Continental Shelf Research, Vol 3, No. 2, pp 191 to 200, 1984
Printed in Great Britain

0278–4343/84 $3 00 + 0 00

Freshwater contents and heat budgets of James Bay and Hudson Bay

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(*Received* 10 *August* 1983; *in revised form* 6 *January* 1984, *accepted* 17 *January* 1984)

Abstract—The freshwater and heat budgets of James Bay and Hudson Bay showed that for a yearly cycle the annual ice cover and runoff are major and equal components of the freshwater budgets. James Bay has a baywide freshwater layer thickness of 6.25 m, while Hudson Bay has a 4.7 m layer; these represent summer residence times of 10 months and 4.1 years, respectively

The heat budget results indicated that the incoming surface heat flux is mainly balanced by the heat required to melt the seasonal ice cover and bring the water temperature up to the observed summer values Thus, an assessment of hydroelectric developments in the surrounding watersheds should not only investigate the changes that will occur in the marine environment, but also in the seasonal ice cover, as they together determine the oceanic climate pattern of the two bays

INTRODUCTION

HUDSON Bay is a large inland sea that has a semi-annual ice cover. It is located deep inside the North American continent and connected to the Atlantic Ocean via the Hudson Strait and the Labrador Sea (Fig. 1). The surface area equals 83×10^4 km^2, similar to the State of Texas or France; it is on the average 120 m deep with depths reaching only to 250 m. In the summer, it provides a general sea climate to the surrounding coastal areas, while in the winter it acts as an extension of the snow-covered land and permits Arctic air masses to reach unmodified far south into central Canada.

Major man-made changes in the runoff due to hydroelectric developments (PRINSENBERG, 1980) were the reason for the collection of oceanographic data during the 1970s in an effort to document the pre-development condition of this large inland sea. Hydroelectric developments in the southern drainage basins will increase the winter runoff rate into James Bay by 60% and into the total Hudson Bay region by 20%. Both the seasonal ice cover and runoff cause large seasonal variations in the heat and freshwater content of the region. The purpose of the present paper is to use the available data in the calculations of the summer and winter heat and freshwater contents and determine the relative importance of the present and future runoff cycles.

FRESHWATER CONTENT

James Bay

Hydrographic data from Hudson Bay and James Bay was used to calculate the heat and freshwater content for specific depth layers. A dissolved substance content program used for

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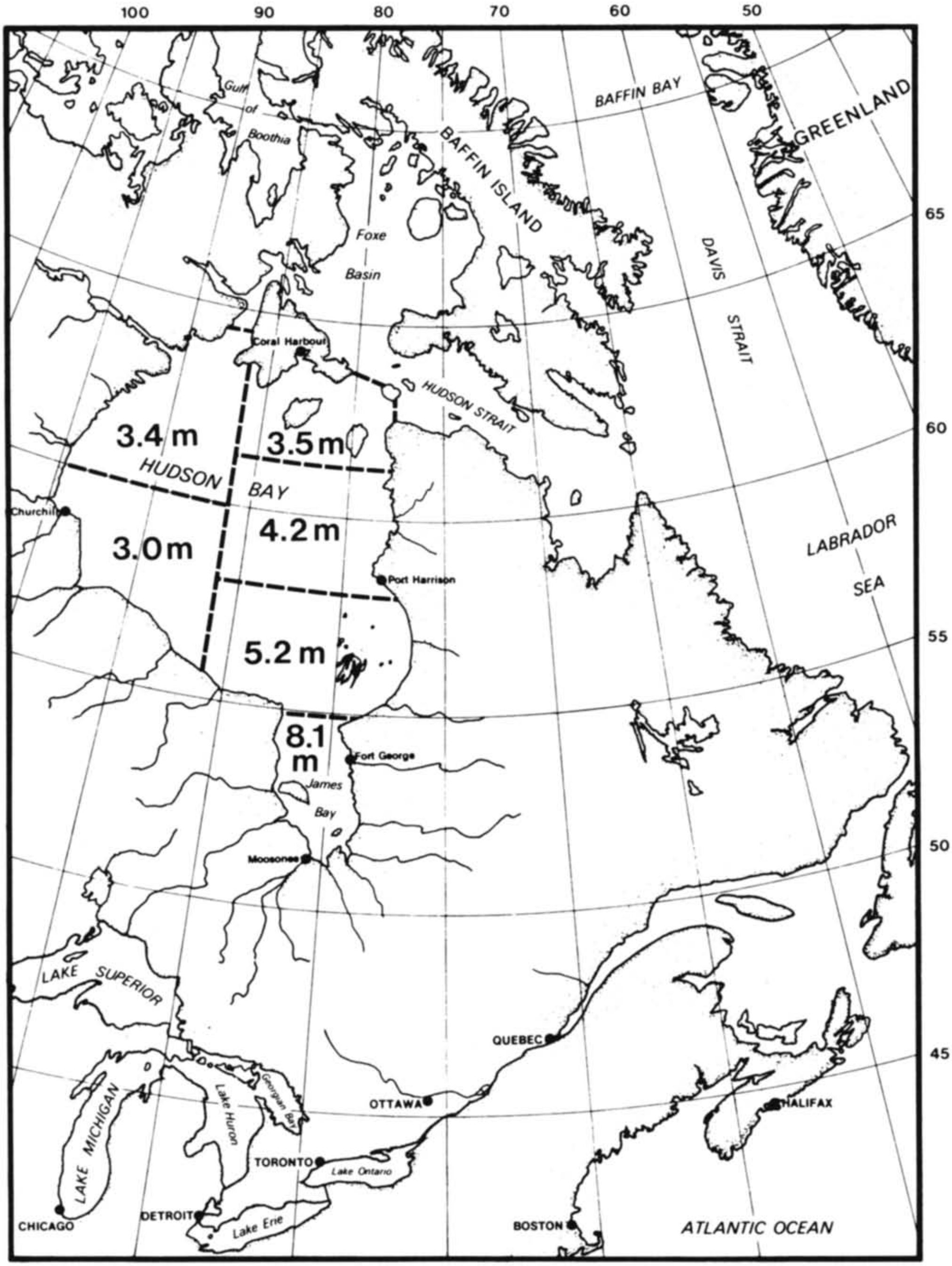

Fig 1 Location map of Hudson Bay and James Bay showing the boundaries and freshwater layer thicknesses of the sub-areas.

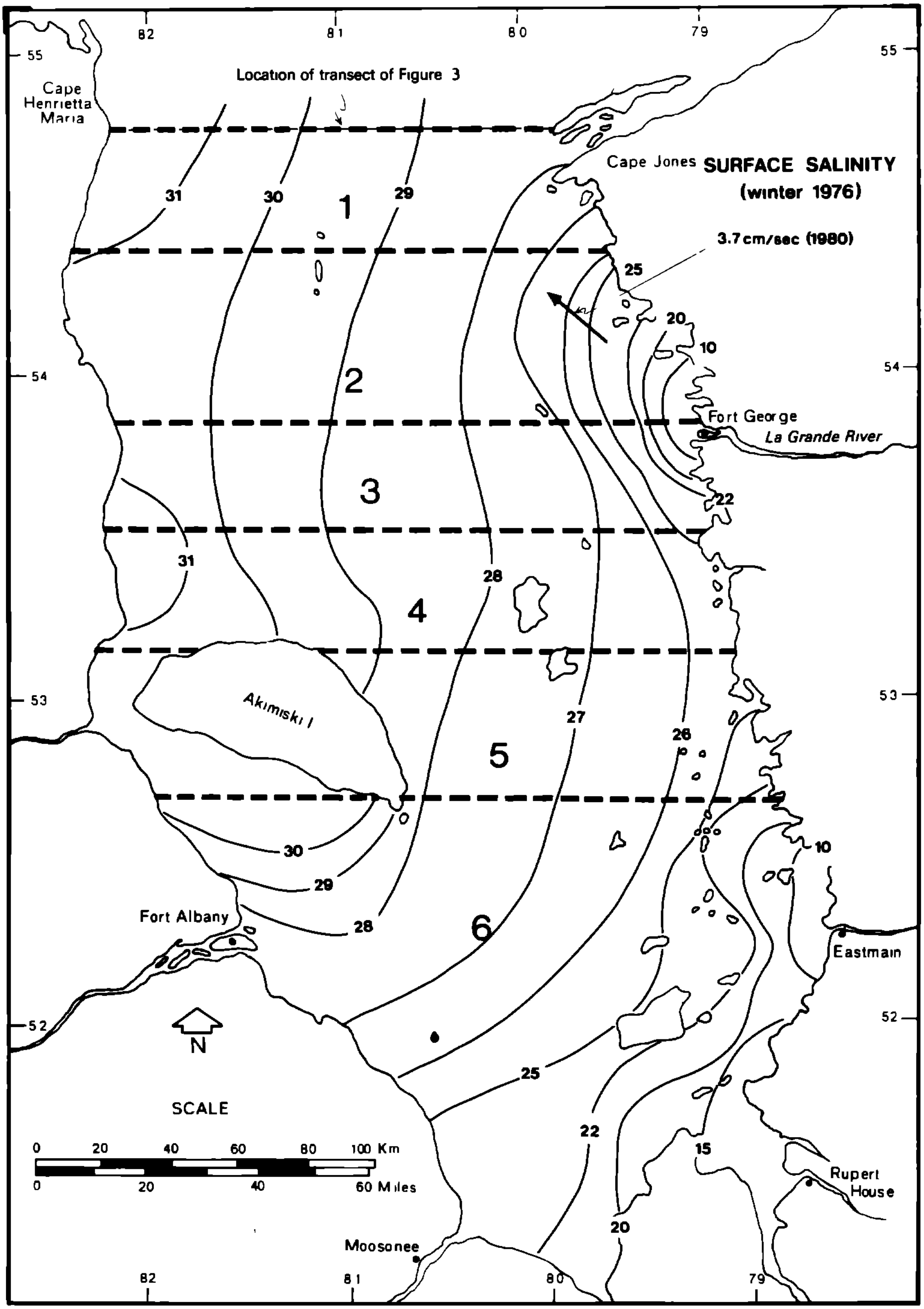

Fig 2 James Bay winter salinity distribution and boundaries of sub-areas.

Great Lakes surveillance cruise data (BOYCE *et al.*, 1977) was modified for oceanic application It calculates the content values for each layer and specified sub-areas (zone) from oceanographic profile data of randomly located stations. James Bay was split up into six zones (Fig. 2). The 1976 winter surface salinity distribution shows that surface water of high salinity content (31×10^{-3}) enters James Bay along the western shore, is diluted to 28×10^{-3} by the runoff as it flows cyclonically around the bay and leaves along the eastern shore. During the summer, the surface salinity distribution is similar to that found in the winter but with lower salinity values as a result of increased runoff and melting of the ice cover. Surface water (25×10^{-3}) enters James Bay along the western shore of the bay and leaves along the eastern shore with a salinity value of 23×10^{-3}. Summer current meter data (Fig. 3) showed that in addition to the surface inflow there is a distinct bottom layer entering the bay with a salinity value $>30.5 \times 10^{-3}$ (PRINSENBERG, 1982). For James Bay, this salinity is used as the base salinity in the calculation of freshwater contents.

As expected the results indicate that the summer freshwater layer thickness decreases towards the entrance of James Bay, away from the main source (Fig. 4). Exceptions to this trend are zones 4 and 6 whose large shallow areas contribute less to freshwater layer thickness. The mean of the six zones for James Bay is 6.3 m, which represents a summer 'residence' time of 10.2 months for the freshwater input of 61.2 cm per month. The winter freshwater thicknesses have a similar trend as those observed in summer. The values decrease towards the entrance and the values of zones 4 and 6 are again smaller than the mean trend. Each zone thickness is 3.6 m lower in winter than in summer but do not include yet the freshwater contribution of the ice cover. The yearly 'Ice summary and analysis' (CANADIAN GOVERNMENT, 1964–1979) shows that the ice reaches its maximum thickness of 1.6 m in early May. Assuming a 15% reduction for the thickness in the middle of March and a 5×10^{-3} salinity content for the ice, the freshwater thickness associated with the ice cover in the middle of March is 1.1 m. This means that the mean freshwater layer thickness relative to a 30.5×10^{-3} base salinity during March is 3.8 m. This is 60% of the summer mean value and

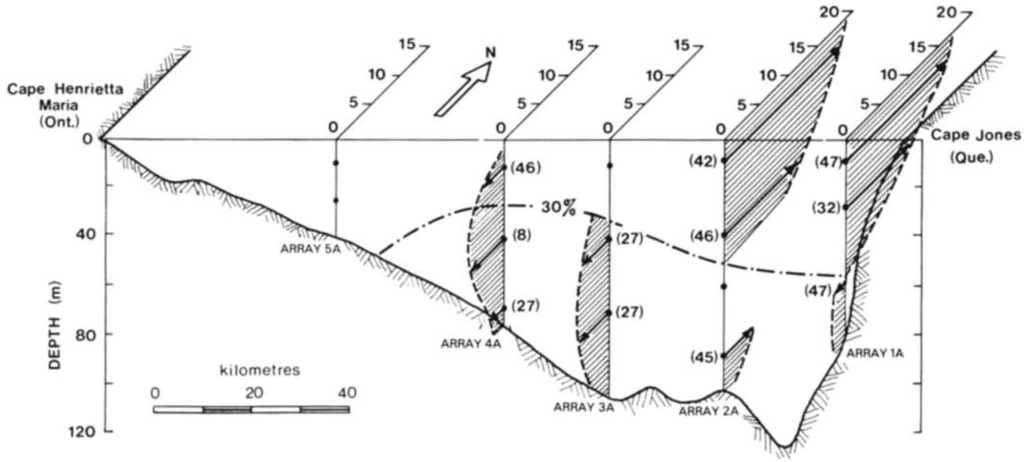

Fig 3 Cross-sectional diagram at entrance of James Bay showing mean summer longitudinal speed values; numbers in brackets indicate length of records in days

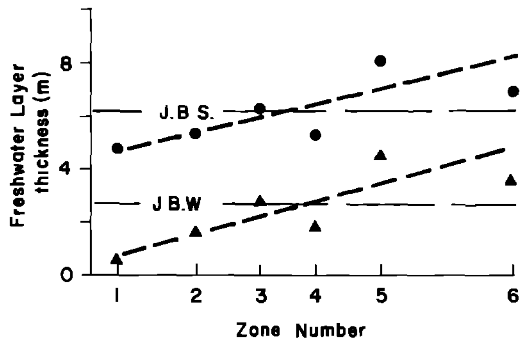

Fig. 4. Freshwater layer thicknesses of James Bay for winter ▲ and summer ● conditions; mean summer and winter are indicated by J.B.S. and J.B.W., respectively.

represents a 'residence' time of 20.0 months for a winter freshwater input rate of 19.1 cm per month. The residence time during summer is half of that found in winter and is a reflection of the slower observed winter circulation (PRINSENBERG, 1982).

There are several contributions which cause the freshwater layer thickness to increase by 2.5 m over the six-and-a-half month period. Freshwater is brought into the area by runoff and precipitation minus evaporation (R + P − E) and amounts to a 2.9 m layer (PRINSENBERG, 1980). The difference, 0.4 m or 2.9×10^{10} m^3, is the net amount of freshwater that must advect from James Bay. Advection will bring in freshwater as well as transport it out of the bay. Only for the month of August can the net amount be calculated from available current meter data. The outflow (Fig. 3) is confined to a cross-sectional area of 21.3×10^5 m^2 of the eastern half of the entrance. For a mean current of 6.5 cm s^{-1} and a relative to a base salinity of 30.5×10^{-3} it transports 5.4×10^{10} m^3 of freshwater out of James Bay in August. The transports of the other months can only be estimated from this value using the runoff cycle as a guide for rate changes. Due to the large distance and the slow drift velocity, it is estimated that the August transport at the entrance is caused by the June runoff. Using this delay time for the other months, the total net advection out of James Bay between winter and summer is 3.9×10^3 m^3. What was needed was only 2.9×10^{10} m^3. The excess is offset by a small net advection of ice, 0.8×10^{10} m^3 (freshwater), entering James Bay from Hudson Bay as indicated by results of a simple box model of MURTY and BARBER (1974). It should be noted that the freshwater exchange values of ice and water transports are an order of magnitude smaller than those of R + P − E and freshwater layer contents. Considering the possible errors in the latter two, the ice and water freshwater transports are insignificant in the freshwater budget calculations, but their contributions were in the right direction thus providing more confidence in all the other calculations of the freshwater budget.

The increase in freshwater content in James Bay from winter to summer is thus mainly attributed to the net freshwater addition (R + P − E) with smaller contributions from a net loss due to water transport and a small gain due to ice transport into James Bay. The hydroelectric developments will decrease the difference between the summer and winter freshwater content of James Bay due to increased winter runoff. However, the change in runoff cycle will not significantly change the total freshwater addition from winter to summer so that a new balance will be established by increasing the net winter freshwater transport out of the bay by advection. Simple freshwater budget analysis thus predicts an increase in the strength of the surface winter circulation of James Bay as was predicted more directly by an analytical model (PRINSENBERG, 1982).

Hudson Bay

Bay-wide salinity and temperature data for Hudson Bay is only available for the summer with some winter data for the southern inshore regions. Data collected in the summer of 1975 (PRINSENBERG, 1977) was used to calculate the freshwater layer thicknesses for the six zones shown in Fig. 1. Current and profile data (PRINSENBERG and FLEMMING, 1982) from the entrance of Hudson Bay indicated that the bottom layer coming into Hudson Bay has salinity values $>32.8 \times 10^{-3}$ which was used as a base salinity for the freshwater layer depth calculations. As expected, James Bay has the highest value (8.1 m) followed in succession by the zones located north and downstream of James Bay. Freshwater leaves James Bay and moves towards the entrance of Hudson Bay in the general counter-clockwise circulation. Along the way the salinity increases due to horizontal and vertical diffusion. Hudson Bay alone has an average freshwater layer thickness of 3.9 m, which increases to 4.2 m when James Bay is included. In comparison, the seasonal ice cover has a maximum thickness of 1.6 m and $R + P - E$ brings in annually a 0.64 m layer of freshwater. A residence time for the total Hudson Bay is 6.6 years, which is eight times longer than that for James Bay. This indicates that Hudson Bay will react much slower than James Bay to any man-made changes in the runoff cycle. No winter data is available to obtain a winter freshwater layer thickness to check on the freshwater budget from summer to winter conditions.

HEAT CONTENTS

James Bay

Heat content values are calculated relative to the freezing temperature of the seawater in question As expected, most of the summer heat content is located above the average pycnocline depth of 25 m. This volume represents 55% of the total volume and contains 83% of the total heat (48.5×10^{18} J). Winter data shows that the temperature of the surface mixed layer is at or just below the freezing temperature of the water. During active freezing there exists a layer of brine underneath the ice whose temperature is below the freezing temperature of the surface mixed layer. Some of this heat deficit is diffused into the surface mixed layer and causes its temperature to be below its freezing temperature. The surface mixed layer reaches depths of 30 to 40 m and accounts for 66% of the total volume. Below this depth the water warms slowly up again to values of 0.15 °C above the freezing temperature. The total heat content of James Bay still shows a small heat deficit of 0.1×10^{18} J, which for all practical purposes equals zero when considering the magnitudes of other heat budget contributors and errors in their calculations.

Similar to the freshwater calculations, the heat budget will follow the change in heat content from winter (the start of May) to the middle of summer (the end of August). Heat is put into James Bay through the air–sea interface, runoff, and water transport. DANIELSON (1969) calculated the total heat flux through the air–sea interface for Hudson and James Bays. His results give a net heat input for James Bay over the period of 107.0×10^{18} J for normal weather conditions. This is about twice that observed in the water column in the summer and resulted from about average weather conditions in winter to summer of 1975 (CANADIAN

GOVERNMENT, 1975). In addition, runoff into James Bay brings in another 9.2×10^{18} J during this period which was obtained from runoff rates and monthly average water temperatures of rivers entering the area (CANADIAN and MANITOBA GOVERNMENTS, 1971–1975; MARCOTTE, 1976). The other source is by water transport. Using the same transport calculations as those used in the freshwater budget and an average excess of temperature above the freezing temperature of 3°, the heat transported into James Bay in August is 5.4×10^{18} J. Data from a fixed location in western Hudson Bay at various times during the summer of 1975 showed that the heat content of the water column lags the solar heating cycle. For this reason the heat transport into James Bay during July is estimated to be 5.4×10^{18} J, while those of June and May are 2.8×10^{18} and 1.0×10^{18} J, respectively, for a total of 14.6×10^{18} J. Thus 130.8×10^{18} J enters James Bay between winter and summer and is mainly comprised of surface flux (82%) with minor contributions from runoff and water transport.

During this period heat is used in James Bay to heat the water column and to melt the seasonal ice cover, and also leaves the bay by ice and water exchanges. During August, the current meter data indicates that 3.7×10^{11} m^3 water leaves the bay with a mean temperature of 6°C. This represents 11.7×10^{18} J of heat leaving the bay during the month of August. Similar to above, the heat flux for July is estimated as 11.7×10^{18} J, 8.5×10^{18} J for June and 3.5×10^{18} J for May, a total of 35.4×10^{18} J. This is one third the amount that enters James Bay over the same period. The other heat deficit is due to the melting of the local ice cover as well as the ice advection into the bay from Hudson Bay. The 1.6 m thick ice cover requires 30.1×10^{18} J to melt, 5.1×10^{18} J to heat it to its melting temperature, and 3.2×10^{18} J to melt the snow cover (DANIELSON, 1969). The results of MURTY and BARBER (1974) indicate that there is also a net ice transport of 118×10^{8} m^3 of ice into James Bay between 1 May and 31 August. This is equal to a 17.7 cm layer of ice for the entire bay and requires another 4.2×10^{18} J to heat and melt it. The total heat required to decay the seasonal ice cover is 38.4×10^{18} J, which is about one third of the heat input of James Bay. The other large heat requirement was for heating the water column up to its observed summer value. Table 1 shows a summation of the heat budget of James Bay and indicates a balance between the heat brought into the bay and that which is used. The heat entering James Bay between winter and summer is evenly used to melt the seasonal ice cover, heat the water column, and account for

Table 1 *Heat budget results of Hudson Bay and James Bay for an observation period from* 1 *May to end of August*

	James Bay ($\times 10^{18}$ J)	Hudson Bay ($\times 10^{20}$ J)
Winter heat content	−0.1	1.2
Surface heat flux	107.0	11 7
Heat due runoff	9.2	0.2
Ice and snow cover	−38.4	−5.0
Heat of ice transport	−4.2	≈ 0
Advection of heat in	14.6	0 2
Advection of heat out	−35.4	−0.6
Balance	52.7	7 7
Summer heat content	48.5	7.6
Difference	4 2	0.1

the loss due to surface outflow. After the hydroelectric developments, the loss due to surface outflow will decrease in the spring but the heat requirement to melt the ice cover may increase, as less ice will be exported by the reduced spring surface outflow. Due to the lack of oceanographic data, year-to-year differences are ignored. However, since the ice cover takes so much heat to melt, the summer water temperature is inversely related to the severity of the preceding winter as more ice is formed which has to be melted in the spring. Strong coupling between atmospheric, ice cover, and oceanic properties thus exists and changes in one will be reflected in the others.

Hudson Bay

Similar to James Bay, most of the heat content (7.6×10^{20} J) of the combined Hudson Bay and James Bay area is found above the average depth of the pycnocline (25 m). The volume above 25-m depth represents only 20% but contains 74% of the total heat. These results were obtained from data that was mostly collected between 12 August and 28 September; so a mean observation of 1 September was used for the end of the radiation input period. The winter heat content had to be estimated indirectly. Winter data from James Bay and the southeast corner of Hudson Bay showed that there exists a mixed surface layer whose temperature is at the freezing point. From summer data, it appears that the remnant of the winter mixed layer is at around 60 m. The summer data also indicates that the excess temperature above the freezing temperature of the bottom layer is about 0.5°C, which would mean that the winter content of Hudson Bay area is 1.2×10^{18} J, one sixth of that found during the summer. Between winter and summer some 6.4×10^{20} J are required by Hudson Bay to heat up the water to observed summer values. The net heat flux into Hudson Bay through the air–sea interface is calculated from the monthly heat flux values of DANIELSON (1969). The heat input between the start of May and the end of August is 11.7×10^{20} J, with the peak input during July. This is twice the amount required to heat the water of the bay, the remainder is mainly used to melt the seasonal ice cover.

The seasonal ice cover of 1.6 m needs 4.0×10^{20} J to melt, 0.6×10^{20} J to heat to its melting temperature, and 0.4×10^{20} J to melt the annual snow cover (DANIELSON, 1969). Thus a total of 5.0×10^{20} J is required to melt the seasonal ice and snow cover. This is about half the surface heat input and is equal in magnitude to that required to heat the water column.

As in the case of James Bay heat is transported in and out by the circulation at the entrance. Summer salinity data indicates that there is a surface outflow from Hudson Bay which extends half across the entrance and reaches a depth of 60 m. Using current meter data (PRINSENBERG and FLEMMING, 1982), it is estimated that the transport rate out of the bay is 0.3×10^6 m^3 s^{-1}, which will mean a loss of 0.4×10^{20} J from the bay during August. Since the surface water is heated during June and July, the transports of heat out of the bay are estimated relative to that of August to be 0.1×10^{20} J for June and 0.2×10^{20} J for July. From 1 May to the end of September, a total of 0.6×10^{20} J advects out of the bay, more than an order of magnitude less than the surface heat flux. The surface water flowing into the bay is colder by about 2° than that going out, while the bottom layer has an average temperature of just -1.4°C. Using current meter data, it is estimated that the heat advected into the bay (0.2×10^{20} J) is less than half that advected out. The heat exchange by water transport at the entrance of Hudson Bay is not as an important factor as it was for the James Bay heat budget.

The other two heat budget contributions, runoff and ice transport, are also irrelevant to the total budget. The total heat brought into Hudson Bay by runoff during this period is 0.2×10^{20} J, about 1/50 of that supplied by the surface heat flux. The results of the box model of MURTY and BARBER (1974) indicate that there is a net ice transport of 3.5×10^{10} m^3 out of the bay between the start of May and the end of August. This is only a 4 cm layer of ice and is ignored in comparison with the inaccuracy that is associated with the 1.6 m value of the seasonal ice cover.

Table 1 shows the estimated values of the heat budget of Hudson Bay between winter and summer conditions. For Hudson Bay the surface heat flux input during this period is mainly balanced by the heat required to melt the seasonal ice cover and to heat the water column. The advection of heat by currents is negligible as are the other contributors. However, for James Bay the transport of heat by the general clockwise circulation is an important factor in the heat budget.

CONCLUSION

The summer freshwater layer thickness of James Bay has a baywide average value of 6.25 m. It decreases towards the entrance of the bay and represents a residence time of 10.2 months for the freshwater input rate of 61.2 cm per month. During the winter, the freshwater layer thickness has a mean value of 3.8 m and represents a residence time of 4.1 years. The change of freshwater content from winter to summer conditions is accounted for by the freshwater addition (R + P − E) and a net advection of freshwater out of the bay by the counter-clockwise circulation. For Hudson Bay the freshwater layer depth for the summer is 4.7 m, which compares to a yearly freshwater input of 0.64 m (R + P − E) and a seasonal maximum ice cover thickness of 1.6 m (freshwater). The residence time of Hudson Bay is 4.1 years when a mean summer freshwater input rate is used.

For the James Bay and the Hudson Bay heat budgets, contributions from surface heat flux, advection by ice, circulation, runoff, and seasonal ice cover were considered. The results show that, for Hudson Bay, the incoming surface heat flux between May and August is mainly balanced by the heat required to melt the seasonal ice cover and to bring the water temperature up to the observed summer values. The other factors in the heat budget are an order of magnitude smaller. For the same period in James Bay the heat lost by advection due to circulation also becomes an important factor in the heat budget.

The freshwater budget calculations show that the seasonal ice cover and the runoff are the major components, while for the heat budget the ice cover and the water column are the main benefactors of the incoming surface heat flux. The properties of the seasonal ice cover and marine environment are thus closely tied and changes in one will affect the other. Hydroelectric developments will affect the runoff cycles of James Bay and Hudson Bay, and through the strong coupling between the marine and ice cover environments, will affect the seasonal ice cover and eventually the local atmospheric conditions. An assessment of the effects of hydroelectric developments should thus not only look at the marine environment, but also at the seasonal ice cover and the atmospheric environment, as all are interrelated to each other. Further, the assessment should address the cumulative effects of all hydroelectric developments, operational and planned for the area, not each separately.

Acknowledgements—The author would like to thank Mr R. Gottinger for his assistance with the computer programming and Messrs D. Brooks and S Baird for acting as officers-in-charge of the various field surveys whose data was used in this manuscript.

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