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Initial incorporation of phytoplankton into young ice in Saroma Ko lagoon, Hokkaido, Japan

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Abstract: The initial incorporation of phytoplankton into young ice was examined on February 25-28, 1998 in Saroma Ko lagoon, Hokkaido, Japan to test our hypothesis that some physical selection would occur to establish the ice algal assemblages during the formation of young sea ice and the development of fast sea ice. An open pool (2 $\times$2 m) was employed for the experiment. Young sea ice was collected for a 24hr experiment. Relative brine volume in the young sea ice might be related to air temperature. Incorporated contents of chlorophyll *a*, biogenic silica, particulate organic carbon and nitrogen were directly related to the relative brine volume. The larger than 2 μm fractions of chlorophyll *a* and biogenic silica were 95% and 78%, respectively. The most abundant species incorporated into the young sea ice were *Navicula transitans* (33%) and *Achnanthes taeniata* (12%). Those species were originated from a water column where they were released from the bottom surface of seasonal sea ice in the vicinity of the experimental pool. Cell density of the incorporated phytoplankton ranged from 46 to 154 cells ml^{-1} into the young sea ice and 17$\pm$5 cells ml^{-1} in the sea water under the young sea ice. Those microscopic observations suggested the selective incorporation of phytoplankton into the young sea ice at the beginning of ice formation and it might accelerate selective development to establish the ice algal assemblages with the growth of fast sea ice.

key words: phytoplankton, incorporation, brine, temperature, ice algae

Introduction

In polar and subpolar regions, dense development of ice algal assemblages has been reported on the bottom surface of sea ice (*e.g.* Bunt and Wood, 1963; Grossi *et al.*, 1984; Grossi and Sullivan, 1985; Watanabe, 1987; Garrison, 1991). Ice algae plays an important role in primary production at high latitudes (Poulin, 1990). Primary production in sea ice is high although light is intercepted by overlying snow and ice (Satoh *et al.*, 1989; Smith *et al.*, 1990). Primary production in a water column under the sea ice is usually insignificant due to little light and hydrostatic instability of the water column (Subba Rao and Platt, 1984; Fukuchi *et al.*, 1989). Ice algal assemblages continue to develop in the brine pockets and channels as long as the sea ice grows (Horner, 1990). The brine volume in the sea ice is habitable space for organisms; it varies with various processes during ice growth. As a consequence, the size of the ice

algal biomass is also variable with ice condition and brine volume (Gleitz and Thomas, 1993). Ice algal assemblages are eventually released into a water column when the sea ice melts and breaks (Ackley *et al.*, 1979; Palmisano and Sullivan, 1983; Garrison and Buck, 1991; Taguchi *et al.*, 1997). These released ice algal cells either immediately sink to the bottom (Riebesell *et al.*, 1991; Taguchi *et al*, 1997) or act as a seed population for surface phytoplankton along the ice edge (Garrison *et al.*, 1987). However, studies of the initial establishment of ice algal assemblages in fragile sea ice (young ice) are very limited due to lack of logistic support (Garrison *et al.*, 1983, 1989). Cooling of surface water induces thermal convection and when the water temperature falls below the freezing point, ice crystals begin to form in the upper layer with a several meter thickness (Weeks and Ackley, 1982). Langmuir circulation cells, which are formed by winter wind, transport ice crystals throughout the upper water column (Lange *et al.*, 1989). The buoyancy of ice crystals results in accumulation at the sea surface (Eicken and Lange, 1989). The physical mechanism of young ice formation may involve a selection processes of algal cells due to the buoyancy of algal cells with ice crystals rising to the surface and aggregation of ice crystals (Clarke and Ackley, 1984; Garrison *et al.*, 1989).

Saroma Ko lagoon is a semi-closed enbayment located in the northeastern part of Hokkaido, Japan. It is connected to Sea of Okhotsk by two open channels (Fig. 1). The sea surface freezes during winter and ice algal assemblages form at the under surface of seasonal sea ice (Hoshiai and Fukuchi, 1981). The amount of chlorophyll *a* reached higher than 100 mg chlorophyll *a* m^{-2} in the bottom 3 cm of sea ice in March 1992 (Robineau *et al.*, 1997). After the sea ice melts and breaks, ice algae are released into the water column; it contributes about 20% of the total algal population in the spring bloom (Taguchi, 1993).

The purpose of this study was to test whether some physical selection of phytoplankton would occur or not in the formation of young ice. The physical selection might influence the characteristic ice algal assemblages with sea ice growth. Unfortunately, it was logistically difficult to collect young ice at the beginning of sea ice formation. The present experiment was designed to study the process of incorporation of phytoplankton into the sea ice in the open pool that formed in the middle of the ice season. Young ice was collected and analyzed to study its chemical properties and the species compositions of ice algal assemblages to test our hypothesis.

Materials and methods

Sampling

The experimental site was located near the coast of Sakae-ura in Saroma Ko lagoon, Hokkaido, Japan (Fig. 1). The thickness of sea ice was 65 cm with 5 cm of overlying snow. A square pool was made and polycarbonate plates were placed along the side wall of sea ice to prevent contamination directly from the exposed ice algal layer in the side wall of the sea ice. The pool was divided into four sections by polycarbonate plates. The area of each section was about 10^4 cm^2. After sea ice was completely removed from the surface, new ice formation experiments were initiated on February 25, 26, and 27, 1998, respectively; they lasted for 24 hr each. The experiment con-

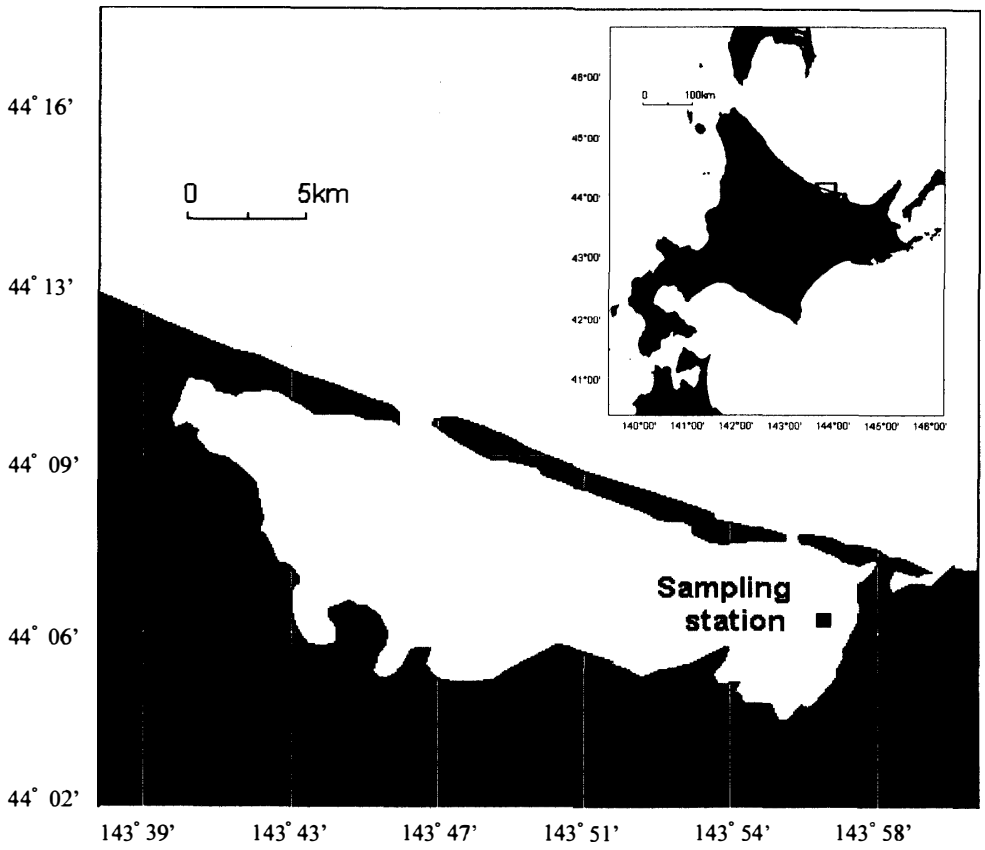

Fig. 1. Location of experiment and sampling station in Saroma Ko, lagoon, Hokkaido, Japan.

ducted from February 25 to 26 was referred to as Exp. 1, that from February 26 to 27 as Exp. 2, and that from February 27 to 28 as Exp. 3. Sea ice samples were collected from the same subarea in all experiments. Surface sea water was collected by a NISKIN bottle from the ice-water interface. An ice core was obtained from the vicinity of the pool on February 26, using a CRREL core sampler (Rand and Mellor, 1985) and the bottom 0–3 cm section of core was collected. Photosynthetically available radiation was measured in air and water with and without the young ice by a LICOR 2π sensor model LI-190SB. Water and ice temperature were monitored every two minutes from 1700 on February 25 to 0900 on February 28, 1998 with the NICHIYU GIKEN KOGYO underwater thermometer Model NWT-SN, which was placed in the sea ice immediately above the sea surface. All ice samples were placed in the 3.2% NaCl solution and allowed to melt at < 20°C. Salinity was determined on an ATAGO salinity refractometer Model S/Mill-E. Brine volume (V_b) was estimated by the following equation,

$$V_b\ (\mathrm{m}l) = \text{Sampling area } (\mathrm{cm}^2) \times \text{Ice thickness (cm)} \times \text{Sea ice density} - \text{Volume of melted young sea ice } (\mathrm{m}l), \quad (1)$$

where sea ice density, 0.945 (-2°C, 10‰), was used to convert the ice volume into

water volume (Tabata, 1977). V_b was divided by melted sea ice volume to obtain the relative brine volume.

Subsamples were filtered onto Whatman glass fiber filters (type GF/F) for analysis of chlorophyll pigments, and precombusted Whatman glass fiber filters (type GF/F) for particulate organic carbon and nitrogen. Second subsamples were filtered onto membrane filters for analysis of biogenic silica. Third subsamples were filtered through Millipore Millex HV filters for analysis of macronutrients. Fourth subsamples were preserved in 2% buffered Formalin solution for microscopic observation.

Analysis of Chlorophyll Pigments, Macro Nutrients, Biogenic Silica, and Particulate Organic Carbon and Nitrogen

Chlorophyll pigments were extracted with N, N-dimethylfolmamide (DMF) in opaque vials (Suzuki and Ishimaru, 1990) and measured on a TURNER DESIGN fluorometer Model 10-AU with the method recommended by Holm-Hansen *et al.* (1965). Macronutrients including nitrate, nitrite, phosphate and silicate were analyzed on a BRAN LUBBE Autoanalyzer Model AACS-II. Biogenic silica was determined spectrophotometrically by the method of Paasche (1980). Particulate organic carbon and nitrogen were analyzed on a FISON elemental analyzer Model NA 1500 NCS standardized by acetanilid. Means were calculated from duplicate samples for all analysis.

Microscopic observation

Taxonomical identification and enumeration of algal species were carried out by light microscopy. A total of >1000 cells was enumerated to avoid the influence of sample size on the index values of species diversity. Taxonomy was based on Tomas (1997); diatom systematics was based on Round *et al.* (1990). Percent similarity was calculated by the method of Whittaker (1952).

Results

Chemical and physical characteristics of young ice and seawater under the sea ice during the experiments

Water and ice temperature varied between -1.0 and -2.7°C during the experiment (Fig. 2). Temperature did not change and stayed at -1.2°C for Exp. 1, decreased from -1.0 to -2.7°C for Exp. 2, and increased from -2.7 to -1.2°C for Exp. 3. The sea ice grew to 3.6 cm in thickness for Exp. 1 and 2 but only 1.2 cm in thickness in Exp. 3 (Table 1). A sudden increase of temperature might have been responsible for the formation of thin ice in Exp. 3 although the development of ice thickness was related to air temperature (Shirasawa, 1993). Estimated relative brine volume in the young ice ranged from 7.5% to 55% during the present experiment (Table 1). Salinity of the young ice was about 13.3 in Exp. 1 and 2 and 22.9 in Exp. 3 (Table 1). However, not all macronutrients in the sea ice and in the water column show similar trend to salinity among the experiments. Nutrient concentrations in the sea ice did not show much variability in any of the experiments (Table 1). They were $0.5 \pm 0.06\,\mu$M for nitrite, $10 \pm 0.7\,\mu$M for nitrate, $0.8 \pm 0.1\,\mu$M for phosphorus and $39 \pm 1.9\,\mu$M for silicate in the sea

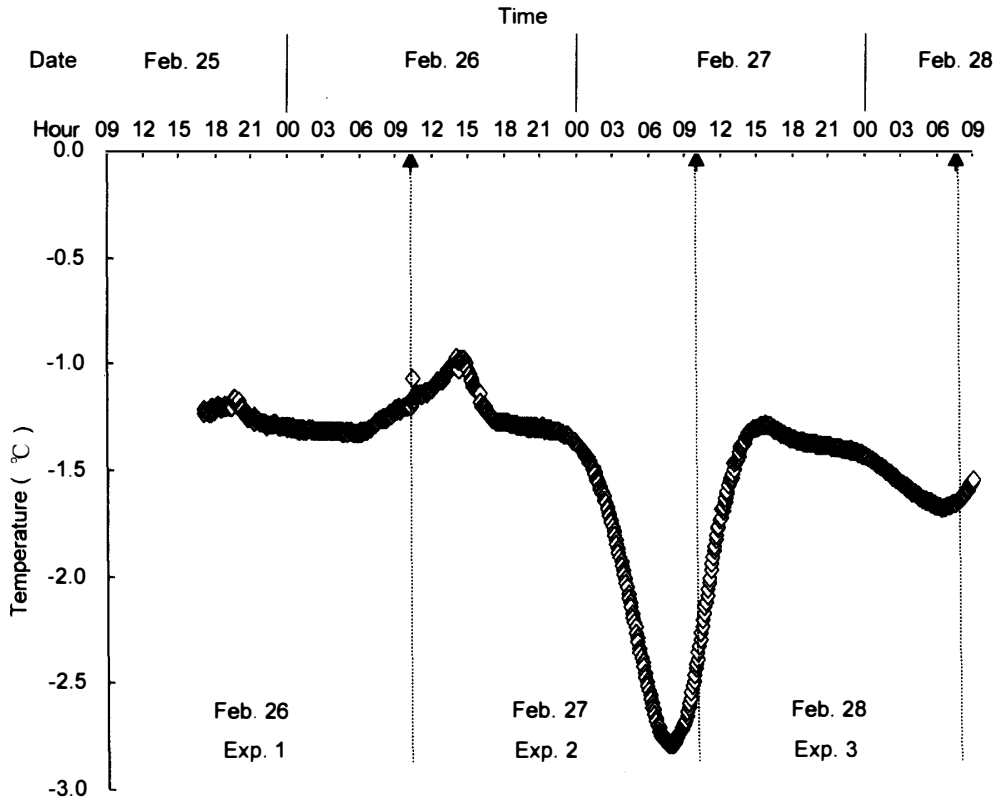

Fig. 2. Water and ice temperature during three consecutive experiments. Arrows point to sampling times of each experiment.

Table 1. Thickness and volume of ice collected during the 24 hr experiment with estimated brine volume. Salinity, nitrate, nitrite, phosphate and silicate in the young ice and surface sea water under the sea ice.

Samples	Young ice			Sea water		
Experiment	1	2	3	1	2	3
Date	Feb. 26	Feb. 27	Feb. 28	Feb. 26	Feb. 27	Feb. 28
Thickness of ice (cm)	3.6	3.6	1.2	–	–	–
Volume of sea ice (cm)	31120	29340	7230	–	–	–
Estimated brine volume (Vb)(*ml*)	1476	3438	3696	–	–	–
Relative brine volume (Vrb)	0.047	0.12	0.51	–	–	–
Salinity (PSU)	13.4	13.3	22.9	25.2	25.0	24.0
Nitrate (*μM*)	9.3	10.4	10.5	24.2	24.3	11.5
Nitrite (*μM*)	0.44	0.54	0.52	0.61	0.53	0.51
Phosphate (*μM*)	0.70	0.70	0.87	0.22	0.31	0.27
Silicate (*μM*)	38.7	36.7	40.5	101.6	71.6	76.8

ice. Nitrate and silicate were diluted to about 40% in the young ice. Nitrite did not show much difference between the young ice and the seawater under the sea ice. However, phosphorus indicated some accumulation, by a factor of 2.8, in the young ice. These results might indicate that nitrate and silicate were consumed rapidly by micro-algae incorporated into the young ice.

Table 2. Pigments, biogenic silica, particulate organic carbon (POC) and nitrogen (PON) and ratios of particulate matter in the young ice and surface sea water under the sea ice.

Samples	Young ice			Sea water		
Experiment	1	2	3	1	2	3
Date	Feb. 26	Feb. 27	Feb. 28	Feb. 26	Feb. 27	Feb. 28
Chlorophyll *a* (ng cm^{-3})	0.93	1.16	2.61	0.34	0.38	0.51
Pheopigments (ng cm^{-3})	0.43	0.43	3.46	0.42	0.27	0.36
Biogenic silica (ng cm^{-3})	14.1	16.3	30.0	5.1	17.3	3.0
POC (ng cm^{-3})	1025	1055	1440	400	293	285
PON (ng cm^{-3})	47	75	114	68	44	46
Chl *a*/Chl *a* + Pheopigments	0.68	0.73	0.43	0.45	0.58	0.58
C/Chlorophyll *a*	1105	912	552	1179	765	559
C/N	22	14	13	5.9	6.6	6.1
BioSi/Chl *a*	15.2	14.1	11.5	14.9	45.3	5.8
BioSi/C	73	65	48	78	17	95

C/N, C/Chl *a*, BioSi/Chl *a* and BioSi/C indicate mass ratios of carbon to nitrogen, carbon to chlorophyll *a*, and biogenic silica to chlorophyll *a*, respectively.

Table 3. Relative abundance (%) of sizes such as >10, 10-2, and 2-0.2μm for chlorophyll *a* and biogenic silica.

Samples	Chlorophyll *a*			Biogenic silica		
Experiment	1	2	3	1	2	3
Date	Feb. 26	Feb. 27	Feb. 28	Feb. 26	Feb. 27	Feb. 28
>10μm	84.2	86.1	70.9	39.3	52.2	56.6
10-2.0μm	12.2	9.3	22.7	33.2	23.3	29.0
2.0-0.2μm	3.6	4.6	6.5	27.5	24.5	14.5

Incorporated chemical constituents

Concentrations of chlorophyll *a* and pheopigments in the young ice were similar between Exp. 1 and Exp. 2 but about 2.5 and 2.3 times higher in Exp. 3 than Exp. 1 and 2 (Table 2). Chlorophyll *a* contents were 3 in Exp. 1 and 2, and 5 times higher in the young ice, although chlorophyll *a* concentrations in sea water varied little with 0.41$\pm$0.09 ng Chl *a* cm^{-3} (Table 2). Most chlorophyll *a* was observed in the size fraction larger than 2.0μm with a mean of 95.1$\pm$1.5% of total chlorophyll *a* in the young ice (Table 3). The pigment ratios defined as chlorophyll *a* divided by chlorophyll *a* plus pheopigments in the young ice were about 0.7 in Exp. 1 and Exp. 2 but 0.4 in Exp. 3 (Table 2). The pigment ratios in seawater did not change in any of the experiments, with 0.54$\pm$0.08 (Table 2).

Concentrations of biogenic silica in the young ice showed a similar trend to those of chlorophyll pigments. Concentration of biogenic silica ranged from 14.1 to 30 ng cm^{-3} in the young ice (Table 2). Biogenic silica contents in the size fraction larger than 2.0μm accounted for 77.9$\pm$6.9% of the total concentration of biogenic silica (Table 3). Concentrations of biogenic silica in sea water varied from 2.97 to 17.3 ng cm^{-3} (Table 2). Biogenic silica contents were enhanced by 3 to 10 times in the young

Table 4. Cell density and relative abundance (%) of abundant taxa occurred in the young ice and sea water under the sea ice.

Young ice				Sea water	
Exp. 1 Feb. 26		Exp. 3 Feb. 28		Exp. 1–3 Feb. 26–28	
Cell density	(cells ml^{-1}) 46	Cell density	(cells ml^{-1}) 154	Cell density	(cells ml^{-1}) 170.0±5
	Relative abundance (%)		Relative abundance (%)		Relative abundance (%)
Navicula transitans	27.9	*Navicula transitans*	37.7	*Achnanthes taeniata*	29.8±3.06
Achnanthes taeniata	18.5	Gymnodiniales	14.7	*Navicula transitans*	21.7±6.02
Detonula confervacea	13.1	Euglenophyceae	10.5	*Detonula confervacea*	11.8±3.86
Thalassiosira spp.	4.4	*Achnanthes taeniata*	6.0	*Fragilariopsis* cf. *oceanica*	7.4±4.31
Pinnularia quadratarea var. *constricta*	4.0	Peridiniales	4.9	Euglenophyceae	4.9±1.86

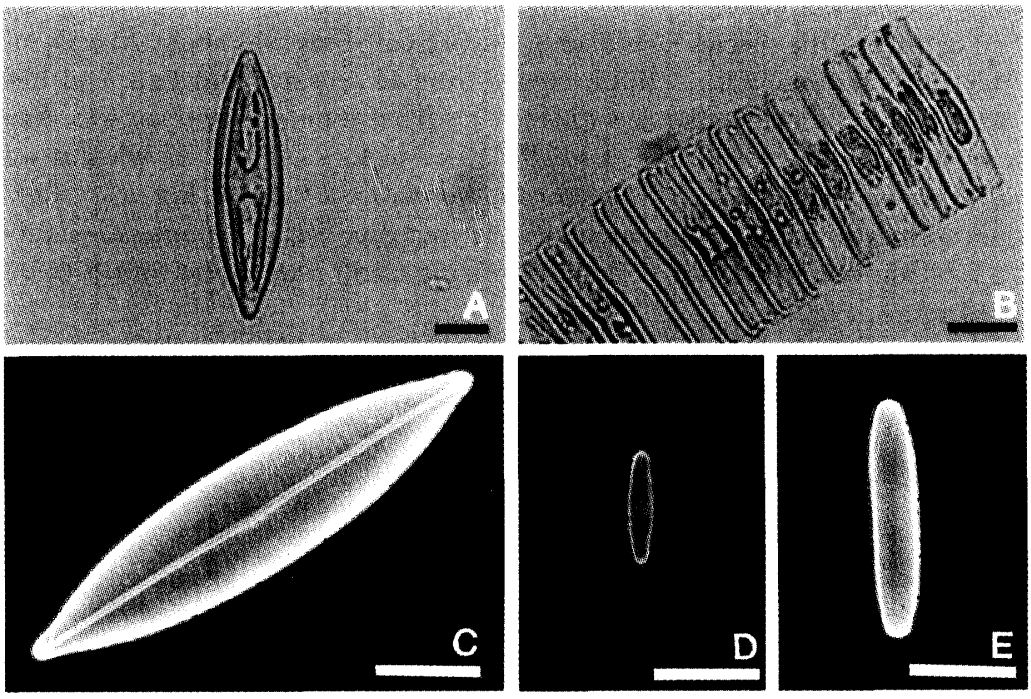

Fig. 3. Light micrographs of *Navicula transitans* (A, C) and scanning electron micrographs of *Achnanthes taeniata* (B, D, E). Scale bars represent 10 μm.

ice, although almost no enhancement was observed in Exp. 2.

Concentrations of POC and PON in the young ice also indicated a similar trend to those of chlorophyll pigments, ranging from 1025 ng cm^{-3} to 1440 ng cm^{-3} and 47 ng cm^{-3} to 114 ng cm^{-3}, respectively (Table 2). Highest concentrations of POC and PON were observed in Exp. 3. The concentrations of POC and PON in sea water did not show much variability, with means of 326±64 ngC cm^{-3} and 52.8±13 ngN cm^{-3}, respectively. Contents of POC and PON were 2 to 4 times higher than in sea water.

Table 5. Relative abundance of abundant taxa found in the bottom 3 cm layer of the ice core on February 26, 1998.

Species	(%)
Navicula transitans	51
Achnanthes taeniata	25
Odontella aurita	7
Detonula confervacea	6
Thalassiosira spp.	3
Pinnularia quadratarea var. cf. *constricta*	3
Melosira arctica	2
Nitzschia frigida	2
Pinnularia quadratarea var. cf. *minor*	1
Entomoneis sp.	0.4

Microscopic observation

Cell density of the species identified in the present study was about 20 cells ml^{-1} in sea water under the young ice. But it ranged from 46 cells ml^{-1} for Exp. 1 to 154 cells ml^{-1} for Exp. 3 in the young ice (Table 4). The dominant species was *Navicula transitans* in the young ice in Exp. 1 (27.9%) and in Exp. 3 (37.7%) while it was the second in sea water (21.7±6.0%) under the young ice (Table 4, Fig. 3). The most abundant species in the water column under the young ice was *Achnanthes taeniata* (29.8 ±3.1%), which was second (18.5%) in the young ice in Exp. 1 and fourth (6.0%) in Exp. 3 (Table 4, Fig. 3).

Navicula transitans (51%) and *Achnanthes taeniata* (25%) were the most abundant species in the bottom 0–3 cm layer of the sea ice in the vicinity of the pool obtained on February 27 (Table 5).

Discussion

Brine is produced in sea ice from the beginning of sea ice formation although its volume is variable due to temperature (Table 1, Fig. 2). Those values might be overestimated, since air bubbles produced in the young ice were not considered. Brine volume is considered as one of the limiting factors for the ice algal community since it is to the only habitable space found in the sea ice (*e.g.* Horner, 1990; Weissenberger *et al.*, 1992; Gleitz and Thomas, 1993). This consideration is supported by the regression model among the incorporated chemical components and the relative brine volume (V_{rb}) determined in the presented study as follows;

$$\text{Chl } a = 3.55\, V_{rb} + 0.65, \quad r^2 = 0.999 \tag{2}$$

$$\text{BioSi} = 33.7\, V_{rb} + 11.5, \quad r^2 = 0.999 \tag{3}$$

$$\text{POC} = 899\, V_{rb} + 94.2, \quad r^2 = 0.994 \tag{4}$$

$$\text{PON} = 125\, V_{rb} + 46.5. \quad r^2 = 0.914 \tag{5}$$

Significant relationships were obtained among concentrations of chlorophyll *a*, biogenic silica, POC and PON and relative brine volume in the young ice ($p<0.05$). This observation may suggest that brine volume in the young ice is the important factor which controls the incorporated biomass. Concentrations of chlorophyll *a* and biogenic silica were 5 and 10 times higher than those in a water column at maximum, respectively. Those accumulation factors were similar to those obtained in the Antarctic (Garrison *et al.*, 1983). Contents of POC and PON were 2 to 5 times higher than those in sea water. Comparison of C/N ratios indicated that POC was more efficiently harvested into the sea ice than PON (Table 2). Other ratios did not suggest similar accumulation. These observations in the present study may indicate dissimilar incorporation among chemical constituents during the young ice formation, although a considerable carbon contribution was not expected in the young ice due to the results of nonselective harvesting and concentration of organisms and detritus (Garrison and Close, 1993).

The source of seed population for microalgae incorporated into the young ice could be either phytoplankton in the water column or ice algae released from the bottom surface of the sea ice surrounding the pool. Ice algae have been reported to be released continuously from the bottom surface of even well developed seasonal sea ice (Carey, 1987; Taguchi *et al.*, 1997). This is also confirmed by the simultaneous occurrence of *Navicula transitans* and *Achnanthes taeniata* in the bottom 0–3 cm layer of the ice core taken from the vicinity of the pool (Table 5) and the water column beneath the young ice (Table 4). Once ice algal cells are released into the water column, they play the role of seed population for ice algae incorporated into young ice. This is also evidenced by the two abundant species in the young ice, particularly in Exp. 1 (Table 4) and a relatively strong similarity in the species composition between the water column and young ice (Fig. 4). Pennate diatoms have a characteristic linkage among cells by

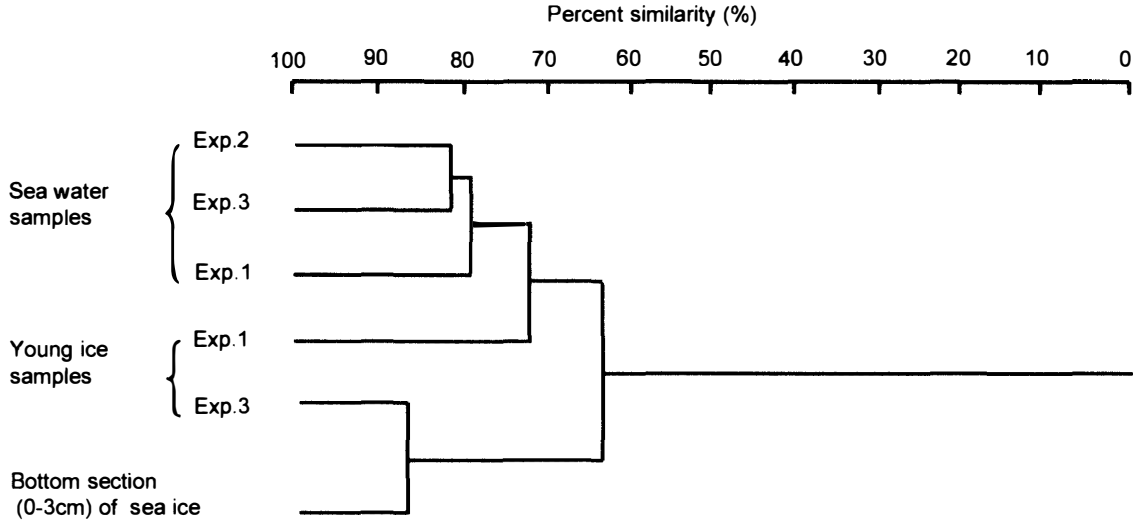

Fig. 4. A dendrogram of cluster analysis on similarity of microalgal populations in the new sea ice and sea water samples. Percent similarity index was calculated by the method recommended by Whittaker (1952).

mucilage (*e.g.* Lewin, 1958). A large amount of mucilage secretion may play a possible role in harvesting and concentration of organisms during aggregation of ice crystals. However, other motile species which belong to Gymnodiniales and Euglenophyceae have come to be dominant in the young ice in Exp. 3 than those two common species, which gave the lowest similarity of species composition in the water column in the present study (Fig. 4). Gymnodiniales and Euglenophyceae are known as phototactic (Halldal, 1962) so that they seem to be attracted to the lit area underneath young thin sea ice in the water column and phytoplankton cells are harvest (McPhee, 1990; Garrison *et al.*, 1989). Centric diatoms, *Odonthella aurita* from one of the abundant species at the bottom of the ice core collected from the vicinity of the pool in the present study (Table 5) but this species is not incorporated into the young ice (Table 4). These observations also support the hypothesis of selective incorporation of phytoplankton into the young ice.

Nitzschia frigida has been reportedly developed significantly in the ice algal assemblage (Takahashi, 1981), reaching 551 cells ml^{-1} as the winter season progresses in Saroma Ko lagoon (Kudoh, 1994). *N. frigida* corresponded to only 4% of the total population incorporated into the young ice in Exp. 1 and 0.8% in Exp. 3. The cell abundance contributed only 2% to the total number of cells at the sea ice bottom (Table 5). These observations may suggest that predominant species of ice algae are incorporated from the beginning of young ice.

Achnanthes taeniata is observed as one of the abundant species in the incorporated population during this experiment; however, this species has not been reported yet in Saroma Ko lagoon (Takahashi, 1981; Kawanobe and Kudoh, 1995) but is found as plankton commonly in the Arctic (Hasle, 1990; Krammer and Lange-Bertalot, 1991) and as ice algae in the Arctic (Horner, 1985). *A. taeniata* has been probably confused with other species such as forming ribbon like community (Hasle, 1997).

In conclusion, the ice algal population can be harvested in the young ice from available phytoplankton species in the water column and developed selectively in the available brine space due to physiological differences such as differential tolerance to chemical variations among species (Gleitz and Thomas, 1992; Grossmann and Gleitz, 1993; Gleitz *et al.*, 1996) and the ecological difference in a trophic relation with grazers (Garrison and Buck, 1991; Thomsen *et al.*, 1991; Garrison and Close, 1993). However, the interpretation of the present experimental approach should be cautious since an artificial pool is a prototype of a small scale of polynya where physical properties and biological activity are quite different from those in open water at the beginning of young ice formation (Muench, 1990).

Further effort is needed to characterize the ice algal dynamics by which the incorporated algae become seeding for ice algae and the species composition changes with young ice growth.

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