distinct spatial and temporal variability was evident in many regions. The following addresses the spatial and temporal aspects of these trends as they relate to long-term changes in various climatic variables over the Northern Hemisphere.

Climatic relationships to break-up

A somewhat elusive goal in river-ice research has been an objective methodology for predicting ice break-up based on climatological data. The timing of river-ice break-up is governed by a diverse set of hydraulic and hydro-climatic variables, the state of some being dependent on conditions not just at break-up but also over the winter period and even at the initial freeze-up (Prowse and Beltaos 2002). Complex methods for examining ice break-up have been tested but require a knowledge of, for example, river stage, ice thickness and ice strength (see Prowse 1995). These methods require a suite of meteorological variables to quantify processes such as the various heat fluxes. Unfortunately, these variables often have limited availability, particularly in the higher-latitude regions of the Northern Hemisphere. Given this complexity, the most common approaches involve relating break-up to an air-temperature index. In the case of rivers, air temperatures are used to reflect the degree of ice decay (resisting force) and the magnitude of the spring snowmelt wave (driving force). However, because the values are empirical and site specific, they are often not spatially transferable. Despite these identified difficulties in the forecasting of river-ice break-up timing based only on air temperature, there has been significant recent interest in how temporal trends in such timing have responded, or will respond, to climate change – the common measure of which being air temperature. To this end, a number of researchers have attempted to define from long-term data the average rate of change between ice-break-up dates and pre-break-up air temperatures.

Air temperatures and break-up

The long-term and multiple site analysis by Magnuson *et al.* (2000) found that break-up (lake and river) had advanced over the last 150 years by an average 6.3 d/100 yr, which corresponded to approximately a 1.2°C/100 yr increase in air temperature. Over this period, however, the rate of warming has not been constant. Figure 1 shows reconstructed and instrumental annual air temperatures over the Northern Hemisphere for the last 1000 years (Mann *et al.* 1999). The series is characterized by a distinct temperature increase following the cessation of the Little Ice Age in the early 1800s. However, this increase consisted of a warming period from 1850 to the 1920s/30s, a slight cooling in the 1940s/50s, followed by a more marked trend to warmer temperatures since approximately 1950 that has been attributed in part to anthropogenic induced climate change (IPCC 2001). In reference to these trends, it is worth noting that Magnuson *et al.* (2000) determined the rate of change (from the longest term stations) was most pronounced since the 1850s and most records showed increased interannual variability following the 1950s. In addition, many of the 100+ yr break-up records displayed inter-decadal cycles that can reasonably be linked to similar variability in air temperature (even though these cycles were not explicitly evaluated by Magnuson *et al.* (2000)). Such decadal variability complicates the interpretation of regional trends from much less than 100 yr records, many of which have differing lengths and starting/ending periods. For example, it may explain why some of the trends identified in Smith's (2000) analysis of major Russian rivers (54–71 yr record lengths) are opposite to those found for the longer-term and broad regional studies of Soldatova (1993) for the same areas.

Although more climate-break-up investigations have focused on lake-ice (e.g. Palecki and Barry 1986; Robertson *et al.* 1992; Livingstone 1999), a number of river studies have also been conducted (e.g. Rannie 1983; Zachrisson 1989; Soldatova 1993). Most have pointed to the importance of mid- to late-spring temperatures as being most highly correlated with break-up timing, thereby suggesting that it is the pre-break-up melt and runoff period that is more important to the timing of break-up than the overall winter severity and maximum ice thickness. As summarized by Prowse and Beltaos (2002), although the data are relatively meagre, a first approximation of river-ice response to climate change is that a long-term mean increase of 2–3°C in spring air temperature has produced an approximate 10–15 day advance in break-up. This concurs with the typical 0.2°C/day rate of change in phenological data for numerous lakes and a few rivers around the Northern Hemisphere estimated by Magnuson *et al.* (2000).

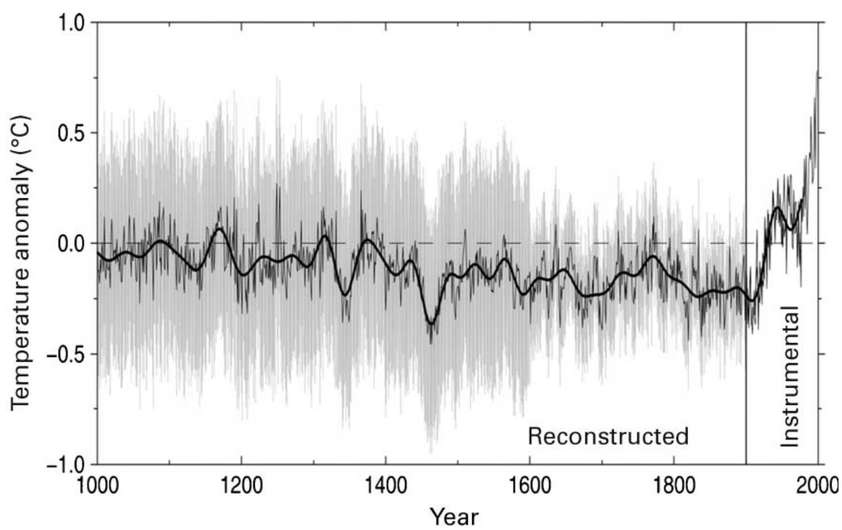

Figure 1 Northern Hemisphere annual air temperatures (reconstructed and instrumental) for the years 1000 to 1999 (after Mann *et al.* 1999). The smoothed line represents the 50-yr running mean and the 95% confidence range is shown in grey. Anomalies are relative to the 1961–90 mean

Trends in spring warming and break-up

Over mid to high latitudes of the Northern Hemisphere, significant temperature trends have been observed in recent decades, with the most pronounced changes occurring during winter and spring (e.g. Serreze *et al.* 2000). From 1966–95 for example, these trends consisted of pronounced warming over most of Eurasia and western North America, and cooling over eastern North America and Greenland (Figure 2). This same pattern in winter and spring temperature trends over Canada was also observed by Zhang *et al.* (2000) for the period 1950 to 1998. Although the periods of record differ, the spring trends in Figure 2 are generally consistent with the previously described large-scale trends in break-up over the Northern Hemisphere including the pronounced west to east gradient over North America. Recent analysis, however, has revealed a change to winter and spring warming trends in eastern North America and Greenland, particularly during the most recent 1991–2000 decade (e.g. Box 2002). This may be a forerunner of future warming forecasts for the entire circumpolar Arctic that will see the disappearance of west to east gradients in air temperature and related ice break-up trends over North America.

In another approach to assessing the effects of spring climate on break-up timing, Prowse *et al.* (2002) focused on changes in spring 0°C-isotherm dates as defined by Bonsal and Prowse (2003). They first established that there was a strong temporal relationship (albeit lagged) between the timing of 0°C conditions (smoothed interval) and that for: (a) the spring freshet pulse (that typically drives river-ice break-up) and (b) the dates of the first annotations for the respective season of "ice-cover effects" in hydrometric records. This was noted to concur with Allen's (1978) observation that spatial patterns of freshwater-ice break-up closely mirror the progression of 0°C air temperatures. Figure 3 displays linear trends in the dates of spring 0°C isotherms from 1950–98 as derived from 210 Canadian stations (Bonsal and Prowse 2003). Within southern Canada, the map shows significantly earlier dates over much of the southwest (10–20 days) but a gradual weakening effect towards the east. This west-to-east pattern corresponds to that for river-ice break-up dates summarized in the first section (e.g. Zhang *et al.* 2001) and to the spring air temperature trends in Figure 2. As noted by Prowse *et al.* (2002) for the northern latitudes, a similar west-to-east gradient in river-ice break-up exists for selected rivers spanning the Canadian north.

Along climatic margins of the cold regions, break-up can also occur during the main winter season that has also been associated with significant warming over much of the

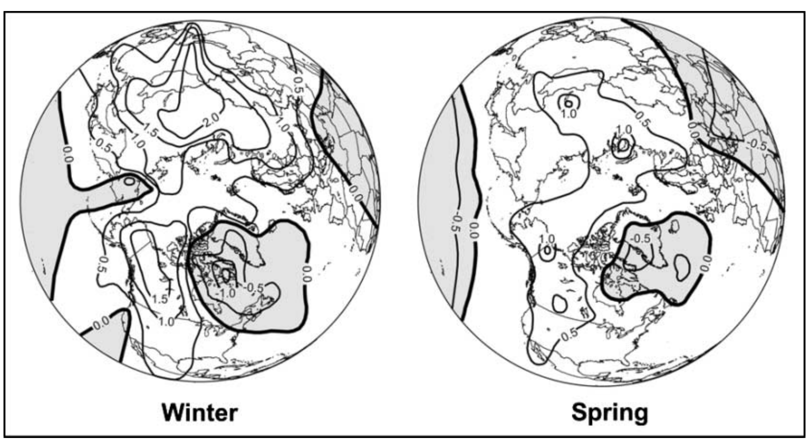

Figure 2 Northern Hemisphere winter (December, January, February) and spring (March, April, May) surface air temperature trends for the period 1966–95 (after Serreze *et al.* 2000). Trends are in °C per decade and the contour interval is 0.5°C. Regions with negative temperature trends are shaded

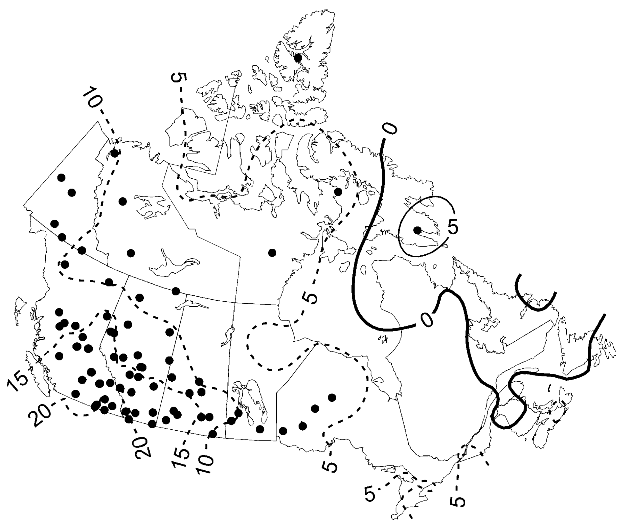

Figure 3 Trends in spring 0°C-isotherm dates over Canada from 1950–98 (from Bonsal and Prowse 2003). Units are in d/49 yr and the contour interval is 5 d. Negative values (i.e. earlier dates) are dashed. Filled circles denote stations with significant trends at the 5% level

Northern Hemisphere (Figure 2). Recent studies have pointed to the difficulty in predicting mid-winter break-ups and their enhanced ability to impact both physical and ecological systems (e.g. Cunjak *et al.* 1998; Beltaos 2002). Doyle (1997, personal communication, cited by Prowse and Beltaos 2002) examined the ice-in and ice-out dates (first and last dates on which ice has a significant effect on the flow) for south-western Canada (intermontane British Columbia), where the winter ice season is relatively short and often intermittent. However, no significant trend over the period of record (35–70 years) was found. It should be noted that the change in mean winter temperature for that part of Canada from 1895–1992 was reported as +0.8°C (Environment Canada 1995), which is much smaller than that associated with the shorter 1966–95 period shown in Figure 2. This may account for the lack of identified trends in Doyle's analysis. Although not specifically focused on break-up timing, Brimley and Freeman (1997) considered the duration of the ice season in southeastern Canada (Atlantic provinces), as revealed by hydrometric gauge records over approximately the past 45 years. Their results highlight the spatial variability of a maritime climate and are reasonably consistent with local winter temperature trends over the same period. The largest rates of change were found in Cape Breton and Newfoundland (up to +3 d/yr), in response to modest decreases in winter temperatures. A possible explanation for such a pronounced increase in ice-cover duration is that small amounts of winter cooling would produce a shift from an ice regime dominated by brief and often intermittent ice-cover formation to one that is more stable and continuous.

To determine the regional nature of mid-winter events and their historical trends, Prowse *et al.* (2002) analyzed hydro-climatic conditions along the "temperate region" of North America. This region, as shown in Figure 4, was defined on the basis of ice-cover conditions (i.e. cold enough to produce a significantly thick permanent ice cover (~30 cm) but warm enough to experience warming episodes that could induce mid-winter break-up). The southern edge was estimated to correspond with the 400 freezing degree-day (FDD) isoline derived from winter (Dec–Feb) mean daily temperatures (1961–90). The northern boundary was determined through examination of numerous hydrometric and climate station records to ensure that a sufficient number of mid-winter runoff and warming events were observed

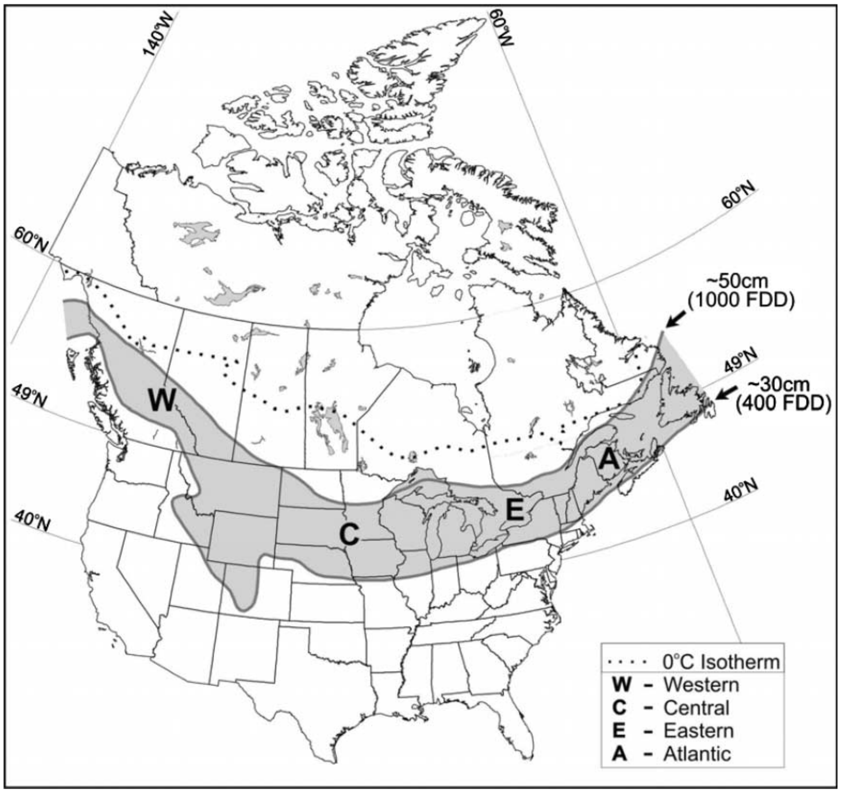

Figure 4 Map showing the temperate region (shaded area), the mean annual 0°C-isotherm (dashed line) and the four sub-regions used in Prowse *et al.* (2002)

during the instrumental period. From this analysis, the northern boundary corresponded to an ice thickness of ~50 cm. The analysis first involved the linking of mid-winter warming trends with runoff and associated ice break-up events (Jan–Feb) and then examining their occurrence and frequency across four sub-regions of the temperate zone (i.e. Western, Central, Eastern and Atlantic; see Figure 4). As shown in Figure 5, there was little evidence of any trend along the southern boundary, which was characterized by considerable decadal-scale variability. Notably, however, an increasing trend in the number of events through the 20th century at the northern boundary was observed. This is particularly evident for the western region that has also experienced the most pronounced increase in winter air temperatures over the last century (Zhang *et al.* 2000). Furthermore, while the Atlantic and Central sub-regions were devoid of mid-winter events prior to 1950, these areas have subsequently experienced an increasing frequency of events in recent decades. This appears to contradict winter temperature trends that have not risen significantly, or even cooled in some areas of the Atlantic region (Figure 2). Reasons for these inconsistencies require further investigation but may reflect differences between longer (three-month) seasonal temperature trends and relatively shorter (seven-day) event-based warming trends in this region.

Large-scale circulation/teleconnections

The majority of the aforementioned trends and variations in Northern Hemisphere temperatures have been related to large-scale atmospheric and oceanic oscillations or teleconnections. Perhaps the most studied is the El Niño/Southern Oscillation (ENSO) that

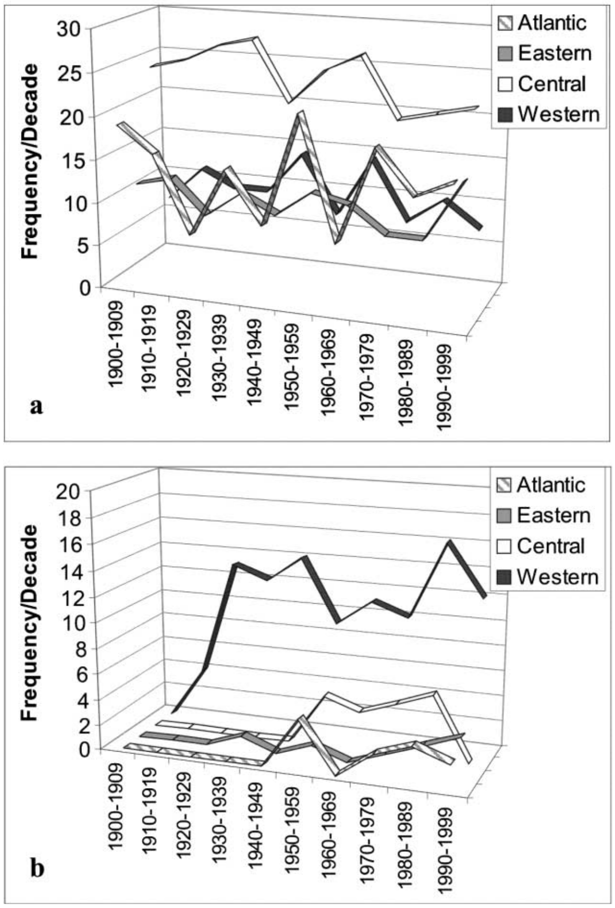

Figure 5 Frequency of mid-winter temperature events (per decade) for (a) southern and (b) northern boundary stations at the four regions in Figure 4 (from Prowse *et al.* 2002)

characterizes atmosphere–ocean interactions in the tropical Pacific. ENSO consists of two phases, namely El Niño and La Niña events. Other examples of Pacific-related teleconnections include the Pacific Decadal Oscillation (PDO), which measures variability in North Pacific sea-surface temperatures (Mantua *et al.* 1997), the Pacific North American (PNA) pattern that represents atmospheric oscillations over the North Pacific and North America (Wallace and Gutzler 1981) and the North Pacific (NP) index that measures the intensity of the Aleutian Low (Trenberth and Hurrell 1994). Regarding the Atlantic, the North Atlantic Oscillation (NAO), which describes differences in sea-level pressure (SLP) between the Icelandic Low and the Azores High, is the primary teleconnection pattern (e.g. Hurrell 1996). Recently, the Arctic Oscillation (AO) has been identified as the dominant mode of SLP variability over the Northern Hemisphere. It resembles the NAO, but its primary center of action covers more of the Arctic (Thompson and Wallace 1998).

These oscillations account for a substantial amount of the observed 20th century Northern Hemisphere temperature trends and variability, particularly during winter and spring (Hurrell 1996). For example, ENSO, the PNA and the PDO are closely linked to winter and early spring temperature variability over much of North America and, in particular, the west. This includes warmer temperatures associated with El Niño events, and positive phases of the PNA and PDO, which are all representative of a deepened

Aleutian Low (and vice versa) (e.g. Wallace *et al.* 1995; Bonsal *et al.* 2001). The most notable feature in the Pacific involved a shift toward a deeper Aleutian Low following 1976 that has been associated with the trend toward warmer winter and spring temperatures over western North America (e.g. Trenberth 1990). A positive NAO (deep Icelandic Low and strong Azores High) is associated with colder winter and spring temperatures over eastern North America and warmer conditions over western Europe and vice versa (Hurrell 1996). A trend toward more positive NAO values in recent decades is consistent with the winter and spring cooling observed over most of north-eastern North America. This, along with the Aleutian Low shift in 1976, helps explain the west to east gradient in both air temperature and associated break-up observed over Canada during the last 50 years (e.g. Zhang *et al.* 2001; Prowse *et al.* 2002). Thompson and Wallace (1998) determined that the significant trend toward warmer winter and spring temperatures over western North America and most of northern Eurasia during the last 20–30 years has coincided with a shift toward highly positive values of the AO. Regional investigations have found that the AO accounted for more than half of the spring surface air temperature trends over Alaska and Eurasia (Rigor *et al.* 2000), and explained 25–30% of the winter (Jan–Mar) and 15–20% of the spring (Apr–May) surface temperature variations over northern Russia (Kryjov 2002). Twentieth century trends and variability in spring 0°C-isotherm dates over Canada were also influenced by large-scale oscillations in the Pacific and Atlantic. In particular, the NP index significantly impacted variations over western regions of the country, while the NAO was significantly related to spring isotherms in the east (Bonsal and Prowse 2003). Shabbar and Bonsal (2004) determined that for the period 1950–98, the frequency and duration of winter warm spells over most of Canada were significantly increased in association with El Niño events as compared to La Niña events. This increase would directly impact the occurrence of mid-winter thaws and associated break-ups during the winter period.

Given the correspondence between large-scale oscillations and winter/spring temperatures, a few attempts have been made to relate teleconnection patterns to ice break-up over various regions of the Northern Hemisphere. The vast majority of these investigations, however, have focused on lake ice. Benson *et al.* (2000) found that, for the period 1969–88, lake-ice break-up dates over several regions of North America were significantly related to the PNA pattern. In particular, a shift to earlier break-ups in 1976 appeared to be influenced by the aforementioned shift toward a deepening of the Aleutian Low (positive PNA values) during the winter half of the year. This shift was also associated with the shortening of the ice season in western Ontario (Schindler *et al.* 1990) and Wisconsin (Anderson *et al.* 1996). Long series (~130 yr) of break-up dates for five lakes over the circumpolar Northern Hemisphere (Finland, Switzerland, Siberia and mid-western United States) were also shown to be significantly associated with large-scale circulation patterns (Livingstone 2000). Although the strength of the relationships varied throughout the period, the NAO was significantly related to break-up in the two Finnish lakes, and to a lesser extent with those in Switzerland, Russia and the central United States. Similar temporal variations in the strength of the relationship between NAO and other high-latitude cryospheric processes, such as Fram Strait sea-ice export, have also been documented (e.g. Schmith and Hansen 2003). The influence of ENSO and, in particular, El Nino events on 20th century variations in lake and river-ice cover over the Northern Hemisphere has been examined by Robertson *et al.* (2000). In terms of break-up, it was found that dates were significantly earlier throughout North America and slightly later (although not significant) over Finland and Russia in association with strong El Niño events. ENSO events and the mid-1970 s shift in North Pacific circulation have also influenced maximum ice covers on the Laurentian Great Lakes of North America (Assel and Rodionov 1998).

Future changes and research recommendations

In response to the increasing recognition of the economic and ecological significance of river ice, a growing need to forecast how it will react to climate change has been identified (e.g. Anisimov *et al.* 2001). Unfortunately, to date, very few studies have attempted to examine changes to ice-break-up dates resulting from future climate warming, and even then the majority have focused on the simpler case of lake ice. Prowse *et al.* (2002) made some first-order estimates for river-ice conditions at both northern and temperate latitudes of North America. Relying on the on average 0.2°C/d rate of change in phenological break-up dates estimated by Magnuson *et al.* (2000), they approximated that an increase of 3–7°C in spring air temperatures by the end of this century (as projected by several Global Climate Models (GCMs) (IPCC 2001)) would result in a 15–35 d advance in river-ice break-up over northern regions of Canada. Whether this temporal shift in break-up timing will produce more or less severe break-up events remains in doubt, largely because of the complicating role of precipitation which has the potential to control both the driving and resisting forces that affect break-up severity (see Prowse and Beltaos 2002). Given the importance of changes to freshwater ice regimes, it is recommended that future research should focus on more physically based modelling of climate change effects, taking into account such complicating factors as shifts in precipitation and runoff regimes.

Prowse *et al.* (2002) also suggested that there would be a significant northward shift of the temperate climate zone that currently experiences mid-winter break-up events (Figure 6). These shifts are based on a 2°C and 6°C warming in winter temperatures over the temperate

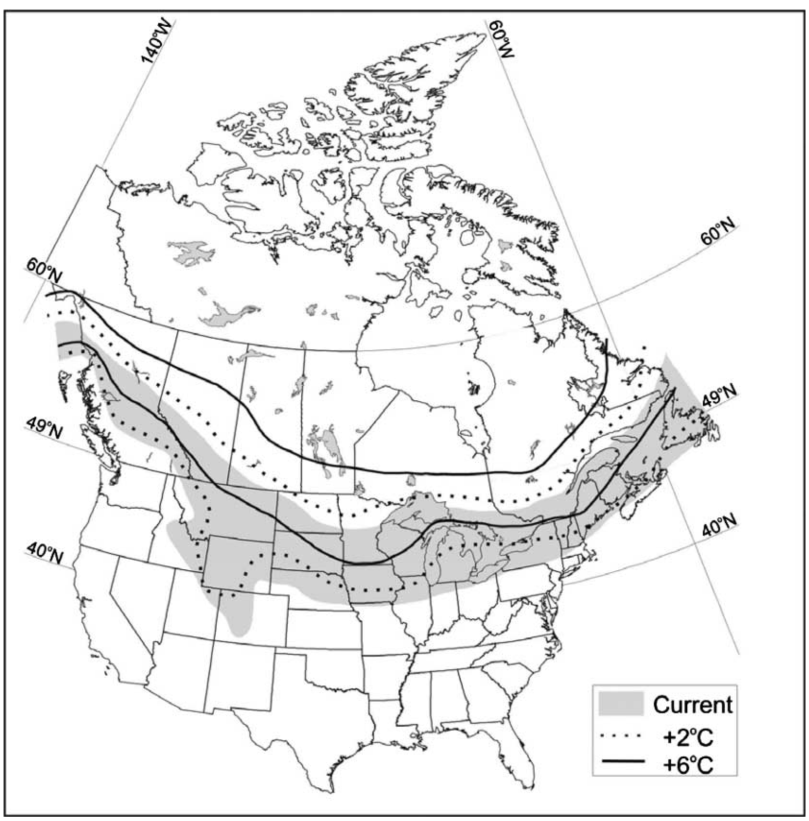

Figure 6 Projected shift in the temperate region of North America based on mean winter temperature increases of 2 and 6°C (from Prowse *et al.* 2002)

region as estimated from several GCM projections (IPCC 2001). The dramatic northward shift to these boundaries is significant since rivers that currently do not experience mid-winter warming events will be susceptible to river-ice break-ups which could produce dramatic impacts on the hydro-ecology of these river systems. Given the current difficulties in predicting the timing of such events, the disruption that they can pose to water resource uses, such as hydroelectric production, and their potential to produce major flood impacts and ecological disturbance, they may be one of the least recognized major threats that are likely to result from climate change. Additional research needs to focus on more precisely defining the new river regimes that will be affected by significant mid-winter warming events, the timing of the northward migration of the temperate zone and the range of potential economic and ecological impacts and related adaptation measures. To help accomplish these research needs, reliable projections of future climate at the appropriate spatial scales are required, including changes to major large-scale circulation patterns that have been shown to influence climate over the Northern Hemisphere.

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