Small scale melt processes governing the flushing of nutrients from a first-year sea ice, Hudson Bay, Canada

Ice
Melting
Brine
Nutrients
Arctic

Glace
Fonte
Saumure
Sels nutritifs
Arctique

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ABSTRACT

This work formed part of a multi disciplinary research programme conducted 25 km offshore of Kuujjuarapik in southeastern Hudson Bay (Canadian Arctic). Large differences in salinity and nutrient concentration between brine, ice and under-ice surface water were used to study the different phases observed during the period of melt initiation. We present a discussion of processes governing the flushing of brine and the development of a melt layer below first-year sea ice. Phosphate, nitrate + nitrite and silicic acid distributions within the first 30 cm below the ice are described. Three distinct steps were observed during the melt initiation: a phase of brine rejection; a phase of flushing associated with the development of a buoyant melt layer rich in nutrients; and a phase of melt of the ice-water interface characterized by the development of a melt layer poor in nutrients. The flux of brine during the four days of brine flushing was estimated at 0,009 m^3/day/m^2 (*i.e.* equivalent to a melt rate of 9 mm/day). Our findings confirm that exchanges between the water column and the sea-ice sheet are dominated by tidal current fluctuations. The increase of current velocities provoked the pumping of a fraction of the bottom-ice brine content and a dissipation of vertical structures. Low tidal velocity periods created conditions suitable for the development of a melt layer.

RÉSUMÉ

Processus associés au drainage des sels nutritifs d'une glace marine de première année durant la période d'initiation de la fonte, Baie d'Hudson, Canada.

Cette étude fut entreprise dans le cadre d'une campagne de recherche multi-disciplinaire à 25 km au large de Kuujjuarapik, au sud-est de la baie d'Hudson (Arctique Canadien). Les différences de salinité et de concentration en sels nutritifs entre la glace, la saumure contenue dans la glace et les eaux marines de surface furent utilisées pour étudier les différentes phases observées au début de la fonte pour une glace de première année. Trois phases furent observées durant la fonte: une phase de rejet de saumure et une phase de « flushing » associée au développement d'une couche d'eau de fonte riche en nutriments, et une phase de fonte associée au développement d'une couche d'eau de fonte pauvre en nutriments. Le flux de saumure pour les 4 jours de la phase de « flushing » est estimé à 0,009 m^3/jour/m^2 (*i.e.* équivalent à un taux de fonte de 9 mm/jour). En outre, nos résultats confirment que les échanges entre le couvert de glace et la colonne d'eau sont fonction des courants de marée avec alternativement le développement et la dissipation des structures verticales induites par les apports en eaux de fonte. Parallèlement, on observe un pompage d'une partie de la saumure contenue dans le bas du couvert de glace lors des phases de flot.

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INTRODUCTION

In studying exchanges between a sea ice-sheet and the water column, interface characteristics have to be considered along with ice properties and boundary layer dynamics. The under-ice boundary layer is particularly difficult to understand because of the wide range in surface roughness (Untersteiner and Badgley, 1965; Maykut, 1986).

Almost all of Hudson Bay is covered by annual sea ice from late December to early May. In the southeast part of the bay, a broad (typically 10^4 km^2) landfast sea-ice sheet occurs in most years (Markham, 1986; Larouche and Galbraith, 1989). Away from ridging areas, maximum ice thicknesses range from 1 to 1.5 m. The relative strength of wind, wave and current forcing, at the time of freeze-up, can alter the roughness characteristics from one year to the next. Rafting and ridging often generate a heterogeneous distribution of both large and small roughness elements. For example, in our study area, features related to pressure ridging ranged in sail height up to 5 m with keels 2 to 3 times this value and a density between 1.9 and 4.1 ridges per km (Hudier *et al.*, 1993). These large-scale features surrounded unbroken plates whose maximum length, along their major axis, typically ranged between 500 m and 1 km. The underside of these large and relatively smooth plates consists of aggregated platelets with a mean roughness height of 3 mm. Although pressure ridge distribution varies yearly, these characteristics are representative of most first-year sea-ice sheets (Tucker *et al.*, 1979; Weeks *et al.*, 1988; Wadhams and Davy, 1986; Lytle and Ackley, 1991; Williams *et al.*, 1975).

The thermodynamic balance of sea ice is well described in Maykut and Untersteiner (1971). During the period of ice growth, salt is rejected from the ice through brine channels (Lake and Lewis, 1970; Niedrauer and Martin, 1979; Lewis and Perkin, 1986). This results in the formation of a brine channel skeletal feature (Tucker *et al.*, 1984) in which brine saltier and coldier than sea water moves downward under convective forces. Changes in the distribution and concentration of salt in sea ice are controlled by phase equilibrium requirements, which dictate that any change in the temperature of the ice must be accompanied by freezing or melting on the walls of brine pockets or channels, leading to reductions or enlargments of brine channels (Gow and Tucker III, 1990; Perovich and Gow, 1991).

On the underside of the ice, melt water or brine fluxes associated with temperature changes contribute to stabilize or mix the upper boundary layer. During the freezing process, the brine rejected from the ice induces penetrative convection and contributes to vertical mixing of the surface layer (Lewis and Walker, 1970; Lake and Lewis, 1972; McPhee and Smith, 1976). In contrast, the melt process, with production of fresh water, acts to suppress vertical displacements of fluid and increase stratification immediately under the ice (Turner, 1973; McPhee, 1981). In a same way, melt rates will strongly depend on the boundary layer dynamics (Mellor *et al.*, 1986; Svensson and Omstedt, 1990). The development of a melt-water viscous sublayer, in which most of the salinity gradient occurs (Steele *et al.*, 1989), will reduce exchanges between the ice and the underlying water. It must be pointed out that the viscous sublayer always exists; however, for most of the physical and biological applications, it will be considered when its influence is measurable. In the present study, we consider small-scale processes at the roughness element length scale *i.e.* processes which may induce changes in the small region of northern seas where most of the primary production occurs (Cota and Horne, 1989; Grossi *et al.*, 1987).

MATERIAL AND METHODS

Our sampling station was located about 24 km offshore of the Great Whale River mouth, seaward of the large bra-

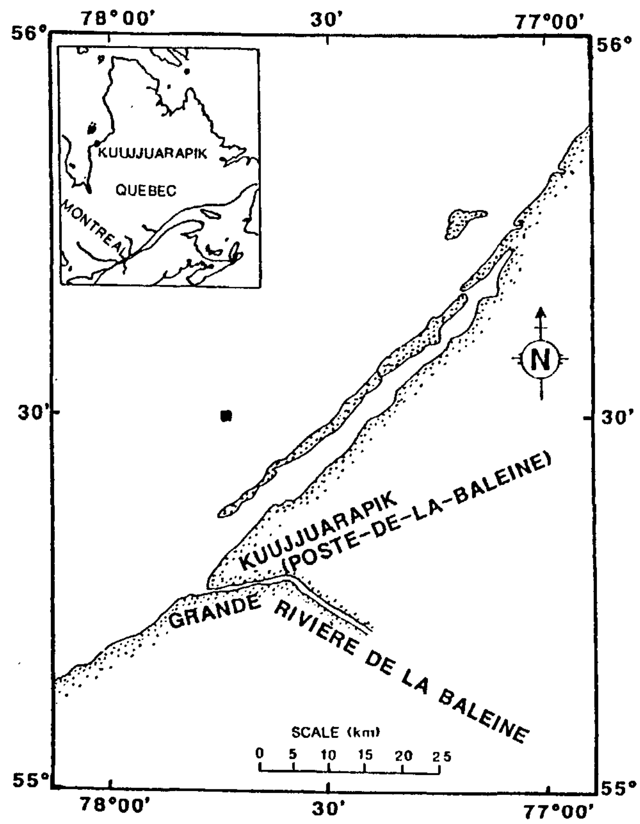

Figure 1

Map of sampling area showing station location (solid square) in southeastern Hudson Bay.

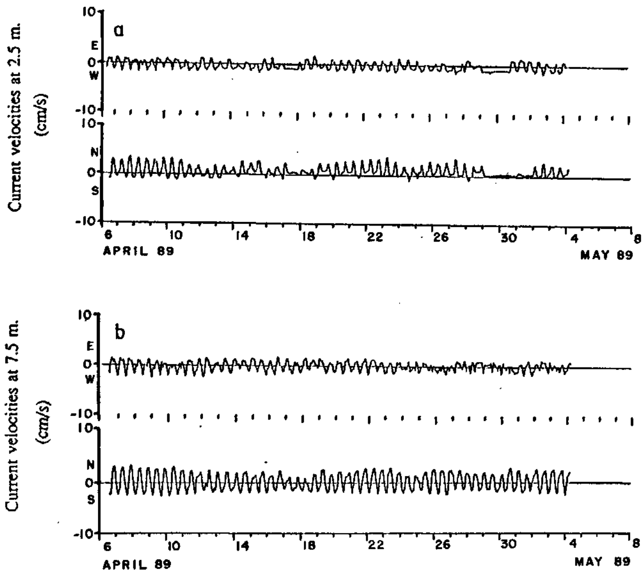

Figure 2

Hourly (decimated) values of North-South and East-West current velocities at depths of 2.5 (a) and 7.5 m (b) below the ice.

ckish plume formed under the continuous sea-ice cover (Fig. 1). No near-surface pycnocline associated with the plume was found during our sampling period from 6 April to 4 May 1989, although the water column is far from homogeneous at larger (> 5 m) vertical scales. Water temperature, salinity, current velocity and direction were recorded every 10 min using Aanderaa current meters moored from the stationary ice sheet at 2.5 and 7.5 m below the ice-water interface (Fig. 2).

From 25 April to 4 May, water temperature and conductivity were recorded every 5 min at 1 and 20 cm below the ice-water interface using Applied Microsystems mini-probes. At a depth of 1 cm below the ice the probes were initially enveloped by ice growth, indicating that the melt had not yet started. Figure 3 shows the salinity fluctuations versus the current velocity (1.1 cm/s corresponds to the stall speed of the Aanderaa RCM4).

Water samples were taken twice daily at 0+, 5, 10, 15, 20 and 30 cm from the ice-water interface. Zero plus (0+) indicates a sample pumped through a tubing laying on the underside of the ice. Sampling was done during one low and one high tide each day. Figure 4 shows nutrient concentrations as a function of depth during the period of the melt initiation. These samples were filtered and frozen within one hour of sampling for later determination of inorganic nutrients ($NO_2 + NO_3$, PO_4, and $Si(OH)_4$) using a Technicon autoanalyser (Strickland and Parsons, 1972; Demers *et al.*, 1989). We are aware of possible bias due the determination of silicic acid from frozen samples. However, we may anticipate that differences of concentration between ice, brine and under-ice surface water should be large enough to make fluxes apparent on silicic acid profiles. The small sampling device, using syringes, was designed to avoid mixing of the under-ice water layers. We used a removable system which was set into position a minimum of 5 hours prior to each new sampling in order to allow the water column to return to equilibrium.

In the present analysis, we shall focus on the period of the melt initiation. Discussions will deal with data recorded from 25 April to 4 May. Because of intermittent generator problems, some intervals of missing data occured.

RESULTS AND DISCUSSION

The Boundary layer structure

Fluxes of nutrient and other scalar properties depend on the magnitude of eddy diffusivity and thus on the strength of current regime (Cota *et al.*, 1987). Fortnightly variations in nutrient concentration have been mentioned previously in the literature (Gosselin *et al.*, 1985; Ingram *et al.*, 1989). Although short in duration, the present study allows us to describe the influence of the neap tide – spring tide changes on the interfacial boundary layer characteristics over the short period of melt initiation.

Overall, near-surface currents at the study site were weak throughout the sampling period. A comparison of under-ice velocities (Fig. 2) at 2.5 and 7.5 m shows noticeable changes of the current regime. While ebb and flood currents were essentially symmetrical at 7.5 m, only the ebb (northward component of the current) was measurable at 2.5 m. It created a flow regime charaterized by a 6-hour stall period. This suggests that our station was probably located within the region under the sheltering influence of a pressure ridge keel. After Arya (1975), that region may extend over a distance ranging between 10 to 15 times the keel height. If we consider the first apparent ridge upstream of the study site during the flow, a 5-metre keel could explain our results. Despite the fact that for the

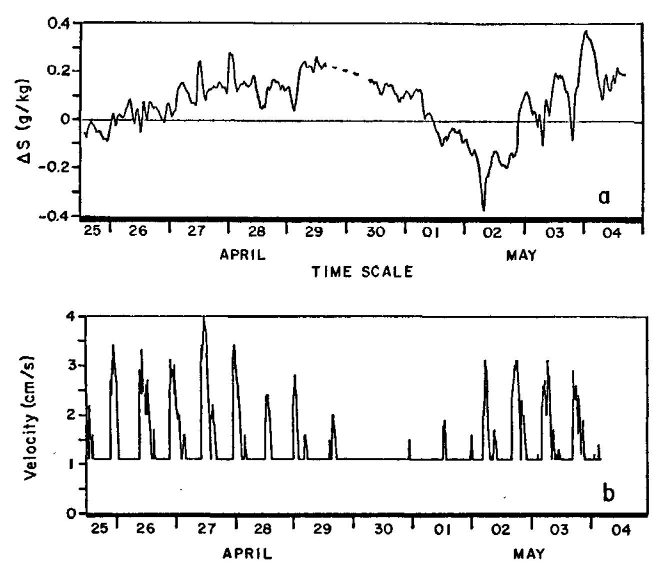

Figure 3

Salinity fluctuations (a), and current velocity (b) at respectively 20 cm and 2.5 m below the ice-water interface. 1.1 cm/s corresponds to the stall speed of Aanderaa RCM4 current meters.

observed sail height, less than a metre, such a keel was not anticipated, this value is not unexpected in that part of the Hudson Bay.

Large salinity fluctuations (Fig. 3*a*) at a depth of 20 cm were observed in phase with changes in the tidal current regime (Fig. 3*b*). These data may be separated into three distinct periods:

– On 27, 28 and 29 April, each current velocity increase was associated with a positive or negative salinity pulse. The short duration of these event suggests the mixing of a limited quantity of brine or melt water in the upper boundary layer. Prior to these observations, data show a series of minor pulses in no particular relation to the current regime. The change of sign of salinity pulses is the most important feature on that part of the records. It indicates a change in the salinity of the bottom-ice brine and in turn the onset of melt. On the other hand, positive pulses demonstrate the dissipation of a brine "layer". Brine being unstable on the underside of the ice, this suggests that turbulent processes may induce exchanges between the bottom-ice layer and the upper water column.

– During the following four days, when current values fell below about 2 cm/s, the salinity time series showed a net decrease. This was the only time interval with a negative salt trend. This confirms the beginning of the melt and shows the rapid development of a buoyant melt layer under low velocity currents (Mellor and Kantha, 1989; Steele *et al.*, 1989).

– After the near-zero current velocities period, the increase of the mean salinity and nutrient concentrations (fourth section of the discussion) demonstrated an upward flux of salt by eddy diffusion. This confirms the importance of the fortnightly cycle in the supply of nutrients just below the ice-water interface (Gosselin *et al.*, 1985; Demers *et al.*, 1989). During low tidal velocity periods, nutrient profiles show the development of a strong stratification within the first 10 cm. This is confirmed by salinity fluctuations which suggest the periodic development and dissipation of a melt layer. This adds further credibility to our hypothesis of development of a melt-water viscous sublayer, which is unstable for currents > 2 cm/s. Furthermore, it indicates that the shadowing influence of pressure ridge keels, which reduced the tidal signal to its only ebb component, strongly influence the structure of the under-ice upper boundary layer and, consequently, the melt rate. The occurrence of a 6-hour stall period with each tide permits the periodic development of the melt layer. We expect this to result in a higher melt rate in the central areas of ice plates where stall periods are shorter than in the part of the plate subject to the shadow-ing influence of pressure ridge keels.

We realize that the Aanderaa instruments used in this study are operating at the lower end of their useful velocity range and that the exact threshold velocity may differ somewhat. However, the velocity data were consistent over the sampling interval and indicate a value within ±1 cm/s of that determined above.

The melt process

There are two kinds of ice-water interfaces: the underside of the sea-ice sheet and the walls of each brine channel or pocket inside the ice (Niedrauer and Martin, 1979; Gow and Tucker III, 1990). At the beginning of spring, ice cores showed obstructed brine channels allowing no penetration of sea water under the effect of hydrostatic pressure (Aota *et al.*, 1988, and pers. comm.). In contrast, cores in late April showed rapid sea-water infiltration, demonstrating the possibility of vertical exchanges through the ice. In addition, prior to the initial decrease in under-ice salinities, typically associated with melting, an increase of salinity and nutrient concentrations was measured at the interface, 27-28 April (Fig. 3 and 5).

As the sea-ice sheet warms up, phase equilibrium requirements (Fujino *et al.*, 1974) induce a melt on the walls of brine pockets, an increase in brine volume and a decrease in brine concentration. This enlargement of brine channels causes a channelization of the brine (Gow and Tucker III, 1990) which may explain the observed positive salinity pulses on Figure 3. A brine layer being unstable on the underside of the ice, our data suggest that a fraction of the bottom-ice brine could be pumped, producing pulse-like increase and later decrease of salinity at the beginning of each ebb (Fig. 3). This indicates that mixing processes may cause exchanges between the bottom of the ice and the upper water column.

As the ice warming continues, the decrease in the temperature gradient in the ice reduces brine concentration gradients and in turn convective exchanges. The change of sign of salinity pulses (Fig. 3) reveals an inversion of the salinity gradient across the ice-water interface which suggests the end of gravity drainage. However, nutrient concentrations profiles show, at the interface, higher concentrations for silicic acid until 3 May (Fig. 5) and lower concentrations for all three nutrients only after 3 May (Fig. 4). This indicates the continuation of a drainage process at least until 3 May. Measurements of nutrient content in brine channels during our field experiment showed very high concentrations twice (for N and P) to four times (for Si) greater than the under-ice surface water mean concentration (nitrates + nitrites 10.4; phosphates 4.1, and silicic acid 42.7 mmol/m^3) (Legendre *et al.*, 1991). This type of gravity drainage or flushing, which drains out of the ice diluted low-salinity brine, occurs due to the hydrostatic head produced by surface melt-water (Weeks and Ackley, 1982).

Nutrient flushing during melt initiation

Phosphate, nitrate + nitrite and silicic acid concentrations showed coherent organized vertical structure only on 28 April and at the end of the field experiment on 3 and 4 May.

On 28 April, we observed maximimum concentrations at the interface. This observation is consistent with the hypothesis of brine rejection at the beginning of the melt. Why this pattern disappeared on phosphate and nitrate + nitrite profiles after 28 April is probably a function of the difference of concentration in surface water and brine which is higher for Si than for N and P (Legendre *et al.*, 1991).

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