Precipitation trends contribute to streamflow regime shifts in northern Canada

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Abstract Autumn runoff events rivalling the size of the spring freshet peak as well as sustained winter streamflow have become more common in the northwestern Canadian Shield since the mid 1990s. Previous circumpolar and large regional-scale studies have implied these phenomena are due to increased water inputs from thawing permafrost. However, results from an investigation of the precipitation and temperature trends provide an alternate explanation for this region. A shift from a nival to a combined nival/pluvial streamflow regime, particularly in small watersheds, can be attributed to trends in the timing and state of autumn precipitation. Because these trends are subtle, careful consideration of hydrological processes, and the temporal and landscape context in which they operate, is important when attempting to explain the observed shifts in regional streamflow. It is important to correctly explain why streamflow regimes are changing because of close relationships with variations in ground thermal conditions and aquatic chemistry, which are of significance to society. These relationships are discussed.

Key words streamflow; precipitation; trends; shifts; Canadian Shield; permafrost

INTRODUCTION

The last half century in the circumpolar north has been characterized by relatively rapid environmental change (Arctic Council, 2005) including the increase of cold season streamflow in watersheds with subarctic nival streamflow regimes (Smith *et al.*, 2007). While most have speculated about the mechanisms behind this increase (e.g. St. Jacques & Sauchyn, 2009), only a few studies have focused on understanding the process and drivers of seasonal hydrological change (Jones & Reinhart, 2010) which are likely to vary across scales and environments (Rawlins *et al.*, 2009). This study focused on the subarctic Precambrian Shield portion of the Canadian Northwest Territories to evaluate if climatic mechanisms could be responsible for streamflow change in this particular region. Many large regional studies evaluate relatively coarse climate data (i.e. annual or seasonal). However, only subtle changes in precipitation and temperature are needed in cold regions to enact significant hydrological changes. In this study, monthly data are evaluated to determine if: (1) there have been changes to the streamflow regimes in the northwestern portion of the subarctic Canadian Shield, and, if so, (2) whether these changes are due to changes in climatic drivers.

DATA AND METHODS

Streamflow data were obtained for the period of record from the four longest operating hydrometric stations in the region (http://www.wsc.ec.gc.ca/hydat /H2O/index_e.cfm) (Table 1). Monthly precipitation and temperature data that overlapped the geographic extent of the basins gauged by these four hydrometric stations (bounded by 62°N, 112.5°W, 66°N, 115.5°W) were extracted from the CANGRID data set (Louie *et al.*, 2002). This experimental Meteorological Service of Canada data set provides precipitation and temperature values across Canada at a 50-km resolution. There is uncertainty associated with this data set. All the gridded precipitation data products available for northern Canada rely on the same sparse network for calibration, but CANGRID is the only one to address undercatch and homogeneity (Mackay *et al.*, 2003), a key source of precipitation estimation error in northern Canada (Metcalfe *et al.*, 1994). The selected four hydrometric gauges represent a spectrum of catchment areas to permit investigation of spatial scale effects on regime change. Analyses were performed on monthly data averaged from daily

Table 1 Traits and statistics for the selected streams. Standard normal variate (*Z*) for trends significant at 90% are in bold and the change points detected with a probability of greater than 70% are listed. Q_f/Q_a is the fraction of basin yield provided in May and June (June and July for Cameron and Snare rivers) and Q_w/Q_a is the fraction of basin yield during winter (October–March).

Station Name	Baker Creek		Cameron River		Indin River		Snare River	
Station ID	07SB013		07SB010		07SA004		07SA002	
Record period	1972–2009		1976–2009		1977–2009		1985–2009	
Location Lat.:	62°30.8′N		62°29.5′N		64°23.3′N		63°58.4′N	
Location Long.:	114°24.3′W		113°32.2′W		115°1.3′W		115°26.0′W	
Area (km^2)	155		3630		1520		13300	
Lake fraction	0.18		0.18		0.04		0.10	
Statistic	*Z*	Shift	*Z*	Shift	*Z*	Shift	*Z*	Shift
January	**3.0**	1997	**3.0**	n/a	2.0	n/a	0.1	n/a
February	**3.1**	1997	**3.1**	n/a	1.6	n/a	0.3	n/a
March	**3.3**	n/a	**3.1**	n/a	**2.7**	1997	0.7	n/a
April	**2.3**	1997	**2.9**	n/a	**2.4**	n/a	0.9	1997
May	0.8	n/a	**2.0**	n/a	–0.3	n/a	0.1	n/a
Jun	0.5	n/a	1.0	n/a	0.5	n/a	–0.9	1998
July	–0.9	n/a	1.0	n/a	0.3	n/a	–0.8	n/a
August	–0.7	n/a	1.6	n/a	0.5	n/a	–0.8	n/a
September	–0.4	n/a	1.7	n/a	1.5	n/a	–0.8	n/a
October	0.5	n/a	**2.6**	n/a	1.8	n/a	–0.3	1997
November	**1.7**	n/a	**3.0**	n/a	1.9	n/a	–0.1	n/a
December	**2.7**	n/a	**2.8**	n/a	2.0	n/a	0.2	n/a
Before/following 1997	<1997	>1997	<1997	>1997	<1997	>1997	<1997	>1997
Q_f/Q_a	0.76	0.50	0.33	0.27	0.55	0.52	0.30	0.30
Q_w/Q_a	0.07	0.19	0.19	0.21	0.08	0.11	0.17	0.21

extracted values. Gradual changes in the mean (i.e. trends) were analysed using the non-parametric Mann-Kendall test with pre-whitening (Mann, 1945; Kendall, 1975; Yue *et al.*, 2002) often used with hydrological data because it is thought to be more suitable for non-normally distributed and censored hydro-meteorological time series. Shifts (i.e. abrupt changes in the mean) were identified using a Bayesian change-point detection model (Seidou & Ouarda, 2007; Ehsanzadeh *et al.*, 2010).

RESULTS

Analysis of monthly precipitation revealed only two significant trends at the 90% confidence level. Precipitation in September is increasing (Z score = 2.0) but decreasing in October (Z score = –1.8). There were upward shifts in precipitation in January, February and April, all in 1997. Temperature trends were limited to January and December (Table 2), which were both positive. The trend in December temperature was interpreted as an upward shift in 1997 by the Bayesian change-point detection model. Upward shifts in temperature were also detected in 1995 (February) and 1991 (March). The overall upward temperature trends and wetter conditions in the autumn have also been recently documented by Zhang *et al.* (2011).

The summer storage deficits that accumulate in this landscape occur because of low precipitation to evapotranspiration ratios (Spence & Rouse, 2002) that prevent a basin runoff response until ~100 mm of rainfall has fallen between mid-July and the end of October (Fig. 1(a)). The observed increase in September precipitation was offset by a reduction in October precipitation. This is the period during which the 0°C air temperature threshold is crossed so that precipitation in September tends to fall as rain, whereas in October it accumulates as snow (Fig. 1(b)). Any increase in rain is not due to an increase in autumn temperatures because no statistically significant trend or shift was found. A trend towards earlier autumn precipitation has resulted in an increase in the frequency with which the rainfall threshold of ~100 mm has occurred

Table 2 Traits and statistics for the subset of the CANGRID domain. Standard normal variate (*Z*) for trends significant at 90% are in bold and the change points detected with a probability of greater than 70% are listed.

	Precipitation		Temperature	
Statistic	*Z*	Shift	*Z*	Shift
January	0.9	1997	**1.7**	n/a
February	0.2	1997	1.0	1995
March	1.1	n/a	0.6	1991
April	0.2	1997	1.0	n.a
May	–0.7	n/a	–1.2	n/a
Jun	0.6	n/a	0.1	n/a
July	0.7	n/a	1.0	n/a
August	0.8	n/a	0.5	n/a
September	**2.5**	n/a	1.0	n/a
October	**–1.8**	n/a	1.1	n/a
November	1.5	n/a	1.2	n/a
December	0.8	n/a	**1.9**	1997

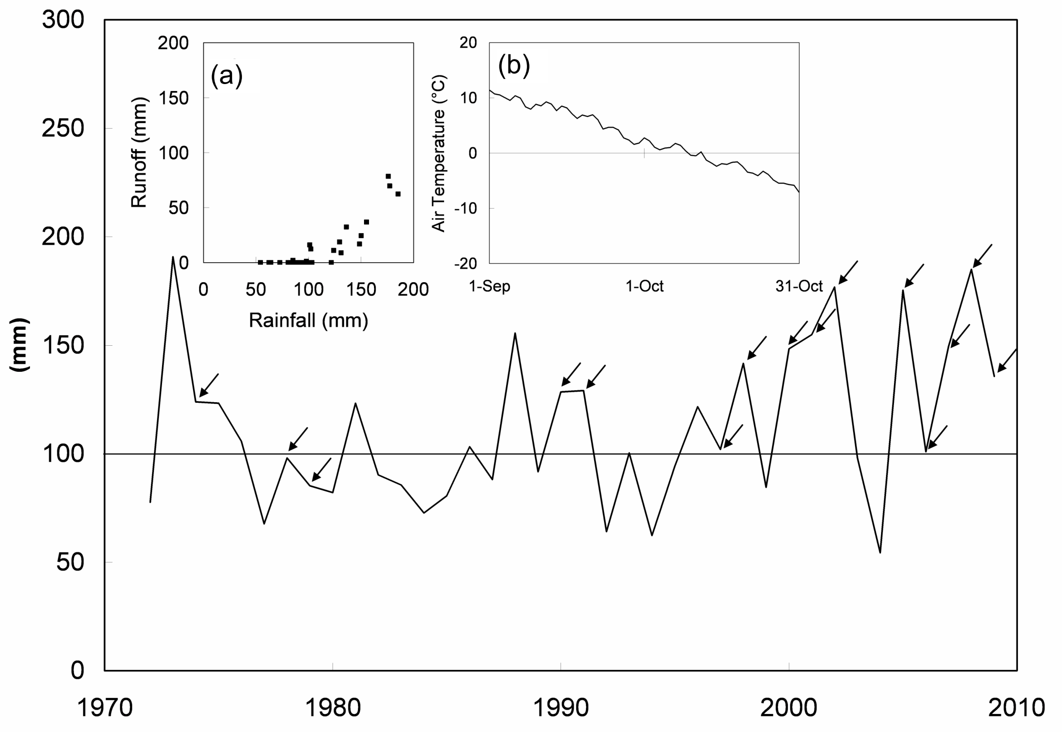

Fig. 1 Seasonal rainfall (15 July–31 October) at Yellowknife. The increased frequency with which autumn runoff was generated is demonstrated by the increase in the number of arrows denoting those years with autumn runoff events since 1997. The black horizontal line is the threshold evident in inset (a) at which runoff tends to be generated. Insets illustrate: (a) the threshold mediated nature of runoff response to seasonal rainfall, and (b) mean daily air temperatures at Yellowknife in September and October for the period of record under study.

since 1997 (Fig. 1). Threshold driven responses, such as runoff generation, can be highly influenced by small changes in forcing variables near the threshold (Zehe *et al*., 2005), and over longer periods this can account for significant trends and shifts in streamflow (McClelland *et al*., 2004).

Discharge trends in cold season months were common to all streams except the Snare, and they were all of similar magnitude. The combined data from the four rivers yielded 148 record-years of hydrometric data, but shifts were only detected in 1997 and 1998 (Table 1). Dividing the period of record into pre- and post-1997 may provide insight into changes in the streamflow regime of the region. An increase in the fraction of discharge in the cold season (Q_w/Q_a) was consistent among all four streams since 1997 (Fig. 2). At the smallest scale (Baker Creek), yield distribution during the spring freshet and winter before (after) 1997 was 76% (50%) and 7% (19%), respectively (Table 1). Annual hydrographs from Baker Creek do not display the classic nival streamflow regimes that they once did, as there are now frequent secondary peaks that rival the freshet in magnitude, with recessional limbs extending well into the winter season. Mean monthly Baker Creek streamflow (± two standard deviations) in January through April since 1997 is outside the range documented before 1997. Early winter streamflow becomes attenuated by large lakes in the larger basins, and the yield distribution does not change at these scales. However, secondary autumn peaks are relatively common so that the smooth and consistent recessions between annual snowmelt runoff events in basins of >1000 km^2 are now being represented by uneven recession curves (Fig. 2). As with late winter streamflow in Baker Creek, post-1997 mean October streamflow (± two standard deviations) in the larger rivers is outside the range observed before 1997.

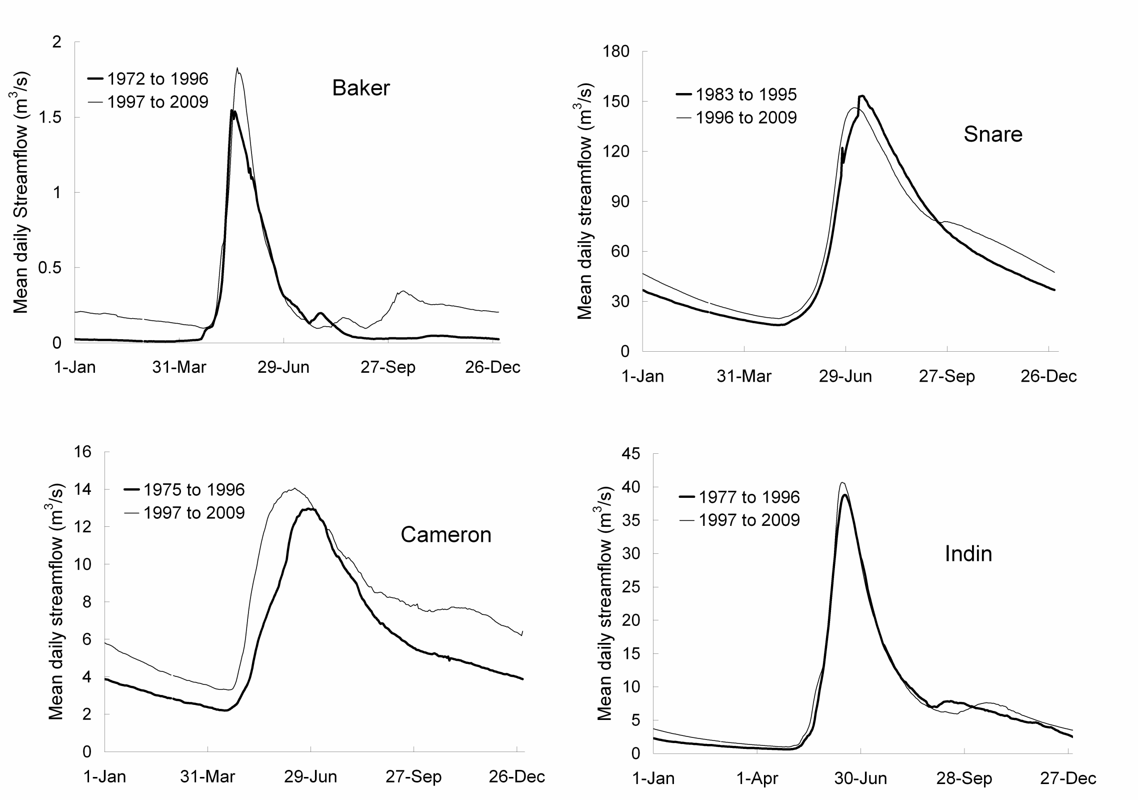

Fig. 2 Average annual hydrographs at each gauge before and since 1997.

DISCUSSION

The results indicate a shift from a nival to a combined nival/pluvial streamflow regime at the small basin scale in this region. This does not manifest in the larger basins of the subarctic Canadian Shield. Watersheds of different sizes may exhibit different streamflow regimes within the same physioclimatic region because of the relative dominance of different hydrological processes with changes in scale. Even though the lake fraction in the Cameron, Baker and Snare watersheds is similar (Table 1), the larger Cameron and Snare watersheds each contain at least two lakes larger than the entire Baker Creek watershed. The presence of large lakes creates a situation where streamflow attenuation is such a significant process that the streamflow regime becomes prolacustrine. This regime is perhaps more resilient to change than the nival regime common to smaller watersheds that are influenced more by hillslope processes.

The changes in the precipitation regime documented here are subtle, but changes near 0°C can have dramatic hydrological effects (Quinton & Carey, 2008). Observed streamflow changes between small and large watersheds were different because of different predominant hydrological processes acting at different scales. Furthermore, small changes in atmospheric circulation patterns that are known to influence northern Canadian streamflow, such as the specific location of cyclones south of the Aleutian Islands (Dery *et al*., 2009), are not always resolved by many currently available circulation indices (Overland & Wang, 2005). These factors, and perhaps others, mean the relationships between northern Canadian streamflow and circulation indices are complex (Woo & Thorne, 2008), and that caution should be exercised when predicting any future changes to northern streamflow regimes in specific locales.

The impacts of increasing autumn rainfall extend beyond shifts in streamflow regimes. Increasing early winter soil moisture with heavier autumn rains, in conjunction with observed trends towards a deeper thawed layer (Burn & Kokelj, 2009) can further prolong active layer freezeback (Osterkamp & Romanovsky, 1999). The precipitation trends documented in this study in conjunction with warming permafrost are likely to have significant hydrogeochemical consequences. Thawing of near-surface permafrost can make previously sequestered soluble materials available for transport by late season runoff (Kokelj & Burn, 2003). The rise in late summer rainfall and early winter runoff, in correspondence with the increased duration of active layer freezeback, suggests that the winter solute flux from terrestrial to aquatic environments may be amplified. It is likely that the net effects of these changes would be an increase in stream nutrient and solute loads (Frey & McClelland, 2009). Through multidisciplinary efforts, small basin hydrological research is needed to test the hypothetical drivers of changing hydrological and geochemical flux in streams across a range of northern environments.

CONCLUDING REMARKS

A trend towards more autumn rainfall in the northwestern subarctic Canadian Shield has been sufficient to permit a more frequent exceedence of runoff generation thresholds, causing late season peaks in discharge and higher winter baseflows. The emergence of a new nival/pluvial regime in small subarctic Canadian Shield streams is causing an increase in the relative winter discharge yields and it is most clearly manifested in small watersheds. Streamflow responses to climate change differ across the diverse circumpolar north because each landscape filters precipitation differently. The results presented here also imply that basins of different sizes filter precipitation differently. Therefore, assumptions that do not account for the distinct physical processes acting within landscapes and across scales will result in poor analysis of the regional impacts of climate change. Because of the integrated nature of relationships between autumn precipitation, streamflow, ground thermal regimes and aquatic chemistry, it will be important to consider these physical processes if sound information is to be generated for present and future environmental conditions in cold regions.

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