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Effect of ice algal community on the increase of chlorophyll *a* concentration during spring in coastal water of the Sea of Okhotsk

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Abstract: A seasonal study of size fractionated chlorophyll *a* concentration was conducted weekly in Monbetsu Harbor from October 1996 to November 1997 to investigate the annually persistent occurrence of the spring peak of the chlorophyll *a* concentration in the $>10\mu$m size fraction immediately after the retreat of sea ice, as described by K. Hamasaki *et al.* (Plankton Biol. Ecol., **45**, 151, 1998). Species composition of natural phytoplankton assemblages was also investigated to study whether phytoplankton or ice algae were responsible for the spring peak in the coastal water. The spring peak occurred immediately after the retreat of sea ice but timing of the occurrence was different between the stations occupied in the present study. The spatial heterogenity in occurrence of the spring peak seemed to be related to the sea ice distribution between the stations. New sea ice provided only a small supply of ice algae due to the relatively short growth period inside of the harbor. Large ice floes provided for a large supply of ice algae due to the long growth period outside of the harbor. The magnitude of the spring peak was related to sea ice growth. However, those ice algae seemed to sink to the bottom with little contribution to phytoplankton assemblage in the harbor, while ice algae contributed significantly to the spring peak outside of the harbor. Species composition revealed relatively fast response of phytoplankton to the environmental change after the disappearance of sea ice. Surface assemblages of phytoplankton including ice algae seemed to respond fully to the regional optical condition by changing in the species composition.

key words: diatom, ice algae, size fractionation, absorption coefficient

Introduction

A spring peak of chlorophyll *a* concentration in the $>10\mu$m size fraction was evident in coastal water of the Sea of Okhotsk along the northeast coast of Hokkaido in March. This peak occurred as the sea ice receded (Hamasaki *et al.*, 1998). There are two possible mechanisms for the occurrence of a high concentration of chlorophyll *a* in the $>10\mu$m size fraction. First, sea ice provides a habitat for ice algae, larger than 10 μm and ice algae such as *Nitzschia frigida* have been known to occur in this region (Tamura, 1951; Hoshiai and Fukuchi, 1981; Takahashi, 1981). Pennate diatoms occur mostly in the ice algal community (Poulin, 1990). Those ice algae are released from sea ice as it retreats (Garrison, 1991). This is associated with the increase of biomass with little adaptation to the lit surface layer, which is formed by density gradient due to

mainly melting sea ice in open water (Smith and Nelson, 1985; Veth *et al.*, 1992). However, the biomass is not sustained for a long time in the surface layer due to immediate downward export enhanced by aggregation (Riebesell, 1991; Kiorboe *et al.*, 1994). Second, phytoplankton or released ice algae grow in the surface layer (Smith and Nelson, 1986; Garrison *et al.*, 1987; Kuosa *et al.*, 1992). They may adapt quickly to relatively strong light, although they are exposed to direct solar radiation in the shallow layer. Therefore, algal cells are sustained in the surface layer and increase as long as the density gradient is strong enough to maintain the cells. However, it is not known whether ice algae were responsible for this bloom-like event in the coastal water such as Monbetsu Harbor. Probably both mechanisms occur simultaneously in the present study area due to a shallow water column (<10 m depth).

This study aims to determine the degree of ice algal contribution to the spring peak in March, which occurs immediately after the disappearance of sea ice, by examining the species composition of natural phytoplankton assemblages in the surface layer and how they respond to the shallow lit surface layer based on the quantitative determination of optical properties of light absorption by surface phytoplankton assemblages.

Materials and methods

Water samples were collected weekly at 0 and 3 m depth at St. B from October 23, 1996 to November 5, 1997 and 2 m at St. C from October 30, 1996 to April 9, 1997 at a pier in Monbetsu Harbor except in February when ice covered the entire harbor (Fig. 1). St. B was located on the east side of Monbetsu Harbor. It is 1.2 km away from St. A where the previous work was done from September 20, 1995 to September 18, 1996 (Hamasaki *et al.*, 1998). St. C was located at the east pier faced to the outside of Monbetsu Harbor. Water depth was 5 m at St. B and 9.8 m at St. C. Sampling was always conducted in the early afternoon. Temperature and salinity were determined with a CTD model SBE-19 (Sea-Bird Electronics, Inc.). Ice coverage data were obtained from the Monbetsu Radar Station at the Sea Ice Research Laboratory, Institute of Low Temperature Science, Hokkaido University. Ice coverage was estimated as the percentage cover over a circular area with a radius of *ca.* 50 km from the sampling station, and was measured at 0900 hr every day.

Water samples were pre-filtered through a 333 μm mesh net. Subsamples of 100 m*l* were filtered onto Whatmann GF/F glass fiber filters for the analyses of chlorophyll *a* and chlorophyll *a* specific absorption coefficient. Filtrates of the subsamples were kept frozen at -20°C for nutrient analysis. The subsamples for the latter analysis were taken from February 5 to March 26, 1997, which covered the peak period. Additional subsamples of 100 m*l* were filtered sequentially through 10, 2.0, and 0.2 μm polycarbonate filters for size fractionation of chlorophyll *a* concentration. A filtration vacuum of <100 mmHg was employed. Subsamples were preserved in 2% formalin for the species identification and enumeration. Taxonomic identification was according to Medlin and Priddle (1990).

Chlorophyll *a* was extracted from each filter with N, N-dimethylformamide (DMF) at 4°C for 24 hr (Suzuki and Ishimaru, 1990). The supernatant of extracted chlorophyll *a* solution was processed on a Turner Design fluorometer Model 10 AU by

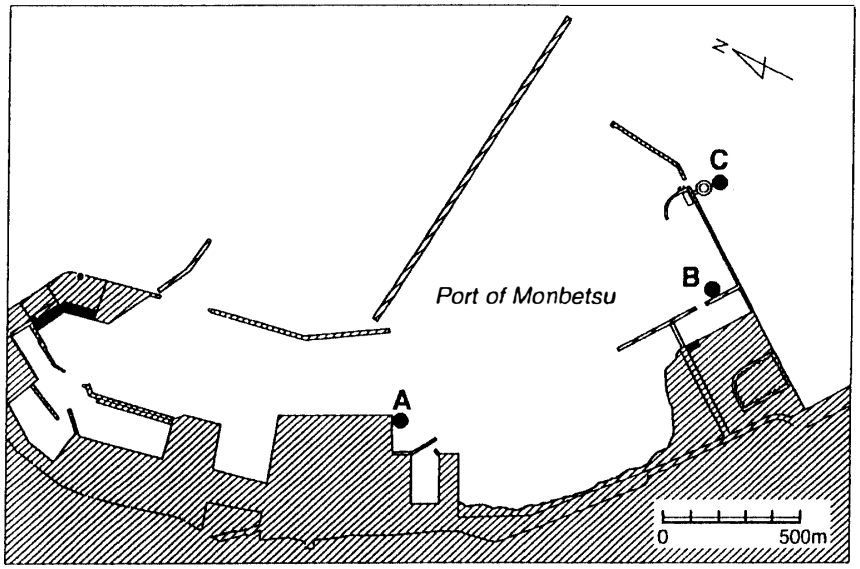

Fig. 1. A map of Monbetsu Harbor showing the sampling stations B and C. St. A was occupied by Hamasaki *et al.* (1998).

the method recommended by Holm-Hansen *et al.* (1965). Chlorophyll *a* specific absorption coefficient was first determined by scanning the samples on a Whatmann GF/F glass fiber filter on a spectrophotometer from 350 to 750 nm with zero absorbance at 750 nm. In order to convert the absorption (OD_f) obtained from phytoplankton particles on the filter to particles in suspension (OD_s), the following equation developed by Mitchell (1990) was employed:

$$OD_s(\lambda) = 0.415\, OD_f(\lambda) + 0.690\, [OD_f(\lambda)]^2. \quad (1)$$

The absorption coefficient $[a_p(\lambda)]$ of total particles was calculated by the following equation,

$$a_p(\lambda) = 2.3\, [OD_s(\lambda)]\, X^{-1}. \quad (2)$$

The factor 2.3 converts $\log_{10}$ to $\log_e$. X is the ratio of the filtered volume to the filtered clearance area of the filter.

Second, the filtered sample was bleached by using the oxidizing agent sodium hypochloride (NaClO) to measure the absorption of particles other than pigments. The bleached sample was analyzed by using the same spectrophotometer. The absorption coefficient of particles excluding pigments $[a_d(\lambda)]$ was calculated by the same eq. (2).

Then the absorption coefficient of pigment $[a_c(\lambda)]$ can be calculated by subtracting the absorption coefficient of particles excluding pigments from the total particles as follows:

$$a_c(\lambda) = a_p(\lambda) - a_d(\lambda). \quad (3)$$

The chlorophyll *a* specific absorption coefficient at each wavelength [$a^*_{ph}(\lambda)$] can be obtained by dividing by the chlorophyll *a* concentration as follows:

$$a^*_{ph}(\lambda) = a_c(\lambda)\ [\mathrm{Chl}a]^{-1}. \quad (4)$$

Concentrations of nitrate, nitrite, phosphate, and silicate were determined using a Bran and Lubbe Model AACS-II Autoanalyzer. Species of phytoplankton were identified and enumerated on the inverted microscope by the method of Hasle (1978).

Results

Minimum temperature (−1.8°C) was observed at both depths at St. B on March 15 and maximum temperature (21.7°C) was observed at 0 m depth at St. B on August 14, 1997 (Fig. 2). The maximum difference (2.0°C) was observed between 0 and 3 m depth on May 28, 1997. Less than 0.1°C difference between the two depths continued from September 11, 1996 to November 5, 1997. Salinity varied mostly between 32 and 34 PSU, generally low in winter and high in summer, except for abrupt decrease due to freshwater runoff in April and May (Fig. 2).

Sea ice was first formed at the end of January and reached maximum coverage of 99% on February 23, 1997 (Fig. 2). Following this maximal period, ice coverage

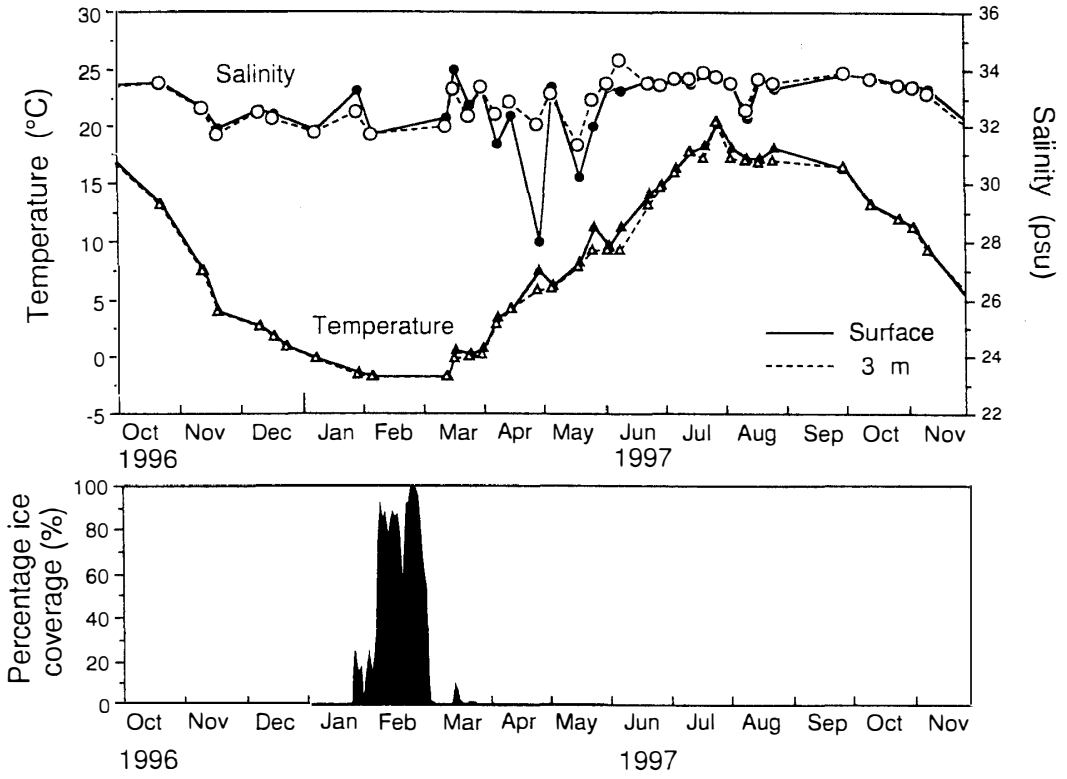

Fig. 2. Seasonal variations of temperature at surface (▲) and 3 m (△) and salinity at surface (●) and 3 m (○) at St. B (upper panel), and percentage ice-coverage in the area monitored by the Monbetsu Radar Station (lower panel).

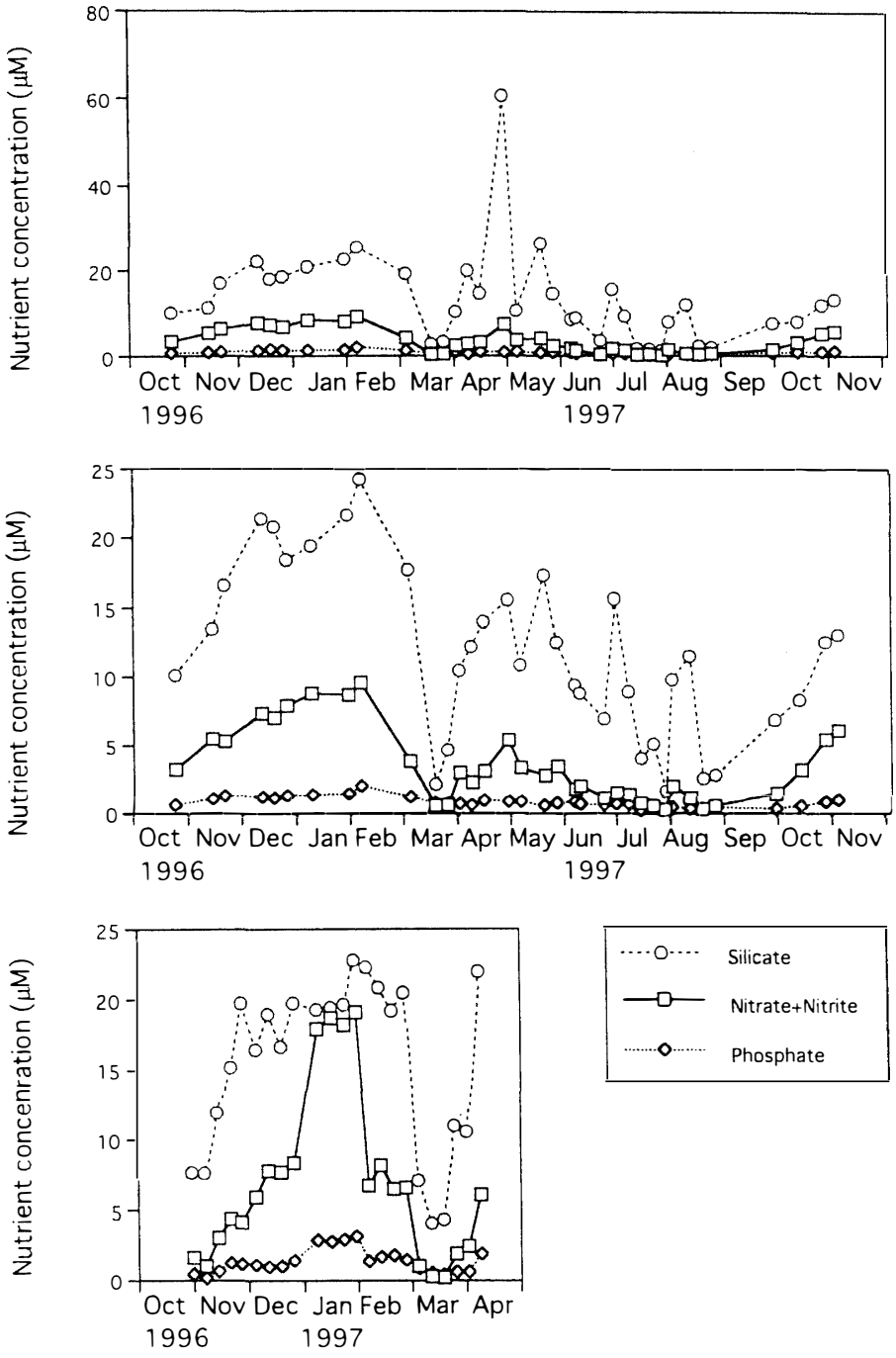

Fig. 3. Seasonal variations of nitrate + nitrite, phosphate, and silicate at 0 m (upper panel) and 3 m (middle panel) at St. B, and 2 m (lower panel) at St. C.

decreased, and sea ice disappeared completely from the circular area on March 26, 1997.

Nutrient concentrations at St. B increased from October 1996 to the first week of February 1997 (Fig. 3). Nitrate plus nitrite concentration varied from 0.39 to 9.3 μM at 0 m and from 0.28 to 9.61 μM at 3 m at St. B. Phosphate concentration varied from 0.31 to 2.12 μM at 0 m and from 0.27 to 2.06 μM at 3 m at St. B. Silicate concentration varied from 1.27 to 60.7 μM at 0 m and from 1.63 to 24.2 μM at 3 m at St. B. The

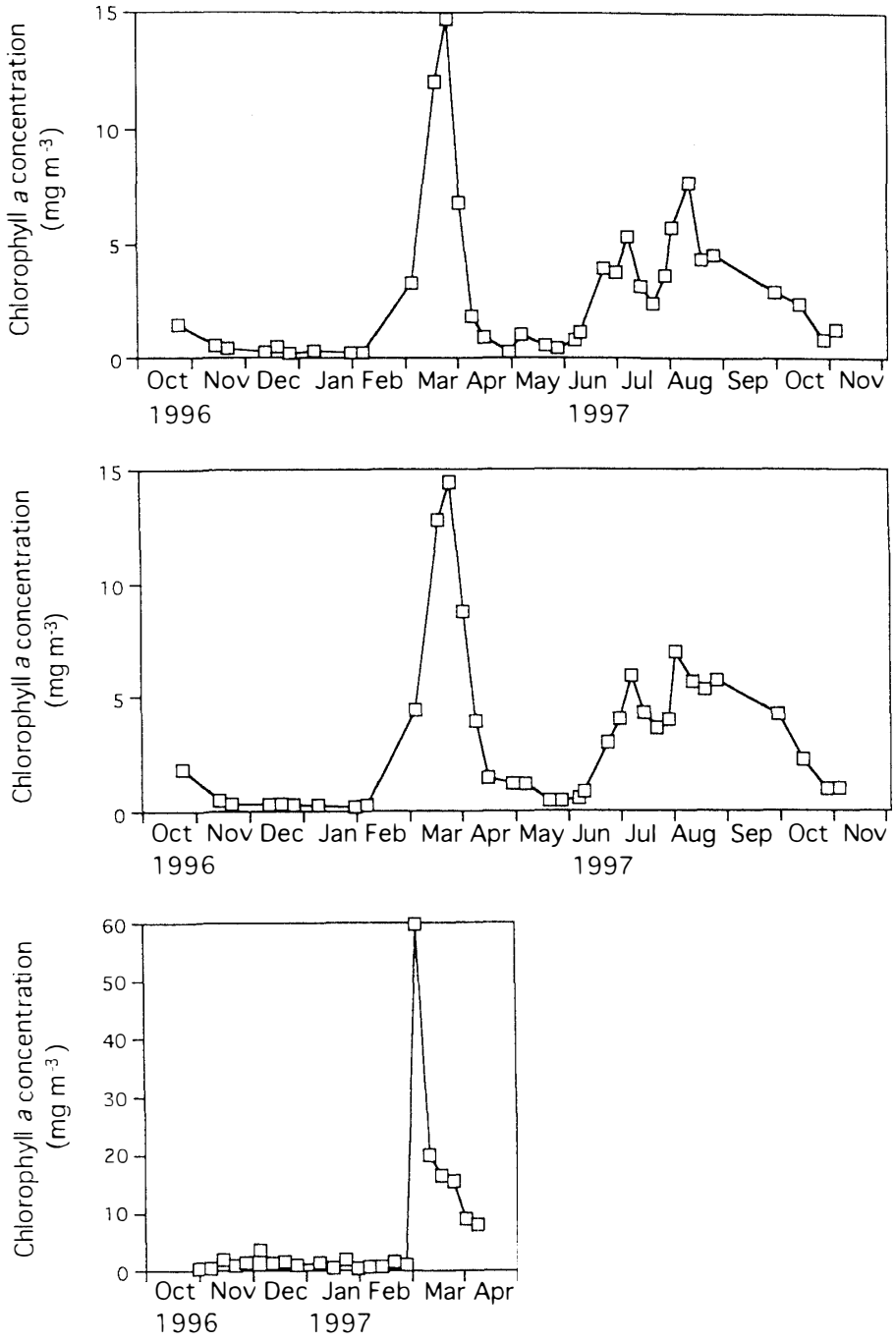

Fig. 4. Seasonal variations of total chlorophyll *a* at surface (upper panel) and 3 m (middle panel) at St. B and at 2 m at St. C (lower panel).

highest concentration of silicate at 0 m was observed on April 30, 1997, which corresponded to the maximum decrease of surface salinity (Fig. 2). The maximum concentration of silicate at 3 m on February 5, 1997 was 40% of the surface maximum. Nitrate plus nitrite concentration at St. C increased from October 1996 to January 7, 1997 and remained at high concentration (about 18μM) until January 29, 1997 (Fig. 3). Phosphate concentration at St. C increased from October 1996 to January 7, 1997

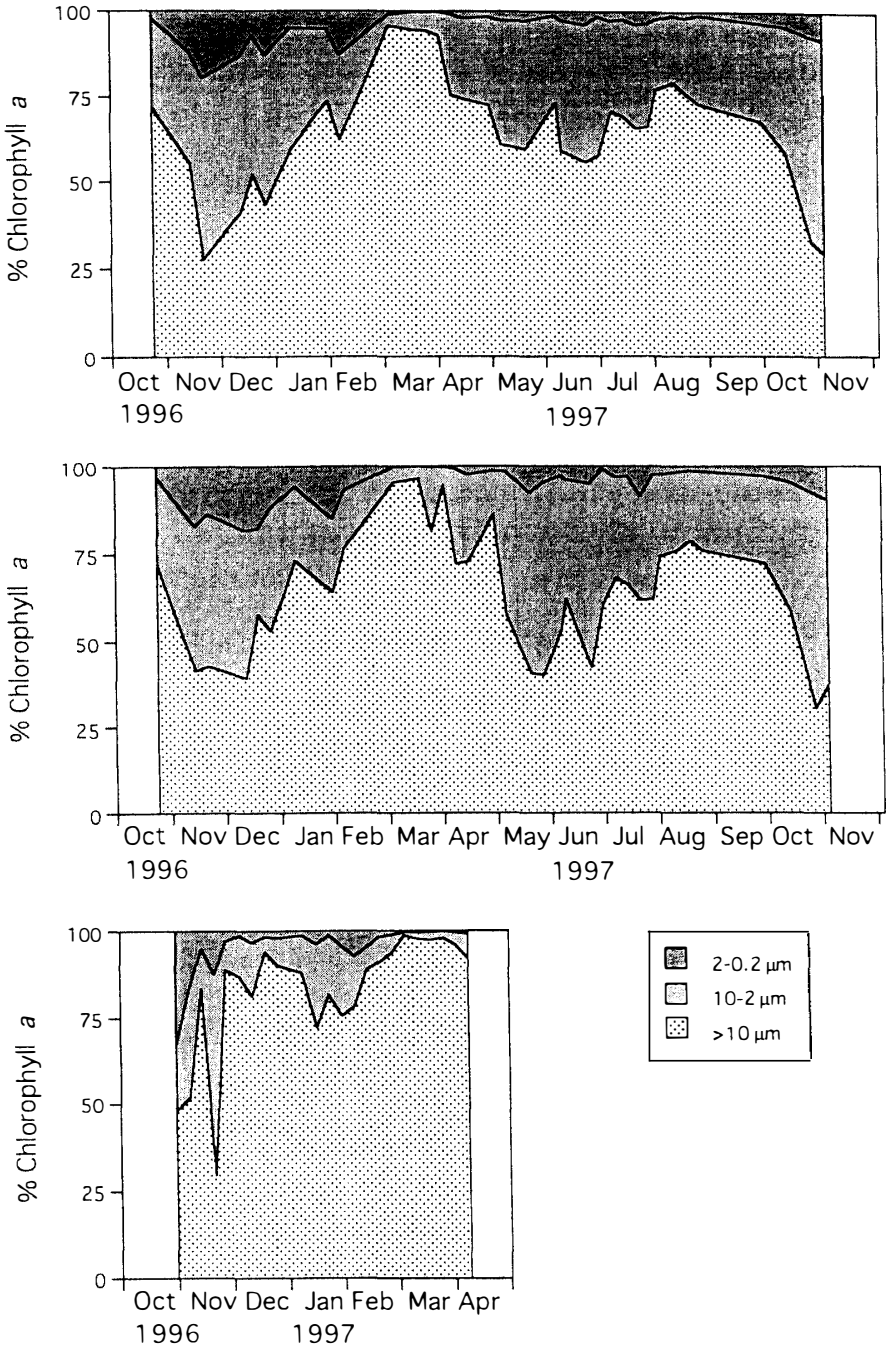

Fig. 5. Seasonal variation in the percentage contribution of three size fraction (> 10, 10–2.0, and 2.0–0.2μm) to total chlorophyll *a* concentration at 0 m (upper pannel) and 3 m (middle pannel) at St. B, and 2 m at St. C (lower panel).

and remained at high concentration (about 3μM) until January 29, 1997 (Fig. 3). Silicate concentration at St. C increased in October and remained at high concentration (about 20μM) until February 26, 1997 (Fig. 3). Lowest concentrations were observed in the middle of March for all nutrients.

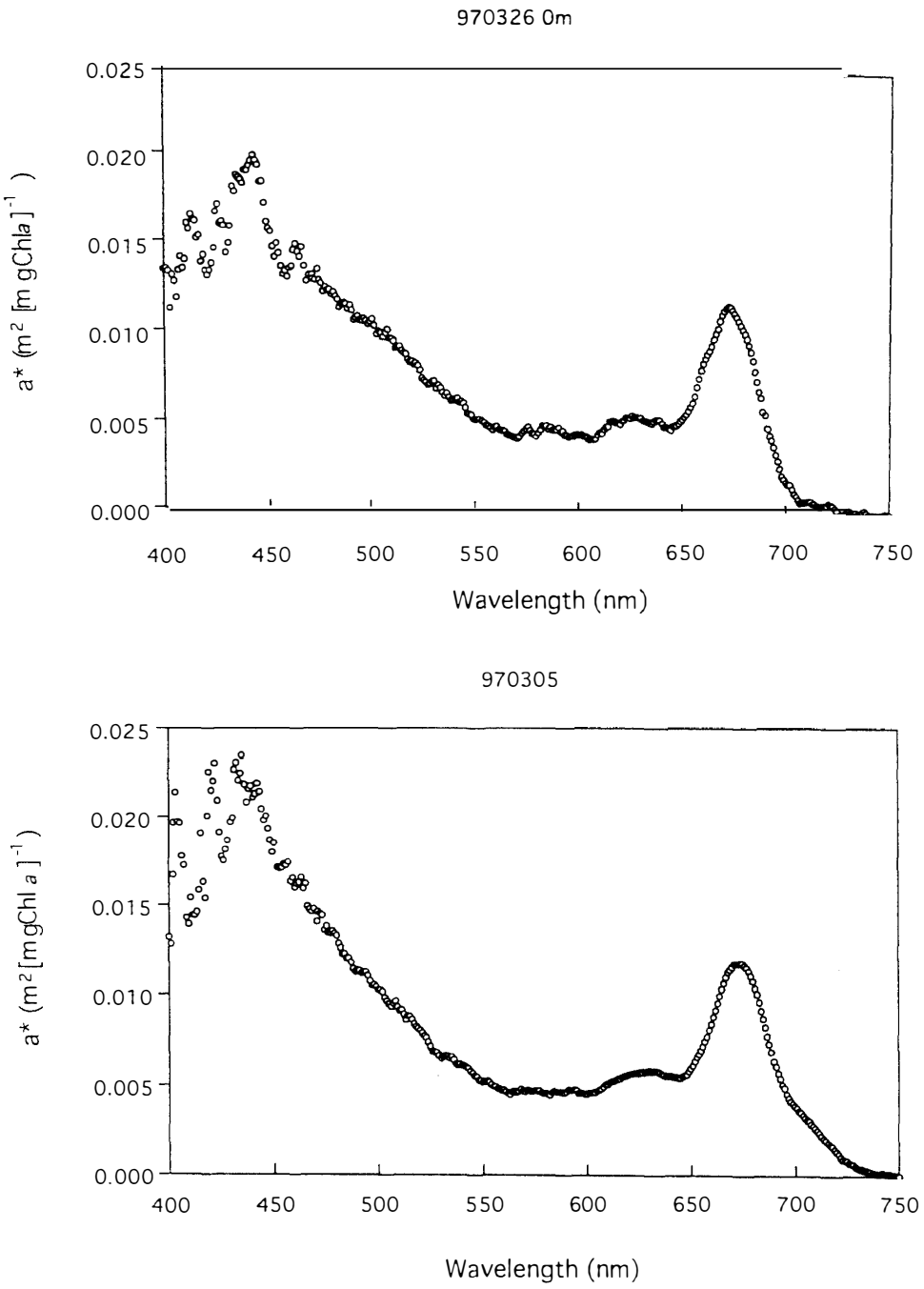

Fig. 6. Spectral distribution of chlorophyll *a* specific absorption coefficient between 400 and 700 nm at 0 m at St. B on March 26, 1997 (upper pannel) and St. C on March 5, 1997 (lower pannel).

Seasonal variation of total chlorophyll *a* concentrations at St. B was similar between 0 and 3 m (Fig. 4). The maxima were about 15 mg Chl*a* m^{-3} at both depths on March 26, 1997. The average concentrations of total chlorophyll *a* were 2.86 ± 3.34 at 0 m and 3.12 ± 3.47 mg Chl*a* m^{-3} at 3 m. Those annual average concentrations were

similar to those reported in the previous year (Hamasaki *et al.*, 1998). Seasonal variation of total chlorophyll *a* concentration at St. C also indicated a spring peak (60 mg Chl*a* m^{-3}) on March 5, 1997 (Fig. 4). The average concentration was 6.50±13 mg Chl*a* m^{-3} at St. C. The chlorophyll *a* concentration in the >10 μm size fraction was responsible for those peak periods at both stations (Fig. 5). They contributed higher than 96% of total chlorophyll *a* concentration. Chlorophyll *a* concentration in the 10–2 μm and 2–0.2 μm fractions exceeded 40% and 10% of the total chlorophyll *a* concentration in December, respectively.

Optical characteristics of phytoplankton, possibly including released ice algal cells, indicated little difference in the chlorophyll *a* specific absorption coefficient between the stations during the spring peak period (Fig. 6) although the concentration of chlorophyll *a* at St. C was four times higher than that at St. B (Fig. 5). A ratio of $a^*_{ph}(440)$ to $a^*_{ph}(673)$ decreased toward the spring peak, becoming 1.64±0.07 at St. B and 1.65±0.14 at St. C, respectively. The chlorophyll *a* specific absorption coefficient did not show much difference between 0 and 3 m during the spring peak from March 19 to 26, 1997 at St. B, or between stations. The mean was 0.0087±0.0010 m^2 [mg Chl*a*]$^{-1}$ at St. B and 0.0096±0.0013 m^2 [mg Chl*a*]$^{-1}$ at St. C during the spring peak from March 5 to 26, 1997 (Table 1), although the maximum chlorophyll *a* concentration at St. C was four times higher than that at St. B.

Several groups of phytoplankton were observed, such as diatoms, dinoflagellates, and silicoflagellates. However, diatoms were the dominant group and occupied more than 90% in cell abundance, particularly during the spring peak period. Among diatoms, the number of species belonging to the centric diatoms was greater than the number of species of pennate diatoms at St. B, and vice versa at St. C. The best represented pennate diatoms, which were common in the coastal water, were *Fragilaria,*

Table 1. Chlorophyll *a* concentration, chlorophyll *a* specific absorption coefficient (a^*_{ph}), relative abundance of chlorophyll *a* in >10 μm size fraction, and dominant species which occupied >40% of total cell abundance at Sts. B and C during the spring peak. *Navi-Nitz: Navicula septentrionalis*, and *Nitzschia cylindrus* and *N.* spp. *Thal: Thalassiosira gravida, T. hyalina,* and *T. nordenskioeldii. Than: Thalassionema nitzschioides.*

Date 1997	Station	Depth (m)	Chlorophyll *a* (mg Chl*a* m^{-3})	a^*_{ph} (m^2[mg Chl*a*]$^{-1}$)	>10 μm (%)	Species
February 5	C	2	0.683	0.0420	78	*Thal. Than.*
February 19	C	2	1.554	0.0114	91	*Navi-Nitz. Thal.*
March 5	C	2	59.8	0.0099	99	*Navi-Nitz Tahl.*
March 12	C	2	19.9	0.0091	98	*Thal.*
March 19	B	0	12.1	0.0096	94	*Thal.*
March 19	B	3	12.8	0.0089	96	*Thal.*
March 19	C	2	16.5	0.0112	97	*Thal.*
March 26	B	0	14.7	0.0090	94	*Thal.*
March 26	B	3	14.4	0.0072	81	*Thal.*
March 26	C	2	15.5	0.0081	98	*Thal.*

Table 2. Cell density and relative abundance of dominant shapes identified at the spring peak at 0 and 3 m at St. B on March 26, 1997 and at 2 m at St. C on March 5, 1997 in the present study.

Shapes	St. B				St. C	
	0 m		3 m		2 m	
	Cell density (cells ml^{-1})	Abundance (%)	Cell density (cells ml^{-1})	Abundance (%)	Cell density (cells ml^{-1})	Abundance (%)
Cylindrical cells						
Chaetoceros	165	18.5	140	15.2	492	4.5
Detonula	32	3.6	39	4.2	32	0.3
Rectangular thin cells						
Navicula/Nitzschia	194	21.7	53	5.7	5000	45.3
Rhabdonema/Stauroneis	33	3.7	44	4.8	1074	9.7
Thalassionema	3.6	0.4	1	0.1	134	1.2
Circular disk-like cells						
Thalassiosira	448	51.1	623	67.6	3982	37.2
Others	16	1.8	22	2.4	316	2.9
Total cells	892	100	922	100	11030	100

Gyrosigma, Grammatophora, Licmophora, Navicula, Nitzschia, Pleurosigma, Rhicosphenia, Surirella, and *Thalassionema* in the present study. However, large chain-forming cells, such as *Fragilaria, Navicula, Nitzschia, Thalassionema,* and *Thalassiosira* were the dominant genus during the spring peak (Table 2). Those cells were retained on 10μm filters. The cell density reached to 11×10^3 cells ml^{-1} at St. C on March 5, 1997 and to 892 cells ml^{-1} at 0 m and 922 cells ml^{-1} at 3 m at St B on March 26, 1997 (Table 2). Thin rectangular cells such as pennate diatoms occupied more than 56% of the total cell abundance at St. C only on March 5, 1997. Those pennate diatoms are known as ice algae which occur in this region. However, circular disc-like large cells, such as *Thalassiosira*, occupied more than 50% of total cell density throughout the spring peak period at St. B. Those species which belonged to this genus were planktonic (Poulin, 1990) and have never been considered a major ice algae species in this region (Seto, 1996: Taguchi, unpublished data) or, for that matter, elsewhere (Poulin, 1990).

Discussion

A sea ice-related spring peak of chlorophyll *a* concentration in the >10μm size fraction was also confirmed for two successive years in 1996 (Hamasaki *et al.*, 1998) and 1997 in the present study. The sampling station location was different from that in the previous study (Hamasaki *et al.*, 1998), even though both Sts. A and B were located within the harbor (Fig. 1). This may suggest persistent occurrence of the spring peak with less spatial heterogeneity within Monbetsu Harbor. However, the spring peak occurred 30 days later at St. B than the maximum coverage of sea ice in 1997, while it

occurred 9 days later at St. A in 1996. This may suggest a temporal variability in the timing between the maximum sea ice coverage and spring peak even within the harbor. Alternative small scale variability in sea ice coverage within the harbor must be considered to detect the spring peak in relation to ice coverage. Some heterogeneity can also be seen between the inside and outside of the harbor (Fig. 4). Timing and magnitude of the spring peak were different between Sts. B and C. The spring peak at St. C, which was located outside of the harbor, occurred three weeks earlier than that at St. B, which was located inside of the harbor. The spring peak at St. C was four times larger than the value of 15 mg Chl*a* m^{-3} at St. B. The latter value was similar to values reported during the spring bloom in Akkeshi Bay (12 mg Chl*a* m^{-3}; Taguchi *et al.*, 1994) and in Funka Bay (12–20 mg Chl*a* m^{-3}; Nishihama *et al.*, 1976, Yoshida *et al.*, 1984; Odate, 1987). However, the high value of 60 mg Chl*a* m^{-3} was much higher than most values found in other coastal waters around Hokkaido. This difference may be provided by the released ice algae. As sea ice retreated, ice algal cells seemed to be released into the surface layer of the water column at St. C; however, the sea ice in the harbor receded slower than outside the harbor. This delay in the retreat of sea ice in the harbor may cause the occurrence of the small peak three weeks later at St. B. This argument is based on the short growth period of ice algae in the sea ice within the harbor compared to long growth period of ice algae in ice floes in the Sea of Okhotsk.

Growth of ice algae in sea ice is known to be related to the growth of sea ice (Kudoh, 1993; Watanabe *et al.*, 1993). Most ice floes that have drifted from the Sea of Okhotsk are too large to enter the harbor, while new sea ice grows in the harbor due to cooling of air temperature in January and February (Shirasawa, 1993), with occasional small ice floes. The thickness of new sea ice in the harbor is thicker than that outside the harbor due to different growth durations of sea ice. However, ice floes have a longer growth period than the new sea ice in the harbor. This may result in the low standing crop of ice algae in the sea ice within the harbor, compared to the high standing crop of ice algae which are supplied by occasional ice floes outside of the harbor.

Water was well mixed in the water column at St. B during the peak period (Fig. 2). This may suggest occurrence of no density gradients, which has been considered to support spring bloom along the ice edge in the polar ocean by Smith and Nelson (1985). Instead of the density gradient, shallow water depths at the present stations may allow phytoplankton to grow with ample nutrients and light in the water column. Little difference in the chlorophyll *a* concentrations was evident between 0 and 3 m depth at St. B, although there was a tendency toward accumulation of chlorophyll *a* at 3 m depth after the peak (Fig. 4). Species composition was also similar between depths (Table 2). Most large chain forming diatoms were planktonic in the present study according to Poulin (1990); this observation may suggest little contribution of ice algae to the spring peak at St. B in the present study (Table 2). This may suggest that once ice algal cells are released into a water column, they are immediately transported into the bottom layer without delay due to aggregation (Riebesell, 1991; Kiorboe *et al.*, 1994). Instead of those situation, planktonic circular disc-like large cells of *Thalassiosira* grew rapidly in a water column. Typical ice algae in this region are Bacillariaceae such as *Detonula confervacea, Fragillaria islandicus* (=*Nitzschia*), and *Nitzschia frigida* (Takahashi, 1981; Seto, 1996), which were found in low cell density in the water column except for

Fragillaria islandicus in the present study (Table 2). *Fragillaria islandicus* and *F. oceanica* were described for ice algae in Saroma-ko lagoon (Seto, 1996), however those species have never been considered as ice algae in the Arctic Ocean (Poulin, 1990) and their identification has to be confirmed in a future study. Those ice algae released from the sea ice could contribute significantly to phytoplankton assemblages at St. C on March 5, 1997. This might have caused the significantly high chlorophyll *a* concentration on that date.

Low values of $a^*_{ph}(440)$ to $a^*_{ph}(673)$, compared to those before the spring peak (*ca.* 2.5), indicate the occurrence of package effect (Morel and Bricaud, 1981). This is also evidenced by the significant increase of circular disk-like large cells such as *Thalassiosira* which are packed by numerous chloroplasts in the cell at St. B, and by the significant increase of thin rectangular small cells such as pennate diatoms, which have usually two chloroplasts in the cells, at St. C on March 5, 1997 (Table 2). The chlorophyll *a* specific absorption coefficient has been indicated to be a function of chlorophyll *a* concentration based on the global data collection (Bricaud *et al.*, 1995). Our results are similar to $0.0072 \pm 0.0012\,m^2$ (mg Chl*a*)$^{-1}$ for platelet ice algae in Antarctica (Robinson *et al.*, 1998). However, the present study may suggest that the chlorophyll *a* specific absorption coefficient could be similar even though the concentration of chlorophyll *a* is different by four fold (Table 1). Cell volume of thin rectangular small cells was as small as $< 10\mu m^3$ while cell volume of circular disc like large cells could be larger than $7000\mu m^3$ in the present study. They were geometrically different in terms of phytoplankton cell shape, and the number and shape of chloroplasts between Sts. B and C at the peak concentration of chlorophyll *a*. Predominance of this rectangular cells at St. C on March 5, 1997 may enhance the chlorophyll *a* specific absorption coefficient due to reduction of the package effect caused by the structure of small thin rectangular cells (Table 2).

The analysis of the species composition of phytoplankton assemblages may suggest that the spring peak composed mainly by the $>10\mu m$ size fraction is caused by the abrupt growth of phytoplankton but not the ice algae released from the sea ice in the present region except St. C on March 5, 1997. Once the sea ice disappeared from the sea surface, the water column received enough light and water temperature increased slightly. This combination provided a favorable environment for phytoplankton growth in the shallow column. Similar optical characteristics of the spring bloom phytoplankton between Sts. B and C are interpreted by the different cell structures including the shape and numbers of chloroplasts in the cell, although the concentration of chlorophyll *a* is significantly different, as observed in the present study. Shapes of cells, and shapes and numbers of chloroplasts in the cells, characterize the optical properties of cells, as suggested by Sathyendranath *et al.* (1987) and Morel *et al.* (1993), in relation to pigment composition (Hoepffner and Sathyendranath, 1991).

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