Observational evidence of an intensifying hydrological cycle in northern Canada

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[1] Trends and variability in the 1964–2007 annual streamflow for 45 rivers spanning 5.2×10^6 km^2 of northern Canada are investigated. Discharge averages 1153 km^3 yr^{-1} with a standard deviation of 71.4 km^3 yr^{-1} and coefficient of variation (CV_Q) of 6.2% over the 44-year period. A trend analysis reveals a recent (1989–2007) 15.5% increase in the annual flows owing to much-above average values recorded over the past decade. Trends in CV_Q computed from 11-year moving windows of annual streamflows exhibit spatially coherent signals with increasing variability across most of northern Canada, excluding some rivers with outlets to the Labrador Sea and eastern James Bay. For the period of interest, 46% and 30% of the available gauged area and river discharge, respectively, experienced detectable increases in variability. This provides observational evidence of an intensifying hydrological cycle in northern Canada, consistent with other regions of the pan-Arctic domain. **Citation:** Déry, S. J., M. A. Hernández-Henríquez, J. E. Burford, and E. F. Wood (2009), Observational evidence of an intensifying hydrological cycle in northern Canada, *Geophys. Res. Lett.*, *36*, L13402, doi:10.1029/2009GL038852.

1. Introduction

[2] There is mounting evidence that the global and pan-Arctic hydrological cycles are undergoing intensification [*Huntington*, 2006; *Holland et al.*, 2007]. This is being manifested and is projected to occur in multiple aspects of the pan-Arctic freshwater system including enhanced atmospheric moisture transport from lower to higher latitudes [*McClelland et al.*, 2004], more frequent hydrological extremes [*Tebaldi et al.*, 2006], and increasing river discharge to the Arctic Ocean [*McClelland et al.*, 2006]. The rapidly declining sea ice extent may be further altering the pan-Arctic hydrological cycle [*Arzel et al.*, 2008]. Thus there is an urgent need to better understand the role of climate variability, climate change, and anthropogenic disturbances on pan-Arctic rivers since they form vital links between the atmosphere, the pan-Arctic land surface, and the Arctic Ocean. Climate change and other forcings may alter these natural pathways for freshwater, leading to further environmental and societal change in the Arctic and beyond.

[3] Given the global implications of a rapidly changing Arctic, the International Polar Year (IPY) is devoting considerable effort toward improving our knowledge of the pan-Arctic freshwater system. In northern Canada, recent studies report no trend in annual flows into the Arctic Ocean between 1964 and 2003 [*Déry and Wood*, 2005] and a decreasing trend into Hudson, James and Ungava Bays from 1964 to 2000 [*Déry et al.*, 2005]. This research, however, lacks information on possible changes in the region's variability in annual streamflow. As an IPY contribution, we explore a potential intensification of the pan-Arctic hydrological cycle by examining the temporal evolution and spatial distribution of annual discharge and its interannual variability for 45 rivers of northern Canada over an extended period (1964–2007) of study.

2. Data and Methods

[4] A total of 45 rivers spanning 5.2×10^6 km^2 in northern Canada with outlets near continental margins are selected for this study (see auxiliary material).[1] The observed daily discharge rates covering the period 1964–2007 (where and when available) are extracted from the online Hydrometric Database (HYDAT) (Water Survey of Canada, 2008, http://www.wsc.ec.gc.ca/). Recent (2001–2007) daily discharge data for rivers of Nunavik (northern Québec) are provided by the Ministère de l'Environnement du Québec (2008, http://www.cehq.gouv.qc.ca/suivihydro/default.asp) with the exception of the intensively dammed La Grande Rivière for which daily hydrometric measurements are supplied by the power generation company Hydro-Québec. In addition, hydrometric data (1964–2007) for the Yukon River near the international border at Eagle, Alaska, are obtained from the United States Geological Survey (2009, http://www.usgs.gov). The study period is limited to 44 years since the network of river gauges degrades considerably prior to 1964. Several streamflow time series are incomplete, particularly in the Northwest and Nunavut Territories in the early years and in northern Ontario and Québec at the end of the period of interest. Data gaps are in-filled with mean daily discharge values over the period of record at each of the gauges [*Déry et al.*, 2005]. Given the paucity of Arctic Archipelago hydrological data [*Spence and Burke*, 2008], missing wintertime (January to May, inclusive) discharge records for Freshwater Creek and the Sylvia Grinnell River in Nunavut are taken as zero, in accord with in-situ observations (C. Spence and R. Wedel, personal communication, 2008).

[5] Apart from La Grande Rivière, several other rivers included here are affected by dams, diversions, and/or

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[1]Auxiliary materials are available in the HTML. doi:10.1029/2009GL038852.

reservoirs. This includes the Churchill River in Newfoundland and Labrador, the Moose River in Ontario, and the Nelson and Churchill rivers in Manitoba. In addition, the Peace River of British Columbia, a major tributary of the Mackenzie River, is dammed near its headwaters. Despite these anthropogenic disturbances, we retain (but highlight) these rivers in our study to better understand freshwater delivery to polar seas. In any case, these artificial influences do not impact overall trends in annual river discharge in northern Canada, although streamflow seasonality may be altered [*McClelland et al.*, 2006]. Several rivers of Nunavut (the Thelon and Kazan rivers, both tributaries of Chesterfield Inlet, and the Burnside and Tree rivers) experienced a change in recording methodology in the mid-1980s that led to possible step changes in streamflow amounts measured during the spring freshet (C. Spence, personal communication, 2008). Results for these rivers are also highlighted owing to the possibility of spurious trends arising from this change in data collection.

[6] We follow an approach similar to *Pagano and Garen* [2005] to examine trends in hydrological variability in northern Canada. Annual streamflow time series are first averaged over 11-year moving windows. This allows the computation of the mean ($\overline{Q}$), standard deviation (σ_Q), and coefficient of variation (CV_Q) in discharge over the sliding time windows for each of the rivers. The sign and magnitude of the monotonic trends in total annual discharge and CV_Q are assessed with Kendall-Theil Robust Lines (KTRLs) [*Kendall*, 1975; *Theil*, 1950]. Given the use of moving windows, CV_Q time series exhibit strong serial correlation that may affect the trend analyses. Thus prior to the trend analyses, time series of CV_Q in addition to total annual discharge are deserialized following *Yue et al.* [2002]. Computing trends on time series of the 11-year moving averages of CV_Q, rather than simply on the corresponding σ_Q, effectively removes the effects of linear trends in mean annual streamflow amounts on the variability analysis.

[7] Since gaps exist in some of the time series and the monitoring network degrades over time, an early (1970–1990), a central (1976–1996), a late (1982–2002), and an overall (1970–2002) period is used for the trend analyses. Here, the start and end years represent median values for the initial and final 11-year moving windows employed for the analyses. For instance, "1970" contains information on CV_Q from 1965 to 1975. This approach also yields information on the dependence of the trends on the selected periods. Results are shown when less than 10% of the daily discharge data are missing and in-filled for a given river and analysis period. *Cohn and Lins* [2005] and others suggest that measures of statistical significance applied to hydrologic trend analyses may be unreliable. Thus we characterize the trends as "detectable" when their signal-to-noise ratios are greater than unity. Dependence of the trends on gauged area, latitude, and longitude is assessed from correlation analyses. To obtain an integrated assessment of hydrological variability across northern Canada, fractions of the available gauged area and mean annual discharge experiencing detectable positive and negative trends in CV_Q are tracked.

[8] The temporal evolution of standardized time series of $\overline{Q}$, σ_Q, and CV_Q for eight representative basins is then presented. These rivers are selected based on the length and completeness of their observational records, spatial coverage and distribution, and the absence of major anthropogenic disturbances (see auxiliary material). In each case, correlations (considered statistically-significant when $p < 0.05$) between detrended time series of $\overline{Q}$, σ_Q, and CV_Q are performed to assess possible causal relationships of changing hydrological variability.

3. Results

[9] The total annual discharge for 45 rivers of northern Canada exhibits considerable interannual variability from 1964 to 2007 (Figure 1). The mean annual rate of discharge for rivers of northern Canada is 1153 $km^3\ yr^{-1}$ with a standard deviation of 71.4 $km^3\ yr^{-1}$ and a coefficient of variation of 6.2%, although values vary from 9.7% to 100.8% in individual rivers (see auxiliary material). There is a 334 $km^3\ yr^{-1}$ range in discharge from the minimum of 976 $km^3\ yr^{-1}$ in 1989 to the maximum of 1310 $km^3\ yr^{-1}$ in 1979. The KTRL reveals a decreasing (but not detectable) trend of 1.1 $km^3\ yr^{-1}\ yr^{-1}$ or a 4.3% decline in annual streamflow over 44 years. The recent (1989–2007) 15.5% (9.3 $km^3\ yr^{-1}\ yr^{-1}$) detectable increase in streamflow, driven in part by near-record values observed in 2005, was preceded by a 10.9% (4.9 $km^3\ yr^{-1}\ yr^{-1}$) detectable decrease in annual discharge over 1964–1989.

[10] The early (1970–1990), central (1976–1996), late (1982–2002), and overall (1970–2002) time periods reveal trends in CV_Q that have similar regional patterns across most of northern Canada (Figure 2). For instance, most rivers flowing into the Labrador Sea and eastern James Bay exhibit detectable negative trends in CV_Q whereas most rivers streaming to eastern Hudson Bay, the Bering Sea, and Arctic Ocean show positive and persistent trends in CV_Q. Rivers flowing into western Hudson Bay and Ungava Bay initially show positive trends that largely become negative over time. The two largest river basins by area, the Nelson and Mackenzie, shift from decreasing to increasing trends in CV_Q from the early to late period. The lack of long, continuous hydrological time series in northern Canada hampers the analysis for the overall period; however, the limited data reveal trends with regional patterns. This includes positive CV_Q trends in most regions of northern Canada with the exception of those rivers with outlets in eastern James Bay and the Labrador Sea (Figure 2d). Based on these results, statistically-significant correlations exist between the signal-to-noise ratios in CV_Q and latitude (r = 0.60) as well as longitude (r = 0.50), but not with gauged area (r = −0.34).

[11] The temporal evolution of the fractions of the available gauged area and river discharge experiencing detectable trends in CV_Q provides an integrated measure of hydrological variability and change in northern Canada (Table 1). The fraction of positive (negative) detectable trends in CV_Q increases (decreases) over time (from the early to the central and the late periods) when weighted both by gauged area and streamflow. For the overall period, more area shows increasing rather than decreasing variability in streamflow.

[12] Figure 3 illustrates the temporal evolution (1970–2002) of the standardized $\overline{Q}$ and CV_Q for eight rivers of northern Canada. Time series of σ_Q are not shown as they

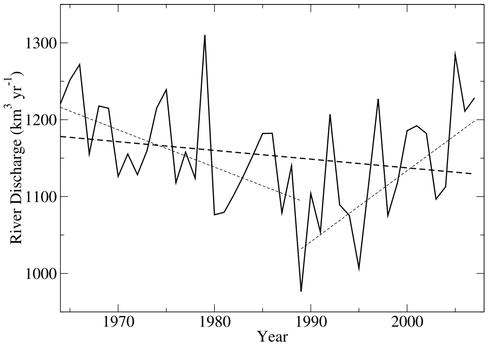

Figure 1. Temporal evolution of the total annual discharge of 45 rivers in northern Canada, 1964–2007. The KTRLs represent trends for the overall 44-year period (thick dashed line) and the shorter periods 1964–1989 and 1989–2007 (thin dashed lines).

all overlap and are correlated to those of CV_Q. Furthermore, CV_Q and $\overline{Q}$ are correlated in the Eagle, Rupert, and Seal rivers but are anticorrelated in the Yukon River. Finally, there are increasing trends in CV_Q in the Grande Rivière de la Baleine and Yukon rivers despite declining $\overline{Q}$ values.

4. Discussion

[13] Some of our previous work revealed a 10% decline in river discharge across northern Canada for the period 1964–2003 [*Déry and Wood*, 2005]. Extending the study period by just a few years to 2007 yields surprisingly different conclusions. The updated analyses reveal a trend reversal in association with the much-above average flows observed recently in this region. This trend reversal (if it persists) suggests that rivers of northern Canada are now responding similarly to climate change and/or other forcings as those in Eurasia with significant implications to the Arctic Ocean freshwater budget and North Atlantic deep water formation [*McClelland et al.*, 2006; *Rennermalm et al.*, 2006].

Table 1. Fractions of the Available Gauged Area and Volumetric Discharge Undergoing Detectable Positive and Negative Trends in CV_Q[a]

Period	Weighted by Gauged Area: Fraction Positive	Fraction Negative	Gauged Area ($\times 10^6$ km^2)	Weighted by River Discharge: Fraction Positive	Fraction Negative	Discharge (km^3 yr^{-1})
1970–1990	0.22	0.43	5.16	0.25	0.43	1135
1976–1996	0.35	0.15	4.96	0.25	0.37	1087
1982–2002	0.81	0.07	4.49	0.63	0.13	915
1970–2002	0.46	0.09	4.42	0.30	0.27	886

[a]Data for the early (1970–1990), central (1976–1996), late (1982–2002), and overall (1970–2002) time periods.

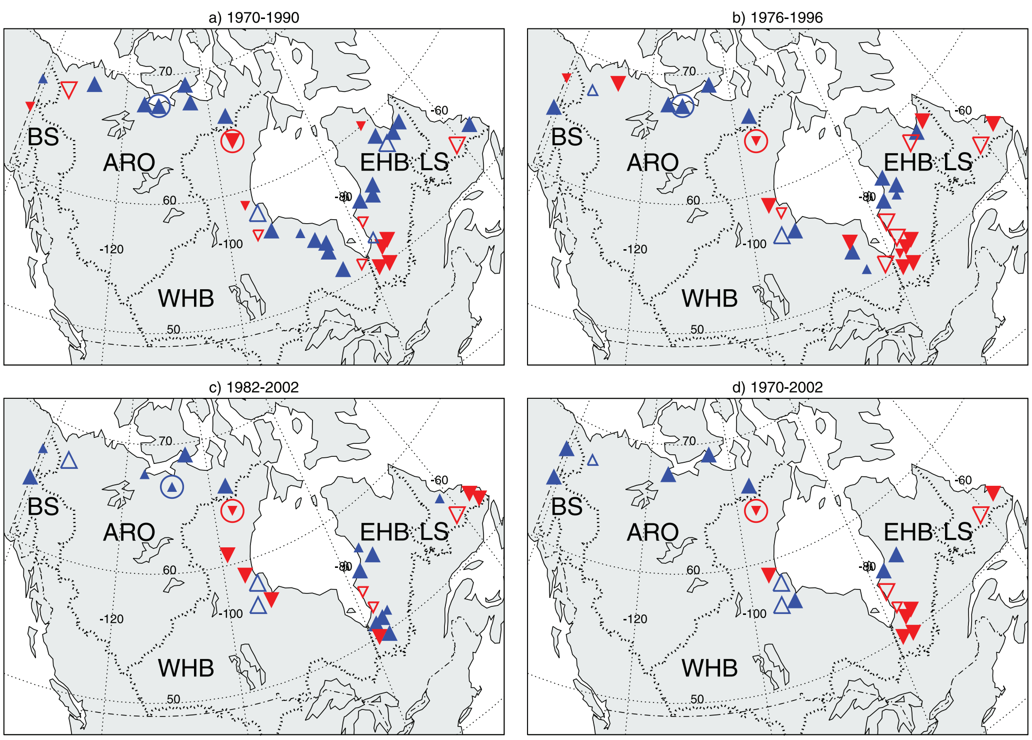

Figure 2. Maps illustrating the spatial variability in the trends of the coefficient of variation in annual streamflow of 45 rivers of northern Canada for (a) 1970–1990, (b) 1976–1996, (c) 1982–2002, and (d) 1970–2002. Upward (downward) pointing triangles indicate positive (negative) trends depicted by larger symbols if detectable. Rivers affected by anthropogenic disturbances (dams, diversions, and/or reservoirs) are shown as open triangles. The gauge coordinates for each river are used to locate symbols. Circles highlight rivers in Nunavut that underwent a change in recording methodology in the mid-1980s (see section 2). Thick dashed lines separate the following regional basins of northern Canada: Labrador Sea (LS), eastern Hudson Bay (EHB), western Hudson Bay (WHB), Arctic Ocean (ARO), and Bering Strait (BS).

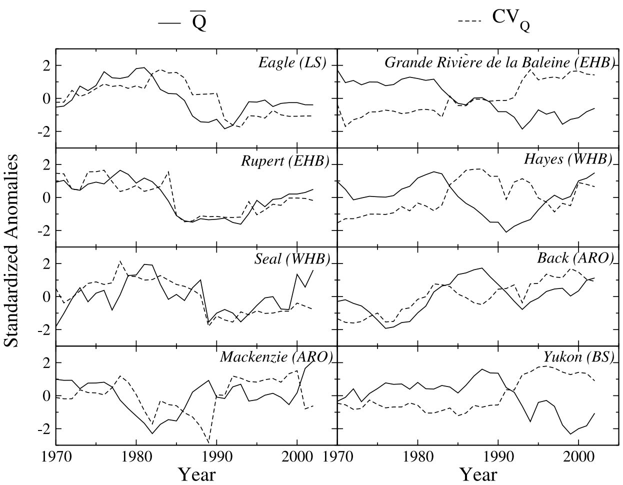

Figure 3. Temporal evolution (1970–2002) of the standardized $\overline{Q}$ and CV_Q for 11-year moving windows of annual discharge in eight representative rivers of northern Canada. The following regional basins are used to depict each of the rivers: Labrador Sea (LS), eastern Hudson Bay (EHB), western Hudson Bay (WHB), Arctic Ocean (ARO), and Bering Strait (BS).

[14] Phase changes in large-scale teleconnections are known to induce step changes or trend reversals in the hydrological regime of North American rivers. For instance, *Woo et al.* [2006] report break points in annual streamflow records across northwestern North America owing to the 1976/77 phase shift of the Pacific Decadal Oscillation (PDO). Unlike northwestern North America, river discharge across northern Canada is largely modulated by the Arctic Oscillation (AO) [*Déry and Wood*, 2004]. The change point in annual discharge rates observed in 1989 may thus be associated with the recent attenuation of the AO and the emergence of a different atmospheric circulation pattern in the Arctic [*Overland and Wang*, 2005]. Assessing the relative impacts of climate variability (e.g., AO phase shifts) and change on hydrological variability and trends of rivers in northern Canada requires continuous, longterm hydrometric data. The paucity of such records and variability in the relations between various teleconnections and hydrologic regimes [e.g., *Burn*, 2008] suggests that alternative datasets, such as proxy or modeling data, may be required to fully establish the role of large-scale teleconnections that are leading to this trend reversal and concurrent increase in streamflow variability in northern Canada.

[15] The CV_Q trend analyses provide observational evidence of increasing hydrological variability in northern Canada from 1964 to 2007. This finding is consistent with trends in streamflow variability of western North America [e.g., *Pagano and Garen*, 2005]. Climate change is often invoked as a possible mechanism leading to an intensifying and more variable hydrological cycle [*Huntington*, 2006]. Indeed, general circulation models (GCMs) project increasing risks of great floods and droughts this century [*Tebaldi et al.*, 2006]. In accord with these studies, our findings suggest that the Arctic response to a warming climate is coincident with increases in the hydrological variability of northern Canada [*Hassol*, 2005].

[16] Mechanisms responsible for a changing pan-Arctic hydrological regime remain subject to debate and further study. It is possible that atmospheric, oceanic, and land surface processes (i.e. enhanced water vapor transport, declining sea ice, and permafrost degradation) may be contributing to these changes [*McClelland et al.*, 2004; *Arzel et al.*, 2008; *St. Jacques and Sauchyn*, 2009]. It is imperative to better understand the causes of the increasing streamflow variability in northern Canada as many of its rivers provide critical water resources for the generation of hydroelectricity, mining, oil extraction, and irrigation. Furthermore, the rapidly changing hydrological state of northern Canada will have major ecological and societal impacts, such as for First Nations communities who rely on subsistence living.

5. Conclusion

[17] The IPY provides a unique snapshot of the state of the environment in the boreal polar region, including its hydrological regime, at the cusp of the 21st century. The findings reported here form a contribution to the Canadian IPY project "Arctic Freshwater Systems" that seeks improved knowledge on the ecohydrology of northern freshwater ecosystems. As a legacy of the IPY, this study provides updated streamflow records (available online at http://nhg.unbc.ca/ipy) for Canadian rivers flowing into polar seas and information on their trends and variability. Northern Canada is a region undergoing rapid climate change with significant environmental, biological, and societal impacts. Given the growing importance of freshwater resources, the IPY may well be the catalyst toward improved monitoring and a better understanding of pan-Arctic river discharge in a rapidly changing environment.

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