SEA ICE CHARACTERISTICS, NUTRIENT DYNAMICS AND COMMUNITY STRUCTURE AND COMPOSITION OF ICE BIOTA FROM GULF OF ST.LAWRENCE, MAGDALEN ISLANDS AREA.

by

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Abstract

Sea ice characteristics were studied in relation to nutrient dynamics, biomass and community structure and composition of ice biota from the Gulf of St.Lawrence at landfast and drifting ice stations in the Magdalen Islands area. The instability of the ice substrate was demonstrated with respect to short duration of cover (8 weeks), ice melt and rafting processes.

The study of nutrient dynamics in ice and in seawater suggests silicates and nitrogen (NO_2+NO_3+NH_4) limitation at landfast ice stations, as well as in situ regeneration of phosphorus in the bottom ice sections. No correlation was found between microalgal biomass and nutrients, but specific growth rates were in the lower range of values reported for Arctic ice algae.

The composition of the microalgal ice biota revealed two types of communities. The first type was composed of a majority of pennate diatoms (abundance >98%), with dominant species such as Nitzschia cylindrus, N. polaris and Navicula karriana, similar to Arctic landfast ice biota communities. The second type was composed of a high percentage of centric diatoms (abundance >46%) due to the abundance of the planktonic diatom Thalassiosira nordenskioldii. Community structure and composition are discussed with respect to the instability of the ice substrate, and the comparison between

landfast and drifting pack ice.

Résumé

Les caratéristiques de la glace du golfe Saint-Laurent ont été étudiées en relation avec la dynamique des sels nutritifs, la biomasse ainsi que la structure et la composition des communautés des biocénoses de la glace, à des stations de glace côtière et de glace de dérive dans la région des Iles de la Madeleine. L'instabilité du substrat de la glace a été démontré en fonction de la courte durée de la saison des glaces, de la fonte et des processus de chevauchement des glaces.

L'étude de la dynamique des sels nutritifs dans la glace et dans l'eau de mer suggère que les silicates et les formes azotées (NO_2+NO_3+NH_4) sont limitants dans les stations côtières, et qu'il y a régénération in situ des phosphates dans les strates inférieures de la glace. Il n'existe cependant aucune corrélation entre la biomasse des microalgues de la glace et les concentrations de sels nutritifs, et les taux de croissance spécifique sont de l'ordre de grandeur des taux les plus faibles observés pour les régions arctiques.

La composition des microalgues des biotopes de la glace a révélé l'existence de deux types de communautés. Le premier type était composé en majorité de diatomées pennées (abondance >98%), avec les espèces dominantes Nitzschia cylindrus, N. polaris and Navicula kariana, semblables aux

communautés des biocénoses des glaces côtières dans les régions arctiques. Le deuxième type de communauté était composé d'un pourcentage élevé de diatomées centriques (abondance >46%) due à l'abondance de l'espèce planctonique Thalassiosira norderskiöldii. La structure et la composition des communautés sont analysées en fonction de l'instabilité du substrat de la glace, et en comparaison entre les glaces côtières et les glaces de dérive.

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Finally, I would like to express my love to my two children, Martin and Gabrielle.

PREFACE

1.) Statement of Originality:

This study presents the first comprehensive investigation of ice biota from the Gulf of St.Lawrence. Its originality lies in the incorporation of sea ice characteristics, nutrient dynamics and community structure and composition of ice biota on a spatial and a temporal scale, and in a comparative framework for landfast and drifting pack ice. It is the first time that sea ice brine volume and residence time of seawater in brine channels are estimated, providing useful information on living conditions within the brine cells. It is also the first extensive study on nutrient dynamics in ice and in sea water demonstrating nutrient limitation particularly for landfast ice biota in Gulf of St.Lawrence, Magdalen Islands area. But the instability of the ice substrate is suggested as limiting factor of ice biota production. Relationship between species composition of ice biota and ice types, i.e. landfast and drifting pack ice is suggested for the first time. Each manuscript represents a significant contribution to scientific knowledge, and collectively the three manuscripts provide a comprehensive data base for future ice biota studies.

2.) Historical background of previously relevant work:

An extensive historical background can be found in the General Introduction, and in the Introduction and text of each chapter.

3.) Declaration of assistance:

The candidate acknowledges the contribution of Dr. M.J. Dunbar for his supervision, guidance and advice rendered during the study, his financial support and critical review of the thesis. Dr. M.J. Dunbar will appear as co-author on future manuscripts from the thesis. In accordance with Section 7 of the Thesis Guidelines, the candidate declares that the study design, field and laboratory work, data analyses and interpretation, and writing of the manuscripts was done by the candidate alone.

4.) Thesis format:

In accordance with Section 7 of the Thesis Guidelines, this thesis has been prepared as a series of manuscripts suitable for submission to refereed scientific journals for publication. For this reason, each chapter contains its own Abstract, Introduction, Materials ans Methods, Results, Discussion and Conclusions, Literature cited, and understandably certain amount of repetition. The present

thesis format has been approved by the thesis committee and by the Chairman of the Department.

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CHAPTER III. Ice biota from the Gulf of St.Lawrence, Magdalen islands area. Part III. Community structure and composition.

General Introduction

The present study was initiated in order to elucidate some of the puzzling questions raised by Dunbar and Acreman (1980) and Demers et al. (1984) who found that biomass of ice algae from the Gulf of St.Lawrence (latitude 45°-50°N), based on chlorophyll a measurements, was one to two orders of magnitude less than at higher latitudes (>60°N). They also reported that centric diatoms in the drifting pack ice in the Gulf of St.Lawrence comprised 43% of the ice biota as compared to less than 4% in Arctic ice communities. Similar results were reported by Demers et al. (1984) for drifting pack ice communities from the St.Lawrence Estuary. Differences in biomass between the two ice regimes of high and low latitudes, as well as differences in systematic composition of the ice floras, were attributed to the duration of the ice cover which lasts only from two to three months in the Gulf of St.Lawrence as opposed to 8 months or more in the Arctic. According to Dunbar and Acreman (1980, p.70): "In the Arctic and Antarctic, the ice forms a more or less permanent upper solid substrate, ecologically comparable with the sea floor, in fact a "ceiling", which has allowed the evolution of a substrate community, analogous to the benthos. The benthic diatoms have taken over the Arctic biotope in a mannner which has not been possible in the Gulf of St.Lawrence, where ice lasts only from January to early

May". Differences in systematic composition of the ice flora were also attributed to higher underice light intensities in the Gulf of St.Lawrence, resulting from thinner ice and increased light levels at lower latitudes. Higher underice light conditions were suggested to favour planktonic, i.e. centric diatoms, over shade-adapted pennate diatoms (Dunbar and Acreman, 1980; Demers et al., 1984). Planktonic algae are indeed better adapted to higher light intensities than ice or benthic algae which are photoinhibited at irradiances thirteen times lower than for planktonic algae (Rivkin and Putt, 1987).

The importance and interest of ice biota as primary production contributors in Arctic and Antarctic regions has been put forward in a number of studies, summarized in Horner's (1985) comprehensive book titled "Sea Ice Biota". One hypothesis suggested to explain enhanced biomass production at the ice-seawater interface is that ice acts as an aquatic "ergocline" defined as a spatial interface between "stable" ice conditions and "unstable" seawater conditions bringing an input of auxiliary energy necessary for ice algal blooms (Legendre and Demers, 1985). According to Reeburgh (1984), elevated ice biota production and biomass result from short residence time of sea water in bottom ice skeletal layer (2-6 hours), where the bulk of the production occurs. This is further supported by the fact that the skeletal layer, which occupies the bottom 10-30 cm of ice, is in

direct contact with the underlying seawater (Weeks, 1976), and that seawater was demonstrated to be the largest source of nutrient supply to ice biota (Cota et al., 1987). The extreme degree of photoadaptation found by Cota (1985) and Rivkin and Putt (1987) for Arctic and Antarctic ice algae, which are actually considered as an obligate shade flora genetically constrained to very low photon flux, is also thought to contribute to the success of their development in ice.

With respect to species composition of ice biota, numerous studies from both polar regions have demonstrated that pennate diatoms are the most abundant group of algae found in ice (Horner, 1985). This is particularly true for Arctic and Antarctic landfast ice studies, where pennate diatoms can contribute more than 90% of the species abundance (Burkholder and Mandelli, 1965; Meguro et al., 1967; Whittaker, 1977; Grainger and Hsiao, 1982; Horner and Schrader, 1982; Pett et al. 1983; Rymes, 1986). On the basis of abundance of pennate diatoms, ice biota communities have been considered as analogous to benthic communities (Dunbar and Acreman, 1980). There is, however, no species correlation between the benthic and the ice diatom flora, except for predominance of pennate diatoms (Horner, 1985). The majority of pennate ice diatoms seem to be typical cryophiles found only in association with ice (Usachev, 1949). In landfast ice from polar regions, centric diatoms are rarely dominant,

although more centric species are reported from the Antarctic where the presence of an underice frazil layer might provide a more favorable habitat for the growth of planktonic species (Horner, 1985). However, there are numerous records from drifting pack ice studies of centric diatoms as dominant species of ice biota communities (Vanhoffen, 1893, 1897; Gran, 1897; Meister, 1930; Hart, 1942; Usachev, 1949; Mel'nikov, 1980). These result suggest a relationship between ice origin, i.e. landfast or drifting pack ice, and species composition dominated either by pennate or centric diatoms. On the basis of similar findings by Sutherland (1852), Apollonio (1985) had even suggested the existence of a drifting pack ice flora ecologically distinct from the landfast ice flora.

The aim of the present study is to test the hypothesis that 1) shorter duration of ice cover in the Gulf of St.Lawrence is responsible for the lower biomass of ice biota communities there than farther north, and that 2) shorter duration of ice cover coupled with higher underice light intensities at lower than higher latitudes favour centric over pennate diatoms.

In chapter I, sea ice characteristics from the Gulf of St.Lawrence are determined for landfast and drifting pack ice, in comparison with sea ice characteristics from higher latitudes and in relation to the stability of the ice subtrate and the microbrine environment as possible limiting

factors of the ice biota biomass. Chapter II deals with nutrient dynamics in ice and in seawater, in relation to the three sources of nutrient supply to ice algae, namely desalination, in-situ regeneration and seawater nutrient supply (Meguro et al., 1967). Nutrients and light are seen as ultimately limiting ice flora. Chapter III is concerned with the structure and composition of the ice biota communities as indicators of the stability of the ice communities, and with the determination of species composition with respect to variables associated with ice origin (landfast and drifting pack ice) and latitude.

Literature Cited

Apollonio, S. 1985. Arctic marine phototropic systems: functions of sea ice stabilization. Arctic 38: 167-173.

Burkholder, P.R. and E.F. Mandelli. 1965. Productivity of microalgae in Antarctic sea ice. Science 149: 872-874.

Cota, G.F. 1985. Photoadaptation of high Arctic ice algae. Nature 315:219-222.

Cota, G.F., S.J. Prinsenberg, E.B. Bennett, J.W. Loder, M.R. Lewis, J.L. Anning, N.H.F. Watson and L.R. Harris. 1987. Nutrient fluxes during extended blooms of Arctic ice algae. J. Geophys. Res. 92: 1951-1962.

Demers, S., J.C. Therriault et C. Descolas-Gros. 1984. Biomasse et composition spécifique de la microflore des glaces saisonnières: influence de la lumière et de la vitesse de congélation. Marine Biol. 48: 185-191.

Dunbar, M.J. and J.C Acreman. 1980. Standing crop and species composition of diatoms in sea ice from Robeson Channel to the Gulf of St.Lawrence. Ophelia 19: 61-72.

Grainger, E.H. and S.I.C. Hsiao. 1982. A study of the ice biota of Frobisher Bay, Baffin Island, 1979-1981. Can. MS. Rep. Fish. Aquat. Sci. 1647: 1-128.

Gran, H.H. 1897. Bacillariophyceae von Kleinen Karajakfijord. Bibliotheca Bot. 42: 13-24.

Gran, H.H. 1904. Diatomaceae from the ice-floes and plankton of the Arctic Ocean. Sci. Res. Norw. N. Polar Exped. 4: 3-74

Hart, T.J. 1942. Phytoplankton periodicity in Antarctic surface waters. Discovery Rep. 21: 261-365.

Hooker, J.D. 1847. The Botany of the Antarctic Voyage of H.M. Discovery ships "Erebus" and "Terror" in the years 1839-1843. In Vol. I. Flora Antarctica, pp. 503-519. Reprinted 1963, J. Cramer, Weinhein.

Horner, R.A. and G.C. Schrader. 1981. Beaufort Sea plankton studies: winter-spring studies in Stefansson Sound and off Narwhal Island, Nov.1978- Jun.1980. Final Report to Outer Continental Shelf Environmental Assessment Program, 138pp.

Horner, R.A. 1985. Sea Ice Biota. CRC Press Inc. Boca Raton, Florida, 203pp.

Legendre, L. and S. Demers. 1985. Auxiliary energy, ergoclines and aquatic biological production. Naturaliste Can. 112: 5-14.

Meguro, H., I. Kuniyuki and H. Fukushima. 1967. Ice flora (Bottom type): a mechanism of primary production in Polar seas and the growth of diatoms in sea ice. Arctic 20: 114-133.

Meister, F. 1930. Mission du "Pourquoi-Pas" en 1929 sous le commandement du Dr. J.-B. Charcot. Diatomées récoltées par R.Ph. Dollfus sur une glace flottante. Bull. Mus. Nat. Hist. Ser. 2:329.

Mel'nikov, I.A. 1980. The ecosystem of Arctic pack ice. In Vinogradov, M.E. and Mel'nikov (Eds.): Biology of the Central Arctic Basin. Moscow: 61-96. (Canadian Translation Fisheries and Aquatic Sci. No 4909)

Pett, R.J., G.P. Vickers, J.C. Acreman and A.G. Ethier. 1983. A seasonal study of the epontic and planktonic communities near the Issungnak artificial island and McKinley Bay in the Canadian Beaufort Sea. Arctic Laboratories Ltd. D.S.S. Contract no. IS281-00026. 64pp.

Reeburgh, W.S. 1984. Fluxes associated with brine motion in growing sea ice. Polar Biol. 3: 29-33.

Rivkin, R.B. and M. Putt. 1987. Photosynthesis and cell division by Antarctic microalgae: comparison of benthic, planktonic and ice algae. J. Phycol. 23: 223-229.

Rymes, C. 1986. An investigation of temporal and spatial variation of ice diatoms and associated meiofauna in Eclipse Sound, Baffin Island. M.Sc. Thesis. McGill University, 183pp.

Sutherland, C.P. 1852. Journal of a voyage in Baffin's Bay and Barrow Straits, in the years 1850-1851 performed by H.M. ships "Lady Franklin" and "Sophia", under the commands of Mr. William Penny, in search of the missing crews of H.M. ships "Erebus" and "Terror". Longman, Brown, Green and Longmans, London. Vol. 1 and 2.

Usachev, P.I. 1938. Biological analysis of ice-floes. Compt. Rend. (Dokl.) Acad. Sci. URSS 19: 645-648.

Usachev, P.I. 1949. The microflora of Arctic ice. (In Russian). Tr. Inst. Okeanol. Akad. Nauk. SSSR 3:216-259.

Vanhöffen, E. 1893. Frühlingsleben in Nordgrönland. Verh. Ges. Erdk. Berl. (cited from Gran, 1904).

Vanhöffen, E. 1897. Fauna and Flora Grönlands, Grönland-Exped. Ges. Erdk. Berl. (cited from Gran, 1904).

Whittaker, T.M. 1977. Sea ice habitats of Signy Islands (South Orkneys) and their primary productivity. In Llano, G.A. (Ed.): Adaptations within Antarctic ecosystems, pp. 75-82. Proceedings of the 3rd SCAR symposium on Antarctic Biology, Smithsonian Institute, Washington.

CHAPTER I

ICE BIOTA FROM THE GULF OF ST.LAWRENCE, MAGDALEN ISLANDS AREA.

PART I: SEA ICE CHARACTERISTICS.

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Abstract

Sea ice characteristics were studied at six landfast ice stations and one drifting ice station in the Magdalen Islands area, Gulf of St.Lawrence. Ice coverage lasted for a maximum of 8 weeks, from mid-February till the second week of April. Average ice thickness was 54.6 cm in February and 40.8 cm in March. Ice desalination rates were similar to those of Arctic ice in the first week of ice formation, with a 78% decrease in salinity, but further desalination rates were more rapid, with ice salinity down to ≤2.0°/oo associated with flushing and ice melt. However, salinity of the liquid brine, estimated from percent brine volumes, gave values ranging from 2.0 to 85.0°/oo in the first part of March, and values close to underice seawater salinity (20-38°/oo) in the latter part of March. Residence time of seawater in brine channels above the skeletal layer was estimated at 3-24 hrs for minimum ice thickness and brine volume, and at 2-18 days for maximum ice thickness and brine volume. The instability of the ice substrate is considered with respect to short duration of ice cover, ice melt and rafting processes and in relation to lower biomass in the Gulf of St.Lawrence as compared to Arctic ice biota. Longer residence time of sea water in the upper ice is suggested as a limiting factor for the development of ice biota above the skeletal layer.

INTRODUCTION

In a comparative study of ice biota from different latitudes, Dunbar and Acreman (1980) found that algal biomass of ice biota from the Gulf of St.Lawrence drifting pack ice was one to two orders of magnitude less than for landfast Arctic ice communities. Similar results were reported by Demers et al. (1984) from the St.Lawrence Estuary. Short duration of ice coverage was suggested as the responsible factor for the reduced biomass. In order to further understand the controlling mechanism of ice biota production in the Gulf of St.Lawrence, and as part of a comprehensive study of ice biota communities from lower latitudes, sea ice characteristics of landfast and drifting pack ice were determined, in comparison with Arctic ice characteristics and with a view to defining the living conditions for ice biota within the ice habitat for the skeletal layer and the upper ice.

The Gulf of St.Lawrence is the most southerly region of the northern hemisphere where sea ice is normally found. Ice in the Gulf never develops beyond first year stage and has a maximum thickness of 100 cm (Dunbar and Acreman, 1980). Ice starts to form in sheltered areas in December, increasing rapidly in January and February to the point that virtually the whole sea surface is covered by the beginning of March. Ice dispersal and melting starts in April, proceeding

generally from west to east. The two main types of ice found in the Gulf are landfast ice and drifting pack ice. Landfast ice may be formed in situ from sea water or it may result from drifting pack ice being pushed to shore. Landfast ice is generally stable, subjected to limited vertical displacements, particularly in the Magdalen islands area where maximum tidal amplitude is only 0.91m (Auclair, 1977), and is therefore well suited for temporal studies of ice biota. Drifting pack ice, also referred to as "ice floes", originates from three main sources in the Gulf: Labrador ice from the North drifting through the Strait of Belle Isle, ice from the St.Lawrence River and Estuary, and ice formed within the Gulf itself (Matheson, 1967). Drifting ice is subjected to rapid movement (1.2cm/sec: Ingram, 1973) and intense deformation during the winter months, due to frequent high winds (Owens and McCann, 1980) and strong currents (Campbell et al., 1977). In the Gulf of St.Lawrence, prevailing winter winds are from the northwest and dominant Gulf ice drift motion is in a southeast direction through Cabot Strait (Ingram, 1967). Apart from regular reports on ice coverage, ice types and thickness, issued by the Ice Forecasting Centre in Ottawa, there is little information available on sea ice characteristics from the Gulf of St.Lawrence. Salinity and ice thickness were reported for drifting ice floes in the St.Lawrence Estuary by Demers et al. (1984) and in the Gulf of St.Lawrence by Dunbar and Weeks (1975) and Dunbar and

Acreman (1980).

Salinity is an important characteristic of sea ice, particularly in relation to the development of ice biota. It is generally measured by the melted ice core technique. Sea ice salinity results from trapping and concentration of salts in brine cells during the formation of pure ice crystals as sea water freezes (Pounder, 1965). In the early phase of ice formation, very dense brine concentrations can be found. Lewis and Milne (1977) report salinities of 68 °/oo in liquid brine. The initial freezing period is followed by a rapid decrease in salinity. At Eclipse Sound (Nakawo and Shina, 1981), ice salinity of 25 °/oo during the initial stages of freezing dropped to 8.5 °/oo within a week of ice formation. After this initial rapid decrease, salinity of Arctic ice attains quasi-stable values which then decrease slowly throughout the season, down to around 10% of the original seawater salinity by the end of the first growth season (Grainger, 1977). The dominant mechanism responsible for removing salts from growing sea ice is through gravity drainage (Weeks and Ackley, 1982). Gravity drainage implies a downward movement of brine due to density differences between concentrated liquid brine in the ice and the underlying seawater. Flushing, a particular type of gravity drainage, is the most effective ice desalination mechanism. However, it can only occur in cases of surface ice melt and is therefore most important at lower latitudes where air temperatures can

rise above the freezing point during winter, or in the Arctic during the spring ice melt (Weeks and Ackley, 1958).

Determination of ice salinity by the melted ice core technique gives only diluted salinity concentrations. In order to determine the actual salinity to which the ice algae are exposed in the ice, it is necessary to determine the salinity within the brine cells. This can be done by estimating the brine volume of the ice. Brine volume is defined as the volume occupied by liquid brine with respect to solid ice (Anderson and Weeks, 1977). It results from a complex thermodynamic balance between the solid pure ice phase and the concentrated liquid brine solution. Brine volume is a function of salinity and ice temperature, both of which vary with time and ice thickness. Therefore, brine volume is expected to vary, especially at lower latitudes where ice is thinner and where air temperature can rise above the freezing point. Brine volume fluctuations will also influence salinity and nutrient concentrations of the liquid brine and consequently the ice biota bathing in it.

In order to determine the living conditions of ice biota within the ice, it is necessary to define the ice habitat and the dynamic processes associated with it. On the basis of brine cell features and circulation, sea ice can be regarded as two separate systems: the skeletal layer which occupies the bottom 10 to 30 mm of ice, and the upper ice layer. A number of small and large scale brine cell features

have been described in the upper ice layer of congelation ice. Small scale features comprise brine pockets with a radius of less than 35 µm (Hoesktra et al., 1965) defined as bubbles of brine surrounded by ice that has either limited or no communication with other brine masses. Brine tubes are also important small scale features with diameters of 0.1 to 0.4 mm and lengths of 20 to 30 cm (Lake and Lewis, 1970). According to Niedrauer and Martin (1979), 10% of ice consists of brine in small tubes and Lake and Lewis (1970) report a density of 42 tubes per cm^2. Brine tubes are radially connected to larger brine channels like the branches of a tree. Large scale features include those brine channels which are large vertical cylinders with diameters up to 7 mm and lengths of up to 90 cm in ice 1.6 m thick (Lake and Lewis, 1970). They reach densities of 54 channels per meter square and are probably the primary drainage sites in natural sea ice. The skeletal layer system is defined by Assur in Weeks and Anderson (1958) as a strengthless layer of unconnected vertical ice platelets, located at the bottom of the ice. The skeletal layer is 10 to 30 mm thick and it is in this layer that the bulk of ice biota biomass is found. Ice platelets are not bridged by ice in this layer, contrary to the upper ice, and the skeletal layer is therefore in direct contact with the underlying seawater.

In the upper ice layer above the skeletal layer, water circulates mainly through brine channels. It was initially

thought that brine channels were fed by the network of small brine tubes which surround them. However, Niedrauer and Martin (1979), in a dye experiment, recorded very high water velocities in brine channels (0.25 mm/sec) and very low velocities in brine tubes (5.5 μm/sec). They concluded that low brine velocities found in brine tubes could not account for the high velocities found in the brine channels, and that such high velocities were due to convective replacement of outflowing liquid brine by seawater entering the ice. Convection could not occur in brine tubes which have a radius smaller than 0.4 mm. A convective model for brine channel circulation was proposed with a bi-directional flow where incoming sea water occupied the top portion and outflowing brine occupied the bottom portion in slightly sloping channels. Other models with oscillatory convective motion have been proposed (Martin 1970). Water circulation is different in the skeletal layer from that of the upper ice since the skeletal layer is in direct contact with the underlying seawater. Temperature fluctuations were taken as evidence of convective circulation (Lake and Lewis, 1970) and Niedrauer and Martin (1979) showed that sea water advances up the skeletal layer on a series of broad fronts and exits in discrete plumes separated by about 10 cm and extending down to the ice-interface. Fluxes through the skeletal layer are rapid, about the same magnitude as those across sediment-water interfaces, and residence time is short, in

the range of 2 to 6 hours (Reeburg, 1984).

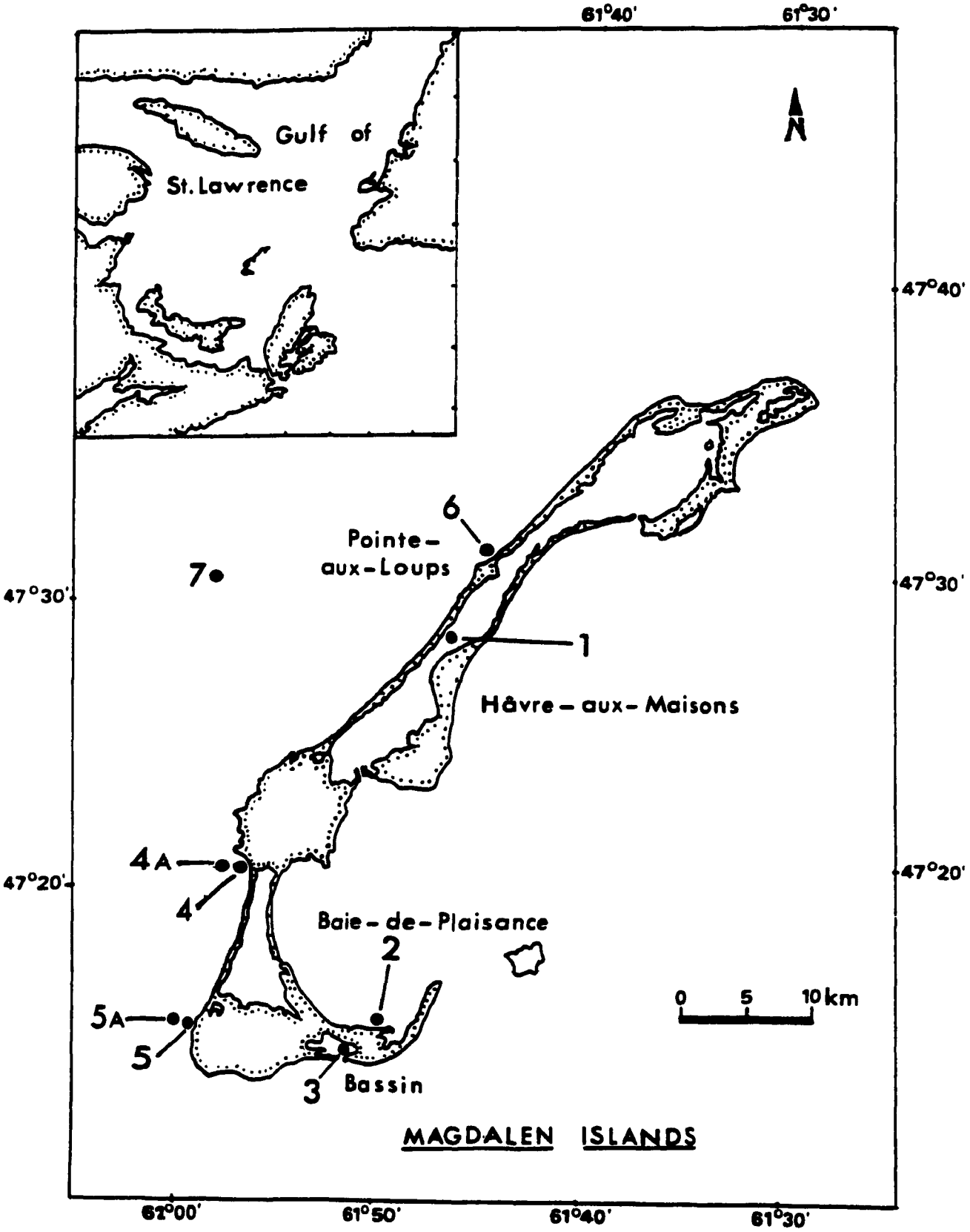
A study of sea ice characteristics from the Gulf of St.Lawrence was undertaken, in consideration of the Dunbar and Acreman (1980) and Demers et al. (1984) results on ice biota communities from drifting pack ice in the Estuary and the Gulf of St.Lawrence. The aim of this study was to define sea ice characteristics and to determine the possible controlling factors of ice biota production in the Gulf of St.Lawrence. Sea ice characteristics were therefore studied for landfast and drifting pack ice, in relation to the living conditions of ice biota within the ice, and in comparison with Arctic sea ice characteristics. Observed ice thickness was compared to theoretical estimations to account for phenomena such as ridging (piling up of one sheet of ice on another), and for comparison between landfast and drifting ice. Salinity profiles and desalination rates were determined for first year ice growth and compared to Arctic regimes. Brine volumes were estimated from ice temperature and salinity data to determine their fluctuations with time and their effects on salinity concentrations of the liquid brine within the brine cells. Residence time of sea water in the upper ice was calculated for the first time and compared to the residence time in the skeletal layer in relation to circulation processes and ice biota production in the two systems.

MATERIALS and METHODS

Study Sites

The Magdalen Islands Archipelago is located in the centre of the Gulf of St.Lawrence, latitude 47° to 48° North and longitude 61° to 62° West. The location of the six landfast ice stations (1 to 6) and of the drifting ice station (7) is illustrated in Figure 1. Stations 1 and 3, located in Havre-aux-Maisons and at Bassin, are the most protected from winds and drifting ice effects. Station 2, located on the eastern coast, is exposed to the northwest winds and to occasional piling up of ice in the Baie de Plaisance. Landfast ice was often surrounded by open water at that station. Stations 4 and 5, located on the western side, are exposed in winter to prevailing northwesterly winds and to southeast drifting ice floes coming from the Gulf of St.Lawrence. At these two stations, ice was sampled mid-way between the shore and the edge of the landfast ice (Stations 4 and 5), as well as at the ice edge (Stations 4A and 5A), the boundary between landfast ice and drifting pack ice. Station 6, on the northwestern side at Pointe-aux-Loups, is the most exposed to winds and drifting ice. Station 7, located approximately 20 km west of Pointe-aux-Loups, is the drifting pack ice station which was used for comparison to landfast ice stations.

FIGURE 1. Map of the Magdalen Islands, Gulf of St.Lawrence. Sampling stations are designated by numbers 1 to 6 for landfast ice stations and by number 7 for the drifting ice station. Stations 4A and 5A are located at the landfast ice edge.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61°30'
Gulf of
St. Lawrence
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6
Pointe-
aux-Loups
7
47°30'
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Hâvre-aux-Maisons
4A
47°20'
47°20'
4
Baie-de-Plaisance
2
0 5 10 km
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Bassin
MAGDALEN ISLANDS
62°00'
61°50'
61°40'
61°30'

Sampling Procedure and Analysis

Sampling Method

Seawater was sampled at stations 1, 4, 5 and 6 in January of 1979, before ice formation. Landfast ice began to form in early February, but sampling of the ice only started at the end of February when the ice was thick enough to safely walk on. From that period on, ice and water samples were collected every two weeks at stations 1 to 6. Ice and seawater were sampled only twice at station 7 by helicopter. Ice samples were collected with a SIPRE ice corer of 7.5 cm diameter. Ice thickness was measured and the cores were cut into 20 cm sections, starting from the bottom of the ice core where the skeletal layer is found. Seawater was sampled by pumping underice water through holes made by the ice corer. Ice temperature was measured by thermistor probes in the bottom and mid-ice sections at station 1. Thickness of the snow cover and depth of the water column were also noted for each station. Seawater and ice samples were brought back to Environment Canada's laboratory at Cape-aux-Meules where salinity was determined, after melting of the ice cores, with an Autosal model 8400A salinometer.

Ice Thickness

Ice thickness was estimated for the Gulf of St.Lawrence using Maykut's thermodynamic model of ice growth (Maykut

1978, 1982). For thin ice (<0.8 m), defined as ice that responds rapidly enough to thermal forcing to maintain an essentially linear temperature profile, growth rate at the bottom of the ice was obtained from the following equation (Maykut 1982):

$$\rho_i L_f \frac{dH}{dt_H} = \tau(T_f - T_o) + (0.124H^{0.28} - 0.26) \cdot F_r e^{-1.5(H-0.1)} - F_{wo}$$

where ρ_i = 900 kgm^{-3}, average density of sea ice

L_f = 0.3348×10^6 Jkg^{-1}, latent heat of fusion of ice

H = ice thickness

τ = $k_i k_s / (k_s H + k_i h)$, the thermal conductance of the ice-snow slab

k_i = 2.034 $W(m^oK)^{-1}$, conductivity of sea ice

k_s = 0.3097 $W(m^oK)^{-1}$, conductivity of snow

h = snow depth

T_f = 271.35°K, freezing point of seawater, 32°/oo

T^o = surface temperature of the ice, °K

F_r = incident short wave radiation in $MJm^{-2}month^{-1}$

F_w = 2 Wm^{-2}, oceanic heat flux beneath the ice

Brine Volume

Since salinity of liquid brine and brine volumes are in equilibrium with ambient ice temperature, the total volume of brine (V_b) is the product of those two variables. V_b can therefore be linearized as a function of $1/\theta$ and S_i, using

the empirical equation developed by Frankenstein and Garner, given in Weeks and Ackley (1967):

$$V_b = \frac{S_i}{10^3}\left(\frac{-49.185}{\theta}\right) + 0.532$$

where θ = ice temperature, °C

S_i = salinity of layer i, expressed in parts per thousand.

Brine volumes were estimated using salinity values determined by the melted ice core technique for the different ice sections, and ice temperature obtained from the in situ thermistor probes for mid-ice and bottom ice sections at station 1. For other stations and other collecting dates, ice temperature was calculated using the following equation from Nakawo and Shina (1981):

$$G_i = \frac{Tm - Ta}{h_i}$$

where G_i = temperature gradient in °C/cm

Ta = air temperature °C

T_m = melting point of ice, corresponding to -1.8°C for sea water of 32°/oo salinity.

h_i = ice thickness in cm

Residence Time

In the upper ice, above the skeletal layer, water circulates mainly through brine channels by convective motion of concentrated brine which drains out of the ice and is replaced by entering sea water. Brine channel fluxes at the ice-seawater interface were obtained from field measurements made by Wakatsuchi (1977) and Wakatsuchi and Ono (1983) on growing sea ice. The fluxes used, and reported in Reeburgh (1984), are the following:

Brine channel fluxes (cc cm^{-2} s^{-1})	References
3.18×10^{-5} to 3.74×10^{-6}	Wakatsuchi 1977
6.3×10^{-6} to 3.4×10^{-5}	Wakatsuchi and Ono 1983

Using these fluxes at the ice sea-water interface, and having determined brine and ice volume, water residence time in brine channels can be calculated from the following equation:

$$\text{Residence time (sec)} = \frac{V_i \text{ (cc } cm^{-2}) \times V_b \text{ (\%)}}{\text{Flux (cc } cm^{-2} \; s^{-1})}$$

where V_i (ice volume) = H (ice thickness) x 1 cm^2.

Statistical Analysis

To determine statistical differences in the various environmental variables of ice and seawater among the stations sampled, the Statistical Analysis System (SAS) package was used in all data analyses (Ray, 1982a,b). All linear model statistics, such as analysis of variance (ANOVA), make the assumption that the underlying population from which the sample data are drawn is normally distributed. To test this assumption, the Shapiro-Wilk, W, statistic and probability plot were computed for all environmental data sets using the Univariate procedure in the SAS system (Ray, 1982b); the Fmax test (Zar, 1984) was used to test the homogeneity of variance assumption. Appropriate transformations were applied to data sets, when necessary, as suggested by Box et al. (1978). A single factor analysis of variance (ANOVA) was carried out to test the null hypothesis H_o: there are no differences in variables among stations (or among seawater and ice sections at the same station) against an alternate H_1: there are differences in variables among stations, or among seawater and ice sections. Where parametric ANOVA rejected the null hypothesis, a specific among stations (or among seawater and ice sections at the same station) comparison of means (at the P=0.05 level), for each of the variables was carried out using the Student-Newman-Keuls (SNK) multiple range test.

RESULTS

Ice Thickness and Snow Cover

Snow coverage rarely exceeded 1 cm in thickness, except at station 6 on March 1st when snow accumulation of up to 20 cm was noted. The ice was often free of snow, due to low precipitation and strong and frequent winds that prevail during the winter months in the Magdalen Islands area.

Landfast and drifting ice were composed mainly of congelation ice, being frozen solid from the top to the bottom. Slush ice was found at the bottom of the ice, namely at station 6 and on some occasions at stations 2, 4A and 5A when ice thickness exceeded 60 cm. Slush ice was also noted at the surface of the ice at all stations during the second week of March when air temperatures rose above the freezing point, causing the melting of surface ice.

Results on ice thickness measurements (Table 1) indicate highest thickness at station 6 with a mean of 76.2 cm, and lowest thickness at station 7 with a mean of 41.1 cm. However, data analysis demonstrated statistically significant differences for station 6 only (Table 2). Vertical profiles of ice thickness versus time (Fig. 2) indicate similar profiles at stations 1, 3, 4, 5 and 7, with ice thickness of about 60 cm in February and beginning of March, followed by a decrease to about 40 cm at the end of March. Different

Table 1. Results of depth, ice thickness and salinity for bottom ice section (B) and sea water (W) at stations 1 to 7 (fig.1). Variables are presented as means with standard deviation in parentheses and number of samples.

VARIABLES		STATIONS								
		1	2	3	4	4A	5	5A	6	7
Depth (m)		8.9	3.0	3.2	3.4	4.4	4.1	6.0	5.1	14.0
Ice thickness (cm)		51.6	55.3	50.0	49.9	57.2	42.9	53.7	76.2	41.1
		(7.3)	(18.9)	(9.4)	(11.5)	(26.4)	(8.7)	(19.4)	(33.5)	(5.5)
		4	5	5	6	3	5	2	4	2
Salinity (°/oo)	B	1.52	2.20	1.27	3.51	2.28	1.74	5.88	6.00	3.26
		(0.67)	(2.64)	(2.42)	(2.86)	(3.10)	(2.28)	(2.21)	(4.26)	(2.58)
		6	6	7	8	3	8	2	6	4
	W	26.51	30.04	23.72	26.43	28.69	28.99	31.10	22.30	31.75
		(3.15)	(1.09)	(12.78)	(9.61)	(2.14)	(3.30)	(2.07)	(11.58)	(8.31)
		10	9	9	12	3	11	2	9	4

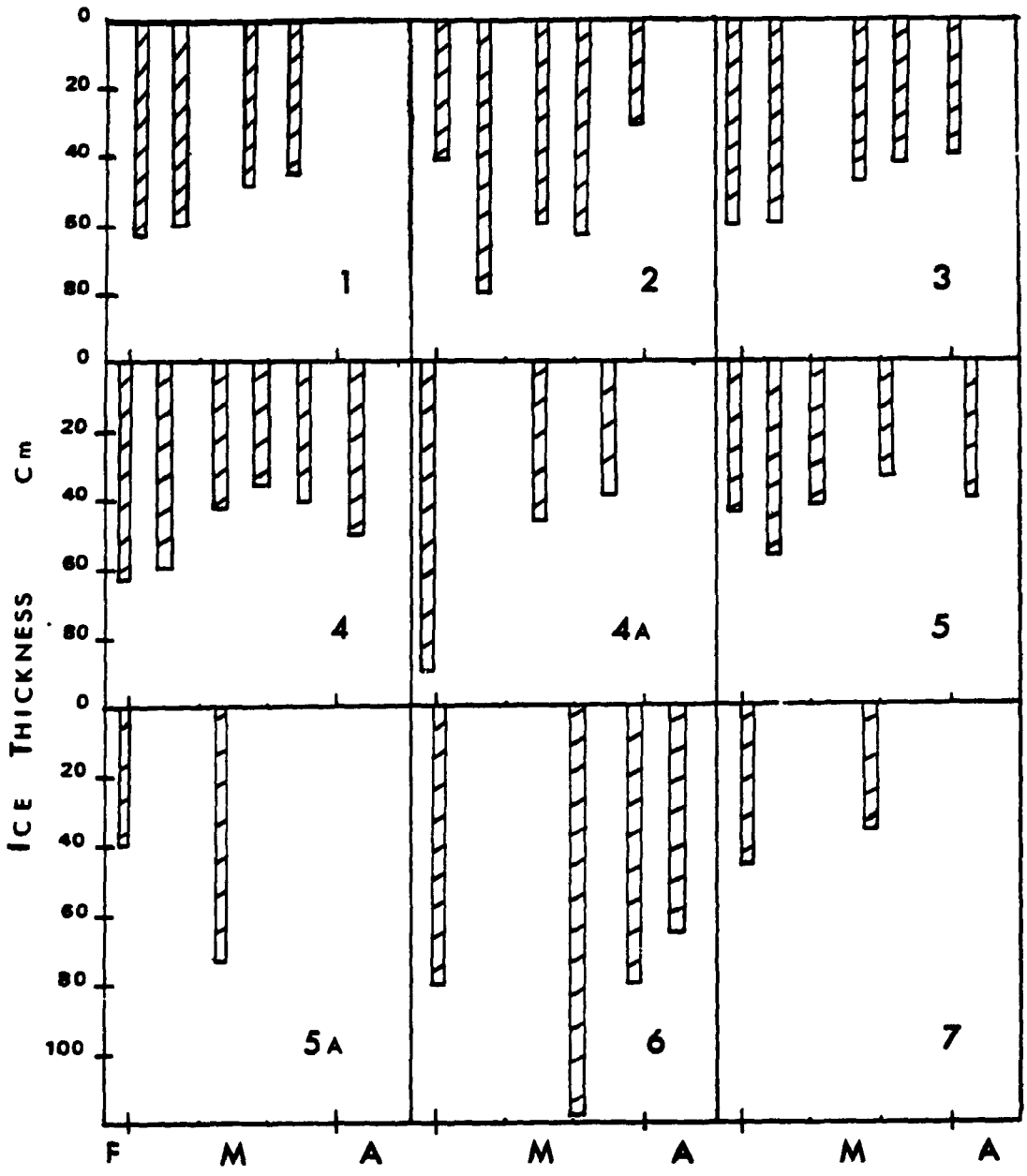
Table 2. Parametric Student-Newmen-Keuls test for significant ($P<0.05$) statistical differences among station means for ice thickness and salinity of surface ice section (1), bottom ice section (B) and seawater (W). Groupings with same letters are not significantly different.

VARIABLES		STATIONS								
		1	2	3	4	4A	5	5A	6	7
Ice thickness (cm)		b	b	bc	bc	b	c	b	a	c
Salinity (°/oo)	1	a	a	a	a	a	a	a	a	a
	B	a	a	a	a	a	a	a	a	a
	W	a	a	a	a	a	a	a	a	a

Table 3. Parametric Student-Newman-Keuls test for significant ($P<0.05$) statistical differences among surface ice section (1), bottom ice section (B) and seawater (W) salinity means for stations 1 to 7. Groupings with same letters are not significantly different.

VARIABLES		STATIONS								
		1	2	3	4	4A	5	5A	6	7
Salinity (°/oo)	1	b	b	b	b	b	b	b	a	b
	B	b	b	b	b	b	b	b	ab	b
	W	a	a	a	a	a	a	a	a	a

FIGURE 2. Vertical profiles of ice thickness in cm for stations 1 to 7, from February to April.


ICE THICKNESS Cm
0
20
40
60
80
100
1
2
3
4
4A
5
5A
6
7
F
M
A
M
A
M
A

profiles are observed at stations 2, 4A, 5A and 6, with ice thickness greater than 60 cm and up to 120 cm at station 6.

In order to compare observed ice thickness to expected ice thickness, Maykut's thermodynamic model (Maykut, 1982) was used to estimate ice growth. Maykut's model was chosen because it is a general model not restricted to a particular location or season by using sufficient information on thermal forcing, and because very accurate growth calculations can be made from it. Surface ice temperature (T_o) was replaced by air temperature (T_a) in the equation (see Materials and Methods), because of the lack of information on incoming long wave radiation (F_L) and relative humidity (r) used in solving for T_o. Ice growth and total ice thickness were calculated for the month of February, with Fr=226 $MJm^{-2}month^{-1}$, snow thickness h=0.01m, Ta=264.55°K and initial ice thickness at time 0 $(dH/dt)_o$ set at a minimum of 11.0cm:

$$\text{Ice growth} = \frac{dH}{dt}_H = 53.0\text{cm}$$

$$\text{Total ice thickness} = f(H) = (dH/dt)_H + (dH/dt)_o$$

$$= 53.0 + 11.0$$

$$= 64.0\text{cm}$$

For the month of March, Fr=301.33 $MJm^{-2}month^{-1}$, h=0.01m, Ta=270.94°K and $(dH/dt)_o$ = 64.0cm:

$$\text{Ice growth} = -7.0\text{cm}$$

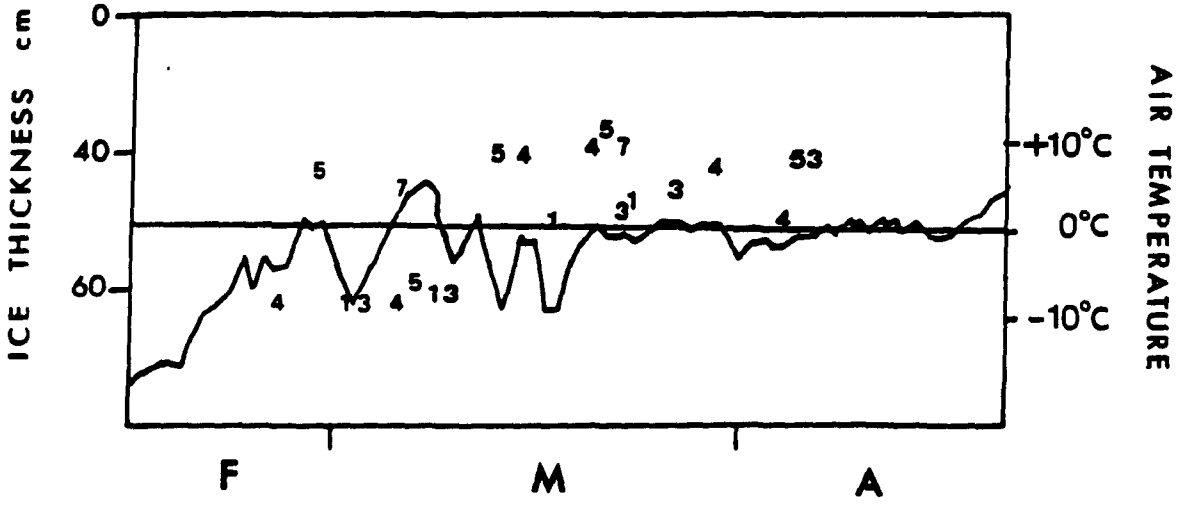
$$\text{Total ice thickness} = -7.0 + 64.0$$

$$= 57.0\text{cm}$$

A comparison of these expected ice thicknesses to the observed values (Fig. 2) indicates that the observed ice thicknesses at stations 2, 4A, 5A, and 6 are often greater than 64.0 cm, the maximum expected from Maykut's equation. Variations in ice thickness within stations, being less than 3.2%, could not account for ice thicknesses a third to nearly double the expected ice thickness. Therefore, processes other than natural ice growth must be involved at these stations. Rafting, a mechanical process whereby one sheet of ice overrides another, is considered as a possible explanation.

In order to define seasonal trends in ice thickness for the Gulf of St. Lawrence, ice thickness was plotted on a time scale (Fig. 3) excluding stations 2, 4A, 5A and 6, where rafting was suspected. This figure shows that ice thickness was between 40 to 60 cm from February until the second week of March, with an average ice thickness of 54.6 cm. After March 10th, ice thickness decreased to less than 50 cm at all stations with an average of 40.8 cm. The decrease in ice thickness resulted from ice melt following air temperature increases above freezing point on the 5th to the 7th of March, as illustrated in Fig. 3.

FIGURE 3. Plot of air temperature and of ice thickness versus time grouped for stations 1, 3, 4, 5 and 7. Stations where rafting occurred (stations 2, 4A, 5A and 6) were not included.

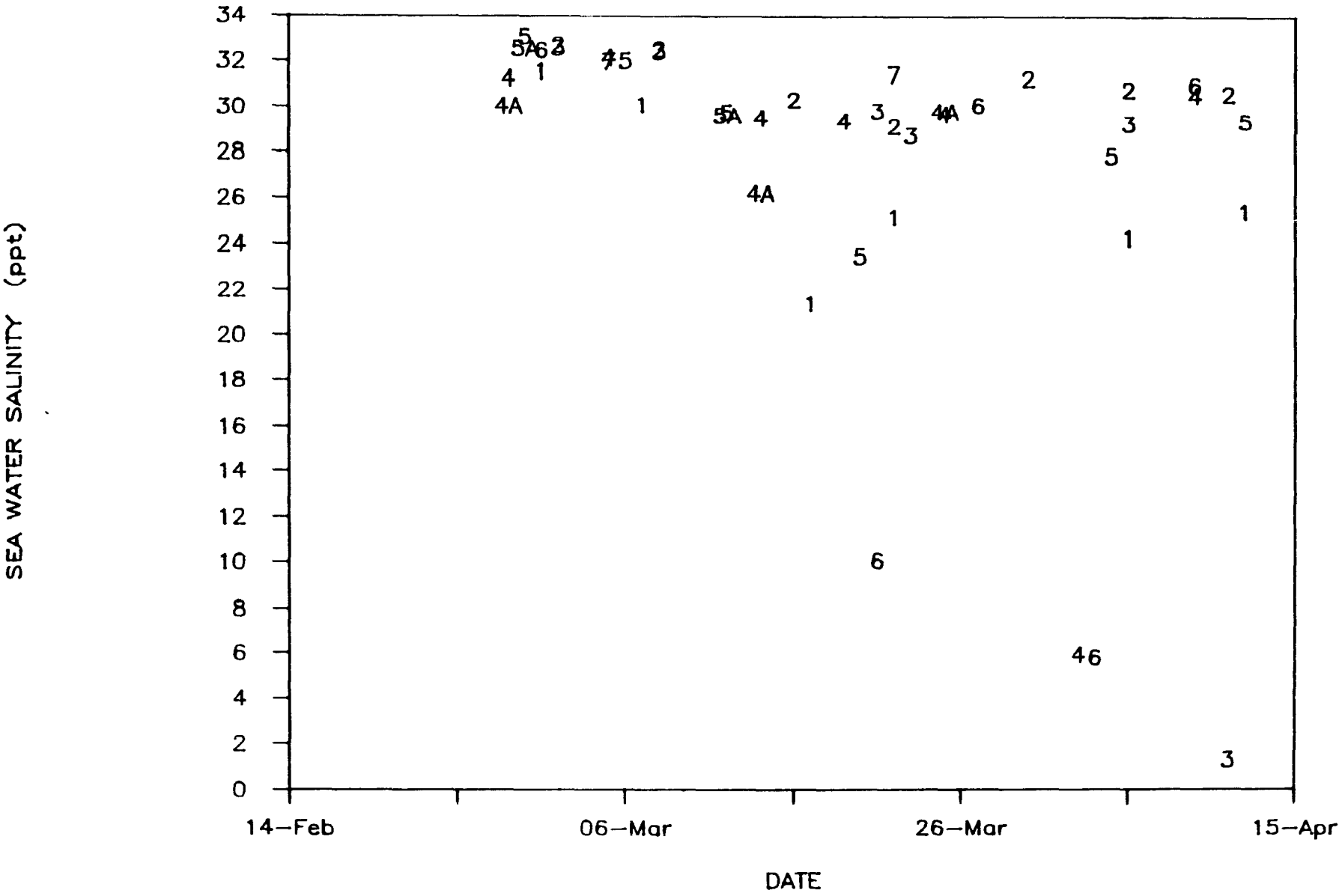

ICE THICKNESS cm
0
40
60
AIR TEMPERATURE
+10°C
0°C
-10°C
F
M
A

Salinity

Mean salinity values for sea water and bottom ice are presented in Table 1. Bottom ice salinity ranged from 1.27°/oo to 6.00°/oo, with highest values at stations 5A and 6, while sea water salinities ranged from 22.3°/oo to 31.7°/oo. Salinity values were analyzed statistically using the multiple comparison Student-Newman-Keuls test. The results presented in Table 2 indicate no significant differences among stations for seawater or for bottom ice salinity. The same test was used for comparing surface ice section (1), bottom ice section (B) and seawater (W) salinity for each station (Table 3). The results indicate that seawater salinities are significantly different from ice salinity (surface and bottom ice section) at stations 1 to 5, and at station 7. At station 6, seawater and bottom ice salinities are not significantly different, but surface ice section (1) salinity is significantly different from these two.

Salinity of seawater was plotted on a time scale for all stations (Fig. 4) to analyse seasonal trends. From February until the middle of March, seawater salinity under the ice varied between 25 to 31°/oo. A decrease in salinity is observed after the middle of March, namely at stations 1 and 6 where seawater salinities decrease to less than 10°/oo. Despite some lower salinity values, average seawater salinity

FIGURE 4. Time scale evolution of sea water salinity in parts per thousand (PPT) for stations 1 to 7.


SEA WATER SALINITY (ppt)
34
32
30
28
26
24
22
20
18
16
14
12
10
8
6
4
2
0
14—Feb
06—Mar
26—Mar
15—Apr
DATE

remains fairly high with a mean around 28°/oo throughout ice coverage.

Sea ice salinity was then analyzed for vertical distribution. Vertical profiles of sea ice salinity including surface to bottom ice sections (Fig. 5) do not show any consistent patterns such as C-shaped distribution or a consistent surface to bottom increase. This latter pattern is however observed in a few cases at station 6 when ice thickness is greater than 60cm. A decrease in salinity with time for all ice sections can be observed in Fig. 5.

Desalination rates where then analyzed by plotting salinities of bottom ice sections for all the stations on a time scale (Fig. 6). This figure shows that in February ice salinity ranged between 5 and 8°/oo. A marked decrease in ice salinity occured at the beginning of March, with a continued decrease until mid-March to salinities less than 2°/oo. Desalination rates, computed from Fig. 6, indicate a salt loss of 78% of the original salt content of the ice, after about a week or two of ice formation. By the end of March, only 15% of the salt was left in the ice and less than 0.5% by April. If we consider that the ice starts to form in February, this means that rapid desalination occurs within a week or two of ice formation, down to 6-8°/oo. This pattern is similar to what has been observed in other ice studies. However, later desalination rates are much more rapid in the Gulf than at higher latitudes.

FIGURE 5. Vertical profiles of ice salinity in parts per thousand (°/oo) at stations 1 to 7, for ice sections 20cm thick. The horizontal width (salinity scale) for each profile/sampling date is shown in the upper right hand corner of the figure.

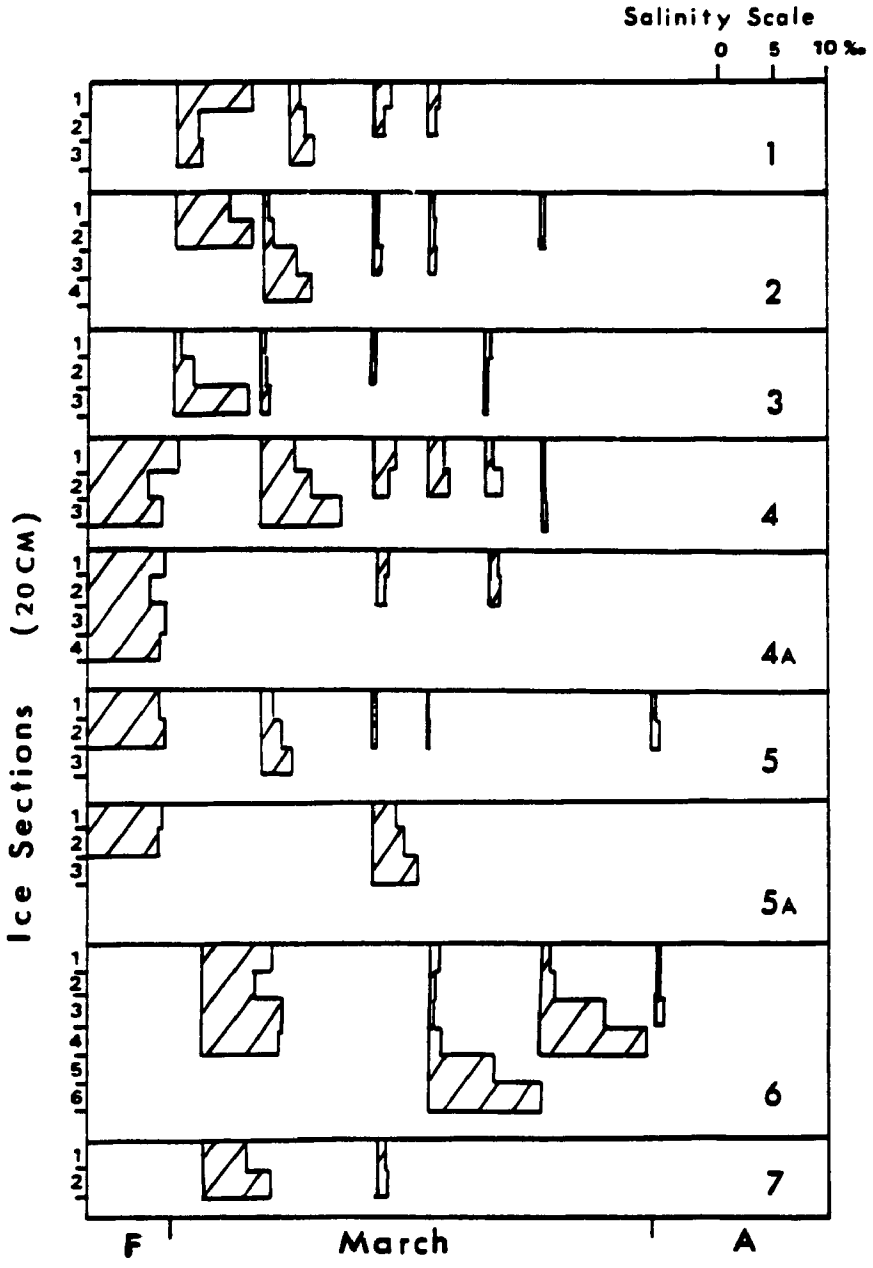
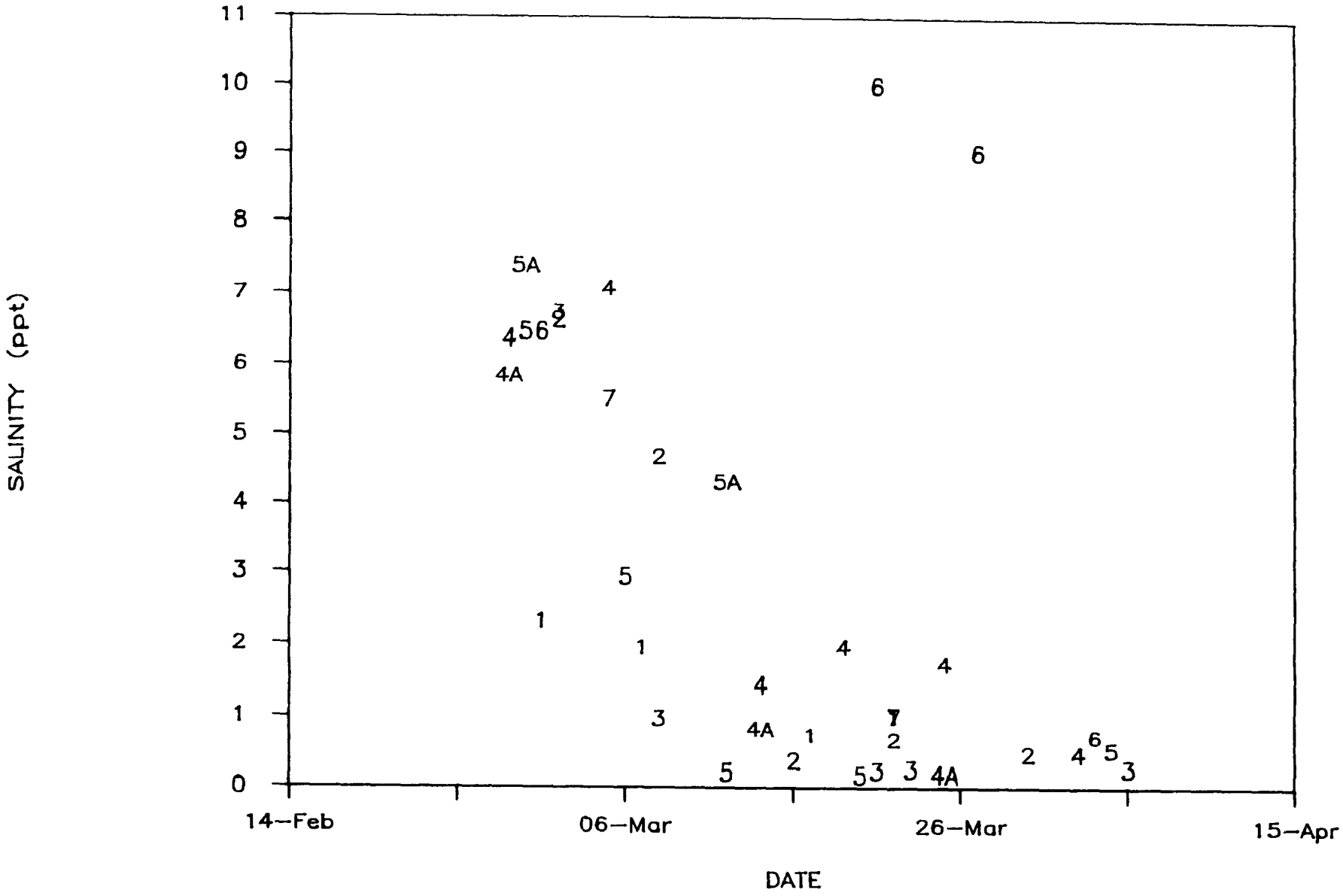

Salinity Scale
0
5
10 ‰
Ice Sections (20 CM)
1
2
3
4
4A
5
5A
6
7
F
March
A

FIGURE 6. Time scale plot of salinity in parts per thousand (PPT) of bottom ice sections for stations 1 to 7.


SALINITY (ppt)
11
10
9
8
7
6
5
4
3
2
1
0
14–Feb
06–Mar
26–Mar
15–Apr
DATE

Brine Volume

Brine volumes were calculated using Frankenstein and Garner's equation (see Introduction). The results are summarized in Figure 7. Brine volumes are expressed as percentage of volume occupied by the liquid brine with respect to the total volume of solid ice. In the first week of March, bottom ice brine volumes generally ranged from 5% to 20%, but there were peaks of 25-45% in late February and 95% on March 6th, coinciding with air temperature rising above the freezing point. After the 10th of March, bottom ice brine volumes decreased to less than 10%, and were down to around 2% and less by the end of March, with few exceptions at stations 4 and 6 again following air temperature increases above the freezing point.

Brine volume determination allowed for calculation of the actual salinity or salt content in the brine cells. Salinity values discussed so far referred to diluted salinities obtained from the melted ice core technique. By dividing these values by the percent brine volume, the actual salinity of the liquid brine can be determined. Results (Fig.8), grouping bottom ice corrected salinities for all stations, show for the first week of March, extremely variable brine salinities with values ranging from 2 to 85°/oo. After the 15th of March, liquid brine salinities are less variable, ranging between 20 to 38°/oo, close to

FIGURE 7. Time scale plot of bottom ice section brine volumes (%), for stations 1 to 7.

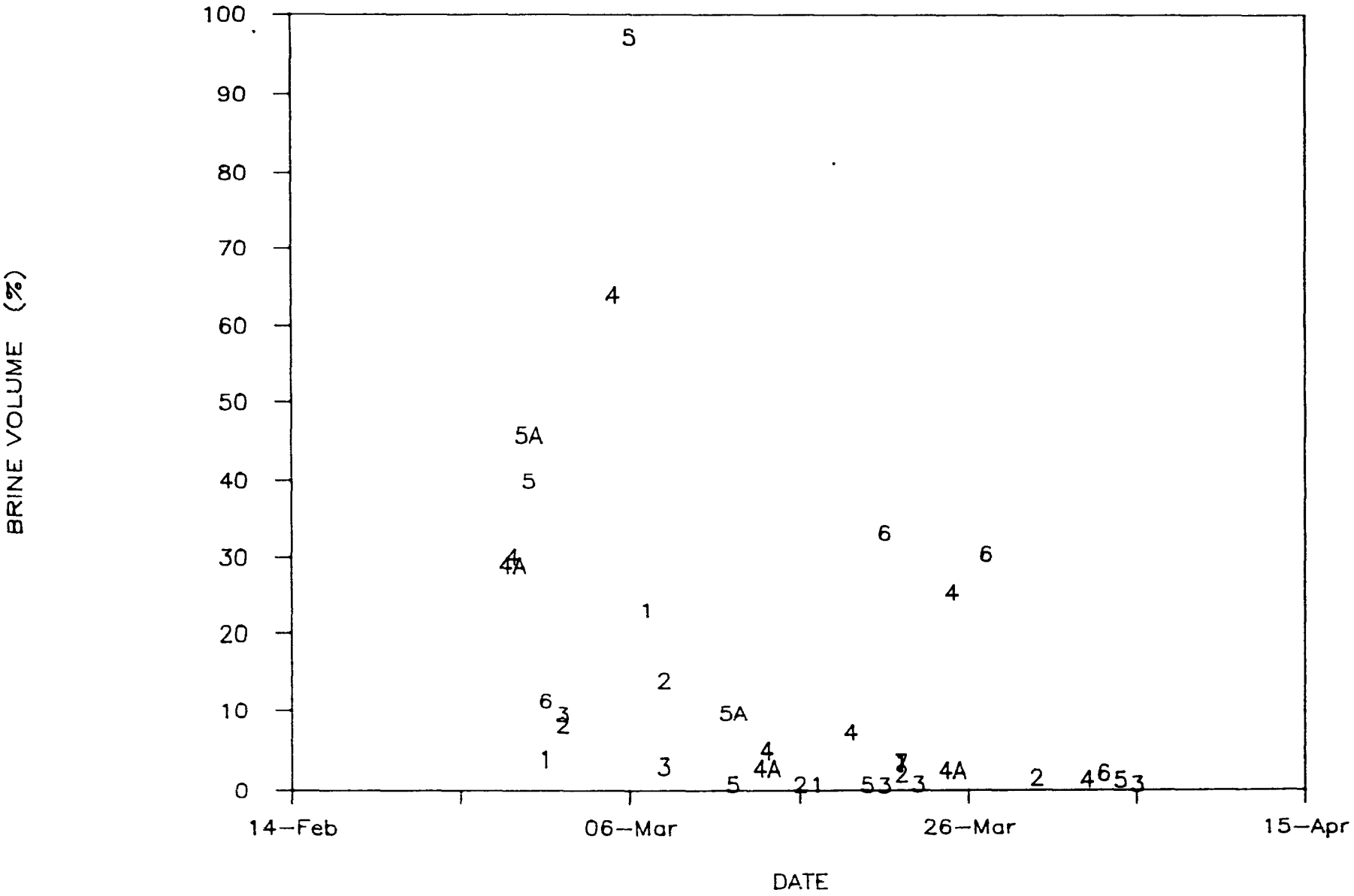
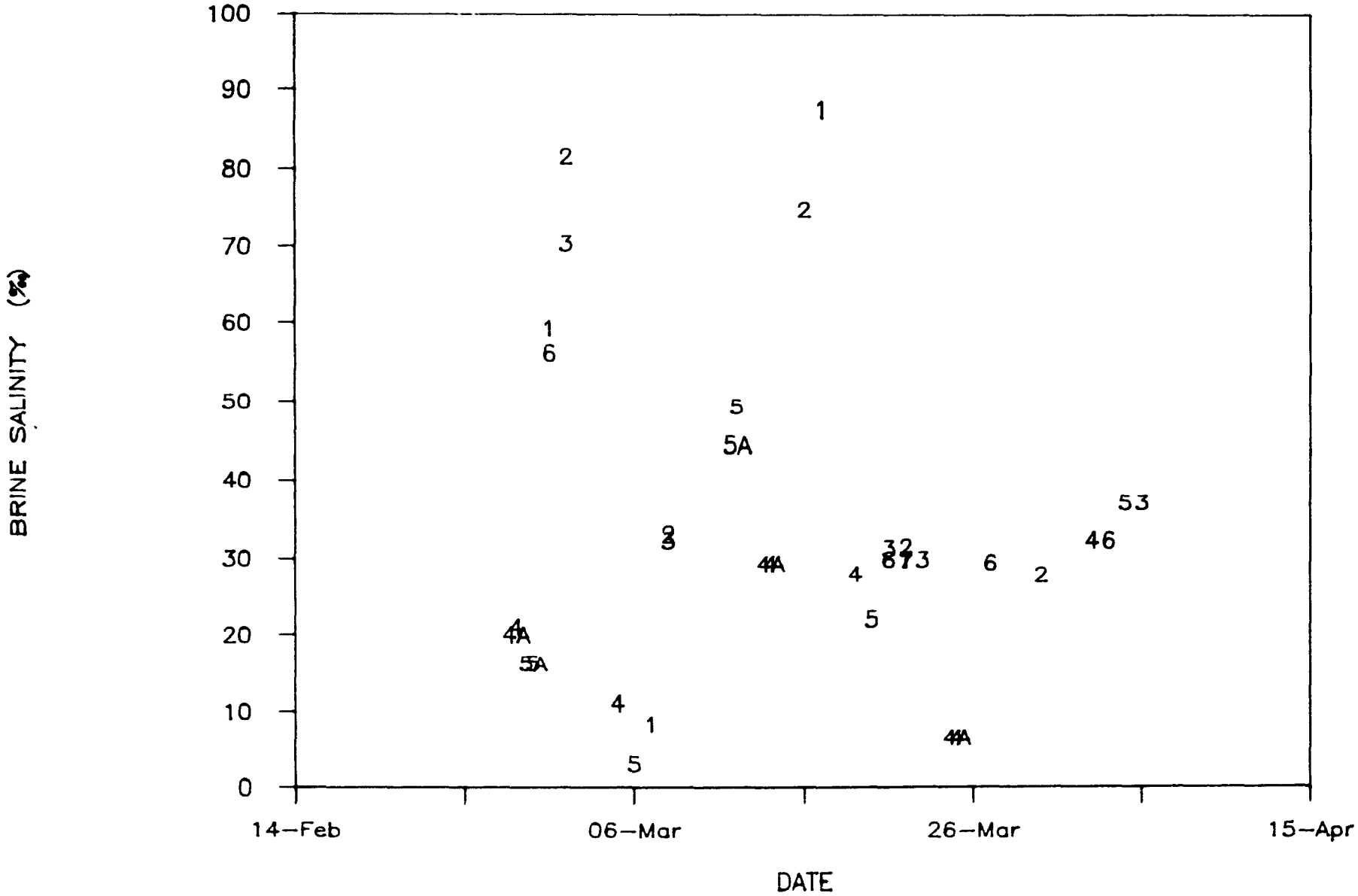

BRINE VOLUME (%)
100
90
80
70
60
50
40
30
20
10
0
14-Feb
06-Mar
26-Mar
15-Apr
DATE

FIGURE 8. Time scale plot of estimated brine salinity of bottom ice sections for stations 1 to 7.


BRINE SALINITY (‰)
100
90
80
70
60
50
40
30
20
10
0
14-Feb
06-Mar
26-Mar
15-Apr
DATE

underice seawater salinity.

Residence Time

Although ice biota is known to be concentrated in the skeletal layer at the bottom of the ice, algal growth also occurs in the upper ice, mainly in brine channels. Residence time of seawater in the skeletal layer has been computed (see Introduction) but there is no such information for brine channels in the upper ice layers. This information is important to know in order to understand the dynamics of seawater circulation in the upper ice layers in relation to ice biota production. As mentioned in the introduction, concentrated brine which is expelled from the ice through brine channels has to be replaced by entering seawater. This has been observed to occur in brine channels by convective replacement of brine by seawater entering the ice (Niedrauer and Martin 1979). Having determined brine volumes (previous section) and using sea ice brine channel fluxes obtained from direct field measurements made by Wakatsuchi (1977) and Wakatsuchi and Ono (1983), it was possible to estimate the residence time of seawater in brine channels. Residence time was calculated for brine volumes of 1% and 10%, and for ice thickness of 40 cm and 60 cm. The results indicate a minimum residence time of 3 to 24 hours for ice 40 cm thick with a brine volume of 1%, and maximum residence time of 2 to 18

days for ice 60 cm thick with a brine volume of 10%.

DISCUSSION and CONCLUSIONS

In 1979 landfast ice started to form around the Magdalen Islands in the first week of February and nearly all the ice had melted by the first week of April, with a total solid ice coverage time of 8 weeks. A maximum ice thickness of 60 cm, resulting from natural ice growth, was found at the end of February and beginning of March, followed by a decrease in ice thickness to around 40 cm in the latter part of March and beginning of April. Dunbar and Weeks (1975) report similar ice thickness of 50 cm for undeformed ice along the south shore of the St.Lawrence estuary. The decrease in ice thickness observed after the first week of March was correlated with air temperature rising above 0°C, causing melting of the surface ice.

Estimation of ice thickness using Maykut's thermodynamic model of ice growth gave an expected ice thickness of 64 cm for February and 57 cm for March. Ice thicknesses greater than these expected values, such as observed at stations 2, 4A, 5A and 6, were considered to have resulted from rafting, especially since ice thickness at these stations was close to double the expected values. Rafting generally occurs in areas subjected to strong winds or drifting ice pressure. All stations where rafting occurred were stations exposed to winds and drifting ice. Station 2, located on the eastern side of the Magdalen Islands, was exposed to the northwest

winds which at times caused piling up of ice in the Baie de Plaisance. Stations 4A and 5A, located at the landfast ice edge and on the western side of the islands, were exposed to prevailing northwesterly winds and to drifting ice floes. Station 6, where the effect of rafting was most apparent, was, by location, the most exposed to winds and drifting ice. Rafting was not observed at stations protected from winds or drifting ice such as station 1 and 3 located in bays, and station 4 and 5 located midway between the shore and the ice edge. Slush ice, present mainly in bottom ice sections, was also associated with rafting since it was found consistently at station 6, and on a few occasions at stations 2, 4A and 5A, when ice was thicker than the maximum expected value for the area. Slush formation resulted from melting of the bottom rafted ice sheet which could not be maintained frozen, the Gulf thermal regime allowing for a maximum expected ice thickness of 64 cm only. Slush ice was also associated with surface ice melt which occurred in the first week of March resulting in a decrease in ice thickness.

With respect to ice thickness, there is evidence that it is less for drifting pack ice (Station 7) than for landfast ice. This is in agreement with Dunbar and Acreman (1980) and Dunbar and Weeks (1975) who reported ice thickness values of 44 cm and 15-20 cm for drifting pack ice in the Gulf of St.Lawrence. Although ice thickness can vary from year to year at different locations, depending on localized thermal

regimes and rafting processes, the results on ice thickness of drifting and landfast ice from the Gulf of St.Lawrence indicate that ice is much thinner than at higher latitudes where it can be of 150 cm or more (Grainger, 1977; Nakawo and Sinha, 1981).

Therefore, in comparison with Arctic ice characteristics, the instability of the ice substrate in the Gulf of St.Lawrence can be demonstrated with respect to short duration of ice coverage, melting and rafting processes. This is an important aspect to consider, especially in relation to ice biota production, since the instability of the ice substrate could account for the limitation of biomass accumulation in the Gulf of St.Lawrence. This aspect, along with thinner ice and resulting higher underice light intensities, will be considered in Chapter II.

Underice seawater salinities show no significant differences between stations nor do they indicate the presence of a brackish layer, such as observed by Legendre et al. (1981) and which has been associated in some studies to underice chlorophyll maximum (Horner 1972). Brackish water with salinity of 5-10°/oo was found in two instances: at station 6 where it resulted from the melting of a rafted ice sheet, and in April at station 1 following the spring snow and ice melt. The absence of a permanent brackish layer is an indication of efficient under ice seawater circulation, even in lagoons and bays (Stations 1 and 3) where one might expect

reduced circulation, especially during ice coverage. This aspect will be considered in relation to nutrient dynamics (Chapt. II).

Average ice salinities (1.52 -6.00°/oo) were in the range of those reported by Dunbar and Acreman (1980) and Demers et al. (1984) for drifting ice from the estuary and the Gulf of St.Lawrence. However, vertical ice salinity profiles did not show a linear increase with depth such as reported by Dunbar and Acreman (1980), or C-shaped profiles such as reported by Dunbar and Weeks (1975). This might be an indication of a difference between drifting and landfast ice. The vertical ice salinity increase, observed at station 6, was again associated with rafting which caused melting of the bottom ice, followed by brine volume enlargement and infiltration of seawater giving bottom ice salinities up to 10°/oo.

Desalination rates indicate that after a week or two of ice formation, ice salinity was down to 5 to 8°/oo, corresponding to a loss of 78% from original seawater salinity. Following this rapid desalination, ice salinity continued to drop rapidly to less than 2%, corresponding to a 15% loss, in a period of two weeks. Initial desalination is generally observed in young sea ice where ice salinity falls to around 8°/oo after a week of ice formation (Nakawo and Sinha, 1981; Weeks and Ackley, 1982). However, at higher latitudes, this rapid desalination is followed by a slow

decrease throughout the growing season: Nakawo and Sinha (1981) report a slow decrease of 0.5% per month at Eclipse sound, in the high Arctic. According to Grainger (1977), salt loss from naturally formed sea ice in the Arctic may be estimated at about 70% of the amount in the original seawater after a week of ice growth, and loss continues subsequently at a rate of about 3 to 4% of the original water content per month, with the content down to around 10% of the original water content by the end of the growing season. Initial rapid desalination results from direct salt rejection of brine at the ice-seawater interface during freezing, but subsequent desalination, at slower rates, is due to gravity drainage, the dominant mechanism by which concentrated brine, under the influence of gravity, drains out of the ice through brine channels. In the Gulf of St.Lawrence, initial desalination rates are similar to those of ice from higher latitudes but subsequent desalination is much more rapid. Flushing is suggested as the mechanism involved in the rapid desalination of ice in the Gulf of St.Lawrence, since rapid desalination coincided with ice melt following air temperature increases above the freezing point, and since flushing only occurs through surface ice melt which provides the necessary pressure head to overcome capillary retention in the brine channels. Flushing is of rare occurrence in Arctic ice, except during the spring thaw period, but there have been reports of rapid desalination rates from Hopedale Labrador

(Weeks and Lee, 1958), that were accounted for by winter thaw periods and associated flushing mechanisms.

Estimation of bottom ice brine volume gave values ranging from 5-20% in the first two weeks of March with peaks of 30% to 95% resulting from temperature increase above freezing point. Following major ice desalination, down to less than 2°/oo, brine volume decreased to less than 10% and was less affected by air temperature variations because of lower ice salinity. A brine volume of 5% was obtained by Lake and Lewis (1970), but Cox and Weeks (1974) estimated, from experimental data, brine volumes greater than 50% . Again, the importance of thaw periods is indicated with respect to the Gulf of St.Lawrence sea ice characteristics, in relation to brine volume variations.As for salinity of the liquid brine, obtained from brine volume estimates, values were much higher than those obtained from the melted ice core technique. In the first week of ice formation, liquid brine salinities were quite variable (2-85°/oo) with highest salinities corresponding to lower brine volume and lowest salinities to highest brine volume. Salinity of liquid brine as high as 68°/oo has been reported for newly formed Arctic ice (Lewis and Milne, 1977). Once the ice has lost more than 78% of its salt content, in the second week of March, liquid brine salinities are similar to the underlying sea water salinities. Reports of direct in situ measures of liquid brine salinities (Alexander et al., 1974; Horner and

Schrader, 1982; Clasby et al., 1976) also give values close to seawater salinity. Such results emphasize the importance of determining the salinity within the liquid brine, since it gives the exact salinity concentrations to which ice algae are exposed in the brine channels. This is the first time that the estimation of brine volume has been used to determine the salinity of liquid brine. This method can also be used for determining other characteristics of the ice habitat such as nutrient concentration within the brine cells. Furthermore, results obtained from this study are in agreement with brine channel circulation patterns whereby concentrated brine leaving the ice through gravity drainage is replaced by entering sea water, resulting in liquid brine salinity similar to underlying sea water salinity. Salinity was thought to be the most important factor limiting the upper extent of the ice algae in sea ice (Meguro et al. (1967). The results indicate that this might be true during the early stages of ice formation when salinity of the liquid brine can be very high, but not later in the ice season.

Based on field measurements of sea ice brine channel volume fluxes, the first estimate of residence time of seawater in brine channels is presented in this study. For the Gulf of St.Lawrence ice conditions, a minimum residence time of 3 to 24 hours was estimated for ice 40 cm thick with a brine volume of 1%, and a maximum residence time of 2 to 18 days for ice 60 cm thick with a brine volume of 10%. These

results indicate that residence time in brine channels is longer than for the skeletal layer, 2-6hrs according to Reeburgh (1984), especially for maximum Gulf ice thickness and brine volumes. This might explain why ice biota production is not as flourishing in the upper ice layers as in the skeletal layer.

Literature Cited

Alexander, V., R. Horner and R.C. Clasby. 1974. Metabolism of Arctic sea ice organisms, Rep. R74-4, 120pp. Inst. of Mar. Sci., Univ. of Alaska, Fairbanks.

Anderson, D.L. and W.F. Weeks. 1958. A theoretical analysis of sea ice strength. Trans. Am. Geophys. Union. 39: 632-640.

Auclair, J.C. 1977. Contribution à l'étude de la production primaire des lagunes des Iles-de-la-Madeleine. Thèse de Doctorat, Université d'Aix-Marseille.

Billelo, M.A., R.E. Bates and J. Riley. 1970. Ice thickness observations along the coast of eastern Canada and southern Greenland. U.S. Army Cold Regions Research and Engineering Laboratory, CRREL Special Report 125: 25p.

Campbell, W.J., R.O. Ramseier, R.J. Weaver and W. Weeks. 1977. Skylab floating ice experiment. Fish. Marine Serv. Publ. 34: 37p.

Clasby, R.C., V. Alexander and R. Horner. 1976. Primary productivity of sea-ice algae. In Hood, D.W. and Burrell, D.C. (Eds.): Assessment of the Arctic Marine Environment: Selected topics, pp. 289-304. Institute of Marine Sciences, University of Alaska, Fairbanks.

Cota, G.F., S.J. Prinsenberg, E.B. Bennett, J.W. Loder, M.R. Lewis, J.L. Anning, N.H.F. Watson and L.R. Harris. 1987. Nutrient fluxes during extended blooms of Arctic ice algae. J. Geophys. Res. 92: 1951-1962.

Cox, G.F.N. and W.F. Weeks. 1974. Salinity variations in sea ice.J. Glaciol. 13: 109-120.

Demers, S., J.C. Therriault et C. Descolas-Gros. 1984. Biomasse et composition spécifique de la microflore des glaces saisonnières: influence de la lumière et de la vitesse de congélation. Marine Biol. 48: 185-191.

Dunbar, M.J. and J.C Acreman. 1980. Standing crop and species composition of diatoms in sea ice from Robeson Channel to the Gulf of St.Lawrence. Ophelia 19: 61-72.

Dunbar, I.M. and W.F. Weeks. 1975. Interpretation of young ice forms in the Gulf of St.Lawrence using side-looking airborne radar and infrared imagery. U.S. Army Cold Regions Research and Engineering Laboratory, CRREL.

Grainger, E.H. 1977. The annual nutrient cycle in sea ice. In Dunbar, M.J. (Ed.): Polar Oceans, pp. 285-301. Arctic Institute of North America, Calgary.

Hoekstra, P., T.E. Osterkamp and W.F. Weeks. 1965. The migration of liquid inclusions in single ice crystals. J. Geophys. Res. 70: 5035-5041.

Horner, R.A. and G.C. Schrader. 1982. Relative contributions of ice algae, phytoplankton and benthic microalgae to primary production in near shore regions of the Beaufort Sea. Arctic 35: 485-503.

Ingram, R.G. 1967. Ice drift motion in the Gulf of St.Lawrence. M.Sc. Thesis, McGill University, 96pp.

Ingram, R.G. 1973. Winter surface current around Cape Breton Island. J. Fish. Res. Board Can. 30:121-123.

Lake, R.A. and E.L. Lewis. 1970. Salt rejection by sea ice during growth. J. Geophys. Res. 75: 583-597.

Legendre, L., R.G. Ingram and M. Poulin. 1981. Physical control of phytoplankton production under sea ice (Manitounouk Sound, Hudson Bay). Can. J. Fish. Aquat. Sci. 38: 1385-1392.

Lewis, E.L. and A.R. Milne. 1977. Underwater sea ice formation. In Dunbar, M.J. (Ed.): Polar Oceans, pp. 239-243. Arctic Institute of North Amarica, Calgary.

Martin, S. 1970. A hydrodynamic curiosity: the salt oscillator. Geophys. Fluid Dynamics 1: 143-160.

Matheson, K.M. 1967. The meteorological effects of ice in the Gulf of St.Lawrence. McGill University, Marine Sciences Centre M.S. Report 3: 110p.

Maykut, G.A. 1978. Energy exchange over young sea ice in the central Arctic. J. Geophys. Res. 83: 3646-3658.

Maykut, G.A. 1982. Large scale heat exchange and ice production in the central Arctic. J. Geophys. Res. 87: 7971-7984.

Meguro, H., I. Kuniyuki and H. Fukushima. 1967. Ice flora (Bottom type): a mechanism of primary production in Polar seas and the growth of diatoms in sea ice. Arctic 20: 114-133.

Nakawo, M. and N.K. Sinha. 1981. Growth rate and salinity profiles of first-year sea ice in the high Arctic. J.

Glaciol. 27: 315-330.

Niedrauer, T.M. and S. Martin. 1979. An experimental study of brine drainage and convection in young sea ice. J. Geophys. Res. 84: 1176-1186.

Owens, E.H. and S.B. McCann. 1980. The coastal geomorphology of the Magdalen Islands, Québec. In McCann, S.B. (Ed.): The coastline of Canada, pp.51-72. Geological Survey of Canada, Paper 80-10.

Pounder, E.R. 1965. The physics of ice. Pergamon Press, Oxford.

Reeburgh, W.S. 1984. Fluxes associated with brine motion in growing sea ice. Polar Biol. 3: 29-33.

Wakatsuchi, M. 1977. Experiments on haline convection occurring under growing sea ice (in Japanese with English summary). Low Temp. Sci. Ser. A35: 249-258.

Wakatsuchi, M. and N. Ono. 1983. Measurements of salinity and volume of brine excluded from growing sea ice. J. Geophys. Res. 88: 2943-2951.

Weeks, W.F. and S.F. Ackley. 1982. The growth, structure and properties of sea ice. U.S. Army Cold Regions Research and Engineering Laboratory, Monograph 820-1: 130p.

Weeks, W.F. and D.L. Anderson. 1958. An experimental study of strength of young sea ice. Trans. Amer. Geophys. Union 39: 641-647.

Weeks, W.F. and A. Assur. 1967. The mechanical properties of sea ice. U.S. Army Cold Regions Research and Engineering Laboratory, CRREL Monograph II-B3.

Weeks, W.F. and O.S. Lee. 1958. Observations on the physical properties of sea ice at Hopedale, Labrador. Arctic 11: 134-155.

CHAPTER II

ICE BIOTA FROM THE GULF OF ST.LAWRENCE, MAGDALEN ISLANDS AREA.

PART II: NUTRIENT DYNAMICS AND BIOLOGICAL VARIABLES.

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Abstract

Ice biota nutrient dynamics were studied in relation to growth and ice algal biomass at six landfast ice stations and one drifting ice station in the Magdalen Islands area, Gulf of St.Lawrence. Ice nitrate and silicate concentrations were low: NO_3 ≤ 2.0 µM and $Si(OH)_4$ ≤ 2.0 µM. Seawater concentrations were higher before ice formation with NO_3: 4-7 µM and $Si(OH)_4$: 8.0 µM, but both nutrients became depleted (≤ 1.0 µM) at landfast ice stations after ice formation. Depletion occurred earlier in time at stations where underice circulation was reduced, but seawater nutrients were not depleted at the drifting ice station. Ice soluble reactive phosphorus levels were also low, PO_4: 0.1-0.2 µM, but concentrations increased with time to ≥ 0.4µM and no depletion was observed in under ice seawater. Further, ratios of nutrient concentrations in ice versus concentrations in seawater (Ci/Cw ratios) compared to Ci/Cw salinity ratios indicated regeneration of phosphorus (SRP), particularly in bottom ice sections. Low nitrogen concentrations (NO_2 + NO_3 + NH_4), N/P ratios <16 and POC/PON ratios >10 suggested nitrogen limitation, while N:Si ratios >1 and poorly silicified frustules suggested silicate limitation. Mean chlorophyll *a* concentration in bottom ice was 12.91 (±10.36SD) $mg.m^{-3}$ with lowest concentrations for drifting ice. Specific growth rates averaged 0.10±.05 d^{-1},

Nutrient limitation, light intensity and the instability of the ice substrate are considered as mechanisms responsible for the limitation of ice algal growth and biomass accumulation in the Gulf of St.Lawrence.

INTRODUCTION

Sea ice algae, predominantly diatoms, are significant contributors to marine primary production in Arctic and Antarctic waters (Horner, 1976; Horner and Schrader, 1982; Palmisano and Sullivan, 1983). They form dense populations in the lower few centimeters of annual sea ice (the skeletal layer), often attaining standing crops of 100 mgChla.m^{-2} or more despite chronically low temperatures (roughly -1.0°C to -1.8°C) and irradiance (a few percent or less of incident surface irradiance) in their growth environment (Smith et al., 1987). Sea ice microalgae have been estimated to contribute as much as 30% of the total annual carbon production in the Arctic Ocean (Alexander, 1974; Horner, 1976).

However, in the Gulf of St.Lawrence, which is the most southerly region in the North Atlantic in which sea ice is regularly formed, Dunbar and Acreman (1980) found chlorophyll a concentrations in bottom sections of drifting ice floes to be an order of magnitude less than for higher latitude ice communities in Hudson Bay, Barrow Strait and Robeson Channel. Differences between the Gulf and Arctic regimes were attributed to the duration of the ice cover (at least 8 months in the Arctic compared to two to three months in the Gulf of St.Lawrence), the extreme density stratification of

the uppermost layer of water in the Arctic, and latitude differences in light regimes coupled with thinner ice in the Gulf. Demers et al. (1984), working on drifting ice floes from the St.Lawrence estuary, also found lower ice algal biomass in comparison to Arctic regions, which they attributed to higher underice light intensities. Cell densities were comparable to those of higher latitudes but chlorophyll a content per cell was much lower than ratios observed in Arctic regions (Cota, 1985), suggesting that higher under ice light intensities in the Gulf were not propitious to the extreme shade adaptation characteristic of polar ice algae.

Apart from duration of ice cover and light intensities, nutrient limitation might be involved in reduced ice algal biomass. With respect to ice biota, Meguro et al. (1967) proposed three potentially important sources of nutrient supply for ice algae: 1) nutrient flux from desalination of concentrated brine, 2) in situ regeneration of inorganic nutrients from dissolved and particulate organic materials, and 3) nutrient flux from the underice seawater.

Meguro and co-workers considered desalination to be the most important mechanism of nutrient supply to ice biota : "concentrated brine formed during initial ice freeze-up is brought to bottom ice algae through desalination processes and the elevated nutrient concentrations in brine are responsible for high ice algal biomass". Desalination has

been invoked as a cause of nutrient enrichment in a number of cases, particularly in bottom ice. In Frobisher Bay, Grainger (1977) reported nitrates and phosphates accumulation in sea ice during the winter with very low levels in the upper part of ice and high levels at the bottom. Alexander et al. (1974) found in the Arctic that nitrates and nitrites in brine were about twice as high in sea ice as in seawater while phosphates and silicates had similar concentrations. Horner and Schrader (1982) measured nutrient concentrations in the ice and in the water column from the Beaufort sea, and found that they were generally similar except for high nitrite and ammonia peaks in the ice late in the season. Cota et al. (1987), working in Barrow Strait, noticed that NO_3 and PO_4 levels in bottom ice showed an enrichment by a factor of about three compared to their concentration in the surface seawater. Tsurikov (1983) reported an enrichment by a factor greater than 4 for phosphates and silicates in Arctic ice. Similar results were obtained by Mel'nikov and Pavlov (1979) for PO_4. Freeman et al. (1982) also report NO_2 and NO_3 concentrations two to three times higher in surface ice than in seawater from James Bay and Hudson Bay. However, Cota et al. (1987) found, by integrating values of nitrates and silicates from whole ice column, that nutrients supplied from desalination would be depleted in a week or two of rapid ice algal growth. They also noted that inorganic nutrients from brine cells were not directly available to ice algae which

are mainly concentrated in the skeletal layer. Indeed, excluded dense brine is shown to leave the ice through brine channels in discrete plumes which do not readily mix back into the bulk water of the surface water layer (Wakatsuchi and Ono, 1983). This is even more apparent when one considers that dense brine is only formed in the initial stages of ice formation, and that the large pulse of nutrients from the ice occurs during "flushing" which coincides with the sloughing off of dense algal mat (Cota et al., 1987). Therefore, in Arctic ice, desalination supplies only a small percentage of the maximum nutrient demand for the whole ice algal bloom.

In situ regeneration was considered by Meguro et al. (1967) as a possible source of nutrients, specially in the case of high phosphate concentrations in the ice. Studies on heterotrophic communities associated with Arctic (Dahlback et al., 1982) and Antarctic (Sullivan et al., 1985) sea ice reveal high abundance and active bacterial growth in ice, plus a potential coupling between bacterial growth and microalgal photosynthetic metabolism in ice (Grossi et al., 1984; Kottmeier et al., 1987). Larger members of the cryofauna such as flagellates, ciliates, amphipods and nematodes can also be found in relative abundance in sea ice (Carey, 1985). However, despite abundant and active heterotrophic communities associated with sea ice, nutrient supply by in situ regeneration seems to represent only a minor component of the total demand for ice algal bloom. Cota

et al. (1987), using order of magnitude estimates for rates of nitrogen (ammonia) excretion, found that regenerative fluxes of nitrogen approached the estimated mean demand in Barrow Strait, but that this was not the case for silicic acid whose regeneration is much slower than other nutrients (Nelson and Gordon, 1982) and not biologically mediated.

Flux from the water column appears to be the largest source of nutrient supply for ice biota (Cota et al., 1987). In Barrow Strait, during the spring bloom of ice algae, Cota et al. (1987) estimated that the seasonal average nutrient demand for the bloom was of a magnitude such that nutrient flux from the water column should be the major source of supply. The fluxes were found to vary by an order of magnitude or more over the fortnightly tidal cycle. The importance of nutrient flux from the water column is further corroborated by Reeburgh (1984) who estimated residence time of seawater in the skeletal layer of ice at 2-6 hours.

Despite the different sources of nutrient supply to ice algae, there is growing evidence that the supply of inorganic nutrients may limit production of ice algae in polar regions (Grainger, 1977; Gosselin et al., 1985; McConville et al., 1985; Palmisano and Sullivan, 1985; Cota et al., 1986; Maestrini et al., 1986). Early development of ice algal blooms appears to be regulated by light availability, but later in the growth season the apparent nutrient consumption ratio (Grainger, 1977) and response to nutrient enrichment

(Maestrini et al., 1986) of Arctic ice algae suggest limitation by nitrogen. In the later stages of ice algal blooms, much photosynthate products are directed into carbohydrates, especially compounds resembling the storage polymer chrysolaminarin, and relatively little into protein (McConville et al., 1985; Palmisano and Sullivan, 1985). Such a protein-poor pattern might suggest nutrient rather than light limitation (Healy and Henzel, 1980; Smith and Geider, 1985). Another line of evidence for possible nutrient limitation of ice algal production was put forward by Cota et al. (1986) in a study in the Central Canadian Arctic. They showed that upward transport of nutrient to the ice algal layer (the skeletal layer) varied strongly and coherently with the fortnightly spring-neap tidal cycle, and that the calculated transport rates during neap tides and associated weak mixing showed reduced nutrient transport that could limit production, while spring tides could support a transport rate roughly matching the demand of rapidly growing ice algae. In Hudson Bay, ice algal photosynthetic efficiency was shown to vary directly with the fortnightly cycle in tidal amplitude (Gosselin et al., 1985), consistent with a controlling role for tidally driven nutrient supply in the production of ice algae.

This study on ice biota from the Gulf of St.Lawrence was undertaken in view of the differences observed between the Gulf of St.Lawrence and Arctic regimes. The aim was to

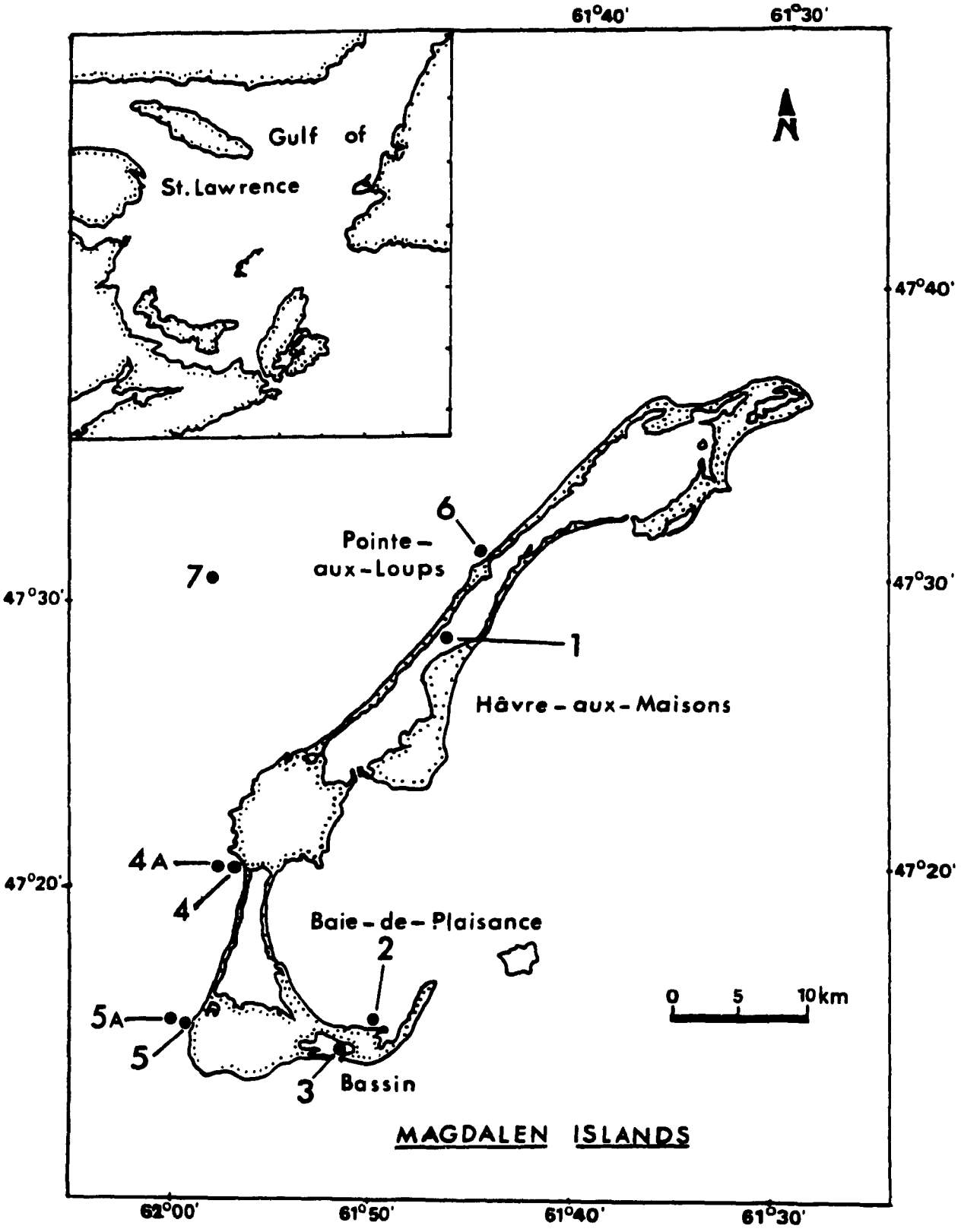
determine environmental variables responsible for reduced ice algal biomass in the Gulf of St.Lawrence. Distinction was made between landfast and drifting ice for a better comparison to Arctic ice studies, the majority being from landfast ice, different from the studies of Dunbar and Acreman (1980), and Demers et al. (1984) which dealt with drifting ice only. Nutrient dynamics in ice and seawater were monitored in relation to the three sources of nutrient supply to ice algae: desalination, in situ regeneration and nutrient flux from the underice water column. Nutrient budget and ice versus seawater nutrient concentration ratios were estimated to define which of the three sources played the most important role. Nutrient limitation was investigated in view of the evidence of nutrient limitation observed for Arctic ice algae and of lower ice algal biomass from the Gulf of St.Lawrence. Other variables such as light intensity and sea ice characteristics (determined in chapter I) were also investigated and compared to Arctic regimes.

MATERIALS and METHODS

Study Sites

The Magdalen Islands Archipelago is located approximately in the centre of the Gulf of St.Lawrence, in latitude 47° to 48° North and longitude 61° to 62° West. Location of stations is illustrated in Figure 1. Station numbers and locations are the same as in chapter 1. Stations 1 and 3 are located respectively at Hâvre-aux-Maisons and Bassin in shallow protected lagoons and bays. Station 2, located on the eastern coast of the Magdalen Islands, is exposed to northwesterly winds and to occasional piling up of landfast ice in the Baie de Plaisance. Stations 4 and 5, located on the western coast, are exposed to prevailing northwesterly winds and to southeast drifting ice floes coming from the Gulf of St.Lawrence. At these two stations ice was sampled mid-way between shore and the edge of the landfast ice (Stations 4 and 5), as well as at the ice edge (Stations 4A and 5A), the boundary between landfast ice and drifting pack ice. Stations 4A and 5A were compared to stations 4 and 5 for ice boundary effects. Station 6, on the northwestern coast at Pointe-aux-Loups, is the most exposed to winds and drifting ice floes. Station 7, located approximately 20 km off shore west of Pointe-aux-Loups, is the drifting pack ice station which was used for comparison

FIGURE 1. Map of the Magdalen Islands, Gulf of St.Lawrence. Sampling stations are designated by numbers 1 to 6 for landfast ice stations and by number 7 for the drifting ice station. Stations 4A and 5A are located at the landfast ice edge.


61°40'
61°30'
Gulf of
St. Lawrence
N
47°40'
47°30'
47°20'
6
Pointe-
aux-Loups
7
1
Hâvre-aux-Maisons
4A
4
Baie-de-Plaisance
2
0 5 10km
5A
5
3
Bassin
MAGDALEN ISLANDS
62°00'
61°50'
61°40'
61°30'

with landfast ice stations.

Sampling Procedures and Analysis

Seawater was sampled in January at stations 1, 4, 5 and 6 before ice formation. Landfast ice began to form in sheltered areas in the first week of February but ice sampling started only in the last week of February, when the ice was thick and compact enough to work on. From that period on, ice and water samples were collected every two weeks at stations 1 to 6. Ice and seawater were sampled only twice at station 7 by helicopter. Ice samples were collected with a SIPRE ice corer of 7.5 cm diameter. A minimum of two cores were collected within a 1 meter distance. Ice cores were cut into 20 cm sections, starting from bottom ice. Seawater was sampled by pumping underice water through holes made by the corer. Samples were kept frozen and brought back to the laboratory for analysis of chemical and biological variables. Seawater and melted ice core sections were filtered onto Whatman GF/C glass fiber filters for chlorophyll a and phaeopigments and onto Whatman GF/C glass fiber filters precombusted (for 6h at 500°C to remove any contaminating C and N) for particulate organic carbon (POC) and nitrogen (PON) determinations. The filtrate was dispensed into 50 ml polyethylene bottles (prewashed with 0.15N HCL) and stored frozen at -20°C for future (within 2 months) determination of

ammonia, nitrites, nitrates, soluble reactive phosphorus (PO_4-P) and silicic acid concentrations. Unfiltered water and ice samples were stored in the same way for total dissolved phosphorus (TDP) determination.

In the laboratory, spectrophotometric determinations of chl *a* and phaeopigments were performed using a Bausch and Lomb Spectronic 21 spectrophotometer. Carbon and nitrogen contents of the particulate matter collected on the filters were determined using a Perkin-Elmer model 240B CHN Elemental Analyser. Nutrient concentrations were determined using manual methods described in Strickland and Parsons (1972).

Statistical Analysis

To determine statistical differences in the various environmental variables in ice and seawater among the stations, a SAS statistical package was used in all data analyses (Ray, 1982a,b). All linear model statistics, such as analysis of variance (ANOVA), make the assumption that the underlying population from which the sample data are drawn is normally distributed. To test this assumption, the Shapiro-Wilk, W, statistic and probability plot were computed for all environmental data sets using the Univariate procedure in the SAS system (Ray, 1982b); the Fmax test (Zar, 1984) was used to test the homogeneity of variance assumption. Appropriate transformations were applied to data sets, when necessary, as

suggested by Box et al. (1978). A single factor analysis of variance (ANOVA) was carried out to test the null hypothesis H_o: there are no differences in variables among stations (or among seawater and ice sections at the same station) against an alternate H_1: there are differences in variables among stations, or among seawater and ice sections. Where parametric ANOVA rejected the null hypothesis, a specific among stations (or among seawater and ice sections at the same station) comparison of means (at the P=0.05 level), for each of the variables was carried out using Student-Newman-Keuls (SNK) multiple range test.

RESULTS

Chemical Variables

Results on chemical variables are summarized in Table 1. They include mean, standard deviation and sample size of the different variables at stations 1 to 7, for seawater and bottom ice sections. Concentrations of silicates and of the nitrogen fractions (NO_3, NO_2 and NH_4) are low in bottom ice sections. They are generally higher in seawater than in the ice and show an increasing trend in mean concentration values from station 1 to station 7. Soluble reactive phosphorus (PO_4) concentrations are, however, somewhat similar for seawater and bottom ice sections, and total dissolved phosphorus (TDP) is, at some stations, even higher in bottom ice sections than in seawater. No trend in seawater phosphorus concentrations is observed between the different stations, but the lowest concentrations are found at station 1 and the highest at station 7.

Chemical variables (Table 1) were analyzed using single factor analysis of variance, parametric ANOVA, to test for statistical differences in variables among ice sections and seawater, and among stations . The results (Table 2) for comparison between surface ice section (I), bottom ice section (B) and seawater (W) indicate that in the ice nutrient concentrations from surface and bottom ice sections

Table 1. Results of nutient analysis for sea water (W) and bottom ice section (B) at stations 1 to 7 (fig.1). The variable are presented as means with standard deviation in parentheses and number of samples. Concentrations are in µM (µg-at/l) and the symbol "*" refers to NH_4 concentrations below 0.03µM, the limit of detection.

VARIABLES		STATIONS								
		1	2	3	4	4a	5	5a	6	7
NO_3-N	B	0.68	0.90	1.19	0.80	0.58	1.23	0.63	1.05	1.27
		(.64)	(0.31)	(0.60)	(0.45)	(0.24)	(0.94)	(0.13)	(0.44)	(0.20)
		4	5	5	6	3	5	2	4	2
	W	19	0.94	1.30	3.77	3.40	3.12	3.02	1.90	7.19
		62)	(0.80)	(1.96)	(2.03)	(1.12)	(2.58)	(2.66)	(3.61)	(2.17)
			6	6	7	3	6	2	5	2
NO_2-N	B	.09	.06	.05	.07	.10	.09	.08	.06	.06
		(.01)	(.01)	(.02)	(.06)	–	(.04)	–	(.02)	(.01)
		2	2	3	3	1	3	1	3	2
	W	.09	.12	.58	.19	.19	.13	.17	.21	.0
		(.11)	(.02)	(.98)	(.07)	–	(.11)	–	(.20)	(.03)
		3	2	4	3	1	3	1	4	2
NH_4-N	B	.06	*	*	*	*	*	*	*	*
		(.05)								
		4								
	W	.15	*	*	*	*	*	*	*	*
		(.11)								
		6								
PO_4-P	B	0.28	0.46	1.09	0.37	0.45	0.37	0.50	0.29	0.41
		(0.18)	(0.22)	(1.57)	(0.15)	(0.15)	(0.13)	(0.23)	(0.14)	(0.30)
		4	5	5	6	3	5	2	4	2
	W	0.08	0.38	0.42	0.77	0.72	0.48	0.64	0.48	1.02
		(0.75)	(0.15)	(0.18)	(0.43)	(0.15)	(0.32)	(0.19)	(0.21)	(0.40)
		6	6	6	7	3	6	2	5	2
TDP	B	1.50	1.72	1.42	1.83	0.87	1.63	1.56	0.92	0.92
		(1.22)	(1.31)	(1.19)	(1.35)	(0.92)	(1.28)	–	(0.68)	(0.92)
		3	5	4	4	2	5	1	3	2
	W	0.47	0.87	0.93	1.23	0.98	1.22	1.40	1.02	1.26
		(0.68)	(0.93)	(0.96)	(1.11)	(0.98)	(1.10)	–	(1.01)	(1.12)
		5	6	5	5	2	6	1	4	2
$Si(OH)_4$-Si	B	1.16	0.40	0.34	0.32	0.49	0.52	0.54	0.48	0.20
		(0.84)	(0.35)	(0.17)	(0.20)	(0.43)	(0.40)	(0.01)	(0.45)	(0.15)
		4	5	5	6	3	5	2	4	2
	W	0.37	1.04	1.57	3.25	3.49	2.91	3.70	2.44	4.72
		(0.13)	(1.77)	(1.61)	(2.86)	(1.58)	(3.23)	(3.61)	(3.04)	(3.84)
		6	6	6	7	3	6	2	5	2

Table 2. Parametric Student-Newmen-Keuls test (Zar 1984) for significant ($P<0.05$) differences between surface ice section (I), bottom ice section (B) and sea water (W) variable means at stations 1 to 7 (Fig.1). Groupings with same letters are not significantly different.

VARIABLES		STATIONS								
		1	2	3	4	4A	5	5A	6	7
NO_3-N	I	a	a	a	b	b	a	a	a	b
	B	a	a	a	b	b	a	a	a	b
	W	a	a	a	a	a	a	a	a	a
NO_2-N	I	a	a	a	a	–	a	–	a	a
	B	a	a	a	a	–	a	–	a	a
	W	a	a	a	a	–	a	–	a	a
$Si(OH)_4$	I	a	a	b	b	b	b	a	a	b
	B	a	a	b	b	b	b	a	a	b
	W	a	a	a	a	a	a	a	a	a
PO_4-P	I	a	b	a	b	b	a	a	b	a
	B	a	a	a	ab	ab	a	a	ab	a
	W	a	a	a	a	a	a	a	a	a
TDP	I	b	b	a	a	a	a	a	a	a
	B	b	b	a	a	a	a	a	a	a
	W	a	a	a	a	a	a	a	a	a
Chl. a	I	c	b	b	b	b	b	b	b	b
	B	b	b	b	b	b	b	b	b	b
	W	a	a	a	a	a	a	a	a	a
Phaeo.	I	b	b	b	b	b	b	b	b	b
	B	b	b	b	b	b	b	b	b	b
	W	a	a	a	a	a	a	a	a	a

do not differ significantly, except for PO_4 concentrations at station 2. However, when comparing seawater to bottom ice nutrient concentrations, significant differences are found for NO_3 at stations 4, 4A and 7, and for $Si(OH)_4$ at stations 3, 4, 4A, 5 and 7, but not for PO_4 nor TDP.

Comparison of variable means between stations, for bottom ice sections and seawater (Table 3) shows no significant differences between stations for bottom ice nutrient concentrations. In seawater, PO_4 and TDP concentration means from station 1 are significantly different from stations 2 to 7, $Si(OH)_4$ from station 7 is significantly different from stations 1 to 6, and NO_3 from stations 1, 2 and 3 are significantly different from station 7, and intermediate concentrations are found at stations 4 to 6.

Distribution of nitrates in the ice is presented as vertical profiles of their concentrations in the ice sections at stations 1 to 7 respectively (Fig. 2). Irregular patterns of vertical distribution are observed from top to bottom ice sections with ice nitrate concentrations less than 2.0µM. Similar patterns were observed for the vertical distribution of nitrites in the ice, with concentrations generally less than 0.10 µM and little variation with time. Time scale evolution of nitrates in bottom ice sections was then analyzed and compared to seawater concentrations for the different stations (Fig. 3). In bottom ice sections,

Table 3. Paramatric Student-Newmen-Keuls test for significant ($P<0.05$) statistical differences between station means for nutrient variables of bottom ice section (B) and sea water (W). Groupings with same letters are not significantly different.

VARIABLES		STATIONS								
		1	2	3	4	4A	5	5A	6	7
NO_3-N	B	a	a	a	a	a	a	a	a	a
	W	a	a	a	ab	ab	ab	ab	ab	b
NO_2-N	B	a	a	a	a	a	a	a	a	a
	W	a	a	a	a	a	a	a	a	a
$Si(OH)_4$	B	a	a	a	a	a	a	a	a	a
	W	a	a	a	a	a	a	a	a	b
PO_4-P	B	a	a	a	a	a	a	a	a	a
	W	b	a	a	a	a	a	a	a	a
TDP	B	a	a	a	a	a	a	a	a	a
	W	b	a	a	a	a	a	a	a	a
Chl. a	B	ab	ab	ab	ab	ab	ab	a	ab	b
	W	a	a	a	a	a	a	a	a	a
Phaeo.	B	a	a	a	a	a	a	a	a	a
	W	a	a	a	a	a	a	a	a	a

Figure 2. Vertical profiles of nitrate concentrations (μM) in ice, at stations 1 to 7, for ice sections 20cm thick. The horizontal width (NO_3-N scale) for each profile/sampling date is also shown in the upper right hand corner of the figure.

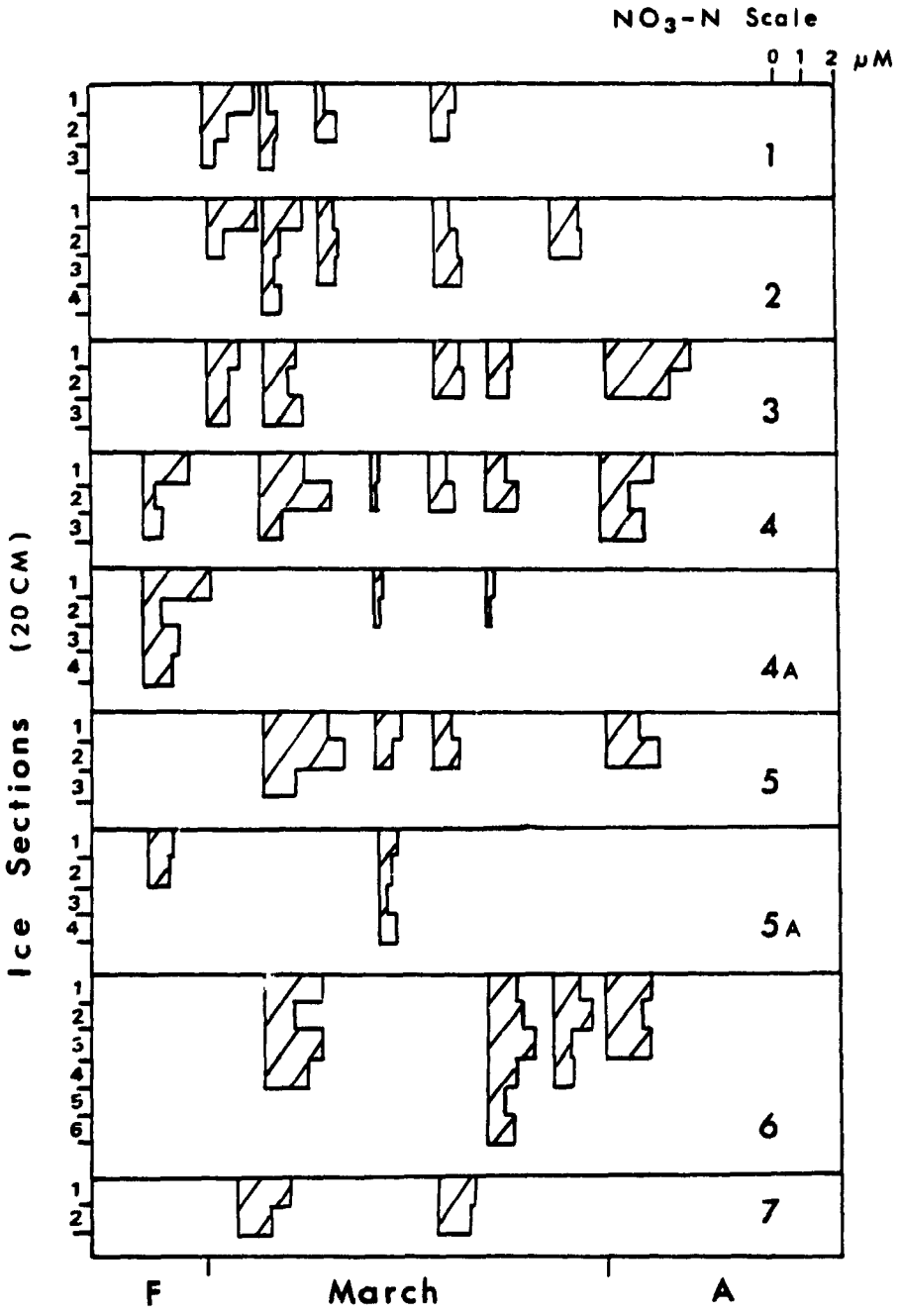
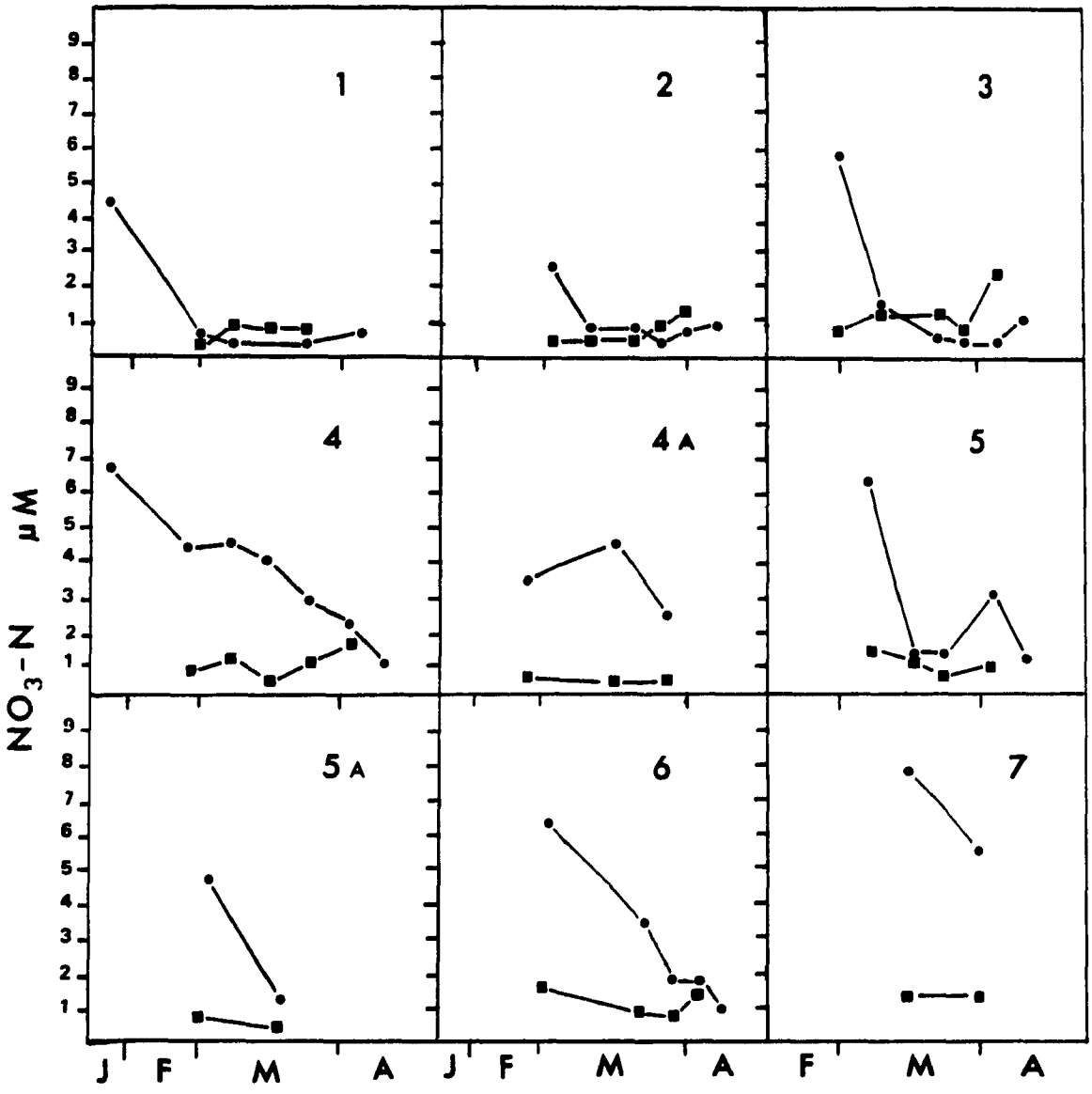

NO3-N Scale
0 1 2 µM
Ice Sections (20 CM)
1
2
3
4
4A
5
5A
6
7
F
March
A

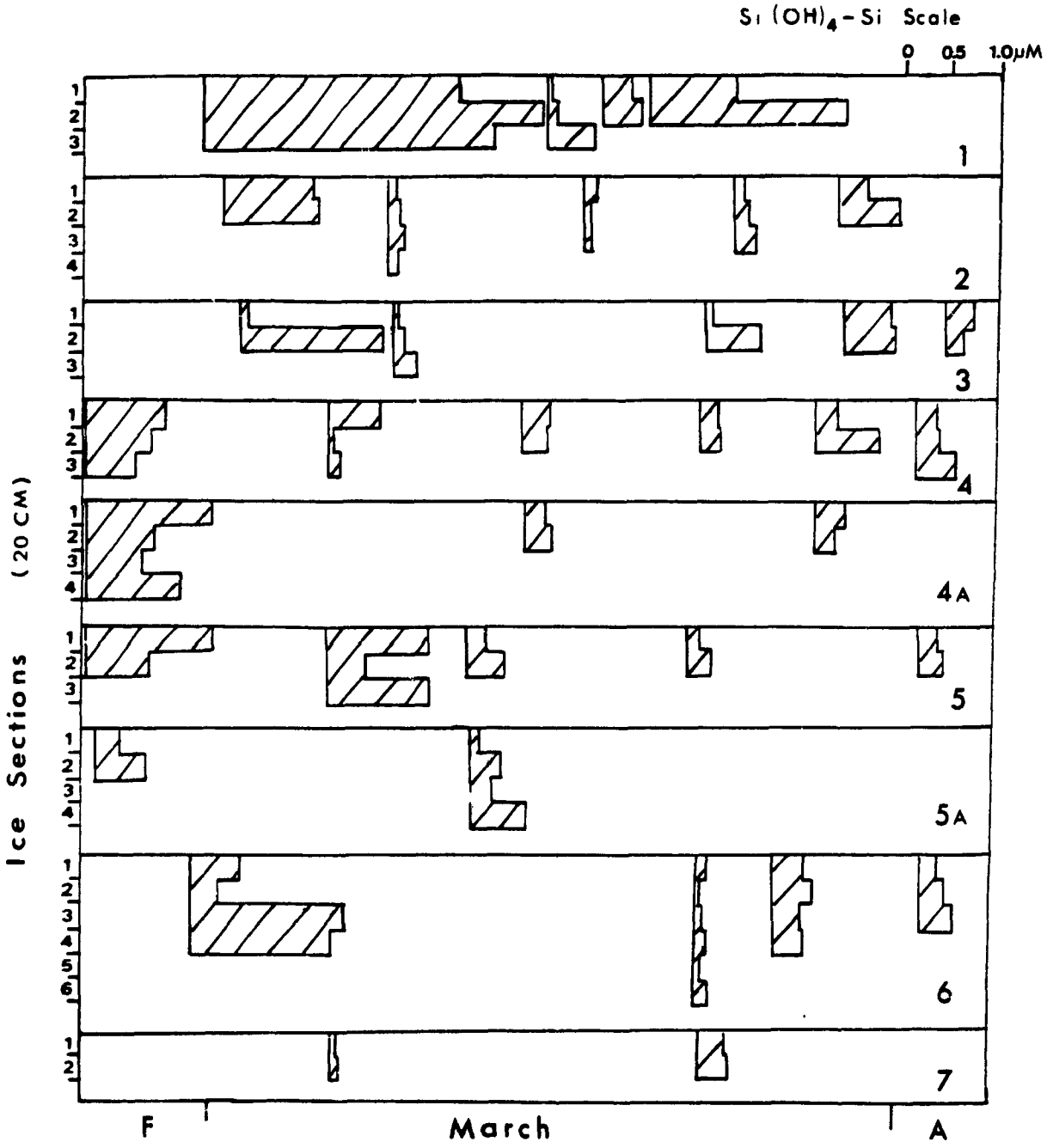
Figure 3. Time scale evolution of nitrate concentrations (µM) in bottom ice sections (■——■) and in seawater (●——●) at stations 1 to 7.


1
2
3
4
4 A
5
5 A
6
7
NO_3-N µM
J F M A

concentrations are less than 2.0 µM, and remain low throughout the ice season without significant changes except for a slight increase at some stations at the end of March and the beginning of April. In seawater, nitrate concentrations are higher than in bottom ice in January, before ice formation, when NO_3 concentrations vary between 4 to 7 µM. After ice formation, i.e. middle of February, seawater nitrate levels decrease at all stations reaching concentrations of 1.0 µM or less, similar to bottom ice NO_3 levels. A trend in seawater nitrate depletion is however observed from stations 1 to 7. Depletion occurs earlier at stations located in lagoons and on the eastern side of the Magdalen Islands (Stations 1, 2 and 3) where seawater nitrate levels are down to less than 1.0 µM by the first week of March. At stations located on the western side of the Islands (Stations 4, 4A, 5, 5A and 6) seawater nitrate depletion does not occur before the second or the last week of March. Nitrate depletion is not observed at the drifting ice station (Station 7). Time scale evolution of nitrites showed the same trends as for nitrates. Ammonia concentrations (Table 1) were low at station 1 (0.11-0.38 µM), and below the limit of detection of 0.03 µM (McCarthy and Goldman, 1979) at stations 2 to 7, and could therefore not be analyzed for vertical distribution or time scale evolution.

Vertical profiles of silicate concentrations in the ice (Fig. 4) indicate more irregular patterns of distribution

Figure 4. Vertical profiles of silicate concentrations (μM) in ice, at stations 1 to 7, for ice sections 20cm thick. The horizontal width ($Si(OH)_4$ scale) for each profile/sampling date is also shown in the upper right hand corner of the figure.


Si (OH)4 - Si Scale
0 0.5 1.0µM
1
2
3
4
4A
5
5A
6
7
Ice Sections (20 CM)
F
March
A

than for nitrates. Bottom ice $Si(OH)_4$ concentrations are in some cores much higher than in surface ice sections but there are generally no significant differences between surface ice and bottom ice sections (Table 2). A decrease in silicate levels is observed in most ice sections at all stations with time. Time scale evolution of silicates in seawater and in bottom ice sections (Fig. 5) indicates that in ice, silicate concentrations are low (1.0-2.0 µM) at the end of February and the beginning of March, and decrease to less than 0.05 µM by the end of March. In seawater, concentrations are greater than 8 µM in January before ice formation (Fig. 5, stations 4, 5 and 6) and decrease to less than 1.0 µM after ice formation at most stations, except for station 7. The pattern of seawater silicate depletion is similar to that of nitrates, with depletion occurring by the first week of March at stations 1, 2 and 3, by the second to the third week of March at stations 4, 4A, 5, 5A and 6, and no depletion at station 7, the drifting ice station. As for nitrates, seawater silicate depletion occurs earlier and is more pronounced at stations located in protected lagoons or on the eastern side of the Magdalen Islands.

Vertical profiles of soluble reactive PO_4 in the ice (Fig. 6) shows a distribution whereby PO_4 concentrations are generally higher in bottom ice sections than in surface ice sections. Concentrations in surface and bottom ice sections are actually significantly different for station 2 and

Figure 5. Time scale evolution of silicates (µM) in bottom ice sections (■——■) and in seawater (●——●) at stations 1 to 7.

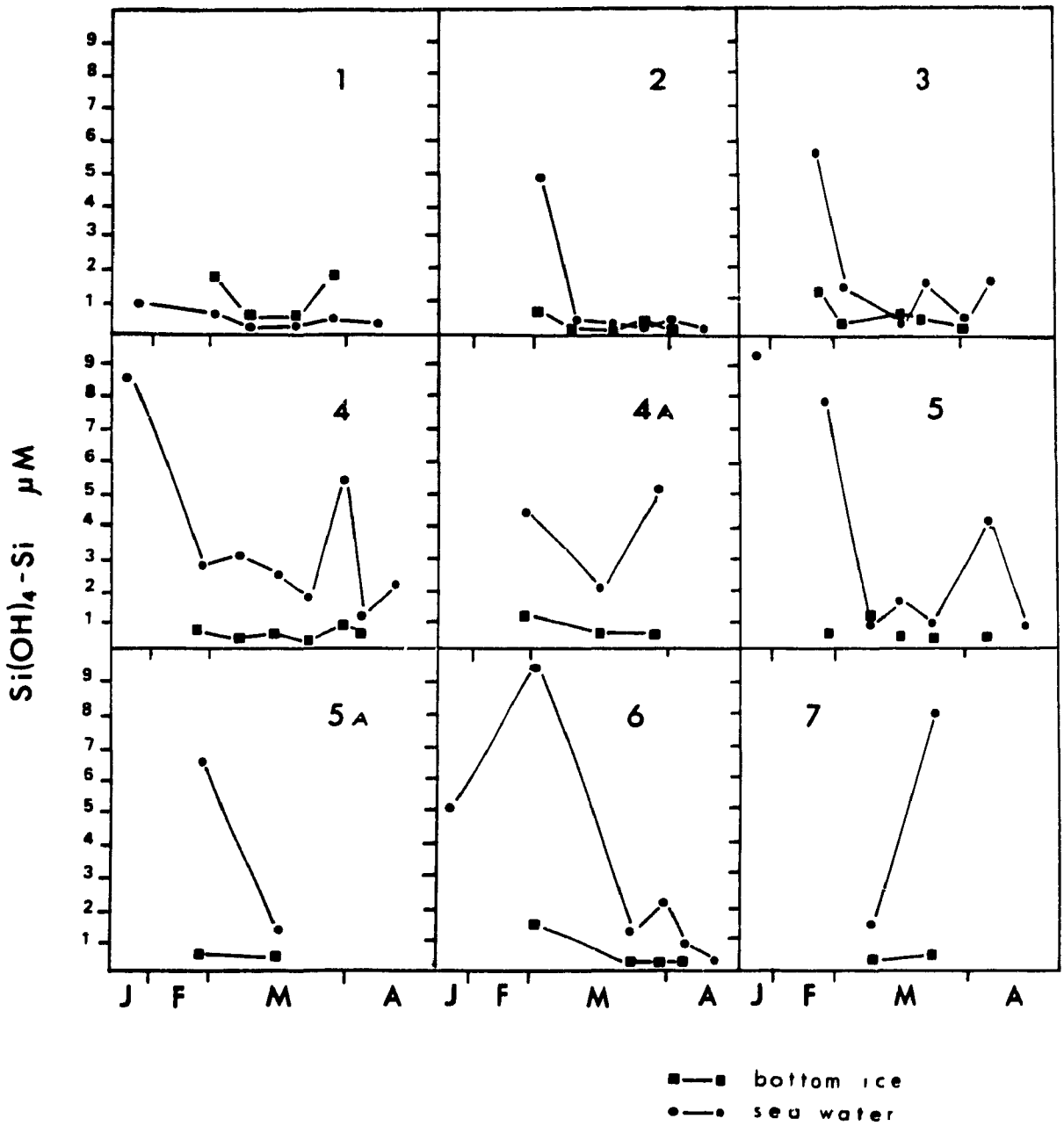
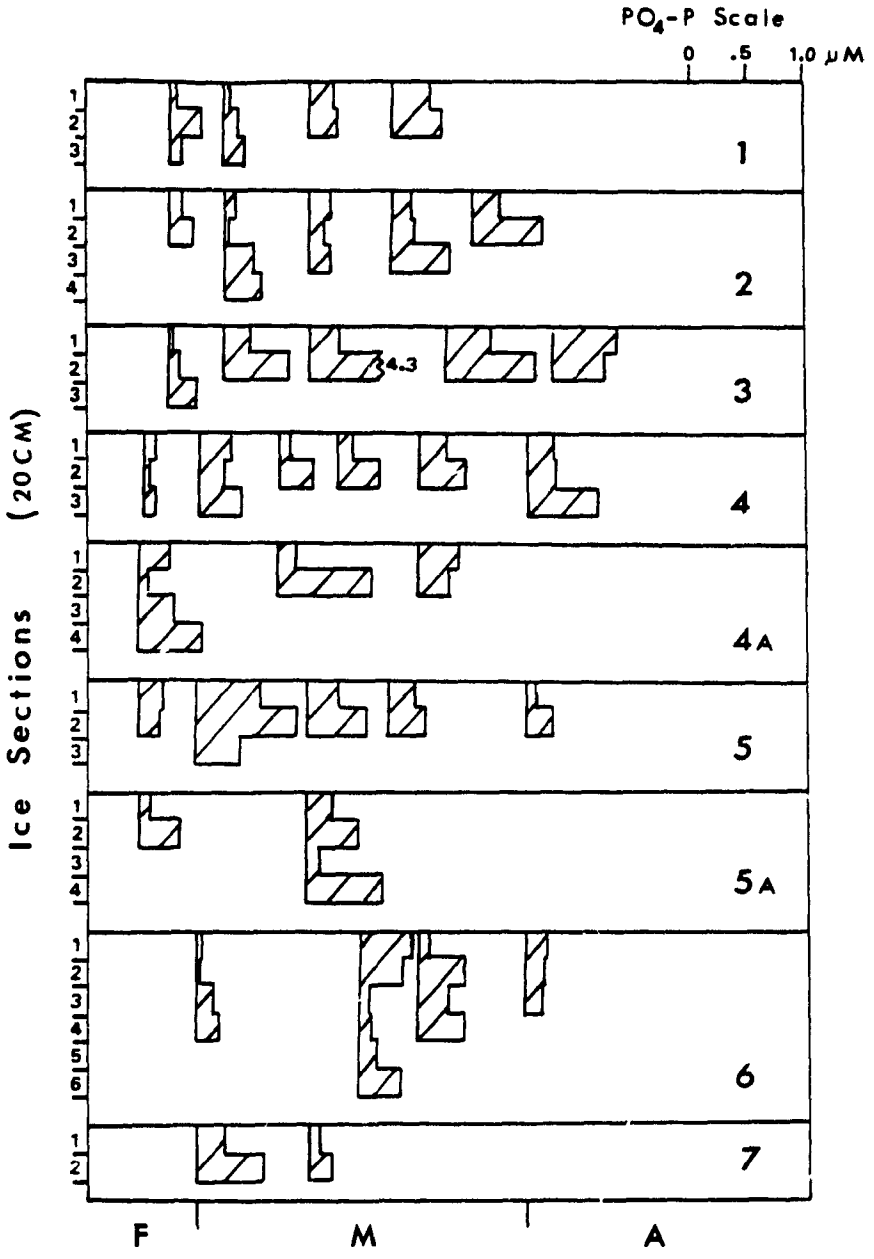

Si(OH)4-Si µM
1
2
3
4
4A
5
5A
6
7
J F M A
bottom ice
sea water

Figure 6. Vertical profiles of soluble reactive phosphorus concentrations (μM) in ice, at stations 1 to 7, for ice sections 20cm thick. The horizontal width (PO_4-P scale) for each profile/sampling date is also shown in the upper right hand corner of the figure.


PO4-P Scale
0
.5
1.0 µM
Ice Sections (20CM)
1
2
3
4
4A
5
5A
6
7
34.3
F
M
A

partially for stations 4, 4A and 6 (Table 2). Time scale evolution of phosphorus (Fig. 7) reveals a different pattern than for nitrates or silicates. First, an increase in ice PO_4 concentrations is observed at most stations, from 0.1-0.2 µM at the beginning of March to more than 0.4 µM by the end of March. Second, seawater PO_4 concentrations do not become depleted after ice formation. In January, before ice formation, PO_4 levels reach up to 0.10 µM. After ice formation the concentrations decrease slightly at most stations with marked fluctuations, but do not reach levels below 0.20 µM. Again, seawater PO_4 concentrations remain much higher at station 7. Station 1 seems to stand out from the others, with significantly lower seawater PO_4 concentrations (Table 3) and with bottom ice levels higher than in seawater (Fig. 7).

Vertical profiles of total dissolved phosphorus (TDP) in the ice (Fig. 8) reveal a more irregular pattern of distribution than for the soluble reactive PO_4 fraction. Bottom ice TDP concentrations are in a few cores higher than for surface ice sections, but, in general, the concentrations are not significantly different (Table 2). Time scale evolution of TDP (Fig. 9) reveals, contrary to all other nutrients, that concentrations are higher for bottom ice sections than for seawater, namely at stations 1, 2 and 3, while they are slightly higher to similar for stations 4, 4A, 5, 6 and 7. TDP concentrations in seawater and bottom ice are

Figure 7. Time scale evolution of soluble reactive phosphorus (μM) in bottom ice sections (■——■) and in seawater (●——●) at stations 1 to 7.

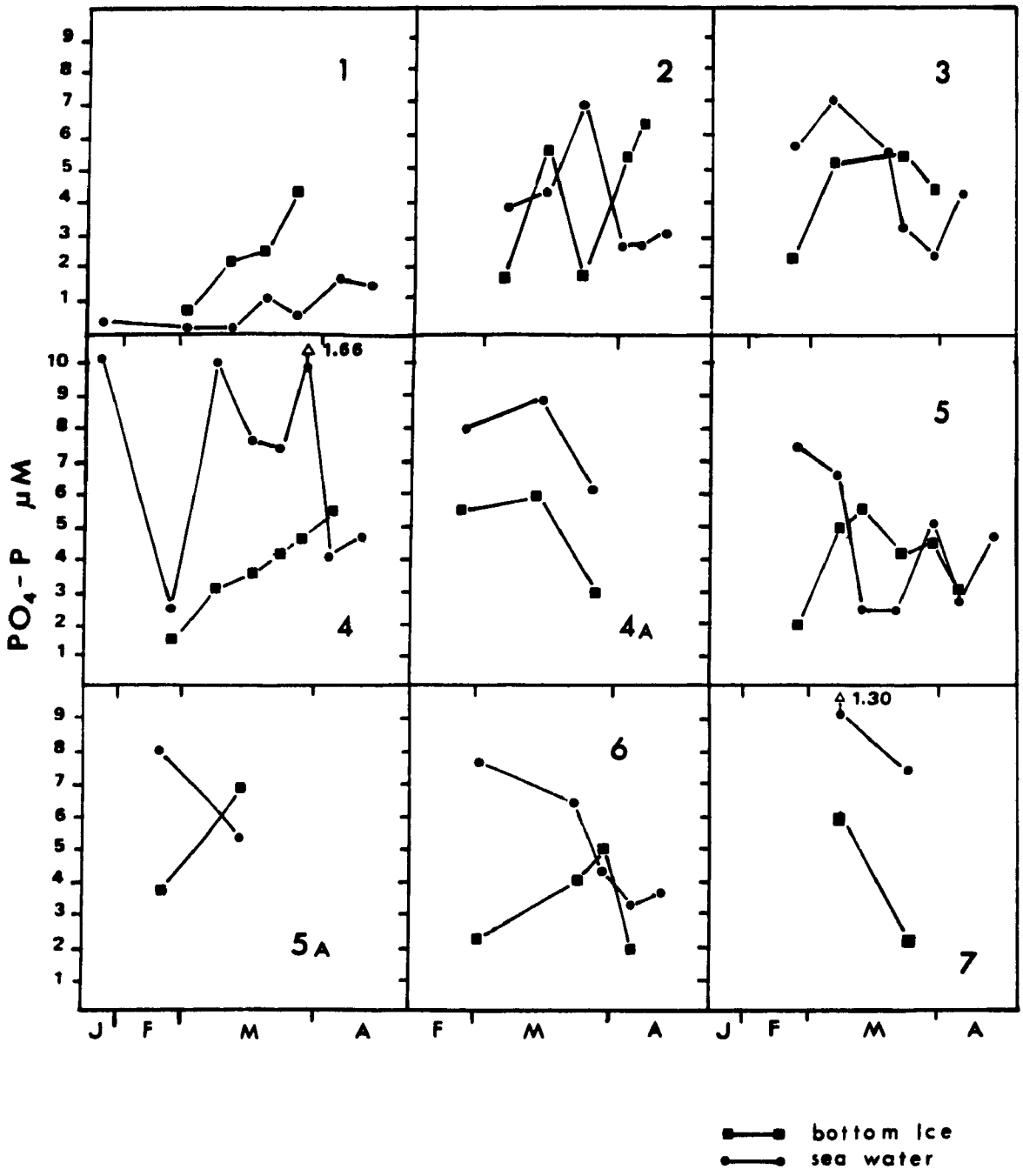

1
2
3
4
4A
5
5A
6
7
1.66
1.30
PO4-P µM
J
F
M
A
bottom Ice
sea water

Figure 8. Vertical profiles of total dissolved phosphorus concentrations (μM) in ice, at stations 1 to 7, for ice sections 20cm thick. The horizontal width (TDS scale) for each profile/sampling date is also shown in the upper right hand corner of the figure.

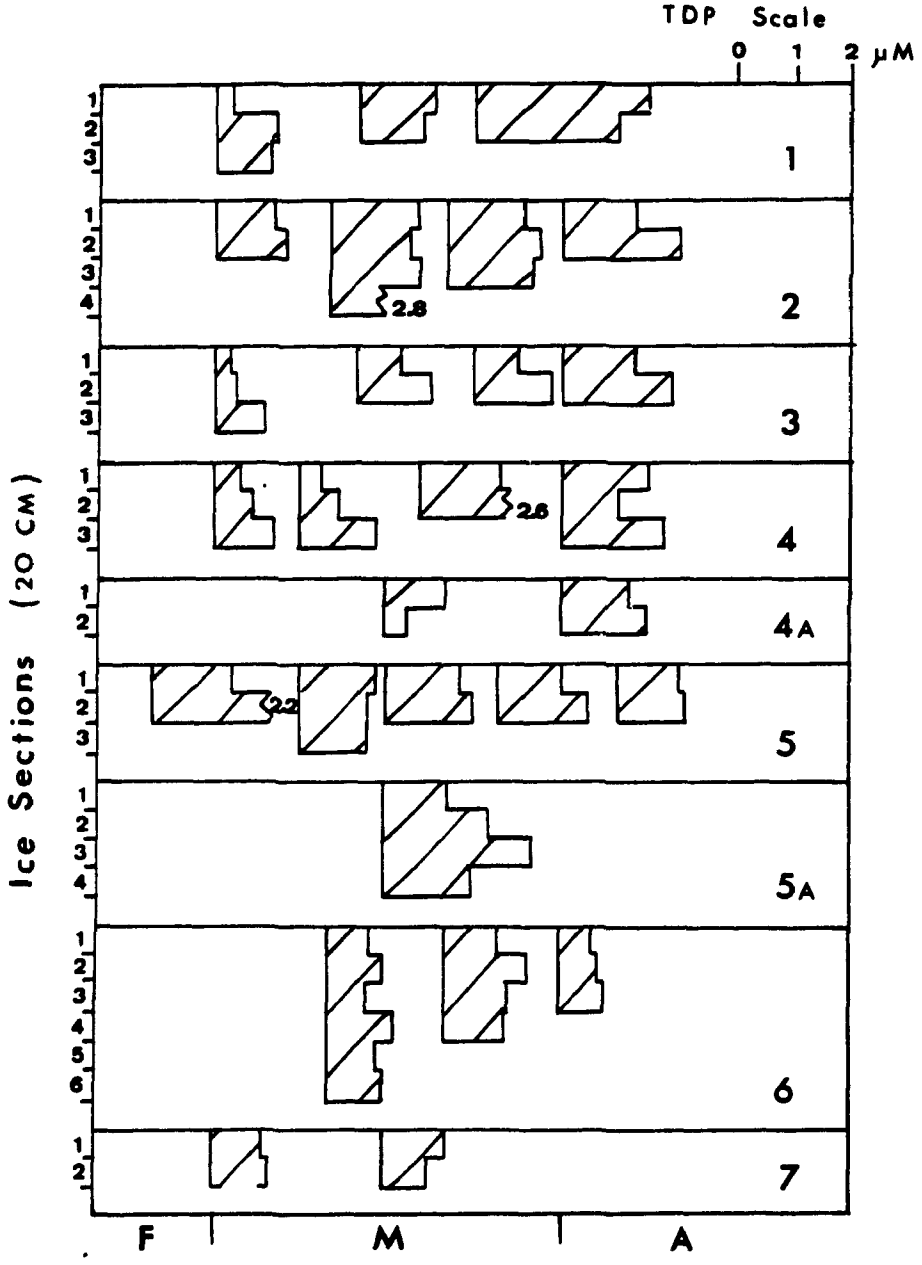
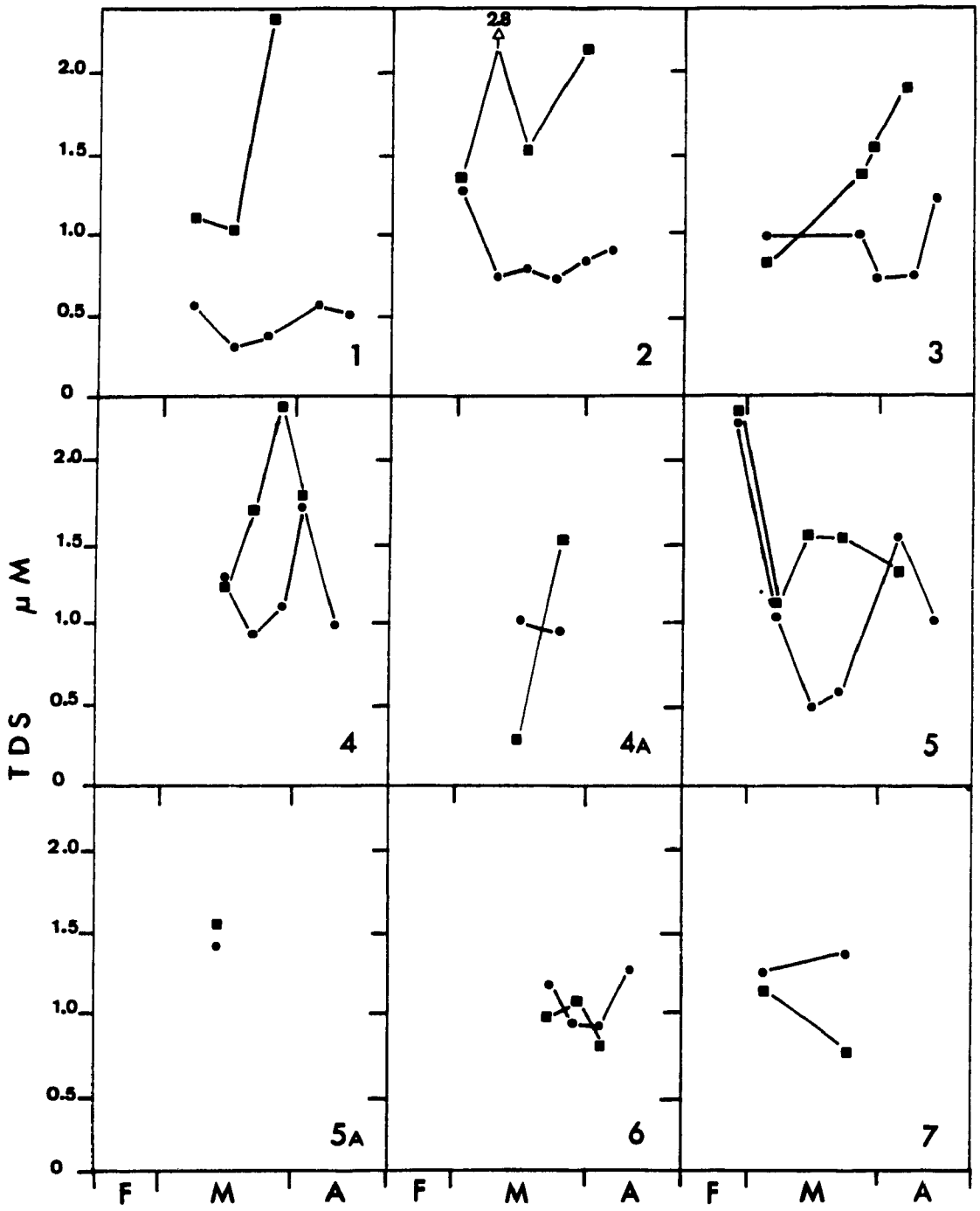

TDP Scale
0 1 2 μM
Ice Sections (20 cm)
1
2
3
4
4A
5
5A
6
7
2.8
2.6
2.2
F
M
A

Figure 9. Time scale evolution of total dissolved phosphorus (µM) in bottom ice sections (■——■) and in seawater (●——●) at stations 1 to 7.

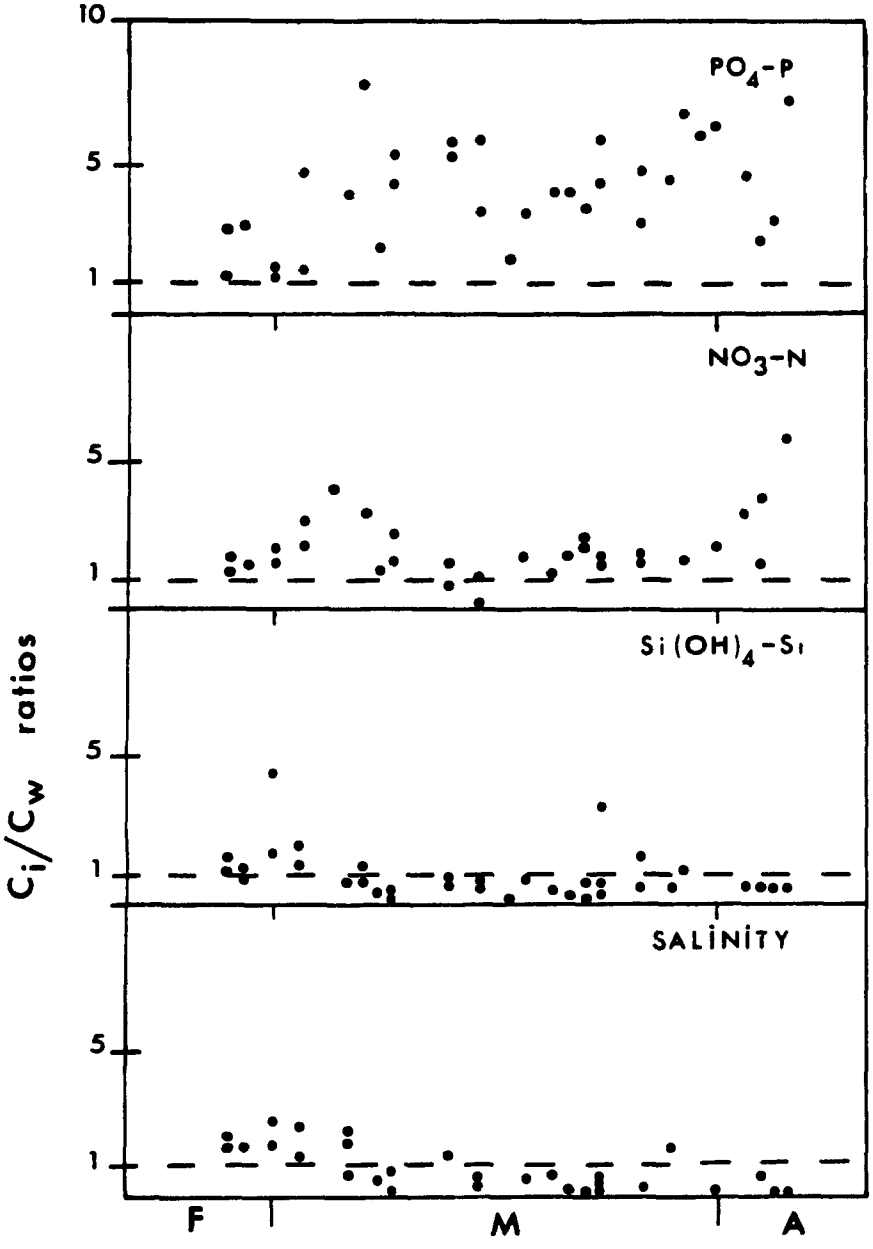

TDS μM
2.0
1.5
1.0
0.5
0
28
1
2
3
4
4A
5
5A
6
7
F
M
A

actually significantly different for stations 1 and 2 (Table 2).

In sumary, seawater and ice nutrients from the Magdalen Islands can be characterized by low NO_3 and $Si(OH)^4$ in ice, and depletion of these nutrients in seawater from February through April. Phosphorus (SRP and TDP), contrary to NO_3 and $Si(OH)_4$, increases in concentration in ice with time and shows no sign of depletion in seawater: SRP decreases slightly in time while TDP is seen to increase.

Sea ice nutrient enrichment, specifically concentrated in bottom ice sections, has been observed in a number of studies, as mentioned in the Introduction. Sea ice nutrient enrichment can be determined by computing Ci/Cw nutrient ratios (Ci:concentrations in bottom ice sections and Cw:concentrations in seawater at the time of ice formation) for the different nutrients and comparing them to salinity ratios. The results (Fig. 10) indicate that Ci/Cw for silicates follow the same trend as for salinity ratios. However, Ci/Cw ratios for nitrates are somewhat higher than salinity ratios, and phosphate ratios are much higher throughout the season ranging between 1 to more than 7. Salinity being a conservative property, Ci/Cw ratios for salinity will vary only as a function of desalination rates. Nutrient Ci/Cw ratios vary as a function of desalination rates but also as a function of biological processes such as uptake or regeneration, and therefore nutrient Ci/Cw ratios

Figure 10. Ci/Cw ratios (Ci:concentration in bottom ice, Cw:concentration in seawater) for salinity, silicates, nitrates and phosphates (SRP), grouping all stations.


10
5
1
PO_4-P
NO_3-N
$Si(OH)_4$-Si
SALINITY
C_i/C_w ratios
F
M
A

higher than salinity ratios are an indication of in situ regeneration.

Biological Variables

Chlorophyll a levels in bottom ice vary from low mean concentrations of 5.45 mgm^{-3} at station 7 to a high of 39.88 mgm^{-3} at station 5A (Table 4). A parametric Student-Newmen-Keuls test (Table 3) indicated that bottom ice chlorophyll a levels from stations 5A and 7 were actually significantly different, but similar for stations 1, 2, 3, 4, 4A, 5 and 6. Vertical profiles of ice chlorophyll a concentrations (Fig. 11) clearly show that maximum chlorophyll levels are found in bottom ice sections at all stations. This trend is however attenuated towards the middle of March when ice chlorophyll a concentrations become more regularly distributed. Time scale evolution of chlorophyll a in bottom ice sections (Fig. 12) indicates for stations 1, 2, 3, 4 and 5, an increase from the end of February until the first week of March, followed by a decrease in the second week of March, an increase in the third week of March followed again by a decrease in the last week of March. By plotting chlorophyll a concentrations from all stations (Fig. 13) the decrease in chlorophyll concentration in the second week of March is more evident, except for stations 4A, 5A, 6 and 7. The decrease follows the air temperature increase above freezing point on the 5th

Table 4. Results of biological variables from sea water (W) and bottom ice section (B) at stations 1 to 7. The variables are presented as means with standard deviation in parentheses and number of samples below. Negative growth rates are represented by "*".

VARIABLES		STATIONS								
		1	2	3	4	4a	5	5a	6	7
Chl a ($mg.m^{-3}$)	B	**10.55** (1.86) 4	**9.57** (8.76) 5	**12.22** (8.90) 5	**12.74** (5.41) 6	**8.33** (8.26) 3	**9.85** (4.65) 5	**39.88** (4.30) 2	**7.62** (6.29) 4	**5.45** (5.34) 2
	W	**0.16** (0.14) 6	**0.67** (0.27) 6	**0.62** (0.33) 6	**0.56** (0.34) 7	**1.05** (1.28) 3	**0.60** (0.53) 6	**0.57** (0.72) 2	**0.77** (0.48) 5	**0.19** (0.11) 2
Phaeop. ($mg.m^{-3}$)	B	**2.49** (3.21) 4	**3.43** (4.04) 5	**6.97** (9.27) 5	**1.37** (1.32) 6	**2.78** (-) 1	**1.08** (0.92) 5	**2.70** (1.27) 2	**2.08** (1.63) 4	**1.29** (1.12) 2
	W	**0.10** (0.05) 6	**0.05** (0.05) 6	**0.07** (0.05) 6	**0.28** (0.26) 7	**0.18** (0.19) 3	**0.11** (0.13) 6	**0.28** (0.39)	**0.10** (0.11) 5	**0.10** (0.10) 2
Growth (day^{-1})	B	**0.04** (.01) 3	**0.18** (0.12) 3	**0.13** (0.02) 4	**0.08** (0.04) 4	*	**0.04** (0.05) 4	*	**0.11** - 3	*

Figure 11. Vertical profiles of chlorophyll a concentrations ($mg.m^{-3}$) in ice, at stations 1 to 7, for ice sections 20cm thick. The horizontal width (chlorophyll a scale) for each profile/sampling date is also shown in the upper right hand corner of the figure.

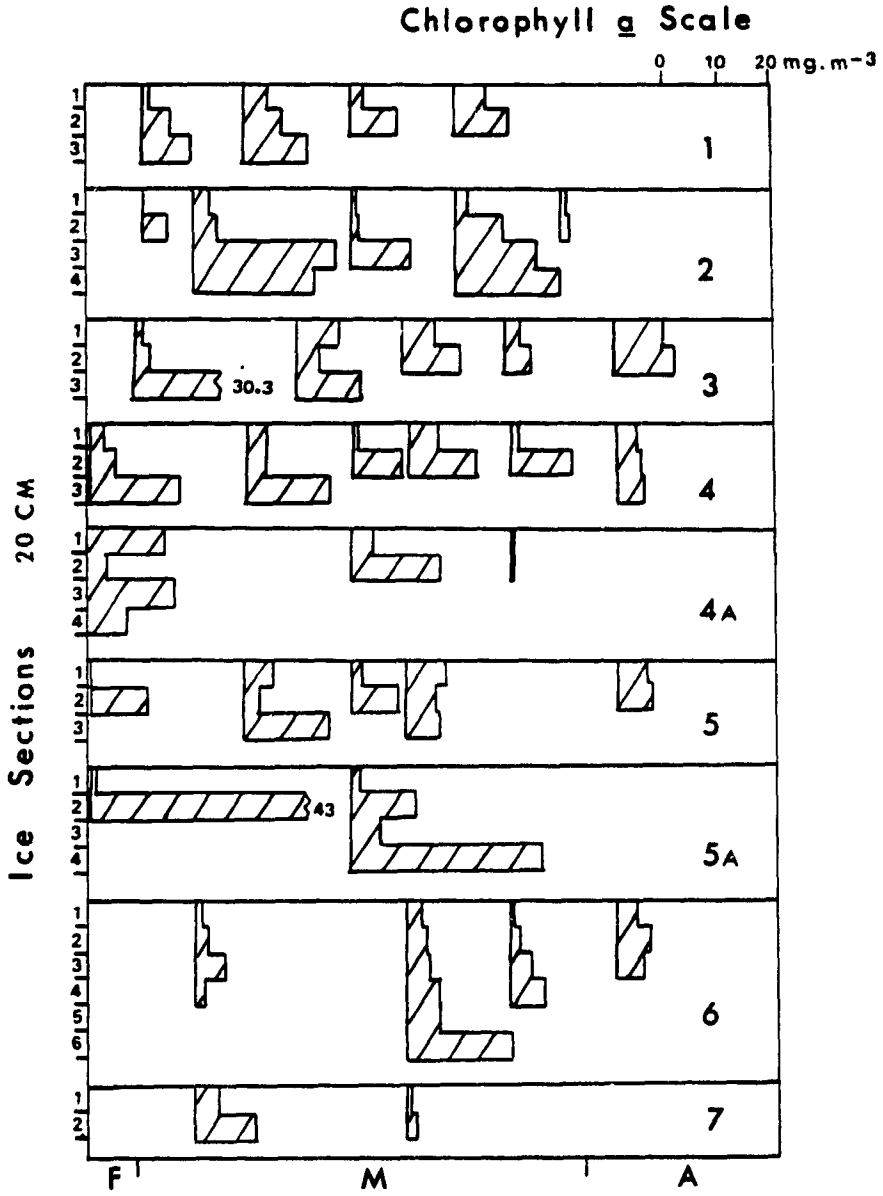

Chlorophyll a Scale
0 10 20 mg.m-3
Ice Sections 20 CM
1
2
3
4
4A
5
5A
6
7
30.3
43
F
M
A

Figure 12. Time scale evolution of chlorophyll a concentrations ($mg.m^{-3}$) in bottom ice sections (■----■) at stations 1 to 7. Seawater chlorophyll a concentrations are not illustrated because values were less than 1.00 $mg.m^{-3}$.

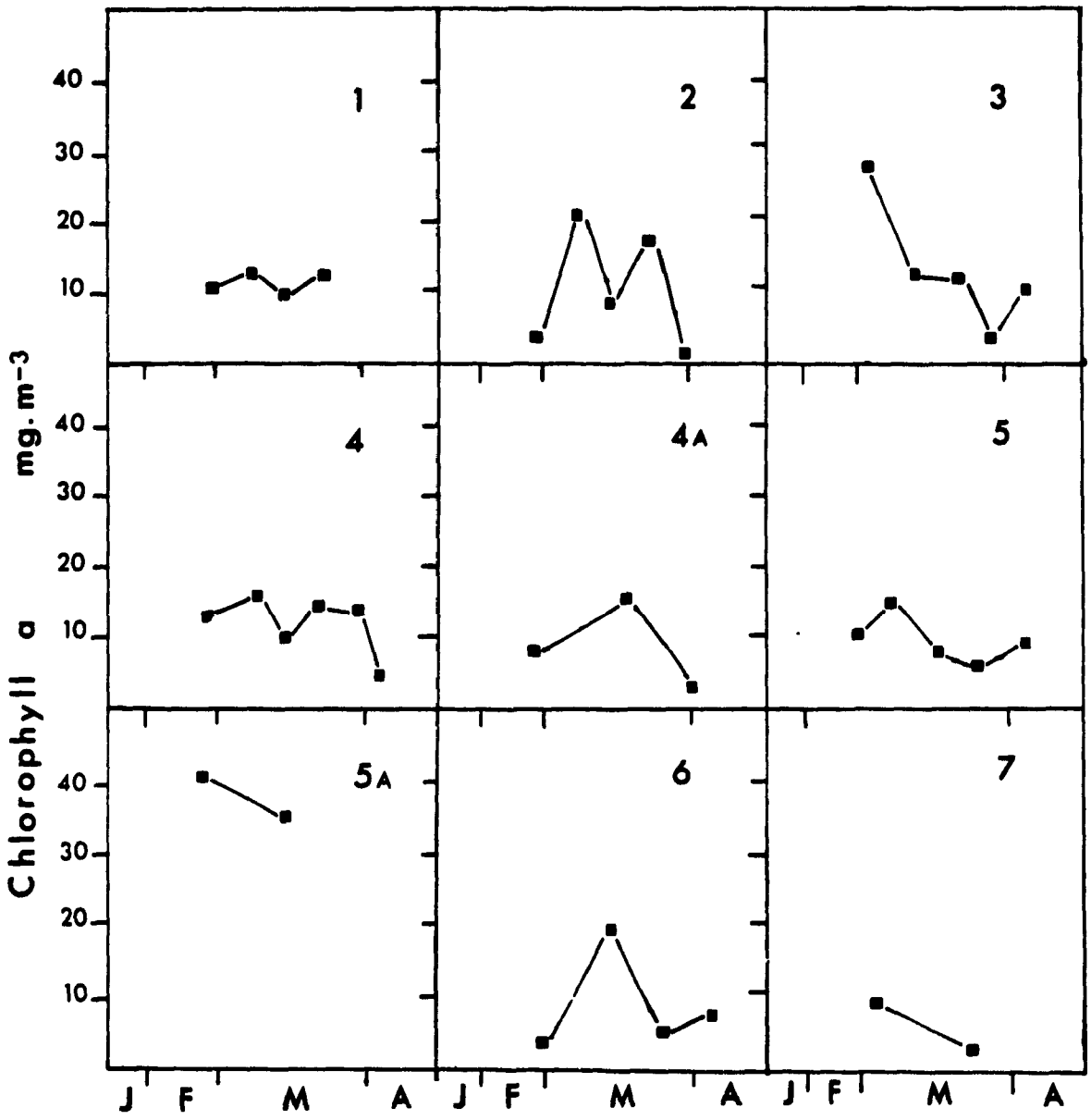
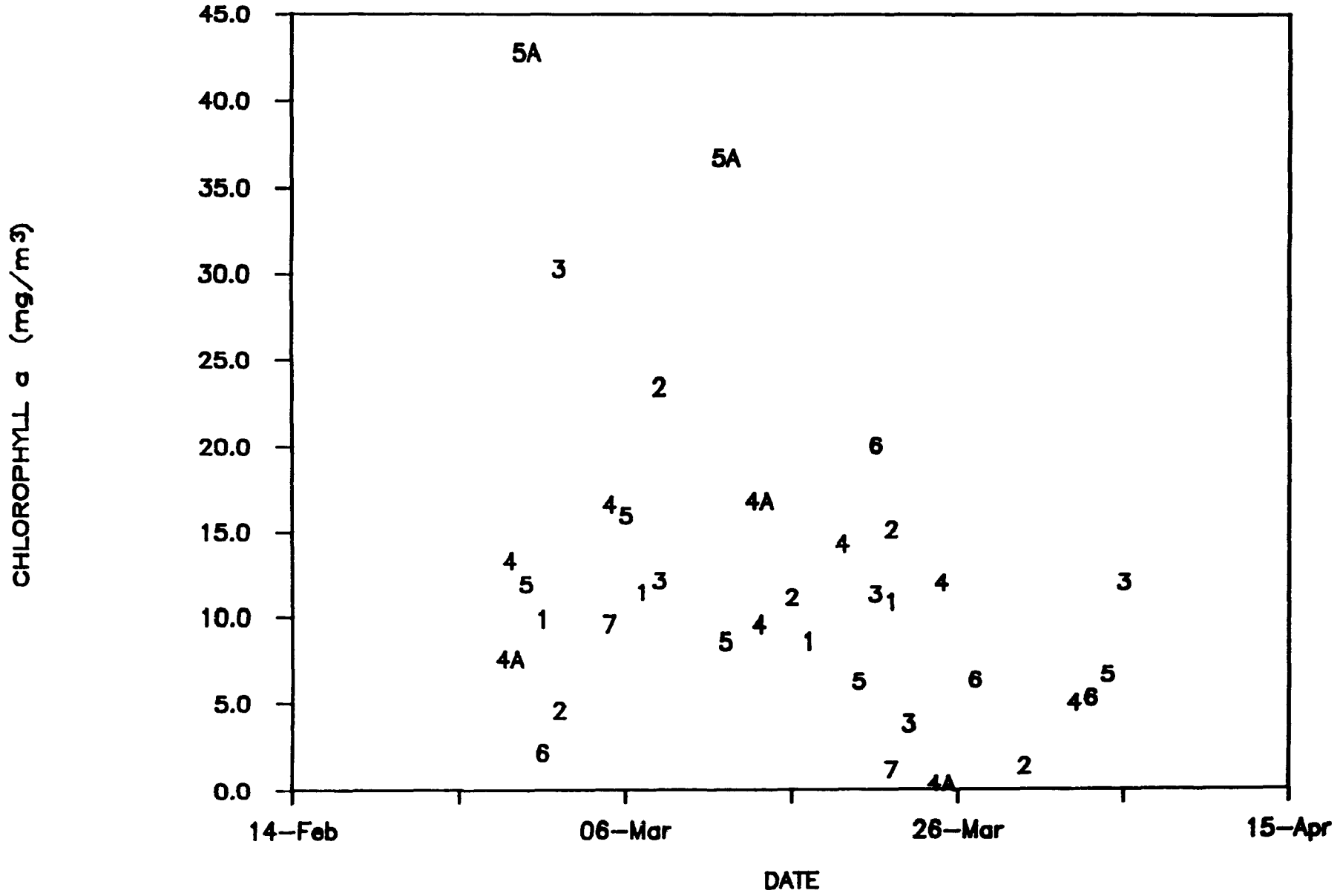

Chlorophyll a
mg.m-3
40
30
20
10
1
2
3
4
4A
5
5A
6
7
J
F
M
A

Figure 13. Time scale evolution of chlorophyll a concentrations ($mg.m^{-3}$) in bottom ice sections grouping stations 1 to 7.

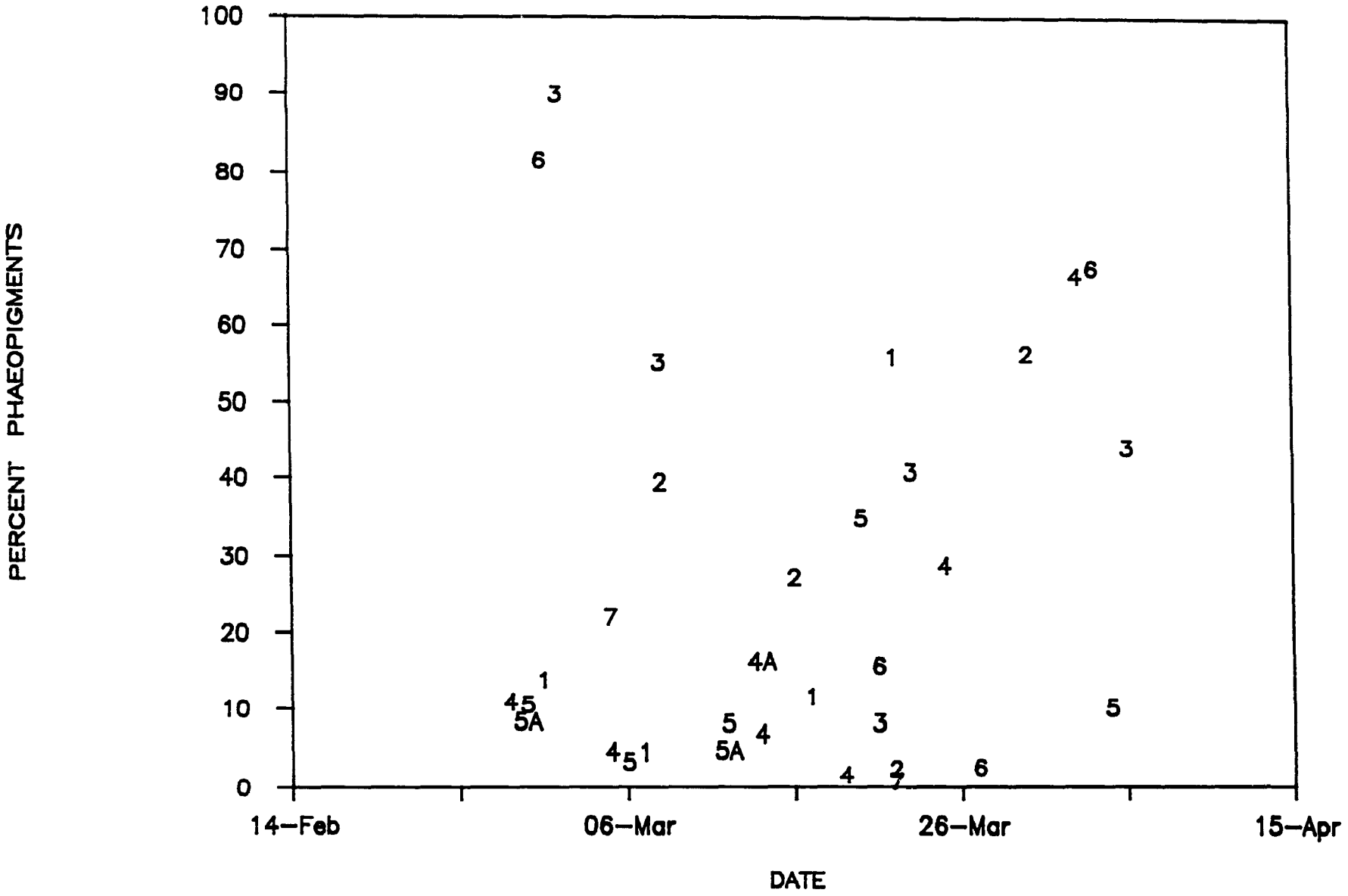

CHLOROPHYLL a (mg/m3)
45.0
40.0
35.0
30.0
25.0
20.0
15.0
10.0
5.0
0.0
14-Feb
06-Mar
26-Mar
15-Apr
DATE

until the 8th of March, which caused a 20cm reduction in ice thickness (see Chapt. I). In seawater, chlorophyll a concentrations were generally less than 1.00 mgm^{-3} (Table 4) with no significant variations in time.

Concentrations of phaeopigments varied from a mean of 1.08 mgm^{-3} at station 5 to 6.97 mgm^{-3} at station 6 (Table 4). No significant differences were observed between the stations (Table 3). Percent ratios of phaeopigments over chlorophyll a were plotted for bottom ice sections from all stations. Results (Fig. 14) seem to indicate an increase in percent phaeopigments from less than 20% in February and early March, exception made of stations 3 and 6, to more than 50% at the end of March. However, no significant regression could be fitted through the data points. Seawater phaeopigment concentrations were low (Table 4), with no significant variations over time.

Estimates of specific growth rates, derived from chlorophyll a concentrations (Table 4) gave positive estimate means of 0.10(±0.05SD) $doublings.day^{-1}$ for bottom ice sections. These estimates should be conservative because they are not corrected for biomass losses associated with sinking, grazing and erosion, and because apparent negative growth rates are not included.

Figure 14. Percentage of phaeopigments with respect to chlorophyll a, in bottom ice sections, grouped for stations 1 to 7 versus time, i.e. from end of February to April.


PERCENT PHAEOPIGMENTS
100
90
80
70
60
50
40
30
20
10
0
14–Feb
06–Mar
26–Mar
15–Apr
DATE

DISCUSSION and CONCLUSIONS

Before sea ice formation, in January, seawater nutrient concentrations were 6.12 µM for NO_3, 6.12 µM for $Si(OH)_4$ and 1.07 µM for PO_4-P. Similar concentrations are reported for winter surface seawater of the Magdalen shallows (Bugden, pers.comm.), Cabot Strait (Coote and Yeats, 1979) and the Gulf of St.Lawrence (Dunbar et al., 1977). After ice formation and throughout ice coverage, a significant decrease in seawater nitrates and silicates is observed, with concentrations of both nutrients falling to less than 1 µM. Depletion is more drastic and occurs earlier at stations 1 and 3 located in lagoons and at station 2 on the eastern coast of the Islands. Depletion is less pronounced and occurs later in time at stations 4, 4A, 5, 5A and 6 located on the western side, while nutrients are not depleted at station 7, the drifting ice station. These results suggest that seawater nutrients are used up by ice algae, and that depletion is more pronounced at stations where underice seawater mixing is reduced such as lagoons and the eastern side of the Magdalen islands. Nutrient depletion is less pronounced on the western side possibly because it is exposed to the prevailing winter northwesterly winds and to drifting ice floes which could enhance underice seawater mixing. No depletion is observed for the drifting ice station where seawater is, contrary to seawater under landfast ice, exposed to vertical mixing

induced by surface winds and by drifting floes. Contrary to nitrates and silicates, seawater phosphorus fractions (SRP and TDP) are not depleted and TDP is even seen to increase with time.

In ice, nitrate fractions (NO_2, NO_3 and NH_4) and silicate concentrations are low (≤1.0 µM) with silicates decreasing to less than 0.5 µM by the end of the ice season: but phosphate fractions (SRP and TDP) concentrated mainly in the bottom ice sections are higher than in seawater and increase in concentration with time.

These results can be interpreted with respect to the three major sources of nutrient supply to ice biota: desalination, in situ regeneration and underice seawater supply. First a look at desalination nutrient supply. An estimate of the potential nutrient supply derived from desalination can be made by integrating nutrient concentrations over the whole ice thickness. For nitrates, average ice concentration of 0.89 mg-atNO_3-.m^{-3} is multiplied by average ice thickness of 0.48m to give a potential supply of 0.42 mg-atNO_3-N.m^{-2}. For silicates, average ice concentration of 1.00 mg-at$Si(OH)_4$.m^{-3} also multiplied by average ice thickness of 0.48m gives a potential supply of 0.48 mgat$Si(OH)_4$.m^{-2}. Ice biota autotrophic nutrient demand, estimated for average bottom ice concentrations of 3.65 mgChl$\underline{a}$.m^{-3} using N:Chl ratio of 9.1 and specific growth rate of 0.10d^{-1}, as mean values obtained in this study, and Si:Chl

ratio of 10 (Nelson and Gordon, 1982) gives an average daily nutrient demand of $0.24 mmol.m^{-2}.d^{-1}$ for nitrates and $0.13 mmol.m^{-2}.d^{-1}$ for silicates. Such estimates of autotrophic nutrient demand, although they are considered as order of magnitude only since the ratios of the major cellular constituents can vary by factors of more than 2 in cases of nutrient limitation (Parsons et al., 1984) or light adaptation (Palmisano et al., 1985), indicate that nutrient supply from the ice is not important. Put another way, the estimated supply from desalination, if it were the only source of nutrient available to the bottom ice algae, would be used up in approximately 4 days. Cota et al. (1987) also found that nutrient supply from desalination represented only a small portion of the bloom's minimum demand for nitrogen and silicon for Arctic ice biota. According to them, this is even more apparent in the Arctic, if one considers that the large pulse of nutrient from the ice occurs during flushing by snow melt waters, and that this event is more or less coincident with the sloughing off of the dense algal mat. In the Gulf of St.Lawrence, flushing occurs more frequently because of higher air temperatures, but the excluded brine is not readily available to ice algae, specially those concentrated in the bottom skeletal layer, since brine leaves the ice in discrete plumes without appreciable diffusion and little mixing back into the seawater layer under the ice (Wakatsuchi and Ono, 1983). However, nutrient supply from

desalination might be more important to ice algae living in brine channels above the skeletal layer since desalination is accompanied by convective replacement of brine by seawater entering the ice through brine channels (Martin, 1970; Niedrauer and Martin, 1979). But long residence time of sea water in brine channels, as estimated in Chapter I, could lead to nutrient limitation despite brine concentrations of nutrients.

Regeneration can be considered as a source of nutrient supply to ice algae. In this study, Ci/Cw ratios for phosphates (SRP) indicated an important enrichment, specially in bottom ice sections. The enrichment is felt mainly in the ice where SOP and TDP concentrations increase with time, but also in seawater where, contrary to nitrates and silicates which are depleted with time, the phosphorus levels remain more or less constant with little decrease, even in protected stations 1,2 and 3 where NO_3 and $Si(OH)_4$ depletion was most apparent. Phosphorus enrichment of bottom ice reported by Meguro et al. (1967), Mel'nikov and Pavlov (1978) and Tsurikov (1983) was thought to result from desalination processes. In this study, Ci/Cw ratios for phosphorus were much higher than salinity ratios indicating that desalination could be ruled out as a possible mechanism of nutrient enrichment. Regeneration is one possible cause for the observed phosphorus enrichment. This is even more apparent considering that enrichment is greatest in bottom ice

sections where the maximum ice algal biomass is found. With respect to Ci/Cw ratios for nitrogen (NO_3, NO_2 and NH_4), some enrichment is observed, particularly in the latter part of March. Regeneration is also suggested here, but enrichment is limited and not sufficient to prevent seawater depletion. This could be explained by the fact that phosphorus regeneration is faster than for nitrogen: Garber (1984) observed regeneration of P occurring after two weeks, but not before 4 weeks for N. In the Arctic, Cota et al. (1987) estimated that regenerative fluxes of nitrogen, based on nitrogen excretion by the heterotrophic community, approached the estimated demand in Barrow Strait, but that this was not the case for silicon for which regeneration is even much slower being mostly a dissolving process (Nelson and Gordon, 1982).

The third source of nutrient supply for ice algae comes from the underice water column. Results on the evolution of nutrients in seawater indicate that nutrient flux from the water column is an important source of supply to ice algae. Nitrates and silicates from the water column are used up by ice algae to the point of depletion, especially at stations protected from winds or drifting ice floes where underice nutrient flux should be reduced. Cota et al. (1987) also found that nutrient flux from the water column was the largest source of nutrient supply for ice algae from Barrow Strait, and that the magnitude of the flux varied

significantly with time over the fortnightly cycle.

Considering that the nutrient flux from the water column is the largest source of supply to ice algae, we can ask ourselves if the observed nitrate and silicate seawater depletion act as a limiting factor to ice algal biomass production in the Magdalen Islands area. Nitrogen reaches concentrations in seawater that are less than the starvation level of 0.3 µM reported by Collos (1980). Furthermore, seawater N:P ratios are generally less than 10 (Fig. 15) with have a mean value of 3.63(±6.55SD), and C:N ratios from POC and PON data give cell ratios of 8-9 for February, increasing to more than 10 by April (Fig. 16). Although it is sometimes misleading to interpret low seawater N:P ratios as indicative of N limitation, it is generally considered that C:N ratios ≥10 represent real subsaturation with nitrogen in marine diatoms (Sakshaugh et al., 1983). C:N ratios increase under N deprivation as a result of photosynthates being directed into carbohydrates and relatively little into proteins (Smith et al., 1987).

Silicate limitation should also be considered with seawater $Si(OH)_4$ concentrations less than 1 µM and N:Si ratios greater than 1 (Fig. 17). Silicate starvation is reported to occur at $Si(OH)_4$ concentrations of 2.0-5.0 µM (Dugdale et al., 1981; Jacques, 1983; Laing, 1985) and Si limitation predicted for N:Si ratios >1 (Levasseur and Therriault, 1987). Si limitation can also lead to an increase

Figure 15. N:P ratios in bottom ice sections grouped for stations 1 to 7 versus time, i.e. from end of February to April.

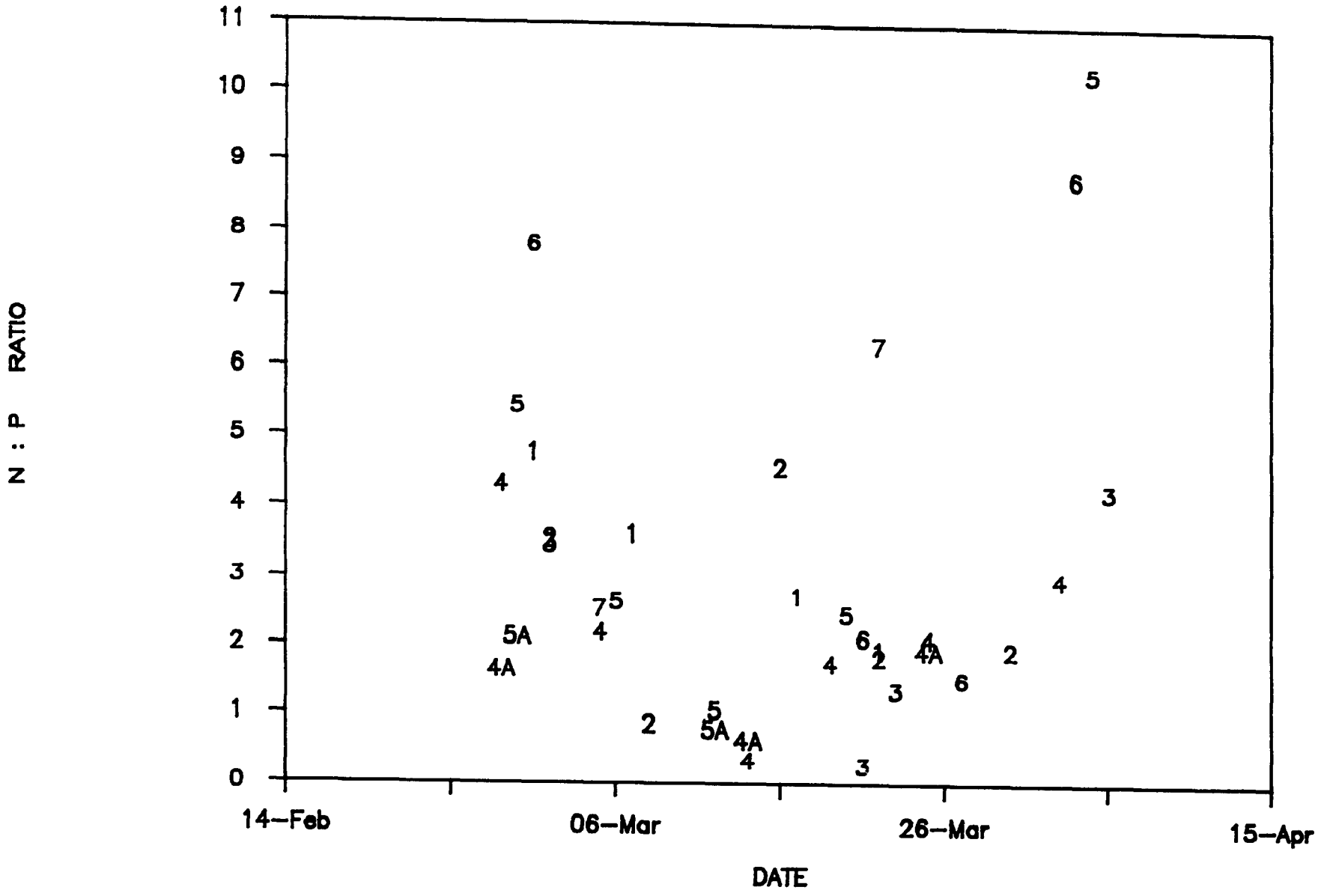

N : P RATIO
11
10
9
8
7
6
5
4
3
2
1
0
14–Feb
06–Mar
26–Mar
15–Apr
DATE

Figure 16. C:N ratios from bottom ice sections, grouped for stations 1 to 7 versus time, i.e. from the end of February to April.

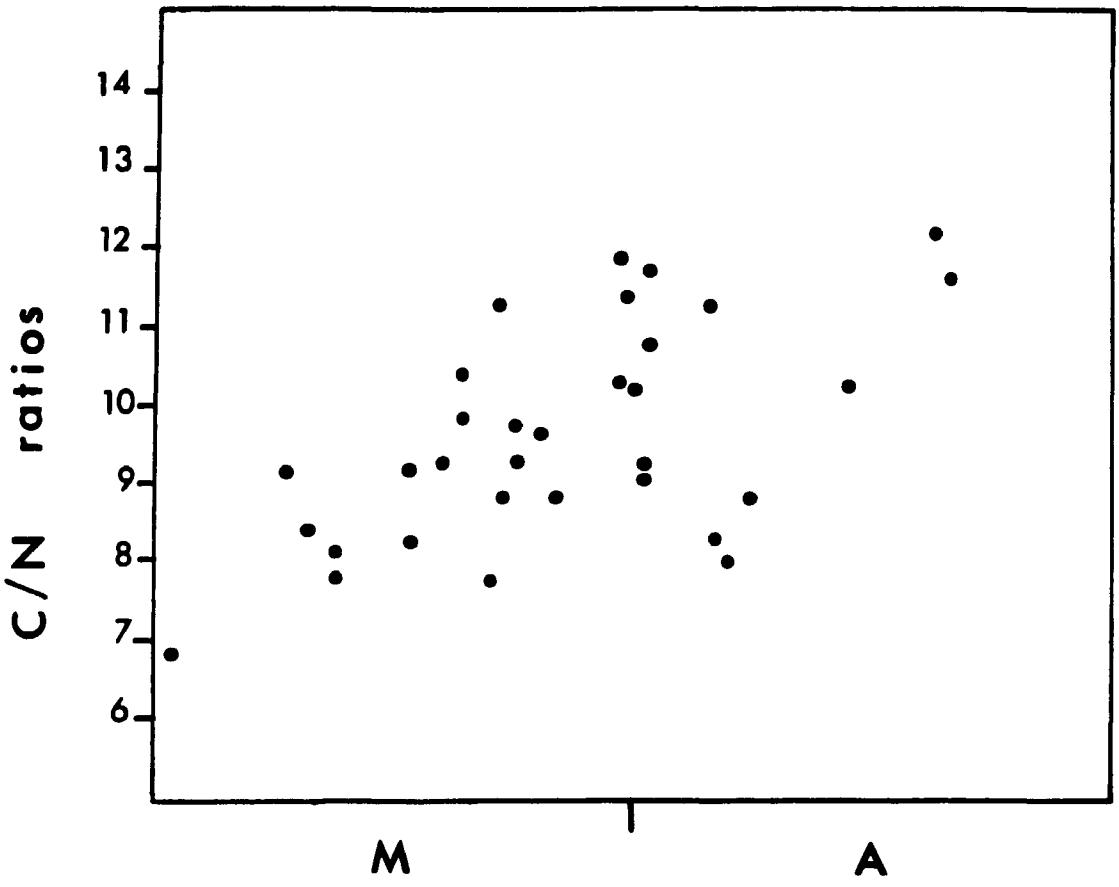
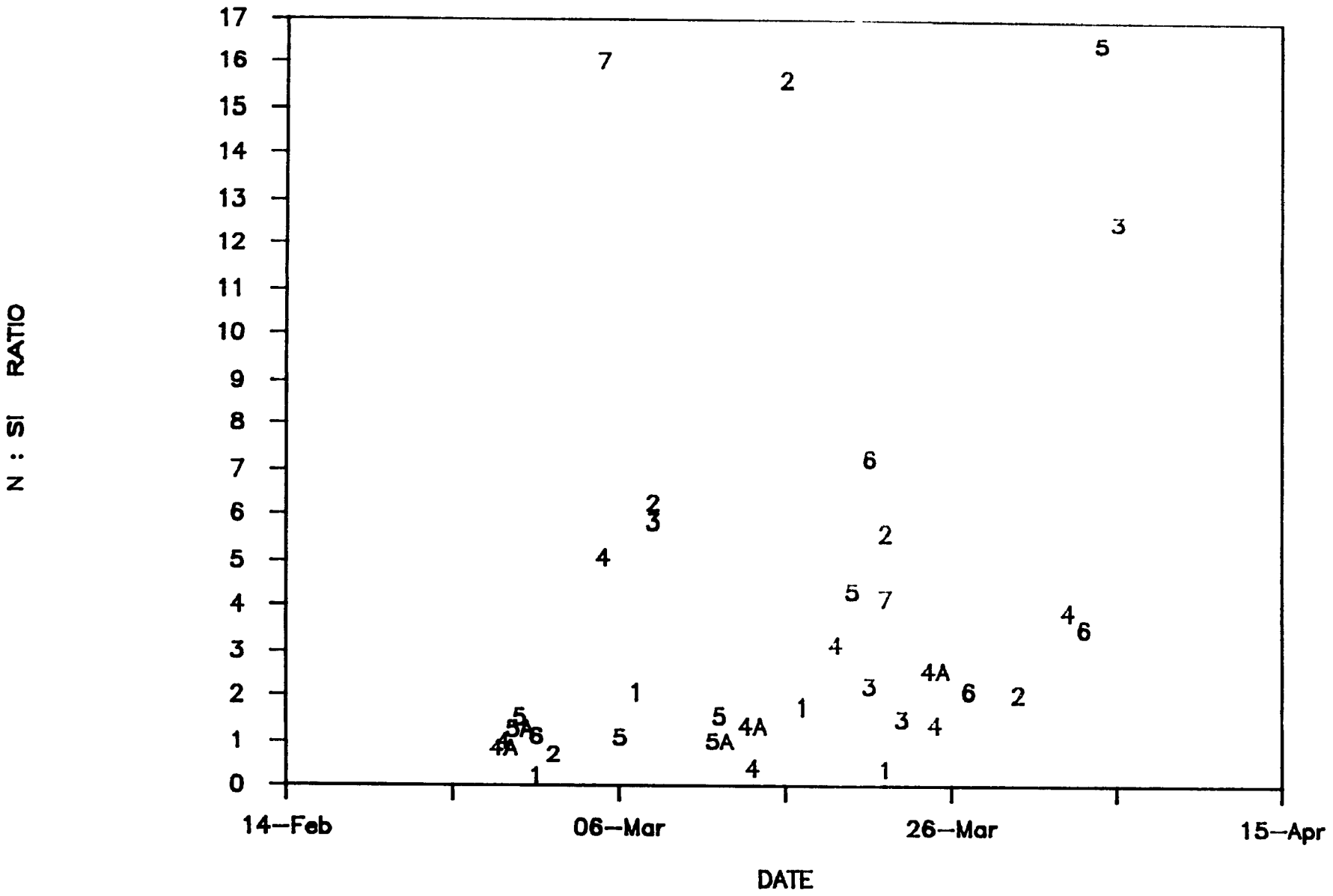

C/N ratios
14
13
12
11
10
9
8
7
6
M
A

Figure 17. N:Si ratios from bottom ice sections, grouped for stations 1 to 7 versus time, i.e. from the end of February to April.


N : SI RATIO
17
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0
14—Feb
06—Mar
26—Mar
15—Apr
DATE

in C:N ratios as a result of lipid accumulation (Taguchi et al., 1987), and to thin walled diatom frustules which were frequently observed in this study.

Chlorophyll measures of ice biota from the Magdalen Islands for bottom ice sections vary from a minimum of 5.45 $mg.m^{-3}$ of chl *a* at station 7 to a maximum of 39.9 $mg.m^{-3}$ at station 5A. Such biomass values are much lower than values found at higher latitudes. Dunbar and Acreman (1980) report bottom ice chl *a* concentrations of 89.31 $mg.m^{-3}$ in Hudson Bay, 49.75 $mg.m^{-3}$ in Barrow Straït and 20.36 $mg.m^{-3}$ in Robeson Channel. Poulin et al. (1983) found maximum chl *a* concentrations of 247 $mg.m^{-3}$ in Manitounouk Sound, Hudson Bay, and Cota et al. (1987) found a mean of 335 $mg.m^{-3}$ in Barrow Strait.

Chlorophyll *a* values from landfast ice stations are significantly higher than at the drifting ice station. These results are in accordance with Dunbar and Acreman (1980) and Demers et al. (1984) who found drifting ice chl *a* concentrations of 2.82 $mg.m^{-3}$ for the Gulf of St.Lawrence and of 0.5-2.3 $mg.m^{-3}$ in the St.Lawrence Estuary. This suggests that drifting ice is less suited for the development of ice biota than landfast ice, possibly because it is less stable and subjected to rapid mouvement and deformation. It should be noted that contrary to results from landfast ice stations, no nutrient depletion occurs at station 7, and therefore nutrient limitation cannot be considered a significant

factor.

Time scale evolution of chlorophyll a for bottom ice sections (Fig. 13) indicates a decrease in chlorophyll concentrations in the second week of March following air temperature increases above 0°C. Air temperature increases above the freezing point cause melting of surface ice and allow for flushing, which is the most effective mechanism for ice desalination. The first ice melt actually resulted in a 20cm decrease in ice thickness (see Chapter 1). Therefore flushing, associated with decreases in ice thickness seems to limit biomass accumulation of ice biota in the Magdalen area, especially at landfast ice stations protected from rafting. At higher latitudes, flushing occurs only at the end of the ice algal bloom and is associated with the sloughing off of the ice algae (Cota et al., 1987). Therefore the instability of the ice substrate, with respect to ice melt, could be suggested here as a limiting factor of ice algal biomass accumulation.

Specific growth rate estimates for bottom ice sections were in the order of 0.10±.05SD doublings per day. Recent data for Arctic species indicate a range of 0.3-0.7d^{-1} (Hegseth, 1982). However, in the high Arctic, Cota et al. (1987) estimated specific growth rates of 0.08-0.25d^{-1}, with a maximum of 0.96d^{-1} for natural assemblages; Alexander et al. (1974) reported 0.13-0.16d^{-1}, and Horner and Schrader (1982) reported 0.26d^{-1}, all from bottom ice chlorophyll

accumulation. Growth rates for ice algae from the Gulf of St.Lawrence would therefore fit in the lower range of Arctic ice biota growth rates. Reduced algal growth rates can result from low temperature, low light intensity, high environmental variability or nutrient limitation. Considering that bottom ice temperature is somewhat similar at all latitudes, it can be asked which environmental factor limits growth and ice algal biomass accumulation in the Gulf of St.Lawrence.

Nutrient limitation, specially of nitrates and silicates, is a possible cause of lower ice algal biomass in the Gulf of St.Lawrence as indicated by N/P and C/N ratios. C/chl$\underline{a}$ ratios of 99.6(±64.3SD) could further support N limitation or indicate poor physiological state (Eppley, 1972). There are indications of nitrogen limitation of ice algal production in the Arctic (Grainger, 1977; Gosselin et al., 1985; Cota et al., 1986; Maestrini et al., 1986) but perhaps not to such an extent as for ice biota in the Gulf of St.Lawrence.

Differences in underice light regimes could also account for reduced ice algal biomass at lower latitudes as suggested by Dunbar and Acreman (1980) and Demers et al. (1983). Underice light intensities, estimated for the Gulf of St.Lawrence using Maykut and Grenfell (1975) light absorption spectra for an average ice thickness of 50cm and an average surface irradiance of 5,266.4ftcd (data obtained from Environment Canada), gave underice light irradiance of 526.6-

1053.28ftcd, compared with 5-10ftcd during Arctic ice algal bloom (Grainger, 1977). Shade adapted Arctic ice algae are reported to be light saturated at 110ftcd with photoinhibition at about 1200ftcd (Bunt, 1964; Sakshaugh, 1983). Low compensation light intensities, achieved through increased numbers of photosynthetic units and chlorophyll a content per cell, is a critical adaptation permitting the growth of ice algae in the Arctic despite low light intensities. Therefore higher underice light intensities in the Gulf of St.Lawrence, coupled with short duration of ice coverage, could possibly limit ice biota production by not allowing for extreme shade-adaptation. Although no direct proof of this exists, since the results of chlorophyll a content per cell were highly variable, the C/chla ratios of 99.6(±64.3SD) could suggest poor adaption to light intensities. Indeed, C/chla ratios of 38 are typical of bottom ice communities adapted to low light levels while ratios ≥100 are found when there is not sufficient time for adaptation to underice light regimes (Bunt, 1964; Palmisano et al., 1985). Palmisano et al. (1985) report that adaptation to low light intensities, resulting in a decrease in C/chla ratios due to a 5 fold increase in chlorophyll a, was found to occur after a period of six weeks. This is about equivalent to the duration of ice coverage in the Gulf of St.Lawrence (6 to 8 weeks).

In summary, the results obtained from this study

indicate nutrient limitation with respect to nitrates and silicates. However, no correlations are observed between nutrients and biomass of bottom ice, based on chlorophyll a concentrations, suggesting that growth rates more than biomass are affected by the nutrient limitation. This is supported by growth rate estimates being in the lower range of values described for Arctic ice algae. The instability of the ice substrate, with respect to ice melt, is also suggested as a limiting factor in view of the decrease in chlorophyll a associated with a decrease in ice thickness. As for higher underice light intensities, there is some evidence of lack of shade adaptation of ice algae in the Gulf of St.Lawrence, but it might be a consequence of the short duration of ice coverage.

Literature Cited

Alexander, V. 1974. Primary productivity regimes of the nearshore Beaufort Sea, with reference to potential role of ice biota. In Reed, J.C. and Sater, J.E. (Eds.): The coast and shelf of the Beaufort Sea, pp. 609-632. Arctic Institute of North Amarica, Arlington, Va.

Alexander, V., R. Horner and R.C. Clasby. 1974. Metabolism of Arctic sea ice organisms, Rep. R74-4, 120pp. Inst. of Mar. Sci., Univ. of Alaska, Fairbanks.

Box, G.E.P., W.G. Hunter and J.S. Hunter. 1978. Statistics for experimenters: an introduction to design, data analysis and model building, 653 pp. John Wiley and Sons, New York.

Bunt, J.S. 1964. Primary productivity under sea ice in Antarctic waters. 2. Influence of light and other factors on photosynthetic activities of Antarctic marine microalgae. Antarctic Res. Ser. 1: 27-31.

Carey, A.G. 1985. Marine ice fauna: Arctic. In Horner, R. (Ed.): Ice Biota, pp. 173-190. CRC Press, Cincinnati, Ohio.

Collos, Y. 1980. Transient situations in nitrate assimilation by marine diatoms. 1. Changes in uptake parameters during nitrogen starvation. Limnol. Oceanogr. 25: 1075-1081.

Coote, A.R. and P.A. Yeats. 1979. Distribution of nutrients in the Gulf of St.Lawrence. J. Fish. Res. Board Can. 36: 122-131.

Cota, G.F. 1985. Photoadaption of high Arctic ice algae. Nature 315: 219-222.

Cota, G.F., S.J. Prinsenberg, E.B. Bennett, J.W. Loder, M.R. Lewis, J.L. Anning, N.H.F. Watson and L.R. Harris. 1987. Nutrient fluxes during extended blooms of Arctic ice algae. J. Geophys. Res. 92: 1951-1962.

Dahlback, B.L., A.H. Gunnarsson, M. Hermansson and S. Kjelleberg. 1982. Microalgal investigations of surface microlayers, water column, ice and sediment in the Arctic ocean. Mar. Ecol. Prog. Ser. 9: 101-109.

Demers, S., J.C. Therriault et C. Descolas-Gros. 1984. Biomasse et composition spécifique de la microflore des glaces saisonnières: influence de la lumière et de la vitesse de congélation. Marine Biol. 48: 185-191.

Dillon, W.R. and M. Goldstein. 1984. Multivariate analysis: methods and applications, 587 pp. John Wiley and Sons, New York.

Dugdale R.C. B.H. Jones Jr., J.J. MacIsaac and J.J. Goering. 1981. In Platt, T. (Ed.): Physiological bases of phytoplankton ecology, pp. 234-250. Can. Bull. Fish. Aquat. Sci. 210: 1-346.

Dunbar, M.J., D.C. McLellan, A. Filion and D. Moore. 1977. The biogeographic structure of the Gulf of St.Lawrence. Mar. Sci. Centre. 143p.

Dunbar, M.J. and J.C Acreman. 1980. Standing crop and species composition of diatoms in sea ice from Robeson Channel to the Gulf of St.Lawrence. Ophelia 19: 61-72.

Eppley, R.W. 1972. Temperature and phytoplankton growth in the sea. Fish. Bull. 70: 1063-1085.

Freeman, N.G., J.C. Roff and R.J. Pett. 1982. Physical and biological features of river plumes under an ice cover in James and Hudson Bays. Naturaliste Can. 109: 745-764.

Garber, J.H. 1984. ^{15}N tracer study of the short-term fate of particulate organic nitrogen at the surface of coastal marine sediments. Mar. Ecol. 16: 89-104.

Gosselin, M., L. Legendre, S. Demers and R.G. Ingram. 1985. Response of sea ice microalgae to climatic and fortnightly tidal energy inputs (Manitounouk Sound, Hudson Bay). Can. J. Fish. Aquat. Sci. 42: 999-1006.

Grainger, E.H. 1977. The annual nutrient cycle in sea ice. In Dunbar, M.J. (Ed.): Polar Oceans, pp. 285-301. Arctic Institute of North America, Calgary.

Grossi, S.M., S.T. Kottmeier and C.W. Sullivan. 1984. Sea ice microbial communities. III. Seasonal abundance of microalgae and associated bacteria, McMurdo Sound, Antarctica. Microb. Ecol. 10: 231-242.

Healy, F.P. and L.L. Hendzel. 1980. Physiological indicators of nutrient deficiency in lake phytoplankton. Can. J. Fish. Aquat. Sci. 37: 442-453.

Hegseth, E.N. 1982. Chemical and species composition of phytoplankton during the first spring bloom in the Trondheimsfjord. 1975. Sarsia 67:131-141.

Horner, R.A. 1976. Sea ice organisms. Oceanogr. Mar. Biol. Ann. Rev. 14: 167-182.

Horner, R.A. and G.C. Schrader. 1982. Relative contributions of ice algae, phytoplankton and benthic microalgae to primary production in near shore regions of the Beaufort Sea. Arctic 35: 485-503.

Jacques, G. 1983. Some physiological aspects of the Antarctic phytoplankton. Polar Biol. 2: 27-33.

Kottmeier, S.T., S. McGrath Grossi and C.W. Sullivan. 1987. Sea ice microbial communities. VIII. Bacterial production in annual sea ice of McMurdo Sound, Antarctica. Mar. Ecol. Prog. Ser. 35: 175-186.

Laing, I. 1985. Growth response of Chaetoceros calcitrans (Bacilariophyceae) in batch culture to a range of initial silica concentrations. Marine Biol. 85: 37-41.

Levasseur, M.E. and J.C. Therriault. 1987. Phytoplankton biomass and nutrient dynamics in a tidally induced upwelling: the role of the NO_3:SiO_4 ratio. Mar. Ecol. Prog. Ser. 39: 87-97.

Maestrini, S.Y., M. Rochet, L. Legendre and S. Demers. 1986. Nutrient limitation of the bottom-ice microalgal biomass (southeastern Hudson Bay, Canadian Arctic). Limnol. Oceanogr. 31: 969-982.

Martin, S. 1970. A hydrodynamic curiosity: the salt oscillator. Geophys. Fluid Dynamics 1: 143-160.

Maykut, G.A. and T.G. Grenfell. 1975. The spectral distribution of light beneath first-year sea ice in the Arctic Ocean. Limnol. Oceanogr. 20: 554-563.

McCarthy, J.J. and J.C. Goldman. 1979. Nitrogenous nutrition of marine phytoplankton in nutrient-depleted waters. Science 203: 670-672.

McConville, M.J., G. Mitchell and R. Wetherbee. 1985. Patterns of carbon assimilation in a microbial community from annual sea ice, East Antarctica. Polar Biol. 4: 135-141.

Meguro, H., I. Kuniyuki and H. Fukushima. 1967. Ice flora (Bottom type): a mechanism of primary production in Polar seas and the growth of diatoms in sea ice. Arctic 20: 114-133.

Mel'nikov, I.A. and G.L. Pavlov. 1978. Characteristics of organic carbon distribution in the waters and ice of the Arctic Bassin. Oceanology 18: 163-167.

Nelson, D.M. and L.I. Gordon. 1982. Production and pelagic dissolution of biogenic silica in the southern ocean. Geochim. Cosmochim. Acta 46: 491-501.

Niedrauer, T.M. and S. Martin. 1979. An experimental study of brine drainage and convection in young sea ice. J. Geophys. Res. 84: 1176-1186.

Palmisano, A.C. and C.W. Sullivan. 1983. Physiology of sea ice diatoms. II. Dark survival of three polar diatoms. Can. J. Microbiol. 29: 157-160.

Palmisano, A.C. and C.W. Sullivan. 1985. Pathways of photosynthetic carbon assimilation in sea ice microalgae from McMurdo Sound, Antarctica. Limnol. Oceanogr. 30: 674-678.

Palmisano, A.C., S.T. Kottmeier, R.L. Moe and C.W. Sullivan. 1985. Sea ice microbial communities. IV. The effects of light perturbation on microalgae at the ice-seawater interface in McMurdo Sound, Antarctica. Mar. Ecol. Prog. Ser. 21: 37-45.

Parsons, T.R., M. Takahashi and B. Hargrave. 1984. Biological Oceanographic Processes, 3rd ed., Pergamon, Elmsford, New York.

Poulin, M., A. Cardinal et L. Legendre. 1983. Réponse d'une communauté de diatomées de glace à un gradient de salinité (Baie d'Hudson). Marine Biol. 76: 191-202.

Ray, A.A. (Ed.). 1982a. SAS User's guide: Statistics, 584 pp. Cary, N.C.: Statistical Analysis Systems Institute.

Ray, A.A. (Ed.). 1982b. SAS User's guide: Basics, 923 pp. Cary, N.C. Statistical Analysis Systems Institute.

Reeburgh, W.S. 1984. Fluxes associated with brine motion in growing sea ice. Polar Biol. 3: 29-33.

Sakshaugh, E., A. Kjersti, M. Sverre and Y. Olson. 1983. Nutrient status of phytoplankton communities in Norwegian waters (marine, brackish and fresh) as revealed by their chemical composition. J. Plankton Res. 5: 175-196.

Smith, R.E.H. and R.J. Geider. 1985. Kinetics of intracellular carbon allocation in a marine diatom. J.

Exp. Mar. Biol. Ecol. 93: 191-210.

Smith, R.E.H., P. Clement, G.F. Cota and W.K.W. Li. 1987. Intracellular photosynthate allocation and the control of Arctic marine algal production. J. Phycology 23:124-132.

Strickland, J.D.H. and T.R. Parsons. 1972. A practical handbook of seawater analysis, 2nd ed. Bull. Fish. Res. Board Can. 167: 1-310.

Sullivan, C.W., A.C. Palmisano, S.T. Kottmeier, S.M. Grossi and R. Moe. 1985. Influence of light on growth and development of the ice microbial community in McMurdo Sound. In Siegfried, R., P.R. Condy and R.H. Laws (Eds.): Fourth SCAR Symposium on Antarctic Biology: Food webs and nutrient cycles, Springer-Verlag, Basel.

Taguchi, S., J.A. Hirata and E.A. Laws. 1987. Silicate deficiency and lipid synthesis of marine diatoms. J. Phycol. 23: 260-267.

Tsurikov, V.L. 1983. Mechanism of sea ice colonisation and the possibilities of a microflora developing in it. Can. Trans. Fish. Aquat. Sci. 1916: 1-29.

Wakatsuchi, M. and N. Ono. 1983. Measurements of salinity and volume of brine excluded from growing sea ice. J. Geophys. Res. 88: 2943-2951.

Zar, J.H. 1984. Biostatistical Analysis, 718 pp. Englewood Cliffs: Prentice -Hall, Inc.

CHAPTER III

ICE BIOTA FROM THE GULF OF ST.LAWRENCE, MAGDALEN ISLANDS AREA.

PART III: COMMUNITY STRUCTURE AND COMPOSITION

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Abstract

The structure and the composition of ice biota communities from the Gulf of St.Lawrence, Magdalen Islands area, were studied at six landfast ice stations and one drifting ice station throughout the period of ice coverage. On the basis of species composition, two types of ice biota communities were found in bottom ice: communities composed of predominantly pennate diatoms (abundance > 98.0%), and communities with a high abundance of centric diatoms (abundance > 46.2%). The first community type, found at stations located in lagoons and on the eastern coast of the Magdalen Islands, is similar to Arctic landfast ice biota communities with Nitzschia cylindrus, N. polaris and Navicula karlana as dominant species. The second community type, found at stations located on the western coast of the Islands and at the drifting ice station, is similar to drifting ice biota communities previously described from the Gulf of St.Lawrence, with a high percentage of centric diatom species (> 46.2%) due to the dominance of the planktonic diatom Thalassiosira nordenskioldii. Species richness and the Shannon-Weaver index of diversity were low, with mean values for bottom ice of S=9.5 and H'=0.57 . Density in number of cells/L was variable with mean values for bottom ice ranging between 10^4-10^6xcells/L, and was negatively correlated with % centric diatoms, the density being two orders of magnitude

higher at stations with low % centric diatoms (< 2%). Results on the structure and the composition of the ice biota communities are discussed in relation to ice type, i.e. landfast and drifting pack ice, and in comparison to ice biota communities from higher latitudes.

INTRODUCTION

The presence of ice algae has been known for nearly 150 years. They were first described from the Arctic by Ehrenberg (1853) and from the Antarctic by Hooker (1847). The literature on ice biota which has grown considerably since then, and more particularly in recent years, was summarized by Grainger (1977, 1979) and by Horner (1976, 1977 and 1985). Three main types of ice microalgal communities have been described: surface, interior and bottom ice communities.

Surface ice communities include microalgae found in association with the snow-ice interface flooded by seawater upon ice depression by snow weight, such as described by Meguro (1962) in the Antarctic. Another type of surface ice community is found in association with ice surface melt pools when there is not enough snow to depress the ice (McConville and Wetherbee, 1983). In pack ice from Davis Strait (Booth, 1984) and in Antarctic waters (Fukushima and Meguro, 1966), surface water washing over ice floes has been observed to seed the surface of the ice with planktonic algae, but without indication of survival or growth of the algae (Horner, 1985). This is also true of surface ice communities described in the Arctic by Grainger and Hsiao (1982) and in the Antarctic by Hoshiai (1977) which are thought to be remnant populations of bottom ice autumn blooms.

Interior ice communities are mainly found in the Antarctic, although there is one report of an interior ice community from the Bering sea (Horner, 1985). In the Antarctic, this type of community results from brine drainage processes initiated by summer warming but not carried to completion (Ackley et al., 1978). This process causes redistribution of salinity and of nutrients in the mid-depth region of the ice, thus promoting ice microalgal growth.

Bottom ice communities are the most important in terms of production and standing crop. In the Antarctic, bottom ice communities are mainly found in frazil ice which forms through aggregation of unconsolidated ice crystals held in place by their positive buoyancy (Bunt and Lee, 1970). In the Arctic, bottom ice communities are concentrated in the skeletal layer which occupies the bottom centimeters of congelation ice and which is in direct contact with the underlying seawater. Seawater nutrient supply to the skeletal layer is responsible for active growth of bottom ice microalgal communities (Cota et al., 1987). An additional type of bottom community, the mat-strand community, forming a mat-like covering with suspended strands of microalgae, is also reported from Antarctica (McConville and Wetherbee, 1983).

Underice phytoplankton blooms have been recorded in Hudson Bay (Legendre et al., 1981) and in the Bering sea (Saito and Taniguchi, 1978) where they were associated with

underice brackish layers and dominated by flagellates. There are also reports of spring blooms associated with frontal structure at the ice edge (Alexander and Niebrauer, 1981) with similar species composition in ice and in seawater. However, underice seawater communities usually consist of senescent, sloughed ice microalgae in low concentrations (Horner, 1977; Horner and Schrader, 1982; Pett et al., 1983; Rymes, 1986).

In sea ice the most commonly occurring microalgae belong to such classes as the Bacillariophyceae (Diatoms), the Chrysophyceae, the Chlorophyceae, the Dynophyceae and the Euglenophyceae. Diatoms are the most abundant group of microalgae found in sea ice with pennate forms being dominant. This is particularly true of landfast ice communities, in both polar regions, where pennate diatoms account for more than 90% of the species abundance (Burkholder and Mandelli, 1965; Meguro et al., 1967; Whittaker, 1977; Horner and Schrader, 1982; Pett et al. 1983; Rymes, 1986). Considering sea ice as a substrate analogous to the benthos, in fact an upper solid substrate or a "ceiling" as proposed by Dunbar and Acreman (1980), it is not surprising to find that ice biota communities are, similarly to benthic microalgal communities, dominated by pennate diatoms. Indeed pennate diatoms, contrary to centric diatoms, are found mainly in association with substrates to which they can attach by mucilaginous secretions and on which they can

move about through cytoplasmic streaming in the raphe (Patrick and Reimer, 1966). Furthermore, a number of studies have shown that pennate diatoms are adapted to low light intensities, a condition inherent to benthic and ice environments (Rivkin and Putt, 1987). There is however no significant species correlation between benthic and ice diatom communities (Horner, 1985). Pennate ice diatoms seem to be typical cryophiles found only in association with sea ice (Usachev, 1949).

Centric diatoms have been reported for landfast ice communities, but only for a few species and never in great abundance (Grainger and Hsiao, 1982). The occurrence of centric species is higher in Antarctic than in Arctic ice, possibly due to the unconsolidated frazil ice structure of Antarctic ice which allows more water to be present between ice crystals, thus providing a more favorable habitat for centric species (Horner, 1985). However, centric diatoms are reported as dominant species in a number of studies on drifting pack ice communities from both polar regions (Vanhöffen, 1893, 1897; Gran, 1897; Meister, 1930; Usachev, 1938, 1949; Hart, 1942). Apollonio (1985), referring to Sutherland's (1852) report of an Arctic summer pack ice community that was dominated by the centric diatom Melosira arctica, even suggested the existence of a second arctic ice flora separated floristically and ecologically distinguishable from landfast ice flora.

Dunbar and Acreman (1980) also found ice biota communities that were dominated by centric diatom species in drifting pack ice from the Gulf of St.Lawrence, but they report that pennate diatoms are dominant in landfast ice communities from higher latitudes. Demers et al. (1984), in their study of ice biota from drifting ice floes in the St.Lawrence estuary, similarly found communities with high abundance of centric species. The differences in species composition between higher and lower latitudes were attributed to the shorter duration of ice cover and higher underice light intensity in the Gulf of St.Lawrence (Dunbar and Acreman, 1980). These conditions were suggested to favour planktonic centric diatoms over shade-adapted pennate ones.

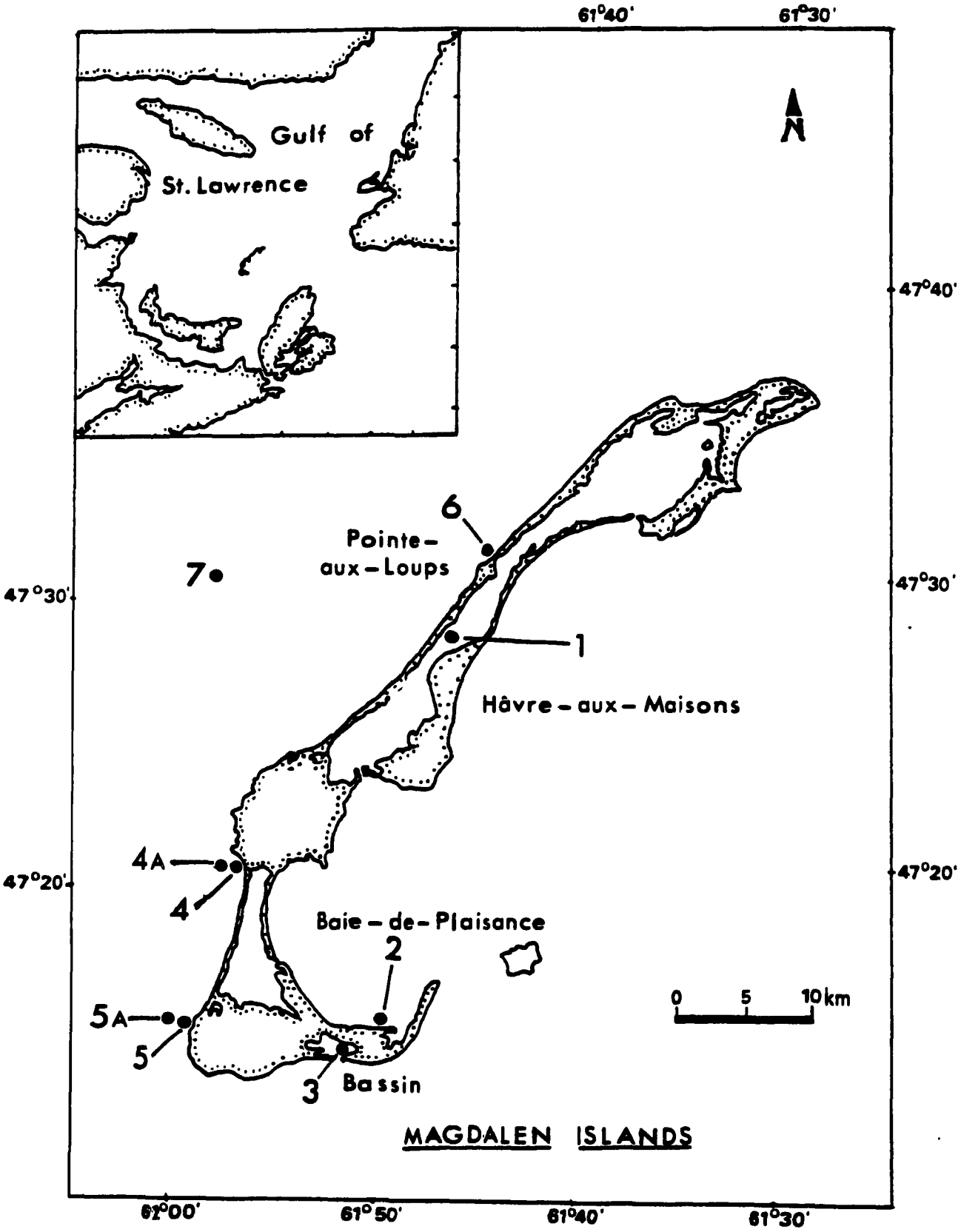
The present study of ice biota from the Gulf of St.Lawrence was undertaken in view of the results obtained by Dunbar and Acreman (1980) and by Demers et al. (1984). The objective of this study was to test the hypothesis that abundance of centric species in ice biota from lower latitudes was favoured by the shorter duration of the ice cover and by the higher underice light intensities. Community structure and species composition were therefore determined for landfast and drifting pack ice stations in relation to 1) sea ice characteristics, 2) environmental variables including nutrient regimes, and 3) ice biota from higher latitudes.

MATERIALS and METHODS

Study Sites

The structure and composition of ice biota communities from the Gulf of St.Lawrence were studied in the Magdalen Islands area, situated in the centre of the Gulf of St.Lawrence at latitude 47° to 48° North and longitude 61° to 62° West. The location of the six land fast ice stations (1 to 6) and of the drifting ice station (7) is illustrated in Figure 1. Station numbers and locations are the same as in Chapters I and II. Stations 1 and 3, located in Havre-aux-Maisons and at Bassin, are protected from winds and drifting ice effects. Station 2, located on the eastern coast, is exposed to the northwest winds and to occasional piling up of ice in the Baie de Plaisance. Landfast ice was often surrounded by open water at that station. Stations 4 and 5, located on the western side, are exposed to prevailing northwesterly winds and to southeast drifting ice floes coming from the Gulf of St.Lawrence. At these two stations, ice was sampled mid-way between the shore and the edge of the landfast ice (Stations 4 and 5), as well as at the ice edge (Stations 4A and 5A), the boundary between landfast ice and drifting pack ice, to determine ice edge effects. Station 6, on the northwestern side at Pointe-aux-Loups, is the most exposed to winds and drifting ice. Station 7, located

Figure 1. Map of the Magdalen Islands, Gulf of St.Lawrence. Sampling stations are designated by numbers 1 to 6 for landfast ice stations and by number 7 for the drifting ice station. Stations 4A and 5A are located at the landfast ice edge.


61°40'
61°30'
Gulf of
St. Lawrence
N
47°40'
6
Pointe-
aux-Loups
7
47°30'
47°30'
1
Hâvre-aux-Maisons
4A
47°20'
47°20'
4
Baie-de-Plaisance
2
0 5 10km
5A
5
3
Bassin
MAGDALEN ISLANDS
61°00'
61°50'
61°40'
61°30'

approximately 20 km west of Pointe-aux-Loups, is the drifting pack ice station which was used for comparison to landfast ice.

Sampling and Laboratory Procedures

Seawater was sampled at stations 1, 4, 5 and 6 in January of 1979, before ice formation. Landfast ice began to form in the first week of February, but sampling of ice only started at the end of February when the ice was thick enough to safely walk on. From that period on, ice and water samples were collected every two weeks at stations 1 to 6. Ice and seawater were sampled only twice at station 7 by helicopter. Ice samples were collected with a SIPRE ice corer of 7.5 cm diameter. A minimum of two cores were collected within a 1 meter distance. The ice cores were cut into 20 cm sections starting from bottom ice. Ice sections were numbered by "1" for surface ice down to "B" for bottom ice. Seawater was sampled by pumping underice seawater through holes made by the corer. The samples were kept in a cooler at 0°C and brought back to Environment Canada's laboratory at Cape-aux-Meules.

In the laboratory, samples were melted in warm water baths (≈16°C). From each sample, two 125 ml aliquots were preserved in Lugol's solution (Throndsen 1978) for systematic determination. One aliquot was prepared for identification

and cell counts of diatoms using the muffle furnace technique (Zoto et al. 1973). The cleaned frustules were then mounted in Hyrax (Patrick and Reimer, 1966) and observed under a Zeiss phase contrast microscope. The muffle furnace technique was preferred over the oxidation technique because it preserves the colonial forms which can be used as a criterion for identification. Since this cleaning procedure destroys microalgae other than diatoms, as well as all cellular components making it impossible to distinguish between dead and live diatoms, the second aliquot was analyzed using the Uthermol (1958) sedimentation technique with a Zeiss phase contrast inverted microscope. This technique is most appropriate for identification and cell count of microalgae other than diatoms, and for evaluation of the percentage of empty diatom frustules.

Data Analysis

A minimum of 500 cells were identified and counted in a series of transects at magnification up to 1250X for subsequent analysis of community structure and composition. The identification and counting of a minimum of 300 individuals is considered to give reliable evaluation of diatom communities (Margalef, 1978). The nomenclature follows Van Landingham (1967-1979), and the taxonomic works of Hustedt (1930a, 1930b, 1959, 1966), Cupp (1943), Cleve-Euler

(1951, 1952, 1953a, 1953b, 1955), Brunel (1962) and Patrick and Reimer (1966, 1975) were used for the identification of diatoms.

The structure of the various communities is analyzed using the following community descriptors:

1) the number of species, S

2) the Shannon-Weaver index of diversity (Shannon and Weaver, 1949),

$$H' = -\Sigma p_i \log p_i$$

where $p_i = n_i/N$ is the proportion of the density of the ith species (n_i) over the total density (N) in number of cells per litre.

3) Pielou's (1966) evenness index,

$$J = H'/ Hmax$$

where Hmax = log S, S being the total number of species encountered in the sample. "J" is defined as the ratio of observed diversity (H') to maximum diversity, the latter being said to occur when the species in a collection are equally abundant. When J=1, there is evenness. Departure from 1 is an indication of increasing dominance. Since H' reflects on both total number of species and their relative numerical representation, Pielou's evenness index is a better indicator than dominance since it distinguishes between these two components.

4) total density in number of cells/L, as a measure of biomass.

5) % centric diatoms, representing the percent contribution in density (n° cells/L) of centric diatom species over the total density.

The species composition of the various communities is determined on the basis of abundance, defined as the percent density (n° of cells/L) contribution of individual species over the total density. Dominant species were defined as species with an abundance greater than 5% .

Statistical Analysis

To determine statistical differences in the various community descriptors, in ice and in seawater among the stations, a SAS statistical package was used in all data analyses (Ray, 1982a, b). All linear model statistics, such as analysis of variance (ANOVA), make the assumption that the underlying population from which the sample data are drawn is normally distributed. To test this assumption, the Shapiro-Wilk, W, statistic and probability plot were computed for all the data sets using the Univariate procedure in the SAS system (Ray, 1982b); the Fmax test (Zar, 1984) was used to test the homogeneity of variance assumption. All community descriptors were normally distributed, except for density values which were log-transformed. A single factor analysis of variance (ANOVA) was carried out to test the null hypothesis H_o: there are no differences in community

descriptors among stations (or among seawater and ice sections at the same station) against an alternate H_1: there are differences in community descriptors among stations, or among seawater and ice sections. Where parametric ANOVA rejected the null hypothesis, a specific among stations (or among seawater and ice sections at the same station) comparison of means (at the P=0.05 level), for each of the descriptors was carried out using the Student-Newman-Keuls (SNK) multiple range test.

Diversity measures are sometimes ineffective in segregating different environments since they do not take into account the species composition of the communities compared. Therefore to estimate similarities (or dissimilarities) of species composition and abundance between the different stations and compartments (ice sections and seawater), Ward's agglomerative hierarchical classification was performed (SAS cluster procedure, Ray 1982a). This procedure groups variables, species density in this case, of high mean similarity with each other based on the square multiple correlation R^2 (the sum of squares between all clusters divided by the corrected sum of squares). Species densities (n° of cells/L) were first root-root transformed to reduce the weighing of very abundant species (Field et al., 1982). The transformed densities were then used to construct a Bray-Curtis dissimilarity matrix (Bray and Curtis, 1957). The Bray-Curtis measure has the form:

$$\delta = \Sigma Y_{ij} - Y_{ik} / \Sigma (Y_{ij} - Y_{ik})$$

where Y_{ij} = density of the ith species at the jth station; Y_{ik} = density of the ith species at the kth station; and δ_{jk} = dissimilarity matrix between the jth and the kth stations summed over all species. δ_{jk} can range from 0 (complete similarity or identical scores for all species) to 1 (complete dissimilarity or no species in common). The values calculated for δ_{jk} are then arranged in a dissimilarity matrix from which a dendogram is produced, using group-average sorting which joins two groups of sample together at the average level of similarity between all members of one group and all members of the other.

Significant relationships between the various environmental variables (Chapt. II) and community structure, based on community descriptors, were determined using Pearson's correlation. To simplify the interpretation of relationships between the environmental variables and the community descriptors, principal component analysis (PCA) procedure (Ray, 1982a) was performed. The aim of the PCA was to delineate independent associations among the sets of environmental and community variables. To draw some inference about the general relationship between the environmental conditions and community structure, simple linear regression analysis was used to test the relationship between the PC scores of the environmental and community data sets.

RESULTS

Species Composition

A total of 86 diatom taxa were identified from ice and water samples (Table 1), with 11 species belonging to the subdivision "Centricae" and 71 species to the subdivision "Pennatae" according to Østrup's (1970) classification system. Only 34 diatom species were found in seawater as opposed to 84 species in ice. Microflagellates were the only other group of microalgae present, and they accounted for a mean abundance of only 1.78% in bottom ice and 0.09% in seawater (Table 1).

Bottom Ice Communities

Dominant microalgal species, defined as species with abundances greater than 5%, were determined and are listed for each station in Table 2. The results for bottom ice sections indicate that species composition differs among stations. At stations 1 and 3, the most abundant species are Nitzschia polaris (abundance of 36.99% and 63.63% respectively) and Amphora straurophora (6.91% and 16.83%). At station 2, the community is almost entirely composed of Navicula kariana with a mean abundance of 91.84% . This species is also dominant at stations 4, 4A, 5 and 5A (56.88%,

Table 1. List of taxa (Bacillariophyceae and Microflagellates) identified from ice and water samples in the Magdalen Islands area, including relative abundance (%) in the total collections from seawater (W) and bottom ice section (B).

TAXA	B	W
Bacillariophyceae		
Centrales		
Actinoptychus undulatus Kütz.	0.25	3.57
Biddulphia aurita (Lyng.)Bréb.	5.35	2.06
B.granulata Rop.	0.09	-
Coscinodiscus asteromphalus Ehr.	0.04	-
C.decrescens var.polaris Grun.	0.38	0.32
Cyclotella Meneghiniana Kütz.	0.40	10.87
C.socialis Schutt	1.23	0.79
Melosira sulcata (Ehr.)Kütz.	2.09	-
Thalassiosira decipiens Grun.	3.48	3.57
T.nordenskioldii Cl.	15.63	8.41
Triceratium alternans Bail.	0.03	-
Pennales		
Achnanthes haynaldii (Schaarschm.em.)A.Cl.	0.01	-
Amphora holsatica Hust.	0.24	-
A.ostrearia (Bréb.)Kütz.	0.05	-
A.perpusilla Grun.	0.04	-
A.proteus Greg.	0.54	-
A.proteus var.oculata Per.	0.01	-
A.staurophora (Castr.)Cl.	4.13	1.78
Caloneis brevis Greg.	<0.01	-
Cocconeis placentula Ehr.	0.38	3.73
C.scutellum Ehr.	0.12	1.71
C.thomasiana Brun.	0.05	-
Cymbella sp.1	0.05	0.14
Diatoma elongatum var.tenuis Ag.	0.08	0.65
Diploneis incurvata Greg.)Cl.	0.01	-
D.Smithii (Bréb.)Cl.	1.26	0.40
D.splendida (Greg.)Cl.	<0.01	-
D.suborbicularis (Greg.)Cl.	1.41	-
Epithemia zebra (Ehr.)Kütz.	0.05	1.19
Eunotia lunaris var.ventosa (Berg.)Cl.	<0.01	-
E.pectinalis (Kütz.)Rab.	0.01	-
E.vanheurckii Patr.	<0.01	-
E.veneris (Kütz.)O.Müll.	0.47	-
Eunotogramma productum (Grun.)V.H.	0.01	-
F.construens (Ehr.)Grun.	0.09	-
Fragilaria investiens (W.Sm.)Cl.	0.08	-

Table 1. (continued)

TAXA	B	W
F.lapponica (Grun.)V.H.	0.01	-
F.virescens Ralfs	0.06	0.22
Gomphonema sp.1	<0.01	-
Gyrosigma balticum Ehr.	-	1.19
G.rectum (Donk.)Cl.	0.01	-
Hantzschia amphioxys (Ehr.)Grun.	0.20	-
H.sp 1.	0.01	-
Licmophora gracilis var.anglica Per.	0.20	-
Mastogloia angulata Lewis	<0.01	-
M.apiculata W. Sm.	<0.01	-
Navicula bacillum Ehr.	0.01	-
N.cancellata Donk.	3.27	0.89
N.cryptocephala var. veneta (Kütz.)Rabh.	0.01	-
N.directa W.Sm.	0.37	0.14
N.forcipata Grev.	<0.01	-
N.gallica Pant.	0.14	-
N.glacialis Cl.	<0.01	-
N.gracilloides A.Mayer	0.13	-
N.Grevillei (Ag.)Heib.	1.03	4.54
N.humerosa Bréb.	0.17	-
N.kariana (Grun.)Cl.	20.02	18.14
N.laevis A.Cl.	1.00	1.19
N.lanceolata (Ag.)Kütz.	0.22	-
N.lyra Ehr.	5.20	1.19
N.muralis Grun.	2.20	1.49
N.protracta Grun.	0.20	-
N.rhyncocephala Kütz.	0.05	0.29
N.spicula (Hick.)Cl.	2.26	-
N.sp.1	<0.01	-
N.sp.2	<0.01	-
N.sp.3	0.85	0.30
N.yarrensis var.americana Cl.	0.91	5.95
Nitzschia acuminata (W.Sm.)Grun.	<0.01	-
N.capitellata var.lapponica	0.15	-
N.cylindrus (Grun.)Hasle	5.39	8.70
N.linearis (Ag.)W.Sm.	-	0.79
N.littoralis Grun.	<0.01	-
N.polaris Grun.	12.01	8.37
N.thermalis (Kütz.)Grun.	0.03	-
N.vitrea Norm.	0.01	-
Pinnularia aestuarii βinterrupta(Hust.)A.Cl.	-	0.001
P.baltica (Schulz)	0.01	-
P.globiceps var.Krookii Grun.	3.30	2.59

Table 1. (continued)

TAXA	B	W
P.quadratarea var.balticum Grun.	0.13	1.19
P.streptographe Cl.	0.01	-
Plagiogramma staurophorum (Greg.)Heib.	0.03	-
Pleurosigma elongatum var.fallax Grun.	0.05	-
Synedra pulchella (Ralfs)Kütz.	0.18	-
Surirella islandica Ostr.	0.27	-
Trachyneis aspera Ehr.	0.03	3.57
Microflagellates	1.78	0.09

Table 2. List of dominant diatom species (abundance ≥ 5%) from bottom ice sections, at stations 1 to 7, including percent mean abundance, mean density and standard deviation (in parentheses) per station.

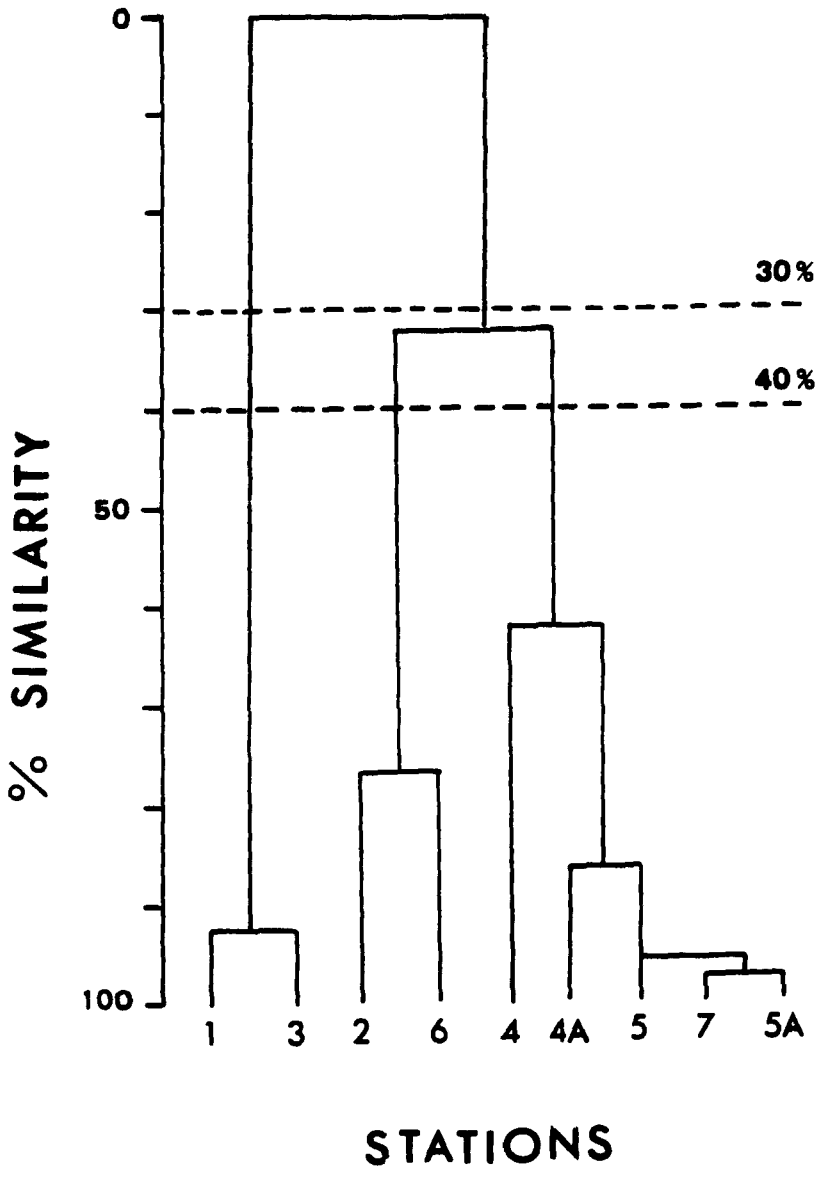
STATIONS	SPECIES	ABUNDANCE (%)	DENSITY (10^3xcells/L)
1	Nitzschia polaris	36.99	85.9 (±96.5)
	Navicula cancellata	20.83	48.4 (±71.2)
	Pinnularia globiceps var.Krookii	15.11	35.1 (±32.8)
	Amphora staurophora	6.91	16.1 (±23.7)
2	Navicula kariana	91.84	359.6 (±425.4)
3	Nitzschia polaris	63.63	157.9 (±201.6)
	Amphora staurophora	16.83	41.8 (±46.8)
	Navicula muralis	8.67	21.5 (±25.2)
4	Navicula kariana	56.88	6.1 (±10.8)
	Thalassiosira nordenskioldii	27.14	2.9 (±3.1)
4A	Thalassiosira nordenskioldii	46.22	2.9 (±5.2)
	Navicula kariana	38.66	3.1 (±4.3)
5	Thalassiosira nordenskioldii	48.22	3.7 (±5.5)
	Navicula kariana	27.74	3.6 (±8.4)
	Nitzschia cylindrus	6.23	0.9 (±8.6)
5A	Thalassiosira nordenskioldii	58.83	3.4 (±4.8)
	Navicula kariana	34.32	2.0 (±2.8)
6	Nitzschia cylindrus	55.25	65.7 (±131.4)
	Navicula kariana	36.73	43.7 (±87.3)
	Thalassiosira nordenskioldii	36.98	43.7 (±87.3)
7	Thalassiosira nordenskioldii	35.98	3.5 (±8.3)
	Nitzschia cylindrus	16.01	1.5 (±2.2)
	Navicula laevis	10.96	1.1 (±1.9)

38.66%, 25.74% and 34.32%), but dominance at these stations is also shared by the centric species Thalassiosira nordenskioldii (27.14%, 46.22%, 48.75% and 58.83%). Species composition differs slightly at station 6 with Nitzschia cylindrus being most abundant (55.25%) followed by N. kariana (36.73%) and Thalassiosira nordenskiöldii (4.56%). At the drifting ice station 7, T. nordenskioldii is again dominant (35.98%) with Nitzschia cylindrus (16.01%) and Navicula laevis (10.96%).

To estimate similarity of species composition between the different stations, Ward's agglomerative hierarchical classification was used. Figure 2 is the resultant dendogram produced by group average sorting of stations using the Bray-Curtis dissimilarity matrix, based on mean density of each species. A broken line drawn at an arbitrary similarity level of 30% delineates 2 major groups of stations. The first group includes stations 1 and 3, the protected lagoon stations. The second group divides into two major subgroups at the 40% similarity level: landfast ice stations 2 and 6, located respectively on the eastern coast and on the northwestern coast of the Islands, forming the first subgroup, and landfast ice stations 4, 4A, 5 and 5A located on the western coast plus the drifting ice station 7 forming the second subgroup.

The structure of the bottom ice community was defined on the basis of a number of community descriptors including:

Figure 2. Dendogram showing classification of stations 1 to 7 based on community composition, i.e. mean species density (n° of cells/L). Densities were root-root transformed before comparison using group-average sorting of Bray-Curtis dissimilarities. Stations split into two main groups at the 30% similarity level, and the second group splits into two main subgroups at the 40% similarity level.


0
30%
40%
50
100
% SIMILARITY
1
3
2
6
4
4A
5
7
5A
STATIONS

number of species (S), the Shannon-Weaver diversity index (H'), Pielou's evenness index (J'), density in nº of cells/L, and percentage of centric species. The results are summarized in Table 3.

The number of species ranged from a mean of 20 at station 1 to a mean of 4.5 at station 5A. Analysis of variance (ANOVA) of the community descriptors (Table 4) indicates that for station 1, the number of species is significantly different from stations 4, 4A, 5A and 6, with intermediate values for stations 2, 3, 5 and 7. The Shannon-Weaver diversity indices (H') were low (Table 3), with mean values ranging from a minimum of 0.40 at station 2 to a maximum of 0.79 at station 7. No significant differences between station means were demonstrated by the ANOVA test (Table 4).

Evenness index varied from 0.76 at station 6 to 0.34 at station 2. Since departure of J from 1 is an indication of dominance, the bottom ice biota communities seem to show signs of dominance. This is particularly true of stations with high percent abundance of dominant species such as station 2 where the dominant species contributes 91.84% of the abundance. But again, the mean J values are not significantly different when compared between stations using the ANOVA procedure (Table 4).

Density, expressed as number of cells per litre, was quite variable ranging from a minimum mean value of 0.97×10^5

Table 3. Community descriptors for seawater (W) and bottom ice section (B) at stations 1 to 7. Descriptors include mean values for S (number of species, H' (Shannon-Weaver diversity index), J (Evenness index), Density (n° of cells/L) and % Centric (percentage of centric diatoms). Standard deviations are also included (in parentheses) and number of samples.

DESCRIPTORS		STATIONS								
		1	2	3	4	4A	5	5A	6	7
S	B	20.2	10.4	9.4	6.5	6.0	11.6	4.5	5.5	11.5
		(1.7)	(6.7)	(6.5)	(3.4)	(8.5)	(3.2)	(6.4)	(3.6)	(0.7)
		4	5	5	6	3	5	2	4	2
	W	-	1.3	0.8	1.8	-	3.1	1.0	2.2	0.5
			(1.7)	(1.6)	(3.0)		(3.8)	(1.4)	(3.2)	(0.7)
			6	6	7		6	2	5	2
H'	B	0.74	0.40	0.58	0.42	0.58	0.76	0.43	0.46	0.79
		(0.10)	(0.39)	(0.13)	(0.12)	(0.09)	(0.12)	(0.18)	(0.21)	(0.16)
		4	5	5	6	3	5	2	4	2
	W	-	0.38	0.27	0.51	-	0.58	0.20	0.65	-
			(0.09)	(0.39)	(0.29)		(0.39)	-	(0.12)	
			3	2	2		3	1	4	
J'	B	0.57	0.34	0.56	0.63	0.54	0.74	0.45	0.76	0.74
		(0.06)	(0.30)	(0.17)	(0.23)	(0.21)	(0.17)	(0.12)	(0.22)	(0.13)
		4	5	5	6	3	5	2	4	2
	W	-	0.86	0.91	0.92	-	0.69	0.65	0.91	-
			(0.12)	-	(0.11)		(0.42)	-	(0.53)	
			3	1	2		3	1	4	
Cells/L ($x10^4$)	B	23.2	48.9	31.0	1.1	1.6	1.4	1.1	12.0	1.0
		(19.2)	(45.1)	(28.9)	(1.6)	(1.3)	(1.7)	(0.9)	(23.7)	(1.3)
		4	5	5	6	3	5	2	4	2
	W	0	0.06	0.12	0.45	0	1.75	0.01	0.30	0.01
			(0.06)	(0.16)	(0.63)		(1.77)	(0.01)	(2.54)	(0.01)
			6	6	7		6	2	5	2
% Centric	B	1.9	1.3	0.3	29.1	47.1	52.2	61.8	5.0	40.8
		(1.9)	(2.1)	(0.1)	(17.3)	(10.2)	(5.2)	(9.1)	(12.5)	(19.4)
		4	5	5	6	3	6	2	4	2
	W	0	10.6	0	12.5	0	7.9	0	33.3	0
			(14.6)		(25.0)		(12.1)		(0)	
			6		7		6		5	

Table 4. Parametric Student-Newmen-Keuls test for significant ($P<0.05$) statistical differences between stations of community descriptors S (number of species), H' (Shannon-Weaver diversity index), J (Pielou's evenness index), Density (nº of cells/L) and % centric (percentage of centric diatoms), in bottom ice section (B) and seawater (W).

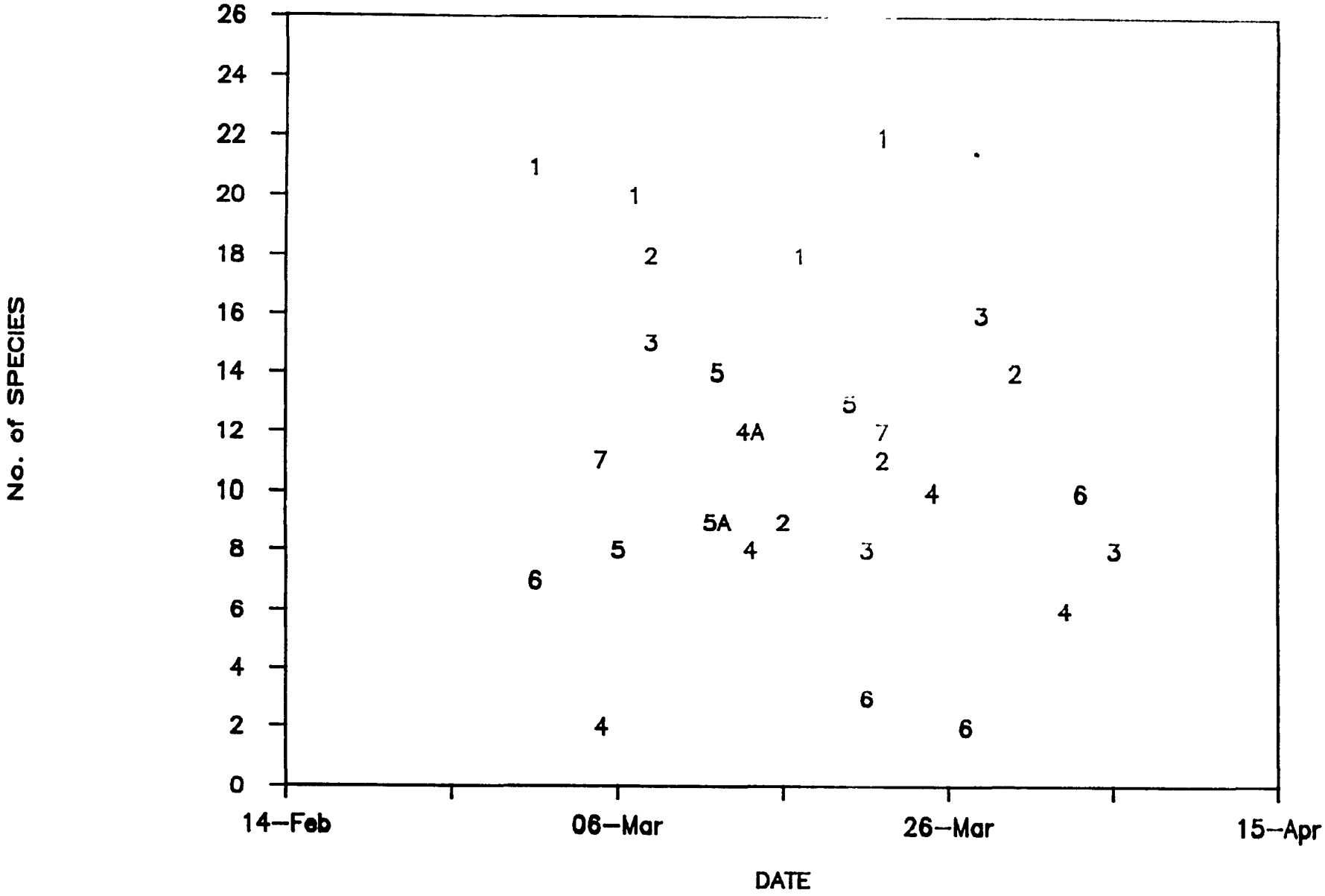
VARIABLES		STATIONS								
		1	2	3	4	4A	5	5A	6	7
S	B	a	ab	ab	b	b	ab	b	b	ab
	W	a	a	a	a	a	a	a	a	a
H'	B	a	a	a	a	a	a	a	a	a
	W	a	a	a	a	a	a	a	a	a
J	B	a	a	a	a	a	a	a	a	a
	W	a	a	a	a	a	a	a	a	a
Density	B	a	a	a	a	a	a	a	a	a
	W	a	a	a	a	a	a	a	a	a
%Centric	B	a	a	a	ab	b	b	b	a	b
	W	a	a	a	a	a	a	a	a	a

cells/L at station 7 to a maximum of 48.9×10^5 cells/L at station 2 (Table 3). The results also indicate that cell numbers are an order of magnitude higher at stations 1, 2, 3 and 6 (10^6 cells/L) than at stations 4, 4A, 5, 5A and 7 (10^5 cells/L). Despite these differences in mean density between stations, the ANOVA performed for density (Table 4) did not show significant differences between station means because of the very high standard deviations associated with cell density.

The results on percent centric species indicate a clear demarcation of community structure between stations (Table 3) with statistically significant differences (Table 4). At stations 1, 2 and 3 located in lagoons and on the eastern coast of the Islands, the communities are composed of a majority of pennate species, with centric diatoms contributing to less than 2% of the abundance. The communities from stations 4, 4A, 5 and 5A, located on the western coast and from the drifting ice station 7 have a different composition, with centric species accounting for 29.13% or more of the abundance.

Community descriptors were then analyzed for time scale evolution. An increase in number of species S (Fig. 3) was noticeable at stations 4 and 5, while variable patterns were observed at stations 2 and 3. Station 1 stands out with constantly higher number of species, and station 6 with low number of species throughout the ice season. No discernible

Figure 3. Time scale evolution of community descriptor S (number of species), for stations 1 to 7.


No. of SPECIES
26
24
22
20
18
16
14
12
10
8
6
4
2
0
14–Feb
06–Mar
26–Mar
15–Apr
DATE

trends in time were observed for diversity (H') and evenness (J). Density plotted on a log scale versus time (Fig. 4) illustrates the same trend as S, with a marked increase in number of cells from February until mid-March, followed by a decrease in the latter part of March, except for station 3. Stations 1, 2 and 3 are distinguished from the other stations by having cell densities one order of magnitude higher. Station 6 stands out again with densities less than 10^3 cells/L in March, followed by a marked increase in April. Graphic presentation of % centric diatoms versus time (Fig. 5) again illustrates the peculiarities in community structure at stations 1, 2 and 3 which have a very low percentage of centrics diatoms (< 3.0%). At station 6, the percentage of centric is around 20% in March and down to less than 5% in April. At stations 4, 4A, 5 and 5A, the percentage of centrics increases from 0 to about 45% and more by mid-March, following the increase in cell density. At station 7 the percentage of centric is always greater than 40% . With respect to species composition, no statistically discernible patterns of species succession could be demonstrated for the bottom ice microalgal communities.

Underice Seawater Communities

The species composition of underice seawater was similar to that of bottom ice communities (Table 5) with Navicula

Figure 4. Time scale evolution of community descriptor Density (nº of cells/L) on a logarithmic scale for stations 1 to 7.

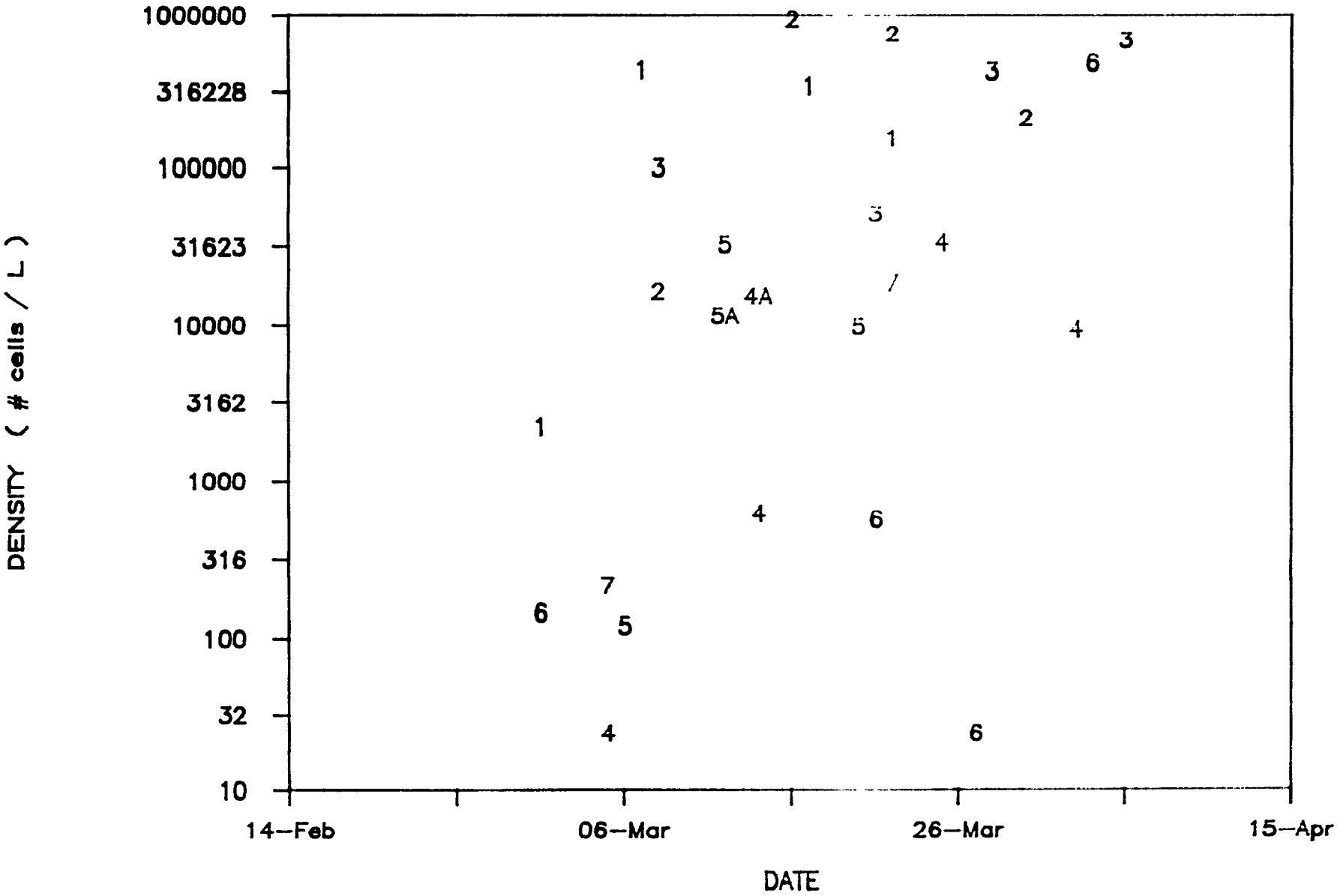

1000000
316228
100000
31623
10000
3162
1000
316
100
32
10
DENSITY (# cells / L)
14—Feb
06—Mar
26—Mar
15—Apr
DATE
2
2
3
1
1
3
6
2
1
3
3
5
4
2
4A
5A
5
4
1
4
6
7
6
5
4
6

Figure 5. Time scale evolution of community descriptor % Centric Diatoms for stations 1 to 7.

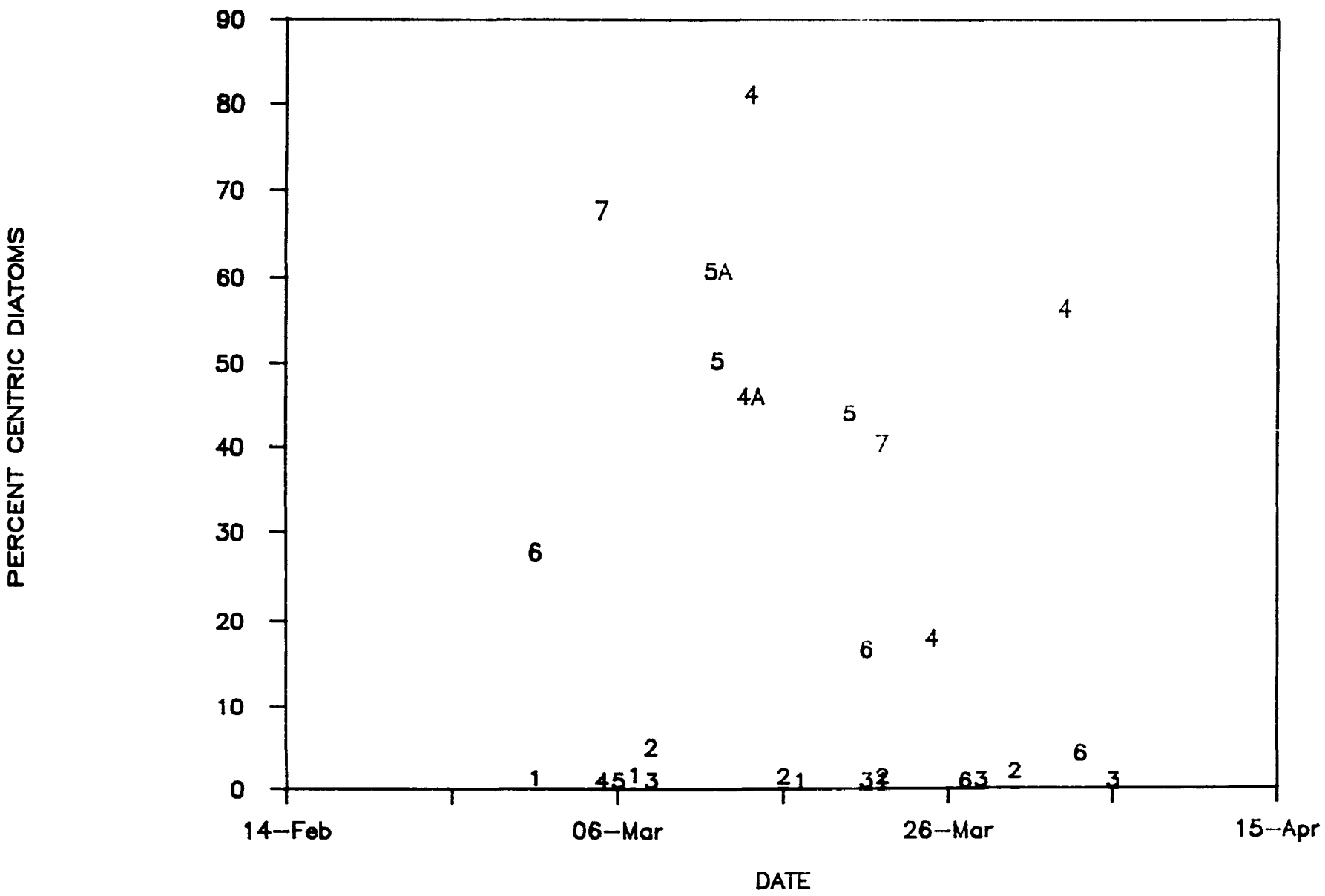

PERCENT CENTRIC DIATOMS
90
80
70
60
50
40
30
20
10
0
14–Feb
06–Mar
26–Mar
15–Apr
DATE
4
7
5A
4
5
4A
5
7
6
6
4
2
1
4
5
1
3
2
1
3
2
6
3
2
6
3

Table 5. List of dominant diatom species (abundance ≥ 5%) from seawater, at stations 1 to 7, including percent mean abundance, mean density and standard deviation (in parentheses) per station.

STATION	SPECIES	ABUNDANCE (%)	DENSITY (cells/L)
1			0
2	Navicula kariana	48.44	131 (±264)
	Thalassiosira nordenskiödii	18.58	50 (±133)
	Actinoptychus undulatus	11.27	30 (±80)
	Biddulphia aurita	6.19	17 (±44)
	Diatoma elongatum var.tenuis	6.19	17 (±44)
3	Nitzschia polaris	36.24	142 (±348)
	Pinnularia globiceps var.Krookii	36.24	142 (±348)
	Navicula kariana	18.12	71 (±174)
	Cyclotella Meneghiniana	9.06	35 (±87)
4	Nitzschia polaris	33.16	597 (±1336)
	Amphora staurophora	24.87	448 (±1336)
	Navicula muralis	20.73	373 (±835)
	Navicula Grevillei	8.29	149 (±334)
4A			0
5	Navicula kariana	66.48	5813 (±13471)
	Thalassiosira nordenskioldii	8.43	737 (±1493)
	Navicula Grevillei	7.11	622 (±1523)
	Nitzschia cylindrus	7.11	622 (±1523)
5A	Navicula yarrensis var.americana	83.33	20
	Navicula lyra	16.67	4
6	Thalassiosira nordenskioldii	33.33	400
	Navicula Grevillei	26.64	320
	Navicula kariana	18.87	227
	Biddulphia aurita	9.99	120
	Nitzschia polaris	5.58	67
7	Cyclotella Meneghiniana	100.00	32

kariana dominant at stations 2, 3, 5 and 6; Nitzschia polaris at stations 3 and 4; Thalassiosira nordenskioldii at stations 2, 5 and 6; Navicula muralis and Amphora staurophora at station 4; and Pinnularia globiceps var. Krokii at stations 3 and 5.

The structure of the community was analyzed on the basis of the same community descriptors as for the bottom ice sections (Table 3). The mean number of species found in seawater was very low at all stations ($S < 3$), and mean values for density ranged from 10^2 to 10^4 cells/L at stations 7 and 5 respectively, with no cells at stations 1 and 4A. Diversity was low ($H' < 0.58$) and mean $J > 0.65$. Percent centric diatoms ranged from a mean of 7.9 at station 5 to 33.3 at station 6. However, for cell counts of less than 300 cells/L, community descriptors and species composition should not be considered as representative of the community.

Communities of Upper Ice Core Sections

The structure and composition of ice microalgal communities were analyzed for vertical distribution in ice section above bottom ice. Again, species composition and community descriptors should not be considered as representative of the communities when cell counts (or densities) are less than 300. The composition of the communities, including only dominant species (abundance > 5%)

is summarized in Table 6. In cases of representative densities (> 300 cells/L), species composition of upper ice sections is similar to bottom ice sections, with the same dominant species throughout the ice sections at respective stations. The only species which shows up as dominant in upper ice sections, despite a low abundance in bottom ice (abundance < 5%) is the centric diatom Biddulphia aurita. Biddulphia aurita is dominant at station 2 in ice sections 2 and 3, at station 5A in section 3, and at station 6 in sections 3, 4 and 5 (Table 6).

The structure of the ice biota communities in the upper ice sections was analyzed using the same community descriptors and compared to bottom ice communities. The results (Table 7) indicate similarity with respect to number of species S, diversity H' and evenness J. However, cell density in upper ice sections is two or three orders of magnitude less than in bottom ice, except at station 3. But again, an ANOVA did not show significant statistical differences between the ice sections (Table 8). The percentage of centric species is similar at stations 1, 3, 4, 5 and 5A, but significant differences (Student-Newman-Keuls test, $P < 0.05$) are observed at stations 2 and 6 with higher % centric diatoms in upper ice sections than in bottom ice (Table 8). Paralia sulcata is responsible for the increased percentage of centric diatoms in the upper ice sections at these two stations.

Table 6. List of dominant diatom species (abundance ≥ 5%) from upper ice sections (vertical profiles) from surface ice section 1 to bottom ice section B at stations 1 to 7, including percent mean abundance and mean density (in parentheses) in cells/L.

STATION	SPECIES	ICE SECTIONS			
		1	2	B	
1	Navicula muralis	56.24% (9880)			
	Nitzschia polaris	19.24% (3380)		36.99% (859,000)	
	Amphora staurophora	10.36% (1820)		6.91% (23,700)	
	Navicula humerosa		16.96% (52)		
	Navicula Grevillei		11.62% (52)		
	Navicula lyra		9.82% (44)		
	Amphora proteus		7.14% (32)		
	Mastogloia angulata		5.36% (24)		
	Navicula directa		5.36% (24)		
	Plagiogramma staurophorum		5.36% (24)		
	Navicula cancellata			20.83% (48,400)	
	Pinnularia globiceps var.Krookii			15.11% (32,800)	
		1	2	3	B
2	Navicula kariana	46.62% (27,360)	41.26% (59,040)		91.84% (359,000)
	Licmophora gracilis v.anglica	11.04% (6480)			
	Nitzschia cylindrus	9.82% (5760)		48.26% (10,560)	
	Eunotia veneris	6.13% (3600)			
	Thalassiosira decipiens	6.13% (3600)			
	Biddulphia aurita		32.71% (46,800)	7.31% (1600)	
	Navicula cancellata		5.53% (7,920)	10.97% (2400)	
	Melosira sulcata			11.52% (2520)	
		1	2	B	
3	Nitzschia cylindrus	28.82% (76,350)	24.75% (39,200)		
	Nitzschia polaris	25.45% (72,460)	45.96% (72,800)	63.62% (157,900)	
	Navicula muralis	23.24% (66,180)	10.10% (16,000)	8.67% (25,200)	
	Navicula kariana	5.05% (14,381)			
	Amphora staurophora			16.83% (41,800)	
			2	B	
4	Thalassiosira nordenskiödii		48.50% (259)	27.14% (2,900)	
	Amphora proteus		16.17% (86)		
	Diploneis smithii		16.17% (86)		
	Nitzschia cylindrus		16.17% (86)		
	Navicula kariana			56.88% (3,100)	
			2	B	
4A	Cyclotella Meneghuniana		62.50% (40)		
	Diploneis smithii		37.50% (24)		
	Thalassiosira nordenskiödii			46.22% (2,900)	
	Navicula kariana			38.66% (3,100)	

Table 6 (continued)

STATION	SPECIES	ICE SECTIONS			
		1	B		
5	Thalassiosira nordenskioldii	39.60% (2905)	48.22% (3,700)		
	Nitzschia cylindrus	19.56% (1435)	6.23% (900)		
	Navicula protracta	6.18% (453)			
	Navicula Grevillei	6.18% (453)			
	Diploneis Smithii	5.18% (380)			
	Navicula kariana		27.74% (3,800)		
		1	2	3	B
5A	Nitzschia polaris	19.72% (1246)			
	Thalassiosira nordenskioldii	15.49% (979)	70.59% (192)	232.26% (960)	58.83% (3,400)
	Paralia sulcata	15.49% (979)			
	Nitzschia cylindrus	11.27% (712)			
	Amphora proteus	7.04% (445)			
	Navicula cancellata	7.04% (445)	8.82% (24)		
	Diploneis Smithii		5.88% (16)	6.45% (16)	
	Biddulphia aurita			22.58% (713)	
	Navicula lyra			12.90% (32)	
	Cyclotella socialis			9.68% (24)	
	Navicula kariana				34.32% (2,000)
		1	2	3	4
6	Thalassiosira nordenskioldii	54.71% (5552)	22.30% (13,766)	28.78% (2136)	36.73% (4560)
	Navicula kariana	30.78% (3124)	17.05% (10,526)	52.70% (3911)	38.77% (4560)
	Nitzschia cylindrus	4.77% (484)	48.47% (29,918)		14.28% (1680)
	Biddulphia aurita			9.60% (714)	
		5	B		
	Navicula kariana	60.38% (128)	36.73% (43,700)		
	Thalassiosira nordenskioldii	15.09% (32)	36.96% (43,700)		
	Biddulphia aurita				
	Nitzschia cylindrus		55.25% (65,700)		
		1	B		
7	Thalassiosira nordenskioldii	100% (8)	35.98% (3,500)		
	Nitzschia cylindrus		16.01% (1,500)		
	Navicula laevis		10.96% (1,100)		

Table 7. Community descriptors from surface ice sections (1) to bottom ice section (B)) at stations 1 to 7. Descriptors include mean values of S (number of species), H' (Shannon-Weaver diversity index), J (Evenness index), Density (n^o cells/L) and % centric (percentage of centric diatoms). Standard deviations from the means are included in parentheses.

STATIONS	SECTIONS	DESCRIPTORS				
		S	H'	J	Density	% Centric
1	1	20.0	0.65	0.49	17,566	1.57
	2	16.5 (±9.2)	1.07 (±0.19	0.91 (±0.03)	448 (±396)	4.46 (±2.17)
	B	20.2 (±1.7)	0.74 (±0.10)	0.57 (±0.06)	232,305 (±192,149)	1.98 (±1.86)
2	1	13.0	0.82	0.74	58,680	11.04
	2	17.0	0.73	0.59	143,080	33.21
	3	17.0	0.80	0.65	21,880	12.43
	B	10.4 (±6.7)	0.40 (±0.39)	0.34 (±0.30)	489,435 (450,816)	1.35 (±2.14)
3	1	9.7	0.71	0.74	284,703	3.92
	2	8.0	0.63	0.70	158,400	1.51
	B	9.4 (±6.5)	0.58 (±0.13)	0.56 (±0.17)	310,208 (±289,109)	0.27 (±0.9)
4	1	-	-	-	0	-
	2	3.0 (±1.4)	0.42 (±0.12)	0.95 (±0.07)	535 (±711)	48.50 (±4.05)
	B	6.5 (±8.5)	0.42 (±0.12)	0.63 (±0.23)	10,813 (±15,588)	29.13 (±17.32)
4A	1	-	-	-	0	-
	2	2.0	0.29	0.95	64	0
	B	6.0 (±8.5)	0.58 (±0.09)	0.54 (±0.21)	15,865 (±10,318)	47.10 (±10.24)
5	1	13.3 (±7.23)	0.78 (±0.35)	0.70 (±0.17)	7,338 (±12,293)	40.02 (±8.01)
	B	11.6 (±6.36)	0.76 (±0.12)	0.74 (±0.17)	14,103 (±16,596)	52,24 (±9.15)
5A	1	8.5	1.04	0.84	12,638	30.98
	2	7.0	0.48	0.57	272	70.59
	3	9.0	0.81	0.85	248	46.13
	B	4.5 (±6.36)	0.43 (±0.18)	0.45 (±0.12)	11,556 (±12,582)	61.77 (±9.15)
6	1	8.0 (±1.4)	0.64 (±0.17)	0.71 (±0.14)	10,148 (±14,159)	54.75 (±4.3)
	2	8.0 (±1.4)	0.65 (±0.07)	0.72 (±0.12)	61,722 (±63,919)	24.92 (±11.01)
	3	4.6 (±2.8)	0.47 (±0.07)	0.81 (±0.20)	7,420 (±12,724)	36.59 (±8.05)
	4	8.0	0.60	0.74	9,491	51.01
	5	10.0	0.55	0.85	197	24.52
	B	5.5 (±3.6)	0.46 (±0.21)	0.76 (±0.22)	118,903 (±237,331)	5.02 (±12.52)
7	1	0.5	-	-	16	0
	B	11.5 (±0.7)	0.79 (±0.16)	0.74 (±0.13)	9,670 (±13,375)	40.79 (±19.44)

Table 8. Parametric Student-Newmen-Keuls test for significant ($P<0.05$) statistical differences between upper ice sections grouped (U) and bottom ice section (B) of the community descriptors S (number of species), H' (Shannon-Weaver diversity index), J (Pielou's evenness index), Density (n° of cells/L) and % centric (percentage of centric diatoms), at stations 1 to 6. Station 7 is not included because no statistical comparison could be made.

VARIABLES		STATIONS								
		1	2	3	4	4A	5	5A	6	7
S	U	a	a	a	a	a	a	a	a	-
	B	a	a	a	a	a	a	a	a	-
H'	U	a	a	a	a	a	a	a	a	-
	B	a	a	a	a	a	a	a	a	-
J	U	a	a	a	a	a	a	a	a	-
	B	a	a	a	a	a	a	a	a	-
Density	U	a	a	a	a	a	a	a	a	-
	B	a	a	a	a	a	a	a	a	-
%Centric	U	a	b	a	a	b	a	a	b	-
	B	a	a	a	a	a	a	a	a	-

Community and Environmental Interactions

To assess relationships between ice biota community structure and the environmental variables, principal component analysis (PCA) was performed for both environmental variables (PENV) and community descriptors (PCOM). This analysis was done for bottom ice section only, since the ice biota is concentrated in that section, and because a more complete data set was available and necessary for PCA analysis. Table 9 presents the results of PCA for 7 environmental variables measured during this study (see Chapter II). The first principal component (PC1), which accounts for 36.7% of the variance in the data, has a high positive loading on silicates and a high negative loading on nitrates, both significant at the $P < 0.002$ level. Positive loading is also observed for chlorophyll *a*, but only at the $P < 0.05$ level. The second principal component (PC2) accounts for 27.7% of the variance, and has a high positive loading on orthophosphates and phaeopigments, significant respectively at the $P < 0.002$ and $P < 0.01$ levels. As PC1 and PC2 together account for 64.4% of the variance, it can be concluded that major differences among the stations are related to nutrients, namely nitrates, silicates and orthophosphates.

In principal component analysis of community descriptors PCOM (Table 10), PC1 accounts for 46.6% of the variance, with a high positive loading on density and percent centric,

Table 9. Eigenvector loadings and Pearson's correlation coefficients (r) for correlations between environmental variables and principal components (PC) 1, 2 and 3; statistical significance (two-tailed test) is indicated by *** at $p < .002$, ** at $p < .01$, * at $p < .02$ and + at $p < .05$; n=9 stations.

Environmental variables	PC1		PC2		PC3	
	Loading	r	Loading	r	Loading	r
Salinity (o/oo)	0.089	0.14	-0.406	-0.56	0.618	0.70+
PO_4-P (µM)	0.032	0.05	0.674	0.94***	0.170	0.19
NO_3-N (µM)	-0.506	-0.81***	0.052	0.07	-0.066	-0.07
NO_2-N (µM)	0.395	0.63	-0.177	-0.25	-0.514	-0.58
$Si(OH)_4$ (µM)	0.541	0.87***	-0.186	-0.26	-0.187	-0.21
Chl a (mg/m^3)	0.417	0.67+	0.064	0.09	0.533	0.60
Phaeop. (mg/mg^3)	0.333	0.53	0.555	0.77**	-0.037	-0.04

Abbreviations used: Chl a = chlorophyll a; phaeop. = phaeopigments.

Table 10. Eigenvector loadings and Pearson's correlation coefficients (r) for correlations between community descriptors and principal components (PC) 1, 2 and 3; statistical significance (two-tailed test) is indicated by *** at $p < .002$, ** at $p < .01$, * at $p < .02$ and + at $p < .05$; n=9 stations.

Community descriptors	PC1		PC2		PC3	
	Loading	r	Loading	r	Loading	r
S	0.389	0.50	0.512	0.63	0.413	0.12
H'	-0.021	-0.05	0.699	0.92***	0.215	-0.03
J'	-0.260	-0.12	0.486	0.67+	-0.775	-0.65
Density	0.630	0.88***	-0.113	-0.22	-0.195	0
% Centric	-0.619	-0.93***	-0.021	-0.15	0.380	0.32

Abbreviations used: S =species richness; H' = Shannon-Weaver diversity index; J' = Pielou's evenness index; Density = number of cells/L; % Centric = percent abundance of centric diatom species.

significant at the $P < 0.002$ level. PC2 accounts for 37.8% of the variance with high positive loading on H' at the $P < 0.002$ level. PC1 and PC2 account for 84.4% of the variance of the community data set. Therefore, major differences in community structure among stations are primarily related to density and % centric diatoms. These two descriptors were actually found to be negatively correlated between each other (Pearson's correlation coefficient $r = -0.83$, $P < 0.005$) with highest densities found at stations where percent centric diatom are low, namely stations 1, 2 and 3. It is also interesting to note that on the basis of the three-dimensional projection onto the PC1, PC2 and PC3 of the PCOM (Fig.6), the stations are grouped similarly as in the dendogram produced in Figure 2 from species composition classification analysis.

To assess the relationship between environmental variables and community structure, Pearson's correlations were performed between the three principal components of PENV and the community descriptors. The results (Table II) indicate a lack of correlation between community descriptors and PC1, PC2 and PC3 of the environmental variables, suggesting that factors other than nutrients are responsible for the variations in density and % centric diatoms observed for the stations.

Figure 6. Three-dimensional projection of stations 1 to 7 onto the first three principal components (PC1, PC2 and PC3) of pricipal component analysis based on a matrix of correlations among community descriptors (PCOM) for bottom ice sections.

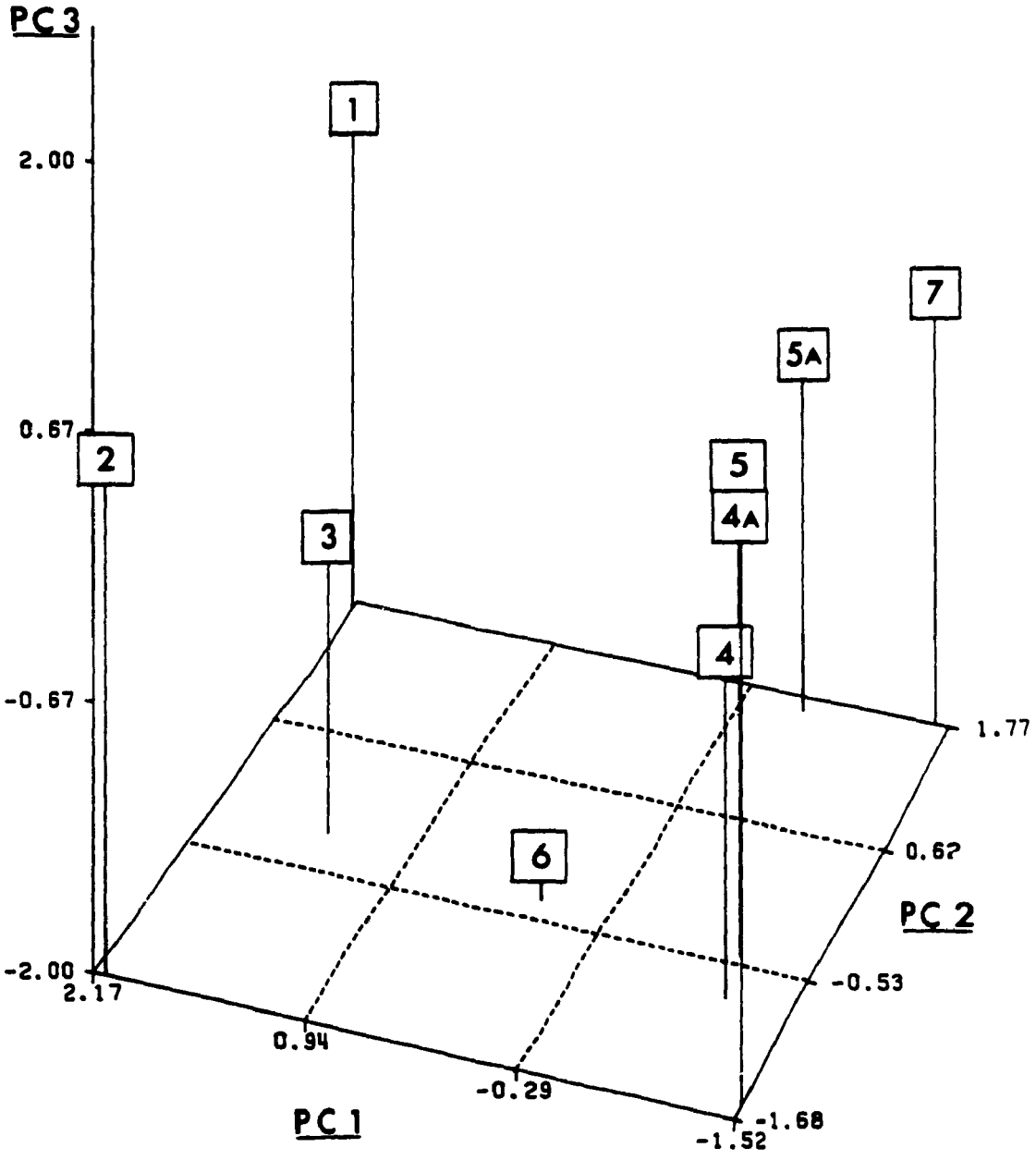

PC 3
2.00
0.67
-0.67
-2.00
1
2
3
4
4A
5
5A
6
7
2.17
0.94
-0.29
-1.52
PC 1
-1.68
-0.53
0.62
1.77
PC 2

Table 11. Pearson's correlation coefficients between three principal components (PC1, PC2 and PC3) of environmental variables and community descriptors; no statistical significance was observed.

Community descriptors	PC1	PC2	PC3
S	0.03	-0.28	-0.55
H'	-0.19	-0.23	-0.64
J'	-0.48	-0.47	-0.11
Density	0.04	0.26	-0.23
% Centric	0.05	-0.16	0.32

Abbreviations used: S =species richness; H' = Shannon-Weaver diversity index; J' = Pielou's evenness index; Density = number of cells/L; % Centric = percent abundance of centric diatom species

DISCUSSION and CONCLUSIONS

Bottom Ice Communities

Ice biota microalgal communities from the Magdalen Islands area were composed almost entirely of diatoms, with microflagellates accounting for less than 2% of the abundance. Similar communities have been described from higher latitudes (Hsiao, 1980; Pett et al., 1983; Poulin et al., 1983). However, ice biota communities with a high percentage of microflagellates have been reported, namely from Baffin Island (Rymes, 1986) and from frazil ice in the Gulf of St.Lawrence (Demers et al., 1984).

Composition of bottom ice communities included the following dominant species: Nitzschia polaris and Amphora staurophora (stations 1 and 3); Navicula kariana (stations 2, 4, 4A and 6); Thalassiosira nordenskioldii (stations 4, 4A, 5, 5A and 7); Nitzschia cylindrus (stations 6 and 7). Nitzschia polaris and N. cylindrus are typical ice species, and are reported as dominant in a number of Arctic ice biota studies (Usachev, 1949; Hsiao, 1979; Horner and Schrader, 1981; Pett et al., 1983; Rymes 1986). Navicula kariana is also reported from higher latitude ice communities, but rarely as a dominant species (Hsiao,1979: Pett et al., 1983; Poulin et al. 1983). Thalassiosira nordenskioldii, a centric diatom with a temperature optimum of 2.3°C (Patrick and

Reimer, 1966) is reported as a dominant spring phytoplanktonic species in the Gulf of St.Lawrencce (Steven, 1974) and in the Arctic (Hsiao, 1983). It is also reported in a number of studies on Arctic ice biota (Alexander et al., 1974; Pett et al., 1983; Rymes, 1986), but never as a dominant species. In the Magdalen Islands, this centric diatom was dominant at stations located on the western coast (stations 4, 4A, 5 and 5A), and at the drifting ice station 7 where it reached an abundance of up to 50% . Dunbar and Acreman (1980) and Demers et al. (1984) found T. nordenskioldii as a dominant species, along with other centric diatoms, of ice biota communities from drifting ice in the estuary and Gulf of St.Lawrence. There, the dominance of Thalassiosira species actually accounted for the high percentage of centrics considered by Dunbar and Acreman (1980) to be characteristic of ice biota from lower latitudes.

Mean species richness and diversity indices of bottom ice communities were low (S=9.5 ; H'=0.57), at landfast and drifting ice stations. These values are much lower than those of ice biota communities from higher latitudes: Rymes (1986) reported a species richness of S=47.7 and diversity values of H'=1.14 for Baffin Island. Considering the ice substrate as an energetic interface or "ergocline" (Legendre and Demers, 1985) similar to a benthic substrate, comparison of the two environments can be made. Diversity of undisturbed benthic

diatom communities average H'=1.40 (O'Quinn and Sullivan, 1983), but can be reduced to less than 0.70 in polluted or turbulent areas (DeSève and Goldstein, 1981; Luttenton and Rada, 1986). Furthermore, Margalef (1978) suggested that species diversity of H'=1.09 are typical of unstable environments (e.g. estuaries, upwelling and polluted areas). In the Gulf of St.Lawrence, instability of the ice substrate, due to melting and rafting of landfast and drifting pack ice (see Chapt. I), could account for the low diversity observed. Further, short duration of ice coverage (less than two months) might be responsible for reduced species richness, typical of diatom communities in the early stages of colonization (Hudon and Bourget, 1981).

Density of bottom ice communities in the Gulf was one to two orders of magnitude less than that of Arctic ice communities, with mean values of 13.5×10^4 cells/L compared to density values of $> 10^7$ cells/L at higher latitudes (Grainger and Hsiao, 1982; Pett et al., 1983; Poulin et al., 1983; Rymes, 1986). Low values of density might again result from the instability and short duration of the ice substrate in the Gulf of St.Lawrence. These two factors combined could prevent biomass and cell accumulation, in addition to nutrient limitation and light level factors discussed in Chapt. II. Densities of bottom ice microalgae found in this study were in the same range as those reported from drifting pack ice in the St.Lawrence estuary (Demers et al., 1984).

Also, density was negatively correlated with percent centric diatoms, with cell n°/l one order of magnitude higher at stations with a low percent abundance of centric diatoms. This important aspect of the ice biota communities of the Gulf of St.Lawrence will be discussed further in the following section.

On the basis of percentage of centric diatoms, two types of ice biota communities can be described from the Magdalen Islands area. The first type is a community almost entirely composed of pennate diatoms, with centric species contributing less than 2% of the abundance. This type of community, found at stations located in protected lagoons (Stations 1 and 3) and on the eastern coast of the Magdalen Islands (Station 2), is similar to landfast ice biota communities from higher latitudes (Horner, 1985). It is the first time that such communities are described for the Gulf of St.Lawrence.

The second type of community is composed of a high percentage of centric diatoms (29.1% to 61.8%) and is found at stations located on the western coast (Stations 4, 4A, 5 and 5A) and at the drifting ice station (Station 7). This type of community is similar to the communities described by Dunbar and Acreman (1980) and Demers et al. (1984) from drifting pack ice in the Gulf and the St.Lawrence estuary where the abundance of centric diatoms was greater than 43% .

Dunbar and Acreman (1980) and Demers et al. (1984) attributed the differences in systematic composition of ice flora between the Gulf and higher latitude communities to 1) the short duration of ice cover in the Gulf (2 months), compared to Arctic and Antarctic regions where the ice forms a more or less permanent substrate allowing for the evolution of a benthic type community not possible for the Gulf, and 2) to higher underice light levels in the Gulf due to thinner ice and increased light intensity from lower latitudes, favouring the growth of planktonic centric diatom over shade adapted pennate forms. With respect to systematic composition for the first community type the explanations given by Dunbar and Acreman and Demers et al. do not hold because ice biota communities similar to Arctic landfast ice communities, with a majority of pennate diatoms, were found in the Gulf of St.Lawrence. Further, their implication of higher underice light levels favouring the growth of centric diatoms over pennate forms is not substantiated in this study due to the fact that communities with a high percentage of centric species have densities one order of magnitude less than communities where pennate diatoms are dominant. However, the explanations given could account for the lower density and biomass of the Gulf communities, in conjunction with nutrient limitation, as discussed in Chapter II.

Principal component analysis relating environmental variables to community structure failed to show any

significant correlations that could account for the existence of the two types of ice biota communities. However, there seems to be a relationship between the two different types of communities and the location of these communities. Communities with a dominance of pennate diatoms are found in lagoons and on the eastern coast of the Islands, at landfast ice stations protected from wind effects and from drifting pack ice. Such landfast ice condition seem to favour the establishment of communities similar to higher latitude landfast ice communities. Communities with a high percentage of centric species are found at the drifting ice station (Station 7) and at stations located on the western coast of the Islands (Stations 4, 4A, 5 and 5A). Similarity of species composition at these stations with the drifting pack ice communities described by Dunbar and Acreman (1980) and Demers et al. (1984), for the Gulf and the St.Lawrence estuary seems to suggest a correspondence in species composition with ice types. This is particularly true considering that the landfast ice stations located on the western coast of the Magdalen Islands are subjected to the influence of drifting pack ice from the estuary and the Gulf of St.Lawrence by 1) being directly in the line of flow of the drifting pack ice and 2) being directly exposed to the prevailing northwesterly winds which cause rafting of drifting pack ice under landfast ice, as demonstrated in Chapter I. Although the occurrence of centric diatoms is rare for Arctic and Antarctic landfast ice

communities (Grainger and Hsiao, 1982; Pett et al. 1983), there are numerous reports of ice biota communities from drifting pack ice where centric diatoms are dominant (Vanhöffen, 1883, 1897; Gran 1897; Meister, 1930; Usachev, 1949; Mel'nikov 1980). Evidence for the existence of two floras on the bottom of Arctic sea ice, distinguishable in species composition and related to ice of different origin, was even put forward by Apollonio (1985) in his account of Sutherland's (1852) report of a drifting pack ice community off the west coast of Greenland dominated by centric diatoms.

How can the two types of ice flora be accounted for on the basis of landfast or drifting pack ice types? The abundance of pennate diatoms in landfast ice communities was thought to result from the close proximity of landfast ice to the benthos, from which it could be seeded by benthic pennate diatoms. There is however no significant species correlation between the benthic and ice diatom flora (Horner, 1985), except for the dominance of pennate forms. Indeed, the majority of widely distributed and dominant ice diatoms are typical cryophiles found only in association with ice (Usachev, 1949). Pack ice formed in deep waters (> 200 m), away from coastal influence, would be expected to contain more phytoplanktonic centric diatoms than pennate diatoms, since they are the dominant species present in the water column. Actually, the co-occurrence of phytoplanktonic species in drifting pack ice and in seawater has led to the

hypothesis that drifting pack ice may be a seasonal habitat for planktonic forms (Garisson and Buck, 1985; Garrison et al. 1987). In the Gulf of St.Lawrence, the abundance of Thalassiosira nordenskiöldii in drifting pack ice and as a spring phytoplankton species would appear to support this hypothesis.

The results obtained in this study indicate a clear relationship between ice types and species composition, but the mechanisms responsible for this are still a matter for speculation. Differences in the life cycle of pennate versus centric diatoms could partly account for the existence of the two floral types. Diatom resting spore formation is common in the life cycle of many centric species (Hargrave and French, 1983), namely for Thalassiosira sp. (Fryxell et al., 1979; Durbin, 1978), and rarely occurs in pennate forms. Only two marine pennate diatoms are know to form resting spores (Von Stosch and Fecher, 1979). The absence of resting spore formation in pennate ice diatoms might restrict their survival to coastal shallow areas, which could partly explain their absence from drifting pack ice. But future research is needed, particularly with respect to the life cycle of pennate versus centric ice diatoms, to fully understand the relationships between ice types and the different ice flora.

Underice Seawater Communities

Density was low in underice seawater, with no cells found at two of the seven stations studied. This indicates the absence of a true underice community such as the ones observed in Manitounouk Sound (Legendre et al., 1981.) and at Cape Hatt (Rymes, 1986). Furthermore, dominant diatom species found in seawater were similar to bottom ice ones suggesting that cells found in seawater originated from the ice. Garrisson et al. (1983) and Pett et al. (1983) also found similarity in species composition in young sea ice and in seawater samples, with much higher cell concentrations in ice than in seawater. The presence of such species as Biddulphia aurita, Cyclotella Meneghiniana, Diatoma elongatum var. tenuis in seawater, and of Nitzschia cylindrus and Thalassiosira nordenskioldii in ice and in seawater, may provide evidence for an impending bloom once the ice breaks up, since all these species are part of the spring phytoplankton bloom in the Gulf of St.Lawrence (Vickers, 1980). Other studies of ice-covered regions of the Arctic have documented similar mixtures of ice pennates and spring bloom centrics before and after ice breakup (Horner and Schrader, 1981; Horner et al., 1974; Legendre et al., 1981; Saito and Taniguchi, 1978), but little is known about the sequence of events occurring during breakup itself.

Communities of Upper Ice Core Sections

Ice biota community structure and composition in upper ice core sections were similar to bottom ice communities except for cell density and % centric diatoms. Species composition of the different ice sections were comparable to bottom ice ones, with similar dominant species for individual stations. The only species found to be dominant in upper ice sections, despite a low abundance in the bottom ice sections, was Biddulphia aurita. The abundance of this centric diatom, namely at stations 2 and 6, resulted in higher percent abundance of centric diatoms in the upper ice sections than in the bottom ice. Rymes (1986) also reported similarity in species composition from bottom ice and upper ice sections in Cape Hatt, with less abundance and co-dominance of added centric species in mid-core sections. However, Hsiao (1980) and Grainger and Hsiao (1982) found in the Canadian Arctic that dominant species composition in the bottom of the ice was different from the dominant species found elsewhere in the ice, but with standing stock one order of magnitude less in the upper ice layers. Differences in species composition or co-dominance of added species in upper ice sections may result from the mechanism by which microalgae originate in sea ice. One of the mechanisms proposed is by successive trapping of different microalgal assemblages at the ice-water interface as the seawater freezes (Meguro et al., 1967;

Horner, 1976). Other mechanisms involve the transportation of microalgae through the water column to the ice under surface by association with frazil ice crystals (Garrison et al., 1983); but this mechanism is unlikely to occur in the Gulf of St.Lawrence where there is no frazil ice formation.

Although distinct and apparently viable algal assemblages are recorded throughout the entire ice core (Hsiao, 1980), recent evidence suggests that active growth is restricted to the lower portion of sea ice (Grossi and Sullivan, 1985), with algae in the upper sections remaining in an anabiotic state (Ackley et al. 1979; Mel'nikov, 1980). In the Arctic, salinity and temperature are thought to limit the upper extent of actively growing populations of algae in sea ice (Horner, 1976). However, for the thinner ice of the Gulf of St.Lawrence, ice temperature and salinity of the liquid brine (see Chapt. I) are within tolerable ranges for diatom growth (Patrick and Reimer, 1966). But, as was demonstrated in Chapter I, residence time of seawater in brine channels is much longer (1-18 days) in upper ice sections than in the bottom ice skeletal layer (2-6 hours, Reeburgh, 1984) which is in direct contact with the underlying seawater. This may cause more pronounced nutrient limitation in the upper ice sections (Grainger, 1977; Grossi and Sullivan, 1985) and account for the lower density of ice algae in the upper ice sections.

Literature Cited

Ackley, S.F., S. Tagushi and K.R. Buck. 1978. Sea and ice algae relationships in the Weddell Sea. Antarct. J. U.S. 13: 70-71.

Ackley, S.F., K.R. Buck and S. Tagushi. 1979. Standing crop of algae in the sea ice of the Weddell Sea region. Deep-Sea Res. 26: 269-281.

Alexander, V., R. Horner and R.C. Clasby. 1974. Metabolism of Arctic sea ice organisms. Inst. of Mar. Sci., Univ. of Alaska, Fairbanks. Rep. R74-4, 120pp.

Alexander, V. and H.J. Niebrauer. 1981. Oceanography of the eastern Bering sea ice-edge zone in spring. Limnol. Oceanogr. 26: 1111-1125

Apollonio, S. 1985. Arctic marine phototropic systems: functions of sea ice stabilization. Arctic 38: 167-173.

Booth, J.A. 1984. The epontic algal community if the ice edge zone and its significance to the Davis Strait ecosystem. Arctic 37: 234-243.

Bray, J.R. and J.T. Curtis. 1957. An ordination of the upland forest communities of Southern Wisconsin. Ecol. Monogr. 27: 325-349.

Brunel, J. 1962. Le phytoplankton de la Baie des Chaleurs. Contributions du Ministère de la chasse et des Pêcheries No.91. Montréal, Canada. 365p.

Bunt, J.S. and C.C. Lee. 1970. Seasonal primary production in Antarctic sea ice at McMurdo Sound in 1967. J. Mar. Res. 28: 304-320.

Burkholder, P.R. and E.F. Mandelli. 1965. Productivity of microalgae in Antarctic sea ice. Science 149: 872-874.

Cleve-Euler, A. 1951. Die Diatomeen von Schweden und Finland. I.K. Svenska Vet.-Akad. Handlingar, Fjärde Serien 2: 1-163

Cleve-Euler, A. 1952. Die Diatomeen von Schweden und Finland. I.K. Svenska Vet.-Akad. Handlingar, Fjärde Serien 3: 1-142.

Cleve-Euler, A. 1953a. Die Diatomeen von Schweden und Finland. I.K. Svenska Vet.-Akad. Handlingar, Fjärde Serien 4: 1-158.

Cleve-Euler, A. 1953b. Die Diatomeen von Schweden und Finland. I.K. Svenska Vet.-Akad. Handlingar, Fjarde Serien 4: 1-225.

Cleve-Euler, A. 1955. Die Diatomeen von Schweden und Finland. I.K. Svenska Vet.-Akad. Handlingar, Fjarde Serien 5: 1-232.

Cota, G.F., S.J. Prinsenberg, E.B. Bennett, J.W. Loder, M.R. Lewis, J.L. Anning, N.H.F. Watson and L.R. Harris. 1987. Nutrient fluxes during extended blooms of Arctic ice algae. J. Geophys. Res. 92: 1951-1962.

Cupp, E.E. 1943. Marine plankton diatoms of the west coast of North America. Bull. Scripps. Inst. Oceanogr. Univ. Calif. 5: 1-237.

Demers, S., J.C. Therriault et C. Descolas-Gros. 1984. Biomasse et composition spécifique de la microflore des glaces saisonnières: influence de la lumière et de la vitesse de congélation. Marine Biol. 48: 185-191.

DeSève, M.A. and M.E. Goldstein. 1981. The structure and composition of epilithic diatom communities of the St.Lawrence and Ottawa Rivers adjacent to the Island of Montréal. Can. J. Bot. 59: 377-387.

Dunbar, M.J. and J.C Acreman. 1980. Standing crop and species composition of diatoms in sea ice from Robeson Channel to the Gulf of St.Lawrence. Ophelia 19: 61-72.

Durbin, E.G. 1978. Aspects of the biology of resting spores of Thalassiosira nordneskioldii and Detonula confervacea. Mar. Biol. 45:31-37.

Ehrenberg, C.G. 1853. Über neue Anschauungen des Kleinsten nördlichen Polarleben. Akad. Wiss. Berlin Monatsber 1853: 522-529.

Field, J.G., K.R. Clarke and R.M. Warwick. 1982. A practical strategy for analysing multispecies distribution patterns. Mar. Ecol. Prog. Ser. 8: 37-52.

Fryxell, G.A., T.A. Villareal and M.A. Hoban. 1979. Thalassiosira sp. nov.: observations on a phytoplankton increase in early austral spring north of the Scotia Ridge. J. Plankton Res. 1: 335-370.

Fukushima, H. and H. Meguro. 1966. The plankton in ice as a basic factor of the primary production in the Antarctic Ocean. Antarctic Record 27: 99-101.

Garrison, D.L., S.F. Ackley and K.R. Buck. 1983. A physical mechanism for establishing algal populations in frazil ice. Nature 306: 363-365.

Garrison, D.L. and K.R. Buck. 1985. Sea-ice algal communities in the Weddell Sea: species composition in ice and plankton assemblages. In Gray, J.S. and Christiansen, M.E. (Eds.): Marine biology of polar regions and effects of stress on marine organisms, pp.103-122. John Wiley, New York.

Garrison, D.L., K.R. Buck and G.A. Fryxell. 1987. Algal assemblages in Antarctic pack ice and ice-edge plankton. J. Phycol. 23: 564-572.

Grainger, E.H. 1977. The annual nutrient cycle in sea ice. In Dunbar, M.J. (Ed.): Polar Oceans, pp. 285-301. Proc. Polar Oceans Conf., Arctic Institute of North America, Calgary.

Grainger, E.H. 1979. Primary production in Frobisher Bay, Arctic Canada. In M.J. Dunbar (Ed.): Marine production mechanisms, pp.9-30. Cambridge Univ. Press.

Grainger, E.H. and S.I.C. Hsiao. 1982. A study of the ice biota of Frobisher Bay, Baffin Island, 1979-1981. Can. MS. Rep. Fish. Aquat. Sci. 1647: 1-128.

Gran, H.H. 1897. Bacillariophyceae von Kleinen Karajakfijord. Bibliotheca Bot. 42: 13-24.

Gran, H.H. 1904. Diatomaceae from the ice-floes and plankton of the Arctic Ocean. Sci. Res. Norw. N. Polar Exped. 4: 3-74.

Grossi, S.M. and C.W. Sullivan. 1985. Sea ice microbial communities. V. The vertical zonation of diatoms in an Antarctic fast ice community. J. Phycol. 21: 401-409.

Hargraves, P.E. and F.W. French. 1983. Diatom resting spores: significance and strategies. In Fryxell, G.A. (Ed.): Survival strategies of the algae, pp.49-68. Cambridge University Press, New York.

Hart, T.J. 1942. Phytoplankton periodicity in Antarctic surface waters. Discovery Rep. 21: 261-365.

Hooker, J.D. 1847. The Botany of the Antarctic Voyage of H.M. Discovery ships "Erebus" and "Terror" in the years 1839-1843. In Vol. I. Flora Antarctica, pp. 503-519. Reprinted 1963, J. Cramer, Weinhein.

Horner, R.A., K.O. Coyle and D.R. Redburn. 1974. Ecology of the plankton of Prudhoe Bay, Alaska. Inst. of Marine Sciences, University of Alaska, Fairbanks, AK. Report no. R74-2. 78pp.

Horner, R.A. 1976. Sea ice organisms. Oceanogr. Mar. Biol. Ann. Rev. 14: 167-182.

Horner, R.A. 1977. History and recent advances in the study of sea ice biota. In M.J. Dunbar (Ed.): Polar Oceans, pp.269-283. Proc. Polar Oceans Conf., Arctic Institute of North America, Calgary.

Horner, R.A. and G.C. Schrader. 1981. Beaufort Sea plankton studies: winter-spring studies in Stefansson Sound and off Narwhal Island, Nov.1978- Jun.1980. Final Report to Outer Continental Shelf Environmental Assessment Program, 138pp.

Horner, R.A. and G.C. Schrader. 1982. Relative contributions of ice algae, phytoplankton and benthic microalgae to primary production in near shore regions of the Beaufort Sea. Arctic 35: 485-503.

Horner, R.A. 1985. Ecology of sea ice microalgae. In Horner, R.A. (Ed.): Sea Ice Biota, pp. 33-194. CRC Press Inc. Boca Raton, Florida.

Hoshiai, T. 1977. Seasonal changes of ice communities in the sea ice near Syowa station, Antarctica. In Dunbar, M.J. (Ed.): Polar Oceans, pp. 307-317. Proc. Polar Oceans Conf., Arctic Institute of North America, Calgary.

Hsiao, S.I.C. 1979. Phytoplankton and sea ice microalgal data from Frobisher Bay, 1971 to 1978. Can. MS. Rep. Fish. Aquat. Sci. 155: 1-82.

Hsiao, S.I.C. 1980. Quantitative composition, distribution, community structure and standing stock of sea ice microalgae in the Canadian Arctic. Arctic 33: 768-793.

Hsiao, S.I.C. 1983. A checklist of marine phytoplankton and sea ice microalgae recorded from Arctic Canada. Nova Hedwigia 27: 225-313.

Hudon, C. and E. Bourget. 1981. Initial colonization of artificial substrates : community development and structure studied by scanning electron microscopy. Can. J. Fish. Aquat. Sci. 38: 1371-1384.

Husdedt, F. 1930a. Bacillariophyta (Diatomeae). In Pascher, A. (Ed.): Die Susswasser-Flora Mitteleuropas, pp. 1-466.

G. Fischer, Jena.

Hustedt, F. 1930b. Die Kieselalgen. In Rabenhorst, L. (Ed.): Kryptogamen-Flora von Deutschland, Osterreich und der Schweiz, VII: 1-920. O. Koeltz, West Germany.

Hustedt, F. 1959. Die Kieselalgen. In Rabenhorst, L. (Ed.): Kryptogamen-Flora von Deutschland, Osterreich und der Schweiz, VII: 1-845. O. Koeltz, West Germany.

Hustedt, F. 1966. Die Kieselalgen. In Rabenhorst, L. (Ed.): Kryptogamen-Flora von Deutschland, Osterreich und der Schweiz, VII: 1-816. O. Koeltz, West Germany.

Legendre, L., R.G. Ingram and M. Poulin. 1981. Physical control of phytoplankton production under sea ice (Manitounouk Sound, Hudson Bay). Can. J. Fish. Aquat. Sci. 38: 1385-1392.

Legendre, L. and S. Demers. 1985. Auxiliary energy, ergoclines and aquatic biological production. Naturaliste Can. 112: 5-14.

Luttenton, M.R. and R.G. Rada. 1986. Effects of disturbance on epiphytic community architecture. J. Phycol. 22: 320-326.

Margalef, R. 1978. Life-forms of phytoplankton as survival alternatives in an unstable environment. Oceanol. Acta 1: 493-509.

McConville, M.J. and R. Wetherbee. 1983. The bottom-ice microalgal community from annual ice in the inshore waters of East Antarctica. J. Phycol. 19: 431-439.

Meguro, H. 1962. Plankton ice in the Antarctic Ocean. Nankyoku Shiryo 14: 1192-1199.

Meguro, H., I. Kuniyuki and H. Fukushima. 1967. Ice flora (Bottom type): a mechanism of primary production in Polar seas and the growth of diatoms in sea ice. Arctic 20: 114-133.

Meister, F. 1930. Mission du "Pourquoi-Pas" en 1929 sous le commandement du Dr. J.-B. Charcot. Diatomées récoltées par R.Ph. Dollfus sur une glace flottante. Bull. Mus. Nat. Hist. Ser. 2:329.

Mel'nikov, I.A. 1980. The ecosystem of Arctic pack ice. In Vinogradov, M.E. and Mel'nikov (Eds.): Biology of the Central Arctic Basin. Moscow: 61-96. (Canadian Translation Fisheries and Aquatic Sci. No 4909)

O'Quinn, R. and M. Sullivan. 1983. Community structure dynamics of epilithic and epiphytic diatoms in a Mississipi stream. J. Phycol. 19: 123-128.

Østrup, E. 1910. Diatoms from North-East Greenland collected by the Danmark-Expedition. Kommisionen for Videnskabelige Undersøgelser i Grønland. Kjøbenhavn, 13/14: 193-256.

Patrick, R. and C.W. Reimer. 1966. The diatoms of the United States. Monogr. Acad. Nat. Sci. Philad. No. 13, Vol. 1. 688pp.

Patrick, R. and C.W. Reimer. 1975. The diatoms of the United States. Monogr. Acad. Nat. Sci. Philad. No. 13, Vol. 2. 213pp.

Pett, R.J., G.P. Vickers, J.C. Acreman and A.G. Ethier. 1983. A seasonal study of the epontic and planktonic communities near the Issungnak artificial island and McKinley Bay in the Canadian Beaufort Sea. Arctic Laboratories Ltd. D.S.S. Contract no. ISZ81-00026. 64pp.

Pielou, E.C. 1966. The measurement of diversity in different types of biological collections. J. Theoret. Biol. 13: 131-144.

Poulin, M., A. Cardinal et L. Legendre. 1983. Réponse d'une communauté de diatomées de glace à un gradient de salinité (Baie d'Hudson). Marine Biol. 76: 191-202.

Ray, A.A. (Ed.). 1982a. SAS User's guide: Statistics, 584 pp. Cary, N.C.: Statistical Analysis Systems Institute.

Ray, A.A. (Ed.). 1982b. SAS User's guide: Basics, 923 pp. Cary, N.C. Statistical Analysis Systems Institute.

Reeburgh, W.S. 1984. Fluxes assiciated with brine motion in growing sea ice. Polar Biol. 3: 29-33.

Rivkin, R.B. and M. Putt. 1987. Photosynthesis and cell division by Antarctic microalgae: comparison of benthic, planktonic and ice algae. J. Phycol. 23: 223-229.

Rymes, C. 1986. An investigation of temporal and spatial variation of ice diatoms and associated meiofauna in Eclipse Sound, Baffin Island. M.Sc. Thesis, McGill University, 183pp.

Saito, K. and A. Taniguchi. 1978. Phytoplankton communities in the Bering Sea and adjacent seas. II. Spring and summer communities in seasonally ice-covered areas.

Astrate 11: 27-35.

Shannon, C.E. and W. Weaver. 1949. The mathematical theory of communication. University of Illinois Press, Urbana. 117pp.

Steven, D.M. 1975. Biological production in the Gulf of St.Lawrence. In Cameron, T.W.M. and Billingsley, L.W. (Eds.): Energy flow, its biological dimension, pp. 229-248. Royal Society of Canada, Ottawa, Ont.

Sutherland, C.P. 1852. Journal of a voyage in Baffin's Bay and Barrow Straits, in the years 1850-1851 performed by H.M. ships "Lady Franklin" and "Sophia", under the commands of Mr. William Penny, in search of the missing crews of H.M. ships "Erebus" and "Terror". Longman, Brown, Green and Longmans, London. Vol. 1 and 2.

Throndsen, J. 1978. Preservation and storage. In Sournia, A. (Ed.): Phytoplankton manual, pp.69-74. Paris, UNESCO.

Uthermol, H. 1958. Zur vervollkommnung der quatitativen phytoplankton- Methodik- Mitt. int. verein. theor. agnew. Limnol. 9: 1-38.

Usachev, P.I. 1938. Biological analysis of ice-floes. Compt. Rend. (Dokl.) Acad. Sci. URSS 19: 645-648.

Vanhoffen, E. 1893. Frühlingsleben in Nordgrönland. Verh. Ges. Erdk. Berl. (cited from Gran, 1904).

Vanhoffen, E. 1897. Fauna and Flora Grönlands, Grönland-Exped. Ges. Erdk. Berl. (cited from Gran, 1904).

Van Landingham, S.L. 1967-1979. Catalogue of the fossil and recent genera of species of diatoms and their synonyms. A revision of F.W. Mill's "An index to the genera and species of the Diatomaceae and their synonyms". Pt. 1-8. J. Cramer, Lehre. 4654.

Vickers, G. 1980. Spring diatom communities of the St.Lawrence River. M.Sc. Thesis, McGill University, 93pp.

Von Stosch, H.A. and K. Fecher. 1979. "Internal thecae" of Eunotia soleiroli (Bacillariophyceae): development, structure and function as resting spores. J. Phycol. 15:233-243.

Whittaker, T.M. 1977. Sea ice habitats of Signy Islands (South Orkneys) and their primary productivity. In Llano, G.A. (Ed.): Adaptations within Antarctic

ecosystems, pp. 75-82. Proceedings of the 3rd SCAR symposium on Antarctic Biology, Smithsonian Institute, Washington.

Zar, J.H. 1984. Biostatistical Analysis, 718 pp. Englewood Cliffs: Prentice -Hall, Inc.

Zoto, A., D.O. Dillon and E. Schlichting, Jr. 1973. A rapid method for cleaning diatoms for taxonomic and ecological studies. Phycologia 12:69-70.

Concluding Remarks

This is the first extensive study of ice biota communities from the Gulf of St.Lawrence, covering temporal and spatial aspects of sea ice characteristics, nutrient dynamics and community structure and composition. Ice biota communities were studied from the beginning of ice formation until after ice melt, in ice and in seawater, at landfast and at drifting ice stations. The purpose of the study was to test the hypothesis that short duration of ice cover and higher underice light intensity in lower latitudes ice communities are responsible for the lower biomass, and that the differences observed in species composition between the Gulf of St.Lawrence and Arctic ice communities, are attributable to higher underice light intensity which favours planktonic diatoms over shade adapted pennate diatoms.

In chapter I, the instability of the ice subtrate is clearly demonstrated by i) short duration of ice cover (2 months), ii) melting of ice with reduction in ice thickness and iii) rafting processes which also account for ice melt and slush ice formation. Differentiation between landfast ice and drifting pack ice is put forward with respect to rafting processes and drifting pack ice influence. Estimated ice brine volumes are used for the first time as a mean of determining the exact salinity concentrations to which the ice microalgae are exposed in the brine cells. From these measurements, it was estimated that salinity of the liquid

brine are within tolerable ranges for diatom growth. However, residence time of seawater in upper ice sections, estimated for the first time, is suggested to limit the upper extent of actively growing ice biota population, and could account for the lower biomass of ice biota in upper ice sections. Indeed, a residence time of 1-18 days was calculated for upper ice sections, as opposed to 2-6 hours in the bottom ice skeletal layer where the highest biomass concentrations are observed. Seawater being the main source of nutrient supply to ice algae, the longer residence time may enhanced nutrient limitation particularly in the upper ice sections.

In chapter II, nutrient limitation was investigated as a possible cause of lower biomass of ice biota communities from lower latitude. Nutrients concentrations were therefore monitored on a temporal and spatial scale in ice and in seawater, and in relation to the three sources of nutrient supply to the ice microalgae. These include i) desalination through brine drainage, ii) in-situ regeneration and iii) seawater nutrient supply. Desalination was found to play a minor role in nutrient supply. In-situ regeneration was demonstrated for phosphorus only. Seawater nutrient supply was illustrated by the decrease of nitrate and silicate concentrations in seawater with time, and nutrient limitation with respect to these two nutrients was clearly demonstrated. Nutrient limitation could account for lower biomass of ice biota communities in the Gulf of St.Lawrence, and specific

growth rates in the lower range of values observed for Arctic ice algae would further support this. However, a lack of correlation between nutrient and biomass concentrations, with lowest biomass at the drifting ice station where nutrient concentrations were highest, suggests that other factors may be involved in the limiting of biomass accumulation. Higher underice light intensity could be involved by not allowing for the extreme shade adaptation necessary and observed in ice microalgae from higher latitudes. This aspect is still opened to future investigations since no evidence of lack of shade adaptation could be demonstrated form the data.

In chapter III, the structure and composition of ice biota communities were studied with respect to the differences observed in ice flora between the Gulf of St.Lawrence and higher latitude ice biota communities, and with respect to the lower biomass. On the basis of very low number of species and low diversity, the structure of the ice biota communities from the Gulf of St.Lawrence is a reflection of an unstable environment. The instability of the ice substrate was put forward in chapter I. But low number of species and low diversity can also be a reflection a community in the early stages of colonization, which suggests that the short duration of the ice cover might also be involved. Analysis of species composition revealed the presence of two different types of ice biota communities: 1) communities composed of a majority of pennate diatoms with a

low percentage of centric species (<2%), and 2) communities composed of a high percentage of centric diatoms (>39%). The presence of ice biota communities of type 1, described for the first time in the Gulf of St.Lawrence area, does not support the hypothesis that higher underice light intensities in the Gulf favours the establishment of ice biota communities of second type only. The ice biota communities of the second type, found at the drifting ice stations and at stations located on the western coast of the Magdalen Islands, are similar to drifting pack ice communities previously described for the Gulf of St.Lawrence, and to drifting pack ice communities found in the Arctic. Since no correlation was found between the structure and the composition of the ice biota communities and the environmental variables, it is suggested, based on association of communities of type one with landfast and of type two community with drifting pack ice, that the differences in ice flora observed are related to ice origin, i.e. landfast ice close to shore in shallow waters and drifting pack ice away from shore in deep waters. Although the origin of ice algae is still a matter for speculation, differences in the life cycle of centric diatoms versus pennate ones might be involved, but further research is needed to fully elucidate the question.