**J1.10**

# CHARACTERISTICS, TRENDS, AND ATMOSPHERIC DRIVERS OF CANADIAN RIVER DISCHARGE TO HIGH-LATITUDE OCEANS

Stephen J. Déry* and E. F. Wood

Princeton University, Princeton, New Jersey

## 1. INTRODUCTION

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 (Sutcliffe et al. 1983; Manak and Mysak 1989; LeBlond et al. 1996). It is therefore critical to assess the impact of climate variability and change on river runoff in these basins. In this study, we compile observational hydrometric data to assess the characteristics and trends in freshwater discharge in the rivers of northern Canada. We also investigate possible links between the Arctic Oscillation (AO; Thompson and Wallace 1998), El Niño/Southern Oscillation (ENSO), the Pacific Decadal Oscillation (PDO; Mantua et al. 1996), and the Pacific North American (PNA; Wallace and Gutzler 1981) pattern with high-latitude river discharge in Canada. The goals of this study are to better understand Canadian river discharge to high-latitude oceans and to explore the atmospheric anomalies that are driving the variability and changes in these fluxes.

## 2. DATA AND METHODS

Measured discharge rates for 64 Canadian rivers with outlets to high-latitude oceans from 1968 to 2002 are extracted from Environment Canada's Hydrometric Database (HYDAT; Government of Canada, available online http://www.msc.ec.gc.ca/wsc/hydat/H2O/index_e.cfm, 2004). These measurements cover $5.6 \times 10^6$ km$^2$, or more than half of the Canadian landmass. 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 35 years since the network of river gauges degrades considerably prior to 1968 and data for 2003 to the present remain largely unavailable at this time.

Dams, diversions, and reservoirs affect several of the rivers including the Nelson, Churchill, Moose, and La Grande (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. The first phase of the James Bay hydroelectric complex in Québec involved the construction of several large reservoirs on La Grande Rivière between 1979 and 1986 (Messier et al. 1986). The total estimated capacity of these reservoirs is 182 km$^3$ of water (International Lake Environment Committee, available online http://www.ilec.or.jp/database/database.html, 2004). Filling of the reservoirs therefore accounts for a mean reduction of 23 km$^3$ yr$^{-1}$ in river runoff to James Bay during that period. The diversion of the Churchill River (Manitoba) to the Nelson River system in 1976/1977 raised the water level of Southern Indian Lake by 3 m and its volume by 7 km$^3$. 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 dataset of monthly discharge rates corrected to remove the artificial control of upstream reservoir levels (R. Roy, unpublished data, 2004). This dataset 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. 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.

From the time series of observed 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; Déry et al. 2004). The Kendall-Theil Robust Line forms the linear equation by which the sign and magnitude of the trends are detected (Theil 1950).

The river runoff data are then compared to

* *Corresponding author address:* Stephen J. Déry, Program in Atmospheric and Oceanic Sciences, Princeton University, Princeton, NJ, 08544; e-mail: sdery@princeton.edu

Table 1: The total maximum gauged area and the mean annual discharge rates for 5 major river basins of northern Canada.

| River Basin | Area ($\times 10^6$ km$^2$) | Flow (km$^3$ yr$^{-1}$) | Flow (mm yr$^{-1}$) |
|---|---|---|---|
| Labrador Sea | 0.13 | 86.4 | 658.7 |
| Eastern Hudson Bay | 0.71 | 381.6 | 539.0 |
| Western Hudson Bay | 2.32 | 331.3 | 142.6 |
| Arctic Ocean | 2.05 | 355.0 | 173.2 |
| Bering Strait | 0.35 | 86.2 | 243.7 |
| Total | 5.57 | 1240.6 | 222.9 |

a time series of the annual AO, ENSO, PDO, and PNA index values obtained from the Climate Diagnostics Center (National Oceanic and Atmospheric Administration, available online http://www.cdc.noaa.gov/ClimateIndices/, 2004). 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.

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, 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 in each of the 5 basins.

## 3. RESULTS

Table 1 provides the mean annual total river discharge rates for the 5 regions of interest in northern Canada for 1968-2002. Of these basins, Eastern Hudson Bay receives the greatest influx of freshwater on an annual basis (382 km$^3$), followed by the Arctic Ocean (355 km$^3$) and Western Hudson Bay (331 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 1241 km$^3$ yr$^{-1}$, equating one fourth of the total annual river runoff to the Arctic Ocean (Shiklomanov et al. 2000).

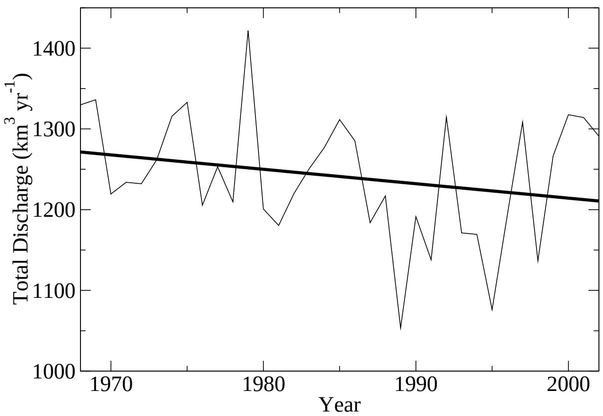


Figure 1: The temporal evolution of the total annual freshwater discharge of 64 Canadian rivers that drain into high-latitude oceans, 1968-2002. The thick solid line denotes the Kendall-Theil Robust Line.

Figure 1 depicts the trend in the total annual discharge rates recorded for 64 Canadian rivers with outlets into high-latitude oceans from 1968 to 2002. Significant interannual variability exists in total discharge rates, with a range of nearly 370 km$^3$ yr$^{-1}$ between the annual maximum (1422 km$^3$ in 1979) and minimum (1054 km$^3$ in 1989) runoff rates. Interannual variability explains deviations of up to $\pm 15\%$ from the mean annual runoff rates. According to the Kendall-Theil Robust Line, the overall trend shows a significant decrease ($-1.8$ km$^3$ yr$^{-1}$ yr$^{-1}$) in the amount of freshwater reaching high-latitude oceans over 1968-2002 (significant at the $p = 0.07$ level). This represents a reduction of 62 km$^3$ yr$^{-1}$ ($-5\%$) of Canadian freshwater discharge to high-latitude oceans over a period of 35 years.

Table 2 provides the correlation coefficients of a 5-year running mean of the observed discharge anomalies and of the atmospheric teleconnection indices. This shows that there is a statistically-significant anticorrelation between the overall freshwater discharge from Canadian rivers to high-latitude oceans and the AO, with lesser agreement with the other 3 large-scale atmospheric anomalies examined in this study. In agreement with Déry and Wood (2004), river discharge in the Hudson Bay Basin is negatively correlated to the AO, whereas river runoff to the Arctic Ocean and the Bering Strait is positively correlated to the AO. In addition, river discharge to the Arctic Ocean and Western Hudson Bay is positively correlated with ENSO and negatively correlated with the PDO. On the other hand, the PNA pattern influences to a significant degree river discharge to the Labrador Sea and in Eastern Hudson

Table 2: The correlation coefficient between the five-year running means of the annual observed discharge rates in 5 major river basins of northern Canada and four large-scale atmospheric anomaly patterns, 1968-2002. Values significant at the $p$ <0.01 level are marked in bold.

| River Basin | AO | ENSO | PDO | PNA |
|---|---|---|---|---|
| Labrador Sea | **−0.68** | −0.04 | 0.26 | 0.37 |
| Eastern Hudson Bay | **−0.68** | −0.12 | 0.19 | **0.57** |
| Western Hudson Bay | **−0.57** | **0.51** | **−0.51** | −0.25 |
| Arctic Ocean | 0.42 | **0.65** | **−0.48** | −0.39 |
| Bering Strait | **0.56** | 0.04 | −0.22 | 0.04 |
| Overall | **−0.65** | **0.54** | −0.40 | 0.17 |

Bay.

## 4. CONCLUSIONS

In this study, we examined freshwater discharge rates to high-latitude oceans in 64 Canadian rivers. The mean annual discharge rate attains 1241 km$^3$ yr$^{-1}$ for an area of 5.6 × 10$^6$ km$^6$. This equates to an average runoff rate of 223 mm yr$^{-1}$ for the Canadian landmass drained by high-latitude rivers (excluding the Canadian Archipelago where insufficient data exist). Application of the Mann-Kendall test to the data reveals a 5% decrease (−62 km$^3$ yr$^{-1}$) in the total annual river discharge to the Arctic and North Atlantic Oceans from 1968 to 2002. In addition, this study provides evidence of a statistically-significant link between the AO and ENSO to the total annual freshwater discharge in Canada's northern rivers at interannual-to-decadal timescales. On a more regional basis, ENSO and the PDO are significantly correlated to river runoff to Western Hudson Bay and to the Arctic Ocean whereas the PNA is significantly correlated to river runoff to Eastern Hudson Bay and the Labrador Sea.

Although this study establishes statistical links between large-scale atmospheric anomalies and observed streamflow to high-latitude oceans, further research on the physical mechanisms driving these relationships is needed. Thus comprehensive water budget studies for the Canadian landmass during the alternating phases of the atmospheric anomalies is required to determine the source of atmospheric moisture and precipitation as well as factors governing evapotranspiration. Thus future efforts involving coupled atmospheric/oceanic/land surface models supported by precise observations are necessary to better understand the role of large-scale atmospheric anomalies in the global hydrologic cycle and its potential future state.

## 5. ACKNOWLEDGMENTS

R. Roy (Ouranos) generously provided the unpublished discharge data compiled by Hydro-Québec for La Grande Rivière. Supported by the NSF through grant OPP02-30211 (Collaborative research: The role of spatial and temporal variability of Pan-Arctic river discharge and surface hydrological processes on climate) (E.F.W.) This report was prepared by Stephen J. Déry under award NA17RJ2612 from National Oceanic and Atmospheric Administration (NOAA), U.S. Department of Commerce. The statements, findings, conclusions, and recommendations are those of the author and do not necessarily reflect the views of NOAA or the U.S. Department of Commerce.

## 6. REFERENCES

Déry, S. J., and E. F. Wood, 2004: Teleconnection between the Arctic Oscillation and Hudson Bay river discharge. *Geophys. Res. Lett.*, **31**, L18205, doi: 10.1029/2004GL020729.

Déry, S. J., M. Stieglitz, E. C. McKenna, and E. F. Wood, 2004: Characteristics and trends of river discharge into Hudson, James, and Ungava Bays, 1964-2000. submitted to *J. Climate*.

Kendall, M. G., 1975: *Rank Correlation Methods*. Charles Griffin, 202 pp.

LeBlond, P. H., J. R. Lazier, and A. J. Weaver, 1996: Can regulation of freshwater runoff in Hudson Bay affect the climate of the North Atlantic? *Arctic*, **49**, 348-355.

Lettenmaier, D. P., E. F. Wood, and J. R. Wallis, 1994: Hydro-climatological trends in the continental United States, 1948-1988. *J. Climate*, **7**, 586-607.

Manak, D. K., and L. A. Mysak, 1989: On the relationship between Arctic sea-ice anomalies and fluctuations in Northern Canadian air temperature and river discharge. *Atmos.-Ocean*, **27**, 682-691.

Mann, H. B., 1945: Non-parametric test against trend. *Econometrika*, **13**, 245-259.

Mantua, N. J., S. R. Hare, Y. Zhang, J. M. Wallace, and R. C. Francis, 1997: A Pacific interdecadal climate oscillation with impacts on salmon production. *Bull. Amer. Meteorol. Soc.*, **78**, 1069-1079.

Messier, D., R. G. Ingram, and D. Roy, 1986: Physical and biological modifications in response to La Grande hydroelectric complex. *Canadian Inland Seas*, edited by I. P. Martini, Elsevier, Amsterdam, pp. 403-424.

Robertson, A. W., 2001: Influence of ocean-atmosphere interaction on the arctic oscillation in two general circulation models. *J. Climate*, **14**, 3240-3254.

Shiklomanov, I. A., A. I. Shiklomanov, R. B. Lammers,

B. J. Peterson, and C. J. Vorosmarty, 2000: The dynamics of river water inflow to the Arctic Ocean. *The Freshwater Budget of the Arctic Ocean*, edited by E. L. Lewis, Kluwer Academic, Dordrecht, pp. 281-296.

Sutcliffe, W. H., Jr., R. H. Loucks, K. F. Drinkwater, and A. R. Coote, 1983: Nutrient flux onto the Labrador Shelf from Hudson Strait and its biological consequences. *Can. J. Fish. Aquat. Sci.*, **40**, 1692-1701.

Theil, H., 1950: A rank-invariant method of linear and polynomial regression analysis. *Indagationes Math.*, **12**, 85-91.

Thompson, D. W. J., and J. M. Wallace, 1998: The Arctic Oscillation signature in the wintertime geopotential height and temperature fields. *Geophys. Res. Lett.*, **25**, 1297-1300.

Thompson, D. W. J., and J. M. Wallace, 2001: Regional climate impacts of the Northern Hemisphere annular mode. *Science*, **293**, 85-89.

Vörösmarty, C. J., and D. Sahagian, 2000: Anthropogenic disturbance of the terrestrial water cycle. *Bio-Science*, **50**, 753-765.

Wallace, J. M., and D. S. Gutzler, 1981: Teleconnections in the geopotential height field during the northern hemisphere winter. *Mon. Wea. Rev.*, **109**, 784-812.

Ziegler, A. D., J. Sheffield, E. P. Maurer, B. Nijssen, E. F. Wood, and D. P. Lettenmaier, 2003: Detection of intensification in global- and continental-scale hydrological cycles: Temporal scale of evaluation. *J. Climate*, **16**, 535-547.