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Ice algae and phytoplankton in the late ice-covered season in Notoro Ko lagoon, Hokkaido

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Abstract: The chlorophyll *a* biomass and species composition of ice algae and phytoplankton were investigated in the late ice-covered season, late February to mid-April 1992, at a fixed station in Notoro Ko lagoon, Hokkaido, Japan. Ice algal biomass was 6.11 mg m $^{-2}$ on February 25. In early March it decreased to one-half and this level of biomass was retained until the end of March. *Navicula* spp. and *Fragilaria* spp. dominated in the ice but *Fragilaria* spp. and *Detonula confervacea* predominated in the phytoplankton. However, most of the constituent taxa were common to both the ice and water column under the ice. The biomass of phytoplankton began to increase in mid-March in the water column under the sea ice and after ice melting, a remarkable increase occurred in the near bottom layer. The temporal sequence of the ice algal and phytoplankton biomass in Notoro Ko resembled that observed by other researchers in Saroma Ko in the same season, because the climatic and oceanographic conditions of Notoro Ko and Saroma Ko are similar due to their geographical proximity and their connection to the Sea of Okhotsk.

key words: Notoro Ko, ice algae, phytoplankton, cell density, chlorophyll

Introduction

Notoro Ko lagoon is one of the relict lagoons along the northeast coast of Hokkaido, Japan. This lagoon (44°03′N, 144°09′E) is about 25 km southeast of Saroma Ko lagoon and is connected to the Sea of Okhotsk by an artificial channel. Its area is about 59 km^2 and its averaged and maximum depths are approximately 8.5 m and 21 m, respectively.

The salinity of most of the water in both lagoons is reported to be similar to that in the outer sea due to the exchange (Shirasawa *et al.*, 1993; Asami *et al.*, 1995). In winter, usually between January and early April, the lagoons are covered with sea ice. Consequently these lagoons are suitable locations for multidisciplinary scientific research on sea ice (Horner *et al.*, 1992). Moreover, fisheries activities such as cultivation of scallops and catching wild fish are intensively carried out in both lagoons. Accordingly it is necessary to accumulate basic information on their environments to aid in keeping the ecosystems of the lagoons adequate to sustain fisheries yields.

Scientific studies in Saroma Ko have included ecological research on ice algae (*cf.* Taguchi and Takahashi, 1992; Fukuchi *et al.*, 1997). In Notoro Ko, physical and

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chemical conditions and phytoplankton biomass in the water column and their seasonal change have been observed (Kurata and Nishihama, 1987; Asami *et al.*, 1995; Imada *et al.*, 1995). Watanabe *et al.* (1991) reported an ice algal assemblage at the bottom of the sea ice in Notoro Ko, however thereafter little information has been obtained on the ice algae. To fill this gap, we observed the temporal sequence of ice algal biomass and species composition of the ice algal community in the sea ice and those of phytoplankton in the water column under the ice from late February to the end of March 1992 with those of phytoplankton immediately after ice melting in Notoro Ko lagoon.

Materials and methods

Ice sampling was conducted on February 25, March 10, 18 and 30, 1992 at a fixed station on the sea ice in inner part of Notoro Ko (Fig. 1). After snow depth measurement, an ice pillar, of cross section 10 cm square, was cut out with a chain-saw. Total ice thickness and the thickness of the colored layer stained by ice algae were measured. Then the colored layer was melted with 5 *l* of lagoon water filtered through a Whatman GF/F glass filber filter. For the chlorophyll *a* measurement, 1 *l* water out of the above melt water was brought back to the laboratory in a cooled bag. Out of this sample, 0.2 to 1.0 *l* was filtered with a 47 mm Whatman GF/F filter. The filters were frozen and kept for about 3 months before the chlorophyll *a* measurement. Following the procedure of Meeks (1974), chlorophyll *a* was extracted with methanol for 24 hours. Chlorophyll *a* concentration was measured with a Model 111 Turner fluorometer.

One liter of the above melt water was fixed with 2% neutral formalin immediately

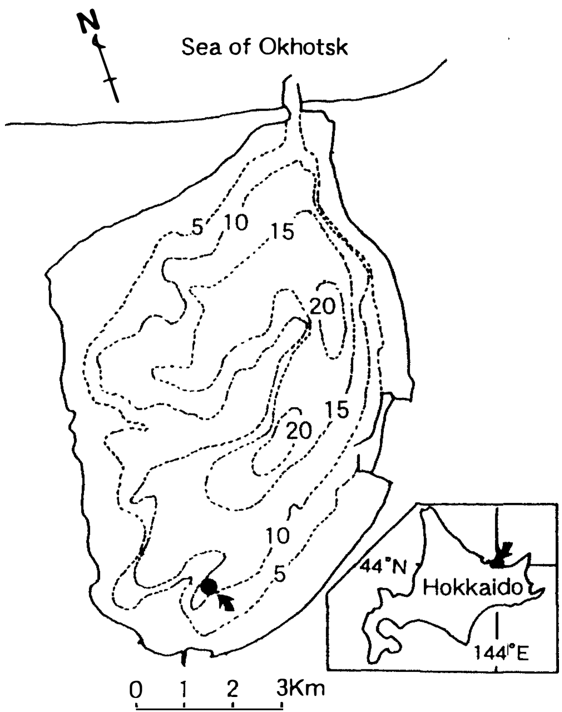

Fig. 1. Sampling site (•) in Notoro Ko lagoon.

after melting. The fixed water sample was concentrated to 10 m*l* by siphoning off supernatant after 24 hours of settling. Algal cells in 0.025 m*l* of water out of the 10 m*l* sample were identified and enumerated with an inverted light microscope.

Water under the ice was sampled with a 6 *l* Van Dorn bottle at the same time as the ice sampling. On February 25, water was sampled from 0 (surface), 2, 5 and 10 m depths, during March, water was taken from 1.5 m only. After sea ice disappeared on April 15, additional water samples were taken from 0, 5 and 10 m. One liter of water out of each sample was used for chlorophyll *a* measurement and one liter for cell count. The handling procedure for chlorophyll *a* measurements was same as that for ice samples. Phyoplankton in 0.1to 0.2 m*l* water out of 10 m*l* sample were identified and enumerated with an inverted light microscope. For the species identification of diatoms, Cupp (1943) and Kokubo (1960) were referenced.

Results

On February 25, when this work was begun, the sea ice thickness was 33 cm and a bottom 4 cm layer was stained brown by ice algae. Temporal change of the depth of snow cover on ice, ice thickness and the thickness of the colored layer are illustrated in Fig. 2. The snow cover and sea ice thickness reached a peak on March 18, the colored layer thickness increased until the end of March.

The temporal changes of cell density and chlorophyll *a* concentration of ice algae are shown in Table 1. Both cell density and chlorophyll *a* had already reached high

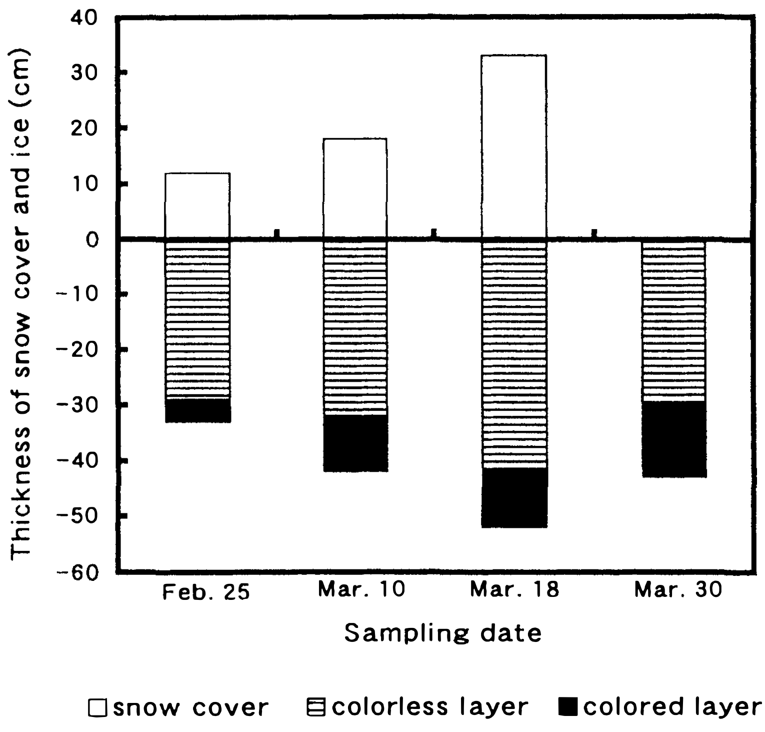

Fig. 2. Temporal change of snow depth, sea ice thickness and thickness of colored layer at the bottom of sea ice in Notoro Ko lagoon, 1992. The sea level is taken as 0 cm.

values at the beginning of the observations. Then in early March cell density decreased to one-eighth of that on February 25, this cell density was maintained until the end of March. Concurrently the chlorophyll *a* concentration decreased to one-fifth of that on February 25. Then it continued to decrease slightly toward the end of March. However, the thickness of the colored layer increased to two and half times that on February 25 in early March, followed by a relatively stable state. Accordingly, one-half of the ice algal biomass of February 25 was retained in the ice until the end of March (Table 1).

The species composition of ice algae is shown in Table 2. Relative abundance of *Fragilaria* spp. and *Navicula* spp. were high through the observation period, while their cell density and chlorophyll *a* concentration varied. *Detonula confervacea, Navicula vanhoffenii* and *Nitzschia frigida* formed the second most numerous group. The proportion of flagellates increased as the season progressed.

As shown in Table 3, the cell density and chlorophyll *a* concentration of phytoplankton in the water column are remarkably lower than those in the sea ice through the observation period. Both cell density and chlorophyll *a* in water at 1.5 m depth reached peaks on March 18. On April 15 high cell density and chlorophyll *a* concentration were observed throughout the water column, particularly high cell density

Table 1. Cell density, chlorophyll *a* concentration and biomass of ice algae in the late ice-covered season 1992 in Notoro Ko.

Smapling date	Feb 25	Mar 10	Mar 18	Mar 30
Thickness of colored layer (cm)	4	10	10	13
Cell density (x10^4 cells l^{-1})	5521	716	850	743
Chlorophyll *a* concentration (mg m^{-3})	152.95	33.60	29.94	27.14
Biomass (mg chl. *a* m^{-2})	6.11	3.36	2.99	3.53

Table 2. Species composition, density of ice algal cell ($\times 10^4$ cells l^{-1}) in the sea ice and its relative abundance (%) in the ice-covered season 1992 in Notoro Ko.

Smapling date	Feb 25	Mar 10	Mar 18	Mar 30
Amphiprora alata	8.5 (0.15)	1.4 (0.20)	7.0 (0.82)	2.0 (0.27)
Detonula confervacea	640.5 (11.60)	43.2 (6.03)	34.0 (4.00)	32.9 (4.43)
Fragilaria spp.	2906.0 (52.64)	255.0 (35.59)	179.2 (21.07)	161.0 (21.68)
Lauderia gracialis	11.0 (0.20)	0.0	0.0	0.0
Melosira nummuloides	0.0	0.0	0.8 (0.09)	2.3 (0.31)
Navicula vanhoffenii	42.5 (0.76)	33.6 (4.69)	35.2 (4.14)	55.5 (7.47)
Navicula spp.	1897.5 (34.37)	359.0 (50.11)	525.6 (61.81)	317.8 (42.80)
Nitzschia frigida	1.0 (0.02)	7.4 (1.03)	28.2 (3.32)	92.2 (12.42)
Thalassiosira sp.	8.5 (0.15)	0.0	0.0	0.0
pennate unidentified	1.5 (0.03)	1.0 (0.14)	0.0	1.1 (0.15)
flagellates	4.0 (0.07)	15.8 (2.21)	40.4 (4.75)	77.8 (10.48)

Table 3. Cell density ($\times 10^4$ cells l^{-1}) and chlorophyll *a* concentration (mg m^{-3}) of phytoplankton in the water volume in the ice-covered and ice-free seasons 1992.

(a) Cell density (x10 ^{4}cells l^{-1})

Smapling date	Feb 25	Mar 10	Mar 18	Mar 30	Apr 15
Sea ice *	+	+	+	+	−
Sampling depth (m)					
0	11.0				18.3
1.5		7.6	222.4	184.6	
2	1.2				
5	1.4				13.9
10	1.2				116.4

*The symbols of + and − show the presence of sea ice or not, respectively.

(b) Chlorophyll *a* concentration (mg m^{-3})

Smapling date	Feb 25	Mar 10	Mar 18	Mar 30	Apr 15
Sampling depth (m)					
0	1.11				0.91
1.5		0.59	4.90	1.73	
2	0.68				
5	0.51				0.68
10	0.43				15.05

and chlorophyll *a* concentration were found in the near bottom layer.

The species composition of phytoplankton is shown in Table 4. *Detonula confervacea* and *Fragilaria* spp. were dominant in the whole of the water column on February 25 and also at 1.5 m depth throughout March. The species composition of phytoplankton in the whole water column of April 15 after ice melting differed from that of the other samples. In particular increases of *Thalassiosira nordenskioeldii, Fragilaria* spp. and *Chaetoceros subsecundus* were observed.

During the ice-covered period, the species composition of phytoplankton was relatively simple and the dominant taxa were common to the sea ice and the water column. However, *Navicula* spp., which was one of dominant components in the sea ice, was a minor taxon in the water column, while *D. confervacea*, which was a member of the second most numerous group in the ice, was the most abundant in the water under the ice.

Discussion

It has been reported that the water temperature and salinity of Notoro Ko in mid-March 1985 and 1986 were −1.1 to +1.0°C and 31.4 to 32.2 (Kurata and Nishihama, 1987) and those of Saroma Ko in early March were −1.4 to −1.1°C and

Table 4. Species and density ($\times 10^4$ cells l^{-1}) of phytoplankton appeared more than 1000 cells l^{-1} in the water column. Values on Feb. 25 and Apr. 15 are mean values throughout the water column (0–11 m). March values include figures only obtained from 1.5 m depth samples.

Species	Feb 25	Mar 10	Mar 18	Mar 30	Apr 15
Asterionella japonica	0	+	0	0	1.0
Chaetoceros affinis	0	0	0	0	0.3
Chaetoceros compressus	0	0	0	0	0.4
Chaetoceros debilis	0	0	0	0.3	0.6
Chaetoceros debilis resting spore	0	0	0	0	0.1
Chaetoceros socialis	0	0	0	0.3	1.6
Chaetoceros subsecundus	0	0	0	0.2	5.8
Chaetoceros sp.	0	0	+	0	0.1
*Detonula confervacea**	0.9	2.8	82.9	40.0	0.2
D. confervacea resting spore	0	0	0	65.1	0.3
Fragilaria spp.*	0.9	4.3	135.1	12.0	12.4
*Lauderia gracialis**	+	+	1.4	0.2	0.1
*Navicula vanhoffenii**	+	0.2	1.0	0.1	+
Navicula spp.*	+	+	0.3	0.2	0.3
*Nitzschia frigida**	0	+	0	0.1	0
Thalassiosira gravida	+	0	0.7	0.4	1.6
Thalassiosira nordenskioeldii	+	+	0.6	0.4	15.2
Thalassiosira rotula	+	0	0.3	+	0
Pennate diatoms unidentified*	+	+	0	0	0.1
flagellates	+	+	0.1	0.1	+

* occurrence also in ice

32.4 to 33.5 (Satoh *et al.*, 1989), respectively. Notoro Ko and Saroma Ko belong to the same climatic regime, and similarity in the oceanographic conditions of both results from this as well as their geographical proximity and their connection to the Sea of Okhotsk.

Watanabe *et al.* (1991) recorded 29.4 mg m^{-3} and 49.1 mg m^{-3} of chlorophyll *a* concentration from the colored layer of bottom 3 cm of sea ice at two stations near the mouth part of Notoro Ko on March 10, 1987. These values are comparable to those of the present observation. According to their record, the dominant species were *Detonula confervacea, Nitzschia frigida* and *Pinnularia quadratarea* var. *leptostauron*. The former two species appeared as common constituents of the ice community in this observation (Table 2). Thus it is probable that the ice algal community in Notoro Ko is often dominated by diatoms.

In the same season, on March 7 and 8 1987, Watanabe *et al.* (1991) observed an ice algal community in Saroma Ko. The community was dominated by *N. frigida*, other *Nitzschia* species and *Tharassiosira hyperborea*. Chlorophyll *a* concentrations of two samples taken from this community were 111 and 306 mg m^{-3}. Previously, in late February 1979, Takahashi (1981) observed an ice algal community dominated by

Nitzschia frigida, Fragilaria striatura, Dunaliella sp. and *Gymnodinium* sp. in Saroma Ko. Kawanobe and Kudoh (1995) reported that there was an ice-algal community volumetrically dominated by *Melosira hyperborea* and *Pinnularia quadratarea* var. *constricta* at the sea ice bottom in Saroma Ko from late February to mid-March 1992. On the other hand, between February 25 and March 21, 1992 in Saroma Ko, Kudoh *et al.* (1997) observed a quite similar trend in the seasonal change of ice algal biomass and vertical expansion of the colored layer as is observed in Notoro Ko. The vertical expansion of the colored layer over time seems to be due to the diffusion of algal cells in the interstitial water among ice crystals. The dominant species was *D. conervacea*. Such pennate diatoms as *Navicula septentrionalis, N. pelagica* and *Nitzschia frigida* were common constituents in the ice algal community. It seemed that there was a concurrence in the timing of the development of ice algal community between Notoro Ko and Saroma Ko, though the species compositions of diatoms were different. The reason for this difference in species composition should be investigated in the future.

A remarkable decrease in the ice algal biomass was observed on March 10 and thereafter the value of biomass remained at about 3 mg m^{-2} (Table 1). Using a sediment trap, Taguchi *et al.* (1997) estimated that the amount of ice algal biomass produced was equal to the amount released in the water column in a day during the ice melt season in Saroma Ko. The present finding, that the dominant components of the ice algal community appeared simultaneously as the dominant constituents of phytoplankton community in the water column under the ice, supports Taguchi's finding. However, the explanation for the difference in numerical proportion of *Navicula* spp. and *D. confervacea* between ice and water column (Tables 2, 4) remains to be solved. It is relevant here that Michel *et al.* (1997) collected a large amount of *Detonula* species with a sediment trap but found little in water sampled in Saroma Ko in February and March 1992.

As shown in Table 3, the increases of phytoplankton occurred on two occasions in the observation period. One was observed in mid-March under the ice, probably due to the increase of released ice algae. The other increase was observed on April 15. The spring bloom which occurs after the ice melt seems to be one of the annual events in Notoro Ko (Kurata and Nishihama, 1987; Asami *et al*., 1995). Both biomass and species diversity of phytoplankton became high and the biomass was concentrated in the 10 m depth layer. The salinities of the 5 m and 10 m depth layers were 31.6 and 32.8, respectively on April 15, 1992. This may indicate the appearance of different water from the upper part of water column. *Thalassiosira nordenskioeldii, Fragilaria* spp. and *Chaetoceros subsecundus* were dominant in this period. The former two taxa were present through the observation but *C. subsecundus* first appeared in the late ice-covered season and increased in the open water. Fukuchi *et al.* (1989) recorded an increase of chlorophyll *a* in the water column under the ice between mid-March and mid-April, three weeks after ice disappearance, with a chlorophyll-measuring buoy moored in Saroma Ko. It seemed that the spring bloom began but the species composition was not reported. Nishihama *et al.* (1989) showed that the pattern of seasonal change of chlorophyll *a* in the water column was common to Saroma Ko, Notoro Ko and the coastal area of the north east coast of Hokkaido.

In the late ice-covered season, in Notoro Ko, the close relation between ice algae and phytoplankton has been clarified by examining the algal biomass and species composition of algae both in the ice and in the water column. Through the examination of data on the temporal change of the ice algal biomass and dominant taxa in Notoro Ko and Saroma Ko, it has become clear that both lagoons are comparable in ecological processes relating to sea ice.

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