ABSTRACT
River-ice breakup at higher latitudes is primarily a late spring event but historical records suggest that it is becoming earlier in many regions. Analysis of the timing of spring 0 °C-air temperatures and ice breakup in a defined Northern Region of Canada over the last 50 years indicates a similar trend, the greatest change occurring in western areas. A first approximation regarding the effects of future climate change indicates that by the end of this century, breakup in northern Canada will be about two weeks to one month earlier. Within a defined Temperate Region that marks the edge of the cold regions, mid-winter warming events have become more common at its northern boundary over the last 100 years, but little difference is observed at the southern limit. A projected 2 °C to 6 °C warming under future climate will produce a major northward retreat of this temperate zone and a new set of river systems will be exposed to the effects of mid-winter warming and associated ice breakup.

INTRODUCTION
River-ice breakup is an integral component of cold-regions hydrology, an important modifier of related biological, chemical and physical processes (e.g., Prowse and Culp, 2003), and capable of causing extensive and costly damage to the built environment (Belch, 1995). Given its broad ecological and economic significance, scientific concern has been expressed regarding climate change impacts on future river-ice regimes (e.g., IPCC, 2001). Specifically, interest has focused on the high latitudes where warming is forecast to be most pronounced, and at the margins of the cold regions where cryospheric components are most sensitive to increased temperatures. Unfortunately, knowledge of past changes in river-ice breakup is rather limited compared to other cryospheric variables such as snowcover, glaciers and lake ice. Some long-term and regional assessments, however, have been made. Analysis of the longest records of ice breakup (lakes and rivers) showed that the most dramatic changes have occurred over the last 150 years during which breakup advanced (i.e., became earlier) by an average 6 d/100yr (Magnuson et al., 2000). This corresponds to a ~1.2 °C/100yr increase in air temperature. Unfortunately, there were few rivers in the
data set, and those included were widely spaced thus providing no indication of regional effects. A number of additional analyses have been conducted on records of approximately 100 years, the most detailed regional evaluation existing for the Former Soviet Union (FSU; Soldatova, 1993). Breakup on major rivers in the European FSU and western Siberia were found to have advanced by an average 7–10 d/100yr, although some rivers in central and eastern Siberia exhibited an opposing trend (later breakup). Similar to the results for the western FSU, an advance in long-term (~100+yr) breakup dates has been recorded on rivers in Scandinavia and Latvia (Zachrisson, 1989; Kuusisto and Elo, 2000). Significantly earlier breakup over approximately the same period has also been observed for a few rivers in North America (Sagarin and Micheli, 2001; Jasek, 1999; Rannie, 1983).

Notably, many of the 100+yr records often displayed inter-decadal cycles. This variability complicates the interpretation of regional long-term trends from <<100yr records, mainly because of the problems of differing lengths and starting/ending periods. These may explain why some of the trends identified in Smith’s (2000) analysis of major Russian rivers (54 to 71 yr record lengths) are opposite to those found for the longer-term and broad regional studies of Soldatova (1993). Within North America, the most extensive regional 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 sites with the former showing trends towards earlier breakup. A similar distinction was not evident between northern and southern sites. The breakup signal at southern locations can be quite complicated due to the compounding effects of thinner ice covers and the potential for mid-winter breakups (Prowse and Beltaos, 2002). Although a limited number of case studies of such events have been conducted (e.g., Beltaos, 2002; Brimley and Freeman, 1997; Cunjak et al., 1998), none have examined their characteristics on a continental-scale basis.

STUDY APPROACH AND DATA SETS
Analyzing historical time series of river-ice breakup in Canada is difficult because of the scarcity of long-term stations and the lack of suitably archived data. Even the work of Zhang et al. (2001) was not based on actual breakup records but on annotations (‘B’ dates) in discharge records that refer to the end of “ice-affected flow conditions” as opposed to breakup initiation. In effect, there is no cataloguing of breakup timing and it can only be derived from the original water-level recordings and associated hydrometric field notes. The best available data are summarized in site-specific case studies of ice jams but their scarcity precludes regional analyses. With extensive resources, it would be possible to extract sufficient data from the original hydrometric records to permit a regional examination of breakup timing but even then, the records would be relatively short and sparse in some areas, particularly at higher latitudes. Another alternative is to identify a climatic variable with long-term records and extensive spatial coverage that is linked to breakup. One logical choice is air temperature; particularly since a number of researchers have already identified that the timing of spring breakup is associated with pre-breakup air temperatures (e.g., Soldatova, 1993; Zachrisson, 1989; Rannie, 1983). More specifically, the 0 °C isotherm has been linked to the seasonal timing of freshwater-ice breakup (e.g., Allen, 1978). Above freezing air temperatures have also been related to the occurrence of mid-winter breakups; events that can be more catastrophic than those in the spring (e.g., Beltaos, 2002; Prowse and Beltaos, 2002).
Employing such a widely-measured climatic variable with lengthy records also more readily permits explanation of identified temporal and regional trends from an atmospheric circulation perspective. Moreover, it allows the forecasting of breakup conditions for future climate-change scenarios using available temperature data from GCMs (Global Climate Models).

In consideration of the above, this study presents trends in the occurrence of spring 0 °C temperatures across Canada. More specifically, it focuses on a Northern Region (i.e., north of the mean annual 0 °C isotherm; Figure 1) where climatic warming is projected to be most pronounced (IPCC, 2001), and compares observed temperature trends with those for breakup from longer-term hydrometric stations in contrasting regions. Also examined are spatial and temporal characteristics of mid-winter warming (>0 °C) events in a Temperate Region where climate change has the potential to dramatically alter winter breakup. The shaded area in Figure 1 displays this region that is 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 breakup). Using a degree-day ice-growth model (Michel, 1971), the southern boundary 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 (Jan–Feb) runoff and warming events were observed during the instrumental period. From this analysis, the northern boundary was defined by a line corresponding to an ice thickness of ~50 cm (1000 FDD isoline; Figure 1). Note that characteristics of breakup observed in case studies within this zone were also found to be consistent with the above noted definition criteria.

Figure 1: Map showing the temperate region (shaded area), the mean annual 0 °C isotherm (dashed line) and the four sub-regions used in the temperate zone analyses.
Derivation of the temperature variables for the two regions relied on air temperature data from 210 Canadian (Vincent et al., 2002) and 660 U.S. stations (Easterling et al., 1999). The available temperature series were longer for the south (~1900–98), and shorter in the north (1950–98). Hydrometric data were extracted from standard Environment Canada and U.S. Geological Survey archives. Periods of hydrometric record vary among stations with southern areas generally having data from the early to mid 1900s to 1998, and northern locations from approximately the mid 1950s/early 60s to 1998.

RESULTS
Northern Region
Figure 2 depicts linear trends in the dates of spring 0 °C isotherms for the period 1950–98 as derived from the 210 Canadian stations. A trend toward significantly earlier dates exists over much of southwestern Canada (10 to 20 days) but weakens in an easterly direction. This west-to-east spatial pattern corresponds to that for river-ice breakup dates identified by Zhang et al. (2001). Focussing on the Northern Region, there is also a discernible west-to-east gradient. Significantly earlier dates occur over north-western Canada (10 to 15 days) while central areas are associated with smaller, generally insignificant earlier trends (5 to 10 days). Conversely, extreme north-eastern regions experience trends toward later springs. To determine if similar spatial patterns are evident in river-ice breakup indicators, relationships between the spring isotherm dates and readily available breakup related indices were also examined for several rivers in the Canadian north with long-term high-quality records (represented by the capital letters in Figure 2). Two hydrologic indices relevant to breakup conditions were examined. The first involves the previously described ‘B’ date and the second is the timing of the first major pulse in spring discharge that typically drives river-ice breakup in high-latitude nival regimes.

Figure 2: Trends in the dates of spring 0 °C isotherms over Canada for the period 1950–98. Units are in days/49 years and the contour interval is 5 days. Negative values (i.e. earlier dates) are dashed and the zero contour thickened. Stations with significant trends at the 5 % level are denoted by filled circles.
Although periods of record vary, time series comparing dates of spring 0 °C isotherms, first major spring pulses, and last ‘B’ dates for the four rivers show significant correlations among all variables. Figure 3 provides an example of these comparisons for region ‘A’ over north-western Canada. Quantitative comparisons are provided in the corresponding Table. The graph shows that spring 0 °C-isotherm dates occur somewhat earlier than pulse and last ‘B’s (over 20 days). This is likely attributable to the lagged response between the occurrence of 0 °C-temperatures and the large-scale melting of ice and snow. Pulse dates and last ‘B’s tend to occur near the same time. Significant correlations are observed between 0 °C-isotherm and pulse dates, and between the isotherms and last ‘B’s. All variables are also associated with significant trends toward earlier dates (of similar magnitude). In addition, extreme years (both early and late) coincide for all three variables. Correspondence between the breakup indices and spring isotherm dates were also found for case studies in regions B, C, and D (not shown), indicating similar spatial variability in river-ice breakup trends to those of isotherm dates in Figure 2.

Figure 3: Comparisons of spring 0 °C-isotherm dates from Mayo, Yukon with first major spring pulse dates and last ‘B’ dates for the Pelly River, Yukon for the period 1953–1998 (Site A on Figure 2). The corresponding table provides correlation coefficients and linear trends (days/46 years) associated with these time series. Values significant at the 5 % level are denoted by asterisks.

Regarding future climate, a visual examination of spring mean air temperature projections from several IPCC-recommended GCMs indicates an increase of between 3 °C to 7 °C over northern regions for the 30-year period centred on the 2080s. Based on the 0.2 °C/day rate of change in phenological breakup dates estimated by Magnuson et al. (2000), such an increase in spring temperature would approximate a 15 to 35 day advance in river-ice breakup. Although regional differences in future climate are likely to occur, this general advance in breakup could produce numerous related impacts on the hydro-ecology of river and related riparian systems in the Northern Region.

**Temperate Region**
Mid-winter (Jan–Feb) hydrologic and temperature warming events were examined at various locations along the northern and southern boundaries of the defined Temperate Region. Hydrologic events consisted of significant mid-winter pulses in flow that, as is the case for northern regions, can initiate river-ice breakup. Four sub-regions spanning...
the zone were analyzed including: Western, Central, Eastern and Atlantic (Figure 1). Although the full set of criteria used to define runoff and warming events was complex, mid-winter runoff events were essentially identified by a 50 %+ increase in flow within a 7-day period. Similarly, temperature events occurred when 25+ melting degree days (based on mean daily air temperature) accumulated during a similar interval. Such base values were derived from iterative evaluations of station case studies across the sub-regions.

In summary, it was found that the identified temperature events were almost always accompanied by a runoff event. However, a few runoff events with no corresponding warming episodes also occurred. Preliminary analysis suggests that these hydrologic pulses were influenced by significant rainfall during short (less than 7-day) warming periods. Nonetheless, the correspondence between temperature and runoff events indicates that these warming episodes are good indicators of mid-winter breakup in this region. Figure 4 displays the frequency of mid-winter warming events (by decade) for the northern and southern boundaries of the four sub-regions. For the south (Figure 4a), the time series show considerable decadal-scale variability with little evidence of any long-term trends for any of the sub-regions. The north (Figure 4b), however, shows an increasing trend in the number of events through the 20th century. Furthermore, while the Atlantic and Central sub-regions were void of any events prior to 1950, these areas have subsequently observed an increasing frequency of events.

![Figure 4: Frequency of mid-winter temperature events (per decade) for southern (a) and northern (b) boundary stations at the four regions in Figure 1.](image)

Based on several GCM projections of future (2080s) climate over this temperate region, winter temperatures are expected to increase between 2 °C to 6 °C. Figure 5 shows the shifts to the *Temperate Region* given both a 2 °C and 6 °C increase in mean winter temperature. The map shows dramatic northward shifts to these boundaries in a warmer climate. In fact, with the 6 °C increase, the new southern limit is located near the current (1961–90) northern limit. This shift is significant since rivers that currently do not experience mid-winter warming events will be susceptible to river-ice breakups. Similar to the *Northern Region*, this could produce significant related impacts on the hydro-ecology of these river systems and, additionally, on the more developed infrastructure that characterizes these more southerly latitudes.
CONCLUSIONS
A pronounced west to east gradient has been shown to exist in the occurrence of spring 0°C temperatures across Canada over the last 50 years. This spatial trend is also mirrored in the dates of river-ice breakup indicators at representative longer-term stations in the Northern Region of Canada. A first approximation regarding the effects of future climate change on this high-latitude area indicates that by the end of this century, breakup will be about two weeks to one month earlier. Within the Temperate Region that marks the edge of the cold regions, mid-winter warming events have become more common at the northern edge over the last 50 years, but little difference was observed at the southern limit. Although this regional contrast is possibly related to cryospheric-feedback processes associated with climate change, more research is required for validation. A 2 °C to 6 °C warming under future climate will produce a major northward retreat of this Temperate Region and a new set of river systems will be exposed to the effects of mid-winter warming and associated ice breakup. Changes to the intensity of such events are difficult to estimate, however, primarily because of major uncertainties in the predictions of future precipitation amounts and patterns.

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