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# Ice-Cover and Ice-Ridge Contributions to the Freshwater Contents of Hudson Bay and Foxe Basin

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ABSTRACT. Runoff and precipitation add 65 cm of fresh water to Hudson Bay annually. The ice cover does not account for a net contribution of fresh water over a one-year period; however, on weekly time scales, it contributes as much or more than runoff. The maximum thickness of ice averaged over the bay is 160 cm and represents a 140 cm layer of fresh water when sublimation is accounted for. This fresh water is twice as large as the amount annually brought in by runoff and precipitation and is added to the surface layer in the spring and removed from the surface layer in the fall.

Freshwater budgets of Hudson Bay and Foxe Basin indicate up to 90% more ice is produced than indicated by ice thickness data. Part of this difference can be attributed to the ice accumulated in ice ridges, which for Hudson Bay accounts for 25 cm of ice and as much as 58 cm of ice for Foxe Basin, where extreme rough ice conditions occur.

Key words: Hudson Bay, Foxe Basin, ice cover, ice ridges, freshwater content

RÉSUMÉ. La baie d'Hudson reçoit chaque année 64 cm d'eau douce provenant des eaux de ruissellement et des précipitations. L'apport d'eau douce dû à la couverture de glace est négligeable sur une durée d'un an, mais, durant certaines semaines, il devient égal ou supérieur à celui des eaux de ruissellement. L'épaisseur maximale de la glace, calculée sur l'ensemble de la baie, est de 160 cm et représente une couche d'eau douce de 140 cm si on tient compte de la sublimation. Cette quantité d'eau douce est deux fois plus importante que la quantité annuelle due au ruissellement et aux précipitations, et elle s'ajoute à la couche de surface au printemps et s'en élimine à l'automne.

Les bilans d'eau douce de la baie d'Hudson et du bassin de Foxe montrent que la production de glace est de jusqu'à 90 p. cent supérieure à celle indiquée par l'épaisseur de la glace. Cette différence peut s'expliquer en partie par la glace qui est accumulée sous forme de crêtes, ce qui représente 25 cm de glace pour la baie d'Hudson et 58 cm pour le bassin de Foxe où se trouvent les formations de glace les plus accidentées.

Mots clés: baie d'Hudson, bassin de Foxe, couverture de glace, crêtes de glace, volume d'eau douce

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## INTRODUCTION

The annual ice cover in Canada's northern waters advances in winter as far south as James Bay and the Gulf of St. Lawrence (Fig. 1) and retreats in summer to the middle of the Canadian Archipelago. Where the ice is level and not ridged, the maximum ice thickness ranges from 1.0 m in southern James Bay to 2.0 m in Foxe Basin (Markham, 1981). During normal years landfast ice is found in sheltered inshore areas of Hudson Bay and James Bay, while a more mobile ice cover with ice concentration greater than 9/10 is found offshore.

Salt rejected during ice growth affects the vertical stratification of the underlying water column. The salt rejected over shallow continental shelves of the Arctic Ocean is thought to be responsible for the formation of the cold waters of the upper halocline of the entire Arctic Ocean (Aagaard *et al.*, 1981). Melling and Lewis (1982) also detected this process over the Beaufort Sea shelf. The cold saline bottom water observed by Campbell (1964) in southern Foxe Basin was similarly produced over the extensive shallow shelves in the northern half of the basin. In Hudson Bay, tidal mixing generated at the ice-water interface and salt rejection from the growing ice cover continually deepens the pycnocline until the end of April, when maximum ice-cover thickness and pycnocline depth of 95 m are reached (Prinsenberg, 1986).

Water, from melting ice and runoff, released in the spring stabilizes the surface layer, which suppresses mixing and the upward transports of heat and nutrients. The variation in the vertical nutrient flux due to variations in the horizontal freshwater flux in Hudson Strait has been shown to affect the yearly fish abundance downstream in the Labrador Sea (Sutcliffe *et al.*, 1983). In their study, Sutcliffe *et al.* (1983) assumed the fresh water came from runoff of the large drainage area upstream of the Hudson Strait. In this paper it will be shown that the growth and decay of the ice cover affects the freshwater content of the surface layer more than the freshwater addition by runoff. It is also shown, from budget calculations, that the amount of salt rejected from the growing ice and of fresh water released from decaying ice depends strongly on the size and frequency of ice ridges, which can increase the ice volume by as much as 90% above values derived assuming smooth, level ice.

## FRESHWATER CONTRIBUTIONS OF THE ICE COVER AND RUNOFF

Fresh water is removed from the surface layer by ice growth and evaporation and is added by ice melt, runoff from land and precipitation. When the vertical freshwater flux associated with ice growth and decay is treated as increased evaporation in the early winter and as increased precipitation in the spring, it can be compared directly to evaporation, precipitation and runoff rates after the runoff is also converted into a surface flux term by spreading it equally over the total surface area of the bay.

Maps of maximum ice thickness and ice concentrations available for Canadian arctic waters are based on 15 years of sea ice observations at coastal stations where the ice is usually fast to the land (Markham, 1981). The 15-year mean maximum ice thickness for Hudson Bay ranges from 1.0 m in southern James Bay to 2.0 m in northern Hudson Bay and has an areal average of ~1.6 m (Fig. 1). Time series of maximum ice thickness values have large interannual variations. Normalized standard deviation (error) or coefficient of variance for maximum ice thickness values ranges from 0.09 to 0.18, with a mean of 0.14 for the six monitoring stations around Hudson Bay (over the period of 1961-81). Figure 2 shows the interannual variability in the ice thickness data of two of these locations in Hudson Bay, Moosenee in southern James Bay and Chesterfield Inlet in northwestern

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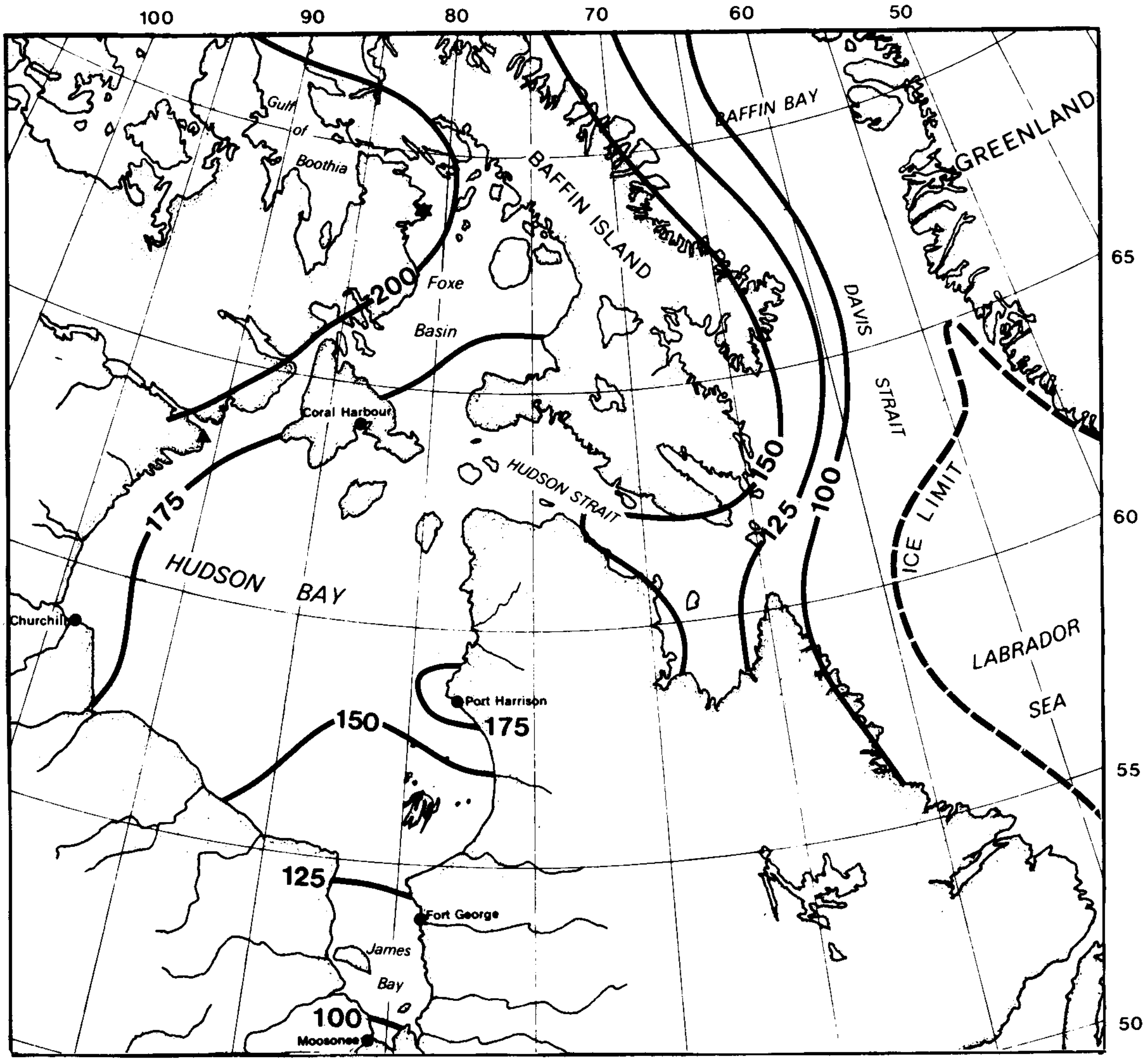

FIG. 1. Maximum sea-ice thicknesses (cm) for eastern Canada, from Markham (1981). Hall Beach in northwestern Foxe Basin is denoted by * and Chesterfield Inlet in northwestern Hudson Bay by Δ.

Hudson Bay, as well as Hall Beach, a station in Foxe Basin. The ice thickness data was collected by the Ice Centre of Environment Canada and published yearly as "ice thickness data" (Atmospheric Environment Service, 1961-81). To obtain the total ice growth, the maximum ice thickness data need to be corrected for sublimation, which between November and April amounts to a 0.2 m layer of ice (Danielson, 1969). This increases the total areal mean ice growth to 1.8 m and converts to a 1.4 m layer of fresh water when the ice density is taken as 0.9 $gr \cdot cc^{-1}$ and an average salinity of 5 ppt (Tucker *et al.*, 1984a) is taken for the ice cover in comparison to the 32.9 ppt for the remaining water column.

Figure 2 also shows the yearly mean addition of fresh water by runoff to the Hudson Bay region. For the period ending in 1981, the averaged yearly mean runoff rate is $2.07 \times 10^4 m^3 \cdot s^{-1}$, or equivalent to a yearly addition of a 0.78 m layer of fresh water spread out over the entire surface area of the bay. Due to lower runoff rates since 1975 (Fig. 2), this value is lower than the 0.85 $m \cdot year^{-1}$ value obtained for the period ending in 1976 and previously used in freshwater budgets (Prinsenberg, 1980, 1984). For Hudson Bay, the freshwater addition by runoff is about half the amount exchanged annually between the ice cover and water column during the growth and decay of the ice cover. Thus, both freshwater fluxes associated with the ice cover and runoff need to be considered when modelling seasonal pycnocline cycles or seasonal freshwater fluxes leaving Hudson Strait for the Labrador Sea.

On shorter time intervals the contribution of the ice may become even more significant because ice melt water is added over a shorter period than land runoff (Fig. 3). On the other hand, the circulation pattern and salinity distributions of Hudson Bay indicate that most of the fresh water added by runoff enters and moves along the southern and eastern coasts before leaving the bay. Thus, in these inshore areas the runoff contribution increases relative to that of the ice cover. But even if the runoff is spread over only one-half the surface area of the bay, the freshwater contribution from melting ice is still equal to or larger than that from runoff (Fig. 3).

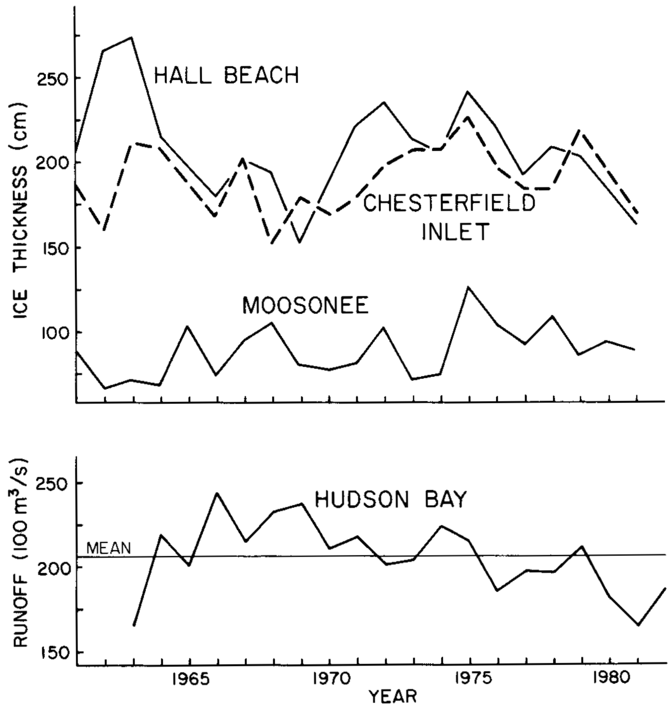

FIG. 2. Time series of yearly mean runoff into Hudson Bay and maximum ice thicknesses for Hall Beach (Foxe Basin), Chesterfield Inlet (N.W. Hudson Bay) and Moosenee (S. James Bay), whose locations are shown in Figure 1.

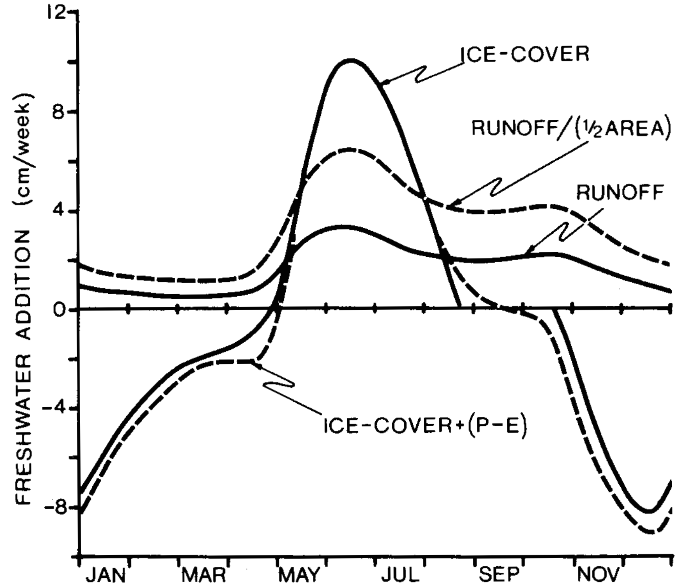

FIG. 3. Freshwater addition by ice cover, runoff (R), precipitation (P) and evaporation (E) for Hudson Bay using a 1.6 m maximum ice-cover thickness.

## FRESHWATER BUDGETS

More fresh water is observed in James Bay, Hudson Bay and Foxe Basin during the summer than can be accounted for by ice melt, runoff, evaporation, precipitation and horizontal transports. It will be shown that this difference indicates that more ice is present and melted than previously assumed from level sea-ice data.

For James Bay, heat and freshwater balances for the period from winter to summer were achieved by using a thick 1.6 m ice cover equal to the climatic mean of Hudson Bay (Prinsenberg, 1984). Salinity and temperature data used in the calculations of the freshwater content of James Bay were obtained during early March and August 1976. The winter of 1976 (Fig. 2) was severe, producing up to 0.15 m more ice by the end of March in southern James Bay (Moosenee) than normally observed. In the heat budget calculations it was further assumed that by early March the ice-cover thickness of James Bay would reach 90% of its maximum value, which for 1976 was taken as the norm (1.10 m) plus 0.15 m. Ninety percent of this 1.25 m of ice converts to a 0.8 m layer of fresh water (Table 1), when again an ice-cover salinity of 5 ppt is assumed and 30.5 ppt is used for a base salinity of James Bay.

TABLE 1. Freshwater layer (m) change or addition between winter and summer; ice values are given in freshwater equivalent units (m)

| | James Bay | Hudson Bay | Foxe Basin |
|---|---|---|---|
| Water column | –3.6 | –2.9 | –2.8 |
| R+P–E | 2.9 | 1.1 | 0.4 |
| Ice transport out | — | –.04 | –0.3 |
| Ice transport in | 0.1 | — | 0.2 |
| Water transport out | –0.5 | –0.2 | –0.4 |
| Water transport in | — | — | 0.6 |
| Estimated ice melt* | 1.1 | 2.0 | 2.3 |
| Observed ice melt | 0.8 | 1.2 | 1.2 |
| % of extra ice required | 40 | 66 | 90 |

*Negative value of sum of above six listed values.

In the heat and freshwater budget calculations (Prinsenberg, 1984) the change (3.6 m) in the freshwater layer content of the water column for James Bay from winter to summer was mainly balanced by the addition of a 2.9 m layer of fresh water brought in by runoff plus precipitation minus evaporation (R + P–E) and the required 1.1 m layer of fresh water by ice melt to balance the budget (Table 1). The spring and summer runoff rates entering James Bay in 1976 were near normal, even though the yearly means were below normal (Fig. 2), due to extremely dry fall conditions. The estimated ice melt (1.1 m) from budget consideration is thus 40% larger than the calculated value (0.8 m) from observed level sea-ice data, suggesting that more ice is annually grown and melted.

Similar results are found for Hudson Bay. In the centre of the bay, the freshwater content changes by a 3.0 m layer from summer (Fig. 4) to winter, when the surface mixed layer reaches a depth of 95 m and has a salinity value of 32.9 ppt (Prinsenberg, 1986). This change in freshwater content of 3.0 m is higher than the 2.7 m observed in southeastern Hudson Bay using 1976 summer data of Prinsenberg and Flemming (1982) and 1977 winter data of Prinsenberg and Collins (1979). The seasonal change in freshwater content in Hudson Bay is taken as the average (2.9 m) of these two known values. Runoff, evaporation and precipitation bring in a 1.1 m layer of fresh water when runoff is spread over just the southeastern half of the bay. The amount of ice transported out of the bay is small, $3.5 \times 10^{10}$ m$^3$ (Murty and Barber, 1974), which equals only a 4 cm layer of ice and can be ignored. During the summer, water is transported in and out of the bay at a rate of $0.3 \times 10^6$ m$^3$·s$^{-1}$ (Prinsenberg, 1984). The mean salinity of the water leaving is 30 ppt, while the salinity content of the water entering ranges from 30 ppt in

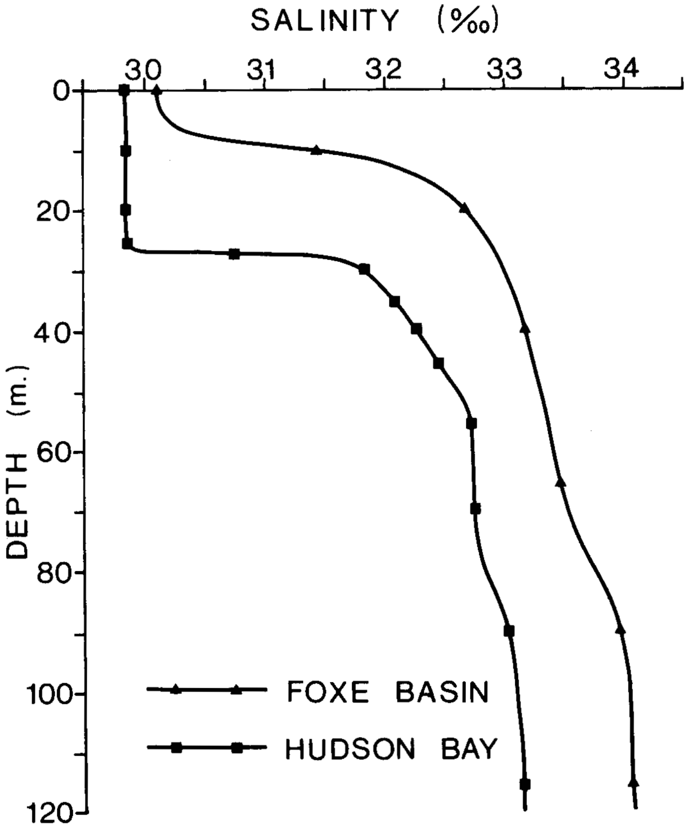

FIG. 4. Salinity profiles for centre of Hudson Bay and Foxe Basin.

the surface to 33 ppt at the bottom, for an average of 31.5 ppt. From these numbers one can show that the bay loses fresh water at a rate of 0.04 m layer per month in the summer. The rate reduces to zero in the winter, as then the salinity values of incoming and outgoing water approach each other. These monthly transports add up to a 0.2 m layer of freshwater loss between winter and summer and leave a 2.0 m layer to be accounted for by ice melt (Table 1). Since the maximum ice-cover thickness of 1.6 m reduces to a 1.2 m layer of fresh water, an additional 0.8 m layer of fresh water, or 66% more ice, is required. Some of this additional ice actually drifts in from the north, so that not all 66% of the extra ice is "new" ice for the bay as a whole.

In northern Foxe Basin, the freshwater content changes by a 2.8 m layer from summer to winter, as the summer stratified water column shown in Figure 4 becomes homogeneous, with a salinity content of 34 ppt (Campbell, 1964). In the summer, arctic water enters the basin in the north at a rate of .01 × $10^6$ $m^3 \cdot s^{-1}$ (Barber, 1965) and has a salinity content of 31 ppt (Grainger, 1959). In the winter, it enters at a rate of 0.04 × $10^6$ $m^3 \cdot s^{-1}$ (Sadler, 1982) and has a salinity content of 32.55 ppt. Relative to 34 ppt, this represents a flux of a 0.18 m layer of fresh water per month in the summer and a 0.04 m layer per month in the winter, for a total of a 0.6 m layer over the period from winter to summer. Runoff, evaporation and precipitation may contribute at most a 0.4 m layer of fresh water, similar to northern Hudson Bay. If the water transport from the basin is equal to that entering in the north and its water salinity is increased due to mixing to 32 ppt in summer and 34 ppt in winter, then the fresh water transported from the basin for the period of winter to summer represents a 0.4 m layer. Up to 20% of the ice cover is transported southward out of the area (Markham, 1981), even though most of this is replaced by an influx from the north (Table 1). The remaining ice melt equals a 1.2 m layer of fresh water, nearly half the amount required to balance the crude freshwater budget (Table 1). Thus possibly 90% more ice is produced in northern Foxe Basin than level ice data indicate.

The availability of data used in the above calculations varies and causes large uncertainties in their estimates. The areal estimates are represented by an average of data observed at specific locations, with the oceanographic data only available for a limited time period but used as summer and winter mean conditions similar to the climatological means of runoff and ice-cover thickness. Time series of ice thickness and runoff data showed large interannual variations of up to 15%. The freshwater content of the water column is dependent on these parameters and should similarly be expected to vary interannually by ±15% from the climatological mean. Since the freshwater content changes are the differences of two values with uncertainties each of ±15%, their uncertainty would be ±30%; combined with a ±15% uncertainty in runoff, the uncertainty of the ice melt estimate would be ±45%. For James Bay this uncertainty is probably smaller, as an attempt was made to correct for the interannual variability.

So although these budget estimates for James Bay, Hudson Bay and Foxe Basin are very crude and the extra ice requirement may be in error of up to 60%, they all show that substantial amounts of extra ice production are needed to produce the observed seasonal variation in salinity and freshwater content values.

## ICE VOLUME OF FIRST-YEAR ICE RIDGES

Freshwater budgets indicate that the offshore ice volume is underestimated. It will now be shown that part of the underestimation is due to the ice volume associated with ridges and rubble fields.

Size and frequency data of ice ridges in Canada's northern waters have become available as a result of research on proposed year-round shipping through the Northwest Passage (NORCOR, 1978; Arctic Pilot Project, 1981). In addition, ridge data from coastal areas of the Arctic Ocean are available for both multi-year and first-year ice (Brooks, 1983; Tucker *et al.*, 1984b). Ridge size and frequency distributions for Hudson Bay and Hudson Strait are similar to those in the eastern end of the Northwest Passage, where the annual ice cover also reaches a maximum thickness of 1.4-1.9 m (Markham, 1986). For first-year ice, the keel depth of ridges ranges from 5 times their height for small ridges to 3.3 times their height for large ridges (Arctic Pilot Project, 1981; Markham, 1986). When an average width of 22 times the sail height H is taken for the ridge keel and sail, then one would expect the ridge to float isostatically with a ratio of keel depth to sail height ($c_1$) of 9. However, subsequent freezing of water in voids between ice blocks causes the ridge to float higher, with the lower observed ratios of keel depth to sail height. Remote-sensed observations measure ridge heights relative to the surface of the surrounding ice cover and thus will not detect this change in the position of sea level relative to the ridge. The magnitude of the change of the sea level within the ridge depends on the age of the ridge (refreezing time) and the time of ridge formation (freezing activity). Sublimation of the ridge further reduces the sail height, lowering the ratio of keel depth to sail height.

To calculate the extra ice volume of a ridge per unit length one adds up the volume of the sail and keel and subtracts the volume of the ice cover it replaces. The ice volume per unit length of ridge's sail, ice cover and keel are given respectively by: $\frac{1}{2}(22\,H)(H - h/10)$, $22\,Hh$, and $\frac{1}{2}(22\,H)(Hc_1 - 9/10h)$, which add up to an ice volume per unit length of $11\,H^2(1 + c_1) + 11\,Hh$. If a consolidation factor $c_2$ accounts for the air and water voids in the ridge, then after the ice volume of the replaced ice cover is subtracted, the extra ice volume per unit length of ridge V is given by: $V(m^2) = 11\,H^2(1 + c_1)c_2 - 11\,Hh(2 - c_2)$, where $c_1$ is the ratio of keel depth to sail height and $c_2$ the consolidation factor, ranging from 0.65 to 0.85. For the three ice-cover thicknesses of Figure 5a, the consolidation factor was taken as 0.75. The curves cover the range of ice thicknesses encountered in our study area and are shown as the additional ice thickness caused by one ridge of given sail height occurring once per kilometre, i.e., the extra volume of ice V was spread over an area of one kilometre by unit length. The amount of additional ice of a ridge decreases slightly with the thickness of the ice cover as the volume of the ice cover it replaces is subtracted from the total ridge volume. The amount of additional ice rapidly increases with sail height, reaching a value of 0.15 m of extra ice for each 2.0 m ridge per kilometre for the 1.6 m thick ice cover of Hudson Bay.

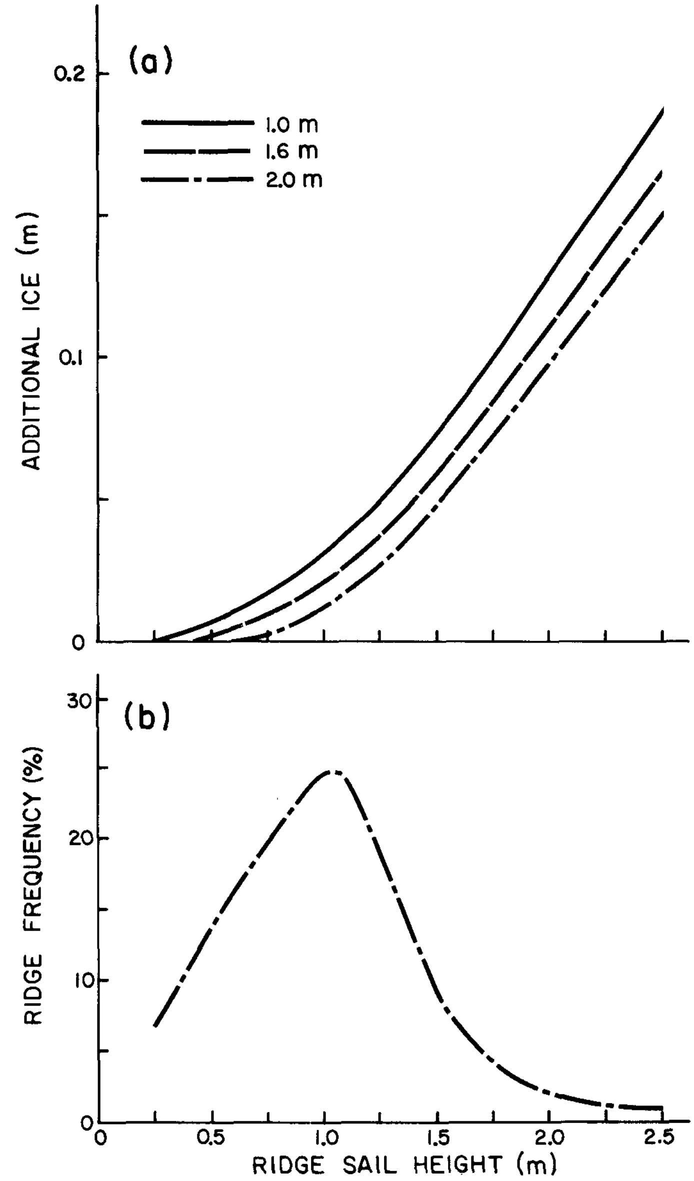

FIG. 5. a) The additional ice thickness (m) for each ridge ($\cdot km^{-1}$) of varying sail height in an ice-cover thickness ranging from 1.0 to 2.0 m. b) Ridge size distribution for first-year ice in Hudson Bay and surrounding areas.

In southern and northern Hudson Bay Markham (1986) observed 4-10 ridges per km, with an average of 6 ridges per km; 6% of them were over 1.5 m in height and 26% over 1 m. Less than 1% exceeded 2 m in height, and the maximum was in the 3.0-3.5 m range. In Hudson Strait, 6-14 ridges$\cdot km^{-1}$ were observed, with an average of 3 ridges$\cdot km^{-1}$. One percent of the ridges exceeded 2 m, 7% 1.5 m and 23% were 1 m in height (Markham, 1986). These size distributions average out to a distribution (Fig. 5b) very similar to those observed in the eastern part of the Northwest Passage (Arctic Pilot Project, 1981), where similar ice thicknesses are observed.

Ice-ridge frequency data is obtained along flight paths. Even though the orientation of ridges are mostly random and their length is not indefinite, the ridge-size frequency can be combined with the additional ice thickness equation to obtain the extra ice thickness due to ridging. This assumes that the ridge frequency data along the flight path is representative of the total area. For the 1.6 m maximum ice-cover thickness of Hudson Bay, the extra ice of ridging ranged from 0.34 m in the southern part of the bay, where up to 10 ridges$\cdot km^{-1}$ occurred, to 0.14 m for the northern part of the bay, where only 4 ridges$\cdot km^{-1}$ occurred (Table 2). This amounts to a 3.4 cm layer of extra ice for each ridge$\cdot km^{-1}$. For Hudson Strait ridge frequencies are higher, with the result that up to 0.47 m of extra ice needs to be considered. Although no ridge frequency data is available for Foxe Basin, it must be larger than that for Hudson Strait, since it has one of the roughest sea ice covers in the Canadian Arctic (Campbell and Collin, 1958). So one expects here possibly 0.58 m or more of extra ice.

TABLE 2. Comparison of the additional ice associated with ridging and that required by freshwater budget

| | James Bay | Hudson Bay | Hudson Strait | Foxe Basin |
|---|---|---|---|---|
| Level ice thickness (m) | 1.15 | 1.6 | 1.6 | 2.0 |
| Ridge freq. (# $\cdot km^{-1}$) | 6-10* | 4-10 | 6-14 | 8-20* |
| Additional ice by ridges (m) | 0.23-0.38 | 0.14-0.34 | 0.20-0.47 | 0.23-0.58 |
| Additional ice by freshwater budget (m) | 0.45 | 1.0 | — | 1.8 |

*Estimated values.

These values of extra ice due to ridging are crude estimates and do not take into account any year-to-year variability. Also, ice-free areas left behind during ridge formation are assumed to refreeze to the same thickness as the original ice cover. Although thin ice grows quickly, these opened areas will not refreeze to the thickness of the remaining ice cover, thus overestimating the ice volume of the total area. This overestimation is offset by the underestimation of the ice ridge volumes due to sublimation of their ridge heights upon which the ice ridge volume calculations are based.

The crude ice volume estimates do show that large quantities of extra ice are associated with ridging and do for a large part account for the extra ice required to balance the freshwater budgets, which are shown in Table 2 in units of metres of extra ice. However, even more ice is required and it is suspected to be associated with rafting. But its volume cannot be estimated presently or obtained from remote-sensed data.

## CONCLUSION

The fresh water exchanged between the annual ice cover and the oceanic surface layer changes the stability of the water column as much as or more than the changes caused by runoff. Freshwater budgets for James Bay, Hudson Bay and Foxe Basin indicate that more fresh water is required to balance the observed seasonal changes in salinity. Part of the discrepancy is caused by the extra ice associated with ice ridges. Using ridge height and frequency distributions for Hudson Bay, Hudson Strait and Foxe Basin, it was shown that the freshwater contribution of the ice cover could be increased by as much as 30%. It is therefore important to know the ice-cover properties as well as the runoff characteristics to determine the seasonal variation of the oceanic stratification and the upward flux of nutrient and heat required in studies on biological and ice-cover extent downstream in the Labrador Sea.

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