Decreasing river discharge in northern Canada

Stephen J. Déry
Program in Atmospheric and Oceanic Sciences, Princeton University, Princeton, New Jersey, USA

E. F. Wood
Department of Civil and Environmental Engineering, Princeton University, Princeton, New Jersey, USA

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[1] Freshwater discharge to high-latitude oceans in 64 Canadian rivers is investigated. The mean annual discharge rate attains 1252 $km^3\ yr^{-1}$ for an area of $5.6 \times 10^6\ km^2$, equating to a sink of 225 mm yr^{-1} in the surface water budget of northern Canada (excluding the Arctic Archipelago where insufficient data exist). Application of the Mann-Kendall test to the data reveals a 10% decrease ($-125\ km^3\ yr^{-1}$ or -22 mm yr^{-1}) in the total annual river discharge to the Arctic and North Atlantic Oceans from 1964 to 2003. This trend in river runoff is consistent with a 21 mm yr^{-1} decline in observed precipitation over northern Canada between 1964 and 2000. We find evidence of statistically-significant links between the Arctic Oscillation, El Niño/Southern Oscillation, and the Pacific Decadal Oscillation to the total annual freshwater discharge in northern Canada's rivers at interannual-to-decadal timescales. **Citation:** Déry, S. J., and E. F. Wood (2005), Decreasing river discharge in northern Canada, *Geophys. Res. Lett.*, *32*, L10401, doi:10.1029/2005GL022845.

1. Introduction

[2] About three quarters of the Canadian landmass is drained by rivers discharging into the Arctic Ocean (including the Bering Strait by the Yukon River) and the North Atlantic Ocean (from Labrador rivers as well as through Hudson Bay and Hudson Strait). This freshwater affects high-latitude oceanic, atmospheric, cryospheric, and biologic processes [e.g., *Aagaard and Carmack*, 1989]. It also provides a critical natural resource exploited for socioeconomic needs and benefits. With rising demands for freshwater in the twenty-first century, we need to better understand the effects of climate variability and change on river runoff in northern Canada.

[3] In this study, we compile and analyze observational hydrometric data to assess the characteristics and trends in freshwater discharge in 64 rivers of northern Canada over a period of 40 years. We also investigate the possible role of large-scale climate anomalies such as the Arctic Oscillation (AO) [*Thompson and Wallace*, 1998], El Niño/Southern Oscillation (ENSO), the Pacific Decadal Oscillation (PDO) [*Mantua et al.*, 1997], and the Pacific North American (PNA) [*Wallace and Gutzler*, 1981] pattern on high-latitude river discharge in Canada. The goals of this study are 1) to assess the recent variability and trend in river discharge in northern Canada and 2) to explore the large-scale teleconnections that are driving the variability and changes in these fluxes.

2. Data and Methods

[4] Measured discharge rates for 64 Canadian rivers with outlets to high-latitude oceans from 1964 to 2003 are extracted from the Water Survey of Canada's Hydrometric Database (HYDAT) (Water Survey of Canada, 2004, http://www.wsc.ec.gc.ca/). These measurements cover $5.6 \times 10^6\ km^2$, or more than half of the Canadian landmass (Table 1). Data for rivers of the Canadian Archipelago are not included in the analysis since less than 1% ($<0.01 \times 10^6\ km^2$) of the Arctic islands are gauged. The study period is limited to 40 years since the network of river gauges degrades considerably prior to 1964 and data for 2004 to the present remain largely unavailable at this time.

[5] Dams, diversions, and reservoirs affect several of the rivers including the Churchill, La Grande, Moose, Nelson, and Mackenzie [*Vörösmarty and Sahagian*, 2000]. For example, the development of the Churchill Falls hydroelectric power plant during the early 1970s on the Churchill River (Newfoundland and Labrador) created three upstream reservoirs with a total capacity of 33 km^3 of water. Several large reservoirs with a total volume of 182 km^3 were built in northern Québec between 1979 and 1986 to enhance the water supply to the massive James Bay hydroelectric complex on La Grande Rivière [*Messier et al.*, 1986; International Lake Environment Committee, 2004, http://www.ilec.or.jp/database/database.html]. A mean reduction of 23 $km^3\ yr^{-1}$ in river runoff to James Bay during that period is attributed to the filling of these reservoirs. In 1976–1977, the Churchill River of Manitoba was diverted toward the Nelson River system through Southern Indian Lake that raised its volume by 7 km^3. The construction of the W. A. C. Bennett dam on the Peace River, a major tributary of the Mackenzie, created Williston Lake in northern British Columbia that was filled with 70.3 km^3 of water between 1968–1972. We added the water used to fill these reservoirs to the total annual observed discharge rates to remove this anthropogenic effect in our data. After 1980, the flow of La Grande Rivière is determined using a data set of monthly discharge rates corrected to remove the artificial control of upstream reservoir levels (R. Roy, unpublished data, 2004). This data set of observed river runoff constructed by Hydro-Québec provides the best estimate of the natural flow of La Grande Rivière after the construction of the James Bay hydroelectric complex.

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Table 1. The Total Maximum Gauged Area, the Mean Annual and the Coefficient of Variation (CV) in Discharge Rates for 5 Regional River Basins of Northern Canada, 1964–2003[a]

River Basin	Area, $\times 10^6$ km^2	Discharge,		CV	Change, %	Correlation Coefficient			
		km^3 yr^{-1}	mm yr^{-1}			AO	ENSO	PDO	PNA
Labrador Sea	0.13	86.2	657.0	0.12	**−10.6**	**−0.59**	−0.04	0.24	**0.55**
Eastern Hudson Bay	0.71	384.5	543.1	0.11	**−11.0**	**−0.75**	−0.03	−0.01	**0.39**
Western Hudson Bay	2.33	334.0	143.6	0.12	**−13.0**	**−0.67**	**0.44**	**−0.61**	−0.27
Arctic Ocean	2.05	360.9	176.0	0.10	2.0	0.30	**0.68**	**−0.53**	**−0.51**
Bering Strait	0.35	86.7	245.0	0.13	−4.8	**0.55**	0.20	−0.25	−0.14
Total	5.57	1252.2	224.9	0.07	**−10.0**	**−0.75**	**0.51**	**−0.56**	−0.04

[a]Changes in river discharge inferred from the Mann-Kendall test over the same period are also indicated. Correlation coefficients between five-year running means of the annual observed discharge rates and four large-scale teleconnection patterns are also listed. Bold values denote trends or correlations significant at the $p < 0.05$ level.

However, the regulation of water in other river systems and its contribution to river discharge is not quantified owing to the lack of precise mass flux data.

[6] From the time series of annual discharge data, the magnitude of the trends in river discharge are established using the Mann-Kendall test [*Mann*, 1945; *Kendall*, 1975]. This non-parametric test has been used in several other studies to detect changing hydrological regimes [e.g., *Lettenmaier et al.*, 1994; *Ziegler et al.*, 2003]. The Kendall-Theil Robust Line forms the linear equation by which the sign and magnitude of the trends are detected [*Theil*, 1950]. Prior to the application of the Mann-Kendall test, time series of river discharge are "pre-whitened" following the methodology of *Yue et al.* [2002] to remove the influence of serial correlations on the trend analyses. Only trends with $p < 0.05$ are considered statistically-significant in this study.

[7] The river runoff data are then compared to time series of the annual AO, ENSO, PDO, and PNA indices obtained from the Climate Diagnostics Center (National Oceanic and Atmospheric Administration, 2004, available online at http://www.cdc.noaa.gov/ClimateIndices/). Since these large-scale climatic phenomena operate most prominently at interannual-to-decadal time scales [e.g., *Robertson*, 2001], a running mean of 5 years is used in the comparisons.

[8] To facilitate a regional analysis of the discharge data, the Canadian landmass is divided into 5 separate drainage basins that are identified by the main body of seawater adjacent to the outlets. These 5 regions (from east to west) are: 1) the Labrador Sea, 2) Eastern Hudson Bay (including Ungava Bay), 3) Western Hudson Bay, 4) the Arctic Ocean, and 5) the Bering Strait. The Yukon and Porcupine Rivers are gauged in Canada near the international border and hence do not include the Alaskan contribution to total discharge into Bering Strait. Table 1 lists the total maximum area gauged (≈75% of the total study area) in each of the 5 regional basins.

3. Results

3.1. Mean, Variability, and Trends in River Discharge

[9] Table 1 provides the mean annual total river discharge rates in the 5 regional basins of northern Canada for 1964–2003. Of these basins, Eastern Hudson Bay receives the greatest influx of freshwater on an annual basis (385 km^3), followed by the Arctic Ocean (361 km^3) and Western Hudson Bay (334 km^3). River discharge rates per contributing area are greatest for rivers draining into the Labrador Sea and Eastern Hudson Bay where annual precipitation rates are relatively high and annual evapotranspiration rates are relatively low. The mean freshwater flux from Canadian rivers to high-latitude oceans reaches 1252 km^3 yr^{-1}, equating to a sink of 225 mm yr^{-1} in the surface water budget of northern Canada. The coefficient of variation in annual river discharge ranges from 10 to 13% in the 5 regional basins, with an overall value of 7%.

[10] Figure 1 depicts the trend in the cumulative annual discharge rates recorded for 64 Canadian rivers with outlets into high-latitude oceans from 1964 to 2003. Significant interannual variability exists in total discharge rates, with a range of nearly 400 km^3 yr^{-1} between the annual maximum (1443 km^3 in 1979) and minimum (1051 km^3 in 1989) runoff rates. According to the Kendall-Theil Robust Line, the overall trend shows a significant decrease (−3.1 km^3 yr^{-1} yr^{-1}) in the amount of freshwater reaching high-latitude oceans over 1964–2003 (significant at the p = 0.007 level). This represents a 10% reduction (−125 km^3 yr^{-1} or −22.4 mm yr^{-1}) in Canadian freshwater discharge to high-latitude oceans over a period of 40 years. In addition, Table 1 shows that significant regional decreases in river discharge are inferred over the Labrador Sea, Western and Eastern Hudson Bay basins, and that no significant trends are found in the Arctic Ocean and Bering Strait basins.

[11] Figure 2 illustrates the spatial variability in trends of annual discharge for 64 rivers of northern Canada over a 40-year period. This plot shows the predominance of

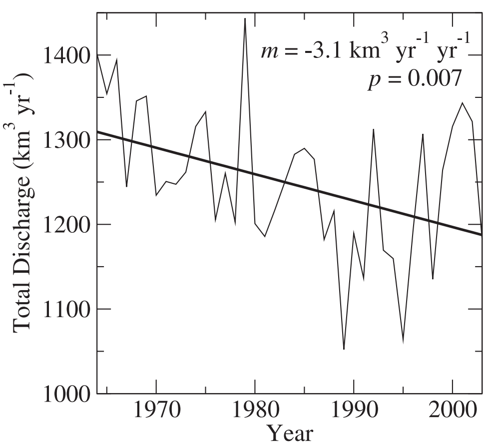

Figure 1. The temporal evolution of the total annual freshwater discharge of 64 Canadian rivers that drain into high-latitude oceans, 1964–2003. The thick solid line denotes the Kendall-Theil Robust Line.

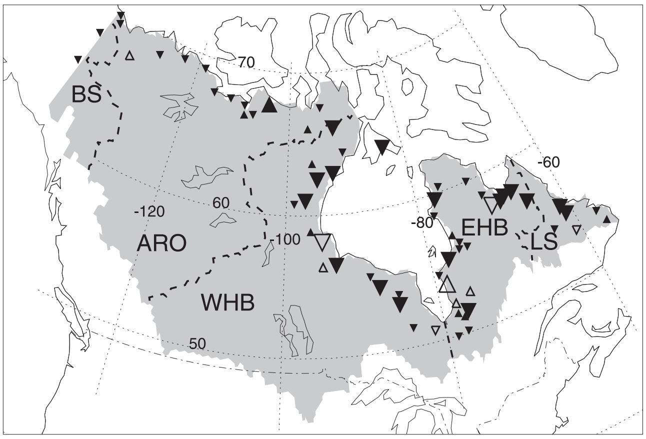

Figure 2. The spatial variability in trends of annual freshwater discharge for 64 rivers of northern Canada (gray shading), 1964–2003. Positive (negative) trends are denoted by upward (downward) pointing triangles, with statistically-significant trends ($p < 0.05$) denoted by larger symbols. Open triangles denote rivers affected by major dams, diversions, and/or reservoirs. The symbols are located at the coordinates of the measuring gauge of each river nearest the outlet to high-latitude oceans. Dashed lines denote 5 regional basins of northern Canada (LS, Labrador Sea; EHB, Eastern Hudson Bay; WHB, Western Hudson Bay; ARO, Arctic Ocean; BS, Bering Strait).

downward trends in river runoff across the northern perimeter of conterminous Canada, from rivers draining into the Labrador Sea, Hudson Bay, Arctic Ocean, and Bering Strait. Significant negative trends occur in 16 river basins not affected by dams, diversions, or reservoirs whereas a single significant positive trend is inferred for undisturbed river basins. Nearly 80% of the rivers studied exhibit decreasing trends in streamflow between 1964 and 2003. Basins with natural flows experienced an overall 11% decline in river discharge over the 40-year period whereas basins impacted by major anthropogenic disturbances underwent a more moderate decrease of 9%.

[12] Previous studies on river discharge in northern Canada have focused on relatively smaller and undisturbed watersheds. *Zhang et al.* [2001] analyzed streamflow trends for 243 rivers of (mostly southern) Canada over the period 1967–1996 and inferred declining runoff in northern Ontario and Québec but increasing river discharge into Chesterfield Inlet of Nunavut. Using the same hydrometric network, *Burn and Hag Elnur* [2002] found statistically-significant negative (positive) trends in streamflow for 6 (5) rivers of Canada over the period 1960–1997, without specifying their locations. *Spence* [2002] discerned no significant trend in the Back and Kazan Rivers (a major tributary of the Chesterfield Inlet Basin) over the period 1965–1998. Although these are generally consistent with our results, differences in the river basins and periods examined may lead to discrepancies in the inferred river discharge trends.

3.2. Teleconnections

[13] Table 1 further provides correlation coefficients between 5-year running means in observed discharge and large-scale teleconnection indices. In agreement with *Déry and Wood* [2004], river discharge into Hudson Bay and the Labrador Sea is significantly anticorrelated to the AO, whereas river runoff to the Bering Strait is significantly correlated to the AO. In addition, river discharge to the Arctic Ocean and Western Hudson Bay exhibits a significant positive (negative) correlation to ENSO (PDO). The PNA pattern is significantly correlated to river discharge into the Labrador Sea and in Eastern Hudson Bay. Owing to the wide expanse of the study area, there are east-west shifts in the sign of the correlations between river discharge in northern Canada and large-scale teleconnections. For the system as a whole, there is a significant anticorrelation between the AO and PDO and a significant correlation between ENSO with freshwater discharge from Canadian rivers to high-latitude oceans.

4. Concluding Discussion

[14] Using the non-parametric Mann-Kendall test, we have detected a statistically-significant downward trend in the total annual freshwater discharge in 64 rivers of northern Canada between 1964 and 2003. This has led to a 10% decrease (-22 mm yr^{-1}) in the total annual river discharge to the Arctic and North Atlantic Oceans over that period. Application of the Mann-Kendall test to precipitation data compiled by the Climate Research Unit of the University of East Anglia [*New et al.*, 2000] reveals a decline of 21 mm yr^{-1} over the same domain between 1964 and 2000. This trend in precipitation is entirely consistent with the observed decline in river discharge in northern Canada and differs from the incompatibility in observed precipitation and runoff trends for the large Siberian watersheds [*Berezovskaya et al.*, 2004]. This suggests that changes in river discharge over northern Canada are driven primarily by precipitation rather than evapotranspiration. Other factors such as changes in permafrost, fires, and anthropogenic disturbances including dams and reservoirs may contribute to long-term trends in pan-Arctic river discharge [*McClelland et al.*, 2004]. In this study, however, we have minimized one of the most important agents by accounting for the filling of artificial reservoirs on the observed river runoff rates. Thus the recent variability and trend in Canadian freshwater discharge to high-latitude oceans is primarily influenced by large-scale teleconnections such as the AO, ENSO, PDO, and, to a lesser degree, the PNA. Recent trends toward more intense, positive (negative) phases of the AO and the PDO (ENSO) have led to reduced precipitation and decreased river discharge over northern Canada.

[15] Apart from its impact on the continental water budget, decreasing freshwater discharge in northern Canada significantly affects the state of the Arctic and North Atlantic Oceans. For instance, *Déry et al.* [2005] reported a salinization of the Labrador Current in response to declining Hudson Bay Basin river runoff between 1966 and 1994. The proximity of many river outlets in northern Canada to the Labrador Sea combined with ocean currents suggests that recent trends in Canadian river discharge may affect the thermohaline circulation. The Labrador Sea is one of the major areas of deep convection in the North Atlantic [*Aagaard and Carmack*, 1989]. The strength of the

thermohaline circulation is driven by deep water formation in the North Atlantic that is, in turn, strongly influenced by surface salinity and pan-Arctic river discharge. Simulations with a comprehensive global climate model have been initiated to better understand the role of pan-Arctic river discharge on the global thermohaline circulation.

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S. J. Déry, Program in Atmospheric and Oceanic Sciences, Princeton University, Princeton, NJ 08544, USA. (sdery@princeton.edu)

E. F. Wood, Department of Civil and Environmental Engineering, Princeton University, Princeton, NJ 08544, USA.