GEOPHYSICAL RESEARCH LETTERS, VOL. 36, L01401, doi:10.1029/2008GL035822, 2009

Increasing winter baseflow and mean annual streamflow from possible permafrost thawing in the Northwest Territories, Canada

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Received 28 August 2008; revised 12 November 2008; accepted 20 November 2008; published 10 January 2009.

[1] Increasing surface air temperatures from anthropogenic forcing are melting permafrost at high latitudes and intensifying the hydrological cycle. Long-term streamflow records ($\geq$30 yrs) from 23 stream gauges in the Canadian Northwest Territories (NWT) indicate a general significant upward trend in winter baseflow of 0.5–271.6 %/yr and the beginning of significant increasing mean annual flow (seen at 39% of studied gauge records), as assessed by the Kendall-τ test. The NWT exports an average discharge of $\geq$308.6 km^3/yr to the Beaufort Sea, of which $\geq$120.9 km^3/yr is baseflow. We propose that the increases in winter baseflow and mean annual streamflow in the NWT were caused predominately by climate warming via permafrost thawing that enhances infiltration and deeper flowpaths and hydrological cycle intensification. To provide hydroclimatic context, we present evidence of a statistically significant positive link between the Northern annular mode and annual NWT streamflow at the interannual-to-decadal timescales.

Citation: St. Jacques, J.-M., and D. J. Sauchyn (2009), Increasing winter baseflow and mean annual streamflow from possible permafrost thawing in the Northwest Territories, Canada, *Geophys. Res. Lett.*, *36*, L01401, doi:10.1029/2008GL035822.

1. Introduction

[2] The hydrology of subarctic northern watersheds is changing in response to recent anthropogenic global warming [*Hinzman et al.*, 2005]. Climate model results predict the intensification of the hydrological cycle and increased river discharge in subarctic and arctic regions [*Milly et al.*, 2005]. Increasing annual flows to the Arctic Ocean have been detected in Eurasian rivers [*Peterson et al.*, 2002; *McClelland et al.*, 2006]. However, decreasing annual flows to the Arctic Ocean have been shown for rivers discharging into Hudson, James and Ungava Bays [*Déry et al.*, 2005]; and basically unchanged annual flow to the Arctic Ocean shown for northern Canadian rivers [*Déry and Wood*, 2005]. The closely related topic of groundwater behavior in permafrost is an understudied subject which will become increasingly important as permafrost, an effective recharge barrier, continues to decay [*Smith et al.*, 2007; *Walvoord and Striegl*, 2007]. Rising minimum daily flows have been detected in northern Eurasian rivers and attributed to a growing influence of groundwater in the high-latitude hydrologic cycle [*Smith et al.*, 2007]. Long-term streamflow records of the Yukon River basin indicate a general significant upward trend in winter baseflow and presumably groundwater contribution to streamflow and little upward trend in annual flow [*Walvoord and Striegl*, 2007]. The first goal of this paper is to examine a geographically comprehensive set of the most recent and longest-term instrumental streamflow records from the neighboring Northwest Territories (NWT), Canada, for any similar increases in winter baseflow and mean annual flow. We pay particular attention to rivers whose watersheds are entirely subarctic, a relatively understudied region.

[3] The hydrology of the NWT has been monitored for a shorter time period relative to that of Eurasia [*Lammers et al.*, 2001]; making it difficult to assess recent changes relative to natural variability. To better understand the climatic drivers of NWT hydrology, and to provide a context for any detected changes in annual flow or winter baseflow, this paper has the second goal of investigating teleconnections between the instrumental hydrometric records and various large-scale atmospheric anomalies such as the Northern annular mode (NAM) [*Thompson and Wallace*, 1998, 2000], the Pacific Decadal Oscillation (PDO), the Pacific North American pattern (PNA), and the El Nino-Southern Oscillation (ENSO). This will provide needed information on the processes that must be resolved by regional and global climate models to accurately project the future state of the terrestrial water budget.

2. Study Area

[4] The NWT is underlain by continuous, discontinuous and sporadic permafrost [*Brown et al.*, 1997] (Figure 1). The subarctic continental climate is characterized by short cool summers and long cold winters. It is relatively dry, although much surface freshwater is present in rivers, wetlands and lakes. For instance, at Yellowknife average daily temperatures are 16°C in July and −29°C in January (Adjusted Historical Canadian Climate Data, Environment Canada, http://www.cccma.bc.ec.gc.ca/hccd). Precipitation averages 265 mm, with ~55% falling as snow. Climate and streamflow records from the NWT are sparse and of short duration.

3. Data and Methods

[5] Twenty-three streamflow gauging stations in the NWT were selected for analysis from the Water Survey of Canada (HYDAT) database http://www.wsc.ec.gc.ca/), attempting to ensure the geographically broadest, longest-term coverage (Table 1). All are 12 month records spanning at least 30 years, and end at the present (2007), except for the Taltson River (1953–1997). The lengths of the records vary. The longest record, the Yellowknife River, is 69 years in length. All 23 rivers have watersheds located in permafrost

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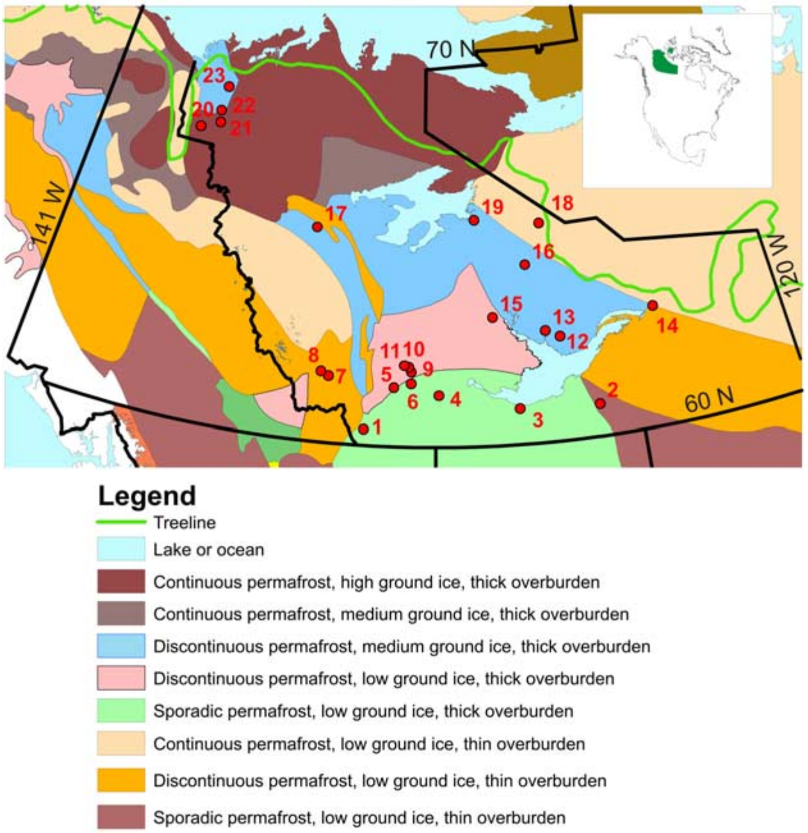

Figure 1. Map of the 23 river gauges and permafrost extent and type, ground ice content and overburden thicknesses for the Northwest Territories (NWT), Canada. Thumbnail shows location of the NWT (green fill) relative to North America.

Table 1. Northwest Territory, Canada, Streamflow Stations, Winter Baseflow and Mean Annual River Flow Rates, Baseflow Contribution to Annual Flow and Trend Analysis Results[a]

			Winter Baseflow			Annual River Flow			
Streamflow Station	Map ID	Period of Record	Mean m^3/s	Total Change Over Period of Record (%)	Average Change/yr (%)	Mean m^3/s	Total Change Over Period of Record (%)	Average Change/yr (%)	Baseflow Contribution (%)
Liard River at Fort Liard	1	1966–2007	351.4	***29.5***	***0.7***	1946.5	7.5	0.2	18.1
Taltson River at outlet of Tsu Lake	2	1963–1997	143.8	6.7	0.2	186.9	41.3*	1.3*	76.9
Hay River near Hay River	3	1964–2007	5.0	***174.4***	***4.0***	112.3	32.8*	0.7*	4.4
Trout River at Highway No. 1	4	1970–2007	1.8	undefined[b]	***+0.07 $m^3/s/yr$***	38.7	***77.8***	***2.0***	4.7
Birch River at Highway No. 7	5	1975–2007	0.05	***3122.6****	***94.6****	2.7	***96.9***	***2.9***	1.9
Jean-Marie River at Highway No. 1	6	1973–2007	0.3	***205.9****	***5.9****	4.8	***145.0***	***4.1***	6.3
Flat River near the mouth	7	1973–2007	17.1	***41.8****	***1.2****	95.5	14.2	0.4	17.9
South Nahanni River above Virginia Falls	8	1970–2007	33.3	***65.7***	***1.7***	226.3	5.4	0.1	14.7
Liard River near the mouth	9	1973–2007	477.2	***31.5***	***0.9***	2488.6	6.7	0.2	19.2
Mackenzie River at Fort Simpson	10	1965–2007	2777.4	***30.4***	***0.7***	6864.0	*7.9*	*0.2*	40.5
Martin River at Highway No. 1	11	1973–2007	0.3	***9505.0***	***271.6***	7.9	***103.4***	***3.0***	3.8
Cameron River below Reid Lake	12	1976–2007	3.6	***137.9***	***4.3***	6.5	***105.3***	***3.3***	55.4
Yellowknife River at inlet to Prosperous Lake	13	1939–2007	22.3	***86.4***	***1.3***	29.4	*35.1*	*0.5*	75.9
Lockhart River at outlet of Artillery Lake	14	1964–2007	106.3	6.7	0.2	125.3	15.9*	0.4*	84.8
La Martre River below outlet of Lac La Martre	15	1977–2007	24.1	***251.7***	***8.1***	33.8	***120.5****	***3.9****	71.3
Indin River above Chalco Lake	16	1978–2007	1.7	***106.0***	***3.5***	8.0	24.8	0.8	21.2
Mackenzie River at Norman Wells	17	1966–2007	3404.5	***21.3***	***0.5***	8512.6	0.3	0.006	40.0
Coppermine River at outlet of Point Lake	18	1966–2007	54.0	0.7*	0.02*	107.9	0.0	0.0	50.0
Camsell River at outlet of Clut Lake	19	1964–2007	88.7	***41.3***	***0.9***	102.4	***43.5****	***1.0****	86.6
Peel River above Fort McPherson	20	1975–2007	92.3	***60.9***	***1.9***	692.0	−3.4	−0.1	13.3
Mackenzie River at Arctic Red River	21	1973–2007	3740.2	***26.3***	***0.8***	9094.2	3.5	0.1	41.1
Rengleng River below Highway No. 8	22	1978–2007	0.04	***6367.7***	***212.3***	3.1	24.9	0.8	1.2
Mackenzie River at Inuvik	23	1973–2007	25.7	***157.0***	***4.5***	137.0	15.3	0.5	18.8

[a] Stations listed according to increasing north latitude. Raw data used for trend analysis. Infilled data used for Portmanteau test (see text for details). Percentage changes derived from the Theil-lines. Italicized, bolded, and underlined values indicate statistical significance of $p \leq 0.1$, $p \leq 0.05$, and $p \leq 0.01$, respectively. * denotes a positive test at the $p \leq 0.05$ level for serial correlation in trend, suggesting statistical significance may be inflated.

[b] Theil trend-line initially negative; therefore annual increase in Theil trend-line reported instead.

regions (Figure 1). Most were free from flow regulation with the exceptions of the four gauges on the Mackenzie River (naturalized following *Déry and Wood* [2005]), the Yellowknife (a power-plant) and the Taltson. The total drainage area of these 23 rivers is 1.8×10^6 km^2.

[6] The gauges are remote and frequently do not have complete records. At most 12% of the monthly mean flows were missing over the period of record. Missing data were therefore inferred using linear least-squares regression from: (1) another gauge on the same river; or (2) another gauge on a geographically nearby river whose record was highly correlated to that being infilled. Where neither of the above was possible and most of a year's monthly means were available, the monthly mean over the period of record was used for the missing data.

[7] Surface runoff during winter is negligible due to freezing conditions. Assuming that all flow measured under ice from January 1 to March 31 derives from subsurface flow, calculated average flow rate over this time period was used to estimate winter baseflow rate [*Walvoord and Striegl*, 2007]. Winter baseflow is defined to include all subsurface flow, presumably from groundwater. *Walvoord and Striegl* [2007] warn that using winter (Jan. 1–Mar. 31) flow as a proxy for baseflow errs on the low side because shallow subsurface flow probably increases during warmer months. Baseflow contribution to total annual flow was estimated by dividing the mean flow (m^3/s) for winter (Jan. 1–Mar. 31) by the annual mean flow (m^3/s), with the winter and annual mean flows averaged over the individual periods of record.

[8] Long-term trends in winter baseflow and mean annual flow over the entire period of record were assessed by the non-parametric Kendall-τ test and approximated using robust Theil-lines [*Burn*, 1994; *Helsel and Hirsch*, 2002]. The residuals were tested for serial correlation using the Portmanteau test. The magnitude of the changes in estimated winter baseflow and mean annual flow over the period of individual record were calculated by the Theil-line and reported as both total percentage changes from the beginning of record, and *per annum*. Both the raw and infilled data were examined for trends. The infilled data were examined for serial correlation. A significance level of $p \leq 0.1$ was used in trend and correlation detection [*Smith et al.*, 2007]. Because the Kendall-τ test applied to differing time periods of analysis can lead to imprecise conclusions [*McClelland et al.*, 2006], trends over 1978–2007 (the longest common time period) were also assessed by the Kendall-τ test for all rivers except the Taltson. In order to explore the driving factors of any increased annual flows, rivers which showed increasing mean annual flow were also analyzed for trends in monthly mean flows using the Kendall-τ test.

[9] To better understand the climatic controllers of natural hydrological variability, the annual infilled river runoff data were then compared to the time series of the annual mean NAM, Multivariate ENSO Index, Southern Ocean Index, Nino 3.4 Index, winter averaged (Nov.–Mar.) PDO and PNA indices obtained from Earth Systems Research Laboratory (National Oceanic and Atmospheric Administration, 2008, http://www.cdc.noaa.gov/ClimateIndices/). Since streamflow is naturally lagged and smoothed from precipitation by surface and subsurface hydrological processes, and large-scale climatic phenomena act most prominently at inter-annual time scales, the streamflow data were lagged relative to the climate indices by 0, ±1, ±2 years, and a binomial smoother of five years was applied to both the stream and climate data.

4. Results

[10] Estimates of baseflow contribution to total annual flow at the 23 stations averaged over the individual periods of record range from 1.2–86.6% (Table 1). Based on records from the furthest downstream stations, the NWT exports at least 120.9 km^3/yr of baseflow annually to the Beaufort Sea, from an average discharge of at least 308.6 km^3/yr. These are underestimates as a number of the most northern rivers do not have year-round long-term records. Baseflow contributes ~41% of the Mackenzie River discharge to the Arctic Ocean (Table 1).

[11] Twenty of the 23 long-term records showed a significant upward trend in winter baseflow over the full period of record, ranging from 0.5%/yr to 271.6%/yr (Table 1); all of these were significant at the $p \leq 0.05$ level (Figure 2a). All four gauges on the Mackenzie River showed a significant increase in winter baseflow. The remaining three records showed a non-significant increasing trend. The trend is seen among watersheds in continuous, discontinuous and sporadic permafrost on thick overburden (Figure 1). This significant increasing winter baseflow result holds across the NWT, except for the easternmost stations where the overburden is thin: the Coppermine, Lockhart and Taltson Rivers. The magnitude of the statistically significant increases in estimated winter baseflow varied from 21.3–9505.0% over the entire period of individual record (Table 1). With the analysis restricted to 1978–2007, 19 of the 22 records showed a significant upward trend in winter baseflow, the exceptions being the Hay, Coppermine, and Lockhart Rivers.

[12] Nine of the 23 stations (39%) showed significant increasing annual flow; seven were significant at $p \leq 0.05$. Seven of the nine increases in annual mean flow became significant in the most recent three years (2005–2007). Geographically, these nine stations are clustered in the southwest and central NWT on sporadic or discontinuous permafrost (Figures 1 and 2b). The Mackenzie River gauge at Fort Simpson showed significant increased annual flow. Twelve of the remaining 14 gauges showed non-significant increasing trends, with one gauge showing zero trend (the Coppermine River) and one showing a non-significant negative trend (the Peel River). The magnitude of the statistically significant increases in mean annual flow varied from 7.9–145.0% over the period of individual record (Table 1). All of these results are for the raw streamflow records, but hold near-identically if the missing records are inferred as described. All nine rivers showed significantly increased monthly mean flows for December through April, with the majority showing significantly increased mean monthly flows for October and November as well. Increased monthly flows occurred in May through September, but in only 40% of the tests. With the analysis restricted to 1978–2007, five additional gauges showed a significant increased mean annual flow: the Flat, Liard near the mouth, Lockhart, Mackenzie at Arctic Red River, and Mackenzie at Inuvik, while the Cameron showed a non-significant increasing trend only.

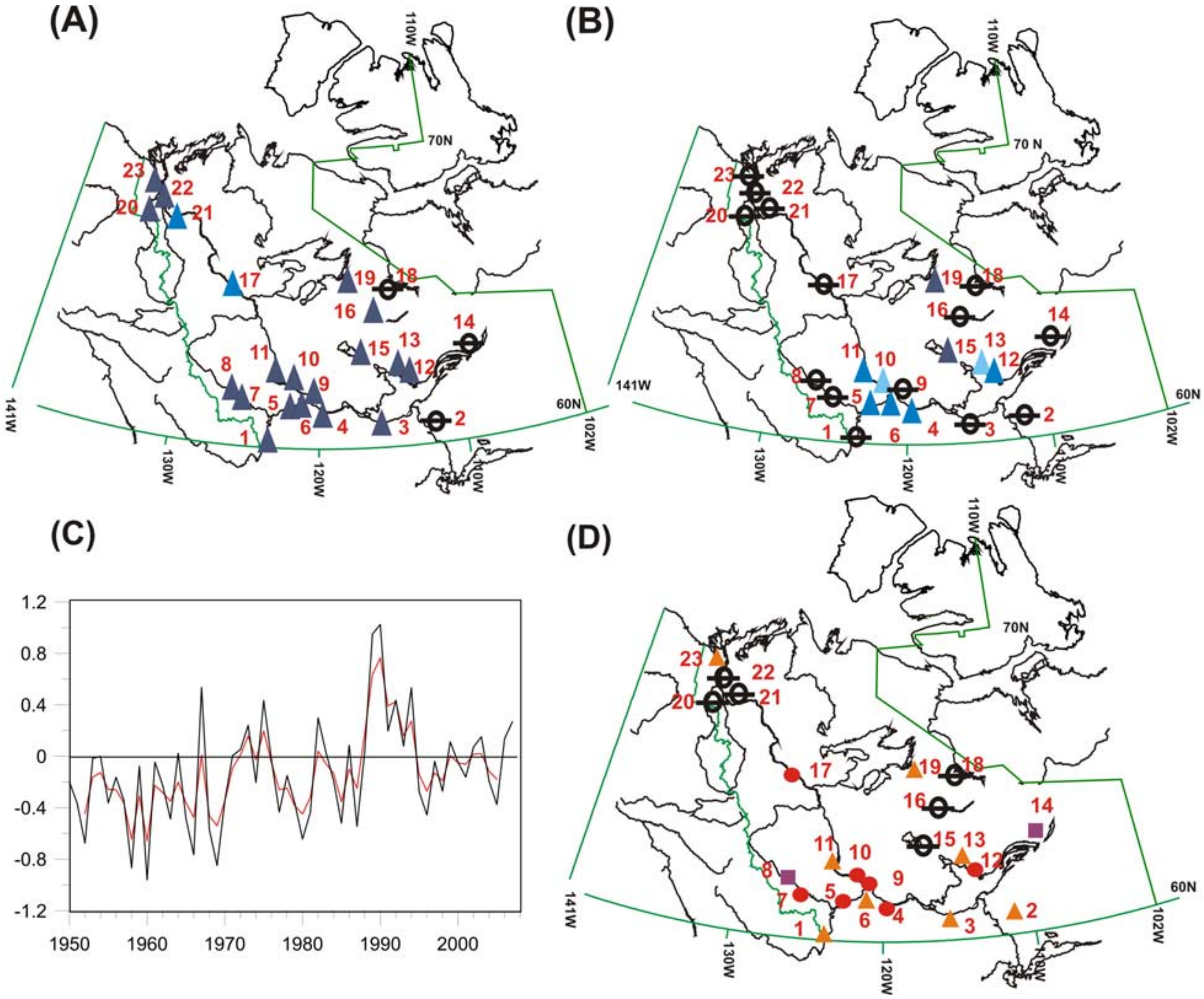

Figure 2. Recent increasing trends in (a) winter baseflow flow (m^3/s) and (b) annual mean streamflow (m^3/s) for 23 rivers in the Northwest Territories (NWT), Canada. (c) Northern annular mode (NAM) annual mean index 1950–2008 (black line), smoothed by a 5-weight binomial filter (red line). (d) Pearson's correlations between the NAM annual mean index and the 23 NWT annual mean flows (m^3/s), with both climate and streamflow data smoothed by 5-weight binomial filters, and with the streamflows leading the NAM index by one year. Significance of trend (or correlation) denoted by light blue triangle (orange triangle) for $0.05 < p \leq 0.1$, medium blue triangle (red circle) for $0.01 < p \leq 0.05$ and dark blue triangle (purple square) for $p \leq 0.01$. A circle with a horizontal line through it denotes no significant trend (or correlation). Station numbers according to Table 1.

[13] A strong positive teleconnection exists between the NAM and NWT streamflow (Figure 2c). The relationship is strongest when the NAM lags the streams by one year: 17 of the 23 gauges show significant positive correlations with the NAM (Figure 2d). Of the six rivers showing no correlation with the one-year lagging NAM, three are located in the eastern NWT: the Coppermine, La Martre and Indin Rivers; and three are located in the northern NWT: the Peel, and Rengleng Rivers and the Mackenzie River gauged at Arctic Red River. However, significant positive correlations do exist between the NAM of the same year and the Peel, Coppermine, and La Martre Rivers, and the Mackenzie gauged at Arctic Red River. As well, a lesser number of significant correlations exist between the NAM of the same year and the other NWT streams, and between the NWT streams of two years prior and the NAM. The various ENSO, PDO, and PNA indices showed fewer significant correlations with NWT streamflows, and are not presented further.

5. Discussion

[14] Comparable results of increasing winter mean flow have been reported from northern Eurasia, from both permafrost and non-permafrost regions [*Smith et al.*, 2007], and from North America, from the neighboring permafrost-underlain Yukon River basin of Canada and Alaska [*Walvoord and Striegl*, 2007]. All of these increasing low flows suggest a broad-scale recent mobilization of subsurface water into rivers. This increase of baseflow, probably from soil- and groundwater inputs into rivers, could be due to permafrost thawing [*Smith et al.*, 2007; *Walvoord and Striegl*, 2007]. This is supported by shrinking and draining lakes in Alaska and Siberia [*Yoshikawa and*

Hinzman, 2003; *Smith et al.*, 2005]. The NWT has experienced significantly increasing maximum and minimum seasonal and annual temperatures during 1950–1998, which would promote permafrost decay [*Zhang et al.*, 2000]. A more deeply or more frequently thawed terrain could result in increased soil infiltration, subsurface water movement, stream network interconnectivity, and shift in water storage from lakes and wetlands to soil- and groundwater and then to increased baseflow [*Smith et al.*, 2007].

[15] Using the same statistical methods as *Walvoord and Striegl* [2007], we report much larger winter baseflow increases for the NWT than for the Yukon River Basin. Some of this augmentation is an artifact of including smaller streams which show the greatest increases. But some could be due to our more recent records (with one exception all ending in 2007) and raises the possibility that permafrost decay could be recently accelerating, as suggested by *Syed et al.* [2007], based upon GRACE satellite data.

[16] Similar to our result of increasing mean annual flows in the south-central NWT, increasing annual flows to the Arctic Ocean have been detected in northern Eurasian rivers [*Peterson et al.*, 2002; *McClelland et al.*, 2006]. Discharge to the Arctic Ocean increased by 5.6 km^3/yr/yr during 1964–2000, the net result of a large increase from Eurasia [*McClelland et al.*, 2006]. Such increased freshwater runoff into the Arctic Ocean is a common global warming scenario from global climate models.

[17] The observed response in northern Canada and Alaska has been very different from that predicted. In their northern Canadian river discharge surveys, *Déry and Wood* [2005] and *Déry et al.* [2005] found that total freshwater discharge is decreasing, particularly from the Labrador Sea and Hudson-James Bay regions. However, they detected a non-significant increase in aggregate river discharge in their Arctic Ocean region (reasonably coincident with the NWT); together with no significant changes at their three individual NWT coastal gauges [*Déry and Wood*, 2005]. By examining the interior, rather than coastal, gauge records, our study found significant increases in annual flow in the southern and central NWT (Figure 2b). Furthermore, *Déry and Wood*'s [2005] use of aggregated coastal discharge weighted the Mackenzie River heavily; however, its principal sources are located in a different climate regime in Alberta and British Columbia [*Woo and Thorne*, 2003]. *Zhang et al.* [2001] and *Woo and Thorne* [2003] found no significant changes in NWT gauge records. Unlike *Walvoord and Striegl* [2007] who detected significant increases in annual flow at only two of 21 Yukon Basin stations, we found significant increases in annual flow at nine of the 23 NWT stations. We conjecture that our different results from other northwestern Canadian studies are due to our study's relatively large number of more recent and longer records.

[18] Our divergence with the northeastern Canadian results relates to hydroclimatic forcing. *Déry and Wood* [2004, 2005] explained their finding of a 15% decline in river discharge into the Hudson and James Bays and the Labrador Sea between 1964 and 1994 by showing that there exists a strong negative correlation between runoff in the corresponding catchment region and the NAM, which has had frequent positive values during this time (Figure 2c). Here, we present evidence that a strong significant *positive* relationship exists between streamflow in the adjacent NWT and the NAM (Figure 2d), which explains the opposite observed trends in streamflows from northwestern and northeastern Canada.

[19] The increased December–April mean monthly flows for the nine rivers showing increased annual mean flows suggests that permafrost melting is the main cause of the increases, as was likewise suggested in the neighboring Yukon [*Walvoord and Striegl*, 2007]. If increased precipitation was the primary driver, consistently increased May–September monthly mean flows would be expected in response to peak discharge from snowmelt and the majority of precipitation. However, increased precipitation from hydrological cycle intensification could be contributory. *Zhang et al.* [2000] reported increased precipitation in the NWT, but also increased temperature, and by extension, increased evapotranspiration. *Woo and Thorne* [2003] and *Smith et al.* [2007] caution that the subarctic precipitation field is poorly sampled due to few stations and that snowfall data are prone to measurement error.

[20] Regardless of exact mechanism in each circumpolar subarctic locality, the finding of increased winter, and presumably groundwater, flow throughout much of the region presages a rising role of groundwater processes in the high-altitude water cycle under global warming. As has been suggested by many researchers [e.g., *Smith et al.*, 2007], this could mean shifts from "above-ground" to "below-ground" water storage, and increased soil infiltration, unsaturated zone storage and groundwater movement in permafrost regions.

[21] **Acknowledgments.** We thank an anonymous reviewer, James Famiglietti, Greg MacCulloch (Environment Canada), Cesar Perez-Valdivia and Suzan Lapp for many helpful comments.

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