1983/84年南極昭和基地周辺のアイスアルジー現存量の季節変化

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Seasonal Variations of Ice Algal Standing Crop Near Syowa Station, East Antarctica, in 1983 / 84[1), 2)]

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Abstract

Ice algal assemblages were investigated at four stations in the fast ice area near Syowa Station (69°00'S, 39°35'E), from March 1983 to January 1984. Chlorophyll *a* standing crop had peaks at three stations in April-June and October-November. The largest standing crop, 125 mg chl. *a* m^{-2}, was reached in mid-November under moderate snow cover with 95.1% of the crop concentrated in the bottom 4 cm layer, where the chlorophyll *a* concentration was 2,980 mg m^{-3}. Ice algal assemblages were found in bottom, interior and surface layers of sea ice. Among them, the bottom assemblage grew most intensively and extensively. A maximal doubling time for the bottom assemblage was estimated to be 15.1 days in spring. The interior assemblage was formed mainly in the grease ice layer at the initial stage of sea ice formation in May, maintaining its standing crop until January at a heavily snow-covered station. The surface assemblage developed in the consolidated snow layer of the heavily snow-covered area from October to January. Annual production by ice algae was estimated to be 0.50-3.42 g C m^{-2} y^{-1} from the increase of standing crop.

Since the nineteenth century, microalgae in the sea ice, i. e. ice algae, have been reported from polar regions. In the past few decades, many workers conducted taxonomical, ecological and physiological investigations of the microalgal assemblages as reviewed by HORNER (1985a). Recent investigations revealed a variety of ice algal assemblages in the Antarctic sea ice. ACKLEY et al. (1979) classified the assemblages into three main groups depending on their location in the ice, i. e., bottom, interior and surface ice algal assemblages. The bottom ones were reported from land fast ice areas of McMurdo Sound (BUNT & WOOD 1963, BUNT & LEE 1970, HOSHIAI 1972, PALMISANO & SULLIVAN 1983) and of East Antarctica, i. e., near Syowa Station (HOSHIAI 1969, 1981a 1985) and near Casey, Davis and Mawson Stations (MCCONVILLE & WETHERBEE 1983). The interior ones were reported from fast ice in East Antarctica (HOSHIAI 1969, 1981a, MCCONVILLE & WETHERBEE 1983) and from ice floes in the Weddell Sea (ACKLEY et al. 1979, CLARKE & ACKLEY 1984). The surface ones were reported from snow that had absorbed sea water on pack ice in Lützow-Holm Bay (MEGURO 1962), from the coastal tide-crack overflow region at Signey Is. (WHITAKER 1977) and from surface melt pools on fast ice near Casey Station (MCCONVILLE & WETHERBEE 1983).

The differences between ice algal assemblages can probably be attributed to the formation and

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decaying processes and environmental conditions of their habitat, i. e., sea ice and consolidated snow. Therefore, it would be important for the understanding of the assemblages to monitor their formation, development and disintegration processes from freezing to the melting of the sea ice, together with those same processes of the sea ice itself and its physical and chemical variables. However, long-term observations of ice algal assemblages at fixed stations in the Antarctic, covering that period are limited to those by BUNT & LEE (1970). HOSHIAI (1969, 1981a) and WHITAKER (1977) and only a few dealt with the relationships among the various types of ice algal assemblages.

In this paper, seasonal variations of chlorophyll *a* standing crop in ice are reported in detail for the fast ice area near Syowa Station, together with the variation of environmental parameters of the habitat during the period between formation and melting of sea ice. Three types of ice algal assemblages classified from their location in the ice are described and their formation and disintegration processes are discussed.

Materials and Methods

Ice core sampling was carried out 18–36 times from March 1983 to January 1984 at four stations (Fig. 1) having different ice and snow conditions on the fast ice field near Syowa Station (69°00′S, 39°35′E). The sea depths of the sampling locations were 12 m at Stn. I, 38 m at Stn. III and more than 700 m at Stn. V. The depth was not measured at Stn. X. A SIPRE coring auger driven by an electric motor was used to collect entire ice cores ca. 7.6 cm in diameter. Cores were taken within a radius of 5 m from a fixed flag pole at each station. A scale marked on the pole was used to measure the thickness of the snow and the sea level. At each sampling, three ice cores were collected, two cores from 1 m apart and the third core from the center.

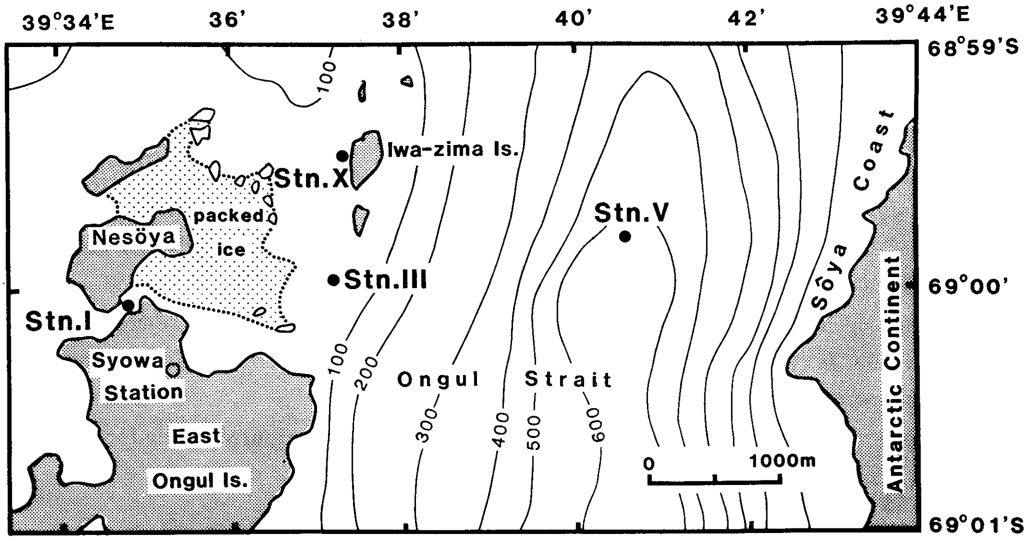

Fig. 1. Location of ice core sampling stations near Syowa Station. Depth contours in meters from FUJIWARA (1971).

The third core was preserved for the subsequent species composition analysis, which will be reported in a separate paper. Averages of pigment concentrations and salinity of ice melt water from the two ice core samples are used in this paper. Ice cores were kept in a polyethylene tube, covered with a blanket and brought back to a laboratory at Syowa Station immediately after collection. The texture of the ice cores and the positions of algal flocks and discolorations were recorded in the laboratory. Ice cores were recorded in the laboratory. Ice cores were sectioned, melted at room temperature, and filtered onto Whatman GF/C glass fiber filters.

Seawater samples of 500 ml were collected at the same time as the ice cores from 3 m beneath the ice bottom using a plastic Kitahara bottle, and were filtered in the same way.

Pigments were extracted in 90% acetone. Chlorophyll *a* and phaeopigment concentrations were determined by the fluorometric method of STRICKLAND & PARSONS (1972) modified by ARUGA (1979) with a Hitachi model 650-40 spectrofluorometer. The conductivity of melt water from sectioned ice cores was measured with a Toa Electronics model CM-8ET conductivity meter before filtration and was converted to practical salinity.

Underwater and incident photosynthetically active irradiance (400-700 nm) were measured with a LI-COR model LI-188 integrating quantum/radiometer/photometer and with a LI-192SB underwater quantum sensor beneath sea ice and a LI-190SB quantum sensor on snow to determine the albedo and extinction coefficients of snow and ice. The measurements were carried out in the fast ice area near Stn. III between 22 November and 3 December 1983.

Results

In this study, three types of ice algal assemblages were distinguished, based on their position in the ice (ACKLEY et al. 1979, HORNER 1985b), and were observed in a relatively small area of coastal fast ice near Syowa Station. The location and duration of the assemblages is given in Table 1. The bottom ice algal assemblage was observed in April-June and in August-January, was concentrated in a thin layer from 5 mm to a few centimeters in thickness, and was situated on the bottom or just above the bottom of the ice. The interior assemblage was

TABLE 1. OCCURRENCE OF THREE TYPES OF ICE ALGAL ASSEMBLAGES OBSERVED AT FOUR STATIONS NEAR SYOWA STATION FROM MARCH 1983 TO JANUARY 1984. SYMBOLS IN PARENTHESES INDICATE ABUNDANT (卌), MODERATE (卄), A LITTLE (+) AND NO (−) APPEARANCE.

Station	Bottom	Interior	Surface
I	Apr.-Jun. (+) Aug.-Jan. (卌)	May-Jul. (+)	(−)
III	Apr.-Jun. (卄) Sep.-Dec. (+)	May-Jan. (卌)	Oct.-Jan. (+)
V	Apr.-Jun. (+) Sep.-Dec. (卄)	May-Sep. (卄)	(−)
X	Apr.-Jun. (+) Aug.-Dec. (卄)	May-Aug. (+)	(−)

found in a consolidated grease ice layer in fast ice 20-70 cm in thickness from the beginning of ice formation in May. It lasted until the end of this study at Stn. III, but disappeared in September at Stn. V, in August at Stn. X and in July at Stn. I. The surface assemblage, causing a pale brown to yellowish green discoloration, was observed in a consolidated snow layer on fast ice at Stn. III between October and January. Therefore, three types of ice algal assemblages were observed between October and December at Stn. III, although the bottom discoloration was weak.

Seasonal variations of chlorophyll standing crop in ice (total crop integrated from the top to the bottom of the ice) at the four stations are shown in Fig. 2. There are standing crop peaks in April-June and October-December at Stns. I, V and X. Standing crops for particular ice layers are also shown in Fig. 2. The "bottom" in the figures denotes the layer ca. 10 cm in thickness from the undersurface of sea ice. The "interior" and the "surface" in Fig. 2b denote the ice layer of 10-70 cm deep and the uppermost 10 cm of sea ice plus consolidated snow, re-

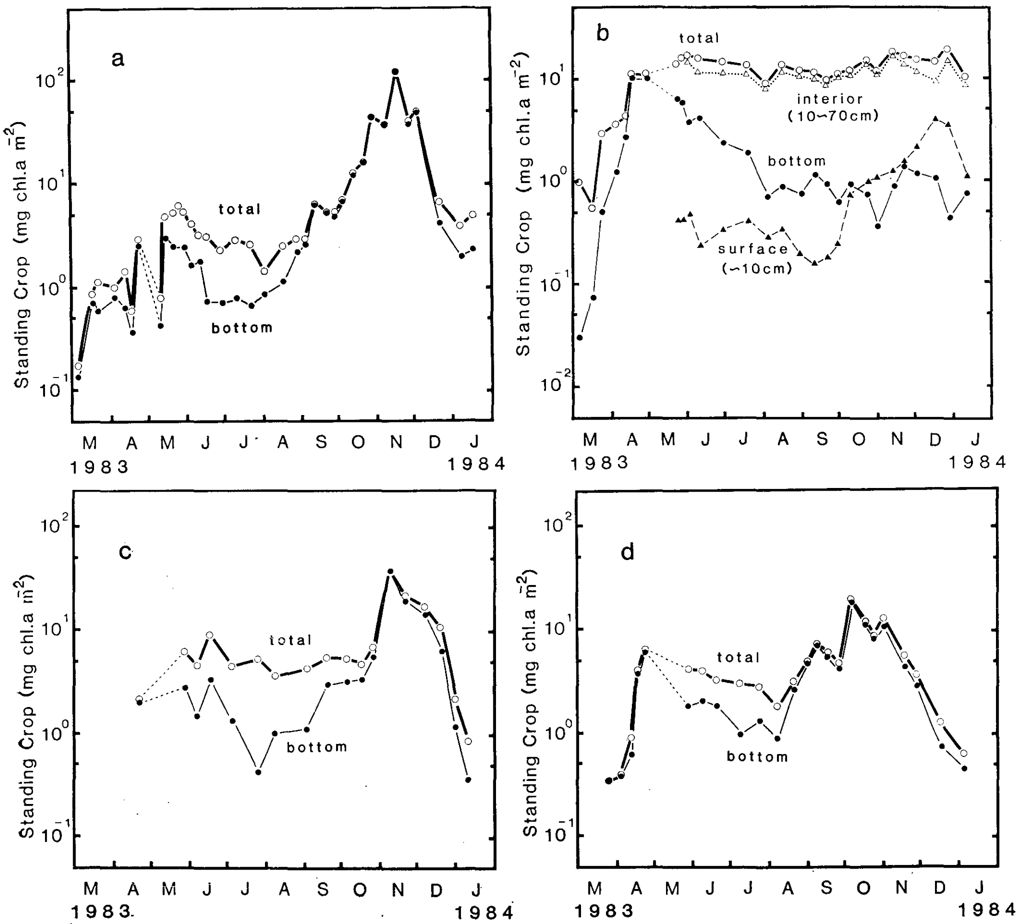

Fig. 2. Seasonal variation of integrated chlorophyll *a* in ice cores at Stns. I (a), III (b), V (c) and X (d). See text for details.

TABLE 2. MAXIMUM CHLOROPHYLL *a* CONCENTRATIONS IN THE BOTTOM LAYER OF SEA ICE WITH THE THICKNESS (cm) OF THE BOTTOM ICE SAMPLE AND TOTAL SEA ICE IN PARENTHESES AND THE DATE OF OBSERVATION. DATA REPRESENT THE MEAN ±RANGE/2 (mg chl. *a* m^{-3}) OF TWO ICE CORES.

Station	Autumn maximum		Spring maximum
	before outflow*	after outflow*	
I	56.9±24.1** (3/78) 23 Apr.	40.3±4.0 (5/45) 20 May	2980±21 (4/119) 18 Nov.
III	247±1** (4/144) 17 Apr.	96.5±3.5 (4/69) 28 May	29.4±12.4 (4/94) 3 Dec.
V	39.3±2.7 (5/40) 21 Apr.	47.7±3.7 (5/55) 27 May	1910±160 (2/92) 10 Nov.
X	237±79 (2/60) 23 Apr.	30.5±2.2 (7/62) 8 Jun.	323±137 (6/116) 6 Oct.

* Multi-year ice sheet was present before 2-3 May 1983; new ice formed after the outflow.
** Multi-year ice.

spectively. These figures show that the bottom assemblage contributed the most in chlorophyll *a* standing crop in ice at Stns. I, V and X. At a maximum standing crop in October and November, 93-96% of the total crop was derived from the bottom assemblage. On the other hand, the interior assemblage dominated standing crop at Stn. III after the formation of new ice in May. Chlorophyll *a* standing crop in the interior layer ranged from 8.44-16.4 mg m^{-2} and was 64-90% of the total crop in the ice at Stn. III between 2 June and 12 January. The surface assemblage reached a maximum of 3.82 mg chl. *a* m^{-2} on 18 December at Stn. III, which accounted for 27% of the total chlorophyll *a* crop. Maximum chlorophyll *a* values in the bottom ice layer for autumn and spring-summer blooms are summarized in Table 2. At Stn. III, a maximum chlorophyll *a* value for the interior assemblage was 42.3±11.1 mg m^{-3} for a 5 cm layer on 14 November and for the surface assemblage, 17.9±1.2 mg m^{-3} for a 10 cm layer on 18 December.

1. *Seasonal variations of salinity, chlorophyll* a *standing crop and pigment ratio in ice*

1-1 *Station I*

Seasonal variations of the thickness of ice and snow and the vertical profile of salinity in the ice at Stn. I are shown in Fig. 3a. At the beginning of this study, there was a multi-year ice sheet which had a water layer in the interior part. Salinity of the ice was generally low (0.6-4.6). The fast ice sheet broke up and flowed away from the sampling sites on 2-3 May 1983, however, new sea ice grew rapidly after the flow out. A distinctive boundary was seen between white and transparent ice layers and the upper white ice layer was found to be ca. 20 cm thick. Sea ice continued to grow up to 120 cm thick by 22 October. From November to mid-January,

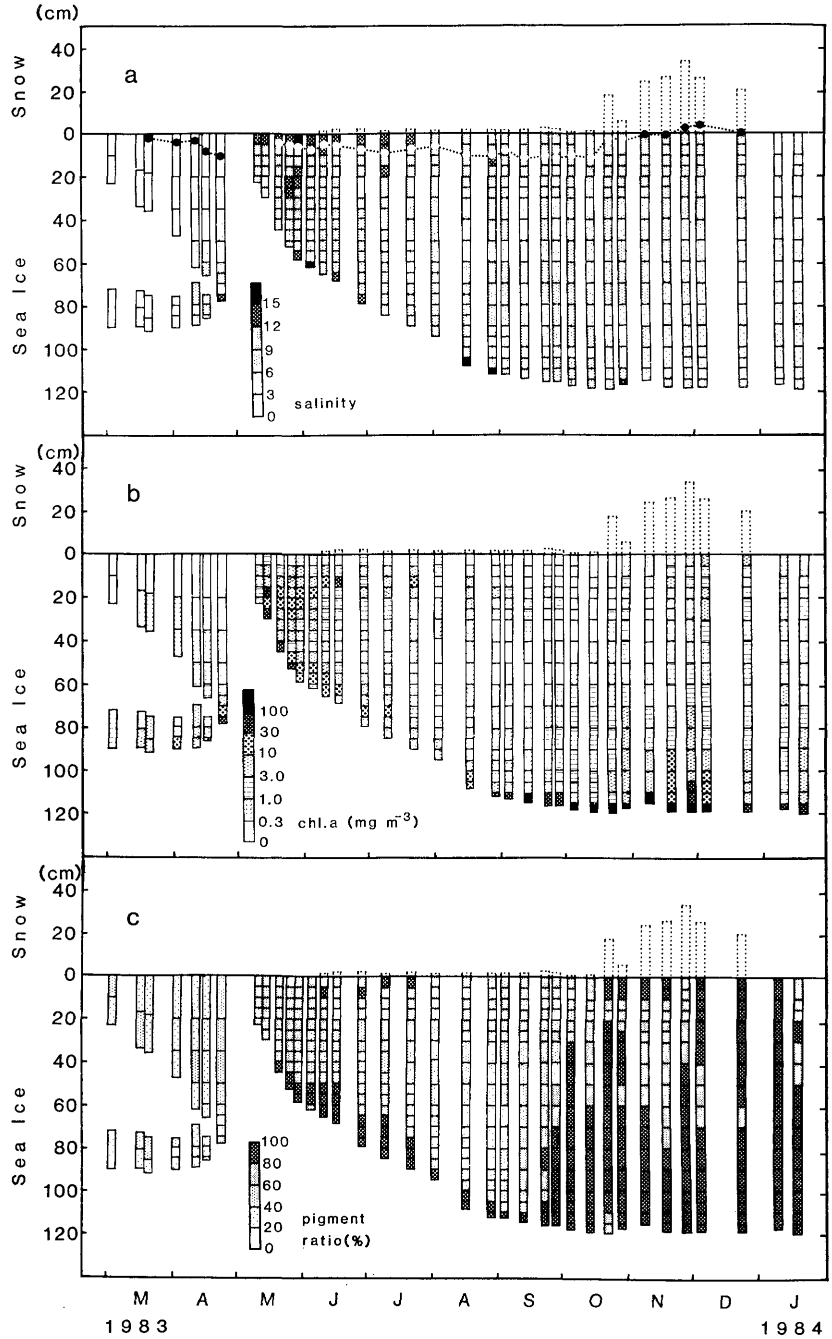

Fig. 3. Seasonal variation of vertical profiles of practical salinity (a), chlorophyll *a* concentration (b) and pigment ratio (c) (ratio of chlorophyll *a* to the sum of chlorophyll *a* and phaeopigments) in the sea ice at Stn. I. Dotted and solid columns above sea ice represent snow and consolidated snow, respectively. Small circles in black or white show sea level.

the ice thickness did not change greatly. Salinity ranged from 7.9–13.3 on 25 May and from 3.3–7.0 on 23 December. A minimum value for the ice cores during that period (2.7–7.9) was located in the lower part of the interior layer from late May to late December. The salinity profile changed greatly between 23 December and 9 January, decreasing to 0.6–4.6 in the whole ice thickness in January. There was little snow over the sea ice from March to late October, but it began to accumulate after late October, reaching a maximum depth of 34 cm on 27 November. Snow cover disappeared on 9 January through sublimation by strong solar radiation.

The variations in chlorophyll *a* in the ice are shown in Fig. 3b. The newly formed part of the upper layer of multi-year ice contained small brown masses of microalgae and from these parts chlorophyll *a* concentration ranged from 1.0–10 mg m^{-3} between late March and early April. The bottom 3 cm layer of multi-year ice turned brown with chlorophyll *a* increasing toward the bottom on 23 April when the concentration in this layer was 56.9 ± 24.1 mg m^{-3} (average$\pm$ range/2). On 10 May, the chlorophyll *a* concentration of the 23 cm thick young white ice was 1.18–9.72 mg m^{-3}. Small brown masses were again found in the 15–25 cm layer, both in consolidated grease ice and in the upper part of the congelation ice layers, which was formed in early and mid-May. Chlorophyll *a* concentration was high (2.51–35.53 mg m^{-3}) in the 10–30 cm deep layer in May. This chlorophyll *a* rich layer remained until August but its value decreased gradually to less than 10 mg m^{-3} in August. Discoloration of ice ca. 1 cm thick occurred at a few centimeters above the bottom between late May and early June. A maximum chlorophyll *a* value in the bottom ice (5 cm thick) was 40.4 ± 4.0 mg m^{-3} on 20 May. Even though the ice was growing so fast, the bottom chlorophyll-rich layer obviously shifted downward until mid-June. From late June to July, this shift appeared to stop and the high chlorophyll *a* layer was left 5–10 cm above the bottom.

TABLE 3. INCREASE OF CHLOROPHYLL *a* STANDING CROP IN THE BOTTOM LAYER OF SEA ICE BELOW 110 cm DEEP AT STN. I, 1983. STANDING CROP REPRESENTS A MEAN OF TWO ICE CORES.

Date	Days elapsed [X]	Thickness of ice sampled (cm)	Standing crop [Y]; (mg chl. *a* m^{-2})
29 Aug.	0	2	1.85
3 Sep.	6	3	2.47
12	15	5	6.25
22	25	6	5.09
27	30	6	4.64
4 Oct.	37	8	6.63
13	46	9	12.22
22	55	10	15.76
28	61	7	42.36
8 Nov.	72	5	35.68
18	82	9	120.32

$$Y=1.743\exp(0.0458\,X)$$
$$r^2=0.924\ (n=11)$$

The spring increase of chlorophyll *a* in the ice began in the bottom layer in mid-August. The chlorophyll *a* was 14.0 mg m^{-3} for the bottom 3 cm layer on 16 August. A discoloration in the bottom layer became visible on 28 August when the concentration was 92.4 mg chl. *a* m^{-3} for the bottom 2 cm layer. It reached a maximum of 2,980±20 mg chl. *a* m^{-3} for the bottom 4 cm layer on 18 November. The increase of standing crop in the bottom ice layer below 110 cm in depth, between 28 August and 18 November is shown in Table 3. From 11 sets of data, a growth rate of the bottom assemblage was determined to be 0.0458 day^{-1}, i.e. 15.1 days per doubling. In the early stage of this spring bloom, chlorophyll *a* seemed to be highly concentrated in a thin bottom layer of less than 1 cm, as perceived from a thin dark discoloration. The bottom chlorophyll *a* concentration decreased drastically from 1,170 mg m^{-3} for 4 cm on 4 December to 92.0 mg m^{-3} for 4 cm on 23 December.

The variations in the pigment ratio in the ice are shown in Fig. 3c. The pigment ratio (ratio of chlorophyll *a* to the sum of chloropnyll *a* and phaeopigments) in multi-year ice was generally low even in the bottom layer (29–46%). The pigment ratio in newly formed ice in May (49–79%) was higher than that in multi-year ice. That in the bottom layer increased to 86% on 20 May and remained high, mostly more than 80% till the end of this study. The pigment ratio in the interior layer decreased in June and July and began to increase in September and October. It ranged from 82–98% in the whole ice thickness from November to January.

1-2 *Station III*

Multi-year ice with honeycomb structure in the lower layer was observed in early March at Stn. III. Salinity of the ice was low, generally less than 4 with a maximum in the interior or bottom layer in March and April (Fig. 4a). A grease ice layer of ca. 68 cm was formed in the upper part of new ice in May. A maximum salinity of more than 15 was observed in the uppermost layer of ice from late May to early June. Sea ice grew to a maximum thickness of 111 cm on 17 August. Vertical brine channels or vertical hollows of ca. 1 cm in diameter were formed in the sea ice from late September and the number of channels increased in December. The thickness of snow on multi-year ice was 3–9 cm in March and April and 9–11 cm on the new ice from late June to early August. Thereafter, it reached a maximum of 76 cm on 14 November. Since the thick snow depressed the ice sheet, the sea level became higher than the upper surface of the sea ice. The lower part of the snow became consolidated by freezing of the infiltrated seawater. The thickness of the consolidated snow layer was 25 cm on 10 October and increased to 48 cm on 12 January.

The highest chlorophyll *a* concentration of 1.48 mg m^{-3} was measured in the middle part of multi-year ice on 5 March (Fig. 4b). The bottom part turned pale brown on 4 April and a concentration of 13.8 mg chl. *a* m^{-3} was detected from the bottom 9 cm ice layer. Small flocks of microalgae were found in the lower part of ice samples collected from late March to mid-April. Intensive brown discoloration was observed in the bottom ca. 5 mm layer on 12, 17 and 29 April. Chlorophyll *a* in the bottom part reached an autumn maximum of 247±1 mg m^{-3} for the bottom 4 cm layer on 17 April and 221±9 mg m^{-3} for 4 cm on 29 April.

In newly formed ice, the bottom layer of a few centimeters appeared brown on 24 May and

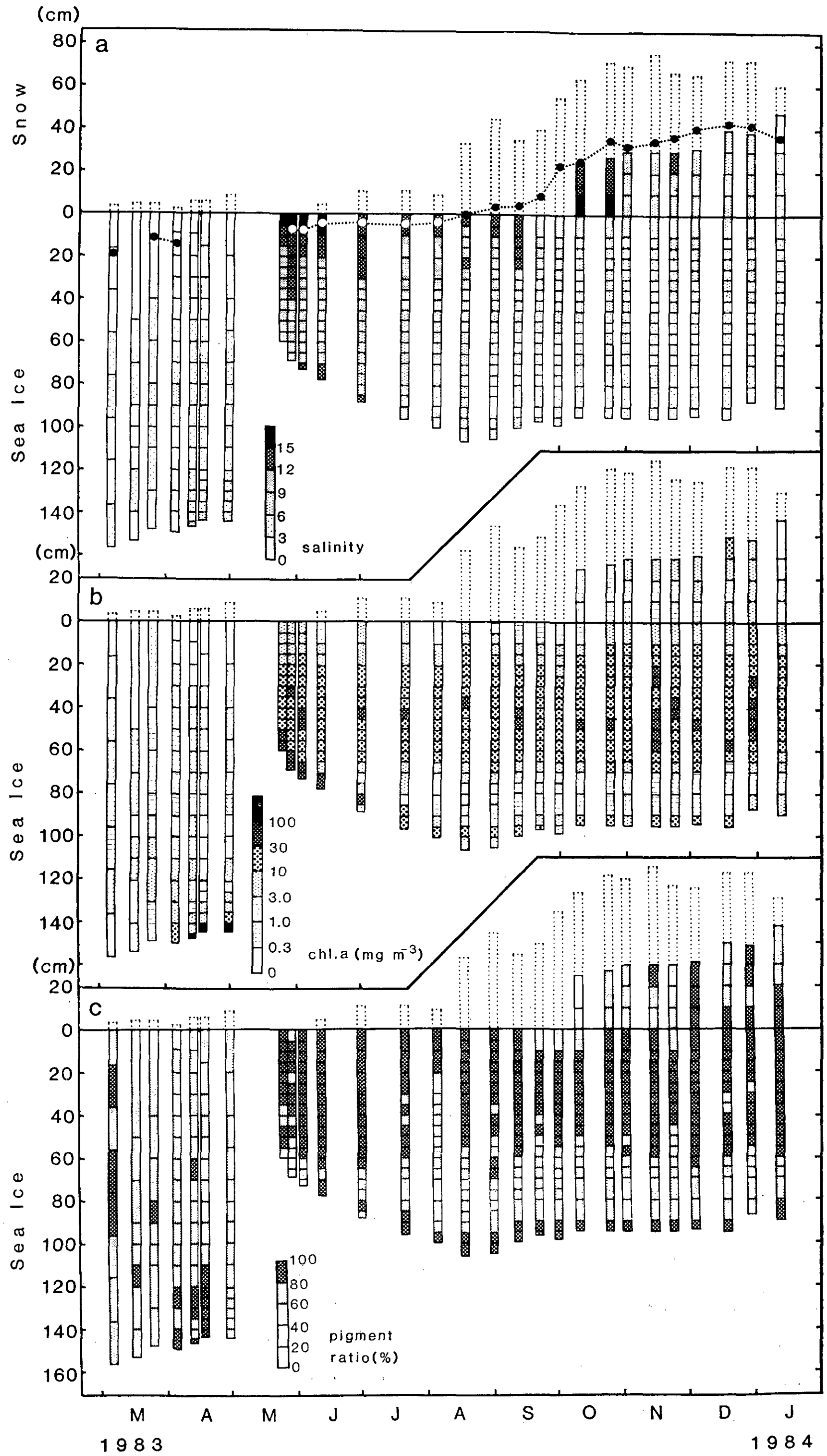

Fig. 4. Seasonal variation of vertical profiles of practical salinity (a), chlorophyll *a* concentration (b) and pigment ratio (c) in the sea ice at Stn. III. For other explanations, see legend for Fig. 3.

this colored layer shifted downward with the growth of sea ice from late May to early June. The highest chlorophyll *a* concentration in autumn, 96.5 ± 3.5 mg m^{-3} for the bottom 4 cm, 65–69 cm deep, was reached on 28 May. The discoloration in the bottom layer, a few centimeters above the bottom surface, faded away by 12 June. A bottom thin layer, less than 5 mm in thickness, turned pale brown on 23 November with a concentration of 27.3 mg chl. *a* m^{-3} for 5 cm, and a chlorophyll *a* concentration of 29.4 ± 12.4 mg m^{-3} for the bottom 4 cm was recorded on 3 December. However, the highest chlorophyll *a* concentration in ice at that time (33.4 ± 1.2 mg m^{-3}) was recorded from the 45–50 cm deep layer of sea ice.

The 20–70 cm deep layer of new ice showed yellow to pale brown discoloration and the chlorophyll *a* concentration of this layer ranged from 16.6–40.4 mg m^{-3} on 2 June and remained high, i. e., 5.61–41.8 mg m^{-3} until 29 December. The chlorophyll *a* concentration of this layer decreased to 5.39–19.4 on 12 January. A maximum chlorophyll *a* concentration in the interior part of the sea ice was 42.3 ± 11.1 mg m^{-3} in the 45–50 cm deep layer on 14 November.

The uppermost 10 cm layer of consolidated snow turned yellowish green to pale brown on 3 December. The maximum chlorophyll *a* concentration of the consolidated snow, i. e., 17.9 ± 1.2 mg m^{-3} for the 10 cm layer, 30–40 cm above the snow-ice interface, was recorded on 18 December. Therefore, three layers of discoloration were observed in an ice core on 18 December. Chlorophyll *a* concentrations in consolidated snow ranged from 3.49–7.67 mg m^{-3} on 29 December but decreased to 0.06–1.87 mg m^{-3} on 12 January.

The pigment ratio in the lower part of the ice was generally high (72–85%) in April (Fig. 4c). After the formation of new ice, the ratio in the interior layer, 20–70 cm in depth, was high, ranging from 77–84% on 2 June and 61–89% on 20 July. It decreased slightly to 54–78% on 4 August. After mid-August, it increased gradually and became 67–98% on 12 January. From May to January, the ratio in the bottom layer was usually more than 80%, whereas that of the 70–90 cm layer, just above the bottom was sometimes lower than 50%. In consolidated snow, the ratio ranged from 47–62% on 10 October and increased to 85–87% on 3 December. It decreased to 56–88% on 12 January.

1-3 *Station V*

This station was occupied in the new ice field. Grease ice of 40 cm in thickness was collected on 21 April. Salinity was relatively high, with the top and bottom 5 cm layers being more than 11 (Fig. 5a). After the flow out of sea ice, the grease ice layer was formed in the upper part of the sea ice above ca. 40 cm in thickness, followed by the formation of a congelation ice layer beneath. Sea ice grew up to 93 cm thick by 19 September and the thickness did not change greatly until 2 January. Vertical brine channels were found in the sea ice after December. The upper and the under surfaces of the sea ice were melted markedly between 2 and 12 January. The salinity of the ice decreased to 1.0–5.2. Snow increased gradually from June to September, up to 30 cm on 2 September, and decreased after December because of strong solar radiation.

The bottom 1.0–1.5 cm layer of the ice was discolored brown on 21 April and the chlorophyll *a* concentration was 39.2 ± 2.7 mg m^{-3} for the bottom 5 cm (Fig. 5b). Small brown patches

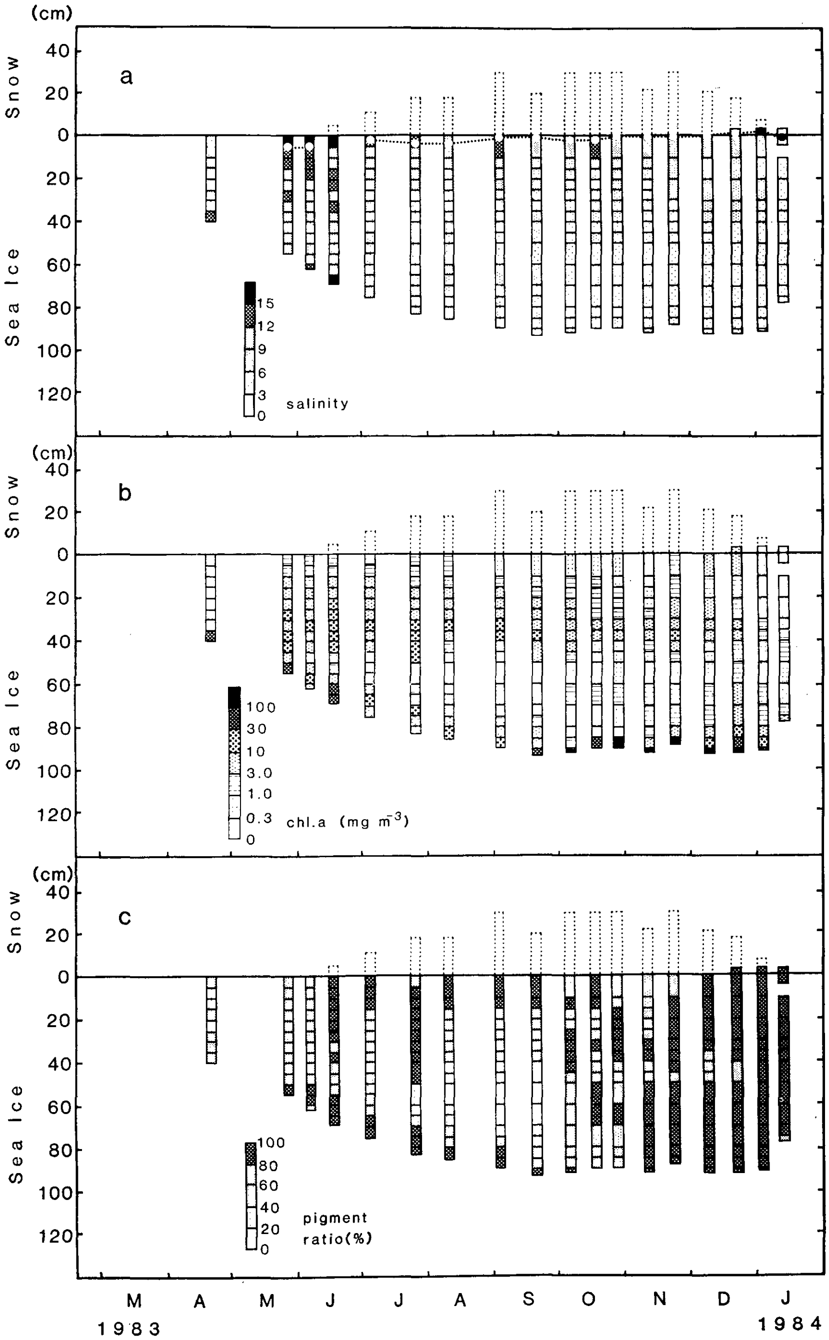

Fig. 5. Seasonal variation of vertical profiles of practical salinity (a), chlorophyll *a* concentration (b) and pigment ratio (c) in the sea ice at Stn. V. For other explanations, see legend for Fig. 3.

of microalgae were found in the 25–45 cm deep layer of the second new ice. Although the bottom layer was not markedly discolored, the chlorophyll *a* concentration in the bottom reached an autumn maximum of 47.7 ± 3.7 mg m^{-3} for the 5 cm layer on 27 May. The chlorophyll *a* concentration ranged from 11.0–28.1 mg m^{-3} in the interior layer (30–45 cm deep) from May to September, but decreased gradually toward January. The spring bloom of ice algae in the bottom layer was first observed on 19 September, when the chlorophyll *a* concentration was 92.1 ± 33.3 mg m^{-3} for the bottom 3 cm layer. Maximum chlorophyll *a* of $1,910\pm160$ mg m^{-3} for the 2 cm layer occurred on 10 November. Mixtures of water and ice scobs coming up in the ice hole were found discolored brown from 17 October to 10 November, but the discoloration was no longer visible after 22 November. Fine threads of filamentous colonies of microalgae were seen extending ca. 10 mm upward into the sea ice from the bottom surface, but the chlorophyll *a* concentration decreased to 193 ± 58 mg m^{-3} for the bottom 2 cm on 21 December. In consolidated snow and in the upper part of sea ice, relatively high concentrations (8.40 and 3.10 mg m^{-3}, respectively) of chlorophyll *a* were measured at that time.

From May to January, the pigment ratio in the upper 40 cm layer remained high (mostly more than 70%) and that in the bottom layer was also high, usually more than 80% (Fig. 5c). Between 25 July and 19 September, the ratio in the 50–70 cm deep layer was very low ranging from 27–52%. It began to increase in October and reached 85–100% on 2 January for the whole ice.

1–4 *Station X*

A transparent layer of newly formed congelation ice, 42 cm in thickness was collected on 25 March (Fig. 6a). Salinity of the upper 30 cm layer was very low (1.0–2.5), while that of the lower 12 cm was 8.5. The sea ice grew up to 60 cm thick by 23 April, with a salinity of the lower part, 30–60 cm deep, ranging from 7.6–15.1. The upper 17 cm layer of the second new ice appeared white and looked like grease ice. Congelation ice formed beneath this layer. After late November, salinity of all the ice decreased markedly and ranged from 0.6–3.6 on 5 January. Vertical brine channels were found in the sea ice after late November. The upper part of the sea ice was melted by solar radiation and many puddles were formed in December and January. Very little snow accumulated over the sea ice during this study.

In the upper transparent 30 cm layer of first new ice, the chlorophyll *a* concentration was less than 0.13 mg m^{-3} in March and April (Fig. 6b). There were small brown masses of microalgae in the layer 35–45 cm deep. Intensive discoloration was observed in the bottom 1–2 cm layer on 16 April. Chlorophyll *a* concentration in the bottom was 2.92 mg m^{-3} for a 12 cm layer on 25 March and 237 ± 79 mg m^{-3} for the bottom 2 cm layer on 23 April. The chlorophyll *a* maximum layer apparently moved downward with the development of sea ice in April.

In the second new ice, a high chlorophyll *a* concentration of 31.6 mg m^{-3} was detected in the 45–50 cm deep layer on 27 May. The chlorophyll *a* concentration increased up to 38.3 mg m^{-3} in the lower interior layer (55–60 cm deep) of sea ice on 8 June. The chlorophyll-rich layer shifted downward at this station as well as at Stns. I and III. The chlorophyll *a* concentration in the upper 5–25 cm layer was high (3.17–19.0 mg m^{-3}) on 27 May and decreased gradually

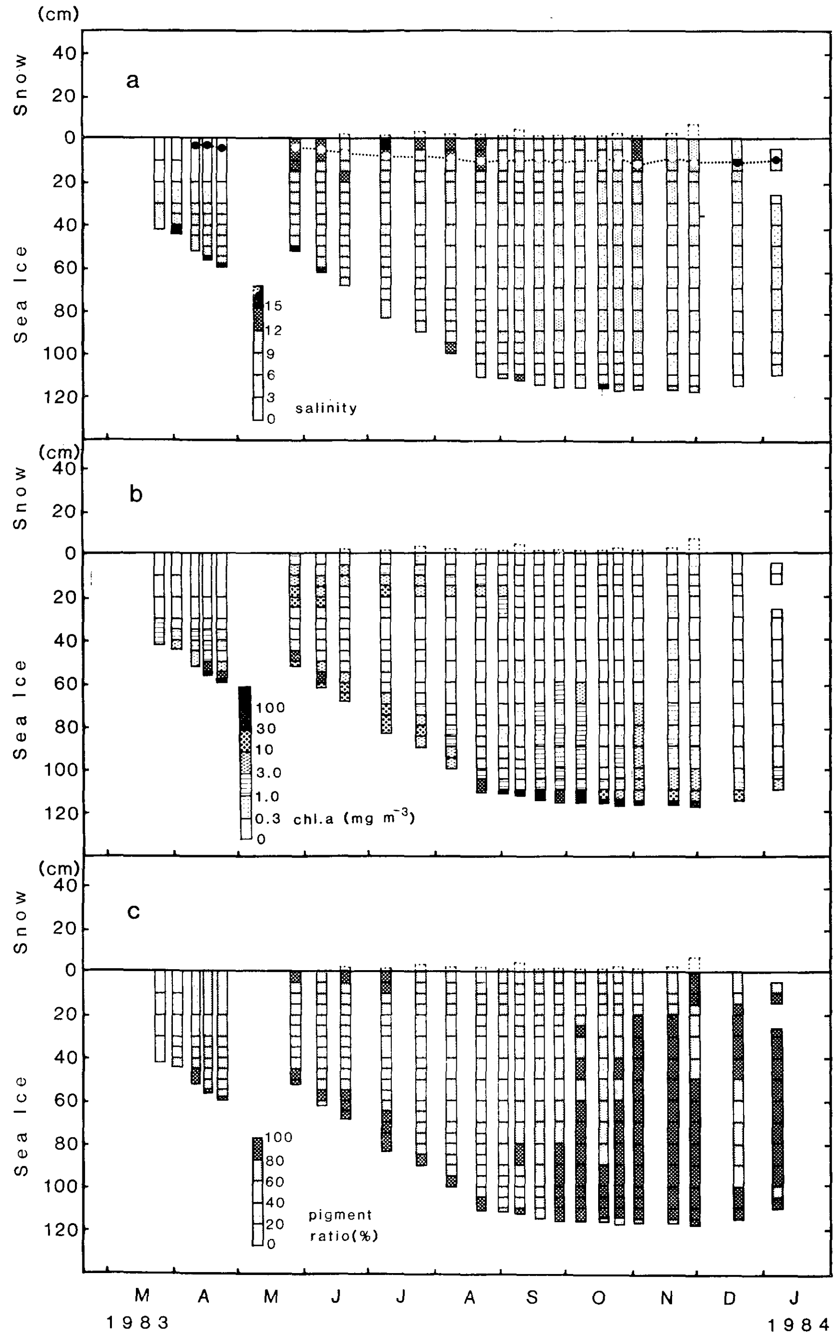

Fig. 6. Seasonal variation of vertical profiles of practical salinity (a), chlorophyll *a* concentration (b) and pigment ratio (c) in the sea ice at Stn. X. For other explanations, see legend for Fig. 3.

thereafter. For the spring bloom, chlorophyll *a* concentration in the bottom layer began to increase from 9.2 mg m^{-3} in the 5 cm layer on 7 August to 43.5 mg m^{-3} for a 6 cm layer causing a discoloration on 21 August and reaching a maximum of 323±137 mg m^{-3} for the bottom 6 cm on 6 October. In the upper part of sea ice, the concentration of chlorophyll *a* was lower than 1.0 mg m^{-3} after 8 September.

The pigment ratio remained high (more than 70%) in the bottom as well as in the upper 20 cm layer from May to August (Fig. 6c). It increased from the top to the bottom of the ice after September.

2. *Environmental conditions of the study area*

Around Syowa Station, fast ice usually persists through the summer season even though it melts to some extent. However, on 2 and 3 May in 1983, the fast ice sheet broke and flowed completely away from the coast of East Ongul Island, on which Syowa is situated. After the flow out, the sea was open for a few days. Strong easterly winds continued to blow over the open water for a few days and small pieces of ice sheet were packed onto the east coast of Nesöya as shown in Fig. 1. The daily mean wind velocity and air temperature on 4 and 5 May were 12.7 and 14.5 m s^{-1} and −6.2 and −7.4°C, respectively (JAPAN METEOROLOGICAL

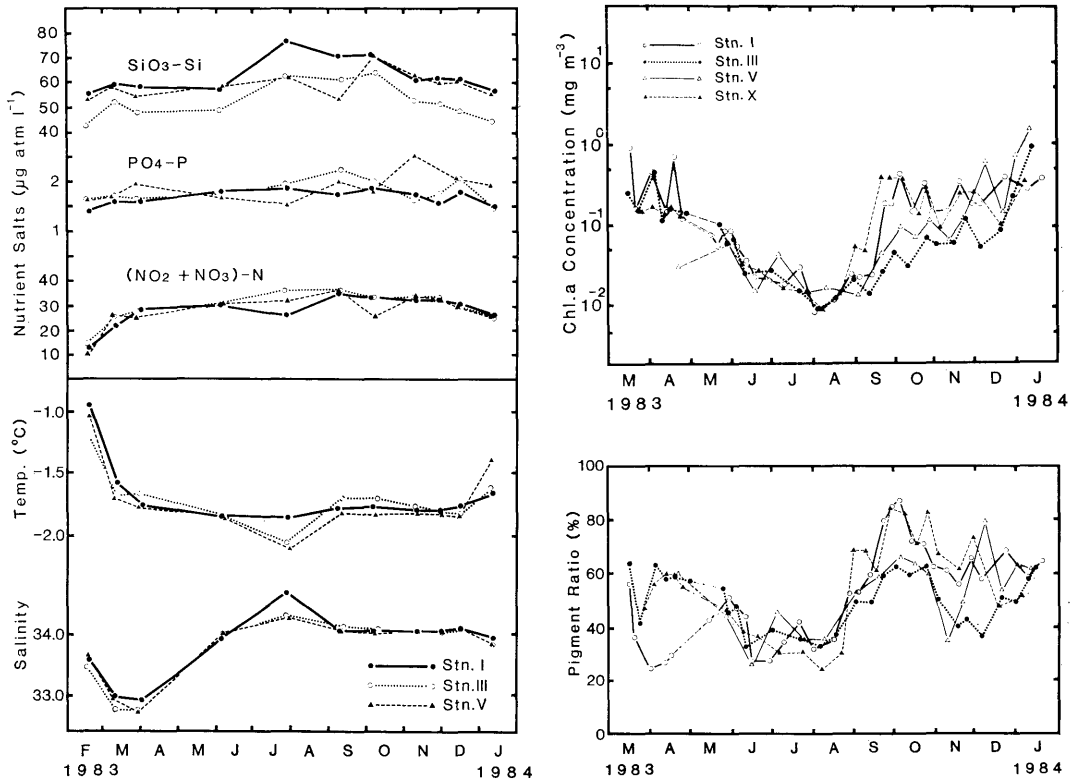

Fig. 7. Seasonal changes of water temperature, practical salinity and nutrient concentration (left) and of chlorophyll *a* concentration and pigment ratio (right) of surface water under fast ice at Stns. I. III and V.

AGENCY 1985). Under such weather conditions, a layer of grease ice was formed on the surface of the sea, blown to the east coast of the islands and frozen to form a white ice layer.

Physical and chemical variables in the water column were measured at Stn. I, III and V from February 1983 to January 1984 (SATOH et al. 1986). Water temperature, salinity and nutrient concentrations at 2 m depth at Stn. I and at 2.5 m depth at Stns. III and V showed similar seasonal variation (Fig. 7).

Variations in chlorophyll *a* concentration and pigment ratio in the 3 m deep layer at Stns. I, III, V and X are shown in Fig. 7. Chlorophyll *a* concentrations more than 0.2 mg m^{-3} were recorded at Stns. I and III and values of 0.1–0.2 mg m^{-3} observed at Stn. X in March and April. They decreased to minimum values, less than 0.02 mg m^{-3}, in early August. Chlorophyll *a* concentration began to increase in late August and reached more than 0.2 mg m^{-3} in January. From June to mid-August, the pigment ratio was at the lowest level, between 26 and 46%, but increased greatly to 60–90% from August to September. In October and November, it decreased by 20–30%, followed by an increase between November and January.

3. *Albedo and extinction coefficients of snow and ice*

Under ice and incident irradiance were measured simultaneously with the thickness of snow and ice. The snow was wind packed and did not seem to begin melting. From eight sets of data, a multi-variate analysis was attempted to determine the albedo and extinction coefficient of snow and ice. With a square multiple correlation coefficient of 0.976 from the analysis, each factor was determined, i.e., albedo=0.72, and extinction coefficients of snow and ice are 0.134 and 0.025 cm^{-1}, respectively. Therefore, under ice irradiance (I) can be estimated as follows;

$$I=0.275\ I_0 \exp\left[-(0.134\,x_1+0.025x_2)\right] \qquad (1),$$

where I_0 is incident solar irradiance and x_1 and x_2 are the thickness of snow and ice in centimeters, respectively.

TABLE 4. MAXIMUM CHLOROPHYLL *a* STANDING CROP IN ICE IN AUTUMN (APR.-JUNE) AND SPRING (OCT.-DEC.) IN THE FAST ICE AREA NEAR SYOWA STATION. AVERAGED DATA WERE OBTAINED FROM TWO ICE CORES.

Location	Date	Standing crop (mg chl. *a* m^{-2})	Source
Stn. I	25 May, 1983	6.22	Present study
	18 Nov.	125	
Stn. V	17 Jun.	8.88	
	10 Nov.	39.5	
Stn. X	23 Apr.	6.59	
	6 Oct.	20.9	
Kita-no-ura Cove	5 May, 1967	27	HOSHIAI (1969)
	1 Dec.	22	
Kita-no-seto Strait (Stn. I)	16 Apr., 1970	30	HOSHIAI (1981a)
	29 Oct.	35	

Discussion

Two peaks (in April-June and October-December) were observed in the seasonal variation of chlorophyll *a* standing crop in fast ice near Syowa Station, which agrees with HOSHIAI (1969, 1981a, 1985). The peak values for autumn and spring-summer at each station are summarized in Table 4. Spring-summer peak values were 3-20 times greater than the autumn values. The autumn peak values reported for this study are much lower than those reported by HOSHIAI (1969, 1981a). This may be accounted for by the fact that the algal assemblages grown in the ice in March and April were lost when the ice sheet flowed completely away from the coast of East Ongul Island on 2 and 3 May, 1983. Chlorophyll *a* concentrations in the ice should be compared carefully, taking into account the thickness of the samples. However, the bottom assemblage is still the most highly concentrated and predominant in the standing crop in the ice. The bottom assemblage was shown to grow most extensively and intensively among the three types of assemblages in this area.

Of the three ice algal assemblages, the bottom one would be the most readily accessible to ice-associated or planktonic consumers. Because there are small channels and pockets in the micro-structure of sea ice (WEEKS & ACKLEY 1982), the consumers, e.g., protozoa, copepods and invertebrate larvae, can dwell and feed in the sea ice layer. An ice-associated copepod, *Paralabidocera antarctica*, was found in a bottom ice layer and shown to depend upon microalgae in sea ice in winter (HOSHIAI et al. in press). For these consumers, long duration of bottom ice algal blooms is thought to be advantageous for survival during the winter when phytoplankton standing crop becomes minimal.

Microalgal flocks, the origin of which was not determined, were found in newly formed sea ice from late March to early May at Stns. I, III and X. This implies that not all of the increase in standing crop in the ice was a result of ice algal growth, although bottom discoloration was observed in autumn as well as in spring. On the other hand, the spring increase of standing crop in the ice is thought to be a result of ice algal growth. Incorporation of algae did not occur in spring-summer when there was little sea ice growth, therefore annual production of ice algae would be more than the amount of the spring increase of ice algal standing crop and less than the sum of the spring and autumn increases in ice. From increases of standing crop in the ice in autumn and spring, annual production of ice algae is estimated as 124-130, 36.1-42.9 and 19.1-25.3 mg chl. a m^{-2} y^{-1} at Stns. I, V and X, respectively. Using a carbon/chlorophyll *a* ratio of 26.3 (SATOH & WATANABE 1986) measured from a sample of a bottom assemblage in early November near Stn. I, these values can be converted to 3.26-3.42, 0.95-1.13 and 0.50-0.67 g C m^{-2} y^{-1}, respectively.

1. *Bottom assemblage*

Microalgal flocks were observed incorporated in a newly formed ice layer from late March to early April at Stns. I, III and X and just after the flowout of sea ice in early May at Stn. I. Although analyses on the species composition are needed, these flocks may possibly be an inoculum for the later bloom in a bottom ice layer.

With the development of the sea ice, a bottom chlorophyll maximum layer apparently

TABLE 5. CHANGES IN CHLOROPHYLL *a* CONCENTRATION AND PIGMENT RATIO IN THE LAYER 40-45 cm DEEP IN SEA ICE AND TOTAL ICE THICKNESS AT STN. I IN 1983.

Date	Total ice thickness (cm)	Chlorophyll *a* ($mg\ m^{-3}$)	Pigment ratio (%)
20 May	45	40.3	85
25	53	2.55	73
4 Jun.	62	0.66	51
28	79	0.45	50

shifted downward from mid-May to early August at the four stations. This phenomenon can be perceived also in figures by HOSHIAI (1969, 1981a). Standing crop of chlorophyll *a* in a particular ice layer decreased greatly after the layer was incorporated in an interior part of the ice as a result of sea ice growth. Changes in chlorophyll *a* standing crop and pigment ratio in an ice layer of 40-45 cm deep at Stn. I between 20 May and 28 June are shown in Table 5. This layer was on the bottom on 20 May and contained 40.3 mg chl. $a\ m^{-3}$. The chlorophyll *a* concentration decreased drastically in a few days. The pigment ratio in that layer decreased gradually from 85 % on 20 May. From late May to late August, a higher chlorophyll *a* concentration was often found in the lower interior part rather than in the bottom of the ice at the four stations. It is presumed that the downward development of sea ice exceeded the growth and the downward shift of ice algae. Stability of the bottom surface would be one of the important factors to induce a bottom discoloration by ice algae (HOSHIAI 1981b).

The concentration of chlorophyll *a* became higher in the lower part of the sea ice in early August. The bottom discoloration became visible in late August at Stns. I and X. From mid-June to late August, the chlorophyll *a* concentration in the water beneath the ice was at a minimum level ranging from 0.01-0.05 $mg\ m^{-3}$ with a pigment ratio less than 50 % (Fig. 7). It is presumed that the spring ice algal bloom in the bottom ice layer developed from a seed population in sea ice in autumn and winter rather than from microalgae in the water.

Though the ice algal assemblage in the bottom layer began to increase in mid-August at Stns. I, V and X, the dates and values of the maximum chlorophyll *a* concentration (Table 4) were different in conjunction with ice and snow conditions. Relationships between the estimated under-ice irradiance and chlorophyll *a* crop in the bottom (ca. 10 cm) ice layer at the four stations are shown in Fig. 8. Under-ice irradiance was estimated from the ten-day mean of solar radiation at Syowa (JAPAN METEOROLOGICAL AGENCY 1985, 1986) and equation (1) on the assumption that the factors in the equation would be applicable to the four stations during this study. Chlorophyll *a* standing crop in the bottom layer at Stns. I and X was almost the same from mid-August to mid-October, when the snow and ice conditions, based on estimated under-ice irradiance, were almost the same. After early August, snow accumulated heavily at Stn. III, reducing the under-ice irradiance more than at the othe other stations. Chlorophyll *a* standing crop in a bottom layer at Stn. III did not increase as much as at the other stations

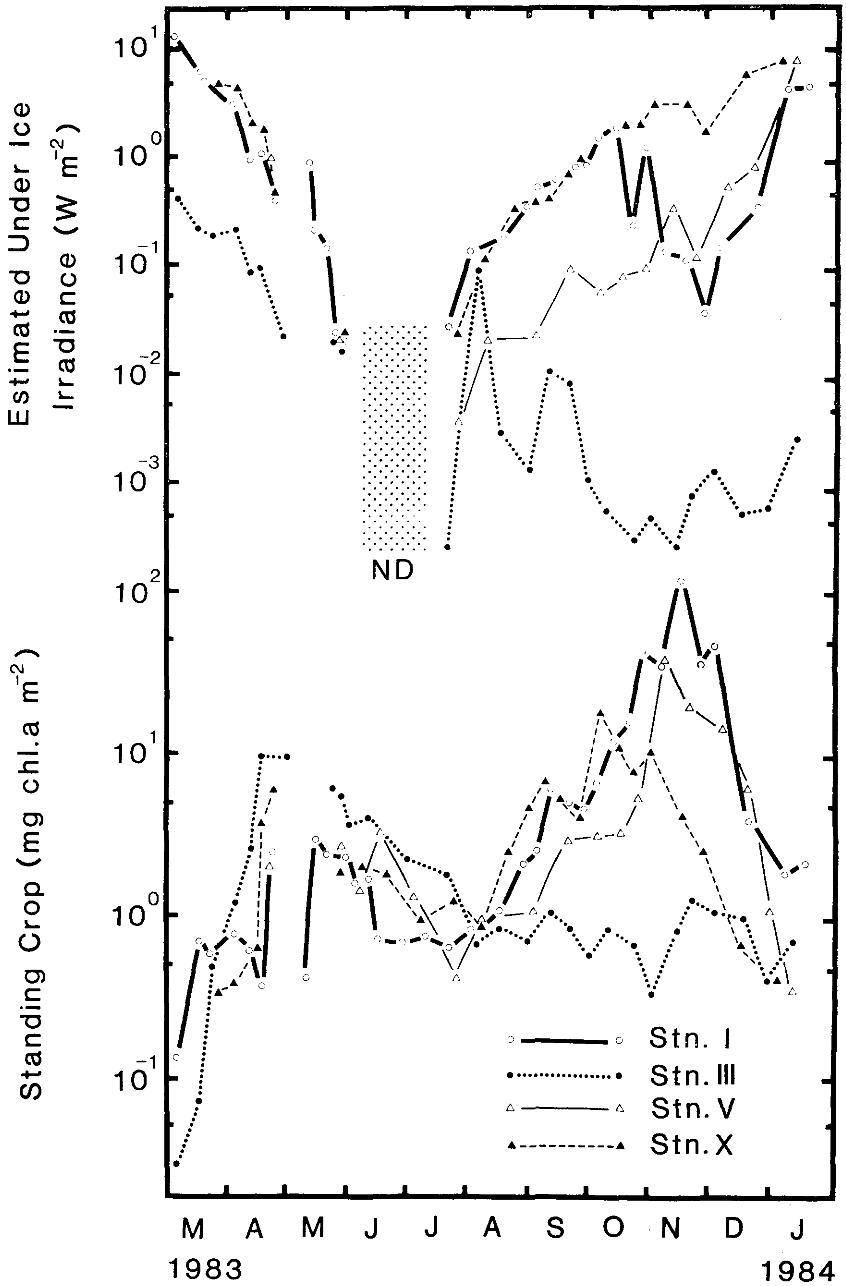

Fig. 8. Seasonal variations of integrated chlorophyll *a* in the bottom (ca. 10 cm) sea ice layer and estimated under-ice irradiance at Stns. I, III, V and X.

from August to the end of this study in January. This suggests a close relationship between bottom ice algal growth and in situ irradiance as SULLIVAN et al. (1985) demonstrated. As the light extinction coefficient of snow was more than five times that of the ice, snow cover would influence greatly the growth of ice algae. In autumn, light extinction by snow and ice would decrease greatly as snow and the upper layer of ice are melted by solar radiation during spring and summer. The absence of snow would be one reason why an ice algal assemblage could grow even in the bottom of thick multi-year ice in autumn.

A maximum chlorophyll *a* standing crop in ice was reached on 18 November, 10 November and 6 October at Stns. I, V and X, respectively (Table 4). After that, it decreased rapidly. The dark layer of the bottom assemblage is thought to absorb heat through solar radiation, therefore melting of the colored layer would be induced leading to separation of the algal assemblage from the bottom ice layer. An increase in water temperature in January at Stns. I, III and V (WATANBE et al. 1986) would be another important factor for the bottom ice melting. The bottom assemblage is concentrated in a thin layer of the sea ice bottom, therefore, a little melting of the bottom results in a great proportion of ice algal loss. On the other hand, ice melting causes dilution of seawater beneath the sea ice. A surface water layer 1 m thick in open coastal water, surrounded by ice floes near Syowa Station in January had less than 5‰ salinity (WATANABE et al. 1982). Brine channels would be penetrated by such low salinity water, therefore, ice algae in the bottom ice layer would not be able to continue their growth. Because both growth and decay of the ice algal assemblage are primarily a function of in situ irradiance, the standing crop of ice algae in a bottom ice layer rests on a delicate balance of snow-ice conditions and solar radiation.

2. *Interior assemblage*

In this study, the interior assemblage was not concentrated in a thin layer like the bottom assemblage, but was dispersed in a thick (10–50 cm) ice layer showing yellow to pale brown discoloration. The greatest discoloration in an interior layer was observed at Stn. III where a grease ice layer was most intensively developed. The chlorophyll *a* concentration ranged from 16.6–40.4 mg m^{-3} on 2 June. At the other stations, high chlorophyll layers were also formed in the consolidated grease ice layer in May, with chlorophyll *a* concentrations ranging from 20–30 mg m^{-3}.

After the flowout of fast ice in early May, a strong cold wind continued to blow over the sea. This generated surface currents and vertical mixing of coastal waters, which would induce microalgae to separate from the substrata (e.g., sea ice). When a cold strong wind blows over open water in polar regions, frazil ice, an origin of grease ice, forms on the surface of the sea (BAUER & MARTIN 1983). These authors showed that ice crystals (i.e., frazil ice) are drifted to the downwind edge of leads and form a grease ice layer an order of magnitude faster than congelation ice. Incorporation of suspended particles including microalgae into the grease ice layer occurs through scavenging and nucleation by frazil ice (WEEKS & ACKLEY 1982, GARRISON et al. 1983). It is presumed that these processes occurred concomitantly after the flowout of fast ice to make the consolidated grease ice layer containing microalgal flocks and particles.

The interior chlorophyll *a* maximum was located in a layer 30–60 cm deep and ranged from 26.8–42.3 mg m^{-3} at Stn. III between May and January. These values are one order of magnitude greater than the values from frazil ice in the Weddell Sea (i.e., 4.54, ACKLEY et al. 1979, and 3.8 mg m^{-3}, CLARKE & ACKLEY 1984). One reason for this might be that cells growing in the bottom ice layer before the outflow of the fast ice sheet were freed from the ice by wind induced currents and then were recaptured into a grease ice layer. This process might possibly occur in pack ice areas where strong wind blows over open water and collision of ice floes occurs frequently.

The standing crop of the interior assemblage did not increase at the four stations, but remained stable or gradually decreased. The interior assemblage is thought to be exposed to a severe temperature-salinity regime, depending on air temperature. Such conditions would prevent the algae from growing or lead to inactivation of the algal assemblage. From the stand point of the distance from the ice-water interface and the structure of the sea ice (congelation ice vs. grease ice), nutrient deficiencies would occur more easily in an interior layer than in a bottom layer if an ice algal assemblage starts growing (CLARKE & ACKLEY 1984). However, this assemblage would grow after the formation of vertical channels in the sea ice in spring which serve to renew the interstitial seawater.

3. *Surface assemblage*

The standing crop of chlorophyll *a* in the ice layer higher than 10 cm deep, and consisting mainly of a consolidated snow layer, began to increase in late September and reached a maximum of 3.82 mg m^{-2} on 13 December at Stn. III. At the other stations, this assemblage did not develop because there was not as much snow as at Stn. III to depress the ice sheet and allow seawater to infiltrate the snow layer. This assemblage is probably the only one that can develop in an area with heavy snow-cover because high light extinction by the snow results in not enough light reaching cells in the interior and bottom layers of the ice. The habitats for this assemblage in previous reports (MEGURO 1962, WHITAKER 1977, MCCONVILLE & WETHERBEE 1983) had close connections with seawater. High salinity (12–15‰) of the consolidated snow layer on 24 October indicated that seawater was transported upward and that microalgae grew in a medium of some salinity. Around Stn. III, vertical hollows (brine drainage channels) ca. 1 cm in diameter were observed in sea ice after late September. These hollows were presumed to serve as channels for seawater transport at Stn. III. Cracks were sometimes found in the fast ice sheet running near Stn. III, from Iwa-zima Is. to the easternmost point of East Ongul Is. However, their contribution to the upward transport of seawater would be small, as their area of influence is limited when compared with brine drainage channels scattering in ice (WEEKS & ACKLEY 1982).

When seawater moves upward in sea ice, it would possibly carry some microalgae adjacent to the channels or in the water column, i.e., interior and bottom ice algal assemblages and the phytoplankton assemblage. The chlorophyll *a* concentration in the water column was at a low level (less than 0.1 mg m^{-3}) until mid-November at Stn. III (Fig. 6). As BUNT (1968) pointed out, it would not be reasonable to think that microalgae in the water column provide an inoculum for the surface assemblage (MEGURO 1962). One possible hypothesis is that the microalgal assemblage in the interior and/or bottom ice layer facing the hollows would be transported by saewater to the consolidated snow layer and start growing as an inoculum because bottom and interior assemblages both existed at Stn. III.

The standing crop of the surface assemblage at Stn. III decreased after mid-December. This might be accounted for by photo-inhibition of the surface assemblage and by lowered salinities from melting snow and ice under the strong solar radiation in summer.

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