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Can Regulation of Freshwater Runoff in Hudson Bay Affect the Climate of the North Atlantic?

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ABSTRACT. A sequence of phenomena links anthropogenic changes in the timing of freshwater runoff in Hudson Bay to a possible impact on the North Atlantic thermohaline circulation. The chain of events starts with the spreading of estuarine plumes under ice and continues with the effect of lowered salinity on the rate of ice formation, regional effects on the scale of Hudson Bay, the export of freshwater to the Labrador Sea, its impact on deep convection in that area, and the relative importance of such changes to the North Atlantic circulation. At each step we compare anthropogenic effects with other factors and place them within the perspective of natural variability.

Our conclusion does not support the contention that freshwater runoff regulation, even of all rivers in the basins of Hudson and James Bays, could have a significant or even a detectable effect on the climate of the North Atlantic.

Key words: freshwater regulation, Hudson Bay, climate

RÉSUMÉ. Une séquence de phénomènes relie des changements anthropiques dans le moment où les eaux douces commencent à s'écouler dans la baie d'Hudson à leur répercussion possible sur les courants thermiques des eaux marines. La séquence débute par la formation d'un panache estuarien sous la glace et se poursuit avec l'effet de la baisse de salinité sur la vitesse de formation de la glace, des répercussions régionales affectant toute la baie d'Hudson, l'exportation d'eau douce vers la mer du Labrador et ses retombées sur la convection profonde dans cette zone, ainsi qu'avec l'importance relative de tels changements sur les courants nord-atlantiques. À chaque étape, on compare les influences anthropiques avec d'autres facteurs pour les situer dans un contexte de variabilité.

Notre conclusion n'appuie pas la thèse que la régulation de l'écoulement des eaux douces, même si elle s'étendait à tous les cours d'eau des bassins de la baie d'Hudson et de la baie James, pourrait avoir des répercussions notables ou même détectables sur le climat nord-atlantique.

Mots clés: régulation des eaux douces, baie d'Hudson, climat

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INTRODUCTION

Links between natural or anthropogenic changes in runoff regime and regional or even ocean-wide effects have been proposed in a number of situations. For example, Neu (1982) warned about the consequences of flow regulation on the productivity of the Gulf of St. Lawrence. Aagaard and Coachman (1975) launched a stimulating controversy when they suggested that reduced freshwater runoff due to diversion of Siberian rivers might lead to ice-free conditions in the Arctic Ocean (cf. also Cattle, 1985). Broeker et al. (1989) and Keigwin et al. (1991) suggested that an abrupt diversion of Laurentide ice sheet meltwaters from the Mississippi to the St. Lawrence drainage at the end of the last glaciation may have choked off the thermohaline circulation in the North Atlantic and affected world climate about 10 000 years ago. Mysak et al. (1990) and Mysak and Power (1992) proposed a feedback loop involving northern Canadian river runoff, Arctic and Greenland–Iceland sea-ice extent, atmospheric cyclogenesis around Iceland, and deep convection to explain decadal scale variability in Arctic climate.

The idea that changes in the intensity or the timing of freshwater discharge into the ocean might have a significant effect on climate is certainly not new. Although most of the suggested mechanisms have not received adequate verification, proposals made in this regard have proven quite challenging and have led to advances in understanding various aspects of ocean dynamics.

In this paper, we examine the influence of changes in the timing of freshwater runoff on the oceanography of Hudson Bay and potential downstream effects into the Labrador Sea. The stimulus for our review is a hypothesis presented by Mysak (1993:iv): he speculates that "cumulative hydro-electric development around Hudson Bay...could lead to a

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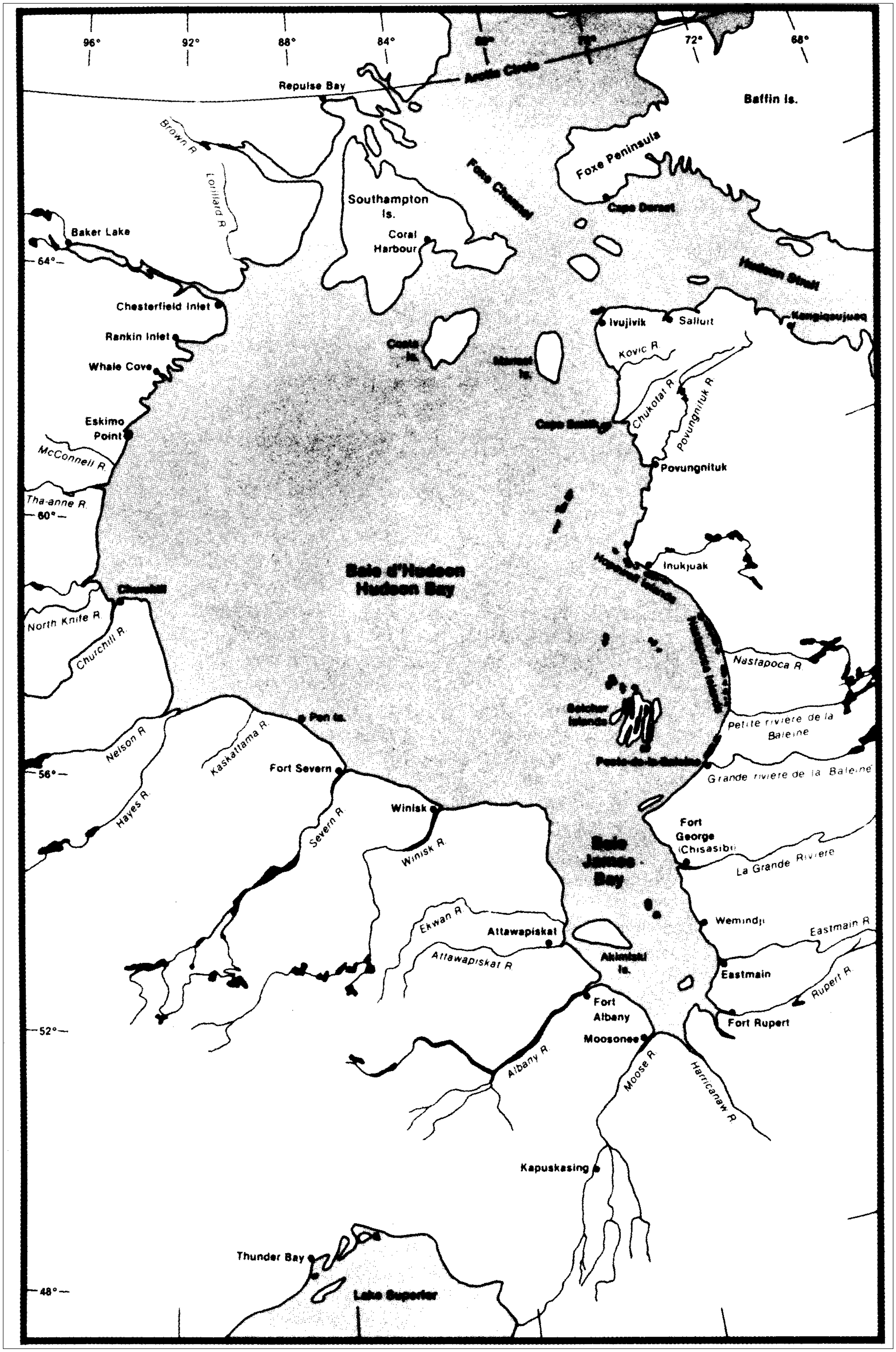

FIG. 1. Hudson and James Bays and the principal rivers which discharge into them.

reduction in the rate of overturning in the Labrador Sea … thus weakening the global thermohaline circulation … resulting in a cooler climate in Europe and eastern North America." We first describe the chain of events arising from runoff regulation, progressing away from river mouths towards the deep sea. We then examine the effects of regulation and of natural causes for each step of the chain to reach an assessment of the validity of the hypothesis.

THE CHAIN OF EVENTS

Changes in the timing of freshwater runoff may be related to possible changes in the intensity of the thermohaline circulation of the North Atlantic through a series of steps.

First, it is clear that hydroelectric regulation will smooth out seasonal variations in runoff, increasing discharge during the winter and reducing it during the summer. While annual total discharge will remain the same, after the reservoirs are full, its seasonal distribution will be different. Freshwater plumes under the ice will become more extensive during the winter than they are now, and summer plumes will be reduced in size. Our first concern will be with the effect of increased discharge on under-ice plumes as one of the main changes accompanying regulation.

Ice formation may be increased to some degree by the extension of under-ice plumes; the importance of this effect will be assessed in the light of physical principles and empirical evidence.

Changed cumulative seasonal discharge may modify regional conditions in the oceanography of Hudson Bay as a whole. These changes should be assessed in the light of the natural variability expected in the area.

Hudson Bay communicates with the ocean through Hudson Strait. The export of freshwater through that Strait into the Labrador Sea and its influence on oceanographic conditions there should then be compared between existing and modified runoff scenarios.

Other contributions to the freshwater budget of the Labrador Sea should also be taken into account and their impact compared to that of modified Hudson Strait runoff on deep convection in the Labrador Sea.

Finally, the relative influence of deepwater formation in the Labrador Sea on the total thermohaline circulation in the North Atlantic has to be assessed.

By that point, after having taken each step into account and put anthropogenic effects in the perspective of other causes and of natural variability, we will have a more precise idea of the potential influence of runoff regulation in Hudson Bay on the thermohaline circulation of the North Atlantic.

UNDER-ICE PLUMES

The area of concern is shown in Figure 1, where the main rivers flowing into Hudson Bay and James Bay are indicated. The total area of the two bays is over 10^6 km^2. Significant

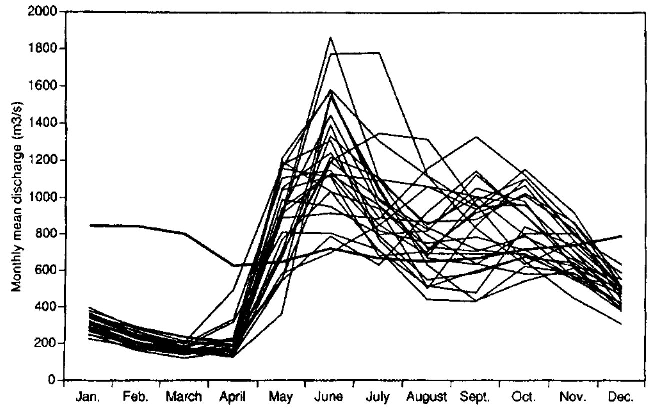

FIG. 2. Discharge curves for the Grande Baleine River, one per year from 1960 to 1986. The heavy line shows the projected discharge rate after regulation. (Figure provided by Danielle Messier, Hydro-Québec).

hydroelectric development has already taken place in the La Grande River complex, flowing into James Bay, and on the Nelson–Churchill system, which discharges into western Hudson Bay. Two smaller rivers flowing into southern James Bay, the Albany and the Moose, have long been dammed and regulated, since 1939 and 1963 respectively (Anctil and Couture, 1994). There are plans for the development of other rivers, in particular the Great Whale River basin. While we are concerned with the cumulative effect of regulation, we nevertheless defer consideration of regional effects to a later section and begin with an examination of well-documented oceanographic changes associated with discharge variations at specific locations.

The direct impact of runoff regulation takes place within the affected rivers and in their immediate vicinity. Typically, freshwater discharge in the area is weak in the winter, with a freshet usually starting in late April and sometimes a secondary maximum in the fall. As a specific example, seasonal and interannual variations in the discharge of the Great Whale River are shown in Figure 2. Over the 26 years of data for that river, the amplitude of the peak spring discharge varies by nearly a factor of three. A proposed post-regulation discharge curve is also shown. Regulation decreases discharge by about a factor of two during freshet, in May and June, and increases it by two to four times in months of minimum discharge during the winter. Interannual variability would be expected to decrease under regulation.

From mid-November to mid-May, most of Hudson Bay and James Bay is ice covered; breakup roughly corresponds to the beginning of freshet (Markham, 1986; Wang and Mysak, 1991). During winter months, freshwater discharge first enters the ocean under a zone of land-fast ice. Observations show that under-ice plumes are much more extended than open-water plumes (Ingram and Larouche, 1987; Messier et al., 1989). A recent fit to measurements taken within eight under-ice plumes (CSSA, 1993; Anctil et al., 1996) yields the following empirical relationship for the area A (in km^2) encompassed by the isohaline of salinity S of a plume arising from a volume discharge rate Q_o (m^3/s) spreading over water of salinity S_b (measured at a depth of 3 m below the pycnocline; S_b ranges from 22 to 27 over the eight rivers examined):

$$A = 17.7\ (Q_o S/S_b)^{2/3}. \qquad (1)$$

Assuming a semicircular plume area, the radius R (in km) of the plume at which $S = S_b$ is

$$R = 3.35\ Q_o^{1/3}. \qquad (2)$$

Let us take the Great Whale River as an example. Current winter discharge is of the order of 200 m^3/s, which yields $R = 19.6$ km. A fourfold increase in Q_o to a proposed discharge of 800 m^3/s would increase the plume radius to $R = 31.1$ km and increase the area within a given isohaline contour by a factor of 2.5. Assuming that winter plumes from neighbouring rivers generally do not overlap, one can estimate the total area of those plumes by summing over all rivers. Total under-ice plume area before any regulation is estimated by assuming that natural winter discharges are one-quarter of the annual mean; post-regulation winter discharges, where not available, are estimated by presuming that regulation without diversion would smooth out seasonal variability and increase winter discharges to the annual mean. Using data from Anctil and Couture (1994), we find the results that are summarized in Table 1. The total area of under-ice plumes increases from about 18 000 to 41 000 km^2 from a state of natural winter runoff to one of complete regulation of all rivers. The difference between the two areas represents the additional area over which the presence of extra freshwater in expanded under-ice plumes might lead to enhanced ice formation: an additional 23 000 km^2, or about 2.3% of the 10^6 km^2 of the total areas of the bays.

TABLE 1. Freshwater discharge and area of under-ice plumes for the principal rivers flowing into Hudson and James Bays[1].

Basin	River	Mean (m^3/s)	Winter (m^3/s)	Plume area (km^2) Pre	Plume area (km^2) Post
Hudson East					
	Great Whale*	639	*841	522	1577
	Little Whale*	211	—	249	—
	Nastapoka	242		314	687
	Others (10)	1500		1980	5000
Hudson West					
	Chesterfield	1547		939	2368
	Churchill*	434	200	402	605
	Nelson*	2962	2850	1449	3559
	Wiaza	309		321	809
	Tha-ann	179		223	562
	Seal	367		360	907
	Hayes	673		539	1360
	Severn	748		578	1459
	Winisk	534		462	1165
	Others (10)	1495		1980	5000
James East					
	La Grande*	3364	> 4500	1577	4825
	Eastmain*	125	20	175	130
	Roggan	128		175	449
James South					
	Notta. Broad.-Rupert*	2500	> 1000	1294	1770
	Harricana	743		576	1452
James West					
	Ekman	182		225	568
	Attawapiska	468		423	1067
	Albany*	1096	200	746	605
	Moose*	1329	500	849	1115
	Others (10)	1082		1590	4010
	Total	**22857**		**17948**	**41049**

[1] Mean and winter discharge data are from Anctil and Couture (1994), and for some regulated rivers from Danielle Messier (pers. comm. 1996). Asterisks indicate systems already regulated or for which post-regulation estimates are available; for others, pre-regulation winter runoff is taken as one quarter of the annual mean, post-regulation winter runoff as equal to the annual mean. Regulation plans divert the Little Whale River into the Great Whale. The discharge of smaller rivers ("Others") is arbitrarily divided into 10 rivers of equal runoff. Areas of under-ice plumes are calculated using estimated winter discharge and equation (2).

ICE FORMATION

The presence of low salinity water at the sea surface, as in estuarine plumes, can affect the formation of sea ice in a number of ways.

For water to freeze, it must first be cooled to its freezing temperature; then, additional latent heat must be removed. Neither the specific heat of water nor the latent heat of fusion is significantly affected by the presence of salt in the concentrations normally found in the ocean: the first may be taken as 1.0 cal/gm, and the second as 80 cal/gm for both salty and freshwater. The freezing point is, however, lowered by the presence of dissolved salt, so that freshwater freezes at a higher temperature than salt water. The freezing point decreases linearly from 0˚C for freshwater at atmospheric pressure to -1.8˚C at a salinity of 30, typical of deeper Hudson Bay waters. The additional quantity of heat which must be extracted from a salt water parcel of that salinity originally at 0˚C to turn it into ice is thus only 1.8 cal/gm, which is only 2% of the total required. In terms of the rate of heat loss at the sea surface at the time of ice formation (about 20×10^{-4} $cal/cm^2/s$ [Prinsenberg, 1983]), the extra time required to remove that quantity of heat from a one-metre layer of water would be only about one day.

Just how much more ice would be formed over a freshwater surface under identical surface heat loss conditions would depend on local temperature and salinity profiles, on vertical mixing by currents (especially tidal) and on the horizontal transport of heat by currents. Macdonald et al. (1995) discussed just how difficult it is to estimate the amount of ice produced off a river mouth (the Mackenzie). Quantitative estimates may be obtained from an ocean model that includes all physical effects. In a model of the Arctic Ocean, Holland et al. (1991) found that 10% more ice would be formed over a freshwater mixed layer than over a mixed layer of realistic salinity. We may take this result as an estimate of the quantitative impact of the presence of additional freshwater on ice formation: 10% more ice over 2.3% of the area of

Hudson and James Bays would yield only 0.23% more ice formation from regulation of all runoff. We also note that among other results, Holland et al. (1991) found that replacing mixed layer salinities with their spatial average value causes very little change in mean ice thickness, so that ice formation does not appear too sensitive to the details of salinity distribution.

A different perspective on the contribution of runoff to ice formation is provided by the results of Macdonald et al. (1995), who found, using isotopic analysis, that about 15% of the freshwater discharge of the Mackenzie River was incorporated into land-fast ice. Similarly, Saucier and Dionne (1996) found, in their coupled ice-ocean model of Hudson Bay, that about 90% of the excess winter runoff associated with regulated flows remained liquid. These results are not surprising: ice is formed only from the topmost part of the water column, and since freshwater is mixed within the estuarine plume, only a small fraction of runoff contributes to ice formation. These results do not suggest that a larger discharge would contribute to more rapid ice formation: as we argued earlier, more freshwater only means a more extensive plume, as given by the relations (1) and (2), not more ice. Moreover, as the isotopic results show that only a small fraction of the winter runoff is left behind as ice, there is no need to consider its effect on the freshwater budget later, at the time the ice melts.

NATURAL VARIABLITY

We have estimated that the amount of extra ice formed by increasing winter river discharge is on the order of 0.2%. This estimate should be seen in the perspective of natural variability in ice volume in the basins. The volume of ice equals its area times its average thickness. Wang et al. (1994) have analyzed interannual variability in ice cover in this area. There is little variability in area during spring and winter, because the bays are entirely ice-covered: shore boundaries impose absolute constraints upon the surface extent of the ice. Summer and autumn values vary by about 20% on either side of a mean which corresponds to about one-third coverage. Variability in ice thickness, averaged over six stations around Hudson Bay, has been examined by Loucks and Smith (1989). Interannual variations of over 10% about the mean are clearly evident. Some of these stations (e.g., Moosonee, Kuujjuarapik), which are located in freshwater within river mouths, are probably poor indicators of ice thickness offshore. On the whole, it does not appear possible to relate area and thickness variability to obtain reliable estimates of ice volume changes. It is nevertheless clear that interannual variability in both the area covered and the thickness of ice found in Hudson Bay is greater than any increase to be expected from increased ice formation due to freshwater regulation of all runoff. Wang et al. (1994) related the observed variability mostly to atmospheric variations, with some part also correlated to variations in the previous year's runoff. Other, more important effects thus contribute to variations, and possibly trends, in the amount of ice formed in Hudson Bay and James Bay besides those related to freshwater regulation.

Prinsenberg (1988) pointed out that ice formation and melting contribute very significantly to the instantaneous freshwater budget of the bays. Under natural conditions, the peak ice melt between May and August contributes more freshwater than runoff, even though runoff is also at a maximum at that time. Under regulated conditions, the small amount of additional ice resulting from increased winter runoff would, as we have seen, be a minor contributor to the total freshwater released at melt time.

Prinsenberg (1983) also modelled the effect of regulation of four major rivers flowing into Hudson Bay: the Nelson–Churchill, La Grande, Nottaway–Broadback, and Great Whale systems, which together make up nearly half of the total natural discharge. He integrated all horizontal variations into a one-dimensional mixed-layer model. While the applicability of this approach may be debatable, its results provide an appreciation of the magnitude of the impact of regulation over both ice-free and ice-covered seasons. Prinsenberg compared model results for regulated discharge to those obtained for natural discharge conditions under both normal and light ice conditions. He found that deviations in temperature and surface layer salinity from the norm that were due to discharge regulation were comparable to those associated with light ice conditions, again placing the broadscale impact of discharge regulation within the scope of natural variability.

FRESHWATER EXPORT TO THE LABRADOR SEA

Our discussion so far suggests that enhanced winter runoff from regulation of all freshwater discharge would lead to only a small (< 0.23%) level of enhanced ice formation, so that the main effect of regulation is to decrease slightly the salinity of Hudson Bay during winter. Prinsenberg's calculations suggest an average, bay-wide change of less than half a salinity unit for regulation of about half of the total runoff. Our earlier discussion of under-ice plumes reminds us that noticeable salinity changes will be concentrated within a few tens of kilometres from shore, near the mouths of the principal rivers. Let us now consider the progress of this extra freshwater towards the Labrador Sea.

Brackish surface water leaves Hudson Bay through Hudson Strait and joins the Labrador Current. Sutcliffe et al. (1983) suggested a link between Hudson Bay runoff variations and the salinity minimum on the Labrador and Newfoundland shelves. Myers et al. (1990) confirmed the presence of a correlation between runoff from Hudson Bay and salinity at Station 27, off St. John's, but with a nine-month, rather than a four-month lag as suggested by Sutcliffe et al. (1983). In a later paper, Myers et al. (1993) found that the amplitude of the salinity minimum at Station 27 is more closely correlated with sea-ice extent on the Labrador and northern Newfoundland shelves than with runoff in Hudson Bay. Nevertheless, Myers et al. (1990) also found that the minimum salinity in the centre of Hudson Strait occurs in November and December, so that there is evidence of a relationship between maximum river discharge in May and June and freshwater export from Hudson Strait. The six-month delay between freshet and central Hudson Strait discharge indicates a mean advection speed of 6 cm/s, which is in keeping with the weak counterclockwise circulation observed in Hudson Bay (Prinsenberg, 1980).

Outflow from the mouth of Hudson Strait is restricted to its southern half and is deflected southward onto the continental shelf, where it forms the shoremost branch of the Labrador Current (LeBlond et al.,1981). The circulation pattern computed by Reynaud et al. (1995) confirms that the circulation in the Labrador Sea and its coastal shelves is largely along isobaths. Hudson Strait water is therefore largely constrained to the shelf and exported to the North Atlantic without entering the central Labrador Sea, where deep convection occurs. As both observations and calculations show, the main contribution to the eastern, seaward part of the Labrador Current is from the Baffin Current, north of Hudson Strait.

Observations of the circulation and water properties near the mouth of Hudson Strait and on the Labrador Shelf thus suggest that freshwater runoff from Hudson Bay does not penetrate into the central Labrador Sea, where deep convection takes place. Nevertheless, because convection is sensitive to the presence of a freshwater surface layer (Lazier, 1973, 1980), let us suppose that some brackish water from Hudson Strait mixes across the Labrador Current.

As we have seen, natural runoff from Hudson Bay rivers places the brackish water pulse in mid-Hudson Strait at the beginning of winter. Given surface flows of 20 – 40 cm/s observed in the eastern part of the Strait (LeBlond et al., 1981), that pulse of freshwater reaches the shelf and the Labrador Sea, a few hundreds of kilometres away, within the same month: late December to early January. Under natural conditions, maximum runoff leakage into the Labrador Sea occurs at the time of maximum cooling, when deep convection normally takes place. A decrease in freshet volume, as brought about by runoff regulation, would decrease the amount of freshwater in the coastal area near the zone of deep convection. A corresponding increase in winter runoff would place additional freshwater on the Labrador Sea coast in the summer, when surface waters are thermally stratified and no convection takes place anyway. Thus, even if there was some leakage of brackish runoff into the centre of the Labrador Sea, the timing of perturbations associated with runoff regulation would be such as to assist rather than impede deep convection.

Other sources of freshwater are more important than Hudson Strait runoff in affecting the surface salinity of the central Labrador Sea. Flow out of Baffin Bay contributes to the offshore part of the Labrador Current, which is nearer to the convective area; that water comes from the Arctic Ocean through the channels of the Canadian Archipelago and from the East Greenland Current. The largest salinity fluctuations on time scales longer than a year seem to be related to pulses of brackish water arriving from the north, via the East Greenland Current, for example, "The Great Salinity Anomaly," described by Dickson et al. (1988).

We end this section with the conclusion that slightly modified freshwater pulses from regulated Hudson Bay runoff 1) would be mostly confined to the Labrador shelf; 2) would occur at the wrong time of the year to have a negative effect on deep convection; and 3) would be a minor contributor to the freshwater budget of the central Labrador Sea.

EFFECTS ON THE THERMOHALINE CIRCULATION

Cold, dense water sinks, as in an upside-down chimney. In the North Atlantic, intense heat loss to the overlying atmosphere causes deep water to be formed in the Greenland, Iceland, and Norwegian (GIN) Seas as well as in the Labrador Sea. These sinking regions are fed in part by warm, saline surface waters flowing from lower latitudes. Because of differences in its northern configuration, including lack of access to the Arctic Basin, as well as greater freshwater discharge, no such deep water is formed in the North Pacific. When one compares the climate of Bodö, Norway (lat. 67˚N; average temperature in January -2˚C, in July 14˚C) with that of Nome, Alaska (lat. 64.5˚N; average temperature in January -15˚C, in July 10˚C), one directly sees the impact of the poleward heat transport associated with the thermohaline circulation. Since the climate of northern Europe, and indeed of the whole Northern Hemisphere, is strongly affected by the existence of deep convection in the North Atlantic, any potential disruption of this circulation would have significant climatic implications. Therein lies the interest of this discussion.

Analyses of the thermohaline circulation in the North Atlantic show that most of its impetus is derived from the overflow of dense water over the ridge that links Greenland to Iceland and Iceland to the Faroes at a depth of 600 – 800 m (Wright, 1972; Ross, 1984; Dickson et al., 1990; Schmitz and McCartney, 1993). Part of the overflow travels around the periphery of the Labrador Sea, where it picks up additional water (Lazier and Wright, 1993; Lazier, 1995). The Labrador Sea is not the main source of energy for the thermohaline circulation; its contribution is made more in passing, through entrainment of Labrador Sea Water by the deep flow emerging from the overfall of Arctic waters. Cessation of deep convection in the Labrador Sea would not, by itself, affect the Arctic water overflow; entrainment of Labrador Sea Water would still take place, even in the absence of convection, although that water might have different properties. Transport estimates suggest that the Labrador Sea contributes only 20 – 25% of the volume flux of the North Atlantic Deep Water and would thus contribute in a similar percentage to the poleward thermohaline heat flux in the surface waters (Schmitz and McCartney, 1993).

CONCLUSIONS

Regulation of all rivers flowing into Hudson Bay and James Bay would smooth discharge, increasing winter runoff fourfold and eliminating spring freshet. Extended under-ice plumes would appear in winter near river mouths, covering only a small fraction of the area of the bays (0.2%) and leading to only a small (< 0.23%) additional amount of ice formation, comparable to or smaller than its known interannual variability. Freshwater export from the bays to the Labrador Sea is mainly confined to the Labrador Shelf. Should some of the perturbations in discharge reach the central Labrador Sea, that water would arrive there at the wrong time to impede convection. Further, runoff from Hudson and James Bays is a minor contributor to salinity variability in the central Labrador Sea.

Finally, deep convection in the Labrador Sea itself is a relatively minor contributor to the volume flux of the North Atlantic Deep Water.

We conclude that, although regulation of river runoff can certainly affect oceanographic conditions at small scales, especially in the vicinity of river mouths, and the effects of these modifications on the biology remain incompletely known, there is no reason to expect any effect on the North Atlantic thermohaline circulation and on the climate of Europe or North America.

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