Proc. NIPR Symp. Polar Biol., 2, 16–25, 1989

DISTRIBUTION OF NANO-, MICRO- AND NETPLANKTON CHLOROPHYLL IN THE SURFACE WATER OF THE INDIAN SECTOR OF THE SOUTHERN OCEAN, 1985/86

Hiroshi HATTORI[1*] and Mitsuo FUKUCHI[2]

[1]*Laboratory of Oceanography, Faculty of Agriculture, Tohoku University, 1-1, Tsutsumidori-Amamiyamachi, Sendai 980*
[2]*National Institute of Polar Research, 9-10, Kaga 1-chome, Itabashi-ku, Tokyo 173*

Abstract: Size fractionation of phytoplankton stock in the surface water was studied in the Indian sector of the Southern Ocean. Bucket sampling from 0 m and pump sampling from 8 m depth were conducted for the surface water. A total of 75 pairs of samples were collected along the course of the icebreaker SHIRASE during the cruise of the 27th Japanese Antarctic Research Expedition (JARE-27) from December 1985 to March 1986 for observing geographical distribution of phytoplankton stock and for evaluating the effectiveness of the pump system. Chlorophyll *a* concentration in the surface water was high at the southern margin of the Subantarctic water (52–55°S) reaching more than 1.32 $\mu g\ l^{-1}$ (December) and more than 0.59 $\mu g\ l^{-1}$ (February to March). Chlorophyll *a* concentration in the Indian sector of the Antarctic water varied geographically; high in the eastern offing of Enderby Land and low in the western offing. The standing stock of nanoplankton (<5 μm) and microplankton (5–20 μm) was constant at 0.12±0.09 and 0.03±0.03 $\mu g\ l^{-1}$, respectively. Netplankton fraction (>20 μm) was higher than smaller fractions (0.18±0.28 $\mu g\ l^{-1}$). Regional variations of the total phytoplankton chlorophyll stock are mainly associated with variations in netplankton fraction stock. No significant difference of chlorophyll *a* concentration between the bucket-sampled water and the pumped-up water was detected by statistical analysis. This reveals that the pumped-up water is sufficient for chlorophyll analysis in the routine works of marine biological program of JARE.

1. Introduction

To know the distribution of phytoplankton chlorophyll stock in the Southern Ocean is important for evaluating the primay production (KURODA and FUKUCHI, 1982) as well as for estimating the food quantity for zooplankton, particularly for the Antarctic krill (HOLM-HANSEN and HUNTLEY, 1984). Numerous investigations of spatial distributions of phytoplankton in the Southern Ocean have been carried out (*cf.*, FUKUCHI, 1982; EL-SAYED, 1984). Most of them, however, observed the phytoplankton chlorophyll stocks as a whole. A size composition of phytoplankton is known to be

* Present address: Department of Marine Sciences and Technology, School of Engineering, Hokkaido Tokai University, Minami-ku, Sapporo 005.

important for understanding the specific response of the fractionated components to the environmental conditions (MALONE, 1971, 1980).

Since the 7th Japanese Antarctic Research Expedition (JARE-7, 1965/66), surface distributions of phytoplankton chlorophyll in the surface water have been routinely observed using a bucket sampler (*cf.*, FUKUCHI, 1980). A continuous sampling of the surface water with a pump from 8 m depth was first conducted on board the icebreaker SHIRASE since JARE-25 (1983/84) (HAMADA *et al.*, 1985), and the method was improved by JARE-27 (1985/86) (FUKUCHI and HATTORI, 1987). In addition to the bucket sampling, the surface water for chlorophyll analysis could be obtained at the laboratory on the deck with a pump system. However, there has been no study on the difference of chlorophyll concentrations between the bucket-sampled water and the pumped-up water.

In this study, we present information on horizontal distribution of phytoplankton chlorophyll in the surface water of the Southern Ocean with a bucket sampling and a pump sampling system. Three size fractions (>20, 20–5 and <5 μm) of phytoplankton were determined with reference to the regional and temporal chlorophyll variations. Statistical difference of chlorophyll *a* concentration between the bucket water and the pump water was discussed on each size fractionation as well as on the total stock.

2. Materials and Methods

Water samples were collected three times a day (0800, 1300, 1900 by local time) along the course of the icebreaker SHIRASE. Water samplings were carried out from Fremantle, Australia (Stn. 1; Dec. 3, 1985) to Antarctica (Stn. 41; Dec. 19, 1985) and from the Gunnerus Bank, Antarctica (Stn. 42; Feb. 18, 1986) to Port Louis, Mauritius (Stn. 75; Mar. 13, 1986). The surface water was sampled with a bucket from 0 m and with a pump system from 8 m depth at the same time. A total of 75 stations were dealt with throughout the present work. To determine the size composition of phytoplankton chlorophyll *a*, 2 to 3 liters of water was filtered through a 20 μm and a 5 μm nylon meshes successively, and the filtrate was filtered through a Whatman GF/C filter after adding 1 m*l* of 1% $MgCO_3$. Pigments on the both meshes and on the filter were extracted with 90% acetone. Chlorophyll *a* and pheopigment concentrations were determined fluorometrically (STRICKLAND and PARSONS, 1968) with a Shimadzu RF-501 spectrofluorometer.

In this study, size fractionations of phytoplankton sieved by the 20 μm mesh, 5 μm mesh and the GF/C filter were tentatively referred to net-, micro- and nanoplankton, respectively. The sum of three fractions is regarded as the total chlorophyll *a* standing stock. The values of chlorophyll *a* and water temperature at the sampling sites of JARE-27 are reported in HATTORI and FUKUCHI (1988).

3. Results

Latitudinal and longitudinal variations of the size fractionated phytoplankton chlorophyll *a* concentrations in the surface water in December and February–March are shown in Figs. 1 and 2, respectively. The Indian sector of the Southern Ocean is

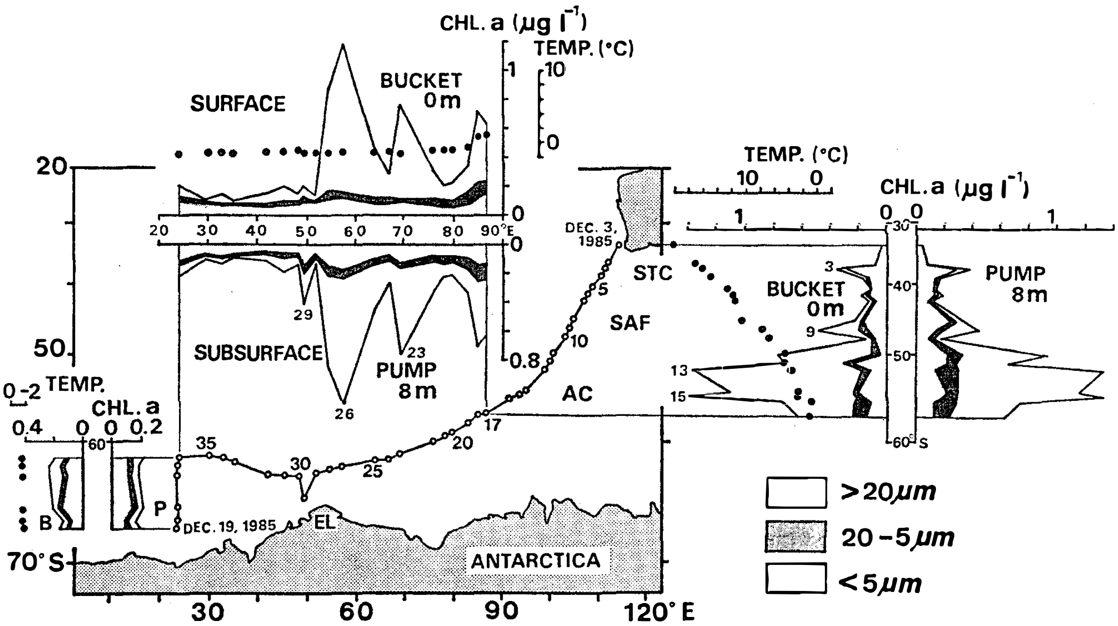

Fig. 1. Latitudinal and longitudinal distributions of chlorophyll a stock of net (>20μm)-, micro (20–5 μm)- and nanoplankton (<5 μm) in the surface water (by bucket, 0 m and by pump, 8 m) along the course of the SHIRASE in December, 1985. Surface temperature is denoted by filled circle. Locations of the Subtropical Convergence (STC), Subantarctic Front (SAF) and Antarctic Convergence (AC) are shown by the shaded areas. Numbers are serial station numbers. B and P mean the data obtained by the bucket sampling (0 m) and the pump system, respectively. EL means Enderby Land.

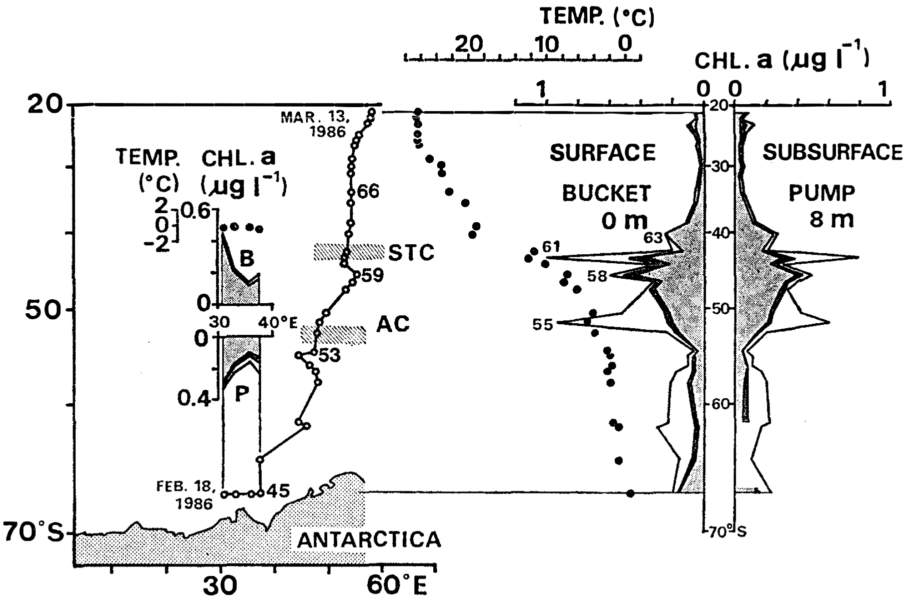

Fig. 2. Latitudinal and longitudinal distributions of chlorophyll a stock obtained in February to March, 1986. Explanations are as in Fig. 1.

separated from the Subtropical water by the Subtropical Convergence (STC) and is divided into two water masses, the Subantarctic water and the Antarctic water, by a distinct oceanic front of the Antarctic Convergence (AC, same as the Polar Front). Approximate locations of the Subtropical Convergence (STC), the Subantarctic Front (SAF) and the Antarctic Convergence (AC) in December were 38°S, 46°S and 55°S, respectively. In February–March, locations of the STC and the AC were 41–44°S and 52–53°S, respectively, but that of the SAF was not detected.

3.1. Fremantle to Breid Bay, Antarctica (December 1985; Stns. 1–41)

During the southward cruise (Stns. 1–15), a sharp decrease of the surface water temperature from 10.6 (Stn. 8) to 7.4°C (Stn. 9) was observed at the SAF. In the northern part of the Antarctic water (Stns. 16–18), water temperature was low around 0.8°C. From the northern edge of pack ice zone (Stn. 19), water temperature decreased below zero ranging from −0.5 to −1.9°C.

Total chlorophyll *a* concentrations south of Australia (Stns. 1 and 2) were as low as 0.1 $\mu g\,l^{-1}$ in the surface layers, and increased to about 0.40 $\mu g\,l^{-1}$ in the north of the STC (Stn. 3). After crossing the STC, chlorophyll concentrations decreased to less than 0.20 $\mu g\,l^{-1}$. Low concentrations ($<0.2\,\mu g\,l^{-1}$) were continuously observed toward the north of the SAF (Stn. 8). A marked increase occurred at Stn. 12 (1.36 $\mu g\,l^{-1}$). The maximum concentrations reaching 1.38 $\mu g\,l^{-1}$ were observed in the north of the AC (Stn. 15). Thus, high chlorophyll *a* concentration was observed in the southern part of the Subantarctic water. In the eastern offing of Enderby Land of the Indian sector of the Antarctic water (Stns. 16–27), chlorophyll *a* concentration varied regionally with two conspicuous peaks around 70°E (Stn. 23) and 57°E (Stn. 26). In the sea area off Enderby Land (Stn. 28) to the north of Breid Bay (Stn. 41), chlorophyll *a* concentrations were low (0.20 $\mu g\,l^{-1}$) except at Stn. 29 where the SHIRASE broke into the pack-ice sea.

In the contribution of different size group fractions to the total chlorophyll *a* concentration, netplankton ($>20\,\mu m$) was the most important fraction making some marked peaks in the water masses. Contributions of netplankton at five peaks in the Southern Ocean are as follows; 61% at Stn. 9, 82% at Stn. 13, 81% at Stn. 15, 82% at Stn. 23 and 84% at Stn. 26. The mean concentrations of size fractionated chlorophyll *a* and their percent compositions in the water masses are summarized in Table 1.

3.2. Antarctica to Port Louis (February to March 1986; Stns. 42–75)

The northern edge of the pack-ice area receded southerly from December (around 60°S, 30°E) to February–March (around 68°S, 30°E). Along the pack-ice edges at the Gunnerus Bank (Stns. 42–45), the mean surface water temperature was −0.3°C. Water temperature increased to 1.0°C when the SHIRASE turned to north in the ice-free area (Stn. 46). After crossing the AC, temperature increased to 4.8°C (Stn. 55). A marked increase of temperature was observed in the southern part of the Subtropical water (Stn. 63, 19.4°C) from the northern margin of the STC zone (Stn. 62; 11.7°C).

Chlorophyll *a* concentrations in the Antarctic water (Stns. 42–54) were as low as 0.20 $\mu g\,l^{-1}$ except for Stn. 42. It decreased toward the AC and subsequently decreased to 0.06 $\mu g\,l^{-1}$ at the northernmost station of the Antarctic water (Stn. 53). In the Subantarctic water, three peaks of chlorophyll *a* concentration were observed at Stns. 55, 58 and 61. One of the peaks (Stn. 55) was located in the southern marginal area of the Subantarctic water. A similar location of this peak was observed in December. After crossing the STC, chlorophyll concentrations decreased rapidly to 0.26 $\mu g\ l^{-1}$ at Stn. 63. Chlorophyll *a* concentrations in the Subtropical water were constantly as low as 0.10 $\mu g\ l^{-1}$.

In the Gunnerus Bank area (Stns. 42–45), nanoplankton largely contributed to total phytoplankton stocks ranging 57–92%. In the Antarctic open water (Stns. 46–50), however, netplankton components increased to 50–74%. In the Subantarctic water, netplankton fractions predominantly contributed to make two peaks of phytoplankton stocks (Stns. 55 and 61), accounting for more than 50%. At one peak at Stn. 58, however, contribution of netplankton was around 10%. This peak was formed by nanoplankton which accounted for 80% of the total stock. In the Subtropical water (Stns. 63–75), nanoplankton were the most important components, ranging 32–98%. The

Table 1. Mean chlorophyll a concentration and percent composition (in parentheses) of net (>20 μm)-, micro (20–5 μm)-, nanoplankton (<5 μm) and total stock with mean temperature and nutrient salts concentration in the respective water masses obtained in December (above) and February to March (below). STC, SAF, AC and EL mean Subtropical Convergence, Subantarctic Front, Antarctic Convergence and off Enderby Land, respectively. + means <0.01 μg chl a l^{-1}.

Water mass		Subtropical water	Subantarctic water		Antarctic water	
			STC	SAF	AC	EL
Station No.		1–3	4–8	9–15	16–27	28–41
Date		3–4 Dec.	4–6 Dec.	6–8 Dec.	8–12 Dec.	12–19 Dec.
Temp. (°C)		17.7	12.1	4.5	−0.7	−1.5
SiO_3 (μg-at Si l^{-1})		3.0	3.8	10.0	44.9	55.1
NO_3 (μg-at N l^{-1})		0.0	8.0	22.9	27.0	26.7
Bucket	net	0.02 (11.8)	0.02 (14.5)	0.66 (77.6)	0.40 (71.4)	0.06 (35.3)
(0 m)	micro	0.01 (5.9)	0.01 (7.2)	0.05 (5.9)	0.06 (10.7)	0.02 (11.8)
	nano	0.14 (82.3)	0.13 (78.3)	0.14 (16.5)	0.10 (17.9)	0.09 (52.9)
	Total	0.17	0.17	0.85	0.56	0.17
Pump	net	0.03 (17.6)	0.03 (15.8)	0.59 (69.6)	0.37 (67.3)	0.06 (35.3)
(8 m)	micro	0.01 (5.9)	0.02 (10.5)	0.08 (9.7)	0.07 (12.7)	0.02 (11.8)
	nano	0.13 (76.5)	0.14 (73.7)	0.18 (20.7)	0.11 (20.0)	0.09 (52.8)
	Total	0.17	0.19	0.85	0.55	0.17
Station No.		63–75	54–62		42–53	
Date		9–13 Mar.	6–8 Mar.		18 Feb.–5 Mar.	
Temp. (°C)		24.0	8.2		0.9	
SiO_3 (μg-at Si l^{-1})		1.7	4.3		43.4	
NO_3 (μg-at N l^{-1})		0.0	19.1		26.3	
Bucket	net	0.01 (14.3)	0.20 (40.0)		0.06 (30.0)	
(0 m)	micro	+ (7.0)	0.04 (8.0)		0.01 (5.0)	
	nano	0.06 (79.7)	0.26 (52.0)		0.13 (65.0)	
	Total	0.07	0.50		0.20	
Pump	net	0.01 (12.5)	0.13 (31.7)		0.06 (30.0)	
(8 m)	micro	0.01 (12.5)	0.02 (4.9)		0.02 (10.0)	
	nano	0.06 (75.0)	0.26 (63.4)		0.12 (60.0)	
	Total	0.08	0.41		0.2	

chlorophyll stocks and their size compositions in February–March are summarized in Table 1.

4. Discussion

FUKUCHI (1980) summarized the phytoplankton chlorophyll stocks obtained during the period from JARE-7 (1965/66) to JARE-18 (1976/77) and showed average figures of those in the Southern Ocean in December and February–March as 0.38 and 0.23 $\mu g\, l^{-1}$, respectively. In the present study, the mean chlorophyll *a* concentrations over the entire stations in the Southern Ocean in December and February–March were 0.41 and 0.31 $\mu g\, l^{-1}$, respectively. These values were higher than the average values of FUKUCHI (1980).

In the frontal zones, ranges of the total phytoplankton stock against the water temperature observed in the present study were included in the ranges of the previous JARE works (Fig. 3).

In December (Fig. 3-A), negative or positive correlations between chlorophyll stock and temperature were observed in each cruise at every frontal zone. However, a negative trend increasing chlorophyll stock with decreasing temperature, appeared as a whole. In the AC zone, this relationship was reverse around 3°C, resulting that the higher chlorophyll concentrations were observed at 3°C, even though nutrients concentrations were rich in the area (Table 1). NEORI and HOLM-HANSEN (1982) and YAMAGUCHI *et al.* (1985) showed experimental results that photosynthetic rates of Antarctic phytoplankton increased with temperature rise from ambient up to 7–10°C and decreased rapidly above this temperature. According to these results, however, there were no precise environmental information other than water temperature; temperature

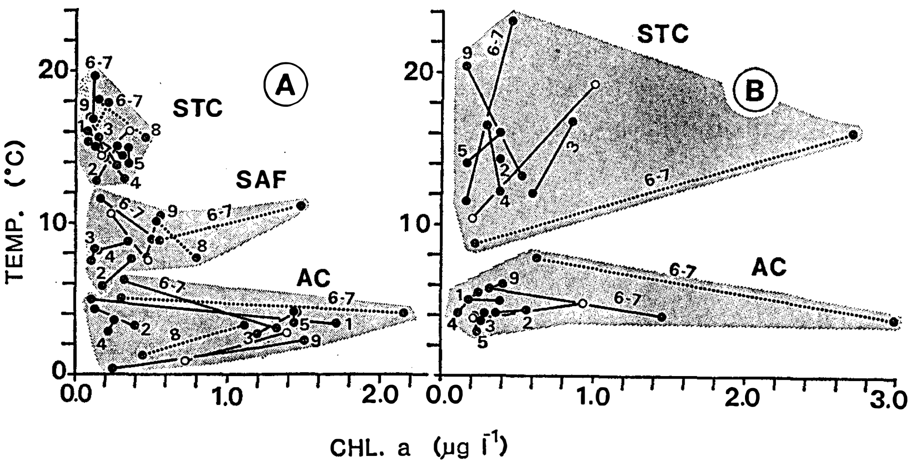

Fig. 3. Relationships between chlorophyll a concentration and temperature observed across the Subtropical Convergence (STC), Subantarctic Front (SAF) and Antarctic Convergence (AC). A and B are the data obtained in December and in February–March, respectively. Open circle shows the present study. Filled circles represent former works of JARE, 1; FUKUCHI (1980), 2; TANIMURA (1981), 3; FUKUCHI and TAMURA (1982), 4; WATANABE and NAKAJIMA (1983), 5; SASAKI (1984), 6; HAMADA et al. (1985), 7; TANIGUCHI et al. (1986), 8; FUKUCHI et al. (1986), 9; FUKUDA et al. (1986). Range connected by dotted line mean the Turner measurements.

below 3°C may be considered to limit the growth of the Antarctic oceanic phytoplankton and 3°C seems to be the highest temperature for the Antarctic water.

In February to March (Fig. 3-B), the reversed relationship at 3°C did not occur in the AC zone. Range of chlorophyll stocks was twice at the STC and a half at the AC in comparison with those observed in December except for the pump data of the JARE-25 (Nos. 6–7). This difference may reflect the seasonal and/or geographical change of phytoplankton stock and species composition, because, particularly in the Antarctic water, similar nutrients concentration level and water temperature were observed in February to March compared to those observed in December (Table 1).

Size fractionation of Antarctic phytoplankton has been carried out in the Scotia Sea (BROCKEL, 1981), the Weddell Sea (EL-SAYED and TAGUCHI, 1981; BROCKEL, 1985), the Ross Sea (NELSON and SMITH, 1986; WILSON *et al.*, 1986) and the Australasian Southern Ocean (YAMAGUCHI and SHIBATA, 1982; KOSAKI *et al.*, 1985; HOSAKA and NEMOTO, 1986). WEBER and EL-SAYED (1987) observed a wide area of the Antarctic Ocean from Elephant Island to Enderby Land *via* south of Africa. In the JARE works, SASAKI (1984) and HAMADA *et al.* (1985) measured size-fractionated chlorophyll *a* distributions along the courses of the FUJI and the SHIRASE, respectively. Most studies showed that smaller cells (less than 10 μm) largely contributed to the total phytoplankton stocks or primary productions, but SASAKI (1984) demonstrated that the mean contributions of microplankton (larger than 10 μm) in the Subantarctic and the Antarctic waters in December were 64.8 and 68.9%, respectively. In the present study, netplankton (larger than 20 μm) account for 67.3–77.6% of the total phytoplankton stocks in the same water masses in December (Table 1; Stns. 9–27). Besides, the standing stocks of nanoplankton (smaller than 5 μm) and microplankton (5–20 μm) in December were relatively constant at low levels in all the water masses (Table 1). If SASAKI (1984) used one more larger size of mesh opening such as 20 μm for the size fractionation, the result would be similar to the present study. These suggest that the regional variation of total phytoplankton chlorophyll stock approximately reflects the change of netplankton stock. In February–March, however, there was not any clear relation between the netplankton contribution and the total phytoplankton stock.

In the Antarctic Ocean, the total phytoplankton stocks and contributions of microplankton in December were higher than those in February–March even though nutrient concentrations were similarly high (Table 1). FUKUCHI (1980) explained that the difference of phytoplankton stocks between December and February–March was attributed to the seasonal periodicity. Besides, at the high nutrient levels, a growth rate of large phytoplankton is faster than that of small one in optimum ambient condition as described by PARSONS *et al.* (1977). The present study shows that this seasonal periodicity may be represented by the increase of netplankton contribution to the total phytoplankton stock in December.

Significant (95% confidence limit) regression lines and correlation coefficients of the surface chlorophyll *a* concentrations were obtained between the bucket samples and the pump samples (Table 2). There was no significant statistical difference (Analysis of Variance for one-way layout) between the bucket and the pump chlorophyll stocks of each size fraction as well as the total stocks. This may be owing to the mixing that the surface water undergoes along the ship's hull to the intake of the pump system. The statistical result suggests that the pump system is sufficient for the water sampling to observe geographical changes of phytoplankton stock. The bucket sampling seems to be needless to the routine works of the biological program of the JARE. For the temperature measurement of the surface water, however, temperature of the pump water was statistically higher than that of the bucket water (Fig. 4). This comes from the heating effect as the pump water moves through the piping within the ship.

Table 2. Range and mean chlorophyll a concentration ($\mu g\ l^{-1}$) of net (>20 μm)-, micro (20–5 μm)-, nanoplankton (<5 μm) and total concentration in the surface layers (bucket, 0 m and pump, 8 m) obtained in December and Februaly to March. SD, Cb and Cp mean the standard deviation of mean chlorophyll concentration, the bucket chlorophyll a concentration and the pump chlorophyll concentration, respectively.

Size	Bucket, 0 m		Pump, 8 m		Regression bucket on pump	
	Range	Mean (SD)	Range	Mean (SD)		
Fremantle–Breid Bay (December)						
Net	0.00–1.18	0.25 (0.33)	0.00–1.03	0.23 (0.29)	Cb= 0.002+1.112*Cp	r=0.975
Micro	0.00–0.11	0.04 (0.03)	0.00–0.16	0.04 (0.04)	Cb= 0.009+0.613*Cp	r=0.852
Nano	0.04–0.29	0.11 (0.05)	0.04–0.28	0.12 (0.06)	Cb= 0.025+0.694*Cp	r=0.789
Total	0.04–1.38	0.40 (0.36)	0.04–1.32	0.40 (0.36)	Cb= 0.003+0.999*Cp	r=0.974
Antarctica–Port Louis (February–March)						
Net	0.00–0.72	0.08 (0.15)	0.00–0.39	0.06 (0.09)	Cb=−0.016+1.614*Cp	r=0.964
Micro	0.00–0.10	0.02 (0.02)	0.00–0.10	0.02 (0.02)	Cb=−0.002+0.999*Cp	r=0.885
Nano	0.01–0.45	0.13 (0.12)	0.03–0.40	0.13 (0.10)	Cb=−0.012+1.138*Cp	r=0.970
Total	0.02–1.00	0.23 (0.23)	0.04–0.79	0.20 (0.17)	Cb=−0.038+1.319*Cp	r=0.970
All courses						
Net	0.00–1.18	0.18 (0.28)	0.00–1.03	0.15 (0.24)	Cb= 0.003+1.137*Cp	r=0.970
Micro	0.00–0.11	0.03 (0.03)	0.00–0.16	0.03 (0.03)	Cb= 0.005+0.688*Cp	r=0.868
Nano	0.01–0.45	0.12 (0.09)	0.03–0.40	0.13 (0.08)	Cb=−0.007+1.022*Cp	r=0.920
Total	0.02–1.38	0.32 (0.32)	0.04–1.32	0.31 (0.30)	Cb=−0.000+1.030*Cp	r=0.968

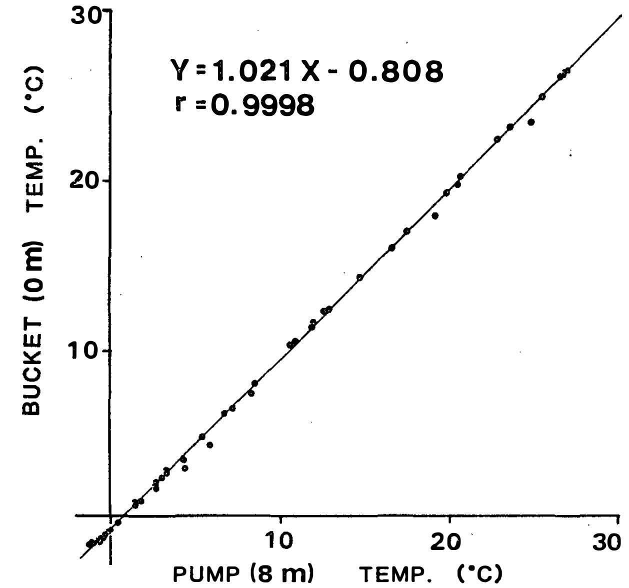

Fig. 4. Relationships between the water temperature observed by the bucket, 0 m and the pump system, 8 m from Fremantle to Port Louis via Antarctica. A total of 75 pairs of the surface water temperature are used in the calculation.

Acknowledgments

We thank Mr. Y. IWANAGA and Mr. H. TOHJU of the Hydrographic Department of Japan Maritime Safety Agency for their collaboration in deck works. We also wish to thank Prof. Y. YOSHIDA, leader of the JARE-27, of National Institute of Polar Research for his kind support given to us on board. The cooperation and assistance of the crew and officers of the icebreaker SHIRASE during the JARE-27 cruise are appreciated.

References

BROCKEL, K. von (1981): The importance of nanoplankton within the pelagic Antarctic ecosystem. Kieler Meeresforsch. Sonderh., **5**, 61–67.

BROCKEL, K. von (1985): Primary production data from the southeastern Weddell Sea. Polar Biol., **4**, 75–80.

EL-SAYED, S. Z. (1984): Productivity of the Antarctic waters—A reappraisal. Marine Phytoplankton and Productivity, ed. by O. HOLM-HANSEN *et al.* Berlin, Springer, 19–34.

EL-SAYED, S. Z. and TAGUCHI, S. (1981): Primary production and standing crop of phytoplankton along the ice-edge in the Weddell Sea. Deep-Sea Res., **28**, 1017–1032.

FUKUCHI, M. (1980): Photoplankton chlorophyll stocks in the Antarctic Ocean. J. Oceanogr. Soc. Jpn., **36**, 73–84.

FUKUCHI, M. (1982): Ichiji seisan (Primary production). Nankyoku no Kagaku, 7. Seibutsu (Science in Antarctica, 7. Biology), ed. by Natl Inst. Polar Res. Tokyo, Kokon Shoin, 11–32.

FUKUCHI, M. and TAMURA, S. (1982): Chlorophyll *a* distribution in the Indian sector of the Antarctic Ocean in 1978–1979. Nankyoku Shiryô (Antarct. Rec.), **74**, 143–162.

FUKUCHI, M. and HATTORI, H. (1987): Surface water monitoring system installed on board the icebreaker SHIRASE. Proc. NIPR Symp. Polar Biol., **1**, 47–55.

FUKUCHI, M., FUKUDA, Y., OHNO, M. and HATTORI, H. (1986): Surface phytoplankton chlorophyll distribution continuously observed in the JARE-26 cruise (1984/85) to Syowa Station, Antarctica (SIBEX II). Mem. Natl Inst. Polar Res., Spec. Issue, **44**, 15–23.

FUKUDA, Y., OHNO, M., IWANAMI, K. and TOHJU, H. (1986): Chlorophyll *a* content in the surface and subsurface waters along the course of the SHIRASE to Antarctica in 1984–1985. Nankyoku Shiryô (Antarct. Rec.), **30**, 103–109.

HAMADA, E., TANIGUCHI, A., OKAZAKI, M. and NAITO, Y. (1985): Report on the phytoplankton pigments measured during the JARE-25 cruise to Syowa Station, Antarctica, November 1983 to April 1984. JARE Data Rep., **103** (Mar. Biol. 7), 89 p.

HATTORI, H. and FUKUCHI, M. (1988): Report on the phytoplankton pigment concentrations, zooplankton and benthos sampling during the JARE-27 cruise, November 1985–April 1986. JARE Data Rep., **135** (Mar. Biol. 11), 28 p.

HOLM-HANSEN, O. and HUNTLEY, M. (1984): Feeding requirements of krill in relation to food sources. J. Crust. Biol., **4** (Spec. No. 1), 156–173.

HOSAKA, N. and NEMOTO, T. (1986): Size structure of phytoplankton carbon and primary production in the Southern Ocean south of Australia during the summer of 1983–84. Mem. Natl Inst. Polar Res., Spec. Issue, **40**, 15–24.

KOSAKI, S., TAKAHASHI, M., YAMAGUCHI, Y. and ARUGA, Y. (1985): Size characteristics of chlorophyll particles in the Southern Ocean. Trans. Tokyo Univ. Fish., **6**, 85–97.

KURODA, K. and FUKUCHI, M. (1982): Vertical distribution of chlorophyll *a* in the Indian Sector of the Antarctic Ocean in 1972–1973. Nankyoku Shiryô (Antarct. Rec.), **74**, 127–142.

MALONE, T. C. (1971): The relative importance of nannoplankton and netplankton as primary producers in tropical oceanic and neritic phytoplankton communities. Limnol. Oceanogr., **16**, 633–639.

MALONE, T. C. (1980): Algal size. Studies in Ecology VII, The Physiological Ecology of Phytoplankton, ed. by I. MORRIS. Oxford, Blackwell, 433–463.

NELSON, D.M. and SMITH, W. O., Jr. (1986): Phytoplankton bloom dynamics of the western Ross Sea ice edge-II. Mesoscale cycling of nitrogen and silicon. Deep-Sea Res., **33**, 1389–1412.
NEORI, A. and HOLM-HANSEN, O. (1982): Effect of temperature on rate of photosynthesis in Antarctic phytoplankton. Polar Biol., **1**, 33–38.
PARSONS, T. R., HARRISON, P. J. and WATERS, R. (1977): An experimental simulation of changes in diatom and flagellate blooms. J. Exp. Mar. Biol. Ecol., **32**, 285–294.
SASAKI, H. (1984): Distribution of nano- and microplankton in the Indian sector of the Southern Ocean. Mem. Natl Inst. Polar Res., Spec. Issue, **32**, 38–50.
STRICKLAND, J. D. H. and PARSONS, T. R. (1968): A practical handbook of seawater analysis. Bull. Fish. Res. Bd. Can., **167**, 311 p.
TANIGUCHI, A., HAMADA, E., OKAZAKI, M. and NAITO, Y. (1986): Distribution of phytoplankton chlorophyll continuously recorded on the JARE 25th cruise to Syowa Station, Antarctica (SIBEX I). Mem. Natl Inst. Polar Res., Spec. Issue, **44**, 3–14.
TANIMURA, A. (1981): Distribution of the surface chlorophyll *a* along the course of the FUJI to and from Antarctica in 1979–1980. Nankyoku Shiryô (Antarct. Rec.), **72**, 35–48.
WATANABE, K. and NAKAJIMA, Y. (1983): Surface distribution of chlorophyll *a* along the course of the FUJI (1980/81) in the Southern Ocean. Nankyoku Shiryô (Antarct. Rec.), **77**, 33–43.
WEBER, L. H. and EL-SAYED, S. Z. (1987): Contributions of the net, nano- and picoplankton to the phytoplankton standing crop and primary productivity in the Southern Ocean. J. Plankton Res., **9**, 973–994.
WILSON, D. L., SMITH, W. O., Jr. and NELSON, D. M. (1986): Phytoplankton bloom of the western Ross Sea ice edge-I. Primary productivity and species-specific production. Deep-Sea Res., **33**, 1375–1387.
YAMAGUCHI, Y. and SHIBATA, Y. (1982): Standing stock and distribution of phytoplankton chlorophyll in the Southern Ocean south of Australia. Trans. Tokyo Univ. Fish., **5**, 111–128.
YAMAGUCHI, Y., KOSAKI, S. and ARUGA, Y. (1985): Primary productivity in the Antarctic Ocean during the austral summer of 1983/84. Trans. Tokyo Univ. Fish., **6**, 67–84.

(*Received May 31, 1988*; *Revised manuscript received November 24, 1988*)