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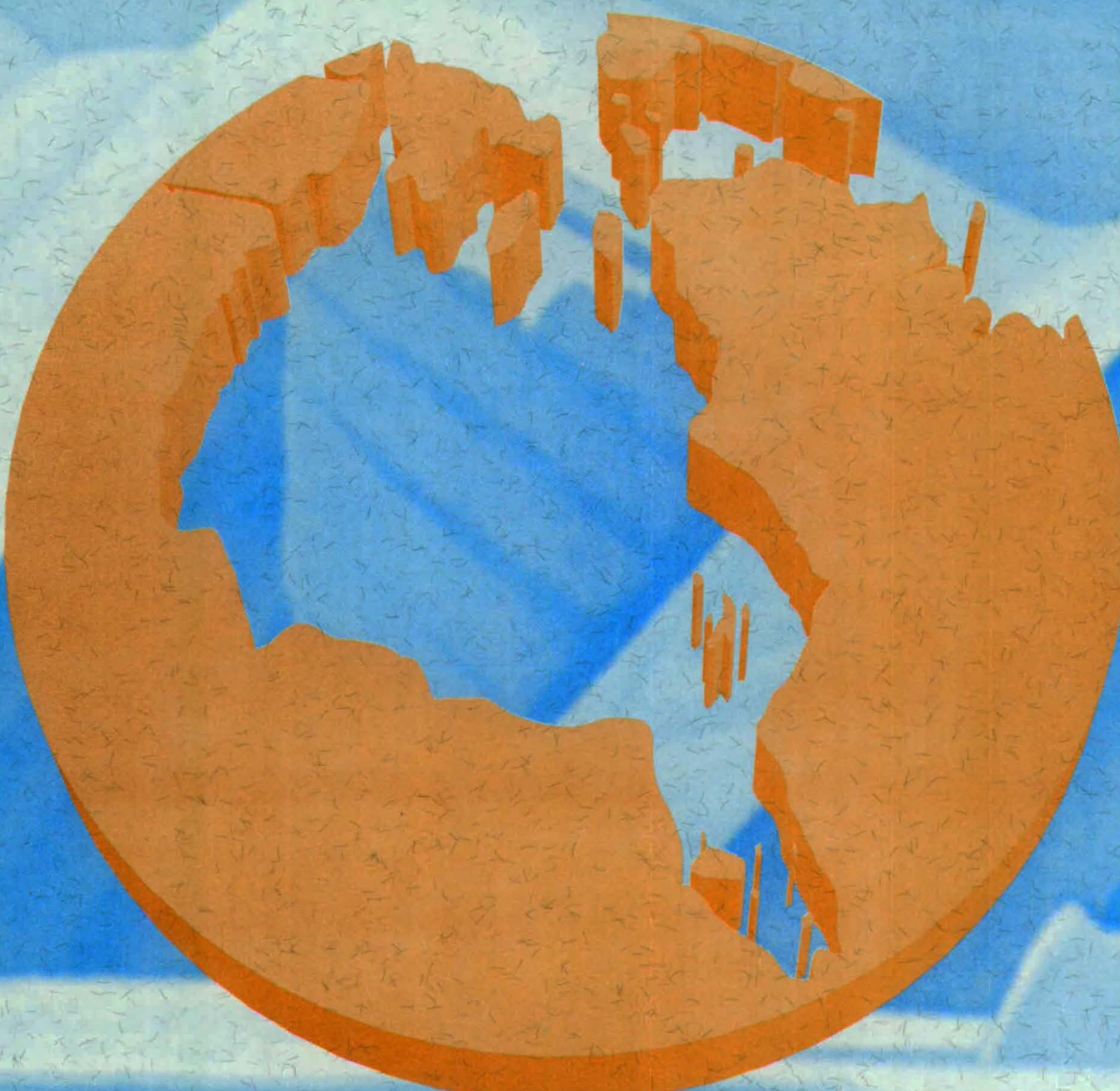

HUDSON BAY PROGRAMME SUR LA BAIE D'HUDSON

EFFECTS OF HYDRO-ELECTRIC PROJECTS ON HUDSON BAY'S MARINE AND ICE ENVIRONMENTS

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ABSTRACT

Hydro-electric developments are altering the runoff cycles of Hudson and James Bay drainage basins. Since oceanographic processes of these Bays are partly estuarine, changes in the timing and amplitude of the runoff rates will alter the oceanographic and ice cover properties of the region. The present known oceanographic and ice cover properties of the Bays as well as the possible changes in winter oceanographic and ice cover conditions due to hydro-electric developments are presented. Models predict that the strength of the winter estuarine circulation in James Bay will double, freshwater plumes outside rivers affected by projects will increase in size, vertical nutrient fluxes will be reduced, and thickness and duration length of the Bay's ice cover will increase.

INTRODUCTION

Hudson Bay and James Bay form a large inland sea whose water properties and tides, although externally forced respectively by the Arctic Ocean and Atlantic Ocean, are mostly modified by processes within the Bays. Water and ice cover properties of the region are greatly dependent on atmospheric conditions as they are not buffered against changes by a nearby large marine reservoir such as the Atlantic Ocean. Salinity, temperature, and nutrient distributions are controlled by circulation, vertical mixing, and processes relating to the freshwater and heat fluxes, all of which are interrelated. Changes in the runoff cycle by hydro-electric developments have altered the contributions by these oceanographic processes; however, the degree of change is hard to determine since no long period oceanographic data are available to distinguish between permanent changes and those due to interannual variability.

This paper will summarize what is known about the physical oceanography of the area and indicate what the expected effects of hydro-electric developments may be. A more detailed paper discussed the effects of the Grand Canal Diversion, a project to turn part of James Bay into a freshwater lake (Milko, 1986). First the freshwater budget is discussed including the runoff modifications and ice cover contribution. Then the circulation pattern and current structure is presented, followed by the vertical and horizontal distributions of the water properties. Finally, expected changes in the marine and ice environments due to hydro-electric developments are discussed.

FRESHWATER BUDGET

The Hudson Bay drainage basin extends as far west as the Rocky Mountains and borders the drainage basins of the Mackenzie River in the north and that of the St. Lawrence River/ Great Lakes in the southeast. As noted by Prinsenberg (1980), the annual mean discharge rate of $22.6 \times 10^3 m^3/s$ from Hudson Bay is twice as large as either that of the Mackenzie River ($9.9 \times 10^3 m^3/s$) or the St. Lawrence River ($10.1 \times 10^3 m^3/s$). The drainage area of James Bay alone accounts for $10.1 \times 10^3 m^3/s$, half of the total. Natural discharge rates vary during the year with low values in winter, high in spring, and medium in summer (Fig. 1). Hudson Bay also receives and loses freshwater to the atmosphere directly by evaporation and precipitation. Over a year, the total Hudson Bay region loses freshwater to the atmosphere whereas just James Bay alone gains as much water during one year by precipitation as it loses by evaporation (Prinsenberg, 1984).

The other large contributor to the freshwater budget is the annual ice cover. During ice growth, ice rejects salt in the form of brine which sinks to depths of 100 m. This affects the water column similarly as that caused by removal of water by evaporation. In spring when ice melts, nearly freshwater is returned to the surface layer similarly as during precipitation. Not only does the growth and decay of ice redistribute freshwater vertically, it also redistributes freshwater horizontally since the southward motion of ice under predominantly NW winds represents a southward freshwater flux. The ice drift is largest in early winter when the Bay's southern parts are still ice free. Even as ice concentration increases in winter, the southward ice drift continues but at a reduced rate as seen by the increasing ridge frequency from north to south.

In the north, the freshwater moving south as ice is replaced by salty water from deeper layers. Level ice thicknesses range from 175 cm in the north to 100 cm in the south and have an areal mean of 145 cm. This converts into a freshwater layer of 115 cm which is almost twice as much as the 64 cm 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 greater when ice ridges and rubble fields are included in the calculation (Prinsenberg, 1988). The ridges and rubble fields increase the effect of ice by $35 \pm 10\%$ depending on the area in question; the effect is greater in the south, where the ice cover is moving towards and is trapped by the coastline. However, freshwater runoff is confined to coastal areas by the effect of the Coriolis force which deflects movement to the right in the northern hemisphere. But even if the runoff is spread over half the total surface area of Hudson Bay to reflect just the 100 km wide coastal area, the freshwater budget is still as much controlled by melt water as by runoff (Fig. 2). Freshwater from runoff and precipitation minus evaporation is the only net addition of freshwater to the system and needs to be considered in the volume and salinity budgets. The ice formation and melting do not constitute a net change but rather a redistribution of freshwater within the Bay.

The interannual variability of the contributions to the freshwater budget is large. The ice area (Mysak and Manak, 1989; Ikeda, 1990), the time of ice breakup (Wang, 1992; Etkin, 1991), the ice thickness (Loucks and Smith, 1989), and runoff (Prinsenberg et al., 1987) all have large interannual variabilities about their long-term mean. This makes any man-made change in these parameters and their effects on other processes that much harder to measure or to predict. Year-to-year variability of the ice cover is often quantified by its maximum and minimum yearly areal extent. This method works well for areas with open boundaries such as the Labrador Shelf where extra ice during severe winters moves farther south and offshore. This method is not as useful for Hudson Bay which is 100% ice covered during both severe and mild winters. Ice thickness is used as well, though observations are not readily available (Wang, 1992). For Hudson Bay the average ice thickness of six land-fast ice stations can be used to represent the variability of the Bay's ice cover severity (Fig. 3). Locations of the land-fast ice stations are shown on Fig. 4. Maxima are clearly visible during the severe winters of the early and late 1970's, mid 1980's, and early 1990's in both the ice thickness data of the Hudson Bay region and the ice extent along the Labrador and Newfoundland coasts south of 55°N. The ice in both regions responds in varying degrees to the same weather patterns that are caused by changes in the strength of the Icelandic Low. When the Icelandic Low deepens, more persistent and stronger northwesterly winds bring more cold Arctic air to the region (Ikeda, 1990; Wang, 1992; Agnew, 1993). This increases ice thickness in Hudson Bay and southward ice transport along the Canadian east coast (Fig. 3). The North Atlantic Oscillation (NAO) is a measure of the sea level atmospheric pressure difference between Iceland and the Azores and provides a convenient index to quantify the strength of the Icelandic Low. Since Hudson Bay is located farther from Iceland, its ice cover does not respond as coherently to the NAO index (correlation coefficient of 0.34) as the ice cover along the Labrador coast (correlation coefficient of 0.68).

A similar atmospheric index for the Pacific Ocean, called the Southern Oscillation Index (SOI), is based on the sea level pressure difference between Tahiti and Darwin. Wang (1992) and Etkin (1991) found that weather pattern variabilities associated with the SOI correspond to the duration of ice cover in Hudson Bay (correlation coefficient of -0.39). During the onset of a low SOI episode, the generally colder temperatures over the Bay delayed spring ice melt and advanced the appearance of fall ice cover. During consecutive years of high NAO and/or low SO indexes (1972-73, 1983-84, and 1990-91), severe ice anomalies appear to occur in Hudson Bay and along the Labrador coast (Fig. 3). However, further research is required to establish firmly the relationships between the SO and NAO indexes and the ice cover properties of Hudson Bay.

Since the ice cover makes up the largest portion of Hudson Bay's seasonal freshwater budget, the variability of the ice thickness is important to know in order to separate its effects from the effects that alteration in runoff cycles may have on the oceanography of the Bay. In addition, the ice cover also is a major contributor to the Bay's heat budget. Half of the annual atmospheric heat flux is used to melt the ice cover while the other half is used to heat the water column. Changes in annual ice cover properties will thus be felt in both the freshwater and the heat budgets of the area. In turn, these influence salinity, temperature, and circulation patterns.

Within the Hudson Bay region, hydro-electric developments are planned or under way in most of the drainage basins of southern Quebec, Manitoba, and northern Ontario. After completion of these projects, the total freshwater input into James Bay during winter months will double while that of Hudson Bay will increase by about half (Prinsenberg, 1980). Although the total annual runoff rate will not change, the seasonal cycle will be altered, with much more freshwater entering the Bays in winter and less in summer (Fig. 1). The winter ice cover greatly inhibits mixing of freshwater into underlying oceanic layers, permitting changes in runoff to be felt over large distances.

CIRCULATION

Summer circulation in Hudson Bay and James Bay is partially wind driven and partially density driven (estuarine) which results from the addition of freshwater runoff. The runoff generates a surface outflow of low salinity water whose salinity export is replaced by a subsurface inflow of high salinity water. The summer circulation is cyclonic (anti-clockwise), with mean monthly observed speeds of 0.04 m/s (Prinsenberg, 1986). Larger speeds do occur, such as the outflow from James Bay where mean monthly values of 0.19 m/s were found (Fig. 4). With a mean surface current of 0.04 m/s a surface water parcel spends just under two years circulating around Hudson Bay. Since the mean residence time of a water parcel in Hudson Bay is 6.6 years (Prinsenberg, 1984), a parcel of water potentially travels around Hudson Bay 3.5 times and would be involved in three ice growth and ice melt cycles before it leaves Hudson Bay as part of the surface outflow.

Both the surface salinity and the temperature fields reflect this cyclonic circulation. Low-salinity surface water occurs inshore and downstream of major rivers. As the surface water moves around the Bay, its temperature increases because of heat input from the atmosphere. The heat and freshwater are mixed downwards as the surface mixed layer deepens from 15 m in the spring to 40 m in the fall. Surface water flows out of Hudson Bay into Hudson Strait in the northeast. This surface current consists of warm, low-salinity water relative to the incoming colder and more saline water from Foxe Basin and Hudson Strait. The salinity content of the surface outflowing water relative to the inflowing water is diluted by 12.5%. Any conservative contaminant entering Hudson Bay as part of runoff will similarly be diluted by a factor of 8 by the time it leaves Hudson Bay as part as the surface outflow. 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 and vertical convection during ice growth.

Recent modelling work at McGill University in Montreal, Quebec, has developed coupled models of Hudson Bay to simulate winter and summer water circulation patterns as well as the growth, decay, and movement of the ice cover (Wang, 1992). Results show that surface cyclonic circulation occurs year-round due to the forced inflow through Roes Welcome Sound, the channel to Foxe Basin in the northwest corner of Hudson Bay. In summer the cyclonic circulation is reenforced by anti-clockwise wind forcing (Fig. 5). The contribution due to density (runoff) enhances the wind-driven circulation to produce strong coastal currents along all coasts except the northern one. Monthly-averaged summer circulation was found to be about 0.11 m/s and is made up of 46% due to wind forcing, 27% due to volume continuity (expected in-flow), and 27% due to density-forced coastal currents. The recirculation around Hudson Bay (i.e., the water that does not leave by Hudson Strait) was found to be generated by wind, whereas the circulation by the other two contributors leaves the Bay as a surface outflow. The results support earlier assumptions that the summer cyclonic pattern occurs year-round (Fig. 4). Model results also simulated strong vertical mixing that occurs in the upper 50 m layer in winter and only in the upper 10 m layer in the summer due to the increase in summer stratification as a result of ice melt and runoff. With new data being collected by the Maurice Lamontagne Institute of Department of Fisheries and Oceans in Mont-Joli, Quebec, further refinement of the models is planned at both McGill University and Maurice Lamontagne Institute.

The circulation speeds discussed above represent averages over several months to simulate seasonal conditions; currents on shorter time scales have much larger amplitudes and variability. Available data show that currents in Hudson Bay and James Bay are dominated by 0.2 to 0.3 m/s semidiurnal (vary with periods of about 12 hours) tidal currents (Lepage and Ingram, 1991; Prinsenberg, 1982, 1987). Wind-generated inertial currents that vary with a period of 14 hours reach 0.3 m/s but are mainly restricted to surface layers and only occur during ice-free periods. Storms also produce 5-6 day oscillatory motion whose current amplitudes are up to 0.15 m/s. These reach to the bottom and occur throughout the year. All currents interact with each other and can reinforce each other to produce current amplitudes of up to 1.0 m/s.

Particular attention should be paid to James Bay where most of the alteration in the runoff cycles will occur. Winter and summer circulation in James Bay are also cyclonic (Prinsenberg, 1982). Hudson Bay surface water, entering James Bay along the western shore, is diluted by runoff as it circulates anti-clockwise around the Bay until it leaves along the eastern shore. The mean summertime circulation is about four times larger than that observed during the winter because of increased effects of runoff and wind forcing. The currents caused by runoff are mainly restricted to coastal regions (up to 50 km wide) and their magnitude is related to the runoff rate.

VERTICAL MIXING

During spring and early summer, runoff and melt-water form a thin 2 m 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 and Ingram, 1991; Prinsenberg, 1987). When the ice cover disappears, mixing by wind also occurs. In late summer and fall, the surface mixed layer deepens rapidly because of convection caused by cooling, the decrease in runoff, and the increase in wind mixing. In winter, it continues to deepen when brines, caused by salt rejection from the growing ice cover, sink and destabilize the surface mixed layer. Maximum mixed-layer depths of 95 m 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. Numerical models (Prinsenberg, 1983; Wang, 1992; Wang et al., 1993) have been used to reproduce the mixed-layer depth cycle (Fig. 6) and can indicate the direction of changes in the mean summer surface layer as a result of runoff modifications (Fig. 7). The model used in the early 1980's was not an interactive model, meaning that the boundary conditions (ice cover thickness) were prescribed and could not be altered by the ocean. More sophisticated models (Wang, 1992) will overcome this but will still be hampered by uncertain boundary conditions at the entrances to Hudson Bay due to a lack of data. The 1980s' results (Fig. 7) show an unrealistic -3.0°C surface layer temperature predicted for the late winter which should be interpreted as an imbalance in the surface boundary condition. It 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 nearshore area where the runoff modification effect is that more severe. Due to the large interannual variability in duration and thickness of the ice cover, this effect will be difficult to verify. Now with more sophisticated ice-ocean coupled models and with new data being collected, further sensitivity analysis with numerical models can be done to determine what effect runoff modification has on oceanographic and ice cover properties.

In winter, the ice cover reduces the wind contribution to surface layer mixing. This allows the surface runoff to extend over large horizontal distances under the ice cover when not inhibited by land-fast ice shear ridges (Macdonald and Carmack, 1991). These can extend below the water to depths of up to four times their sail height. Under three times the natural winter runoff rate, the La Grande River plume extended about 20 km offshore, to where the land-fast ice occurred. It also extended about 50 km alongshore, where vertical tidal mixing finally broke down the density stratification of the surface plume (Freeman et al., 1982). Now, and at seven times the natural runoff rate, the plume (20 ppt salinity contour) extends alongshore another 15 km to join up with a smaller plume created by the Roggan River (Messier et al., 1989). Winter rates of 10 times the normal rate are predicted when winter power demands are high, potentially increasing the size of the plume and thereby moving high primary production zones. Similar changes in plume sizes were observed by Ingram and Larouche (1987) for the plume of 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 the level of turbulence in the water and inversely proportional to the density stratification. High rates of ice algae and near-surface phytoplankton production can be maintained for a short time period under stable stratification as nutrients are quickly depleted. Sustained production requires a continuous or intermittent nutrient flux, without increasing mixed layer depth beyond the euphotic zone (Gosselin et al., 1985). In the plumes studied in Hudson Bay and James Bay, high biological activity occurred in areas where the vertical nutrient flux is maintained intermittently by tidal mixing, at a time when tidal currents reach their maximum amplitude (Gosselin et al., 1985).

HYDRO-ELECTRIC EFFECTS ON THE ICE AND MARINE ENVIRONMENTS

The most direct effects of the hydro-electric developments are on the freshwater budget and circulation patterns. Changes in the freshwater budget are the easiest to predict and shown in Fig. 1. To determine subsequent effects on circulation, ice cover, and nutrient flux patterns is more difficult. To measure the effects of the changes becomes nearly impossible. Changes in the marine environment caused by the hydro-electric developments will be felt mostly in the winter when the largest runoff changes occur.

At present, models can be used to predict trends. Model results indicate that the surface mean salinity in northeastern James Bay will freshen in winter by 1.5 ppt while the resulting currents will double in the surface mixed layer to 0.06 m/s (Prinsenberg, 1982). The mean flow in deeper layers will also increase, reflecting an increase in strength of estuarine circulation in northern James Bay. Within Hudson Bay, the density component of circulation will increase (50%) in winter, with major effects being felt downstream of James Bay along the eastern coast of Hudson Bay. A mixed-layer model for Hudson Bay (Prinsenberg, 1983) suggested the new surface layer is established earlier in the winter and that this reduces the maximum mixed layer depth. The model also suggested that the surface temperature in summer would decrease in Hudson Bay as a result of hydro-electric developments. A subsequent atmospheric model (Prinsenberg and Danard, 1985) showed that due to the colder sea surface temperature, the air above the sea surface would be more stable. It is thought that this would increase the heat flux into the water and offset the temperature decrease predicted by the mixed-layer model. Hudson Bay is thus buffered against forced temperature changes when atmospheric conditions remain the same, leaving the onset of the following ice season to be solely determined by the atmospheric conditions of fall and winter (Etkin, 1991).

Inshore, large changes in the marine environment will occur in winter near the outlets of the hydro-electric projects. Not only will the plumes become larger after completion of the projects (Ingram and 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 farther alongshore under the land-fast ice. Dilution of the La Grande River plume may extend as far as the proposed outflow of the Great Whale River hydro-electric project, where extensive land-fast ice conditions occur between the mainland and the Belcher Islands (Larouche and Galbraith, 1989). Therefore, assessment of each project should not be looked at in isolation but cumulative effects should be addressed. Water column stability in these plumes will increase. Areas where favorable conditions existed for high ice algae and phytoplankton spring blooms will decrease or move downstream. But as long as runoff changes within an ice season are gradual, blooms will occur but at different locations.

Although ice cover movement, thickness, and ridge frequency are mainly controlled by atmospheric conditions and exhibit large interannual variability, oceanographic conditions affect these ice properties as well. Due to proposed runoff modifications, ice conditions will be altered indirectly but will be difficult to quantify by present models. Model results do suggest that for central Hudson Bay the shallow mixed layer in late winter will be established earlier (Fig. 7) as a result of the runoff modifications. The increase of stratification near the surface will reduce the heat flux from deeper layers and allow a longer ice growth season. Ice breakup in Hudson Bay and James Bay is initiated in the south (early June) and is caused, in part, by the first occurrence of runoff (reduced and delayed after completion of projects). In estuaries and rivers, initial runoff clears the ice and floods the remaining ice cover reducing its albedo. The runoff water also is a heat source, about 10% of the incoming heat for James Bay, and actually contributes to melting of the ice cover. All these relations indicate that the breakup of the ice cover may be delayed, a topic that needs to be further investigated in the context of future hydro-electric developments.

Finally, one should remember that oceans are interconnected and events occurring in one location may subsequently be felt a long distance away. Indeed, Sutcliffe et al. (1983) suggested that seasonal salinity variability off St. John's, Newfoundland, reflected seasonal runoff variability into Hudson Bay and James Bay. They further found that intense vertical mixing by tides at the eastern entrance to Hudson Strait mixes nutrient rich deep waters into the near-surface layers. This surface water is subsequently carried by the mean currents onto the Labrador Shelf and Grand Banks. Sutcliffe et al. (1983) hypothesized that high freshwater runoff into Hudson Bay increases the stratification in Hudson Strait. This would decrease the amount of vertical mixing, thus reducing the surface nutrient concentrations and the subsequent biological production in summer. More recent studies by Myers et al. (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 but to a lesser extent be observed off St. John's. Since the surface water at the entrance to Hudson Strait is made up of contributions from Hudson Bay, the effect of the Hudson Bay runoff on the Labrador Shelf coastal waters is much smaller than originally suggested by Sutcliffe et al. (1983) and changes to the runoff cycle may not be measurable.

CONCLUSION

The hydro-electric developments in Hudson Bay and James Bay have stimulated extensive research that otherwise would not have occurred. Much has been learned about the area, but due to its size and remote location, available data have not been able to determine, specifically, what effects each project has had on the marine and ice environment or what the cumulative effects will be. The models used so far are very simple and are forced by varying atmospheric and uncertain oceanographic boundary conditions. Further model development and sensitivity analysis as well as data collection are required to understand the connections between the changes occurring in the atmosphere and drainage basin, and the changes in ice cover and ocean environments of Hudson Bay. Current research at McGill University and renewed initiatives at the Maurice Lamontagne Institute should be able to address some of the questions about cumulative effects, in particular, the effects that hydro-electric projects may have on the marine and ice environments within Hudson Bay itself and downstream on the Labrador and Newfoundland shelves.

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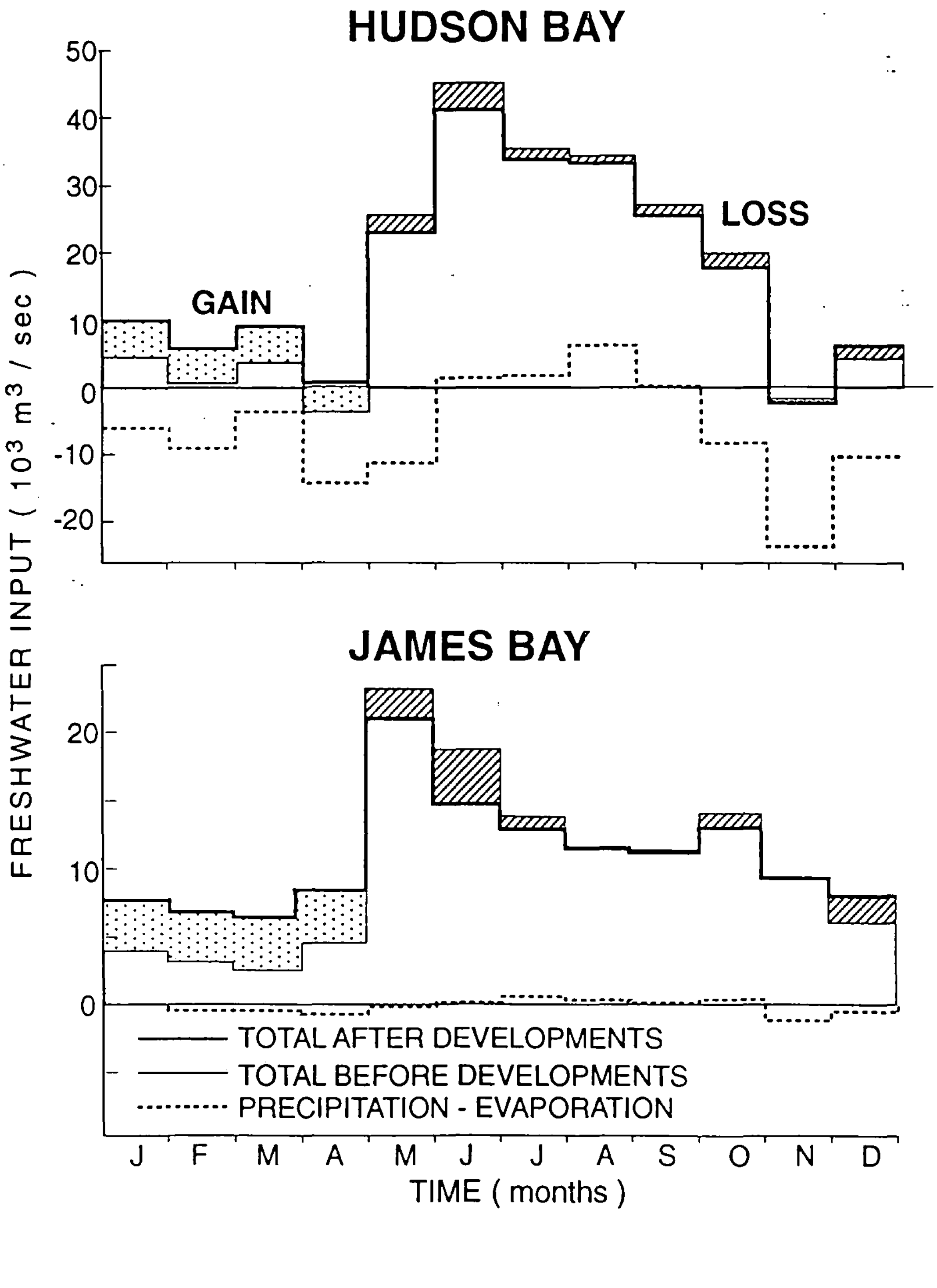

Fig. 1. Rates of monthly input for Hudson Bay and James Bay including contributions from runoff (R), direct precipitation, and evaporation (E) before and after proposed hydro-electric developments (Prinsenberg, 1980 & 1986).

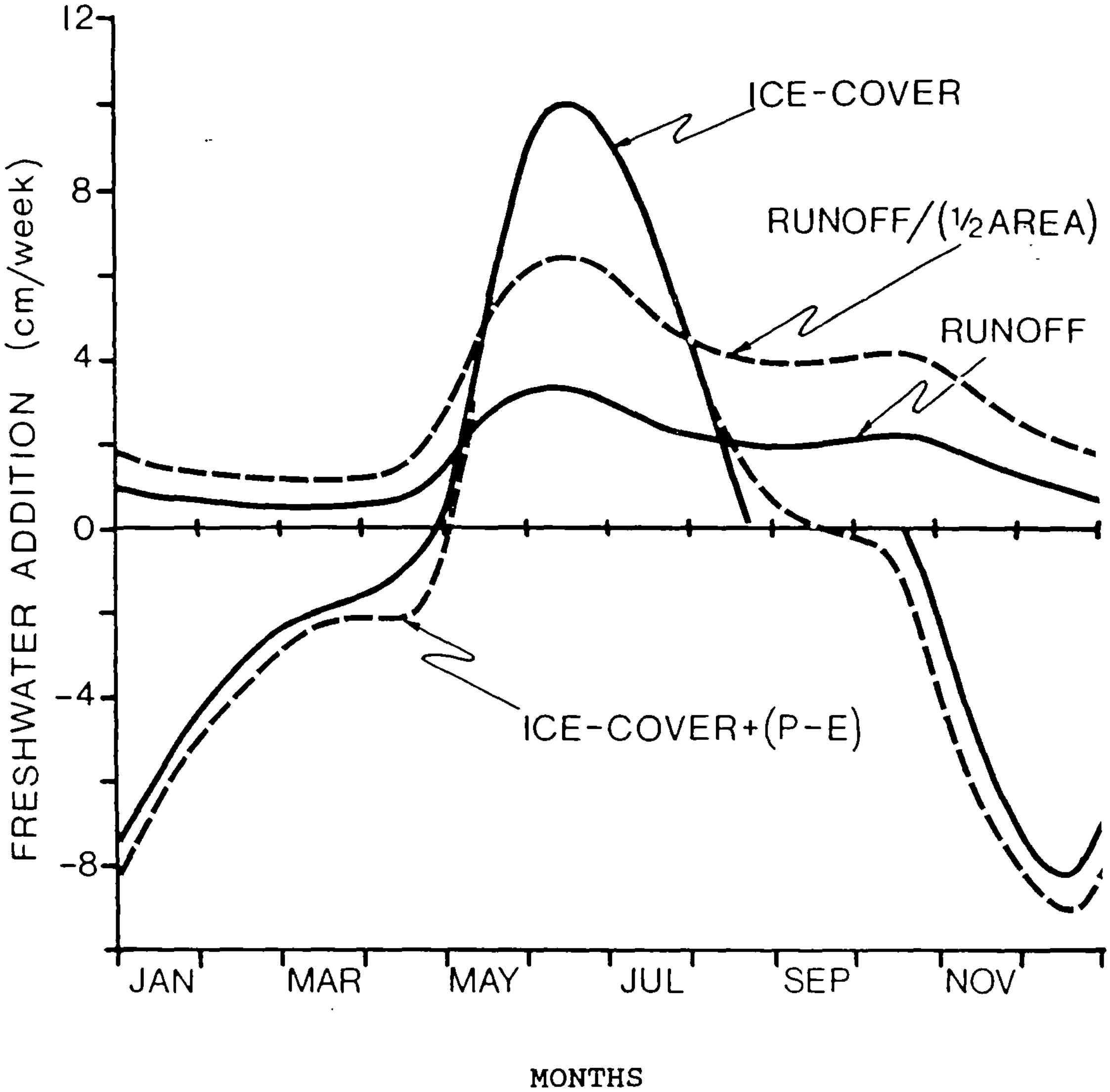

Fig. 2. Freshwater addition by ice cover, runoff (R), precipitation (P), and evaporation (E) for Hudson Bay. Ice cover does not include ridge or rubble field contributions (Prinsenberg, 1988).

HUDSON BAY/SOI AND LABRADOR/NAO

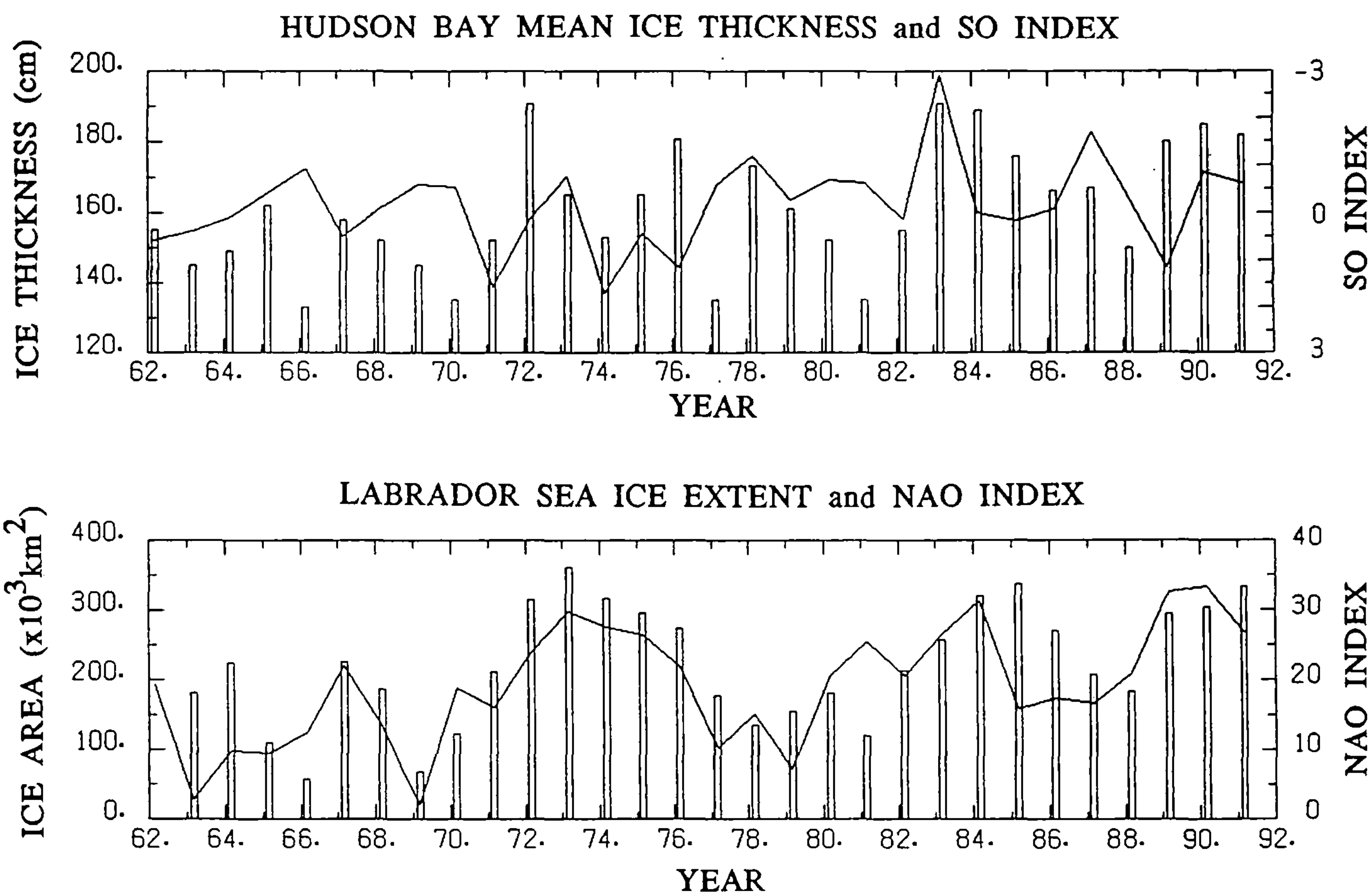

Fig. 3. Time series of average maximum ice thickness for Hudson Bay region and SO Index (top panel) and average winter's ice extent south of 55°N along Labrador coast and NAO Index (bottom panel).

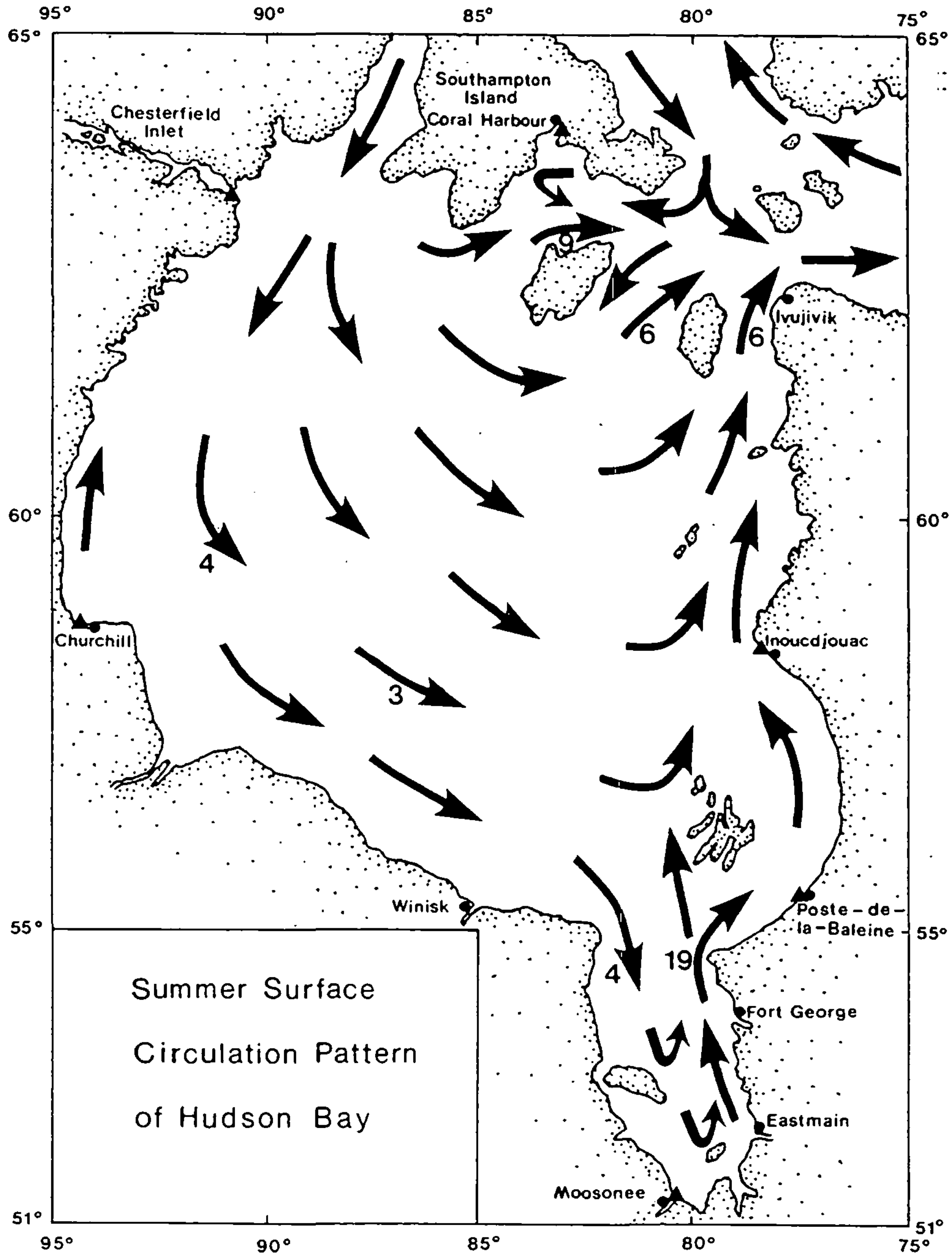

Fig. 4. Summer circulation pattern in Hudson Bay and James Bay with monthly observed speeds in cm/s (Prinsenberg, 1986). Locations of the six land-fast ice stations are shown by solid triangles.

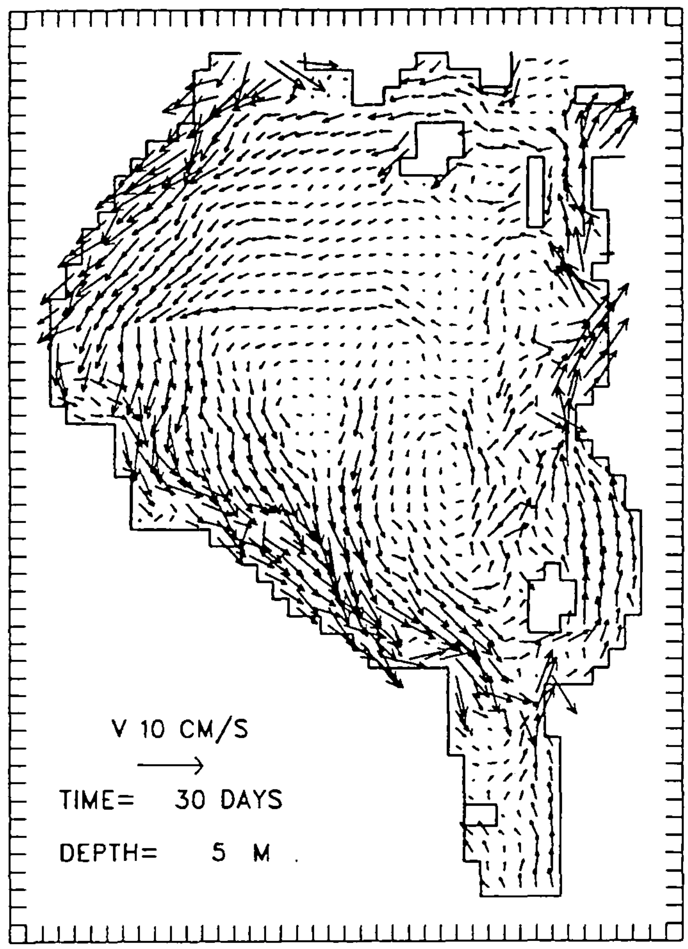

Fig. 5. Modelled summer surface circulation pattern (Wang, 1992).

0.100E+00
MAXIMUM VECTOR

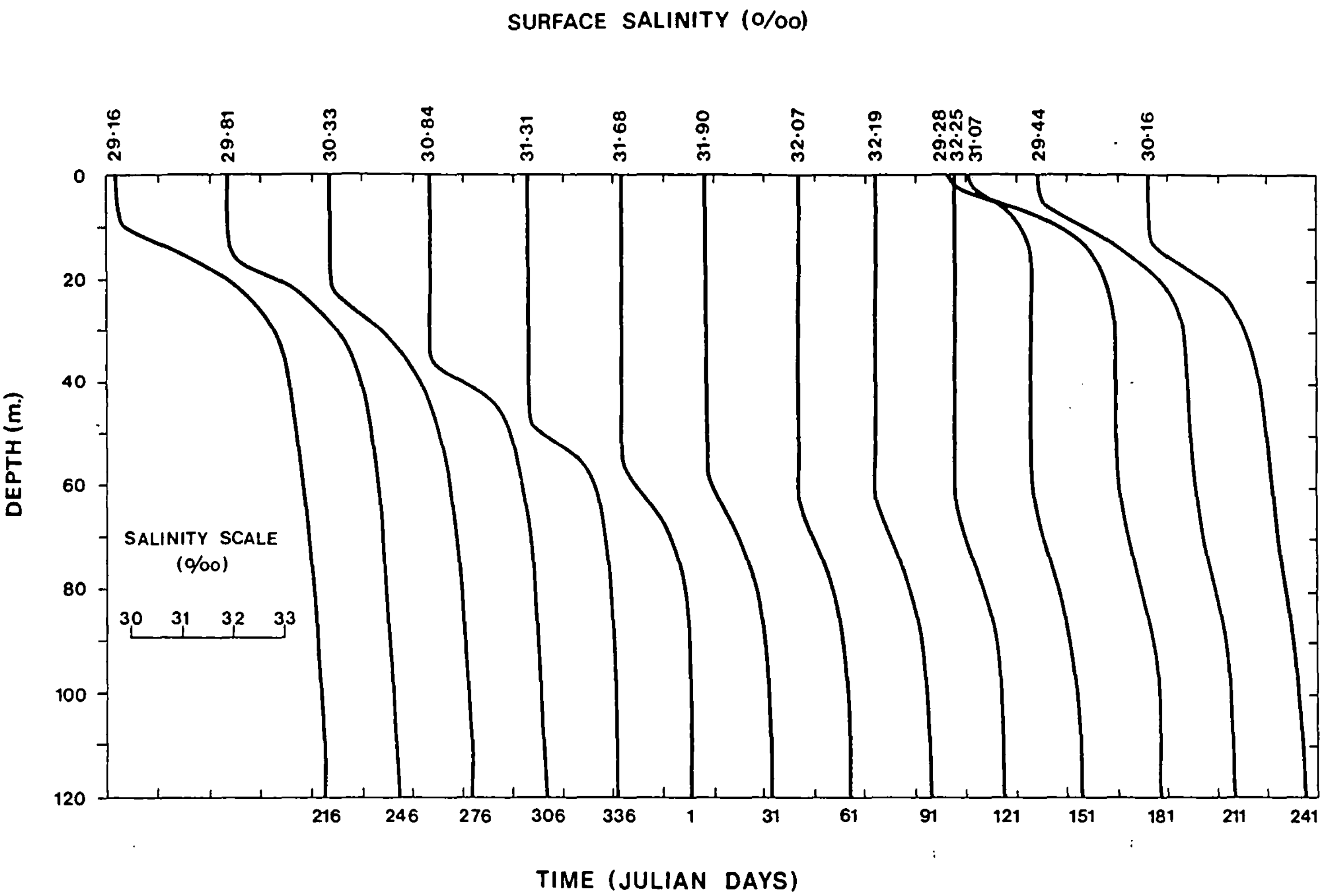

Fig. 6. Annual cycle of salinity profiles for Hudson Bay (Prinsenberg, 1983). Each profile is stepped to the right by 1.5 salinity units and its surface value is noted at the top of each profile.

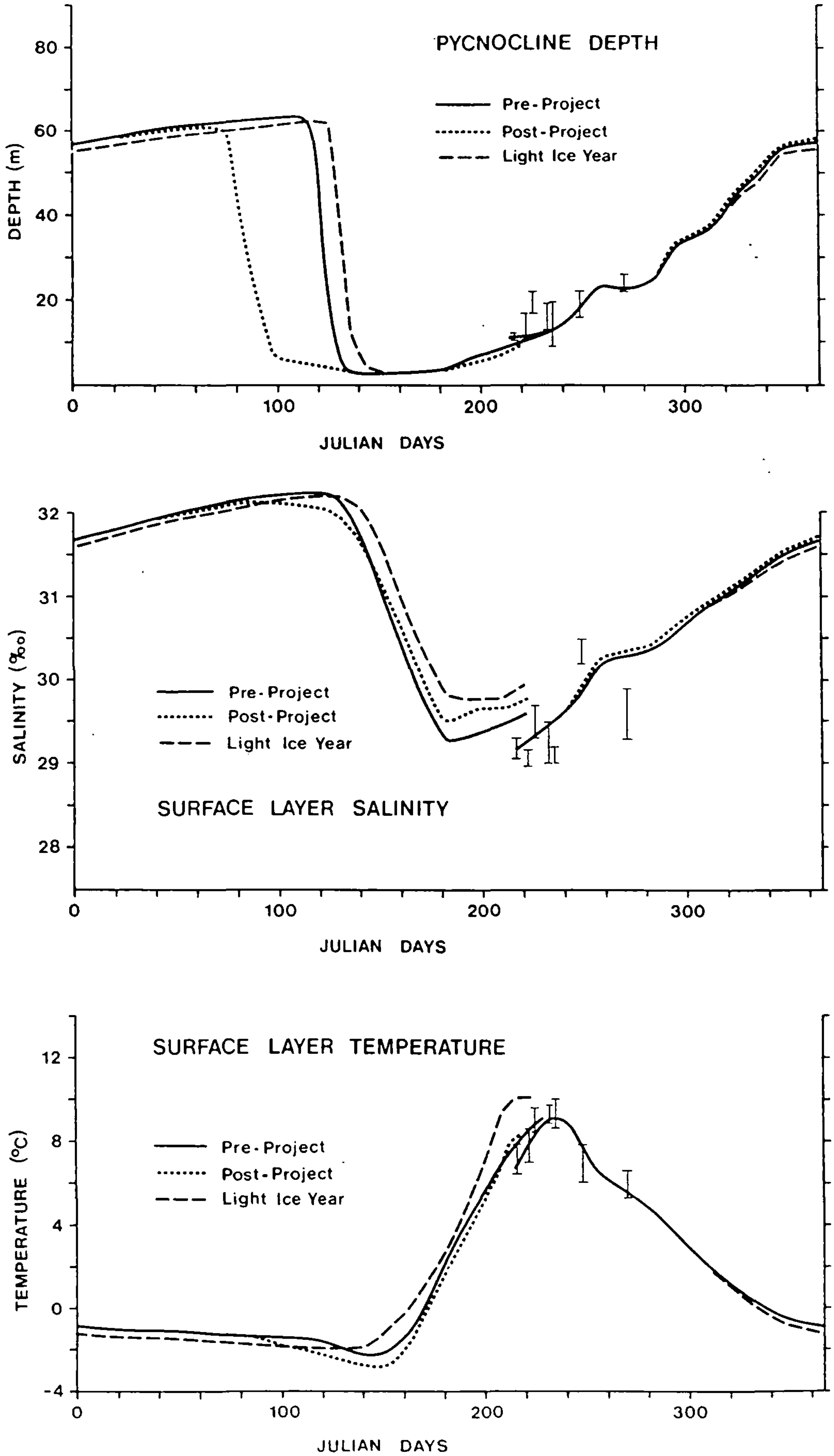

Fig. 7. Predicted seasonal patterns of mixed layer depth (pycnocline) and surface layer salinities and temperatures for the centre of Hudson Bay as compared to observed data ranges (bars) from 1975 (Prinsenberg, 1983).