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Trends in Canadian streamflow

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Abstract. This study presents trends computed for the past 30–50 years for 11 hydroclimatic variables obtained from the recently created Canadian Reference Hydrometric Basin Network database. It was found that annual mean streamflow has generally decreased during the periods, with significant decreases detected in the southern part of the country. Monthly mean streamflow for most months also decreased, with the greatest decreases occurring in August and September. The exceptions are March and April, when significant increases in streamflow were observed. Significant increases were identified in lower percentiles of the daily streamflow frequency distribution over northern British Columbia and the Yukon Territory. In southern Canada, significant decreases were observed in all percentiles of the daily streamflow distribution. Breakup of river ice and the ensuing spring freshet occur significantly earlier, especially in British Columbia. There is also evidence to suggest earlier freeze-up of rivers, particularly in eastern Canada. The trends observed in hydroclimatic variables are entirely consistent with those identified in climatic variables in other Canadian studies.

1. Introduction

The detection and attribution of past trends, changes, and variability in climatic variables is essential for the understanding of potential future changes resulting from anthropogenic activities. This is especially true for high-latitude regions such as Canada where climatic change signals are projected to be stronger [*Nicholls et al.*, 1996] and where the impacts of climatic change may be more severe. Recent analyses [*Zhang et al.*, 2000a] of trends in Canadian climate revealed a generally wetter and warmer climate during the last half of the twentieth century. It was found that annual precipitation totals have changed by −10% to 35%, with the strongest increases occurring in the northern regions of the country. Significant decreasing trends in winter precipitation and in the proportion of spring precipitation falling as snow were identified in southeastern Canada. Annual mean temperature showed an increasing trend in southwestern Canada but exhibited a decreasing trend in the northeast. This pattern of changes in temperature is especially strong during winter and spring. Changes in the mean state of climate, such as annual precipitation totals and mean temperature, are associated with changes in both mean and extreme daily values. There was no evidence to suggest changes in the frequency of heavy precipitation events (daily rainfall/snowfall larger than a threshold value which is exceeded by an average of three events per year) across Canada [*Zhang et al.*, 2000b], but significant trends have been identified in extreme temperatures (daily temperatures larger than 95 or less than 5 percentiles). The increasing trend in spring temperature has also resulted in earlier starting dates of both frost-free period and growing season [*Bonsal et al.*, 2000] during the last half of the twentieth century. Such changes in both precipitation and temperature are likely to have impacted the hydrology of Canadian rivers, such as volume and timing of streamflow and river ice conditions.

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The hydrologic regime of a stream under specific geomorphic conditions represents the integrated basin response to various climatic inputs, with precipitation and temperature being very important ones. The evolution of basin geomorphology is very slow compared with possible climatic changes caused by anthropogenic increases of greenhouse gases. Therefore the changes in the hydrologic regimes of pristine or stable, unregulated basins generally reflect changes in climatic conditions and thus can be used as indicators for the purpose of climate change detection. It is thus important to analyze trends in various hydrologic variables of river basins which are not subjected to human regulation. In addition to providing an understanding of the impacts of climatic change on society and ecosystems, such analyses may provide independent corroborative evidence to confirm and/or to verify the results of trend detection for climate variables.

Lins and Michaels [1994] revealed statistically significant increases over the period 1948–1988 in natural streamflow in autumn and winter over nearly all regions of the contiguous United States. The most significant increases were generally found from the Rocky Mountains eastward to the Atlantic Ocean. Along the west coast of the United States the increases in autumn and winter streamflow were associated with decreases in the proportion of streamflow during the period April–July to the annual totals [*Aguado et al.*, 1992]. Those findings were further confirmed by *Lettenmaier et al.* [1994], who analyzed trends in monthly precipitation, temperature, and streamflow for the continental United States and found strong increases in streamflow during the period November–April at almost half of the stations, with the largest magnitudes in the north central states. In an attempt to determine whether trends have occurred in U.S. streamflow over a range of discharge quantiles, *Lins and Slack* [1999] tested for trends in seven quantiles of daily mean streamflow, including annual minimum, the tenth, thirtieth, fiftieth, seventieth and ninetieth percentiles and annual maximum values. They found that trends were most prevalent in the annual minimum to median flow categories and were least prevalent in the annual maximum category. Furthermore, at all but the highest quantiles, streamflow had increased across broad regions of the United States. These findings led them to conclude that the United States was getting wetter but less extreme.

Most previous studies of trends in Canadian streams focused on regions. *Gan* [1998] used Kendall's test to identify hydroclimatic trends and possible climatic warming in the Canadian prairies. He found that climate tended to be warmer and drier in the region, but there was no significant trend in the severity and duration of drought. *Leith and Whitfield* [1998] and *Whitfield and Cannon* [2000] examined trends and climate-moderated shifts in hydrology in British Columbia and the Yukon. They found a trend toward earlier onsets of spring freshet. *Burn* [1994] attempted to detect hydrologic effects of climatic change in west central Canada and found that a great number of rivers exhibited earlier spring runoff. Attempts to identify trends in Canadian streams on a national basis include that of *Anderson et al.* [1992], who examined the surface water characteristics of 27 basins across Canada. Significant trends were identified in a number of long-term natural discharge records, particularly in the lower to average range of streamflow. However, no clear conclusions could be drawn as to whether there were significant trends at regional or national scales because of poor spatial coverage of the data. *Whitfield and Cannon* [2000] compare the differences between the decades 1976–1985 and 1986–1995 in mean daily streamflow records at 642 stations across Canada. However, this study is limited by the use of short record lengths (20 years). The identification of the Canadian Reference Hydrometric Basin Network (RHBN) [*Harvey et al.*, 1999], a subset of Canada's national hydrometric network, provides a good opportunity to systematically assess trends in various hydrologic variables observed at 243 longer-term streamflow gauging stations.

The major objective of this study was to analyze trends in various variables observed at 243 RHBN stations over the past 30–50 years. Section 2 describes the data sets and methods used in this study. Trends in annual and monthly mean streamflow and in the extremes and various percentiles are analyzed in section 3. Changes in the timing of the freshet (spring high flow) season as well as river ice conditions are investigated in section 4. We conclude our analysis with a discussion in section 5.

2. Data and Methodology

2.1. Data

In the mid-1990s, Environment Canada committed to identifying and maintaining, through its water monitoring partnerships, a national hydrological monitoring network for use in detecting and assessing impacts of climate change and variability on Canada's water resources and aquatic ecosystems. A national expert group of scientists developed and applied selection criteria to Canada's national hydrometric network, resulting in the identification of the Reference Hydrometric Basin Network (RHBN) [*Harvey et al.*, 1999]. The RHBN basins are characterized by either pristine or stable hydrological conditions, with 20 or more years of good quality record. Data are collected at all RHBN stations to a set of consistent, national standard procedures. To ensure a high level of accuracy, the quality of the data for each station was further assessed, with ratings assigned on the basis of the reliability of the stage-discharge relationship, the stability of the channel geometry, and the reliability of water level and flow measurements when affected by ice conditions. Only active hydrometric stations were considered for inclusion in this network, as ongoing monitoring is of prime importance. The historical database of the RHBN was the source of data used in this study.

The RHBN consists of 249 hydrometric stations, including 206 continuous streamflow, 37 seasonal streamflow, and 6 continuous lake level stations. Figure 1 shows the locations and drainage basins of all these stations. The majority of the RHBN stations, and most of the small basins, are located in southern Canada. There are no RHBN stations north of 70° latitude, and there are gaps in some other regions of the country. Still, the RHBN covers many of Canada's major hydrologic regions.

All stations have at least 20 years of record. Sixty percent of the streamflow stations have more than 30 years of record, while the average record length is 40 years. The longest is 88 years.

Of the 243 streamflow stations, 206 stations are operated year-round on a continuous basis, while 37 stations are operated only on a seasonal basis. The 37 seasonal streamflow stations are concentrated in central Canada, primarily in the prairies, with several in the north. The record lengths of the seasonal stations tend to be shorter than those of the continuous stations. Only 5 of the 37 seasonal sites have 40 or more years of suitable data.

Basin sizes for the network of 243 streamflow stations range from 3.9 km^2 to 145,000 km^2. The median basin size is about 1150 km^2. Most of the basins found in the middle-to-northern latitudes are relatively large. About 10% of the basins are greater than 20,000 km^2 in size; about 10% are less than 100 km^2.

Trend analyses were undertaken for 11 hydroclimatic variables (Table 1) extracted or derived from the RHBN database. Computations were made for three study periods: (1) 1967–1996, (2) 1957–1996, and (3) 1947–1996. Thus, for each variable the length of the time series is 30, 40, or 50 years.

Although there are a total of 243 RHBN basins with streamflow data, the selected study periods determined which basins were available for analysis. On average, the numbers of basins available were 151 for the 30-year period, 71 for the 40-year period, and 47 for the 50-year period. The density of the station network is reasonably good for the 30-year period, especially over British Columbia and the eastern provinces. The spatial patterns of trends do not change in these areas over the last 30 years (when there are more stations) and the last 50 years (when there are far fewer stations), as will be shown in sections 3 and 4. However, station density could be a problem for central Canada, especially for the periods of the last 40 and 50 years when there were very few RHBN stations available in the prairies and western Ontario. Time periods longer than 50 years were not studied because of limitations in record length and spatial distribution of the hydrometric basins. The selection of the 30-, 40-, and 50-year periods allows comparisons to be made with the work of *Zhang et al.* [2000a] on precipitation trends and, to a certain extent, with *Lettenmaier* [1994] with U.S. hydroclimatic data.

2.2. Method

The Mann-Kendall test [*Mann*, 1945; *Kendall*, 1975], a nonparametric test, has been widely used to test for randomness against trend in hydrology and climatology [e.g., *Lettenmaier et al.*, 1994; *Zhang et al.*, 2000a]. One problem associated with the

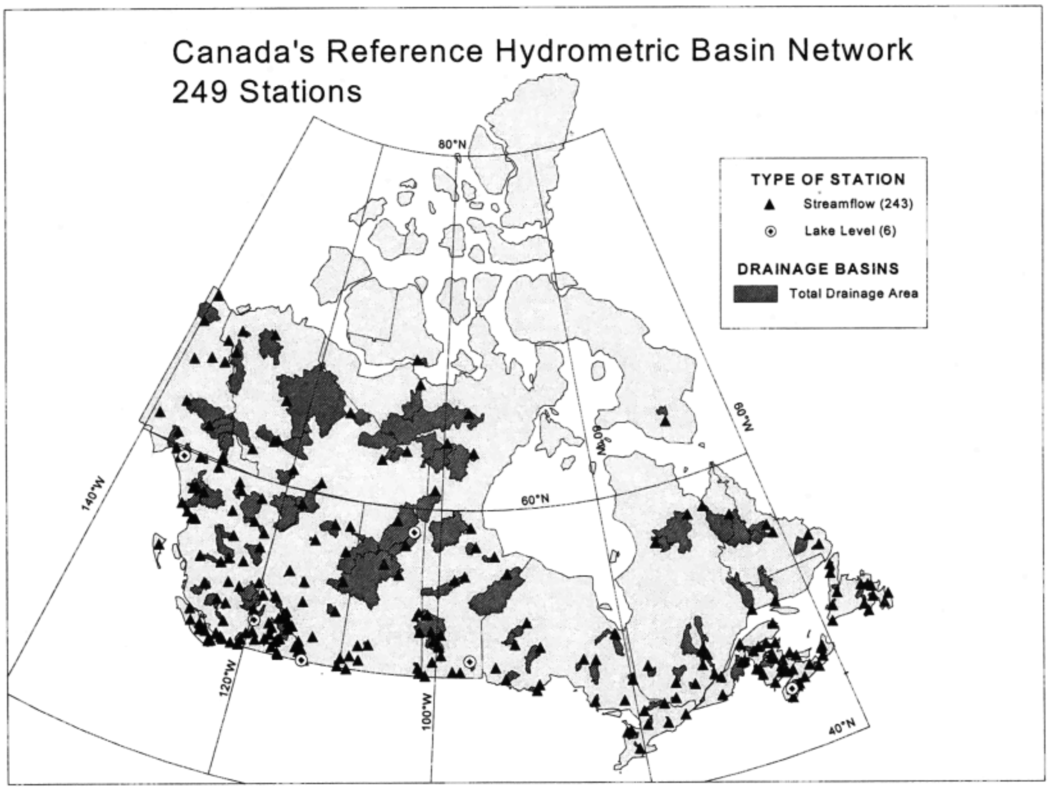

Figure 1. Locations and drainage basins of the Canadian Reference Hydrometric Basin Network (RHBN).

Mann-Kendall test is that the result is affected by serial correlation of the time series. Specifically, *Kulkarni and von Storch* [1995] found that if there is a positive serial correlation (persistence) in the time series, the test will suggest a significant trend in a time series which is actually random more often than specified by the significance level. To eliminate the effect of serial correlation, they and *von Storch and Navarra* [1995] suggest that the time series be "pre-whitened" before conducting the Mann-Kendall test. This study incorporates this suggestion, and the statistically significant trend for the time series $(y_1, y_2, \ldots, y_n)$ is identified using the following procedure: (1) Compute the lag-1 serial correlation c; (2) if $c < 0.1$, the Mann-Kendall test is applied to the time series; otherwise, (3) the Mann-Kendall test is applied to the "pre-whitened" time series $(y_2 - cy_1, y_3 - cy_2, \ldots, y_n - cy_{n-1})$.

The above test for trend against randomness was carried out separately for each basin to determine local significance. For a given variable the percentage of basins where significant trend is detected can be used as a measure of statistical significance of trend across the entire spatial domain, or field significance, of trend. The field significance of the trend was estimated by comparing the percentage of basins where significant trend was detected to the percentage of basins where significant trend would be expected to occur by chance, determined by Monte Carlo simulations as described by *Livezey and Chen* [1983].

3. Trends in Streamflow

3.1. Annual Mean Streamflow

The spatial distribution of trends in annual mean streamflow for the 30-, 40- and 50-year study periods are displayed in Figure 2. Basins located in southern Canada generally show

Table 1. Variables Analyzed

Variable	Definition
Annual mean streamflow	mean river discharge (m^3/s) for each year
Monthly mean streamflow	mean river discharge (m^3/s) for each month
Annual minimum daily mean streamflow	minimum daily mean discharge (m^3/s) for each year
Annual maximum daily mean streamflow	maximum daily mean discharge (m^3/s) for each year
Annual percentiles of daily mean streamflow	discharge (m^3/s) exceeding $X\%$ of daily streamflow in the year
Starting date of spring freshet (high-flow season)	date when the increase in daily streamflow across 4 days is greater than the average from January to July
Date of annual maximum daily mean streamflow	
Centroid of annual streamflow	date by which half of the annual total runoff has occurred
Date of river freeze-up	first date in the fall when, according to a flag in the archive, ice conditions alter the hydraulic characteristics of the channel and affect the computation of streamflow
Date of spring ice breakup	date in the spring when, according to a flag in the archive, channel hydraulics return to open water conditions
Duration of ice cover	number of days when channel hydraulics are affected by ice conditions

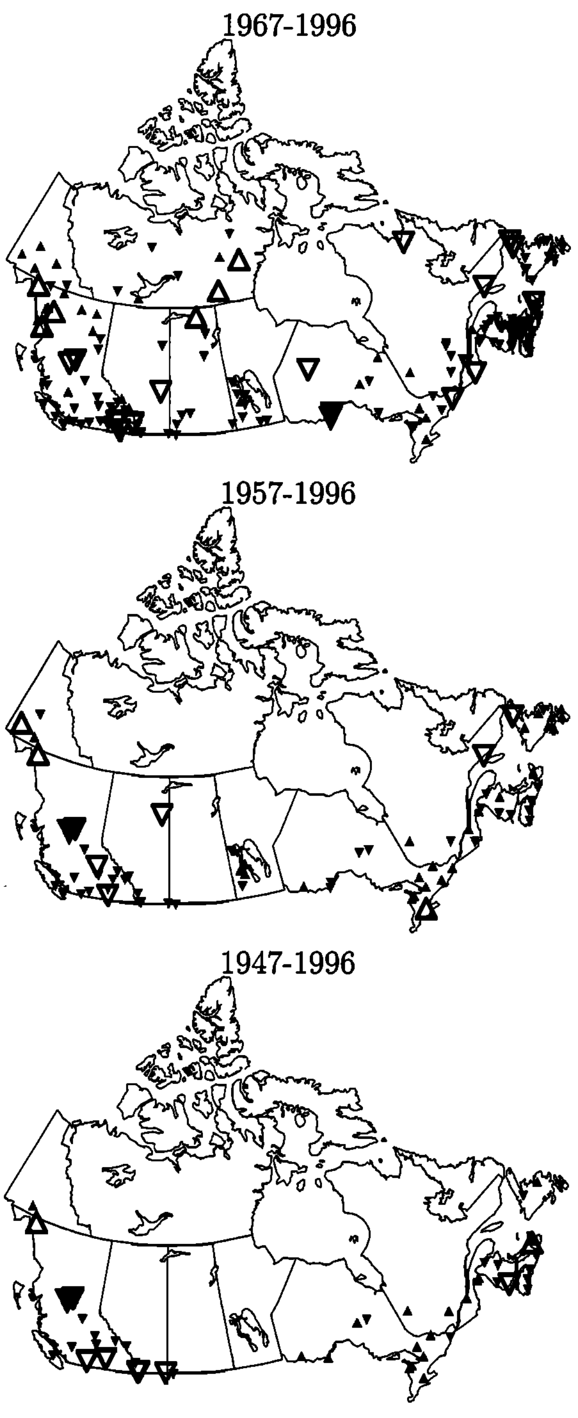

Figure 2. Trends in annual mean streamflow. Upward and downward pointing triangles represent positive and negative trends, respectively. Trends significant at the 1% and 10% levels are marked by larger solid and open triangles, respectively. Smaller triangles indicate that trends are not significant at the 5% level.

negative trends, suggesting a reduction in annual mean streamflow. A small increasing trend in the Great Lakes–St. Lawrence region for the 40- and 50-year periods reverts to a mainly decreasing trend for the 30-year period, an indication perhaps of interdecadal variability. The majority of the stations show negative trends; some of them are significant at the 10% level (Table 2). The trends for the 30- and 50-year study periods are also field significant at the 5% level.

The trends in annual mean streamflow reflect changes in precipitation and temperature observed over the same periods [*Zhang et al.*, 2000a]. Positive trends were found in temperature over southern and southwestern Canada. However, temperature decreased during the 1950s and early 1960s. It is only since the middle 1960s that temperature has increased. Over the southern part of the country, there was, in general, no trend in annual precipitation totals, except for a small increase in southwestern Canada and a small decrease in precipitation over Atlantic Canada. The positive trends in temperature (and hence in potential evapotranspiration) combined with almost no change in precipitation explain the generally negative trend in streamflow.

In an analysis of trend in annual streamflow for the United States during 1948–1988, *Lettenmaier et al.* [1994] showed negative trends in the northwest and positive trends in the middle and northeastern United States. Although the time period used in their study is different from ours, Lettenmaier's results are consistent with the trends shown for the 1947–1996 period in Figure 2.

3.2. Monthly Mean Streamflow

Monthly mean streamflow for most calendar months has decreased, with the strongest decrease in summer and autumn months (Table 2). From June to September the majority of stations showed decreasing trend, and there was almost no basin showing increasing trend significant at the 10% level. March and April show strong and significant increasing trends which are also field significant at the 10% level. Figure 3 presents the spatial distribution of monthly streamflow trends for April and September for each of the three study periods. Basins with significant positive trends in March (not shown) and April are predominantly located in southern British Columbia and the Atlantic region. Many prairie stations also showed positive trends in March. Significant negative trends are observed for August to October over southern British Columbia and for October, December, and February over the Atlantic region. These trends, positive in the spring and negative in the autumn, may indicate a shift in the annual cycle of the hydrologic regime. In the Atlantic region this shift is due to an increasing trend in total spring precipitation (all types) and a downward trend in spring temperature that are attributable to the interdecadal variation of the North Atlantic Oscillation. In other regions this shift is attributable to an earlier snow melt due to warmer spring temperatures [*Zhang et al.*, 2000a] that resulted in less water remaining in the basin later in the year, which caused a trend toward lower streamflow in summer and autumn.

The spatial distributions of trends in southern Canada for the autumn months match well with those published by *Lettenmaier et al.* [1994] for the northern United States. Lettenmaier showed significant negative trends in the northwest and significant positive trends for autumn streamflow in the northeast of the United States. *Lins and Michaels* [1994] also found significant positive trends in the northeastern United States for October mean streamflow. However, there are inconsistencies between the Canadian and U.S. studies in the spatial distribution of trends for the spring months. For example, according to *Lettenmaier et al.* [1994] the northwestern United States experienced significant negative trend for March and April streamflow during 1948–1988, while Figure 2 shows an increasing

Table 2. Percentage of Basins Showing Significant (at the 10% Level) Positive (PI) and Negative (PD) Trends in Annual and Monthly Mean Streamflow[a]

	1967–1996			1957–1996			1947–1996		
	PI	PD	FS	PI	PD	FS	PI	PD	FS
Annual	4.0	11.3	Y	4.2	8.5		4.3	14.9	Y
January	10.2	7.6	Y	7.9	13.2	Y	2.1	12.8	
February	8.8	10.7	Y	5.3	7.9		0.0	8.5	
March	13.6	5.6	Y	20.7	4.6	Y	13.7	2.0	
April	29.4	2.8	Y	23.4	2.1	Y	29.1	5.5	Y
May	4.5	14.5	Y	6.5	12.0	Y	6.9	8.6	
June	2.2	11.1		2.1	21.1	Y	6.9	22.4	Y
July	2.2	9.5		5.2	12.4	Y	3.5	12.3	
August	1.1	13.3	Y	1.0	10.1		3.5	5.3	
September	1.1	12.0	Y	1.0	16.7	Y	5.3	10.5	
October	3.3	6.5		9.9	18.8	Y	19.3	12.3	Y
November	4.2	4.8		10.2	4.5		16.0	2.0	
December	4.4	11.3	Y	2.5	6.2		4.1	16.3	Y

[a]A Y for FS indicates the trends are field significant at the 5% level.

trend in spring streamflow in southwestern Canada during 1947–1996. The inconsistencies may be due to the different time periods used in each study and/or to the influence of different climate processes, such as shifting in the Pacific storm track or the North Pacific westerlies [*Chen et al.*, 1996].

3.3. Annual Minimum and Maximum Daily Mean Streamflow

The spatial distribution of trends in annual minimum and maximum daily mean streamflow for each of three study periods are plotted in Figure 4. Significant negative trends are observed across much of southern Canada for maximum daily streamflow but are not observed consistently for minimum streamflow. However, northern British Columbia and the Yukon show significant increases in minimum daily streamflow. Positive, and statistically significant at the 10% level, trends are also found in maximum daily streamflow in northern British Columbia. The changes in both of those extreme daily mean streamflow variables are also field significant as indicated in Table 3.

Some general circulation model simulations of climate under increasing atmospheric CO_2 conditions [e.g., *Kattenberg et al.*, 1996] have suggested that we can expect to see more extreme events due to an enhanced hydrologic cycle. This has not been consistently observed in the Canadian streamflow data but should not be considered too surprising because the effect of a given change in precipitation and temperature varies considerably between catchments, depending on climate regime

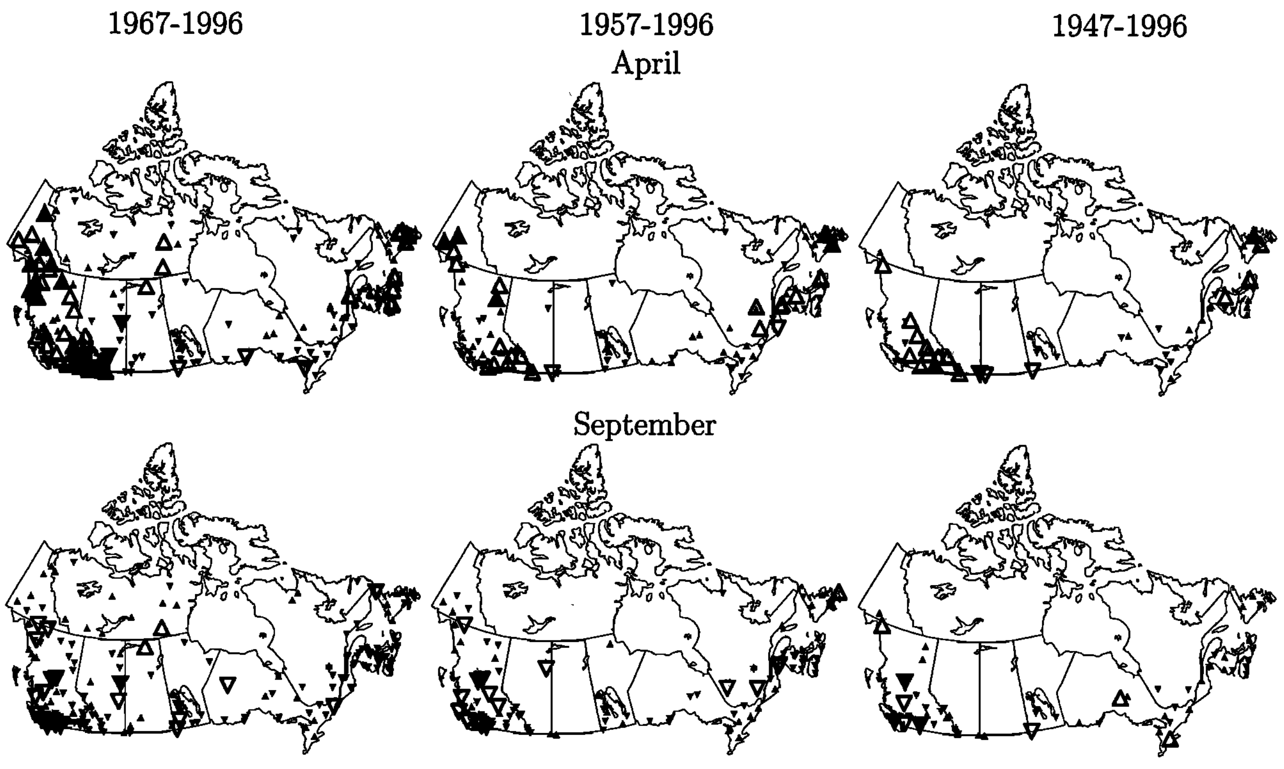

Figure 3. Same as in Figure 2 but for monthly mean streamflows for April and September.

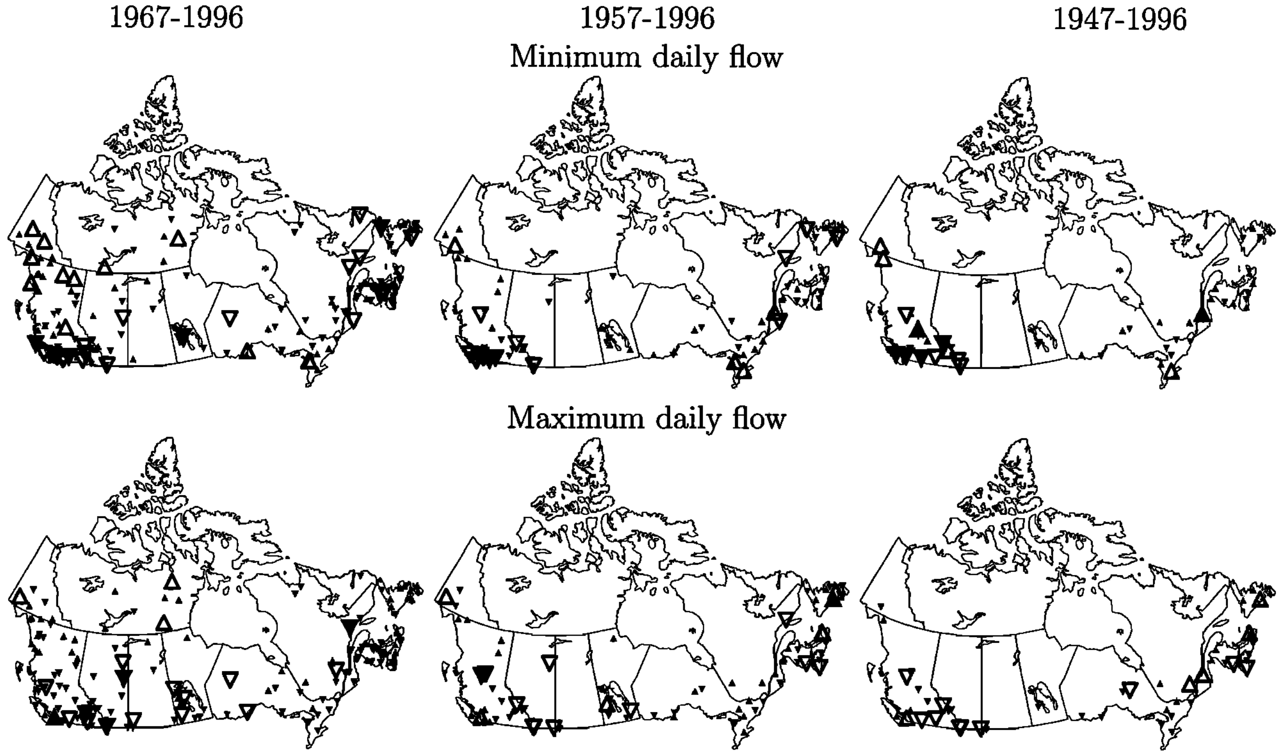

Figure 4. Same as in Figure 2 but for annual minimum and maximum daily streamflow.

and catchment physical and biological characteristics [e.g., *Arnell et al.*, 1996; *Georgievskii et al.*, 1996]. In fact, maximum daily streamflow appears to be decreasing where temperature is rising. Except for some rivers in southern British Columbia, peak streamflows, especially those in large basins, are generally associated with snowmelt. The earlier warming in spring results in earlier but more gradual snowmelt because of shorter length of day and lower Sun angle. In addition, there were no increasing trends in the number of heavy precipitation events or in the magnitudes of annual maximum daily precipitation across Canada [*Zhang et al.*, 2000b].

It should be mentioned that no systematic patterns were found in the trends of annual maximum daily streamflow in the United States [*Lins and Slack*, 1999], even though the proportion of total precipitation contributed by extreme, 1-day events has increased significantly during the twentieth century [*Karl et al.*, 1995; *Karl and Knight*, 1998].

3.4. Percentiles of Daily Mean Streamflow

Trend characteristics for a range of percentiles of daily mean streamflow for the year are summarized in Table 3 and mapped in Figure 5 for each of the three study periods. Trends are field significant in the lower quantiles from the annual minimum to the fortieth percentile daily flow over all three periods, except for the thirtieth percentile during 1947–1996. Trends are also field significant in the highest (ninetieth) percentile and the annual maximum daily mean streamflow. The spatial distributions of trends in the tenth, thirtieth, seventieth, and ninetieth percentiles of daily flow are displayed in Figure 5. Decreasing trends are dominant across southern Canada

Table 3. Same as Table 2 but for the Minimum, the Tenth, Twentieth, Thirtieth, Fortieth, Fiftieth, Sixtieth, Seventieth, Eightieth, and Ninetieth Percentiles and the Maximum of Daily Mean Streamflow

	1967–1996			1957–1996			1947–1996		
	PI	PD	FS	PI	PD	FS	PI	PD	FS
Minimum	8.4	14.4	Y	7.5	17.5	Y	10.2	16.3	Y
10%	9.0	16.8	Y	5.0	16.3	Y	16.3	12.2	Y
20%	13.8	12.0	Y	7.5	15.0	Y	10.2	12.2	Y
30%	7.8	12.0	Y	10.0	13.8	Y	6.1	8.2	
40%	5.4	12.0	Y	8.8	15.0	Y	14.3	8.2	Y
50%	5.4	9.0		10.0	11.3	Y	10.2	2.0	
60%	3.6	7.2		8.8	7.5		6.1	4.1	
70%	4.2	6.0		7.5	6.3		6.1	2.0	
80%	3.6	7.2		5.0	6.3		2.0	6.1	
90%	1.8	10.2		6.3	17.5	Y	2.0	24.5	Y
Maximum	2.4	11.4	Y	8.8	11.3	Y	10.2	28.6	Y

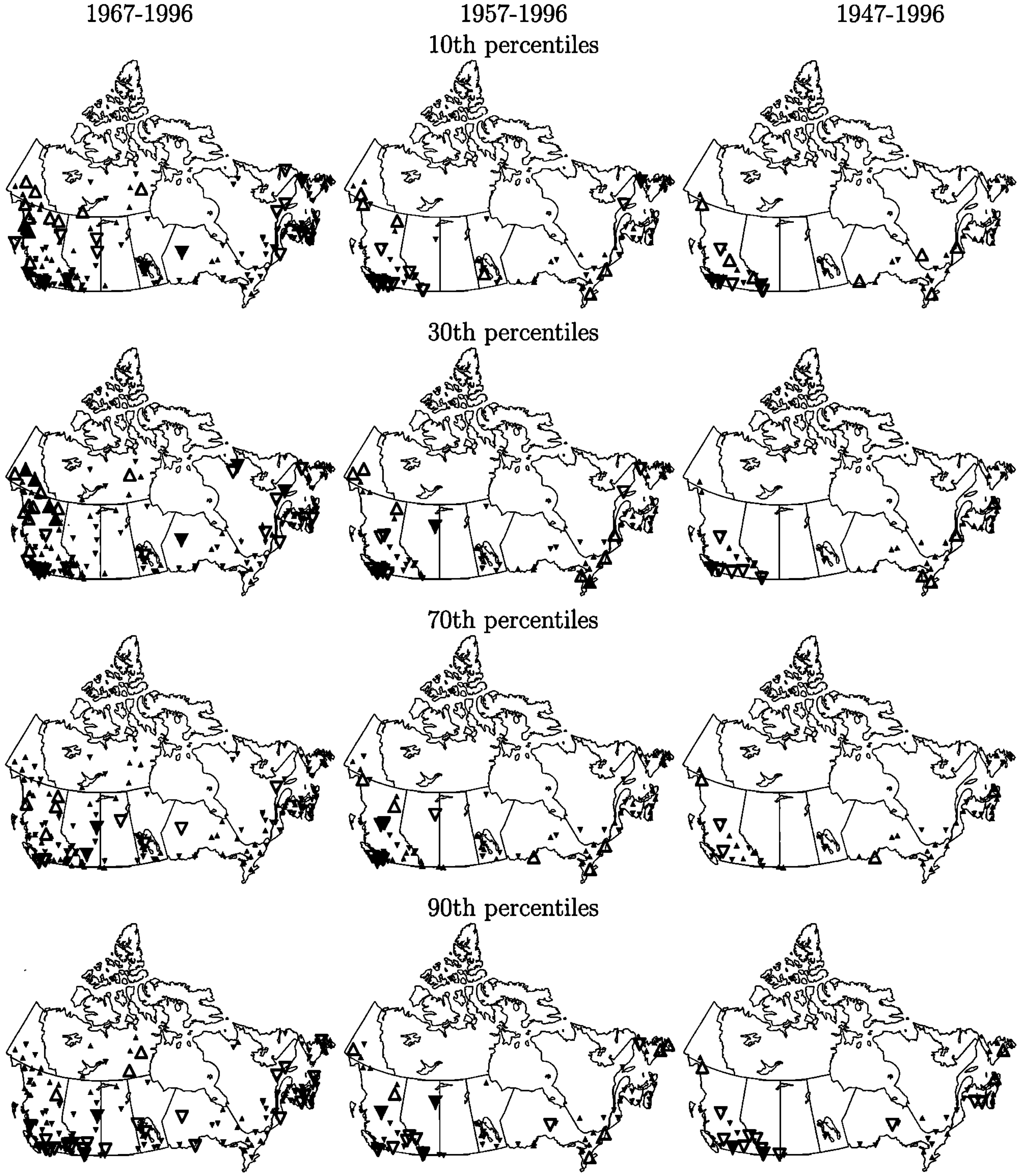

Figure 5. Same as in Figure 2 but for the tenth, thirtieth, seventieth, and ninetieth percentiles of daily mean streamflow.

and in southern British Columbia in particular. Positive trends prevail in northern British Columbia and the Yukon Territory. Nationally, the broad pattern is toward decreasing daily streamflow over the entire range of percentiles. This is consistent with the observed negative trends in annual mean streamflow.

A comparison of these results with those of *Lins and Slack* [1999] indicates consistency in the spatial distribution of trends. However, there are enough differences in trend characteristics across the range of percentiles of daily mean streamflow to suggest that regional climate plays an important role.

3.5. Comparison of Median and Mean Streamflow

Because of the large volumes associated with the higher moments of the daily streamflow distribution, trend in annual mean streamflow does not necessary reflect the trend in the

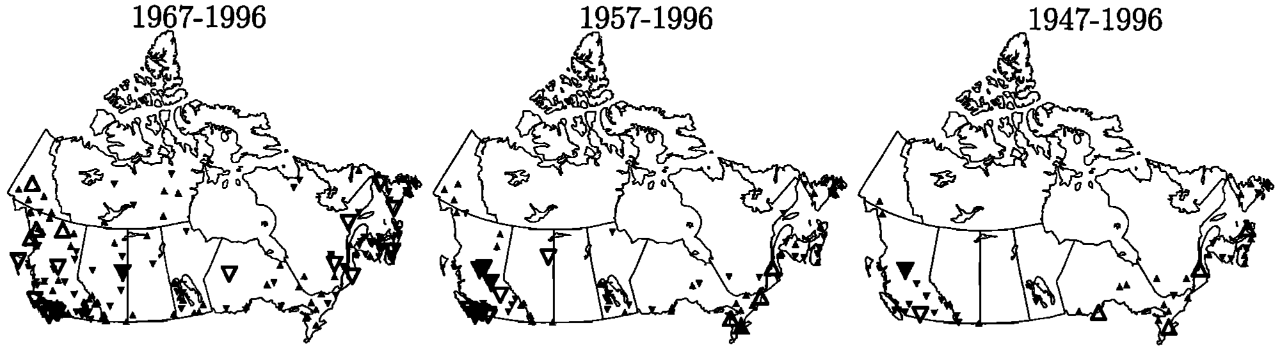

Figure 6. Same as in Figure 2 but for the median or the fiftieth percentiles of daily mean streamflow.

median of daily streamflow. Figure 6 displays trends in the median flow (fiftieth percentile) for the three periods. Comparing Figure 6 with Figures 2 and 5 for the three time periods shows that the spatial pattern of trends in annual mean streamflow (Figure 2) is much more similar to those for the ninetieth percentile (bottom of Figure 5) than those for the median flow. It is thus clear that trends in the mean annual flow are dominated by trends in the higher discharge quantiles, rather than by trends in discharge from average events.

4. Trends in Timing of Streamflow

4.1. Starting Date of Freshet Season

Figure 7 presents the characteristics of trend in the starting date of the freshet season, as defined in Table 1. Test statistics are summarized in Table 4 for each of the three study periods. A trend toward the earlier occurrence of the freshet season is dominant across Canada. During the last 30–50 years the beginning of the freshet season in many basins has advanced by more than a month (not shown). For all three periods, trends are field significant. The trend is especially strong in British Columbia.

The trend toward an earlier freshet season may be the result of warming spring temperatures observed in the last half of the twentieth century. During this period, spring temperatures significantly increased across Canada, with the exception of the northeast, where temperatures decreased [*Zhang et al.*, 2000a]. *Bonsal et al.* [2000] also observed a significant advancement in the starting date of the frost-free period, defined as the last date when the daily minimum temperature is below 0°C in the spring or early summer. Similar trends were also found in the last date when the daily maximum temperature is below the freezing mark.

Earlier, higher spring temperatures contribute to an earlier freshet season in two ways. Snow melts earlier, and more precipitation falls as rain instead of snow. In southern Canada, higher temperatures are associated with lower snow/precipitation ratios [*Davis et al.*, 1999]. In the last half of the twentieth century, there was no significant change in spring precipitation, but the ratio of snow to total precipitation significantly decreased [*Zhang et al.*, 2000a]. The resulting increase in spring rainfall may cause an increase in direct runoff and accelerate the snow melt process.

4.2. Date of Annual Maximum Daily Streamflow

Consistent with the trends observed for the freshet season, the date of annual maximum daily streamflow tends to be occurring earlier. The number of basins showing a negative trend (i.e., earlier date) is twice the number of basins with a positive trend (i.e., later date). Basins with significantly earlier dates of peak daily streamflow are located in the southern fringe of the country. Generally, the local significance of these trends is weak, and there is no field significant trend for any of the three study periods. A possible explanation is that not all flood events are snowmelt-related, and therefore not all will be affected by warmer spring temperatures.

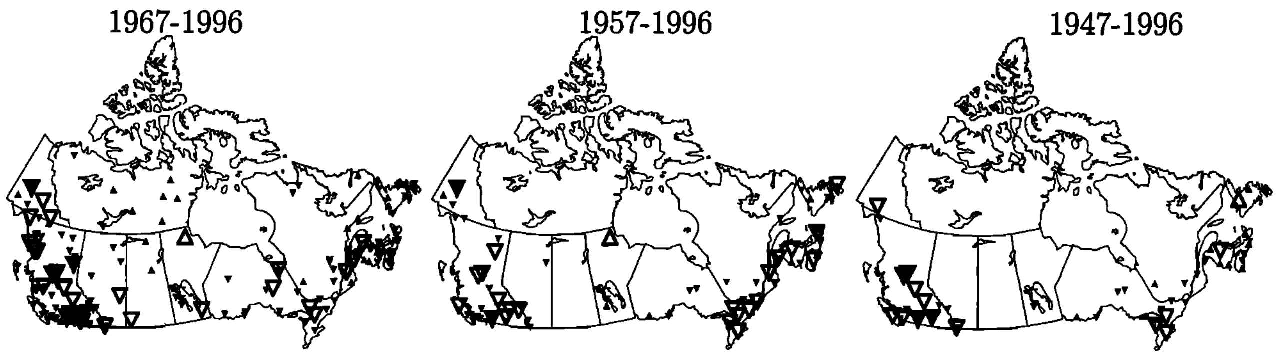

Figure 7. Trends in the starting date of the spring high-flow season. Upward and downward pointing triangles represent delaying and advancing trends, respectively. Trends significant at the 1% and 10% levels are marked by larger solid and open triangles, respectively. Smaller triangles indicate that trends are not significant at the 10% level.

Table 4. Percentage of Basins Showing Significant (at the 10% Level) Trends in the Timing of Freshet Season[a]

Period of Record	Earlier Freshet	Later Freshet	FS
1967–1996	20.0	0.6	Y
1957–1996	31.5	1.4	Y
1947–1996	31.1	2.2	Y

[a]A Y for FS indicates the trends are field significant at the 10% level.

4.3. Centroid of Annual Streamflow

Centroids of annual streamflow were investigated to further explore the significance of an apparent shift in the hydrologic regime. The centroid is defined as the date by which half of the annual total runoff has occurred. A negative trend in the centroid indicates a shift in the annual streamflow distribution toward an earlier date. In this study the number of basins exhibiting negative trends (centroid occurs earlier) is twice the number of basins with positive trend (centroid occurs later). Basins with negative trends are generally located in British Columbia and Atlantic Canada. Basins in central Canada, including the prairies and Ontario tend to have positive trends. Basins with statistically significant negative trends are concentrated in British Columbia. However, there was no evidence to suggest that the trends were field significant at the 5% level.

4.4. River Ice Conditions

Trend test results for the dates of river freeze-up and subsequent ice breakup and the number of days of ice cover are summarized in Table 5. The spatial distribution of the trends is displayed in Figure 8. There is a strong pattern of trends over the last 50 years. The percentage of basins exhibiting significant negative trends for date of freeze-up ranges from a low of 21.4 at 30 years to a high of 50.0 at 50 years of record. The trends are field significant. This is strong evidence indicating that many Canadian streams are tending to freeze up earlier in the year.

There is also good evidence to suggest that river ice break-up is occurring earlier in most regions of Canada. The exception is Atlantic Canada, where break-up is occurring at a later date. The spatial patterns are field significant for all three study periods.

The duration of ice cover appears to be increasing in a majority of basins, with the strongest and most statistically significant trend in eastern Canada. Such changes are mainly the result of earlier freeze-up dates. In addition, delaying ice break-up in Atlantic Canada is also a factor in the significantly longer ice cover periods observed in that region.

These trends in the timing of river ice conditions are consistent with the observed changes in surface air temperature. The spatial pattern of trends for ice break-up reflect well the changes in spring temperature, including the warming in the southwest and the cooling in the northeast. The trend toward earlier river freeze-up is likely related to the trend, over the last 50 years, of decreasing November mean temperature across Canada, decreasing October mean temperature in central Canada, and decreasing December temperature in northeastern Canada. More than 80% of the river freeze-up occurred during these months.

The lengthening of ice cover periods is also directly linked to changes in temperature. The ice cover period has been significantly prolonged for more than a month over eastern Canada and in Atlantic Canada in particular, where decreasing temperatures have been observed in both spring and fall. In the west, especially in British Columbia, the earlier occurrence of the start of both freeze-up and break-up results in no significant change in the length of ice cover period.

The trends observed in this study for river ice breakup are consistent with the findings of *Skinner* [1992], who examined lake ice characteristics of 49 Canadian sites for periods of 18 to 49 years. Results differ for fall freeze-up trends, however, perhaps because of differences in time periods.

5. Conclusions and Discussion

Trends have been observed in various hydroclimatic variables measured in Canadian rivers and streams since 1947. Systematic analyses of 30-, 40- and 50-year study periods provide us with a general picture of how the hydrology of Canada has changed in recent history. The results of these analyses are summarized in Table 6.

A trend of decreasing annual mean streamflow was found across southern Canada. Trends significant at the 10% level are also field significant. Significant increases across Canada, particularly pronounced in British Columbia and the Yukon, were identified in monthly mean streamflow for March and April. However, decreases in monthly mean streamflow are observed in the late summer and autumn months. The upward and downward trends in spring and autumn actually shifted the annual hydrologic cycle toward an earlier spring high-flow season.

Across most of Canada a decreasing trend is evident throughout the entire daily streamflow distribution. This indicates that the decrease in annual mean streamflow is associated with decreases in both high and low daily flow regimes, although trends in the annual mean flow better represent those in the higher quantiles of daily flow. It also indicates that Canada is not experiencing more extreme hydrological events.

There have been significant changes in the timing of both streamflow and river ice buildup and breakup. Significant increases in streamflow were observed during March and April, probably due to earlier spring snowmelt. River freeze-up is

Table 5. Percentage of Basins Showing Significantly (at the 10% Level) Later (PD) and Earlier (PI) Freeze-up, Breakup, or Shorter Ice Cover Period[a]

	1967–1996			1957–1996			1947–1996		
Period of Record	PI	PD	FS	PI	PD	FS	PI	PD	FS
Freeze-up	1.6	21.4	Y	0.0	38.2	Y	0.0	50.0	Y
Breakup	3.2	15.1	Y	9.1	21.8	Y	5.0	30.0	Y
Days with ice cover	14.3	5.6	Y	20.0	3.6	Y	30.0	5.0	Y

[a]A Y for FS indicates the trends are field significant at the 10% level.

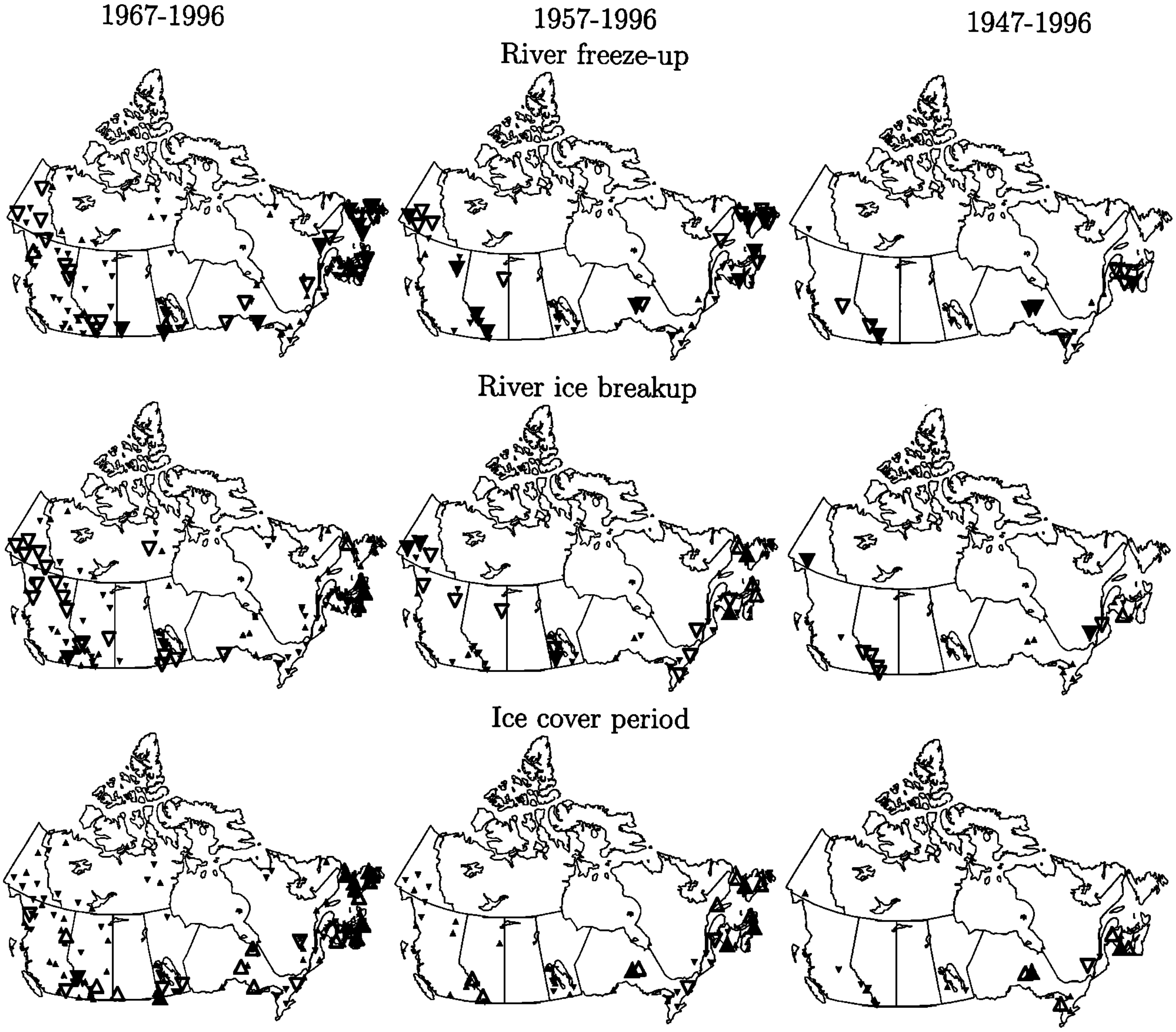

Figure 8. Trends in the dates of river freeze-up, river ice breakup, and periods of ice cover. Upward pointing triangle indicates a delay to the beginning of the freeze-up or breakup periods or to the lengthening of the ice cover period. Downward triangle indicates an earlier occurrence to the start of the freeze-up or breakup periods or to the shortening of the ice cover period. Trends significant at the 1% and 10% levels are marked by larger solid and open triangles, respectively. Smaller triangles indicate that trends are not significant at the 10% level.

occurring earlier in the fall across Canada. Ice breakup is occurring earlier in most regions of Canada but is occurring later in the Atlantic region. As a result, the periods of river ice cover are generally longer, especially in Atlantic Canada.

The observed trends in these hydroclimatic variables are consistent with those identified in previous regional studies [e.g., *Leith and Whitfield*, 1998; *Burn* 1994]. They are also consistent with those found in Canadian precipitation and temperature data sets. The decrease in annual mean streamflow in southern Canada is perhaps a direct result of an increase in mean temperature and an associated increase in evapotranspiration, with little or no change in precipitation. It was found that streamflow is not becoming more extreme with increasing temperature. Earlier breakup of river ice and increasing March and April streamflow are both related to warmer spring temperatures: Snow and ice melt earlier and, in addition, the proportion of rain to total precipitation increases, which, in turn, produces more direct runoff and accelerates snowmelt as the wet snowpack absorbs more radiation. There may also be a link between decreasing air temperatures in the autumn and the earlier buildup of river ice. Spatially, trends in annual and monthly mean streamflow and the distribution of daily streamflow are also broadly consistent with those observed in the United States near the Canadian-U.S. border [*Lettenmaier et al.*, 1994; *Lins and Michaels*, 1994]. It should be noted out that it is difficult to attribute exact causes to the trends in some variables, such as the decreasing trend in maximum daily mean streamflow, without additional detailed regional analyses. For example, a basin by basin comparison of trends observed in hydrological and climatic variables should help us to better understand the relationship on the underlying causes of trends in hydrological variables.

The RHBN streamflow data set provides an excellent foundation for trend detection studies, but limited record length

Table 6. Summary of Trends Detected

Variable	30-Year Trend? 1967–1996	40-Year Trend? 1957–1996	50-Year Trend? 1947–1996	Is Trend Field Significant?	Significantly Impacted Region(s)
Annual mean streamflow	decrease in southern Canada	decrease in southern Canada, except southern Ontario	decrease in southern Canada, except southern Ontario	no	southern British Columbia
Monthly mean streamflow	increase across Canada in March and April; decrease in summer and fall	increase across Canada in March and April; decrease in summer and fall	increase across Canada in March and April; decrease in summer and fall	yes, March and April, all study periods	southern British Columbia, Atlantic region
Annual minimum daily mean streamflow	decrease in southern Canada; increase in northern British Columbia and Yukon Territory	decrease in southern Canada; increase in northern British Columbia and Yukon Territory	decrease in southern Canada; increase in northern British Columbia and Yukon Territory	yes, for 40-year and 50-year trend	southern British Columbia
Annual maximum daily mean streamflow	decrease in southern Canada	decrease in southern Canada	decrease in southern Canada	yes, for 40-year and 50-year trend	southern British Columbia
Percentiles of daily mean streamflow	decrease in southern Canada; increase in northern British Columbia and Yukon Territory	decrease in southern Canada; increase in northern British Columbia and Yukon Territory	decrease in southwestern Canada	yes, below fortieth and above ninetieth percentile	southern British Columbia
Starting date of spring high-flow season	earlier across Canada	earlier across Canada	earlier across Canada	yes, for 40-year and 50-year trend	British Columbia
Date of annual maximum daily mean streamflow	earlier across Canada	earlier across Canada	earlier across Canada	no	extreme south
Centroid (date) of annual streamflow	earlier in British Columbia and Atlantic region; later in central Canada	earlier in British Columbia and Atlantic region; later in central Canada	earlier in British Columbia and Atlantic region; later in central Canada	no	British Columbia
Date of river freeze-up	earlier across Canada	earlier across Canada	earlier across Canada	yes, all study periods	Atlantic Canada
Date of spring ice breakup	earlier all regions except Atlantic	earlier all regions except Atlantic	earlier all regions except Atlantic	yes, for 40-year and 50-year trend	all regions
Duration of ice cover	generally longer, especially in Atlantic Canada	generally longer, especially in Atlantic Canada	longer, especially in eastern Canada	yes, for 30-year and 50-year trend	eastern Canada

and spatial coverage, especially in the north, was a problem. It is difficult to determine if the trends identified with the limited 30–50 years of data actually reflect the long-term tendency or interdecadal variation of hydroclimatic variables. The Northern Atlantic Oscillation, which exhibits strong decadal variability, has profound impacts on temperature in Atlantic Canada [*Shabbar et al.*, 1997]. The interdecadal variation of atmospheric-oceanic circulation over the North Pacific is known to impact climate over North America [e.g., *Chen et al.*, 1996] and the west coast in particular. The strongest changes in all hydroclimatic variables analyzed in this study were observed in British Columbia and the Yukon Territory. A more detailed analysis of this region, using a century-long precipitation and temperature data set [*Zhang et al.*, 2000a], proxy data for the region [*Luckman and Watson*, 1999; *Luckman et al.*, 1997], and additional hydroclimatic information, may shed additional light on the nature of causes of the trends.

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