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A collection made up of four series:

- Hydro-Electric Development: Environmental Impacts
- Hydro-Electric Development: Social and Economic Contexts
- Energy Policy and Alternatives
- Citizen Involvement in Energy Issues

These four series of brief publications are intended to address important issues related to the major hydro-electric developments planned for northern Québec and, secondarily, those projected for the northern regions of neighbouring provinces. This particular series, **Hydro-Electric Development: Environmental Impacts** (ISSN 1192-6457), consists of texts written by senior scientists, graduate students or other persons chosen on the basis of their expertise. Each paper in this series has been reviewed before publication by several scientists, whose comments, where appropriate, follow the text. The views expressed in any text or commentary are those of its author(s) and do not necessarily reflect the opinions of the other participants. Authors and reviewers have been given full liberty of expression.

Les textes écrits en anglais seront traduits et publiés en français (et inversement).

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Effects of Hydro-Electric Projects on Hudson Bay's Marine and Ice Environments

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Effects of hydro-electric projects on Hudson Bay's marine and ice environments
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Introduction

Hudson Bay and James Bay form a large inland sea whose water properties and tides, although externally forced by the Atlantic Ocean via the Hudson Strait, are modified by processes within the bays. Salinity, temperature and nutrient distributions are controlled by processes such as circulation, vertical mixing and processes relating to the freshwater budget; all of which are interrelated. Changes in the runoff cycle by hydro-electric developments will alter the contributions of these processes. However, the degree of change is hard to determine since no long

period data set is available to distinguish between permanent changes and changes due to interannual variability.

This paper will summarize what is presently known about the physical oceanography of the area and indicate what changes the cumulative effects of the hydro-electric developments are expected to cause. A similar but lengthier review paper of the region by Milko (1986), discussed the effects of the Grand Canal Diversion, a project to turn part of James Bay into a freshwater lake. First the freshwater budget is discussed, including the runoff modifications and ice

cover effect. Then the circulation pattern and current structure is presented, followed by the vertical and horizontal structure of the water properties. Finally the expected changes in the marine and ice environment due to the hydro-electric developments are discussed.

Freshwater Budget

The Hudson Bay drainage basin extends as far west as the Rocky Mountains and borders the drainage basin of the Mackenzie River in the north and that of the St. Lawrence River/Great Lakes in the southwest. The annual mean discharge rate of $22.6 \times 10^3 \text{ m}^3/\text{s}$ from Hudson Bay is twice as large as either the rate of the Mackenzie River ($9.9 \times 10^3 \text{ m}^3/\text{s}$) or the St. Lawrence River ($10.1 \times 10^3 \text{ m}^3/\text{s}$) (Prinsenber, 1980). The drainage area of James Bay alone accounts for $10.1 \times 10^3 \text{ m}^3/\text{s}$, half of the total Hudson Bay rate. Natural discharge rates vary during the year, with low winter rates, high spring rates and medium summer rates (Fig. 1). Hudson Bay also receives and loses freshwater to the atmosphere directly by evaporation and precipitation. Over a period of one year, Hudson Bay loses freshwater similarly to oceanic regions whereas James Bay

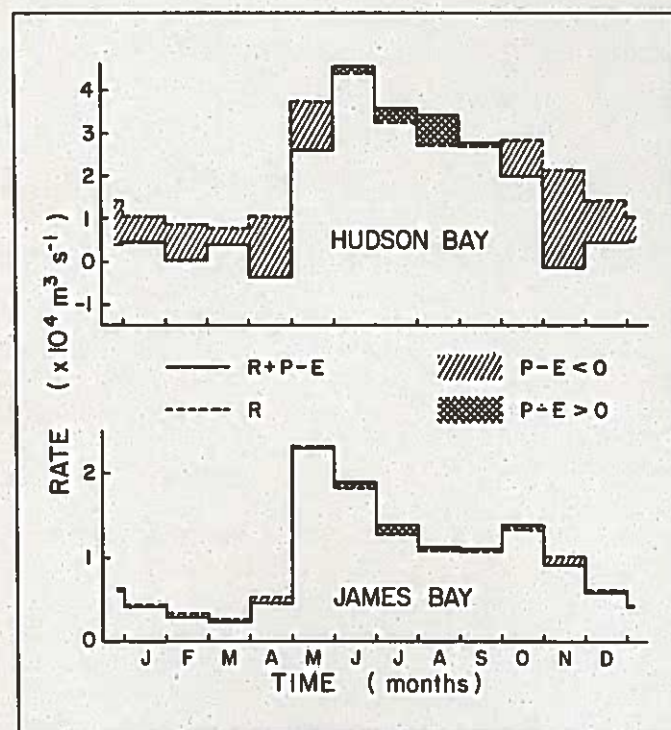


Figure 1. Rates of monthly freshwater input for Hudson Bay and James Bay including contributions from runoff (R), precipitation (P) and evaporation (E) (Prinsenber, 1986).

gains as much water during one year by precipitation as it loses by evaporation (Prinsenber, 1984).

The other large contributor to the freshwater budget is the annual ice cover, which rejects salt into the water column to depths of 100m during ice growth but returns the meltwater to the surface of the water column when the ice cover melts. Not only does the growth and decay of the annual ice cover redistribute the freshwater vertically, but due to the ice cover's generally southward drift, it also transports freshwater horizontally. Freshwater in the form of ice is moved southwards on the surface and replaced by salty water from deeper layers. Level ice thicknesses reach values of 175cm in the north and 100cm in the south for an areal mean of 145cm. This converts into a freshwater layer of 115cm and is twice as much as the 64cm freshwater layer added annually to the surface by runoff, precipitation and evaporation (R+P-E) when this is similarly expressed as a layer of freshwater spread over the entire surface area. The ice cover effect becomes even larger when ice in ridges and rubble fields is included in the calculation (Prinsenber, 1988). The freshwater layer due to the melting ice cover then increases by $35 \pm 10\%$ depending on the area in question; more ridges occur in the south, where the ice cover is moving to, but is trapped by the coast line. However, freshwater input by runoff remains in coastal areas because of the Coriolis effect (due to the earth's rotation). But even if the runoff is spread over half the total area of the region to reflect just the coastal area, the freshwater budget is still as much controlled by ice cover meltwater as by the runoff (Fig. 2). However, freshwater from runoff is the only net addition of freshwater to the system and needs to be considered in the volume and salinity budgets.

Interannual variability of the contributors to the freshwater budget is large. The ice extent (Mysak & Manak, 1989), the ice thickness (Loucks & Smith, 1989) and the runoff (Prinsenber, Loucks, Smith, & Trites, 1987), all have an interannual variability of 30% about their long term mean. This makes any man-made change in these parameters or their effects on other processes that much harder to measure or to predict.

The ice cover is also a major factor in the heat budget. Half of the annual incoming heat flux is used to melt the ice cover while the other half is used to heat the water column. Changes in the annual ice cover properties will thus be felt in both the freshwater and heat budgets of the area, which in turn changes the salinity, temperature and circulation patterns.

Hydro-electric developments are planned or under way in most of the Hudson Bay southern drain-

age basins of Québec, Ontario and Manitoba. After completion of these projects, the total freshwater input into James Bay during the winter months will be doubled while that of Hudson Bay will increase by 52% (Prinsenber, 1980). Although there is no net change in the total yearly runoff rate, the seasonal cycle will be changed, with much more freshwater entering the bays in winter. During this time, the ice cover greatly inhibits the mixing of the freshwater into the underlying oceanic layers, permitting the runoff change to be felt over large distances.

Circulation

The summer circulation in Hudson Bay and James Bay is partially wind driven and partially density driven (estuarine due to freshwater runoff). It is cyclonic (anti-clockwise), with mean monthly speeds of 0.04m/s (Prinsenber, 1986). Larger speeds do occur, such as the outflow from James Bay where mean monthly values of 0.19m/s were observed (Fig. 3). Both the surface salinity and temperature fields follow this circulation pattern. Low-salinity surface water is found inshore and downstream of major river systems. As the surface water rotates around the bay it is heated by surface radiation. Some of this heat and freshwater is mixed downwards as the surface mixed layer deepens from 15m in the spring to 40m in late summer. Near-surface water flows out of Hudson Bay in the northeast. This

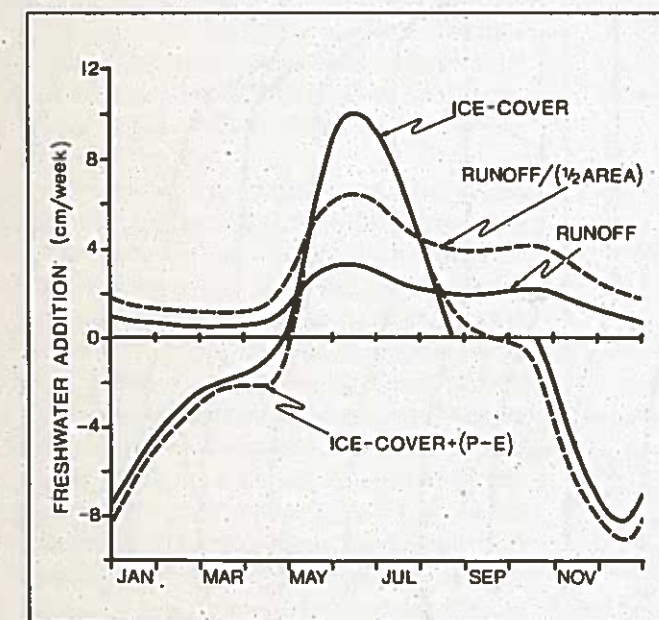


Figure 2. Freshwater addition by ice cover, runoff (R), precipitation (P) and evaporation (E) for Hudson Bay. Ice cover does not include ridge or rubble field contributions (Prinsenber, 1988).

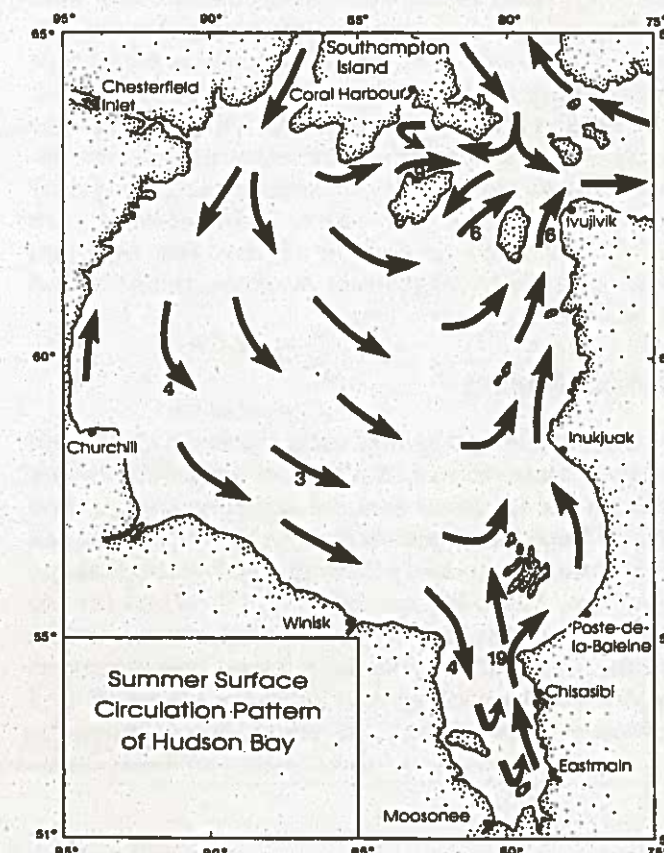


Figure 3. Summer circulation pattern in Hudson Bay and James Bay with monthly observed speeds in cm/s (Prinsenber, 1986).

surface current consists of warm, low-salinity water relative to the incoming colder and more saline water from Foxe Basin and Hudson Strait. Since no surface northwesterly flow has been observed in northern Hudson Bay, volume continuity for the bay must be accomplished by a subsurface flow, whose water is returned to the surface by vertical entrainment in the process of the large scale estuarine circulation.

Currents in Hudson Bay and James Bay are mainly made up of the 0.2 to 0.3 m/s semidiurnal tidal currents (Lepage & Ingram, 1991; Prinsenber, 1982, 1987). Wind-generated inertial currents reach at times 0.3m/s, but are restricted to surface layers and only occur during the ice-free period. Storms also generate 5-6 day oscillatory motion whose current amplitudes are up to 0.15m/s. These reach the bottom and occur throughout the year. All currents interact and can reinforce each other to values of up to 1.0m/s.

Winter and summer circulations in James Bay are similar (Prinsenber, 1982). Hudson Bay surface water enters James Bay along the western shore, is

diluted by runoff as it circulates anti-clockwise around the bay and leaves James Bay along the eastern shore. The mean speed in the summer is about four times as large as that observed during the winter, due to increased effects of runoff and wind forcing. The runoff contribution enters the dynamics of circulation through the density differences introduced by the dilution of the salt water. These currents are mainly restricted to coastal regions (up to 50km wide), and their magnitude is proportional to the runoff rate.

Vertical Mixing

During the spring and early summer, the runoff and melt-water form a thin layer of low salinity water between the ice cover and the saltier sea water. The surface mixed layer slowly deepens by entraining sea water from deeper layers through tidal mixing (Lepage & Ingram, 1991; Prinsenber, 1987). When the ice cover disappears, mixing by wind also occurs. In late summer and fall, the surface mixed layer deepens rapidly due to cooling, the decrease in runoff and increased wind mixing. In winter it continues to

deepen when salt is rejected from the growing ice cover which destabilizes the surface mixed layer. Maximum mixed layer depths of 95m have been observed in western Hudson Bay but elsewhere shallower maximum depths are reached, as indicated by remnants of the winter mixed layer depths in summer salinity/temperature profiles. Analytical models have been used to reproduce the mixed layer depth cycle (Fig. 4) and can indicate the direction the changes will take that would occur in the mean summer surface layer due to runoff modifications (Fig. 5). The above-mentioned oceanic model used in the early 1980s was not an interactive model, meaning that the boundary conditions (ice cover thickness) were prescribed and could not be altered by the ocean. This means that the unrealistic -3.0°C surface layer temperature predicted in the late winter should be interpreted as an imbalance in the boundary condition and means that more ice will be formed in the late winter after the runoff has been altered. This is a mean condition for the total bay; the effect should be larger in the near shore area, where the runoff modification effect is that much more severe. Due to the large interannual variability in ice cover

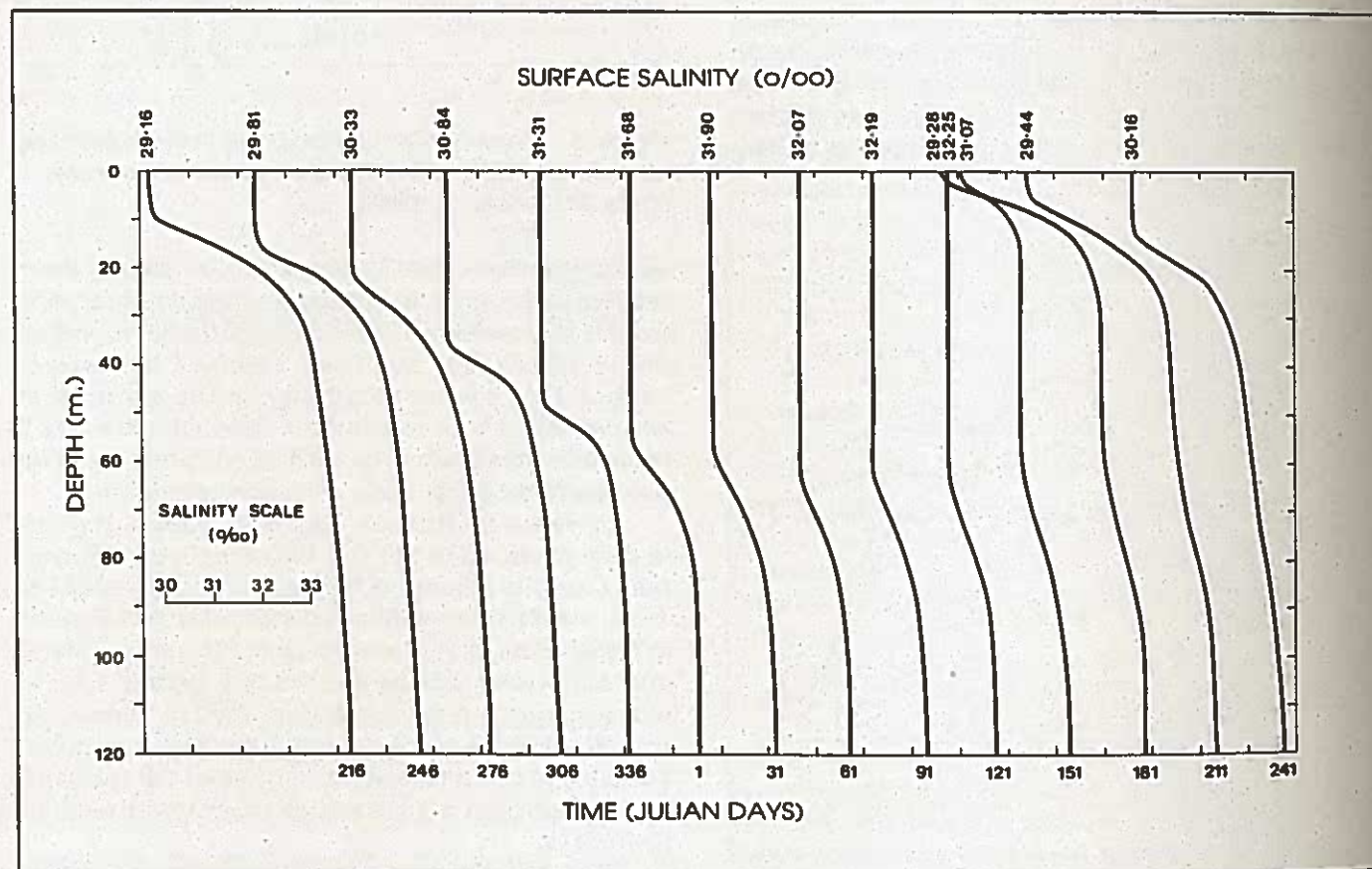


Figure 4. Annual cycle of salinity profiles for Hudson Bay (Prinsenber, 1983). Each profile is stepped to the right by 1.5 salinity units and its surface value is noted at the top of each profile.

properties this effect will be hard to verify. Now with more sophisticated ice-ocean coupled models, further research should be done on the effect of runoff modification on ice cover properties as well as modification due to climate warming.

In winter the ice cover reduces the wind contribution to surface layer mixing. This allows the surface runoff to propagate large horizontal distances under the ice cover when not inhibited by landfast ice shear ridges (Macdonald & Carmack, 1991) which extend below the water to depths of up to four times their sail height. Under three times the normal winter runoff rate, the La Grande River plume extended 20km offshore to where the landfast ice occurs and 50km alongshore, where finally vertical tidal mixing broke down the density stratification of the surface plume (Freeman, Roff, & Pett, 1982). At seven times its natural runoff rate, the plume (20ppt contour) extended alongshore another 15km, joining up with a smaller plume created by the Roggan River (Messier, Lepage, & de Margerie, 1989). Winter rates of 10 times the normal rate are predicted when winter power demands are high in the future, increasing the size of the plume that much more. Similar changes of plume sizes were observed by Ingram and Larouche (1987) for the plume off the Great Whale River in southeastern Hudson Bay.

The vertical stability of the water column is important in determining the magnitude of the vertical nutrient flux required for sustaining surface-layer ice algae and phytoplankton spring blooms. Vertical nutrient fluxes are proportional to turbulent current energy and inversely proportional to the density stratification. High production of ice algae and phytoplankton can only occur in stable stratification for a short period, as nutrients are quickly depleted. Sustained production requires a constant or intermittent nutrient flux without increasing the mixed layer depths beyond the euphotic zone for too long (Gosselin, Legendre, Demers, & Ingram, 1985). In the plumes studied in Hudson and James Bays, high biological activity occurred in areas where the vertical nutrient flux was maintained intermittently by tidal mixing at

the time when tidal currents reached their maximum amplitude (Gosselin et al., 1985).

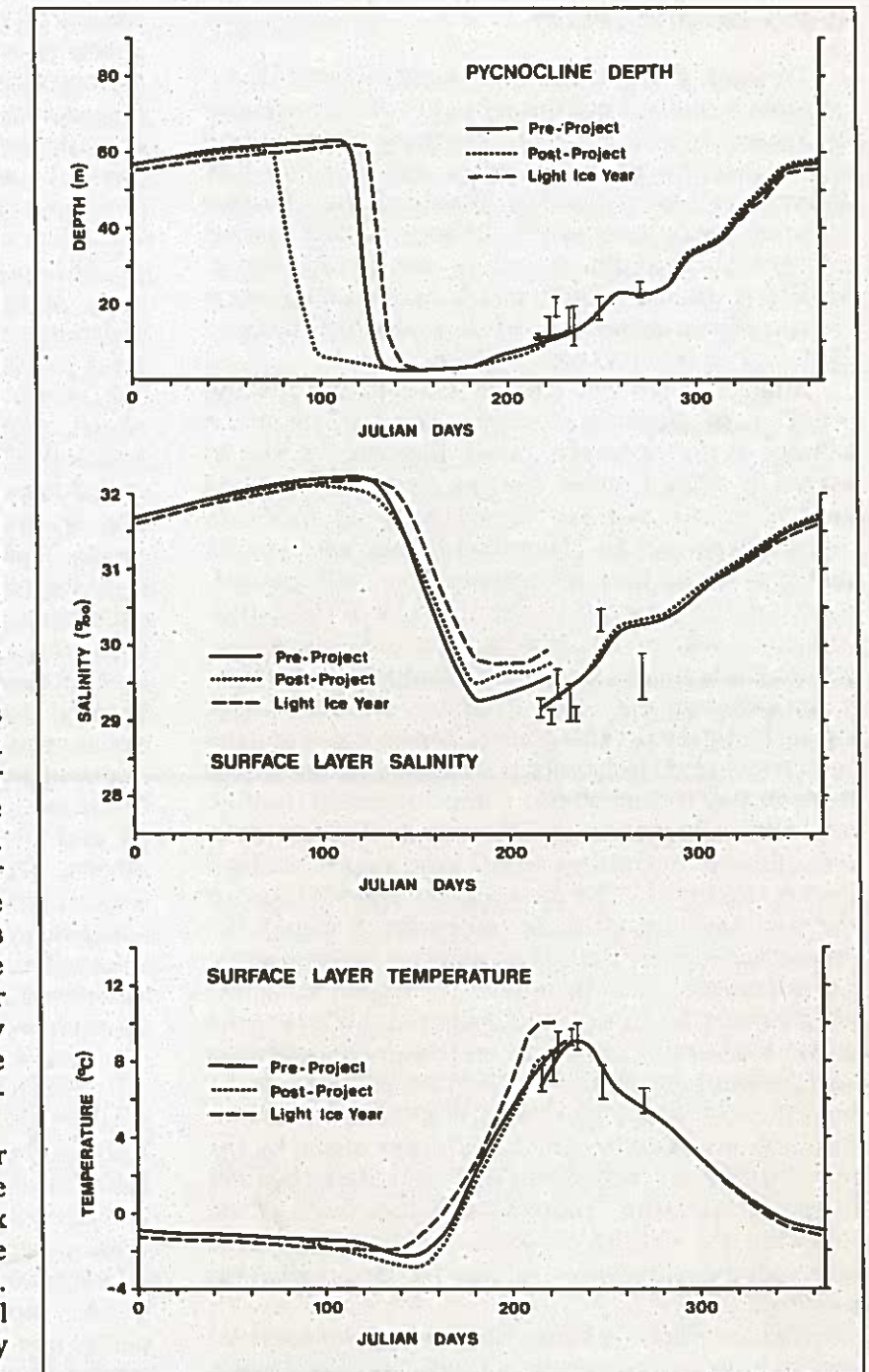


Figure 5. Predicted seasonal patterns of mixed layer depth (pycnocline) and surface layer salinities and temperatures for the centre of Hudson Bay as compared to observed data ranges (bars) from 1975 (Prinsenber, 1983).

Hydro-electric Effects

The most direct effect of the hydro-electric developments is on the freshwater budget. Its changes are the easiest to predict. To follow these changes into effects in circulation, ice cover and nutrient flux patterns is harder, and to measure the changes becomes nearly impossible. Changes in the marine environment brought about by the hydro-electric developments will mainly be felt in the winter when the runoff into James Bay will double while that into Hudson Bay will increase by 52%.

Analytical models can be used to predict the direction of possible changes. The surface mean salinity in northeastern James Bay will freshen in winter by 1.5ppt, while the resulting currents will double in the surface mixed layer to 0.06m/s (Prinsenber, 1982). The model results also predict that the mean flow in deeper layers will double, reflecting the increase in the strength of the estuarine circulation in the northern part of James Bay. Within Hudson Bay the density component of circulation will increase (50%) in winter, with the major effects being felt downstream of James Bay along the eastern coast of Hudson Bay. A mixed-layer model for Hudson Bay (Prinsenber, 1983) suggested that the new surface layer is established earlier in the winter, reducing the maximum mixed layer depth attained during the winter. The model also suggested that in the summer, the surface temperature would decrease in Hudson Bay as a result of hydro-electric developments. A subsequent atmospheric model (Prinsenber & Danard, 1985) showed that due to the colder sea surface temperature, the air above the sea surface would be stabilized. This would increase the heat flux into the water, offsetting the temperature decrease predicted by the mixed-layer model by the end of the year. Hudson Bay is thus buffered against forced temperature changes and the onset of the following ice season is solely determined by the atmospheric conditions of the fall and winter in question.

Inshore, large changes in the marine environment will occur in winter near the outlets of the hydro projects. Not only will the plumes become larger after completion of the projects (Ingram & Larouche, 1987; Messier et al., 1989), but due to their spacing they are expected to affect and interact with each other. For example, plume areas will extend further alongshore under the landfast ice and dilution by the La Grande River plume could be felt as far as the proposed outflow of the Great Whale River hydro project, where extensive landfast ice conditions occur between the mainland and the Belcher Islands (Larouche & Galbraith, 1989). Assessment of each project should

thus not be looked at in isolation, but cumulative effects should be addressed. Water column stability in these plumes will increase. This will locally decrease or move the areas downstream where favorable conditions existed for high ice algae and phytoplankton spring blooms. As long as runoff changes within an ice season are gradual, blooms will occur but at different locations.

Although the ice cover properties such as thickness, ridge frequency and movement are mainly controlled by atmospheric conditions and exhibit a large interannual variability, the sea conditions do affect the ice properties as well. Due to the proposed runoff modifications, ice conditions will be altered indirectly. For the centre of Hudson Bay, the shallow mixed layer in the late winter is established earlier (Fig. 5) as a result of the hydro-electric developments. This will provide less heat to the surface layer from deeper layers in the process of mixed-layer deepening. The ice growth season will lengthen, especially since the surface water in winter will be fresher and thus easier to freeze. Ice breakup in Hudson Bay and James Bay is initiated in the south and is in part caused by the first occurrence of runoff (reduced and delayed after completion of the projects). In the estuaries or rivers, the initial runoff clears the ice and floods the remaining ice cover, reducing its albedo. The runoff water also represents a heat source, 10% of the incoming heat for James Bay, and actually contributes to the melting of the ice cover. All these effects indicate that the ice cover breakup will be delayed, a topic that needs to be further addressed by studies dealing with the hydro-electric projects in southeastern Hudson Bay or James Bay.

A mean current of 0.04m/s would indicate that a surface parcel would spend just under 2 years in Hudson Bay. However, due to the mixed-layer process, the mean residence time of a parcel is 6.6 years (Prinsenber, 1984). This means that a parcel of water potentially travels round Hudson Bay 3.5 times before it leaves Hudson Bay as part of the surface outflow. Contaminants added to the water parcel due to runoff, such as mercury from hydro-electric reservoirs, are thus concentrated by a factor of 3.5. However, runoff makes up only one third of the freshwater dilution of the surface water, the rest coming from ice melt; so that the dilution of runoff contaminants is numerically the same as the dilution of the fresh water content itself. Relative to the salinity of the incoming water, the surface water flowing out of Hudson Bay is diluted 8 to 1 by fresh water; one part of fresh water (contaminant water) to 8 parts of oceanic water (uncontaminated water).

Finally, one should remember that oceans are interconnected and events occurring in one location

may subsequently be felt a long way away. Indeed, Sutcliffe (Sutcliffe, Loucks, Drinkwater, & Coote, 1983) suggested that the seasonal salinity changes off St. John's, Newfoundland, reflect the seasonal runoff pattern into Hudson Bay and James Bay. They further found that intense vertical mixing by the tides at the eastern entrance to Hudson Strait mixes nutrient-rich deep waters into the near-surface layers. This upper-layer water is subsequently carried by the mean currents onto the Labrador Shelf and Grand Banks. Sutcliffe et al. (1983) hypothesized that years of high freshwater runoff into Hudson Bay increases the stratification in Hudson Strait, thereby decreasing the amount of mixing, with reductions in the surface nutrient concentrations and of subsequent biological production in summer. More recent studies by Myers (Myers, Akenhead, & Drinkwater, 1990) indicate that seasonal salinity changes off Newfoundland are influenced more by the melting of sea ice along the Labrador coast, but that the effects of runoff from Hudson Bay can still be observed off St. John's. While the magnitude of the effects of the Hudson Bay runoff on the biology of the Labrador Shelf may not be as large as originally suggested by Sutcliffe et al., they still may play some role.

References

- Freeman, N.G., Roff, J.C., & Pett, R.J. Physical, chemical, and biological features of river plumes under an ice cover in James and Hudson Bays. *Le Naturaliste canadien*, 1982, 109: 745-764.
- Gosselin, M., Legendre, L., Demers, S., & Ingram, R.G. Responses of sea-ice microalgae to climatic and fortnightly tidal energy inputs (Manitounuk Sound, Hudson Bay). *Canadian Journal of Fisheries and Aquatic Sciences*, 1985, 42: 999-1006.
- Ingram, R.G., & Larouche, P. Variability of an under-ice river plume in Hudson Bay. *Journal of Geophysical Research*, 1987, 92: 9541-9547.
- Larouche, P., & Galbraith, P.S. Factors affecting fast-ice consolidation in southeastern Hudson Bay, Canada. *Atmosphere-Ocean*, 1989, 27: 367-375.
- Lepage, S., & Ingram, R.G. Variation of upper dynamics during breakup of the seasonal ice cover in Hudson Bay. *Journal of Geophysical Research*, 1991, 96: 12711-12724.
- Loucks, R.H., & Smith, R.E. Hudson Bay and Ungava Bay ice-melt cycles for the period 1963-1983. *Canadian Contractor Report of Hydrography and Ocean Sciences*, 34. Dartmouth, Nova Scotia: Government of Canada, Department of Fisheries and Oceans, 1989.
- Macdonald, R.W., & Carmack, E.C. The role of large-scale under-ice topography in separating estuary and ocean on an Arctic shelf. *Atmosphere-Ocean*, 1991, 29: 37-53.
- Messier, D., Lepage, S., & de Margerie, S. Influence du couvert de glace sur l'étendue du panache de la Grande rivière (baie James). *Arctic*, 1989, 42: 278-284.
- Milko, R. Potential ecological effects of the proposed Grand Canal diversion project on Hudson and James bays. *Arctic*, 1986, 39: 316-326.
- Myers, R.A., Akenhead, S.A., & Drinkwater, K. The influence of ice-melt and Hudson Bay runoff on the salinity of the inner Newfoundland Shelf. *Atmosphere-Ocean*, 1990, 28: 241-256.
- Mysak, L.A., & Manak, D.K. Arctic sea-ice extent and anomalies, 1953-1984. *Atmosphere-Ocean*, 1989, 27: 376-405.
- Prinsenber, S.J. Man-made changes in the freshwater input rates of Hudson and James bays. *Canadian Journal of Fisheries and Aquatic Sciences*, 1980, 37: 1101-1110.
- Prinsenber, S.J. Present and future circulation and salinity in James Bay. *Le Naturaliste canadien*, 1982, 109: 827-841.

- Prinsenber, S.J. Effects of the hydroelectric developments on the oceanographic surface parameters of Hudson Bay. *Atmosphere-Ocean*, 1983, 21: 418-430.
- Prinsenber, S.J. Freshwater contents and heat budgets of James Bay and Hudson Bay. *Continental Shelf Research*, 1984, 3: 191-200.
- Prinsenber, S.J. The circulation pattern and current structure of Hudson Bay. In I.P. Martini (Ed.), *Canadian Inland Seas*. New York: Elsevier, 1986.
- Prinsenber, S.J. Seasonal current variations observed in western Hudson Bay. *Journal of Geophysical Research*, 1987, 92: 10756-10766.
- Prinsenber, S.J. Ice-ridge contributions to the freshwater contents of Hudson Bay and Foxe Basin. *Arctic*, 1988, 41: 6-11.
- Prinsenber, S.J., & Danard, M. Variations in momentum, mass and heat fluxes due to changes in the sea surface temperature of Hudson Bay. *Atmosphere-Ocean*, 1985, 23: 228-237.
- Prinsenber, S.J., Loucks, R.H., Smith, R.E., & Trites, R.W. Hudson Bay and Ungava Bay runoff cycles for the period 1963 to 1983. *Canadian Technical Report of Hydrography and Ocean Sciences*, 92. Dartmouth, Nova Scotia: Government of Canada, Department of Fisheries and Oceans, 1987.
- Sutcliffe, W.H., Loucks, R.H., Drinkwater, K.F., & Coote, A.R. Nutrient flux and its biological consequences. *Canadian Journal of Fisheries and Aquatic Sciences*, 1983, 40: 1692-1701.

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