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Interannual variability and interdecadal trends in Hudson Bay streamflow

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ABSTRACT

This study investigates the interannual variability and interdecadal trends in streamflow input to Hudson Bay (including James Bay) over 1964–2008. The 23 rivers chosen for this study span a maximum gauged area of 2.54×10^6 km^2 and collectively transport 522 km^3 of freshwater to Hudson Bay each year. Adjusting this value for the missing contributing area yields a total annual freshwater flux of 760 km^3 into Hudson Bay. The standard deviation and coefficient of variation in annual streamflow to Hudson Bay reach 48.5 km^3 and 0.09, respectively. The monotonic trend assessed with a Kendall–Theil Robust Line shows no detectable (|signal-to-noise ratio|<1) change in total discharge into Hudson Bay over 1964–2008. A 5-year running mean in total Hudson Bay streamflow, however, reveals a downward trend from the mid-1960s to the mid-1980s, followed by relatively high flows in the mid-1980s, and then an upward trend, marked by a record annual discharge of 635 km^3 in 2005, until the end of the study period. There is a notable shift in the seasonality of Hudson Bay discharge over time, with a detectable positive (negative) trend in winter (summer) streamflow from 1964 to 2008. Annual hydrographs for regulated and natural rivers over two periods suggest these changes arise from the storage of water in reservoirs during spring and summer that is later released for the generation of hydroelectricity in fall and winter. The naturally-flowing rivers show a marked decline in the variability of daily streamflow input to Hudson Bay in recent years while the opposite trend is found in the regulated systems. The fall 2009 diversion of 14.5 km^3 yr^{-1} or 48% of the total annual streamflow from the Rupert River northward into La Grande Rivière for enhanced power production further exacerbates the streamflow timing shifts observed in Hudson Bay. The potential impacts of flow regulation on the Hudson Bay marine environment are then discussed.

1. Introduction

Hudson Bay is a large inland sea in northern Canada that receives considerable amounts of freshwater through riverine input. Among other factors, the streamflow into Hudson Bay affects the temperature, salinity, and density of water in the marine environment. River discharge also alters biological and chemical processes in Hudson Bay (e.g., Kuzyk et al., 2008; Granskog et al., 2009). These effects are especially notable in the estuaries for the rivers affected by diversions (Messier et al., 1986; Kuzyk et al., 2008). Enhanced streamflow during winter freshens the Hudson Bay waters and favours sea ice formation (LeBlond et al., 1996; Ingram and Prinsenberg, 1998; Saucier et al., 2004). Furthermore, the export of this riverine input into the Labrador Sea is thought to play a significant role in the larger scale circulation of the northern North Atlantic and of its dense water formation regions (e.g., Straneo and Saucier, 2008).

A growing number of studies have examined Hudson Bay streamflow and its impacts on the marine environment. Ingram et al. (1996) projected that, in a $2 \times CO_2$ scenario, regional warming in the Hudson Bay area would advance by one month the spring freshet for the Grande Rivière de la Baleine, affecting the exchanges between its estuary and coastal waters. Westmacott and Burn (1997) explored the impacts of recent climate change on the hydrology of the Churchill-Nelson drainage basin, including the advance of snowmelt runoff events. Déry et al. (2005) compiled discharge data for 42 rivers with outlets into Hudson, James, and Ungava Bays. These records showed a 13% decline in annual streamflow in these basins from 1964 to 2000. Further analyses revealed that annual fluctuations in river discharge into Hudson Bay were related to changing precipitation patterns driven by the Arctic Oscillation (Déry and Wood, 2004, 2005). Changes in river input to Hudson Bay impact sea ice formation in the basin and in turn affect the climate of northeastern North America (Manak and Mysak, 1989; Weatherly and Walsh, 1996; Saucier et al., 2004). On the global scale, it has been speculated that changes in pan-Arctic river discharge may affect deep water formation in the North Atlantic (Aagaard and Carmack, 1989; Peterson et al., 2002, 2006). In addition, simulations using a global climate model of intermediate complexity revealed different sensitivities in the response of the Atlantic meridional overturning circulation (AMOC) to Arctic Ocean and Hudson Bay

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streamflow (Rennermalm et al., 2007). Their findings showed that an increase in river discharge into the Arctic Ocean is more effective in reducing the AMOC than an increase into Hudson Bay. The AMOC is less sensitive to freshening in Hudson Bay because freshwater anomalies build up in the Labrador Sea, causing the northward flows of the Gulf Stream to be disrupted.

The large freshwater fluxes delivered by rivers to Hudson Bay have long been exploited for the generation of hydroelectricity. The Nelson, Churchill, Moose, Eastmain, and La Grande Rivière are some of the large (i.e. by contributing area and annual discharge) rivers that have experienced considerable anthropogenic disturbances (dams, diversions, and/or reservoirs) linked to power production. A number of studies have addressed the potential impacts of the cumulative effects of these developments on the Hudson Bay environment. Anctil and Couture (1994) and Prinsenberg (1980, 1983) described the suppression of the strong seasonal cycle in rivers affected by flow regulation. In turn, the “flattening” of annual hydrographs has substantial implications for the Hudson Bay marine environment. For instance, Messier et al. (1986) reported increases in the salinity of water in the Eastmain River estuary after 90% of its flow was diverted to La Grande Rivière in 1980. Moreover, Whittaker (2006) suggested that La Grande Rivière's winter discharge potentially lowers the winter surface salinities in some parts of southeastern and eastern Hudson Bay by 1 to 3 salinity units. LeBlond et al. (1994) discussed the chain of events associated with streamflow regulation into Hudson Bay, including the extension of under ice plumes and the enhancement of sea ice formation during winter. Their study concluded, however, that the impacts of flow regulation are regional since deep water formation in the Labrador Sea is not appreciably affected by river discharge into Hudson Bay.

The main goal of this study is to provide updated and expanded information on the interannual variability and interdecadal trends in Hudson Bay streamflow. Specifically, we investigate: 1) if the 1964–2000 observed trends in Hudson Bay streamflow (Déry et al., 2005) are persisting when the period is extended to 2008, 2) the seasonality of recent changes in the river input to Hudson Bay for the period 1964–2008, and 3) the impact of flow regulation on these trends. To address these questions, hydrometric data for a set of 23 rivers are extracted for the period 1964–2008. Of note, a recently acquired dataset of the 1979–2008 daily hydrometric data for the regulated La Grande Rivière provides new insights on its contribution to total Hudson Bay streamflow. Annual, seasonal, and daily hydrometric data are analyzed to establish trends and phase shifts in the streamflow input to Hudson Bay. The trend results for naturally-flowing rivers are compared to those obtained for the regulated systems. We further discuss the implications that the observed changes in the riverine input to Hudson Bay have on the surrounding marine environment.

2. Study area

Fig. 1 shows the Hudson Bay drainage basin (our study area) that covers an area of 3.7×10^6 km^2 or more than a third of Canada's land mass. This represents a contributing land area more than three times the combined area (1.2×10^6 km^2) of Hudson Bay and its adjacent bodies of water (Foxe Basin, Hudson Strait, and James Bay). The basin collects freshwater from over five Canadian provinces, two Canadian territories, and four American states that collectively span 24° of latitude and 47° of longitude. The landscape is characterized by the glacierized Rocky Mountains in the far west, dry prairies in the continental interior, cool-wet boreal forest in the mid-latitudes, and Arctic tundra in the high latitudes.

Mean annual air temperature (MAAT) and total mean annual precipitation (MAP) vary considerably across the drainage basin. MAAT ranges from 4 °C in the Canadian Prairies and the American upper mid-western states to −12 °C in Nunavut. MAP minima of 200 mm are found in both northern and southern extremes of the drainage basin, whereas maxima of 800 mm are found at intermediate locations in the boreal forest. Similarly, the annual snowfall ranges from about 100 mm of snow water equivalent (SWE) in the Canadian Prairies to about 400 mm SWE in northern Québec, with even higher amounts in the Rockies. Snowcover typically begins by early October in the northern sections, then progresses southward until the remainder of the basin is covered by mid-November. In turn, snowmelt typically begins in the Canadian prairies by mid-April, and by mid-June in northern Québec and Nunavut (McKay and Gray, 1981). Topography governs a similar advance and retreat of the seasonal snowcover in the mountainous headwaters of the Nelson River Basin, with the spring snowmelt and freshet occurring progressively later at higher elevations (Rood et al., 2008; Tong et al., 2009).

3. Data and methods

A total of 23 rivers spanning $>2.5 \times 10^6$ km^2 in area and with outlets into Hudson Bay (including James Bay) are selected for this study (Table 1). The 1964–2008 observed daily discharge rates (where and when available) are extracted from the online Hydrometric Database (HYDAT) (Water Survey of Canada, 2009, http://www.ec.gc.ca/rhc-wsc/default.asp?lang=En&n=9018B5EC-1). More recent (2001–2008) daily streamflow data for rivers of northern Québec are provided by the Ministère de l'Environnement du Québec (2009, http://www.cehq.gouv.qc.ca/suivihydro/default.asp) with the exception of the intensively dammed La Grande Rivière for which the 1979–2008 daily hydrometric measurements near its outlet into Hudson Bay are supplied by the power generation company Hydro-Québec. There is an insufficient number of gauges prior to 1964 to accurately evaluate the observed streamflow input into Hudson Bay, limiting this study to 45 years in total (Mlynowski et al., 2010). The paucity of hydrometric gauges in the Canadian Arctic Archipelago prevents an analysis of freshwater input to Foxe Basin, which is located north of Hudson Bay (Déry and Wood, 2005; Spence and Burke, 2008). Several streamflow time series are incomplete, most notably in Nunavut during the early years and in northern Ontario and Québec at the end of the period of interest. Following Déry et al. (2005), we use a two-step process to complete the streamflow time series. First, if data are not available at the most downstream gauge for a given river, we employ streamflow data from the nearest upstream station and adjust the discharge rate for the missing contributing area between the two gauges. Second, if additional data from an upstream gauge are not available, we in-fill the data gaps with mean daily discharge values over the period of record at each of the gauges.

Despite being one of the most reliable variables of the hydrological cycle, river discharge measurements remain susceptible to errors (Lammers et al., 2001; Shiklomanov et al., 2006). The errors depend on several factors including the type of gauge used, the frequency of data collection, the environmental conditions (e.g., under ice or spring freshet conditions), and the local geography (e.g., the presence or absence of a flood plain). Lammers et al. (2001) report relative errors of ±2–5% for non-ice conditions in the absence of a flood plain and of ±5–12% with a flood plain. Shiklomanov et al. (2006) estimate relative errors of ±1.5–3.5% for the total annual discharge in the six largest rivers of northern Eurasia. Although a detailed error analysis is beyond the scope of the present study, we assume that similar errors can be expected for the rivers draining into Hudson Bay. In any case, these measurement errors generally have little effect on annual statistics and on trend analyses (Shiklomanov et al., 2006). A possible exception to this arises in the Hudson Bay Basin since two tributaries of the Chesterfield Inlet basin, the Thelon and the Kazan rivers, underwent a modification 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). This may lead to spurious trends for the Chesterfield Inlet system such that these results are also highlighted in this work.

Fig. 1. Map of the Hudson Bay Basin showing the location of rivers with outlets into Hudson Bay or James Bay. The inset shows the overall contributing drainage basin for Hudson Bay shaded in grey.

In addition to La Grande Rivière, the Eastmain, Moose, Nelson, and Churchill rivers are also affected by dams, diversions, and/or reservoirs (Vörösmarty and Sahagian, 2000). Despite these anthropogenic disturbances, we retain and highlight these rivers in our study to better understand freshwater delivery to Hudson Bay. These artificial influences often impact the seasonality of river discharge, but have minimal effects on annual river discharge (McClelland et al., 2004, 2006; Hernández-Henríquez et al., 2010). However, inter-basin diversions (such as on the Caniapiscau River into the La Grande Rivière system) and the filling of water reservoirs developed for hydroelectric projects may influence total streamflow into Hudson Bay. Since we are interested in the actual amounts of freshwater delivered to Hudson Bay, no adjustments are made to the original hydrometric data to account for these anthropogenic influences on the results. In other words, we do not add the water used to fill these reservoirs to our hydrometric time series as done in other studies (e.g., Déry and Wood, 2004, 2005) and instead focus on the actual freshwater fluxes to Hudson Bay that include anthropogenic influences. However, we report the volumes of water used to fill the reservoirs in Section 4 and test the sensitivity of the trend analyses to this anthropogenic disturbance in Section 5.

Following Mlynowski et al. (2010), we construct the 1964–2008 time series of the total annual gauged area within the Hudson Bay Basin, relying on the availability of the hydrometric data at all gauges used in the study. This time series thus yields a spatio-temporal analysis of the fraction of the basin that is monitored in any given year and provides a measure of the amount of the hydrometric data that requires in-filling. It also reveals the evolution of the total area strongly affected by anthropogenic development (dams, diversions, reservoirs) within the Hudson Bay Basin.

The means, standard deviations, and coefficients of variation in annual and seasonal river discharge are computed for the 23 rivers as well as for the total Hudson Bay streamflow. These statistics are computed over the period of data availability that varies for each river.

Table 1
The annual mean, standard deviation (SD), coefficient of variation (CV), and trend in streamflow for the 23 rivers of interest and their tributaries (italicized). Signal-to-noise ratios (SNRs) in bold denote detectable trends.

River	Gauged area (km^2)	Annual streamflow statistics: Mean (km^3)	SD (km^3)	CV	Trend ($km^3\ yr^{-1}$)	Signal-to-noise ratio
Manitoba						
Churchill	290,880	19.4	13.5	0.69	−0.70	**−2.33**
Churchill	289,000	19.0	13.5	0.71	−0.70	**−2.34**
Deer	1880	0.5	0.2	0.32	0.00	−0.45
Hayes	103,000	19.4	5.0	0.26	0.00	−0.01
Nelson	1,075,520	92.6	17.9	0.19	0.43	**1.08**
Angling	1560	0.3	0.1	0.33	0.00	−0.28
Burntwood	18,500	20.3	11.1	0.54	0.59	**2.42**
Limestone	3270	0.7	0.2	0.33	0.00	−0.76
Nelson	1,050,000	70.7	18.2	0.26	−0.19	−0.46
Weir	2190	0.5	0.2	0.31	0.00	−0.48
Seal	48,200	11.4	2.4	0.21	0.03	0.53
Nunavut Territory						
Chesterfield Inlet	224,000	41.1	6.8	0.17	0.16	**1.07**
Kazan	70,000	14.0	2.6	0.19	0.02	0.40
Thelon	154,000	27.2	4.9	0.18	0.14	**1.32**
Thlewiaza	27,000	6.9	0.8	0.12	0.00	0.01
Ontario						
Albany	118,000	31.9	7.8	0.25	0.07	0.38
Attawapiskat	36,000	11.5	3.2	0.28	−0.03	−0.44
Ekwan	16,900	2.7	0.7	0.26	0.00	−0.04
Moose	98,530	39.1	6.2	0.16	−0.14	−0.99
Abitibi	27,500	11.9	1.6	0.13	0.00	0.00
Kwataboahegan	4250	1.3	0.3	0.25	0.01	0.72
Moose	60,100	22.9	4.6	0.20	−0.13	**−1.24**
North French	6680	3.0	0.6	0.19	0.00	0.37
Severn	94,300	21.6	5.4	0.25	0.00	0.00
Winisk	54,710	15.3	4.6	0.30	−0.05	−0.45
Shamattawa	4710	1.3	0.4	0.29	0.00	−0.12
Winisk	50,000	14.0	4.3	0.31	−0.05	−0.49
Québec						
Boutin	5060	0.5	0.1	0.13	0.00	−0.48
Broadback	17,100	10.0	1.5	0.15	0.01	0.29
Eastmain	44,300	13.0	13.0	1.00	−0.68	**−2.35**
Grande Rivière de la Baleine	43,200	19.8	2.6	0.13	−0.08	**−1.32**
Harricana	21,200	10.9	1.5	0.14	−0.01	−0.32
Harricana	10,000	5.0	0.9	0.17	−0.01	−0.31
Turgeon	11,200	5.9	0.9	0.15	0.00	0.00
La Grande Rivière	96,600	80.5	22.9	0.28	1.48	**2.90**
Nastapoca (Loups Marins)	12,500	8.0	0.9	0.11	0.01	0.33
Nottaway	57,500	32.8	4.6	0.14	−0.06	−0.63
Petite Rivière de la Baleine	11,700	3.7	0.4	0.10	0.00	−0.31
Pontax	6090	3.1	0.4	0.12	0.00	−0.03
Rupert	40,900	26.7	2.7	0.10	−0.04	−0.70
All rivers	2,543,190	522.2	48.5	0.09	0.31	0.29

For the seasonal analyses, fall comprises September, October and November, winter consists of December, January and February, spring includes March, April and May, and summer consists of June, July and August. Linear, monotonic trends in annual and seasonal river discharge are assessed with Kendall–Theil Robust Lines (KTRLs) (Kendall, 1975; Theil, 1950). Hydrological time series often exhibit strong serial correlation that may confound the linear trend analyses. Thus prior to computing the KTRLs, streamflow time series are "pre-whitened" following Yue et al. (2002). Cohn and Lins (2005) and Koutsoyiannis and Montanari (2007) suggest that measures of statistical significance applied to hydrologic trend analyses may be unreliable. Thus we characterize the trends as "detectable" when the absolute values of their signal-to-noise ratios (SNRs) (the trend slope divided by the standard deviation in streamflow) are greater than unity. To obtain an integrated assessment of hydrological variability across the Hudson Bay basin, fractions of the available gauged area and mean annual discharge experiencing detectable positive and negative trends in river discharge are tracked.

Since gaps exist in some of the time series and the availability of hydrometric data varies over time, early (1964–1994), central (1971–2001), late (1978–2008), and overall (1964–2008) periods are chosen for the trend analyses of annual streamflow for each river. This approach provides information on the dependence of the trends on the selected periods. Tests are then conducted to evaluate the impact of the in-filling strategy on the trend analysis for three rivers exhibiting either no trend or strong positive/negative tendencies. Monte Carlo simulations are first performed to randomly substitute 10% and 20% of the observed daily discharge records with the mean value for that day over the period of record. The simulations demonstrate that the magnitude of strong trends is attenuated, while their SNRs remain stable (Table 2). As hydrometric data gaps are often sequential in nature rather than randomly distributed, a second test verifies the impact of replacing the first, middle or last 10% of the streamflow time series with the average daily value over the period of record. In this case, trends are generally not highly influenced when the middle portion of the records are substituted; however, strong trends are more greatly affected, with both the trend slopes and SNRs being reduced (Table 3). Thus the in-filling strategy, unavoidable to complete the hydrometric records in this data sparse region, weakens the magnitude of strong trends, especially when the missing records are at either end of the time series. Following these tests, we choose to show results for individual rivers when less than 10% of the daily discharge data are missing and in-filled for a given river and analysis period. However given the paucity of long-term hydrometric records for the study area, trend results for rivers with 10% to 20% missing data are also presented, but highlighted. Thus the trend results must be interpreted carefully, especially when larger data gaps require in-filling.

Changes in the annual cycle of the mean and coefficient of variation in daily streamflow into Hudson Bay are assessed by comparing the 1965–1978 and 1995–2008 hydrographs. These two periods are chosen to highlight: 1) the impact of flow regulation associated with the James Bay Hydroelectric Complex and 2) the availability of hydrometric data before and after its development. Two subsets of rivers are emphasized here: 1) the "regulated" rivers are those strongly affected by fragmentation through dams, diversions and/or reservoirs (Dynesius and Nilsson, 1994; Vörösmarty and Sahagian, 2000); and 2) the "natural" rivers are the remaining ones not affected by major human development.

Table 2
Statistics on the trends and corresponding signal-to-noise ratios (SNRs) for three rivers draining into Hudson Bay following a series of 10,000 Monte Carlo (MC) simulations with random in-filling of 10% (20%) of the daily discharge with the mean daily values over 1964–2008.

River	Annual streamflow trend (km^3 45 yr^{-1}): Observed	Mean of MC simulations	Range of MC simulations	SNR of annual streamflow trend: Observed	Mean of MC simulations	Range of MC simulations
Burntwood	29.3	26.5 (23.6)	23.7 to 29.3 (23.3 to 29.3)	2.42	2.42 (2.42)	2.37 to 2.46 (2.38 to 2.48)
Churchill	−32.9	−29.7 (−26.2)	−32.9 to −29.0 (−32.9 to −25.6)	−2.34	−2.35 (−2.34)	−2.41 to −2.28 (−2.42 to −2.24)
Thlewiaza	1.2×10^{-8}	3.3×10^{-8} (4.8×10^{-8})	6.2×10^{-9} to 9.9×10^{-8} (6.2×10^{-9} to 4.0×10^{-6})	6.9×10^{-7}	2.0×10^{-6} (3.3×10^{-6})	3.8×10^{-7} to 6.1×10^{-6} (4.3×10^{-7} to 2.8×10^{-4})

Table 3
Statistics on the trends and corresponding signal-to-noise ratios (SNRs) for three rivers draining into Hudson Bay following the in-filling of the first, middle, and last 10% of the daily discharge values over 1964–2008.

River	Annual streamflow trend (km^3 45 yr^{-1})				SNR of annual streamflow trend			
	Observed	First 10% in-filled	Middle 10% in-filled	Last 10% in-filled	Observed	First 10% in-filled	Middle 10% in-filled	Last 10% in-filled
Burntwood	29.3	18.6	30.4	20.1	2.42	1.57	2.66	1.86
Churchill	−32.9	−21.4	−34.9	−25.3	−2.34	−1.52	−2.55	−2.25
Thlewiaza	1.2×10^{-8}	1.2×10^{-8}	-3.0×10^{-9}	1.4×10^{-8}	6.9×10^{-7}	6.9×10^{-7}	-1.2×10^{-7}	8.3×10^{-7}

4. Evolution of the hydrometric network and anthropogenic development

4.1. Evolution of the hydrometric network

Fig. 2 shows the evolution of the total gauged area monitored by the hydrometric network near the shorelines of Hudson Bay and James Bay. From 1964 to 1972, hydrometric gauges are being established, leading to the sharp increase in total gauged area. Thereafter, total gauged area attains a relatively stable state (within 2% of the maximum of 2.54×10^6 km^2) for the next 22 years. Starting in 1994, the total gauged area diminishes to a relative minimum in 1998 when it reaches 80% of its former maximum. Throughout 2002–2008, gauged area initially improves, but eventually returns to 80% of its peak value. Since 1994, the decline in gauged area can be attributed to government funding and costs, decision making, and environmental conditions (Mlynowski et al., 2010). Gauges within the boundaries of Ontario (e.g., Albany, Severn, Winisk, and Moose rivers) and Québec (e.g., Boutin, Petite Rivière de la Baleine, Grande Rivière de la Baleine, and Broadback rivers) are most severely affected by this network reduction. The recent deterioration in total gauged area in the Hudson Bay Basin is consistent with a pattern observed across the pan-Arctic region (Shiklomanov et al., 2002).

4.2. Evolution of the anthropogenic development

For the purpose of hydroelectric energy, flood control, and agriculture, among other activities, humans have regulated the spatial and temporal flow of rivers by creating dams, diversions (i.e. intra- and inter-basin), and/or reservoirs. Some of the largest rivers affected by these disturbances in the study area include the Churchill, Nelson, Moose, Eastmain and La Grande (see Fig. 1). In 1976, a portion of the Churchill River was diverted into the Nelson River to augment its flow by 40% (Manitoba Wildlands, 2005), which now has an average discharge of 78.3 km^3 yr^{-1} (Rosenberg et al., 2005). Together the main stems of the Churchill and Nelson rivers (Manitoba's largest rivers) support seven hydroelectric stations, with proposals for more additions in the future (Manitoba Wildlands, 2005). The Moose River has a mean annual discharge of 43.2 km^3 and is fragmented by more than 40 dams and water control structures along its tributaries. The oldest of these structures was built on the Matagami River in 1911; however, most structures were constructed in the 1960s (Rosenberg et al., 2005). In the late 1970s and early 1980s, the average annual discharge (53.7 km^3) of La Grande Rivière was nearly doubled after diverting flow from neighbouring basins: the Eastmain–Opinaca (26.7 km^3 yr^{-1} beginning in July 1980) and the Caniapiscau (21.0 km^3 yr^{-1}starting in January 1984) that naturally flows into Ungava Bay (Quinn, 2004; Hernández-Henríquez et al., 2010). As of 2008, only 30% ($<0.60\times10^6$ km^2) of the total gauged area in the Hudson Bay basin is considered to be in naturally-flowing systems (Fig. 2).

Starting in the fall of 2009, the James Bay Hydroelectric Complex partially diverted the Rupert River, so that its flow is now reduced by 48% at the mouth in James Bay, with a net mean diversion of 14.5 km^3 yr^{-1} (http://www.hydroquebec.com/rupert/en/derivation-partielle.html#; Hydro-Québec, 2008). This recent diversion further alters the "natural" flow of the Rupert River and compounds the effects of anthropogenic disturbances to the Hudson Bay freshwater cycle.

The large reservoirs developed as part of the hydroelectric infrastructures on the Nelson River and La Grande Rivière also influence total streamflow into Hudson Bay. Of note, the impoundments constructed on La Grande Rivière and nearby rivers were filled with a total of about 160 km^3 of water between 1979 and 1996 (http://www.ilec.or.jp/database; International Lake Environment Committee, 2004; Hayeur, 2001; Messier et al., 1986; J. Guidi, personal communication, 2010). To divert the Churchill River into the Nelson River, Southern Indian Lake was filled with an additional 7 km^3 of water in 1976–1977 (Table 4 and Fig. 3). Apart from extraction of water used to initially fill the reservoirs, intra-year and inter-year storage tied to water management for power production alters the Hudson Bay streamflow. Such information, while relevant to an analysis of total basin streamflow, is currently unavailable and is beyond the scope of this study. Nonetheless, future studies for this basin should consider all of these effects to obtain a better understanding of the roles of climate and human interferences on Hudson Bay streamflow (Batalla et al., 2004; Woo et al., 2008).

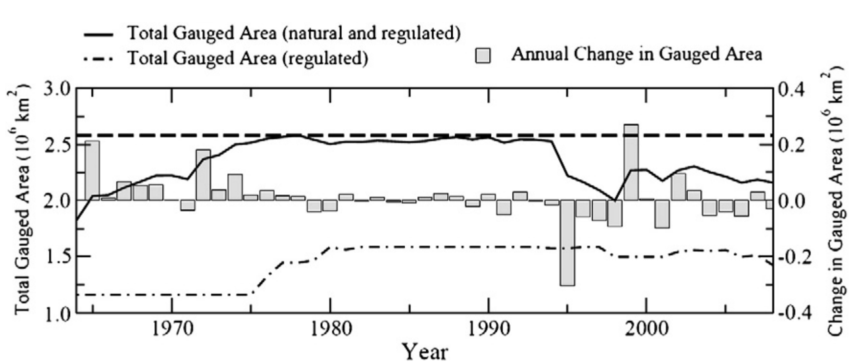

Fig. 2. Temporal evolution of total and annual change in gauged area for the Hudson Bay Basin, 1964–2008. The dashed line marks the maximum total gauged area (2.54×10^6 km^2).

Table 4
Major reservoirs in the Hudson Bay Basin and their province, geographical coordinates, commissioning year(s), and total volumes.

Reservoir	Province[a]	Lat (N)	Lon (W)	Commissioning year(s)	Volume (km^3)
Lake Diefenbaker	SK	51.00	107.22	1967	9.4
Southern Indian Lake	MB	57.08	98.49	1977	7.2
Robert Bourassa (La Grande-2)	QC	53.45	76.57	1979–1981	61.7
La Grande-3	QC	53.50	75.00	1982–1984	60.0
La Grande-4	QC	54.00	73.12	1984–1986	19.5
Opinaca	QC	52.26	76.37	1980	8.5
La Grande-1	QC	53.44	78.34	1994–1995	1.2
Laforge-1	QC	54.10	72.37	1993–1994	6.7
Laforge-2	QC	54.35	71.16	1996	1.8
Total	–	–	–	–	176.0

[a] SK = Saskatchewan, MB = Manitoba, QC = Québec.

5. Results

5.1. Interannual variability and interdecadal trends in annual streamflow

Table 1 provides statistics on the 1964–2008 mean annual, standard deviation, and coefficient of variation in discharge for 23 rivers flowing into Hudson Bay. For the overall gauged area (2.54×10^6 km^2), the 1964–2008 mean annual total discharge is 522.2 km^3 with a standard deviation of 48.5 km^3 and a coefficient of variation of 0.09. This equates to a mean annual runoff rate of 205.3 mm or a discharge rate of 16,548 m^3 s^{-1}. Assuming the remainder of the drainage basin experiences similar runoff rates, a first-order estimate of the total annual streamflow into Hudson Bay (including Foxe Basin and James Bay) then reaches 759.8 km^3.

The two largest rivers by volume are the Nelson (92.6 km^3 yr^{-1}) and La Grande Rivière (80.5 km^3 yr^{-1}), both of which experience artificially enhanced flows from the diversion of nearby rivers for enhanced hydroelectric generation. The largest (by volume) naturally-flowing river system is Chesterfield Inlet that contributes an additional 41.1 km^3 yr^{-1} to Hudson Bay.

Fig. 4 illustrates the 1964–2008 time series in mean annual streamflow into Hudson Bay. This analysis shows no detectable (SNR = 0.29) trend over the period of study, with a slightly positive slope of 0.31 km^3 yr^{-1} in total annual discharge. Considering the effects of reservoir filling (i.e. adding the volumes of water retained to stock the reservoirs; see Fig. 3) decreases the slope magnitude to 0.23 km^3 yr^{-1} (SNR = 0.22). The 5-year running mean in total Hudson Bay streamflow reveals two distinct periods marked by opposite trends. During the first 20 years, mean annual discharge into Hudson Bay decreases, whereas for the most recent 20 years, Hudson Bay streamflow increases sharply. A 5-year period with relatively high Hudson Bay streamflow divides these two opposite trends. Of note, a maximum annual discharge rate of 635.1 km^3 is attained in 2005, contributing to the recent 20-year upward trend.

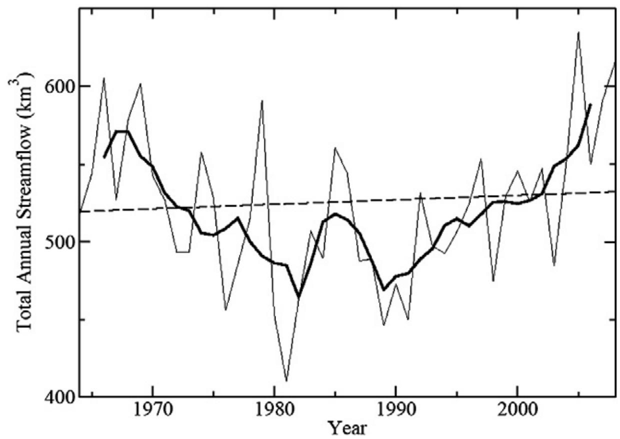

Fig. 4. Temporal evolution of the total annual streamflow into Hudson Bay, 1964–2008. A 5-year running mean (thick line) is shown and the KTRL represents the linear trend for the overall 45-year period (dashed line).

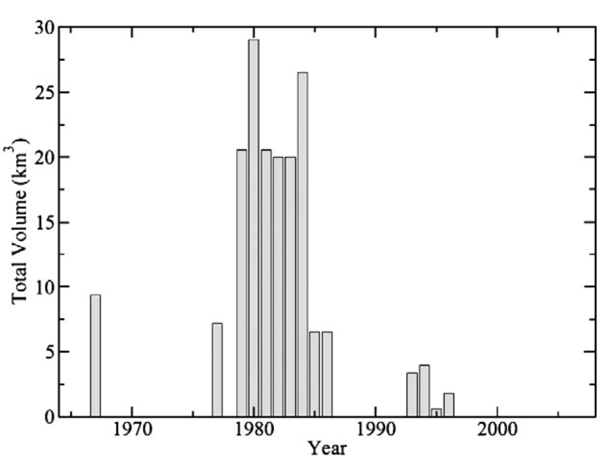

Fig. 3. Time series of approximate water volumes used to fill reservoirs in the Hudson Bay Basin, 1964–2008.

Fig. 5 shows the spatial variation in annual streamflow trends into Hudson Bay. Over the early period (1964–1994), the available hydrometric data reveal dominance of negative trends (eight of which are detectable), with the exception of La Grande Rivière and Chesterfield Inlet. No clear signal emerges over 1971–2001 since there is almost an equal number of rivers experiencing positive and negative trends in annual discharge. In the late period (1978–2008), deterioration in the gauge network limits a complete trend analysis. Based on the available data, only the Churchill, Moose, Harricana, and Nottaway rivers show negative (but not detectable) trends in annual discharge, with all others experiencing increasing streamflow amounts. Over the entire period of study, the trend analysis reveals a mixture of positive and negative trends, dominated by systems experiencing flow diversions.

Table 5 lists the fraction of the available gauged area and streamflow undergoing detectable positive/negative trends for the Hudson Bay Basin over four periods of interest. Predominant negative trends are evident over 1964–1994, and then a reversal to mostly positive trends for 1971–2001 and 1978–2008. For the overall study period (1964–2008), 72% and 15% of the available gauged area undergoes detectable positive and negative trends in streamflow, respectively.

5.2. Interannual variability and interdecadal trends in seasonal and daily streamflow

Table 6 summarizes the seasonal characteristics and trends of river discharge into Hudson Bay. About one third of the annual streamflow input to Hudson Bay occurs during the summer, with lesser amounts in the other seasons. The relatively low value (0.10) in the coefficient of variation in spring streamflow indicates that less interannual variability is experienced in spring than in other seasons.

An examination of the seasonal trends in streamflow input to Hudson Bay is shown in Fig. 6 and a summary of the trend statistics is presented in Table 6. This analysis exposes notable changes in streamflow during the summer and winter seasons, with more modest trends during the shoulder seasons. The slope of the KTRL reaches -0.93 km^3 yr^{-1} (SNR = -1.57) and 0.68 km^3 yr^{-1} (SNR = 2.48) for the summer and winter seasons, respectively. These detectable trends suggest an increase in the storage of freshwater during summer that is

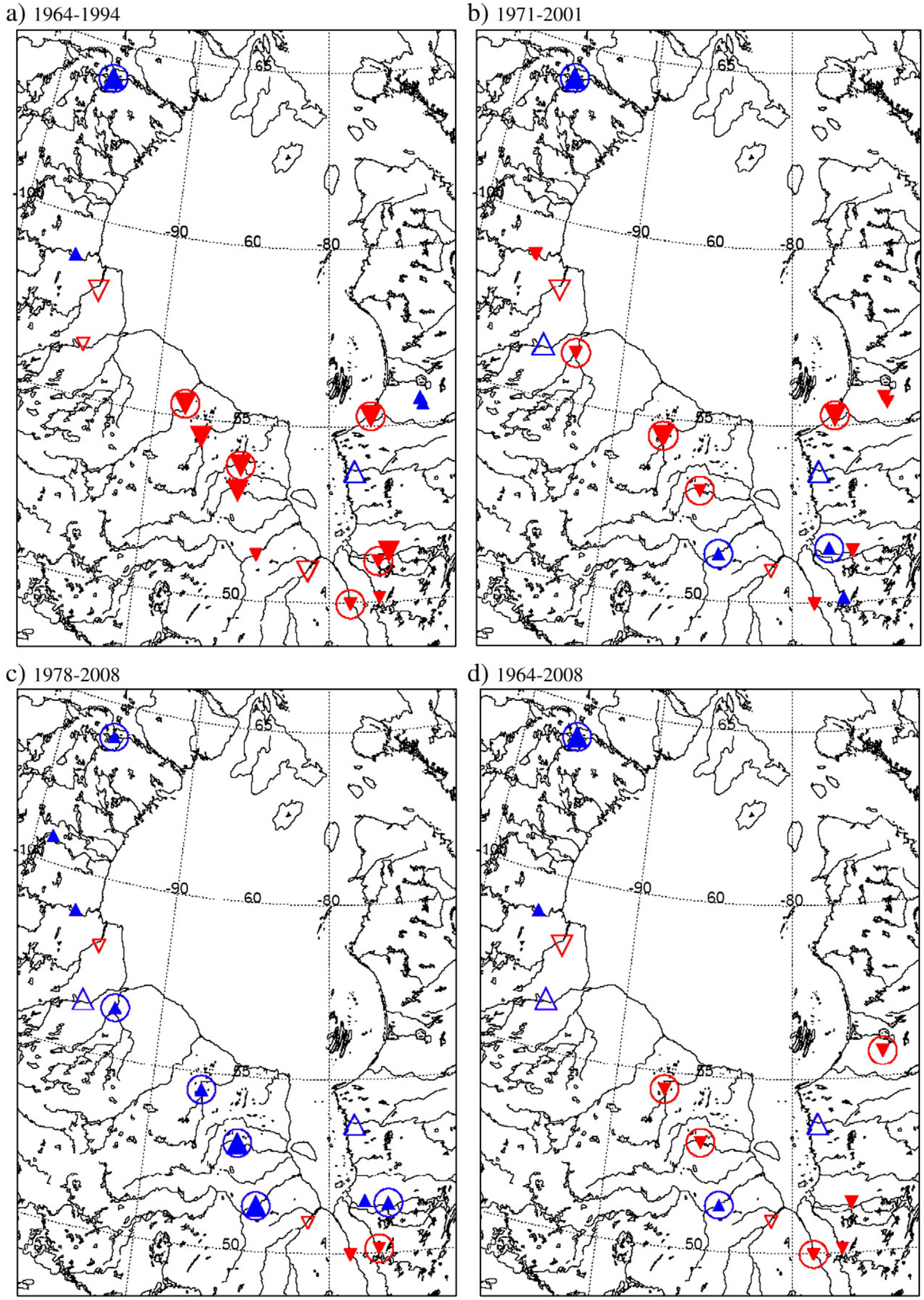

Fig. 5. Maps depicting the spatial variability in the trends of annual streamflow of 23 rivers of the Hudson Bay Basin for (a) 1964–1994, (b) 1971–2001, (c) 1978–2008, and (d) 1964–2008. Upward (downward) pointing triangles denote positive (negative) trends illustrated by larger symbols if detectable. Rivers affected by major anthropogenic disturbances (dams, diversions, and/or reservoirs) are shown as open triangles. Circles highlight the Chesterfield Inlet basin in Nunavut that underwent a change in recording methodology in the mid-1980s and those rivers with 10% to 20% missing data over each period (see Section 3). The gauge coordinates for each river are used to locate symbols.

Table 5
Fractions of the available gauged area and streamflow for the Hudson Bay Basin undergoing detectable positive and negative trends in mean annual streamflow for the early (1964–1994), central (1971–2001), late (1978–2008), and overall (1964–2008) time periods.

Period	Weighted by gauged area			Weighted by annual streamflow		
	Fraction positive	Fraction negative	Gauged area ($\times 10^6$ km^2)	Fraction positive	Fraction negative	Streamflow (km^3)
1964–1994	0.15	0.24	2.16	0.30	0.28	407
1971–2001	0.71	0.15	1.97	0.60	0.05	359
1978–2008	0.62	0.00	1.89	0.57	0.00	305
1964–2008	0.72	0.15	1.93	0.62	0.06	344

Table 6
The mean, standard deviation, coefficient of variation, and trend in total seasonal streamflow input to Hudson Bay, 1965–2008. Signal-to-noise ratios in bold denote detectable trends.

Season	Mean (km^3)	Standard deviation (km^3)	Coefficient of variation	Trend (km^3 yr^{-1})	Signal-to-noise ratio
Fall	137.5	21.7	0.16	−0.44	−0.89
Winter	88.4	12.1	0.14	0.68	**2.48**
Spring	120.6	11.6	0.10	0.23	0.86
Summer	169.1	26.0	0.15	−0.93	−**1.57**

later released for the generation of hydroelectricity in winter when energy demands are high.

Fig. 7a depicts the yearly cycles of daily streamflow for all rivers draining into Hudson Bay for 1965–1978 and 1995–2008 as well as the difference between these two periods. The annual hydrograph for both periods is characterized by low flows during winter, a rapid increase in discharge during May driven by snowmelt, and then a gradual reduction in flows during summer punctuated only by a secondary peak in October. The difference in daily streamflow between the two periods (1995–2008 minus 1965–1978) shows a marked increase in winter low flows, an earlier and less intense spring freshet, and a reduction of summer discharge.

The annual hydrographs for the "regulated" and "natural" rivers for the two 14-year periods reveal the source of the observed changes (Figs. 7b and c). When compared to the naturally-flowing systems, regulated rivers exhibit a flattened hydrograph. This is especially evident over the period 1995–2008, following the development of the James Bay Hydroelectric Complex, which causes an increase in winter and early spring flows and a reduction in discharge into Hudson Bay during the remainder of the year. In contrast, the natural rivers show a seasonal hydrograph typical of nival rivers over both 1965–1978 and 1995–2008, with modest changes between the two 14-year periods. Thus flow regulation for power generation controls most of the observed phase shifts in the timing of streamflow input to Hudson Bay.

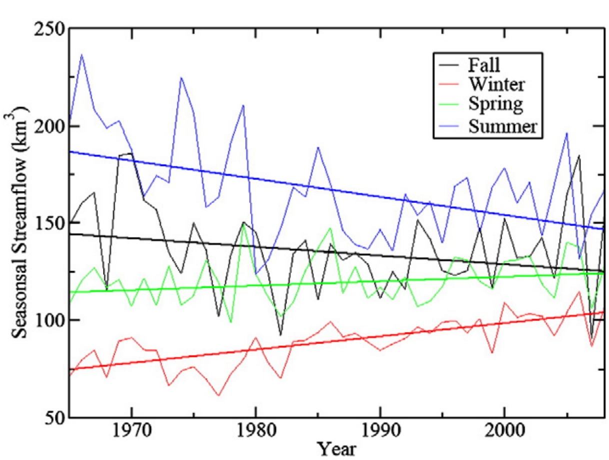

Fig. 6. Temporal evolution of the total seasonal streamflow input into Hudson Bay, 1965–2008. KTRLs (thick lines) represent the linear trends for the overall 44-year period.

Table 7 summarizes the statistics in the annual streamflow input to Hudson Bay for the two periods and subsets of rivers chosen on the basis of data availability. This is to compare the annual hydrographs before and after the development of the James Bay Hydroelectric Complex. Mean annual streamflow input to Hudson Bay decreases by 7.1 km^3 for the most recent period, driven more so by changes in unregulated rivers. The 7.3 km^3 yr^{-1} increase in regulated rivers may be partly explained by the 1984 inter-basin diversion of 21.0 km^3 yr^{-1} from the Caniapiscau River to the La Grande Rivière system. The interannual variability in streamflow input to Hudson Bay, quantified by the coefficients of variation, increases for both the regulated and natural rivers.

The annual cycle in the coefficient of variation in daily streamflow into Hudson Bay reveals further differences in the hydrological regimes of the regulated and natural rivers (Fig. 8). In the regulated systems, the annual cycle in the coefficient of variation in daily discharge shows little seasonal differences, particularly for the most recent periods; however, there is an apparent increase in day-to-day fluctuations in streamflow variability resulting from regulation of La Grande Rivière. Differences between the two periods (1995–2008 minus 1965–1978) reveal a notable increase in variability during winter that coincides with enhanced flows. Natural rivers exhibit a more pronounced seasonal cycle in the variability of daily streamflow input to Hudson Bay, marked by greater values associated with the timing and intensity of the spring freshet. The most recent 14-year period manifests a marked decline in the variability of daily streamflow, with the exception of early spring when there is an earlier timing of the spring freshet.

6. Concluding discussion

Our findings are in accord with previous studies that investigate river discharge into Hudson Bay. For instance, the Canadian Government (1973) and Prinsenberg (1986) report an annual freshwater flux of 694 km^3 by rivers draining into Hudson Bay (excluding the contributing area to Foxe Basin). Shiklomanov and Shiklomanov (2003) and Déry et al. (2005) estimate the annual streamflow input to Hudson, James, and Ungava Bays to reach 938 km^3 and 888 km^3, respectively. Considering only those rivers draining into Hudson and James Bays and adjusting the estimate from Déry et al. (2005) for the missing contributing area yields an annual freshwater flux of 776 km^3 into Hudson Bay for 1964–2000. This nearly matches the estimate of the aggregated annual streamflow input of 760 km^3 into Hudson Bay from 1964 to 2008 when adjusting the rate for the missing contributing area.

Déry et al. (2005) previously found a 13% decline in the total annual river discharge into Hudson, James, and Ungava Bays for the

Table 7
The mean and coefficient of variation in total annual streamflow into Hudson Bay for two periods. Statistics are provided for all rivers as well as regulated and naturally flowing rivers.

Period	Mean annual streamflow (km^3)			Coefficient of variation in annual streamflow		
	All	Regulated	Natural	All	Regulated	Natural
1965–1978	532.4	244.9	287.5	0.08	0.08	0.09
1995–2008	525.3	252.2	273.1	0.08	0.11	0.12

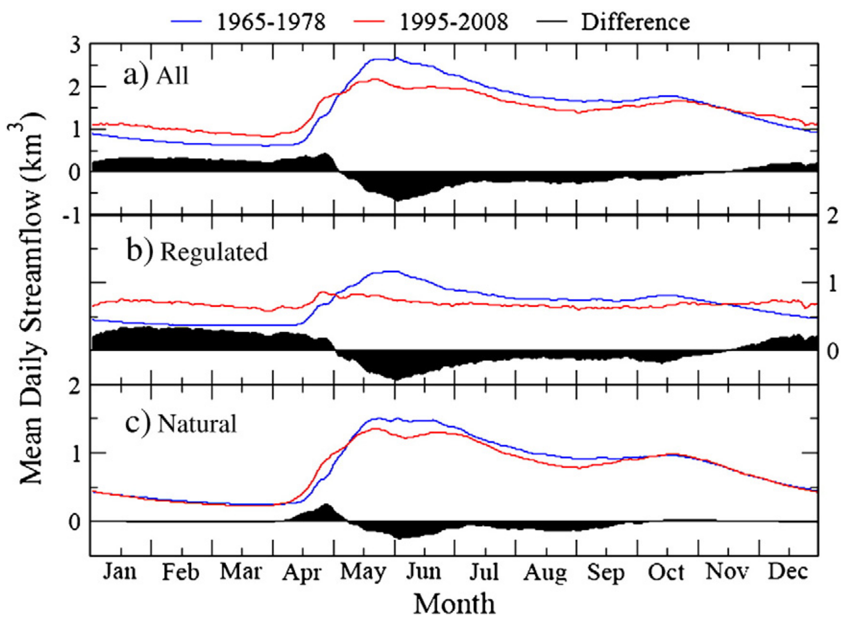

Fig. 7. The annual cycle of total daily streamflow into Hudson Bay for two periods (1965–1978 and 1995–2008) and their difference (1995–2008 minus 1965–1978). Results are shown for (a) all rivers, (b) regulated rivers, and (c) natural rivers.

period 1964–2000. By extending the study period by another eight years, we now obtain no trend in the total annual streamflow into Hudson Bay. Several factors may lead to this surprising result. Annual streamflow amounts into Hudson Bay have been persistently above average since 2000, with a peak value of 635 km^3 yr^{-1} in 2005, thereby offsetting the previous declining trend. Apart from examining a different period, Déry et al. (2005) used a larger set of rivers, with some draining into Ungava Bay in addition to Hudson and James Bays. That study also did not incorporate daily hydrometric data for the regulated La Grande Rivière as recorded by Hydro-Québec. Thus this combination of factors leads to discrepancies between the two studies.

In 2005, total annual streamflow into Hudson Bay peaked at 21.6% above the 1964–2008 average. This was driven in part by record discharge values for the western Hudson Bay rivers. The Hayes, Nelson, Seal and Chesterfield Inlet river systems all attained 45-year record values, while the Thlewiaza River ranked second highest over its period of record. These five rivers alone contributed 257.0 km^3 yr^{-1} or 40.5% of the 2005 total streamflow into Hudson Bay. Large, positive precipitation anomalies were likely the source of these high discharge values as Canada experienced its wettest year on record in 2005 (Shein, 2006). In fact, most of the Hudson Bay Basin saw positive precipitation anomalies of about 20% that year, which explain the record streamflow amounts.

Despite the acquisition of recent (2001–2008) hydrometric data for most of the Hudson Bay rivers, this study has its limitations. Déry and Wood (2004) previously reported a strong teleconnection between the Arctic Oscillation (also known as the Northern Hemisphere annular mode; Thompson and Wallace, 1998, 2001) and Hudson Bay streamflow

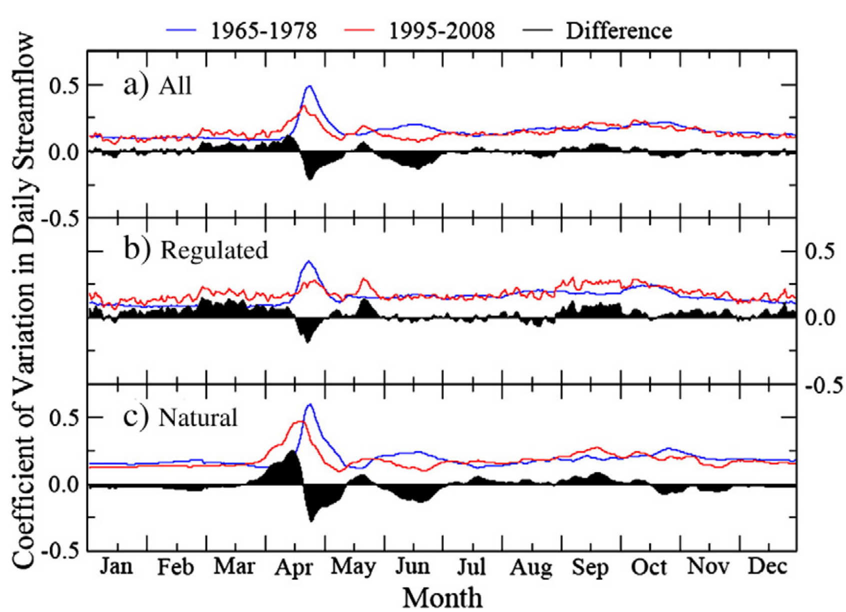

Fig. 8. The annual cycle of the coefficient of variation in total daily streamflow into Hudson Bay for two periods (1965–1978 and 1995–2008) and their difference (1995–2008 minus 1965–1978). Results are shown for (a) all rivers, (b) regulated rivers, and (c) natural rivers.

on a decadal timescale. In these circumstances, the results of linear trend analyses depend highly on the periods chosen for the study (Woo and Thorne, 2003, 2008). Thus the lack of long-term (>45 years) hydrometric records for most of the Hudson Bay rivers impedes a full investigation of the individual roles of large-scale climate oscillations and possible climate change impacts on the regional water cycle.

The annual streamflow input to Hudson Bay shows no detectable trend over 1964–2008 (Fig. 4). Inspection of the 5-year running mean in total Hudson Bay streamflow reveals a downward trend from the mid-1960s to the mid-1980s, followed by relatively high flows in the mid-1980s, and then an upward trend until the end of the study period. Whether the recent 20-year reversal to increasing streamflow into Hudson Bay is a manifestation of an intensifying hydrological cycle in northern Canada (Déry et al., 2009) remains open to debate. A number of studies argue that observed 20th century increases in pan-Arctic river discharge follow the global rise in surface air temperatures (Peterson et al., 2002; McClelland et al., 2006). This pattern concurs with global climate model (GCM) simulations that consistently project increasing rates of pan-Arctic river discharge for the 21st century (e.g., Arnell, 2005; Milly et al., 2005; Wu et al., 2005; Holland et al., 2007). Rising air temperatures allow more moisture loading in the atmosphere that in turn leads to higher net precipitation fluxes in the Arctic. Thus warming in the pan-Arctic is expected to drive an intensification of its hydrological cycle including increasing river discharge. Continued monitoring of Hudson Bay streamflow in the coming years and decades will reveal if the recent 20-year upward trend will persist as projected by most GCM simulations or whether it is part of an interdecadal oscillation tied to large-scale climate variability.

This study exposes the rising impacts of anthropogenic development on the timing of streamflow into Hudson Bay that are not routinely considered in climate change scenarios. Through long term storage and flow regulation, the spring freshet diminishes in intensity and the annual hydrograph is flattened (Woo et al., 2008). The recent diversion of 14.5 km^3 yr^{-1} or 48% of the total annual streamflow from the Rupert River northward into La Grande Rivière for enhanced power production further exacerbates the observed shifts in streamflow timing into Hudson Bay. The loss of the natural component of the Rupert River implies that 257 km^3 yr^{-1} or nearly half of the annual discharge into Hudson Bay currently monitored with hydrometric gauges is now regulated. Consistent with the findings of McClelland et al. (2006), however, our results show that reservoir filling has relatively little influence on long-term trends in total annual Hudson Bay streamflow.

Improved and updated river discharge data are important to better understand the freshwater budget of Hudson Bay. Rivers provide the largest source in Hudson Bay's freshwater budget while outflow through Hudson Strait forms its largest sink. Persistent and/or large deviations in total annual streamflow, such as those observed from 2005 to 2008, can then accumulate as freshwater anomalies in Hudson Bay over a period of up to three years (St-Laurent et al., 2011). Subsequently, ocean currents transport the annual riverine input from Hudson Bay toward Hudson Strait and eventually the Labrador Current (Myers, 2005; Straneo and Saucier, 2008; St-Laurent et al., 2011). Although the Labrador Current transports most of this freshwater southward, a portion enters the Labrador Sea where it may affect deep water formation (Schmidt and Send, 2007). While recent modeling studies suggest that the observed trends in Hudson Bay streamflow are insufficient to significantly affect the thermohaline circulation by changing the freshwater content of the Labrador Sea (Rennermalm et al., 2007), it is still uncertain if GCMs have the appropriate resolution to describe the shelf-interior exchange that would transport freshwater into the Labrador Sea's convection region. Furthermore, a recent study indicates that variations in sea ice formation in the northwestern Labrador Sea, close to the export region from Hudson Bay, strongly impact dense water formation in the Labrador Sea (Våge et al., 2009). Thus variations in the freshwater export from Hudson Bay may impact dense water formation in the Labrador Sea through these various processes. Finally, fluctuations in Hudson Bay streamflow have been linked to changes in the salinity of ocean waters on the inner Newfoundland Shelf (Myers et al., 1990; Déry et al., 2005).

Along with the continued development of hydroelectric generating stations, the recent (1994–2008) degradation in the hydrometric network for the Hudson Bay Basin leads to a loss of long term hydrological records for naturally-flowing rivers. Only four natural rivers (Pontax, Harricana, Thlewiaza and Chesterfield Inlet) have complete (<10% missing) hydrometric records for ≥30 years and ending in 2008. These four rivers drain only 11% of the total maximum gauged area and account for 12% of the monitored streamflow input to Hudson Bay. This imposes serious challenges on our understanding of the impacts of climate change and other factors on freshwater delivery to Hudson Bay. Alternative datasets derived from proxy records such as sediment cores, remote sensing or numerical modeling, may provide the necessary information required to better comprehend the implications of hydrological changes on the marine environment of Hudson Bay. For instance, changes in gravimetric measurements can be used to detect fluctuations and trends in hydrological variables such as snowpack accumulation, surface water and ground water volumes (Frappart et al., 2006; Rodell et al., 2009). Such information is especially useful in the data sparse Hudson Bay Basin where in-situ measurements require extensive efforts during the collection process. The development of these other sources of information on the hydrology of the Hudson Bay basin is especially critical since this region is projected to experience some of the greatest air temperature increases in the 21st century (Westmacott and Burn, 2007; Gough and Wolfe, 2001; Gagnon and Gough, 2005).

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