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River Ice Trends in Canada

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The timing of freeze-up and break-up events are critical to many hydroecological and socio-economic systems in Canada and other cold regions countries. Changes in the dates of such events can have a number of significant and wide-ranging implications, varying from effects on under-ice aquatic productivity to the duration of surface transportation afforded by ice roads. Previous studies, based on somewhat limited data sets, have shown that break-up dates are generally occurring earlier and freeze-up dates later in the Northern Hemisphere and parts of Canada. This study employs the most comprehensive river ice database yet analyzed: the Canadian Ice Database (CID), an amalgamation of ice conditions from the Meteorological Service of Canada (MSC) and the Canadian Ice Service (CIS), spatially augmented with data from Water Survey of Canada stations. Spatial trends of break-up and freeze-up dates are analyzed for major climatic zones across the country and are compared to the related timing of spring/autumn 0°C isotherms. Links are made to 0°C isotherms in the hope that such a temperature index can be used as a surrogate predictor for future ice conditions under changing climatic conditions. Various periods were analyzed but a focus was placed on (i) the often studied 1961-90 period, and (ii) the latter half of the 20th century, employing stations with a minimum 2/3 record length in both cases. In general, the data show that most of the country has been undergoing a trend towards earlier breakup dates, although the freeze-up patterns are more spatially complex and do not bear out similarly clear temporal trends. Also discussed are spatial variations among major climatic regions, which showed a particularly strong trend in break-up dates in western Canada.

Introduction

It has been suggested from an international review of long-term (> 100 yr) lake- and river-ice records gathered from around the Northern Hemisphere that the duration of freshwater ice cover has been decreasing (Magnuson *et al*., 2000). Furthermore, most climate-change predictions for the future indicate that such duration will further decline particularly as a result of earlier break-ups (Anisimov *et al*., 2001). In the case of air temperatures that drive such ice events, Serreze *et al*. (2000) has noted that winter and spring warming has been most pronounced over northern continents and over the central Arctic Ocean since about the 1970s. More specifically, the mean annual air temperature for Canada's south has increased between 0.5 and 1.5°C during the period 1900-98 and for Canada as a whole, has increased by 0.3°C for the 1950-98 period (Zhang *et al*, 2000). Linking trends in air temperature and ice-cover dates, Bonsal and Prowse (2003) found significant trends towards earlier spring dates, especially over most of western Canada over the last 20-30 years. Many of these studies also note the accelerated rate of temperature increase especially over the last half of the century. This has been supported by recent satellite observations that have shown average temperature trends to be generally positive over North America (1.06 +/- 0.22°C $decade^{-1}$) with a recent 20-yr trend as much as 8 times larger than the 100-yr trend (Comiso, 2003).

Although some broad analyses of spatially limited data sets of ice-event dates for Canada have been completed, this study provides a more detailed spatial and temporal analyses of river ice trends by relying on the most comprehensive river ice database yet analyzed: the Canadian Ice Database (CID; Lénormand *et al*., 2002), spatially augmented with data from Water Survey of Canada stations. The CID is an amalgamation of ice conditions from the Meteorological Service of Canada (MSC) and the Canadian Ice Service (CIS). The analysis has two objectives: first, to define spatial trends of break-up and freeze-up dates for major climatic zones across the country and, secondly, to compare these to the timing of spring/autumn 0°C isotherms (i.e., the point of 'phase change' from melting to freezing condition; see Bonsal and Prowse (2003)). Correlations are made to 0°C isotherms in the hope that such a temperature index can be used as a surrogate predictor for future ice conditions under changing climatic conditions; something much more difficult to predict using complex ice modelling approaches.

Data and Methodology

The CID, the major data source for this study, contains 63,546 ice observations from 757 sites across Canada from 1822 to 1999 for rivers, lakes, sea water and deltas. Even with such a comprehensive record, it was necessary to supplement missing records or infill for some data-spare regions, such as in the eastern Keewatin (i.e. western Hudson Bay). This was completed using Water Survey of Canada (HYDAT database; Environment Canada, 2003) last 'B' dates, the 'B' denoting periods when ice affects the stage-discharge relationship (i.e. backwater effect). As clearly shown in Figure 1, the number of reporting stations significantly increased around the mid 1950s (CID) and during the 1960s (HYDAT) only to decline even more dramatically during the mid 1980s (CID) and early 1990s (HYDAT).

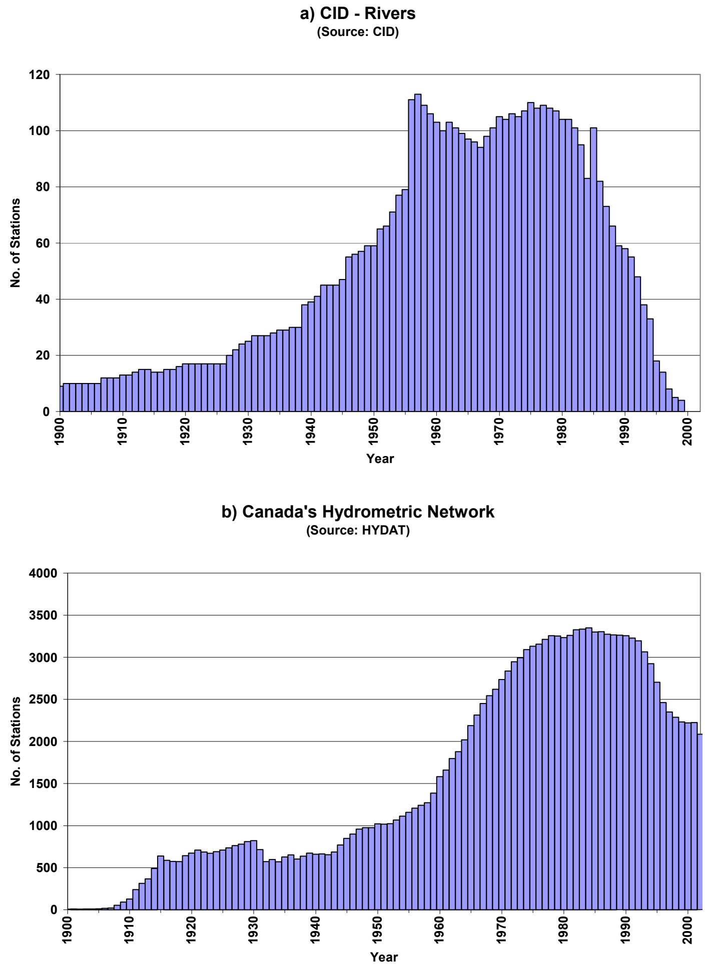

Figure 1: State of break-up/freeze-up stations across Canada from a) the CID and b) HYDAT for the period 1900-2000.

The nonparametric Mann-Kendall test was used to detect trends, and the nonparametric Sen's method for the magnitude of the trends (Mann, 1945; Kendall, 1975; Sen, 1968). The Mann-Kendall test is appropriate to use when trends are assumed to be monotonic, i.e. either increasing or decreasing. The slope of a linear trend is estimated with the Sen's method, which is not greatly affected by single data errors or outliers. Non-parametric Spearman correlations were compared between break-up/spring 0°C isotherms and freeze-up/autumn 0°C isotherms as defined in Bonsal and Prowse (2003).

Analyses were completed only for stations with a minimum 2/3 complete record of break-up or freeze-up dates, which corresponds to 20 years for the three 30-yr periods (i.e. 1951-80; 1961-90 and 1966-95) and 32 years for the last half-century (i.e. 1950-98). The last half-century period was to provide the broader long term perspective, and the three 30-yr periods to permit comparison with the results of previous studies that employed similar time frames (e.g., Serreze *et al*., 2000; Zhang *et al*, 2000; Bonsal and Prowse, 2003). The 1961-90 period was used for correlations of ice events with 0°C isotherms because it contained the largest number of freeze-up/break-up records (Figure 1 and Table 1). The 1950-98 period was also employed to provide a longer term perspective in reference to the warming that has occurred over the last half-century.

Period	Break-up	Freeze-up
1951-80	61	50
1961-90	79	68
1966-95	71	60
1950-98	45	41

Table 1: Number of stations available for trend analysis when approximately 2/3 of the years of record are available.

Analyses were conducted for the whole of the country and for its major climatic regions as defined by Hare and Thomas (1974). As shown in Figure 2, these include the Pacific (1), Cordillera (2), Prairies (3), Boreal (4), Arctic (5), Great Lakes/St. Lawrence (6) and Atlantic (7) (Figure 2). The Boreal climatic region contains the largest number of stations primarily due to its larger area.

Break-Up and Freeze-Up Trends: ***1951-80, 1961-90, 1966-95 and 1950-98***

For all of Canada and for all periods (Figure 2), the results show that the timing of river ice break-up advanced by an overall station average of 3 to 7 days (+/- 11 days), a change of around 1 to 2 days earlier per decade (Table 2). A more variable trend is exhibited by the freeze-up data that shows over the same periods, a change ranging from 3 days later to 0.3 days earlier, corresponding to 1 day per decade later to 0.1 day per decade earlier (Table 2). The weaker signal for freeze-up is also apparent in Figure 2.

Period	**Break-up**				
	Min	Max	Average	Standard Deviation	Days/decade
1951-80	-42.9	33.0	-2.9	12.1	-1.0
1961-90	-40.0	15.0	-6.5	10.8	-2.2
1966-95	-40.3	21.5	-6.0	11.6	-2.0
1950-98	-42.0	12.3	-6.8	10.7	-1.6
	Freeze-up				
1951-80	-32.0	64.3	2.9	18.2	1.0
1961-90	-35.1	46.1	-0.3	16.4	-0.1
1966-95	-42.0	30.0	0.3	12.8	0.1
1950-98	-37.1	32.7	1.3	15.0	0.3

Table 2: Range of days (absolute min/max of all stations), average/standard deviation, and change in days/decade for both break-up and freeze-up by period.

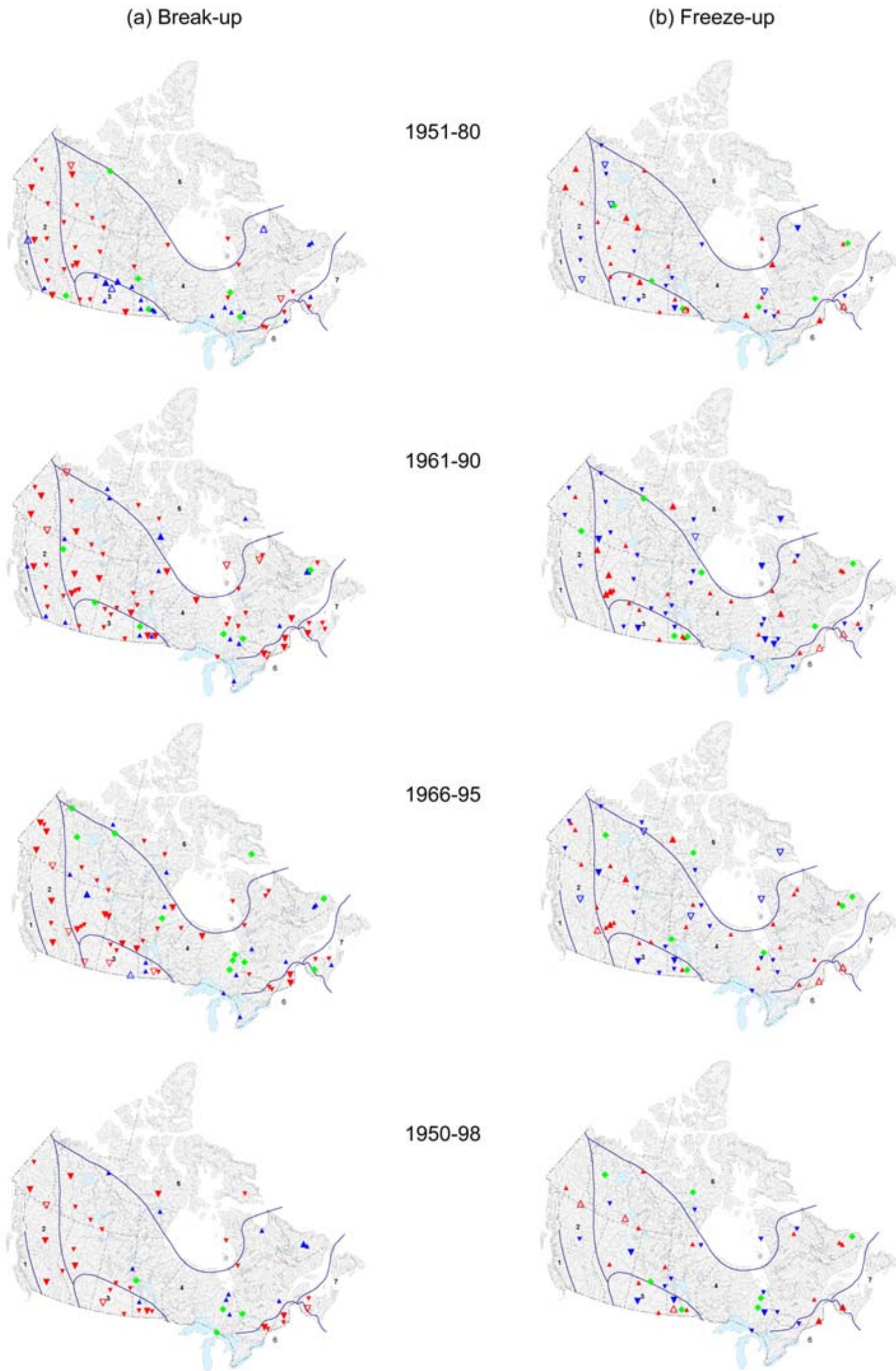

Figure 2: Trends in (a) break-up and (b) freeze-up for all periods. Trends significant at the 5% and 10% levels are denoted by larger solid and open triangles, respectively. Smaller triangles indicate that the trends are not significant at the 10% level. (a) break-up: downward (**red**) triangles and upward (**blue**) triangles represent **negative** and **positive** trends, respectively. (b) freeze-up: upward (**red**) triangles and downward (**blue**) triangles represent **positive** and **negative** trends, respectively. Climate regions are: Pacific (1), Cordillera (2), Prairies (3), Boreal (4), Arctic (5), Great Lakes/St. Lawrence (6) and Atlantic (7).

Table 3 indicates the percentage of sites with earlier/later break-up/freeze-up dates, including percentages by significance level and those with no trend. As indicated by the overall percentages (All), break-up dates for all 4 periods are occurring earlier, i.e. with 56-72% of stations recording earlier break-ups, 20-34% of stations recording later break-ups and the remainder having no significant trend. Data for the various 30-year periods also suggest that the strongest trend to earlier break-ups has occurred in the latter portion of the 20th century, increasing from an average of only 13% (10%) stations at the 10% (5%) significance level for the 1951-80 period to approximately 30% (20%) for the two later periods. Much more mixed signals, however exist for the freeze-up periods with a more even split between earlier and later shifts, lower percentages being significant, and no real distinction between earlier and later 30-year periods.

			Earlier			Later			
	Period	n	All %	10% sig	5% sig	All %	10% sig	5% sig	No Trend
Break-up	1951-80	61	56	13	10	34	8	3	10
	1961-90	79	72	29	23	20	3	3	8
	1966-95	71	65	27	20	22	3	1	13
	1950-98	45	67	27	20	24	2	2	9
Freeze-up	1951-80	50	38	12	4	50	20	16	12
	1961-90	68	51	10	9	38	12	9	11
	1966-95	60	43	13	5	45	10	5	12
	1950-98	41	41	10	5	41	12	10	18

Table 3: Summary of break-up/freeze-up trends by period (see also Figure 2). Number of stations are identified by 'n'. Percentages are given for all stations having earlier/later break-ups/freeze-ups at the 10% and 5% significance levels.

Spatial Distribution of Break-Up and Freeze-Up Trends: *1961-90*

For the purpose of this section, discussion centres on the ***1961-90*** period since it has the highest observation density (Figure 1 and Table 1). Figure 3 shows the frequency distribution of the trends by climatic region for all periods. Bracketed values in Table 4 refer to the number of stations where trends are significant at the 10% level. Figure 3, which re-enforces Figure 2, also shows a general trend towards earlier break-up in all regions. The exception is region 5 that is fairly evenly divided between earlier and later break-ups. For example, earlier break-up in the Pacific region is observed at 11 of 13 stations. This is also true for 8 of 12 stations in the Prairies; 27 of 36 stations in the Boreal region; 3 of 7 stations in the Arctic; 5 of 7 stations in the Great Lakes/St. Lawrence region, and 4 of 4 stations in the Atlantic region.

	Break-up											
Climate Region	**1951-80**			**1961-90**			**1966-95**			**1950-98**		
	Earlier	*No trend*	*Later*	*Earlier*	*No trend*	*Later*	*Earlier*	*No trend*	*Later*	*Earlier*	*No trend*	*Later*
2	10(3)	1	2(1)	11(4)		2(0)	9(7)		0(0)	6(4)		0(0)
3	3(1)	1	9(3)	8(2)	2	2(0)	7(4)		3(1)	7(2)		1(0)
4	15(3)	3	8(1)	27(11)	4	5(1)	20(6)	7	7(1)	8(2)	3	8(1)
5	1(0)	1	0(0)	3(1)		4(1)	3(0)	2	2(0)	3(1)		2(0)
6	4(1)		1(0)	5(4)		2(0)	4(2)		3(0)	4(2)	1	0(0)
7	1(0)		1(0)	4(1)		0(0)	2(0)	1	1(0)	2(1)		0(0)
	Freeze-up											
Climate Region	**1951-80**			**1961-90**			**1966-95**			**1950-98**		
	Earlier	*No trend*	*Later*	*Earlier*	*No trend*	*Later*	*Earlier*	*No trend*	*Later*	*Earlier*	*No trend*	*Later*
2	3(1)		2(2)	4(0)	1	1(0)	3(1)	1	3(1)	1(0)		2(1)
3	2(1)	2	7(2)	4(1)	2	5(0)	4(2)	1	3(0)	3(3)	2	3(0)
4	13(4)	3	12(4)	19(4)	2	14(5)	13(2)	4	16(2)	9(2)	4	8(1)
5	0(0)		2(0)	4(2)	1	2(1)	5(3)	1	1(1)	2(0)	1	1(1)
6	0(0)	1	1(1)	2(0)	1	2(1)	1(0)		3(1)	2(0)		2(1)
7	1(0)		1(1)	2(0)		2(1)	0(0)		1(1)	0(0)		1(0)

Table 4: Total number of stations in each climate region showing earlier, no trend and later break-up/freeze-up dates. Values in brackets are number of stations significant at 10% level

A mixed signal is apparent in the freeze-up trends for the ***1961-90*** period. Although later freeze-ups occur in all regions, general trends towards earlier freeze-ups seem to outweigh those of later freeze-ups, except in regions 3, 6 and 7. For example, in regions 2, 4 and 5 earlier freeze-ups (significant at 10% level) occur 4 (0) out of 6 times; 19 (4) out of 35 times and 4 (2) out of 7 times, respectively. Although earlier/later tendencies are fairly even across region 3, a slightly greater number of later freeze-ups are indicated, i.e. 5 (0) of 11 sites as opposed to 4 (1) of 11 indicating earlier freeze-ups. In both regions 6 and 7, the split is even between earlier/later freeze-ups, i.e. with 2 (0) of 5 stations being earlier in region 6 and 2 (0) of 4 sites in region 7 being earlier, while 2 (1) of 4 stations in each region have later freeze-ups.

Linkages to Spring/Autumn 0°C Isotherms*: 1961-90 and 1950-98*

As earlier noted by Bonsal and Prowse (2003), the timing of many cryospheric events (e.g., snowmelt, break-up/freeze-up) are related to the timing of the 0°C isotherm. Since air temperature is also the most readily available and credible climatic variable predicted by Global Climate Models (GCMs), 0°C isotherms also offer a potential surrogate variable for predicting the future occurrence of such cryospheric events. This would be particularly valuable in the case of river ice since it is such a complex process, controlled by a variety of hydroclimatic variables and difficult to model accurately. This section explores the strength of break-up/freeze-up to 0°C isotherm correlations across the country.

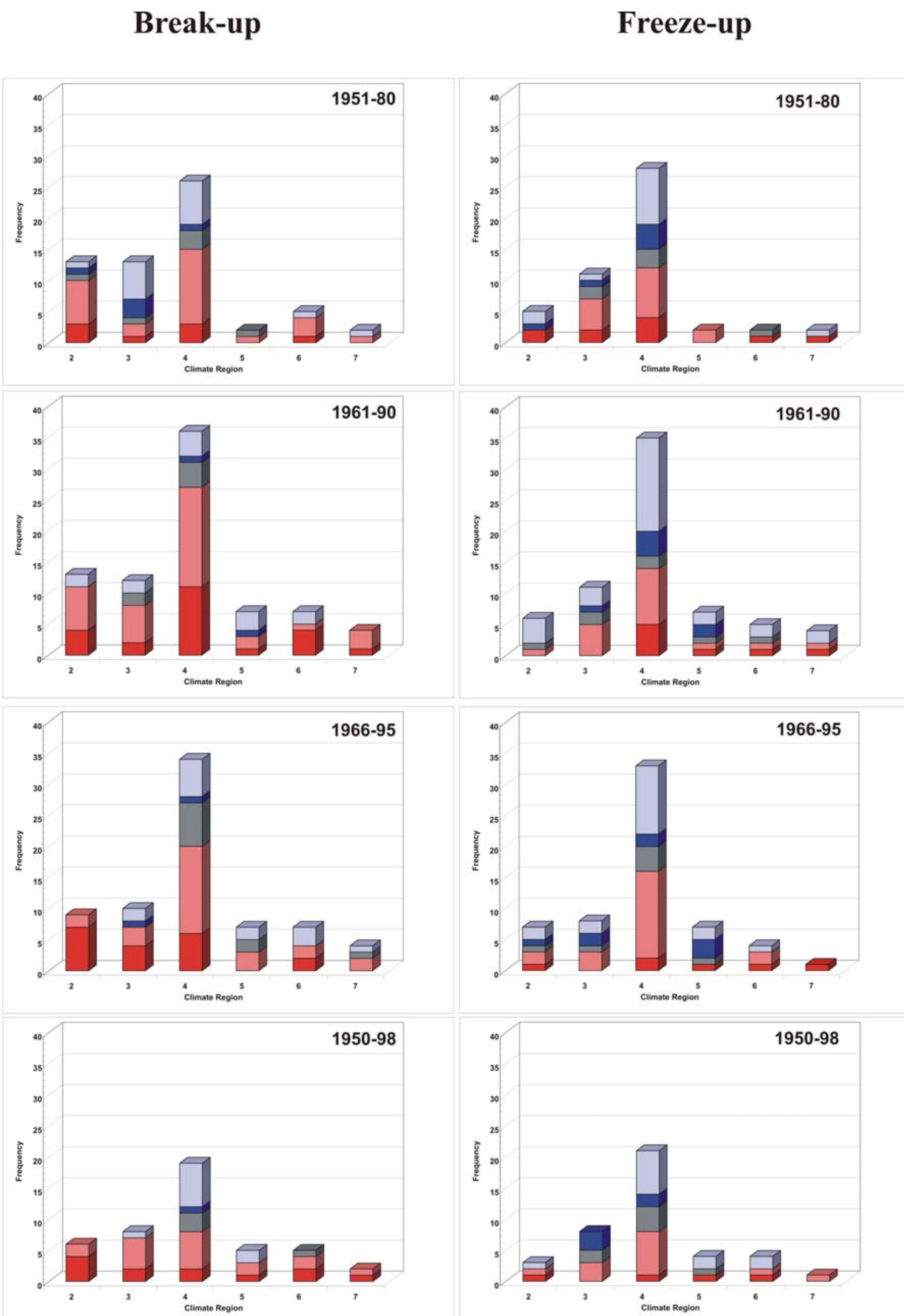

Figure 3: Distribution of trends by climate regions. The darker **red** and **blue** denotes significant **warming**/**cooling** trends at the 10% level.

Nonparametric Spearman correlations were compared between break-ups/spring 0°C isotherms and freeze-ups/autumn 0°C isotherms at the 5% significance level for the 1961-90 period. Spring (autumn) 0°C isotherms are typically defined as the date when mean daily temperature rises above (falls below) 0°C. This highly variable daily value is often crossed over the span of these two seasons. Hence, spring (autumn) 0°C isotherms are explicitly defined as when the 31-day running mean daily temperature crosses 0°C (Bonsal & Prowse, 2003).

An inter-regional distribution of correlations between break-ups and spring 0°C isotherms (Figure 4a) shows that there are a greater number of significant than non-significant correlations within each region. Conversely, the same comparison between freeze-ups and autumn 0°C isotherms (Figure 4b) indicates only that a greater number of significant instances for regions 3, 5 and 7 exist; and in the remaining 3 regions non-significant associations outweigh the significant ones. Overall, 82% of the break-up sites show significant correlations as opposed to only 49% of the freeze-up sites.

Figure 5 provides a breakdown of the above-mentioned distributions into "no" or negative (-0.45-0.0), weak (0.01-0.25), moderate (0.26-0.55), strong (0.56-0.75) and very strong (0.76-0.99) correlations by climate region for both break-ups/spring 0°C isotherms and freeze-ups/autumn 0°C isotherms. Figure 5(a) indicates that for all regions, moderate to very strong associations exist between break-up/spring 0°C isotherms for 62-100% of the sites. On the other hand, Figure 5(b) further substantiates that the signal is not as strong between freeze-up/autumn 0°C isotherms, indicating that for all regions, only 20-75% of the sites exhibit moderate to strong signals, and only one site in region 7 has a very strong correlation.

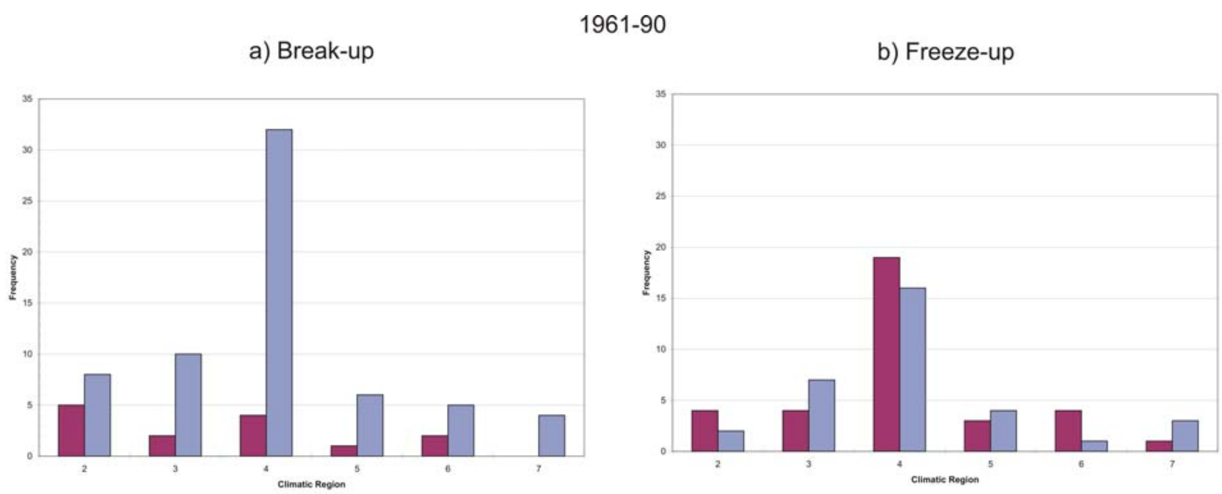

Figure 4: Inter-regional distribution of correlations for the period ***1961-90*** between (a) breakup/spring 0°C isotherm and (b) freeze-up/autumn/0°C isotherm. Blue and red represent significant and non-significant at the 5% level, respectively.

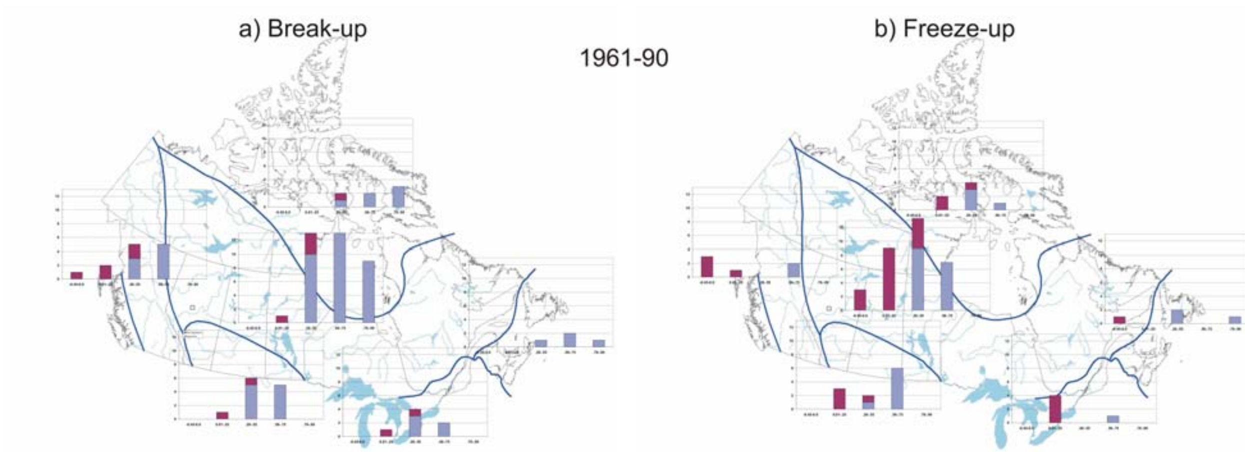

Figure 5: Sum of intra-regional distribution for correlations between (a) break-up/spring 0°C isotherm and (b) freeze-up/autumn 0°C isotherm by climate region for the period ***1961-90***. Blue and red represent significant and non-significant at the 5% level, respectively. The ranges shown correspond to no (-0.45-0.0), weak (0.01-0.25), moderate (0.26-0.55), strong (0.56-0.75) and very strong (0.76-0.99) associations.

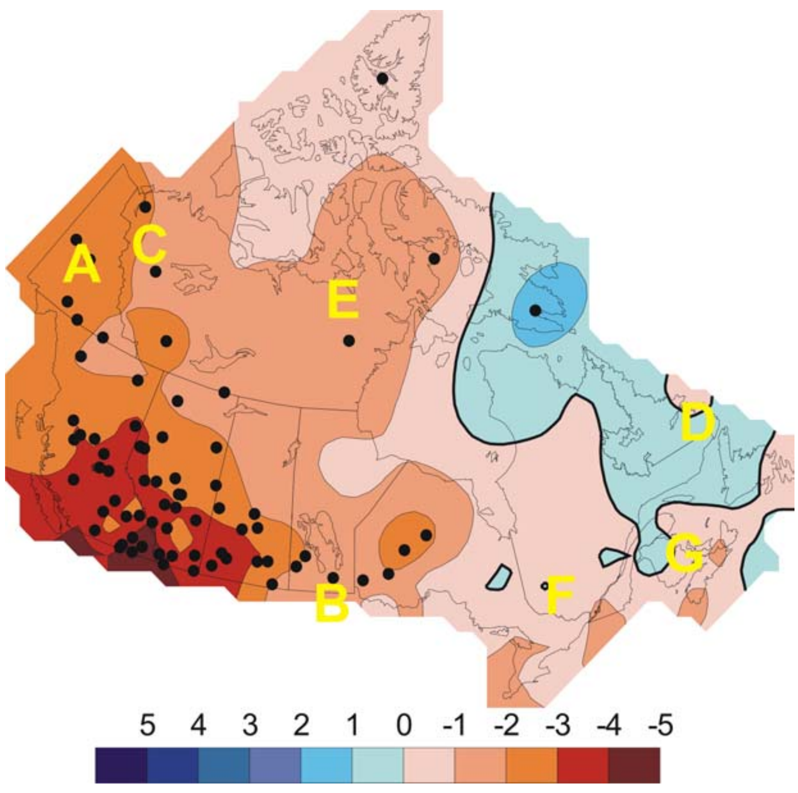

Figure 6: Linear trends in spring 0°C isotherm dates over Canada from ***1950-98*** (days/decade). Stations with significant trends at the 5% level are denoted by filed circles. Capital letters represent locations used in the Figure 7 and Table 5 comparisons. From Bonsal *et al*., 2001.

	A	B	C	D	E	F	G
FuBu ID	FuBu-139	FuBu-554	FuBu-350	FuBu-218	10RC001[a]	FuBu-311	FuBu-199
FuBu name	Klondike River	Red River	Mackenzie River	Churchill River	Back River	Riviere Desert	Saint John River
Weather station ID	2100402	5023222	2202800	8501900	2300500	7034480	8101500
Weather station name	Dawson A	Winnipeg Int'l A	Norman Wells A	Goose A	Baker Lake A	Maniwaki	Fredericton A
Climate Region	**2**	**3**	**4^{west}**	**4^{east}**	**5**	**6**	**7**
Spring isotherm vs BU (r)	0.72**	0.77**	0.60**	0.71**	0.78**	0.41*	0.49**
Spring isotherm trend	-14.5***	-11.3*	-8.5*	1.1	-9.8*	-2.1	-1.3
BU trend	-7.1	-8.2	-7.0*	12.3**	-15.5*	-20.2*	-14.0+
Fall isotherm vs FU (r)	0.04	0.38*	0.22	0.07	0.45**	0.19	0.52**
Fall isotherm trend	3.5	-6.3	0.6	4.0	0.0	-5.9	0.0
FU trend	-5.4[b]	3.5	0.0	8.7	0.0	-2.1	25.3**

Significance: ***99.9, **99, *95, +90

[a] Water Survey of Canada hydrometric station

[b] FU trend, n=31 only

Table 5: Correlation coefficients and linear trends associated with the time series provided with Figure 7 for the period 1950-98.

Although periods of record vary, all 7 sites display significant correlations between spring 0°C isotherms and break-up dates. Values are highest from sites A through E, i.e. in climate regions 2-5, and slightly lower for sites F and G in climate regions 6 and 7.

For the sites in regions 2-4^{west} and in region 5, there is a distinct negative trend in both spring 0°C isotherm and break-up, whereby the spring 0°C isotherm trend is significant in all 4 regions and the break-up trend is significant in region 4^{west} and region 5. At site D in region 4^{east}, both spring 0°C isotherm and break-up trends are positive, and the break-up trend is significant. This coincides well with Figure 6 where the region is indicative of cooling. In regions 6 and 7, the spring 0°C isotherms are fairly 'flat' or 'level' but still slightly negative but insignificant. Meanwhile the break-up trends in these two sites (i.e. F and G), both show significant negative trends.

Summary and Discussions

This analysis has relied on the most comprehensive database about river-ice breakup/freeze-up dates yet employed for Canada. Moreover, given the decline in observation stations, this data set may be the most comprehensive ever available. In general, results of the trend analyses reinforce previous findings for parts of the country that were based on smaller data sets. Overall, the data show that most of the country has experienced a trend to earlier breakup dates, especially over the 1961-90 period, although the freeze-up patterns were found to be more spatially complex and not to show as clear temporal trends. In both cases, intra-period climatic shifts or changes in warming may have complicated the trends and an assumption of linear trends over the shorter 30-year periods may not be safe to assume, particularly with the warming that has been most pronounced in the latter half of the century. In an attempt to minimize these effects, the longer 1950-98 period was also analyzed and the results tended to mirror many of those of the shorter 30-year periods. Caution must, however, still be used in interpreting these trends because of data gaps and the effects of intra-period climatic variability. For example, warming in many parts of the country has been more pronounced in the latter half of the century than in the middle of the century. Overall, however, both the 30- and 50-yr analyses provide a good spatial overview of trends in freeze-up and break-up dates. Future work should focus on comparing these results with relevant work of others (e.g., Serreze *et al*., 2000; Zhang, *et al*., 2001; Bonsal and Prowse, 2003; Comiso, 2003), evaluate inter-decadal trends in the records, and begin to offer physical (climatic and hydrologic) explanations for such trends.

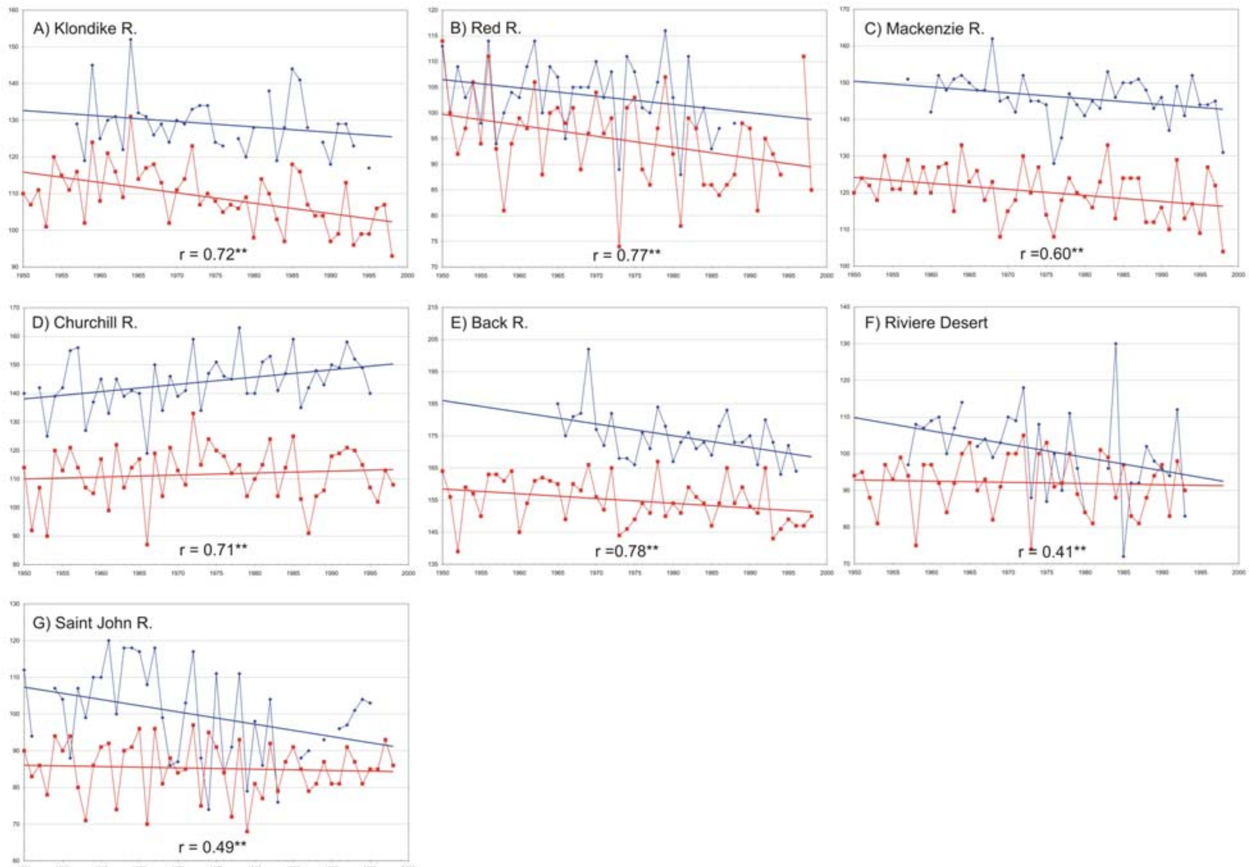

Figure 7: 1950-98 comparison between spring 0°C isotherms dates (red lines) and break-up dates (blue lines) for 7 representative sites within each climate region labeled A-G on Figure 6 and in Table 5. Solid lines represent trends. A) Klondike R. vs. Dawson Airport; B) Red River vs. Winnipeg Airport; C) Mackenzie R. vs. Norman Wells A; D) Churchill R. vs. Goose A; E) Back R. vs. Baker Lake A; F) Rivière Desert vs. Maniwaki; G) Saint John River vs. Fredericton A.

Linkage of breakup/freeze-up dates to the timing of 0°C isotherms produced some strong correlations for spring events but much less so for the autumn. Spatial variations in the strength of correlations might be the result of river-scale or climatic effects. For example, air-temperature for a particular climate station is most likely to be best correlated with low-order small streams and less so for large-order rivers where the breakup/freeze-up conditions are more strongly controlled by broader scale weather conditions, particularly including those much further upstream and possibly quite different from those of the local ice-observing site. Spatial variations might also result from differences in "coldness" of regions; spring warming expected to lead to a more rapid response in temperate snow/ice zones than in higher latitude/altitude zones where significant warming above 0°C must occur before runoff and breakup result. Future work should focus on such thermal lags and river-size effects if strong air-temperature and breakup/freeze-up relationships are desired, particularly for use in the prediction of future climate impacts.

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