THE RELATION BETWEEN PHYTOPLANKTON STANDING STOCK AND WATER TEMPERATURE IN THE ANTARCTIC OCEAN IN SUMMER, 1980–1981

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Abstract: The vertical distribution of chlorophyll *a* in the Antarctic Ocean was observed by R.V. KAIYO MARU during the FIBEX cruise from December 1980 to January 1981. Two different distribution patterns of chlorophyll *a* were found during this period. In December the chlorophyll *a* maximum at most of stations was found in the upper layer above 50 m in Area B, and it coincided with the pycnocline. While in January, the maximum was found in a deeper layer below 75 m in Area A, and it did not coincide with the pycnocline where the particulate matter was concentrated.

It was presumed that the deep chlorophyll *a* maximum in January was not caused by physical accumulation of suspended matter or by factors internal to phytoplankton cells, but depended on the structure of water temperature. The locations of the chlorophyll *a* maximum layers showed good agreement with water temperature within the range of −1.4°C to −0.3°C in both December and January. In December, the water temperatures from the surface to 50 m were within this range. On the other hand, in January the water temperature in the upper layers rose to above 0°C, and phytoplankton biomass would be limited in these layers, whereas maximal biomass occurred in the deeper layers between 50 m and 125 m depth.

The relation between chlorophyll *a* and water temperature was re-examined using the results from icebreaker FUJI and R.V. KAIYO MARU, which showed trends similar to those of the present study.

1. Introduction

The vertical distribution of phytoplankton standing stock in the Antarctic Ocean has been shown throughout various cruises of ELTANIN (EL-SAYED, 1970; EL-SAYED and JITTS, 1973). During ELTANIN cruise 27, EL-SAYED (1970) showed that chlorophyll *a* concentration at several stations is higher at depth, below the euphotic zone. Sometimes the maximum layer reached down to 100 m depth.

A deep chlorophyll *a* maximum has been occasionally found in the oceans. ANDERSON (1969) found the chlorophyll *a* maximum at 60 m off the Oregon coast. According to him it was influenced by the distribution of nutrients, especially by nitrate nitrogen. The chlorophyll *a* maximum has been observed in many different layers, and has often been associated with the pycnocline in the Antarctic Ocean, Gulf of Mexico (HOBSON and LORENZEN, 1972) and the Oyashio Current (TANIGUCHI, 1972). NISHI-

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ZAWA *et al.* (1971) also observed the chlorophyll *a* maximum at 50–100 m depth in the long section from 20°S to 20°N in the Pacific Ocean. Our data (unpublished) in the southern area of Japan (5°–25°N, 142°E) indicate that the chlorophyll *a* maximum appeared at 100 m and coincided with the pycnocline, where the nitrate concentration started to increase.

UNO (1982) recognized two typical patterns of vertical distribution of chlorophyll *a* in the Indian Sector of the Antarctic Ocean. The one was the chlorophyll *a* maximum occurring in the upper layers above 50 m in the eastern half of the sector in December. The other was the maximum in lower layers below 75 m in the western half of the sector in January. It is very interesting that the chlorophyll *a* maximum was not found in upper layers in such a eutrophic region of the Antarctic Ocean.

In the present paper, these different patterns of chlorophyll *a* distribution in the Antarctic Ocean are discussed from several environmental and physiological viewpoints.

2. Methods

The survey of the Antarctic Ocean was done by the R.V. KAIYO MARU in the periods of December 11–25, 1980 (Area B) and of January 16–30, 1981 (Area A). The survey area discussed in this paper is shown in Fig. 1.

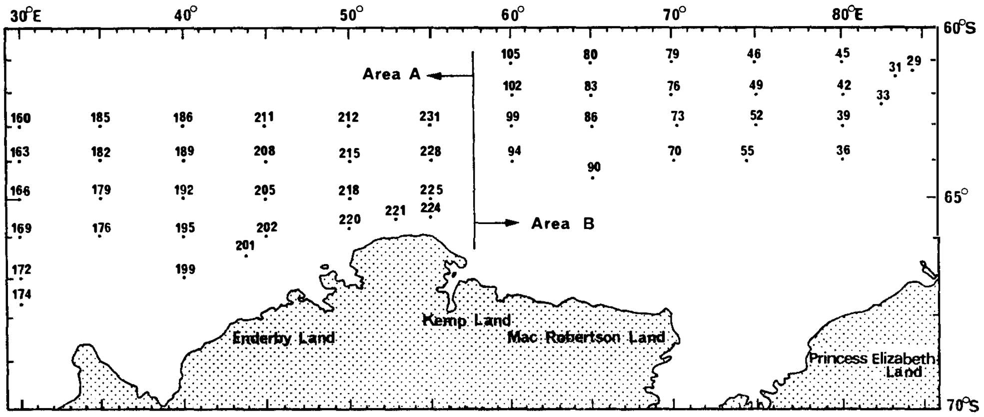

Fig. 1. Positions of sampling stations occupied by R.V. KAIYO MARU during the FIBEX cruise (redrawn from UNO, 1982).

Water samples were taken with 2 *l* Nansen samplers except surface layer samples which were taken by bucket sampler. First, 400–600 m*l* of water was used to determine salinity and dissolved oxygen, and to measure the size and the number of particles. Then the remaining water was passed through Whatman GF/C glass fiber filter (47 mm diameter) to collect phytoplankton. The filtrate was used for analyses of nutrient salts.

Chlorophyll *a* and phaeopigments were extracted in 90% acetone and determined fluorometrically following the method of YENTSCH and MENZEL (1963). The measurement of particle size and number, which was converted to particle volume in ppm, was done on the size range from 4 to 100 μm using a Coulter Counter®. To improve its accuracy, the total count of particle numbers on each sample was checked in advance once or twice. Volumes were used only when the difference in total counts between the trials did not exceed 5%.

3. Results

Vertical distribution of chlorophyll *a*, σ_t, and water temperature at each station in Area B (the eastern part, 61°–64°S, 60°–85°E) are shown in Fig. 2. Almost all the stations had two chlorophyll *a* maximum layers. One was a surface layer and the other was a layer between 20 and 50 m depth in the greater part of stations. The mean value of chlorophyll *a* concentration at the surface was 0.35 $\mu g/l$ in Area B. At most of stations in this area, σ_t was stable in the upper layers, and its values began to increase between 30 and 50 m. The second maximum layer of chlorophyll *a* occurred at this pycnocline except for a few stations where the maximum layer was not obvious.

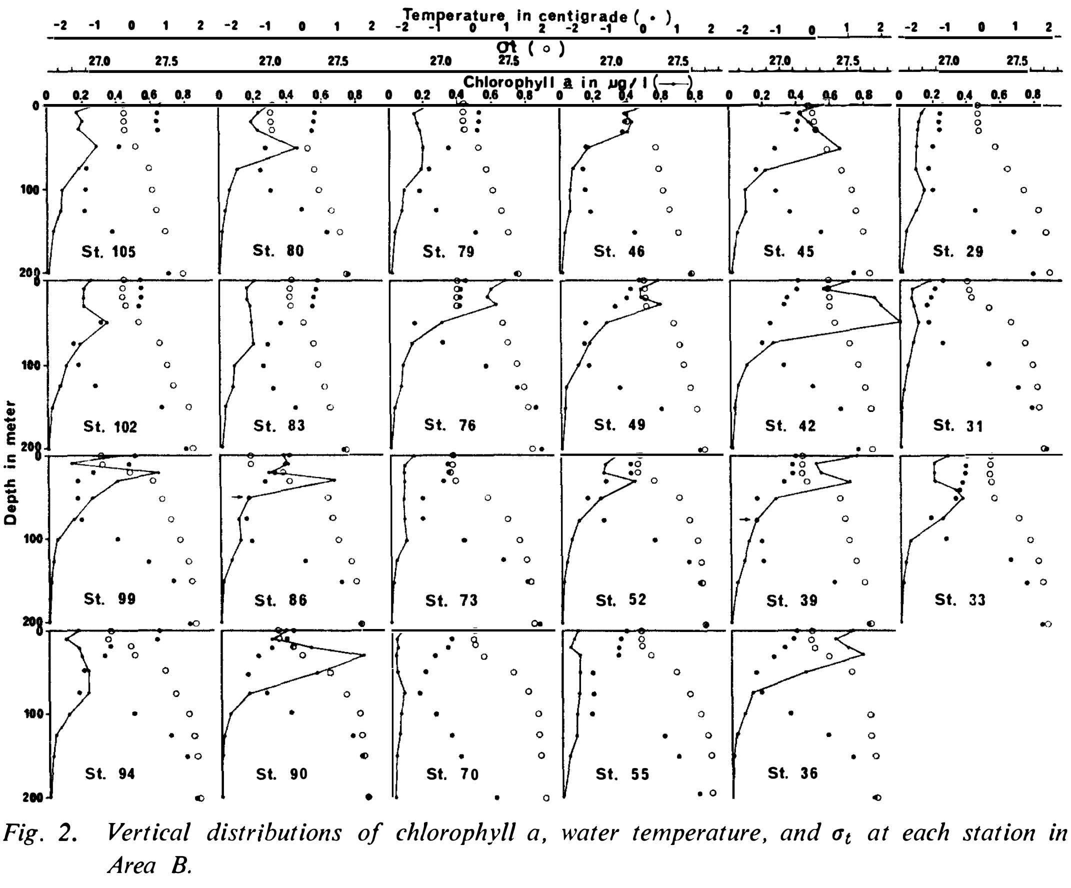

Fig. 2. Vertical distributions of chlorophyll a, water temperature, and σ_t at each station in Area B.

The water temperature of the surface layer in this area ranged from −1.2°C to +0.8°C, with a mean value of −0.6°C. The vertical distribution of temperature was stable in the upper layers, especially in northern stations. Between 50 and 100 m, it attained a minimum below −1.5°C at almost all the stations.

In the same way, the vertical distributions of chlorophyll *a*, σ_t, and water temperature at each station in Area A (the western part, 63°–68°S, 30°–55°E) are shown in Fig. 3. The observations in this area were made about one month later than those in Area B. All the stations also had two maximum layers of chlorophyll *a*. One existed at

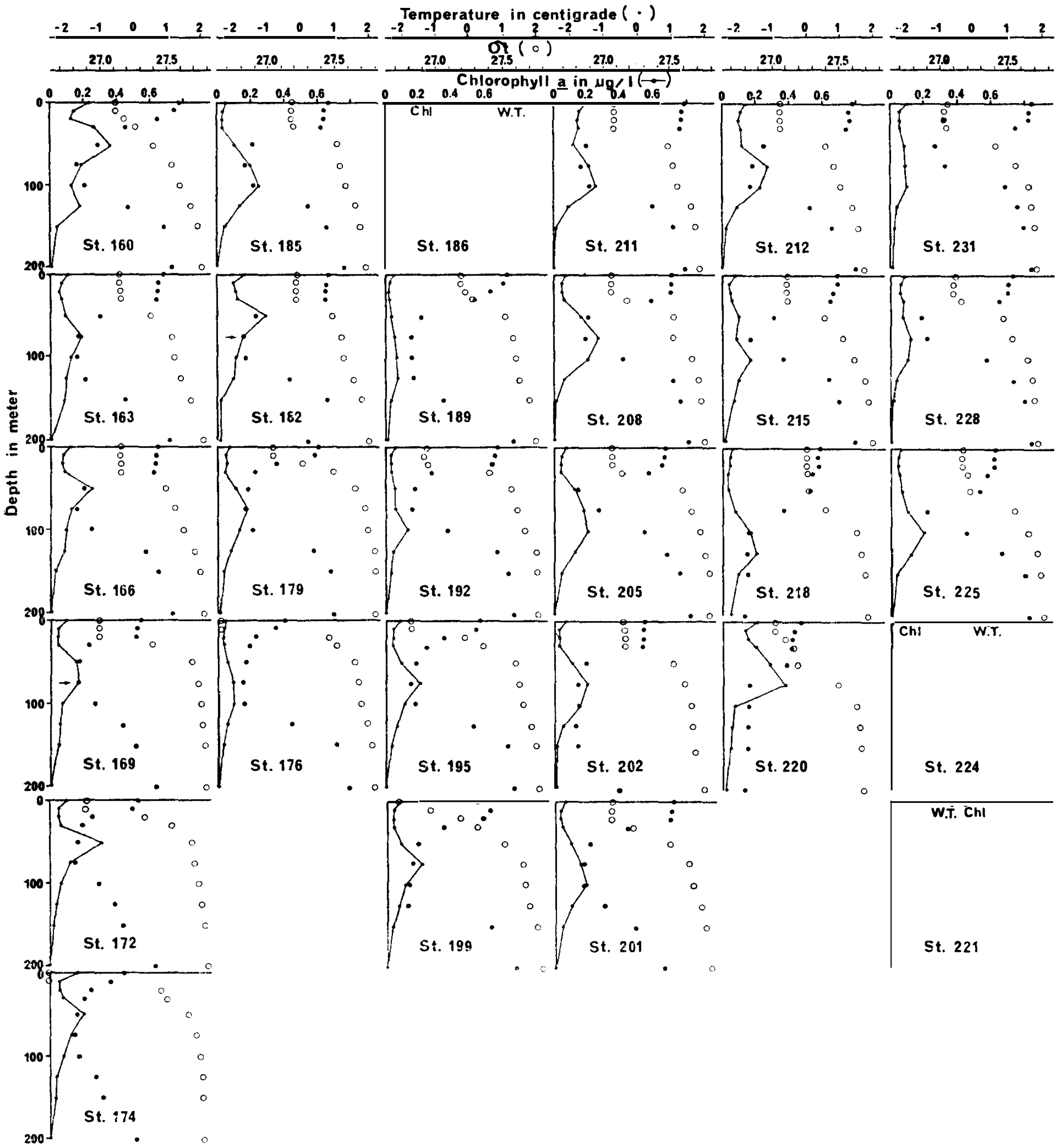

Fig. 3. Vertical distributions of chlorophyll a, water temperature, and σ_t at each station in Area A.

surface and was indistinct. The other was more distinct and occurred in a deeper layer between 50 and 125 m. The mean value of chlorophyll *a* concentration in surface water was 0.11 $\mu g/l$ in Area A. At most of stations in this area, σ_t was also stable in the upper layers except for the two southern stations of the eastern three lines, in which it greatly increased from the surface or 10 m layer, then it gradually increased in deeper layers. The distinct and deeper maximum layer of chlorophyll *a* existed below the pycnocline.

The water temperature of the surface layer in Area A ranged from −0.7°C to +1.7°C, with a mean value of +0.6°C. Thus the mean temperature of the surface water in this area was higher by 1.2°C than that in Area B. It is considered that the value increased within about one month. The vertical profile of water temperature with a minimum layer between 50 and 100 m was similar to that in Area B, excepting the southern two stations of the 50°E line, in which the temperature minimum layer occurred at 200 m depth.

The vertical distribution of chlorophyll *a* was quite different between the two areas. In Area A, there was a unique and incomprehensible pattern. There are two important questions about this difference; one is why phytoplankton (chlorophyll *a*) did not increase in the upper layers, the other is why phytoplankton increased in the deeper layers. To discuss these two questions, some environmental factors will be described.

First, concerning inorganic nutrients in these areas, the nutrient concentration would be enough to allow much growth of phytoplankton. This subject has already been discussed for many different sea areas in a previous paper (UNO, 1982). Then, considering the physical factors of the water mass in both areas, the vertical distributions of particulate matter at six stations are shown in Fig. 4. The upper three figures

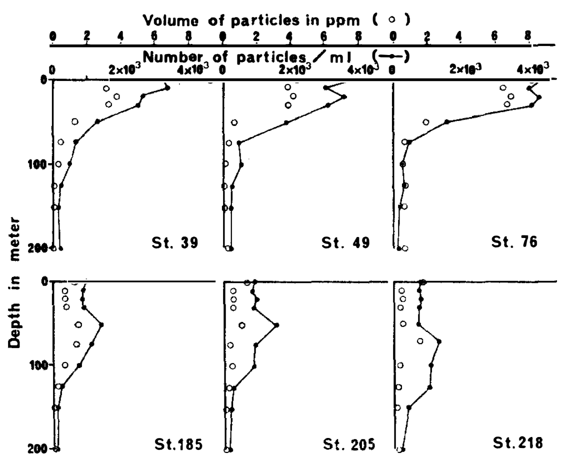

Fig. 4. Vertical distributions of particle number and volume at three representative stations in Areas B and A.

are typical examples of particle distribution in Area B, and the lower three figures are typical of Area A. The second maximum layer of chlorophyll *a* at these three stations in Area B occurred at 30 m while distribution of particle number showed a small maximum at 20 m in the area. The values of chlorophyll *a* and particles suddenly decreased between 30 and 50 m. On the whole, distribution of particles did not differ very much from that of chlorophyll *a*; particle numbers were higher in the upper layers than in the pycnocline and were lower in the deeper layers. On the other hand, in Area A, particle numbers showed a maximum just below the pycnocline at Stns. 185 and 205. At Stn. 218, the maximum was found in the pycnocline. The particle distribution was different from that of chlorophyll *a* in Area A. Generally, the maximum layer of chlorophyll *a* in Area A occurred deeper than that of particulate matter. This difference in vertical distribution indicates that any physical accumulation of particles did not effectively influenced the vertical distribution of chlorophyll *a*.

The vertical distribution of chlorophyll *a* per unit particle number in both areas showed different patterns as illustrated in Fig. 5. At the three stations in Area B, maximum values of chlorophyll *a* per unit particle number were found at 125, 74 and 100 m

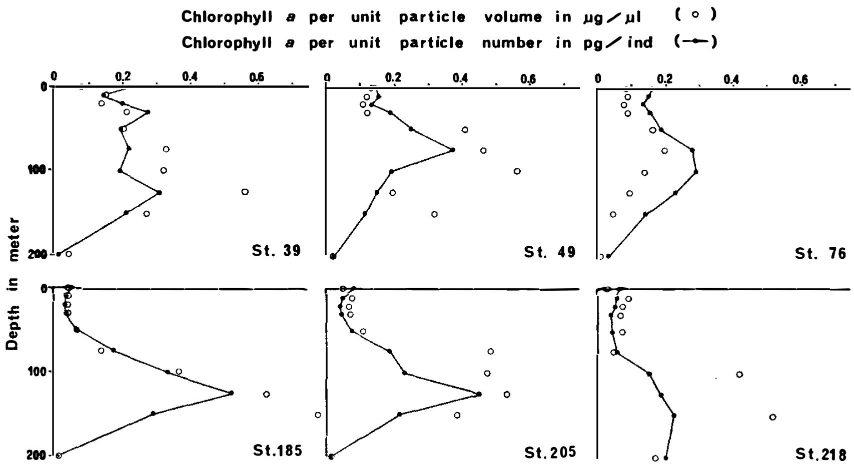

Fig. 5. Vertical distributions of chlorophyll a per particle number and per particle volume.

depth layers. Mean values in the upper layer (from surface to 75 m) at each station were all close to 0.2 pg/individ., and those in the deeper layer (from 100 to 200 m) ranged from 0.12 to 0.20 pg/individ. In Area A, however, maximum values were found in deeper layers at 125 and 150 m. In the same way, mean values in the upper layer were between 0.05 and 0.07 pg/individ., and in the deeper layer were between 0.19 and 0.29 pg/individ. Overall, the values in Area A were lower in the upper layer, and were higher in the deeper layers. The vertical distribution of chlorophyll *a* per unit particulate volume in both areas also showed the tendency described above.

The mean temperature of the surface water in Area A was higher by 1.2°C than that of Area B as previously stated. Chlorophyll *a* concentration and surface water temperature in both areas are plotted in Fig. 6. Most points from Area B occurred in a wide chlorophyll *a* and low temperature region. On the contrary most points from Area A occurred in low chlorophyll *a* and high temperature region. The highest concentration of chlorophyll *a* in each area was found at around −0.7°C. Figure 6 indicates that temperature was probably an important factor in determining chlorophyll *a* concentration.

In the same way, all of the data from Area B, excluding the surface, are plotted in Fig. 7 where the points are found to fall under two groups; the upper layer (from 10 to 75 m) and the lower layer (from 100 to 200 m). The depth of boundary of the two layers was determined by a convenient means, because the depths of pycnocline and euphotic zone were different between the areas. All the points of the upper layer occurred at temperatures from −1.8°C to +0.8°C. The higher values of chlorophyll *a* occurred at lower temperatures from −1.5°C to −0.3°C. All the points of the lower layer occurred over a wide range of temperature, but they did not exceed 0.15 µg chlorophyll *a/l*. The points of the upper layer were further divided into two groups, 0–50 m and 75 m, and are illustrated in the schematic diagram in the upper right corner of the figure. From the surface to 50m, the points were largely distributed in a high chlorophyll *a* and medium temperature zone. At 75 m, they converged on a low chlorophyll *a* and low temperature zone. The points of the deeper layer, from 100 to 200 m, were diffused throughout a low chlorophyll *a* and wide temperature zone. Precisely

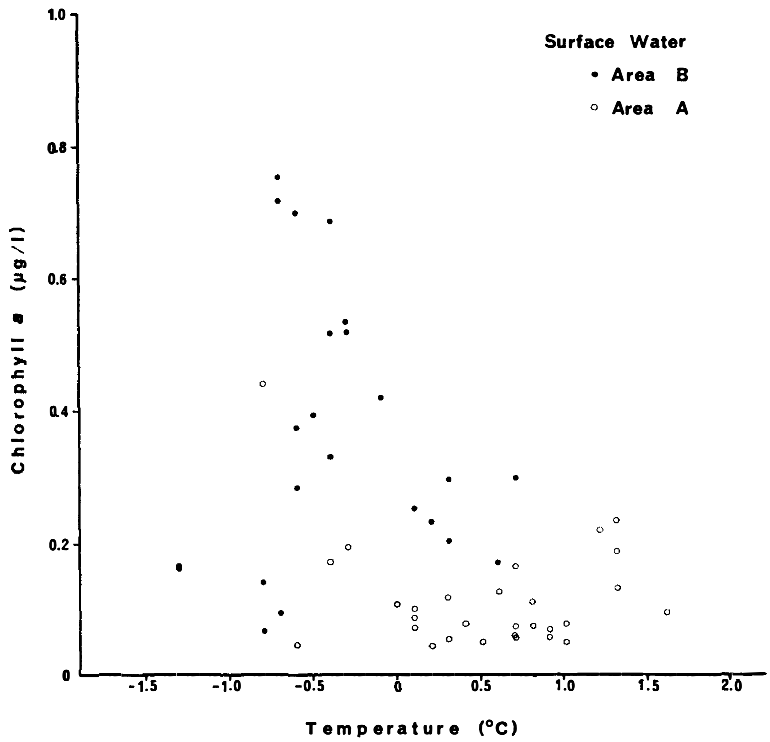

Fig. 6. Relations between chlorophyll a concentration and temperature in surface water in Areas B and A.

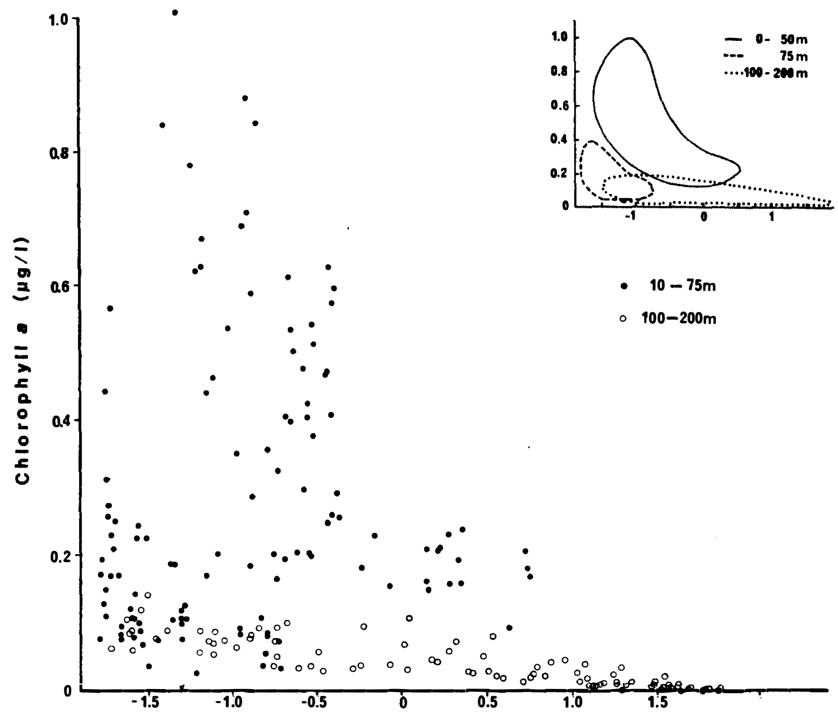

Fig. 7. Relations between chlorophyll a concentration and temperature in the water from 10 to 200 m in Area B. The relations of the three depth groups are indicated schematically in the upper right corner.

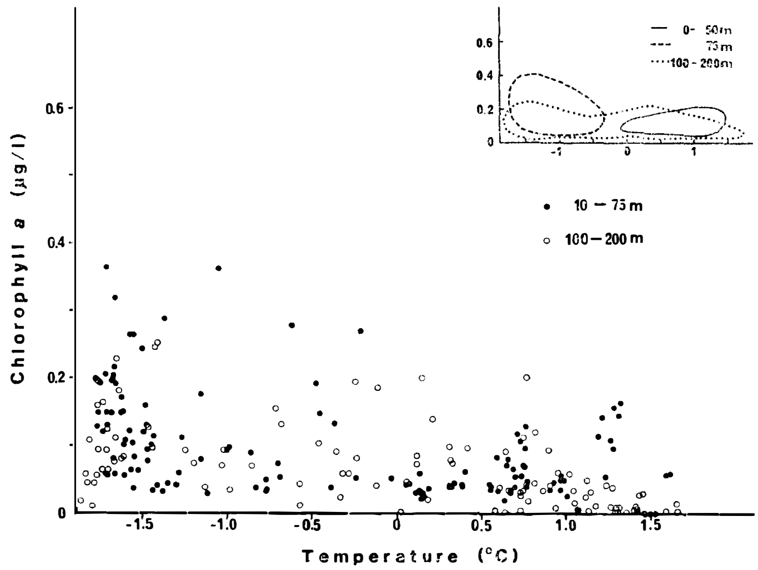

Fig. 8. Relations between chlorophyll a concentration and temperature in the water from 10 to 200 m in Area A. The relations of the three depth groups are indicated schematically in the upper right corner.

speaking on this temperature zone, the points gradually drifted from the lower temperature to the higher temperature with the increase of depth.

Similarly, the relations between chlorophyll *a* and water temperature for all of the data in Area A, excluding the surface, are shown in Fig. 8. The pattern of distribution in the figure is quite different from that of Fig. 7. The points of the upper layers are divided into two groups; one falls under a low chlorophyll *a* and high temperature zone composed of the data from 10 to 50 m, and the other under a low and medium chlorophyll *a* and low temperature zone composed mainly of the data from 75 m. The points of lower layers, from 100 to 200 m, were widely distributed. Their range in temperature was almost similar to that in Area B, but the range in chlorophyll *a* was more widely spread, from 0 to 0.25 $\mu g/l$. These points also drifted from lower temperature territory to higher temperature territory with the increase of depth in this zone.

4. Discussion

From the results shown in Figs. 7 and 8, it appeared that chlorophyll *a* concentration was influenced by the temperature of the environment. The higher chlorophyll *a* concentration necessarily occurred in the low temperature zone, and the values greater than 0.5 $\mu g/l$ were found only in the temperature range below -0.3°C in the upper layer of Area B. In Area A, the water from the surface to 50 m was warmer than 0°C, and the chlorophyll *a* concentration of most samples was less than 0.15 $\mu g/l$. At 75 m, it increased slightly in the low temperature zone.

There have been few experimental results on the relation between phytoplankton productivity and water temperature in the Antarctic Ocean. However, EL-SAYED (1970) noted that the average depth of the euphotic zone for all the combined cruises in the Pacific Sector was about 80 m, and EL-SAYED (1978) pointed out that the magnitude of the photosynthetic activity of the phytoplankton below the euphotic zone cannot be overlooked during ELTANIN cruise 51 in the Ross Sea. HOLM-HANSEN *et al.* (1977) also recognized low photosynthetic capacity of phytoplankton in the layers deeper than 75 m at some stations in the Antarctic Ocean. Recently, EL-SAYED and TAGUCHI (1981) indicated the spatial distributions of phytoplankton pigments, physical and chemical factors, in which the higher pigments concentration was found in the water of lower temperature (less than $-1.5°C$).

Thus, phytoplankton growth in both areas seemed to be adapted to low temperature, particularly from $-1.4°C$ to $-0.3°C$. In Area B, the water temperature in the euphotic layer was within this temperature range, and phytoplankton would be able to grow well. But in Area A, the water temperature in the euphotic layer was not within this range. At the lower limit of the euphotic layer, the water just barely reached this lower temperature. Probably, it ought to have been difficult for the phytoplankton biomass to grow up there. The euphotic zone would have extended deeper in Area A than in Area B because of the paucity of seston as shown in Fig. 4.

UNO (1974) recognized that the chlorophyll *a* content of phytoplankton cells cultured in a turbidostat increased with decreasing irradiance, and *vice versa.* So, if the phytoplankton was healthy, the chlorophyll *a* content of phytoplankton cells would be expected to be higher in the deeper layers. UNO and UENO (1981) reported that the chlorophyll *a* content of *Chaetoceros debilis* cultured in a turbidostat ranged from 0.4 to 1.2 pg/cell. They also reported that the chlorophyll *a* content per unit cell volume of *C. debilis* was between 0.5 and 1.8 $\mu g/\mu l$. Comparing the values of the chlorophyll *a* content in the deeper layers in Area A with the values from UNO and UENO (1981), the seston in the layers appears to have contained many living phytoplankton.

The vertical section of water temperature in both areas indicated a clear difference between them; *viz.* in Area B there was a wide zone of low temperature in upper layer, but in Area A the low temperature zone was scarcely recognizable.

On the whole, it could be explained that the different patterns of vertical distribution of chlorophyll *a* between Area B and Area A in the period were caused by the structure of water temperature in the environment. NAGANOBU and HIRANO (1982) examined the relation between stocks of krill and temperature from the surface to 200 m, and showed that the higher density of krill coincided with lower values of temperature integrated from the surface down to 200 m. In the case of phytoplankton, such a trend was scarcely recognizable. Perhaps, the water temperature would not be a ruling factor but just a necessary condition.

Using the data record for chlorophyll *a* and water temperature in a pre-FIBEX cruise of the KAIYO MARU to the eastern Indian Sector presented by YAMAGATA and FUKUI (1981), the author constructed a figure similar to the ones already discussed. Figure 9 shows the relation in the first half of the pre-FIBEX cruise with two different symbols for northern and southern areas. The points of the two areas are clearly separated. Those of the northern area are situated in a high chlorophyll *a* and high temperature region in the figure, and those of the southern area are situated in a low chlorophyll *a* and low temperature region. In both areas, one is able to see similar trends, with higher chlorophyll *a* values inclined toward lower temperature region. However, the maximal values of chlorophyll *a* in both areas were found at different temperatures;

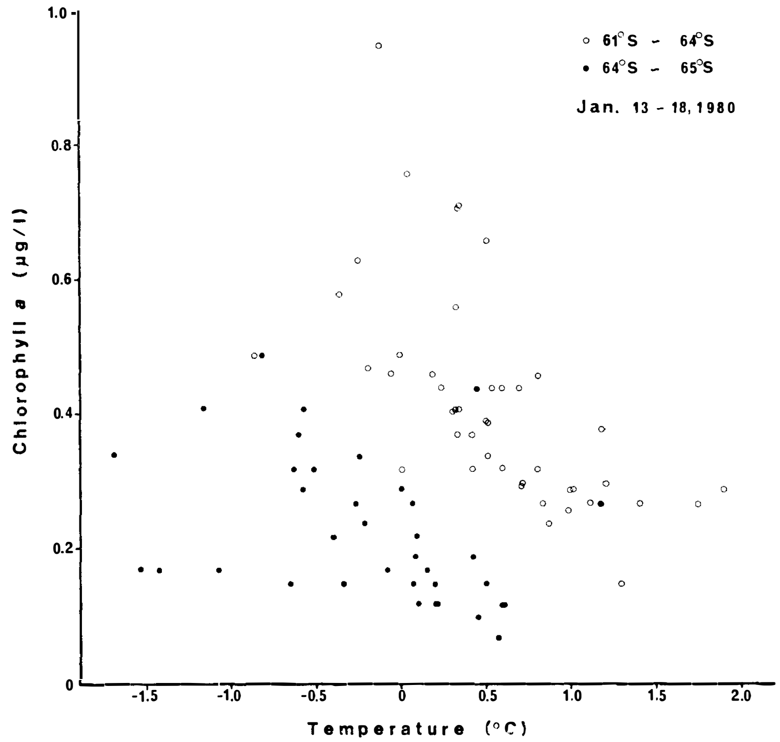

Fig. 9. Relations between chlorophyll a concentration and temperature in the water from surface to 50 m in the middle of January 1980 (drawn from the Data Record of the pre-FIBEX cruise of R.V. KAIYO MARU).

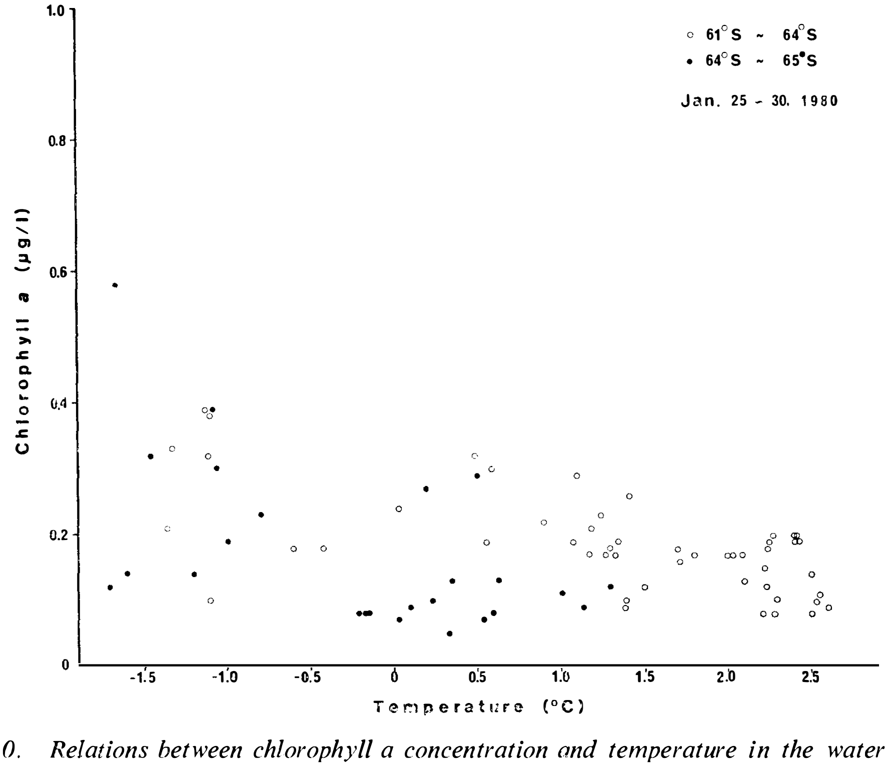

Fig. 10. Relations between chlorophyll a concentration and temperature in the water from surface to 50 m in late January 1980 (drawn from the Data Record of the pre-FIBEX cruise of the KAIYO MARU).

in the northern area the maximum value was found at $-0.1°C$, while in the other area the maximum was found at $-0.8°C$. These results indicate there would be two different optimum temperatures for different phytoplankton communities in these areas.

On the contrary, in the latter half of the pre-FIBEX cruise, the distribution of the points of each area did not show a similar tendency (Fig. 10). The averaged time lag between the first half and the latter half was less than two weeks. But in the latter half, temperatures in the area extended higher, and the values of chlorophyll *a* appeared to decline. In the northern and southern areas, chlorophyll *a* values did not show a maximum as shown in Fig. 9. In the present study, the distribution of chlorophyll *a* and water temperature in the latter half of January showed a quite different pattern from that of the first half. These results suggested that the structure of water temperature in the upper layer in these areas is variable during the period from the middle to the end of January. However, there have been few studies of the short-term variation of phytoplankton standing stock in the Antarctic Ocean.

Icebreaker FUJI has collected chlorophyll *a* data from the surface water of the Antarctic Ocean since 1965. Using these data obtained by colorimetric method, the author re-examined the relation between chlorophyll *a* and water temperature in the area south of 60°S. It is difficult to treat the results equally because of the different number of data points. On the whole, however, a trend of higher chlorophyll *a* values at lower temperatures can be recognized in the data for December reported by seven papers (TAKAHASHI, 1969; NISHIWAKI, 1972; HOSHINO, 1974; OHNO, 1976; OHYAMA and MAYAMA, 1976; FUKUCHI, 1977; KANDA and FUKUCHI, 1979). The data for Jan-

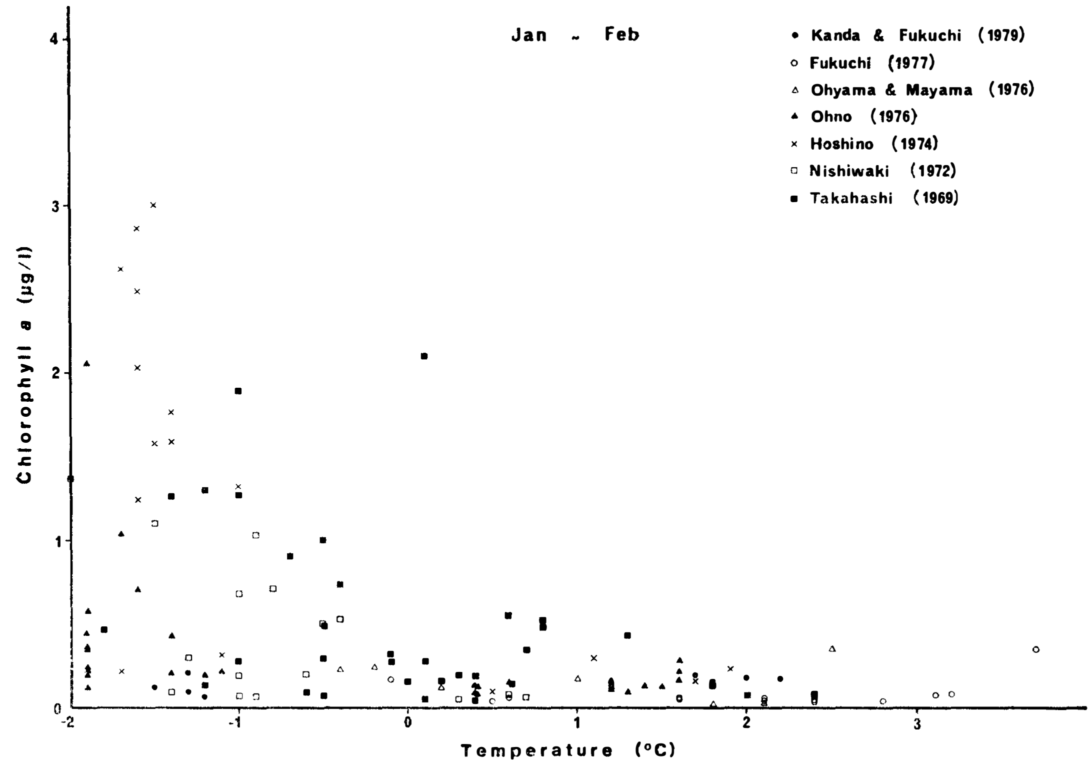

Fig. 11. Relations between chlorophyll a concentration and temperature in surface water south of 60°S from January to February by workers during the cruises of icebreaker FUJI.

uary and February by the same authors are plotted in Fig. 11. In the figure, the range of temperature extends towards higher values, and the trend of higher chlorophyll *a* value in lower temperature range is distinct. The high values of chlorophyll *a* reported by TAKAHASHI (1969), HOSHINO (1974) and OHNO (1976) were mostly from the coastal area close to Syowa Station. So, influences from Antarctica must be considered on the growth of phytoplankton biomass.

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