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VERTICAL DISTRIBUTION OF SIZE FRACTIONATED PHYTOPLANKTON CHLOROPHYLL IN THE INDIAN SECTOR OF THE SOUTHERN OCEAN IN SUMMER (1985/86)

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Abstract: During the icebreaker SHIRASE cruise of the 27th Japanese Antarctic Research Expedition (JARE-27; 1985/86), vertical profiles of phytoplankton chlorophyll *a* concentration in the upper 200 m of the water column were observed at 12 stations in the Southern Ocean and at 3 stations in the subtropical water from December 1985 to March 1986. High phytoplankton chlorophyll standing crops (*ca.* 370 mg m^{-2} in December and 330 mg m^{-2} in February) were observed in Breid Bay, Antarctica. In other stations of the Antarctic Ocean, the standing crops were less than 52 mg m^{-2}. Size fractionation studies revealed that net-phytoplankton (>20 μm) was the dominant fraction of total chlorophyll *a* during the summer bloom in Breid Bay. In Antarctic waters, the high contributions of the net-phytoplankton fraction corresponded to high total biomass. And also, contribution of the net-phytoplankton to the total phytoplankton was supposed to be controlled by the length of the ice-free period. Considering the high phytoplankton growth rates under the nutrient rich condition, duration under optimum light condition and water stability appear to be important factors affecting the phytoplankton crops in the Antarctic Ocean in summer.

key words: size fractioned chlorophyll *a*, vertical distribution, Southern Ocean, water stability, JARE-27

Introduction

Observations of phytoplankton standing crops in the Antarctic Ocean are important for evaluating primary production (KURODA and FUKUCHI, 1982) and in estimating available food for Antarctic krill (HOLM-HANSEN and HUNTLEY, 1984; BODUNGEN, 1986; WEBER *et al.*, 1986). Phytoplankton chlorophyll *a* crops in the water column in the Antarctic Ocean have been observed by numerous workers (*cf*. SAKUSHAUG and HOLM-HANSEN, 1984; EL-SAYED, 1984; WEBER *et al.*, 1987; FUKUCHI and TAMURA, 1982; SASAKI, 1984; OHNO *et al.*, 1987). Low phytoplankton standing crops have generally been observed in the austral

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summer as compared with the reported spring crops in the Bering Sea (ALEXANDER and NIEBAUER, 1981), even though the nutrient concentrations in the Antarctic Ocean are much higher than in the Bering Sea. Some factors causing the lower standing crops in the Antarctic have been proposed (*cf*. EL-SAYED, 1984; NELSON and SMITH, 1986). In the Bering Sea, TANIGUCHI (1969) proposed that water stability in the surface layer is important for phytoplankton growth. Phytoplankton chlorophyll *a* standing crops in the upper 200 m of the Antarctic water column were generally less than 100 mg m^{-2} (EL-SAYED and JITTS, 1973: Indian Ocean, YAMAGUCHI and SHIBATA, 1982; south of Australia, HOLM-HANSEN and HUNTLEY, 1984; Scotia Sea, EL-SAYED and TAGUCHI, 1981; Weddell Sea). Since 1983 (JARE-25), vertical distributions of phytoplankton have been investigated in the Breid Bay, Antarctica; higher standing crops of chlorophyll *a* (>300 mg m^{-2}) have been found compared with other areas in the Antarctic (OHNO *et al*., 1987). In the present study (JARE-27, 1985/86) high chlorophyll *a* crops (>300 mg m^{-2}) were observed in the upper 200 m water column in Breid Bay, while lower standing crops of less than 100 mg m^{-2} were obtained in other areas. In order to elucidate the factors affecting geographic differences in phytoplankton chlorophyll *a* crops, phytoplankton size composition, known to indicate the specific response to certain environmental condition (MALONE, 1980), has been investigated.

Materials and Methods

During the 27th Japanese Antarctic Research Expedition (JARE-27) cruise of the icebreaker SHIRASE, water sampling was carried out 24 times at 12 stations in the Antarctic Ocean, including 24 hr observations at 3 fixed stations (Fig. 1). To compare vertical features of phytoplankton chlorophyll crops, water was sampled at 3 stations in the subtropical water (Sts. 13, 14, and 15 located at 43°51′S-53°08′E, 40°35′S-54°01′E, and 36°08′S-54°30′E, respectively).

In Breid Bay vertical observations including a 24 hr observation were made 9 times at 5 stations under the midnight sun on 25-28 December, 1985. When the second 24 hr vertical observation was done at St. 6, sunset time was at 2224 on 14 February and sunrise was at 0454 the next day. Four vertical observations were carried out in the Gunnerus Bank area at Sts. 7-10 from 18 to 21 February. On 25-26 February, the third 24 hr observation was made at St. 11. The last observation in the Antarctic Ocean in the present study was made at St. 12 on 2 March.

Water samples were collected from 10 layers of the water column (0, 10, 20, 30, 50, 75, 100, 125, 150, and 200 m) with a series of Van Dorn water samplers. To determine the size composition of phytoplankton chlorophyll, 1 to 2 liters of water sample was gently filtered through 20 μm and 5 μm nylon meshes, successively, and the filtrate was then filtered through a Watman GF/C filter after addition of 1 m*l* of 1% $MgCO_3$. Phytoplankton pigments were extracted in 90% acetone with a grinding apparatus. Chlorophyll *a* and pheopigment concentrations were determined fluorometrically (STRICKLAND and PARSONS, 1972) with a Shimadzu RF-501 Spectrofluoromoeter. In this study, each phytoplankton fraction was sieved through 20, 5 μm meshes and a GF/C filter was used to separate net-phytoplankton (>20 μm), micro-phytoplankton (20-5 μm) and nano-phytoplankton (<5 μm). The sum of the three fractions is regarded as the total chlorophyll concentra-

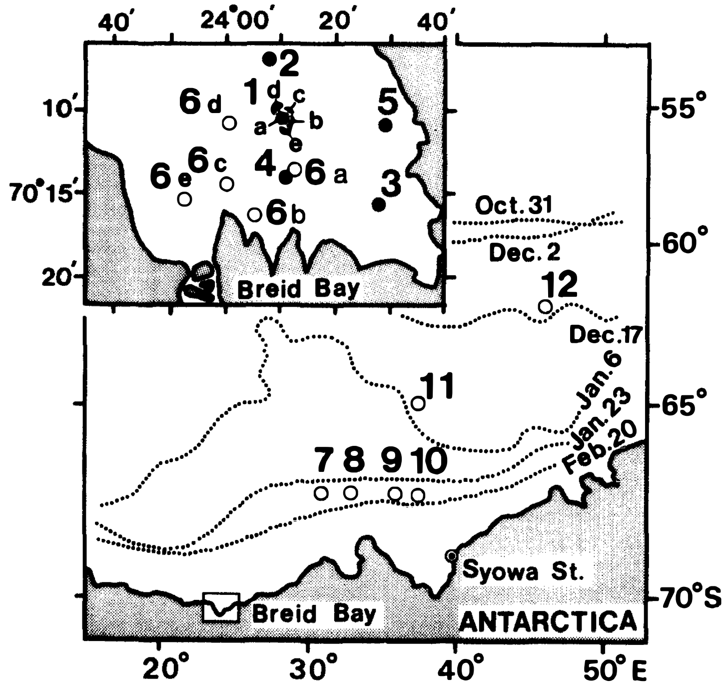

Fig. 1. Locations of sampling stations. Filled circles and open circles indicate December observations and February to March observations, respectively. The changes in the sea ice coverage as determined by satellite NOAA-9 are indicated by dotted lines. The ocean north of 70°05–10′S was covered by heavily packed ice in Breid Bay. The surface of the bay was opening before December.

tion.

Temperature, salinity and nutrients in the water column were measured concurrently and published elsewhere (IWANAGA and TOHJU, 1987)

Results

The changes in the sea-ice coverage as determined by satellite (NOAA-9) for the period from October 1985 to February 1986 as well as the locations of sampling station are shown in Fig. 1. Breid Bay was ice-free in this period (from data of NOAA-9). Bay water was relatively still and calm due to enclosure by the shelf ice in the south and the heavily packed ice in the north of 70°05′S in December and at 70°10′S in February.

Breid Bay (December 1985; Figs. 2 and 3)

The first series of 24 hr observations was carried out between 0913 on 26 December and 0855 on 27 December at St. 1 (Fig. 2). A weak thermocline was found in the 20–40 m layer; the pycnocline was in the 10–50 m depth range.

At St. 1, total chlorophyll *a* at the surface was as high as 4.22 $\mu g\ l^{-1}$ (mean of the station) and a subsurface maximum around 5.41 $\mu g\ l^{-1}$ was found in the 10–30 m layer. Vertical profiles of size-fractionated phytoplankton at St. 1 showed that the net-phytoplankton were the most dominant fraction, accounting for 80.7, 84.8, 86.9, and 66.8% at the surface, the subsurface maximum, 100 m, and 200 m depths, respectively.

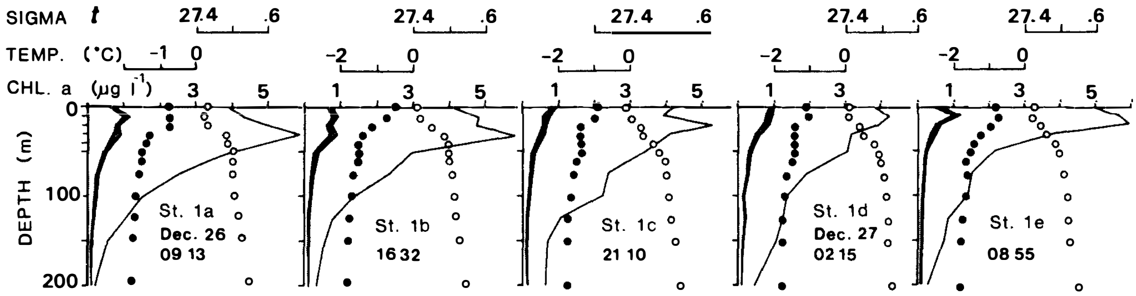

Fig. 2. Vertical profiles of phytoplankton chlorophyll *a* crops at St. 1 in Breid Bay, December. Time of sampling is indicated in each profile. White, darkly shadowed and lightly shadowed portions indicate net- (>20 μm), micro- (20–5 μm), and nano-phytoplankton (<5 μm) components, respectively. Water temperature and density (sigma-*t*) are represented by filled and open circles, respectively.

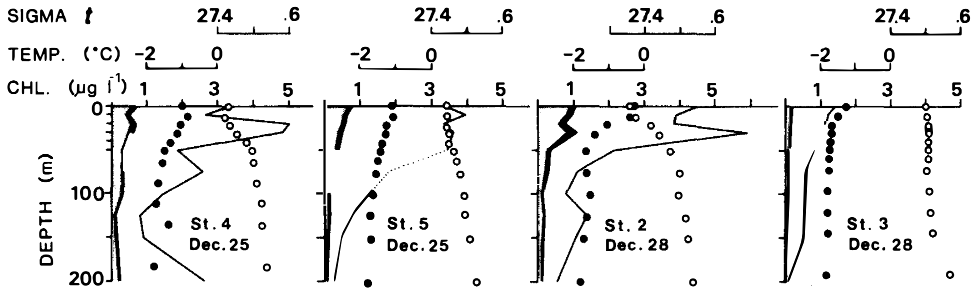

Fig. 3. Vertical profile of phytoplankton chlorophyll *a* crops at Sts. 2–5 in Breid Bay, December. Station number and sampling date are indicated in each profile. Other explanations are the same as in Fig. 2.

Vertical profiles of chlorophyll *a* as well as water temperature and sigma-*t* were observed at Sts. 4–5 and Sts. 2–3 on 25 and 28 December, respectively (Fig. 3). A weak thermocline and pycnocline were found in the 10–50 m layer except at St. 3 where almost no density gradient was observed.

Total chlorophyll *a* concentrations at the surface in Sts. 4, 5, and 2 were as high as 3.75 $\mu g\ l^{-1}$ (mean of three), and the subsurface maximum around 4.88 $\mu g\ l^{-1}$ (mean of three) occurred in the 10–30 m layer. At St. 3, chlorophyll *a* concentration was relatively low: 1.38 $\mu g\ l^{-1}$ at the surface, 0.10 $\mu g\ l^{-1}$ at 200 m. Net-phytoplankton, as shown in Fig. 3, was the dominant fraction in every layer, reaching 80.4% of the total chlorophyll *a* in the surface layer of 4 stations and around 84.3% in the subsurface maximum layer of 3 stations except for St. 3. Total chlorophyll *a* standing crops in the upper 200 m water column in Breid Bay during December were in the range of 130 to 450 mg m^{-2} with mean of 369 mg m^{-2}. The percent compositions of the three size fractions observed in December are summarized in Table 1.

Breid Bay (February; Fig. 4)

The second 24 hr observation was carried out from 1151 of 14 February to 1125 of the next day at St. 6. The sunset and sunrise times were 2224 and 0454, respectively. Because of rapid pack ice drift, successive observations could not be fixed at one position (see Fig.

Table 1. Phytoplankton chlorophyll *a* crops (mg m^{-2}) in the upper 200 m water column and percent composition of net- (>20 μm), micro- (20–5 μm), and nano-phytoplankton (<5 μm) measured at each station.

Area	Date	Time	Station	Chl. *a*	Percent composition		
					Net-	Micro-	Nano-
Breid Bay	25 Dec.	1106	4	426.2	78.8	7.1	13.1
		1520	5	343.8	86.0	2.7	11.3
	26 Dec.	0913	1-a	448.9	83.5	3.3	13.2
		1632	1-b	409.7	84.4	3.4	12.2
		2110	1-c	431.4	87.1	2.8	10.2
	27 Dec.	0215	1-d	379.2	82.1	3.2	14.7
		0855	1-e	375.5	85.8	2.9	11.3
	28 Dec.	0943	2	372.8	81.2	3.9	14.9
		1300	3	131.3	84.3	3.4	12.3
			mean	369.0	83.7	3.6	12.7
Breid Bay	14 Feb.	1115	6-a	386.6	79.3	4.3	16.4
		2120	6-b	291.6	75.5	3.7	20.8
		2357	6-c	321.9	74.4	4.6	21.0
	15 Feb.	0355	6-d	319.0	77.9	4.4	17.7
		1125	6-e	338.0	77.2	6.4	16.4
			mean	331.4	77.0	4.7	18.3
Gunnerus Bank	18 Feb.	1058	7	26.3	6.7	5.2	88.1
	19 Feb.	1041	8	40.1	2.8	1.9	95.3
	20 Feb.	1047	9	26.2	4.8	2.9	92.3
	21 Feb.	1045	10	30.7	7.3	6.2	86.5
			mean	30.8	3.6	2.6	93.8
Antarctic water	25 Feb.	1101	11-a	32.9	34.5	17.2	48.3
		1755	11-b	28.4	27.3	16.3	56.4
		2335	11-c	32.5	34.8	10.4	54.8
	26 Feb.	0400	11-d	37.3	33.5	12.5	54.0
		1100	11-e	35.7	30.4	16.0	53.6
	2 Mar.	1157	12	52.2	41.0	20.0	39.0
			mean	34.8	34.0	15.5	50.5
Subtropical water	8 Mar.	1240	13	80.2	39.7	17.5	42.8
	9 Mar.	0835	14	31.7	3.7	2.6	93.7
	10 Mar.	832	15	19.3	2.7	4.2	93.1
			mean	46.8	25.6	11.9	62.5

1). A weak thermocline was seen between 30 and 50 m depth. Vertical profiles of sigma-*t* showed a conspicuous pycnocline in the 30–50 m layer.

Dense phytoplankton chlorophyll standing crops were observed above the pycnocline.

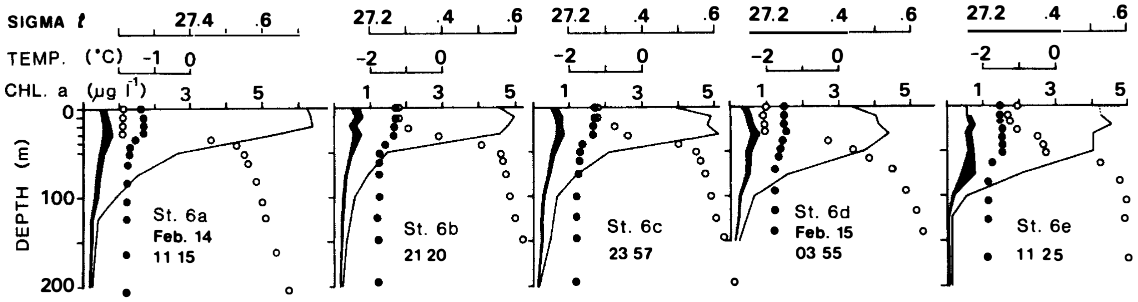

Fig. 4. Vertical profiles of phytoplankton chlorophyll *a* crops at St. 6 in Breid Bay, February. Other explanations are the same as in Fig. 2.

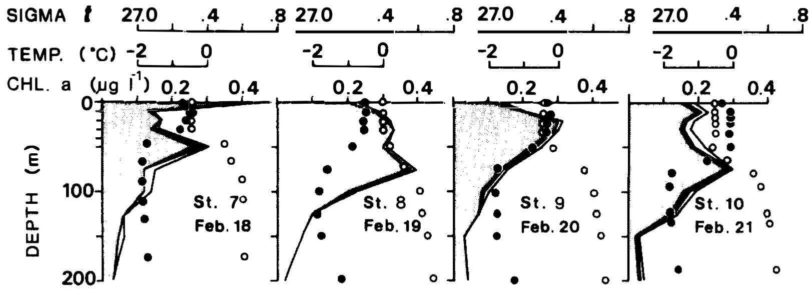

Fig. 5. Vertical profiles of phytoplankton chlorophyll *a* crops at Sts. 7-10 in the Gunnerus Bank area. Station number and date of sampling are indicated in each profile. Other explanations are the same as in Fig. 2.

Total phytoplankton chloropyhyll at the surface was 4.44 $\mu g\ l^{-1}$ (mean of five). It increased with depth, reaching a subsurface maximum around 5.07 $\mu g\ l^{-1}$ at 10-30 m. Net-phytoplankton was the dominant component in the chlorophyll dense upper layer accounting for 86.5% at the surface, 83.8% at the subsurface maximum, and 77.1% at 50 m depth. Dominance of net-phytoplankton was also observed even at 100 m depth (Table 1).

Total phytoplankton chlorophyll *a* standing crops in the upper 200 or 150 m water column were around 330 mg m^{-2} (mean of 5 stations) in the range of 292 to 387 mg m^{-2}.

Gunnerus Bank (Fig. 5)

The Gunnerus Bank area including Sts. 7-10 became ice-free just before the observation (Fig. 1). Vertical profiles of water temperature showed the dichothermal water reaching −1.8°C in the 75-150 m layer. Obvious thermoclines and pycnoclines were found in the 30-100 m layer.

The average concentrations of chlorophyll *a* (*ca.* 0.25 $\mu g\ l^{-1}$ at the surface) were one order of magnitude lower than those in Breid Bay. The subsurface maxima were found in the lower part of the pycnocline, concentrating at 0.32 $\mu g\ l^{-1}$ on average and ranging from 0.26 $\mu g\ l^{-1}$ (St. 7) to 0.39 $\mu g\ l^{-1}$ (St. 8). The nano-phytoplankton fraction was dominant in the water column of each station and the percent contribution was approximately 90%.

Total phytoplankton crops at 4 stations in the upper 200 m water column were in the range of 26 to 40 mg m^{-2}, being lowest among the present study carried out in Antarctic

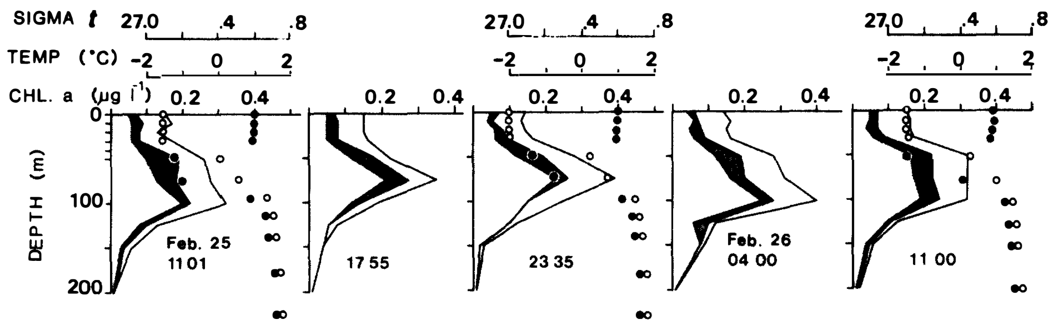

Fig. 6. Vertical profiles of phytoplankton chlorophyll *a* crops at St. 11. Date and time of sampling are shown in each profile. Other explanations are the same as in Fig. 2.

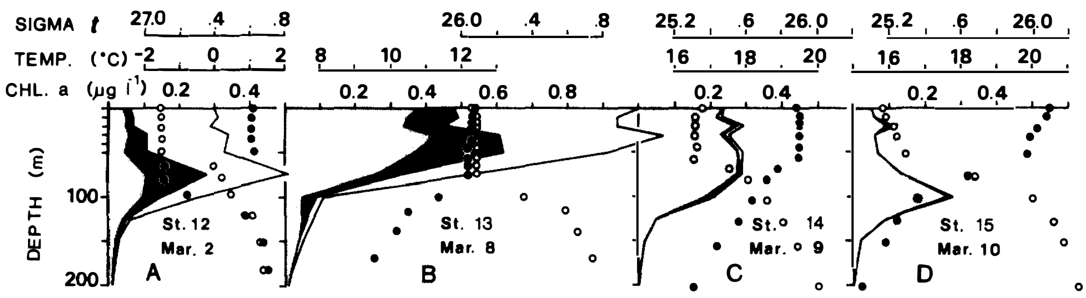

Fig. 7. Vertical profiles of phytoplankton chlorophyll *a* crops at St. 12 in the Antarctic Ocean and at Sts. 13–15 in the subtropical water. Station number and date of sampling are indicated in each profile. Other explanations are the same as in Fig. 2.

stations (Table 1).

Station 11 (Fig. 6)

The third 24 hr observation was carried out between 1101 on 25 February and 1130 on the next day. The sunset time was 2010 and the sunrise time was 0514. Dichothermal water was observed between 50–75 m depth. A clear pycnocline was located in the 30–100 m layer.

Total chlorophyll concentrations at the surface were around 0.15 $\mu g\ l^{-1}$, and those at the subsurface maximum occurring in the 50–100 m layer were around 0.36 $\mu g\ l^{-1}$ (mean of five). The subsurface maxima were always found in the lower part of the pycnocline. Contributions of net-phytoplankton, micro-phytoplankton, and nano-phytoplankton to the total chlorophyll in the upper 30 m layer were approximately 49.7, 15.3, and 35.0%, respectively. Nano-phytoplankton components increased with depth; their percent composition in the water column was 53.4% (Table 1).

From Antarctic to subtropical water (Fig. 7)

At St. 12 in the Antarctic open water (Fig. 7A), the dichothermal water was found in 65–80 m depth. The pycnocline was found in the 50–150 m layer. Total chlorophyll *a* concentration at the surface was 0.30 $\mu g\ l^{-1}$; it increased with depth with some fluctuations to 0.51 $\mu g\ l^{-1}$ at 75 m depth, showing a subsurface maximum. Net-phytoplankton were abundant at the surface accounting for 78.0%; their dominance decreased with depth to 44.2% in the subsurface maximum layer. Below the maximum, the dominant fraction changed from net-phytoplankton to nano-phytoplankton.

At St. 13 in the subtropical convergence zone, the pycnocline was in the 50–130 m layer (Fig. 7B). The chlorophyll *a* concentration in the upper 50 m was 0.97 $\mu g\ l^{-1}$; the concentration rapidly decreased with depth to 0.11 $\mu g\ l^{-1}$ at 100 m depth. Net-phytoplankton and nano-phytoplankton were the dominant fractions in the upper 50 m, accounting for 45.4 and 38.4%, respectively.

At St. 14 in the subtropical water (Fig. 7C), the pycnocline was found in the 60–100 m layer. Phytoplankton chlorophyll was abundant in the upper 100 m depth. Nano-phytoplankton was the dominant fraction in the upper 100 m (94.7%) and in the deeper layers (58.6%).

At St. 15 in the subtropical water (Fig. 7D), the pycnocline was in the layer between 50–100 m depth. Two peaks in phytoplankton concentration were found at 20 m and 100 m depths counting 0.11 and 0.29 $\mu g\ l^{-1}$, respectively. Dominance of nano-phytoplankton fraction was commonly observed in every layer; the percent contributions were 88.2% in the shallower peak and 98.3% in the deeper peak.

In the upper 200 m water column in Antarctic (St. 12) and in subtropical waters (Sts. 13–15), total phytoplankton crops were larger when the net-phytoplankton compositions were higher (Table 1).

Discussion

Many investigations of Antarctic water have indicated that phytoplankton chlorophyll *a* standing crops in the water column are generally lower than 100 mg m^{-2} (EL-SAYED and JITTS, 1973; HOLM-HANSEN *et al*., 1977; EL-SAYED and TAGUCHI, 1981; YAMAGUCHI and SHIBATA, 1982). In previous JARE research, lower phytoplankton crops were often observed in the Indian sector of the Antarctic Ocean (FUKUCHI and TAMURA, 1982; KURODA and FUKUCHI, 1982; WATANABE and NAKAJIMA, 1982; SASAKI, 1984). Only a few occasional observations of high phytoplankton crops (>100 mg m^{-2}) were obtained in the Antarctic (MANDELLI and BURKHOLDER, 1966; HALLEGRAEFF, 1981, HOLM-HANSEN and HUNTLEY, 1984). High nutrient levels in the Antarctic water should be able to support a phytoplankton biomass of 25–40 $\mu g\ l^{-1}$ (HOLM-HANSEN and HUNTLEY, 1984). Among some expected factors limiting the standing crops in the Antarctic Ocean (*cf*. EL-SAYED, 1984), NEORI and HOLM-HANSEN (1982) and YAMAGUCHI *et al*. (1985) suggested that lower ambient water temperature is a major factor causing the low phytoplankton growth rate.

Since JARE-25 in 1983, higher standing crops of chlorophyll *a*, reaching 300 mg m^{-2}, have been found in Breid Bay, Antarctica (HAMADA *et al*., 1985; OHNO *et al*., 1987; FUKUCHI *et al*., 1988). In the present JARE-27 study, higher standing crops were also observed in Breid Bay, while lower standing crops of less than 52 mg m^{-2} were observed in other areas of the Antarctic (Table 1). The summer bloom in Breid Bay seems to occur in every austral summer, and is dominated by net-phytoplankton (>20 μm). HATTORI and MATSUDA (1991) showed that *Thalassiosira antarctica* (equivalent spherical diameter was about 18 μm) was a prominent species in the bay, using a sediment trap set at 120 m depth.

Table 2. Summarized environmental data in each sampling period in the Antarctic Ocean. Temperature (°C), salinity, and of nutrient concentrations (μg-atoms l^{-1}) above the pycnocline are presented.

Area	Breid Bay		Gunnerus Bank	Antarctic water	
Station	1-5	6	7-10	11	12
Sampling date	25-28 Dec.	14-15 Feb.	18-21 Feb.	25-26 Feb.	12 Mar.
Ice-free	Before Nov.	Before Nov.	13-20 Feb.	2-6 Jan.	9-12 Dec.
Length of ice free period	>2 months	>4 months	1 week	2 months	3 months
Temperature (°C)	−0.3∼−1.3	−1.3∼−1.5	−0.3∼−0.7	0.9-1.1	1.1
Salinity (psu)	34.082	33.685	34.061	33.795	33.801
Thermocline (m)	20-40	20-50	30-100	[30-50 75-100	[50-60 80-125
Pycnocline (m)	10-50	30-50	30-100	30-100	50-125
SiO_3-Si	65	55	60	50	40
NO_3-N	20	20	30	30	30

Breid Bay became ice-free in early summer (before December) according to satellite observations. During the long exposure to summer solar radiation, the surface temperature of the bay water increased sufficiently to melt ice due to trapping of heat by the low salinity, therefore low density in the surface water (Table 2 and Figs. 2-4). The high vertical water stability near the surface helps to retain the phytoplankton in the photic layer near the surface and to promote a bloom as has been observed in the Bering Sea (TANIGUCHI, 1969). In Breid Bay, the phytoplankton standing crop at St. 3, without a marked pycnocline, was about one-third that at other stations (Table 1). Although clear pycnoclines were found in areas other than Breid Bay (Figs. 5-7), phytoplankton crops in the upper 200 m were one order of magnitude lower than those obtained in Breid Bay. The dichothermal water contributed to form pycnoclines in a deeper layer at Sts. 11-12 compared to that at Breid Bay (Table 2). Thus, it is apparent that even if high water stability is achieved, maximum phytoplankton crops depending on the depth of the pycnocline. Under nutrient rich conditions, as in the Antarctic Ocean, once the appropriate conditions for growth are achieved, large size phytoplankton bloom is earlier than smaller forms (PARSONS *et al.*, 1977; PARSONS, 1979). This development of large size dominated composition (larger proportion of net-phytoplankton in the total standing crops) should be related to the period of ice-free water. This tendency is clearly seen in Tables 1 and 2 as well as the surface observations of JARE-27 (HATTORI and FUKUCHI, 1989). Thus the combination of duration of the ice-free period and upper layer stability plays an important role in the development of Antarctic phytoplankton blooms, especially for large-sized phytoplankton blooms.

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