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DISTRIBUTION OF PHYTOPLANKTON CHLOROPHYLL CONTINUOUSLY RECORDED IN THE JARE-25 CRUISE TO SYOWA STATION, ANTARCTICA (SIBEX I)

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Abstract: The attempt was made to record the geographical distribution of chlorophyll *a* on a finer scale over semi-global ranges. A prototype of continuous measuring-recording system was designed and built in icebreaker SHIRASE and rich data on chlorophyll distribution were collected on the JARE-25 cruise (1983/84) to Syowa Station in Antarctica. Diel variation of chlorophyll in the Antarctic Ocean was also documented.

The results obtained confirm gross patterns of the geographical distribution and diel variation reported by many previous authors. Furthermore, several facts are newly found: *e.g.*, relationships of chlorophyll to temperature are quite variable among different sea areas, diel variation is less intense in the coastal area where a 12-hour periodicity is influential, and occurrence of a certain hydrographic condition which enhances phytoplankton productivity in the area between the Agulhas Convergence and the Subtropical Convergence south of South Africa.

1. Introduction

Since 1965, geographical distribution of the surface chlorophyll *a* over semi-global ranges has been routinely documented in every JARE (Japanese Antarctic Research Expedition) cruise, which starts from Tokyo in November, reaches Syowa Station, Antarctica, in late December or early January of the following year and returns to Tokyo in April. Because Syowa Station is located in the western part of the Indian Sector of the Antarctic Ocean, such the routine works have been concentrated in the Indian Sector. The historical reviews of these long-term serial observations are given by FUKUCHI (1980, 1982).

In the preceding 15 cruises, sample water was bucketed two to three times every day except the days in port or at Syowa Station. Data obtained in early cruises have suggested that wide geographical variation of chlorophyll *a* standing crops in the Southern Ocean is common and particularly marked variation is closely associated with the frontal zone of the ocean. Therefore, more frequent samplings, *e.g.*, at least at 1 or 2 hours intervals (PLANCKE, 1977; FUKUCHI and TAMURA, 1982; YAMAMOTO, 1986), are essential to picture the spatial variability on a finer scale of chlorophyll distribution within a relatively narrow area around the convergences. Since the main task of JARE cruises is in logistics relating to Syowa Station and other Japanese bases in Antarctica, it is not always possible to spend much time in investigating such subjects by stopping or sailing at a slow speed over the frontal zones.

To obtain the data of chlorophyll distribution on a finer scale over wider geographical ranges in future cruises, we designed a prototype of continuous measuring-recording system to be built in icebreaker SHIRASE, which can be operated throughout the cruises. By test operation of the system, rich information about chlorophyll distribution was obtained during the JARE-25 cruise (1983/84). In this paper, we report geographical distribution of the chlorophyll *a* in relation to hydrographic regimes in the sea areas south of Australia and South Africa. Diel variation of chlorophyll in the Antarctic Ocean is also described. These are given in order following the cruise track.

2. Materials and Methods

Sea water which was pumped up from an intake on the hull (8 m depth) was flowed to an air bubble trap and then led to a Turner Designs 10-005R fluorometer. Intensities of the *in vivo* fluorescence of the flowing water were recorded continuously in analogue form on a chart paper. This method was calibrated with the conventional fluorometric method described below, which had been employed in most preceding cruises. A linear correlation between the results obtained by both methods was confirmed on the logarithmic basis over a very wide range of chlorophyll concentrations (HAMADA *et al.*, 1985). The regression of chlorophyll *a* (Chl. *a*) concentration (μg/*l*) to readings of the *in situ* fluorometry (V) was

$$\text{Chl. } a = 0.00010 V^{1.31} \quad (n=29,\ r=0.951).$$

Then the readings could be converted into the chlorophyll concentrations.

During the continuous recording, the flow cell of the fluorometer was washed at appropriate intervals, mostly once a day. When the intensity of fluorescence dropped significantly by the cell washing, over-recorded values due to phytoplankton sticking to the inside wall of the cell were subtracted from the readings before washing. In those cases, the assumption was made that the degree of contamination increased steadily with time.

Based on the data on total volume of piping and air bubble trap, exhausting capability of the pump, rate of overflow from the babble trap, and flow rate into the fluorometer, the minimum time for the water to pass through the whole system from the intake on the hull to the fluorometer was calculated to be 6.5 min. Because there were a few uncorrectable factors stalling particular water parcel to run through the system such as mixing and turbulence, resolving ability of the system might be lowered to some extent. Therefore, the data were sorted arbitrarily at 15 min intervals.

The relevant data on temperature and salinity measured for the water to cool the ship's engines were also read from the analogue records at simultaneous intervals, which had been pooled in the meteorological office of the SHIRASE. The records on temperature and salinity could not be available in southern areas where the water was too cold to cool engines without preheating. During the icebreaking sail, both temperature-salinity and chlorophyll recording systems did not work due to choking up of the water intake with smashed ice fragments.

The conventional fluorometric determination of chlorophyll concentration (YENTSCH and MENZEL, 1963) was made for outflowed water from the *in vivo* fluorometer. One to two liter aliquot of the water was Whatman GF/C filtered just after a few milliliters of 0.5% $MgCO_3$ suspension were added. Phytoplankton collected on the filter were homogenized and their pigments were extracted in 90% acetone. The amount of chlorophyll *a* and pheopigments in the extract was determined with a Shimadzu RF-500 spectrofluorometer.

Detailes of the prototype continuous recording system and the methods employed are given in HAMADA *et al.* (1985) together with full results obtained.

3. Results and Discussion

Geographical variation in chlorophyll stocks over the entire cruise track is illustrated in Fig. 1. Higher values exceeding 1.0 μg Chl. *a*/*l* were observed around oceanic fronts in the Southern Ocean as well as in the water areas associated with coastal waters of Tokyo Bay, Java Sea, near Cape Town and Antarctica. The maxima reaching 9.00 and 8.93 μg Chl. *a*/*l* were recorded near Cape Town and in Breid Bay (70°13′S, 23°55′E), respectively. On the other hand, lower values were observed in the South

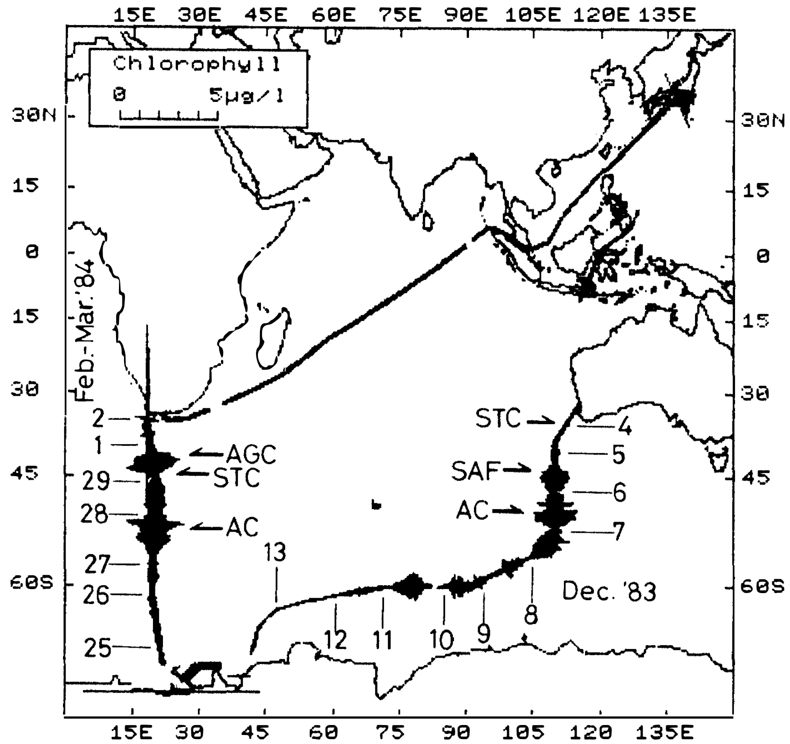

Fig. 1. Geographical variation in chlorophyll a concentration at 8 m depth over the entire cruise track of icebreaker SHIRASE in the austral summer of 1983/84. Numerals indicate the noon position on the respective days in December 1983 on the southward track and in February and March 1984 along the northward track. Approximate position of convergences are also indicated by arrows; STC: Subtropical Convergence, SAF: Subantarctic Front, AC: Antarctic Convergence, AGC: Agulhas Convergence.

China Sea and the Indian Ocean, usually being less than 0.1 $\mu g/l$. Alternative occurrences of larger and smaller stocks in the Southern Ocean are conspicuous. Some of them seem to have relation with the fronts but the others, especially in the southern half of the Ocean, do not. These trends are essentially the same with the previously reported results (*e.g.*, KURODA, 1978; KANDA and FUKUCHI, 1979; FUKUCHI and TAMURA, 1982; SASAKI, 1984; for the works done before 1977 see review by FUKUCHI, 1980, 1982). In this paper, geographical and diel variations of chlorophyll recorded in the sea areas southwest of Australia and south of South Africa are dealt with.

3.1. Geographical variation in the south-west of Australia

The SHIRASE run 1400 miles southward in four days after departure from Fremantle,

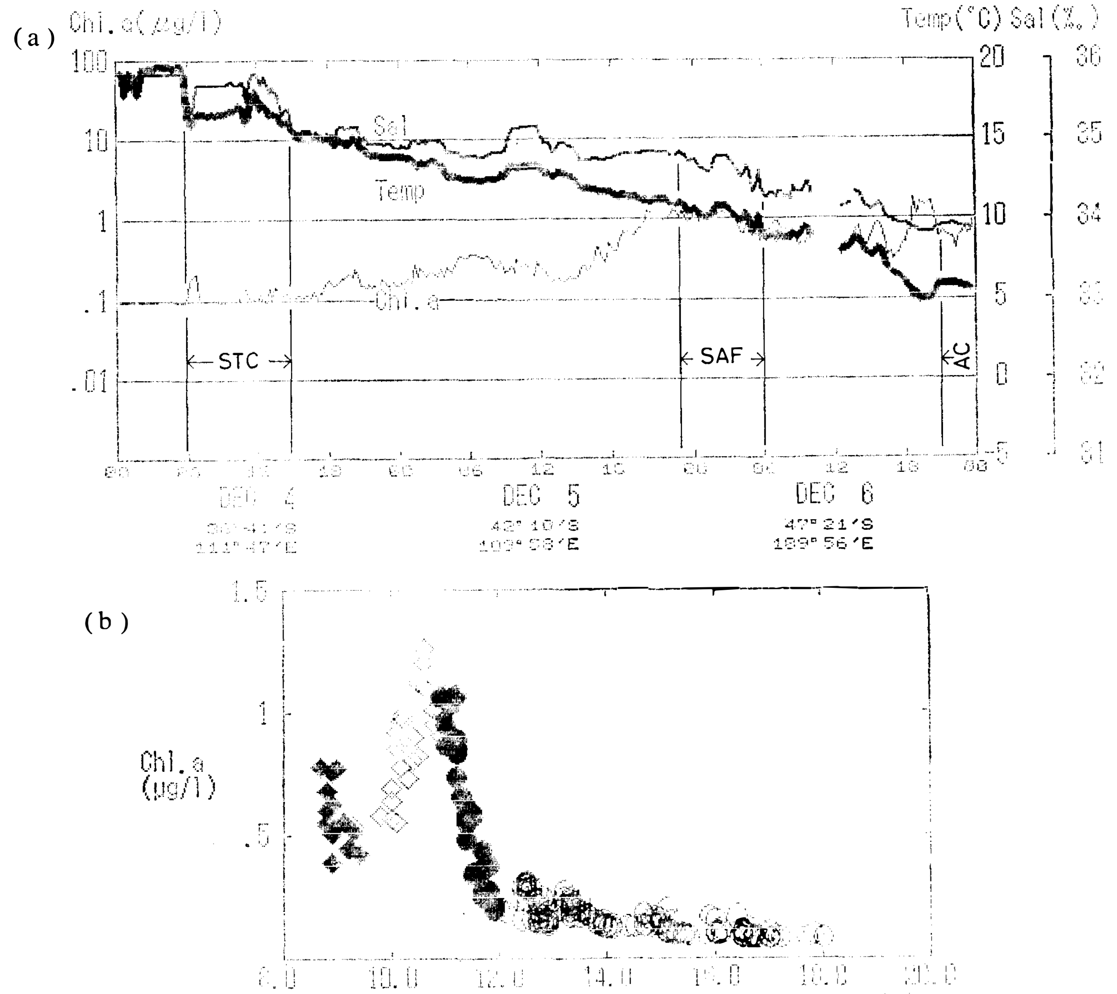

Fig. 2. Variations of chlorophyll a and those of temperature and salinity at 8 m depth in the sea area southwest of Australia recorded during 4–6 December 1983.
(a) Variations in time sequence. STC: Subtropical Convergence, SAF: Subantarctic Front, AC: Antarctic Convergence. (b) Temperature-chlorophyll diagram. Open circle: data obtained between 0600 December 4 and 1545 December 5, solid circle: between 1600 and 2345 December 5, open diamond: between 2400 December 5 and 0545 December 6, solid diamond: between 0600 and 0945 December 6.

Western Australia, on December 3, then changed her course to west by December 13 when she turned again southward or toward Syowa Station (69°S, 39°35'E). During the first half of this course, some peaks were recorded (Fig. 1). Major part of this record is output on a time serial scale (Figs. 2a, 3a). Referring to TORII *et al.* (1959), FUKASE (1962), DEACON (1982) and EDWARDS and EMERY (1982), positions of the Subtropical Convergence (STC), Subantarctic Front (SAF) and Antarctic Convergence (AC, equivalent to Edwards and Emery's Polar Front) were deduced from the present data on temperature and salinity and those on nutrients reported by IWANAMI and FUTATSUMACHI (1986).

General increase with decreasing temperature and salinity in the first half (Fig. 2a) and cyclic change in the latter half (Fig. 3a) are the prevailing variations in chlorophyll

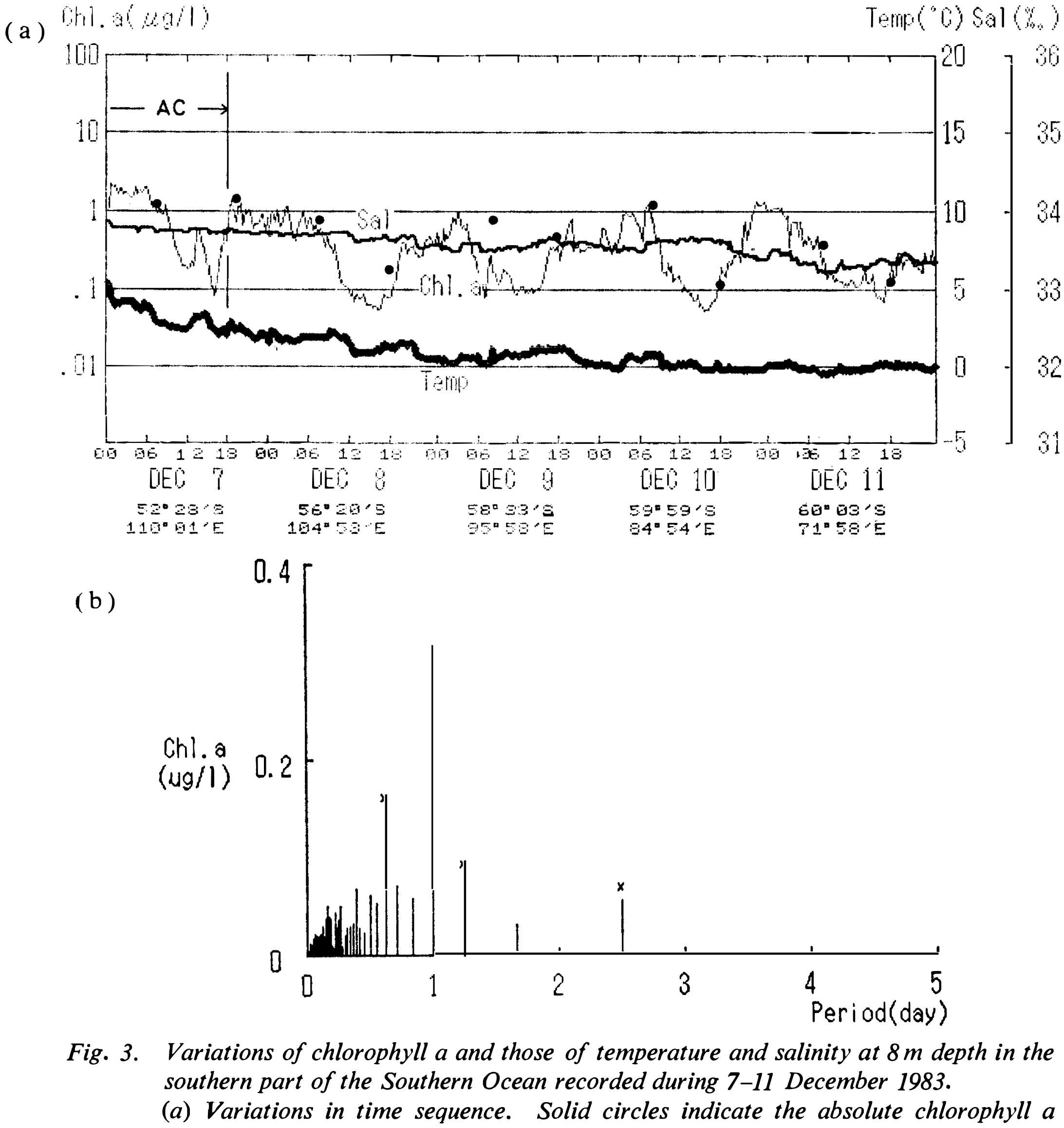

Fig. 3. Variations of chlorophyll a and those of temperature and salinity at 8 m depth in the southern part of the Southern Ocean recorded during 7–11 December 1983.
(a) Variations in time sequence. Solid circles indicate the absolute chlorophyll a concentrations measured by the conventional method. AC: Antarctic Convergence.
(b) Result of a period analysis on data obtained between 0000 December 7 and 2400 December 11 (5 days). Ordinate: amplitude of periodic variations. × denotes periods when the amplitude was overestimated due to algorithm of the analysis.

stocks. Therefore, we determined the geographical variation of chlorophyll in relation to water temperature in the first half and that relating to diel periodicity in the latter half.

A temperature-chlorophyll diagram in the first half is given in Fig. 2b. This covers the period from 0600 December 4 to 1000 December 6. After the last time, continuous recording was interrupted for several hours. Negative relation between chlorophyll and temperature is apparent throughout the Subtropical Convergence zone and the Subantarctic Water north of the Subantarctic Front. These areas were covered during 0600 December 4 to 2345 December 5, till then temperature was higher than 11°C. Among these areas, the Subtropical Convergence zone where temperature exceeded 16°C was characterized by very low chlorophyll concentration. In farther south approaching to the Subantarctic Front, negative inclination of increasing chlorophyll against decreasing temperature became steep and finally attained its maximum of 1.47 $\mu g/l$ at the northern edge of the Front.

Within the Subantarctic Frontal zone (2400 December 5–0545 December 6; one hour was added after 2400 December 5 when the SHIRASE passed the time zone), chlorophyll tended to decrease as temperature decreased toward south. Nitrate concentration increased suddenly as temperature and salinity decreased southward across this frontal zone, while the other nutrients were unvaried (IWANAMI and FUTATSUMACHI, 1986). This and different nature of temperature-chlorophyll relation (positive one in this case) from neighboring waters on both sides of this zone (negative ones as mentioned above and below) might be indicating the existence of the Subantarctic Front which is not always distinguishable (DEACON, 1982). In the Subantarctic water south of the front (0600–1000 December 6), negative relation between chlorophyll and temperature was again apparent. Although the data obtained after 1300 December 6 or after the interruption of the recording are not output in the temperature-chlorophyll diagram, the same negative relation can also be seen till the SHIRASE entered into the Antarctic Convergence (Fig. 2a).

Within the Antarctic Convergence zone, both negative relation in the northern half (Fig. 2a) and positive relation in the southern half (Fig. 3a) were observed between chlorophyll and temperature. This is not always consistent with YAMAMOTO's (1986) assumption adopting the finding of NEORI and HOLM-HANSEN (1982) to the fact found in the Antarctic Convergence south of Tasmania (150°E), where larger chlorophyll stocks seemed to have been produced by accelerated photosynthesis of the Antarctic species on account of elevated temperature due to admixture with the warm Subantarctic water. Although the same trend could be seen in the southern half, it was not the case in the northern half of the convergence in the present study area. HAYES *et al.* (1984), on the other hand, indicated that the dependence of concentration and activity of chlorophyll on temperature is not always positive nor direct (acceleration by elevated temperature) but likely to be variable in the different hydrographic and/or geographic regimes.

Diel periodicity was quite dominant in the Antarctic water south of the Antarctic Convergence as described below. A slight elevation of daily maximum and minimum values just south of the convergence (0100 December 7) compared with those in farther south can be seen in Fig. 4a. This may be attributable to the surface water movement toward the convergence and the derived hydrographic conditions rather than to higher temperature. In farther south, some positive relationship between chlorophyll and slightly variable temperature was also observed on a finer scale (*e.g.*, 0600–1800 December 7, around 1200 December 8, 0600 December 10). Such a relationship, however, hardly extended over entire geographical ranges in spite of the clear temperature change from 3° to −0.5°C. There were homogeneously rich nutrients over the ranges (IWANAMI and FUTATSUMACHI, 1986). These indicate that the positive effect of temperature on chlorophyll stocks which can be suggested by the fact found by NEORI and HOLM-HANSEN (1982) was not always significant but the negative effect was sometimes dominating in the Sub- and Antarctic waters.

In the western area covered on December 12–13, chlorophyll stocks were totally low (Fig. 1), while FUKUCHI (1980, 1982) mentions that the stocks tend to increase around 50° and 65°E in most years. He dealt with only data obtained in late December. Therefore, the difference between his and our results was possibly produced by seasonal as well as annual phenomena. Even a short time lag of a half month can produce

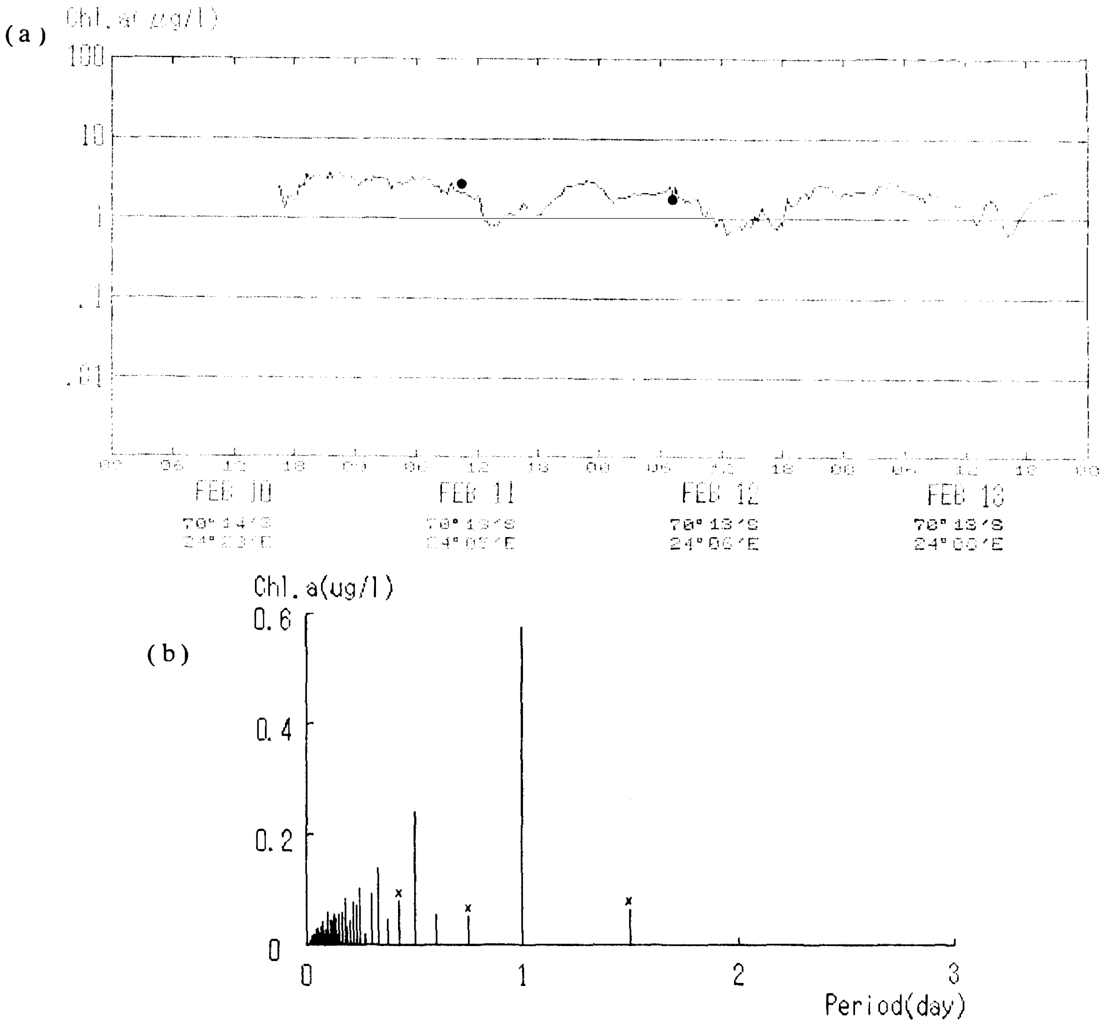

Fig. 4. Variation of chlorophyll a at 8 m depth recorded during a drift in Breid Bay on the Antarctic coast (70°13′S, 24°07′E) between 10 and 13 February 1984.
(a) Solid circles indicate the absolute chlorophyll a concentrations. (b) Result of a period analysis on data obtained between 1800 February 10 and 1800 February 13 (3 days). For details see legend of Fig. 3.

substantial difference in phytoplankton productivity in the southern part of the Antarctic Ocean (HART, 1942; HASLE, 1969; FUKUCHI, 1980, 1982; IWANAMI *et al.*, 1986).

3.2. Diel variation of chlorophyll in the Antarctic Ocean

YAMAGUCHI and SHIBATA (1982) documented marked diel fluctuation of *in vivo* fluorescence in the sea area south of Australia. The highest and lowest values were observed at night and in daytime, respectively. The nocturnal maxima were about threefold larger than the diurnal minima. They also measured in different year the fluctuation in the absolute concentration of chlorophyll, which was measured on acetone extracted pigments, at a station near the pack ice edge. The absolute concentration again varied by factor 1.5 (YAMAGUCHI, personal communication).

Although the same trend of diel variation was also recorded in our investigation, the magnitude of variation was very large (Fig. 3a). Since our investigation was not originally designed to analyze the diel variation, the exact time when the nocturnal maxima and diurnal minima occurred was often missed in our coarse sampling intervals for determination of the absolute chlorophyll concentration. We did it only twice a day, around 0800 and 1800, by the conventional method on outflowed water from the *in vivo* fluorometer. Nevertheless, the minimum absolute values were as low as 0.12 μg Chl. *a*/*l* and the maxima were as large as 1.5 μg/*l*. Records of our *in vivo* fluorometry had been converted into chlorophyll concentration by using a regression equation of absolute concentrations on readings of *in vivo* fluorometry mentioned above. Therefore, the diel variation recorded by *in vivo* fluorometry could follow closely the variation in amount of chlorophyll in the water.

The data obtained during the period from 0000 December 7 to 2400 December 11 (5 days) were offered to a period analysis. The mean chlorophyll concentration averaged over this period was 0.41 μg/*l* and the amplitude of 24-hour periodic variation was 0.32 μg/*l* or $\pm$78% around the mean. This amplitude was extraordinarily large and followed by moderate amplitudes of shorter periods (Fig. 3b). This suggests that the diel periodicity is predominant over fine temporal and/or spatial fluctuations of chlorophyll in the Antarctic Ocean.

The same analysis was done for 10–13 February when the SHIRASE was drifting in an open area of coastal water without ice cover in Breid Bay (70°13′S, 24°07′E). Probably because ice-cover of the Bay had disappeared earlier and the bay water was relatively stagnant due to enclosure by shelf ice in the south and heavily packed ice in the north, an average level of chlorophyll stocks was much higher (Fig. 4a) than in the oceanic area described above (Fig. 3a). Figure 4b shows the results of period analysis of the data obtained in the Bay. A 24-hour periodicity was clearly prevailing as seen in the oceanic area but its amplitude of 0.57 μg/*l* was small in relative sense to average concentration of 1.69 μg/*l*. A 12-hour periodicity with an amplitude of 0.25 μg/*l* was also apparent (Fig. 4b), suggesting that environmental variables bearing a 12-hour cycle such as tidal current also affected chlorophyll stocks to a certain extent in the coastal areas. During the present investigation in Breid Bay, there was neither complete midnight dark nor bright cloudless sky in daytime so that diel fluctuation in solar irradiation was small. This and the interference with the 12-hour periodicity might suppress the amplitude of diel variation of chlorophyll.

3.3. *Geographical variation in the area south of South Africa*

One can read the following gross differences, apart from those of a finer scale, in chlorophyll concentration between the sea area south of South Africa and that of Australia shown in Fig. 1. In the south of Africa, chlorophyll stocks around the Subtropical Convergence were much larger, but diel periodicity in the south of the Antarctic Convergence was less conspicuous than in the south of Australia.

Period analysis made for data obtained on February 25–27 yielded generally the same result as that seen in the southwest of Australia, while the amplitude was further suppressed, *i.e.*, 0.06 $\mu g/l$ or $\pm 23\%$ of the mean concentration of 0.25 $\mu g/l$. This implies that, although the nature of diel variability of chlorophyll was conserved, its extent was restrainted in February. We did not determine the causes; whether or not the environmental conditions such as shortened and reduced solar radiation or the internal conditions such as decreased biomass of phytoplankton itself, etc. are responsible for this restraint. They should be investigated in detail in later cruises after the continuous measuring-recording system was improved.

In the south of Africa, four convergences have been recognized, *i.e.*, from north to south, the Agulhas Convergence (AGC) around 40°S (FUKASE, 1962), the Subtropical Convergence (STC) around only a few degrees south of the Agulhas Convergence, the possible Subantarctic Front (SAF) (DEACON, 1982) and the Antarctic Convergence (AC). In our data the Subantarctic Front was not detected, while the possibility that the SHIRASE passed over it during two hours interruption of the recording on February 29 (Fig. 5a) cannot be denied.

Because the Agulhas and Subtropical Convergences are also located closer to each other, discrimination among them may not be always possible without the continuous recordings. In the present records, striking jump in temperature of *ca.* 9°C within a very narrow latitudinal range of 17′ was recorded around 42°15′S. This change at the Agulhas Convergence occurred too rapidly (the SHIRASE crossed the Agulhas Convergence in one hour) so that the output level of the T-S recorder could not be shifted in time. It was only 2° north of the Subtropical Convergence which was formed between 44°10′ and 45°25′S (Fig. 5a).

The Antarctic Convergence was detected at 51°40′–52°20′S. Silicate concentration (IWANAMI and FUTATSUMACHI, 1986) and temperature changed rapidly but salinity was nearly constant on both sides of the convergence (Fig. 5a). In the convergence zone, phytoplankton was likely to be accumulated. Although a positive relationship between chlorophyll and temperature seemed to exist (Fig. 5b), it may not be held if more data could be sorted in the convergence zone (*cf.* Fig. 5a). In the Subantarctic water between the Antarctic and the Subtropical Convergences, a negative temperature-chlorophyll relationship was prevailing as seen in the south of Australia.

In the areas between the Subtropical and the Agulhas Convergences, chlorophyll stocks were very large compared with the eastern Indian Ocean as mentioned above. In detail, however, the stock in the Subtropical Convergence zone, though increased toward the northern half as reported by PLANCKE (1977), was not large especially in its southern half. The stock in the Agulhas Convergence zone was large but did not exceed the highest value which occurred in the middle area between the two convergences. This is likely to indicate that an unknown phenomenon inducing the phytoplankton

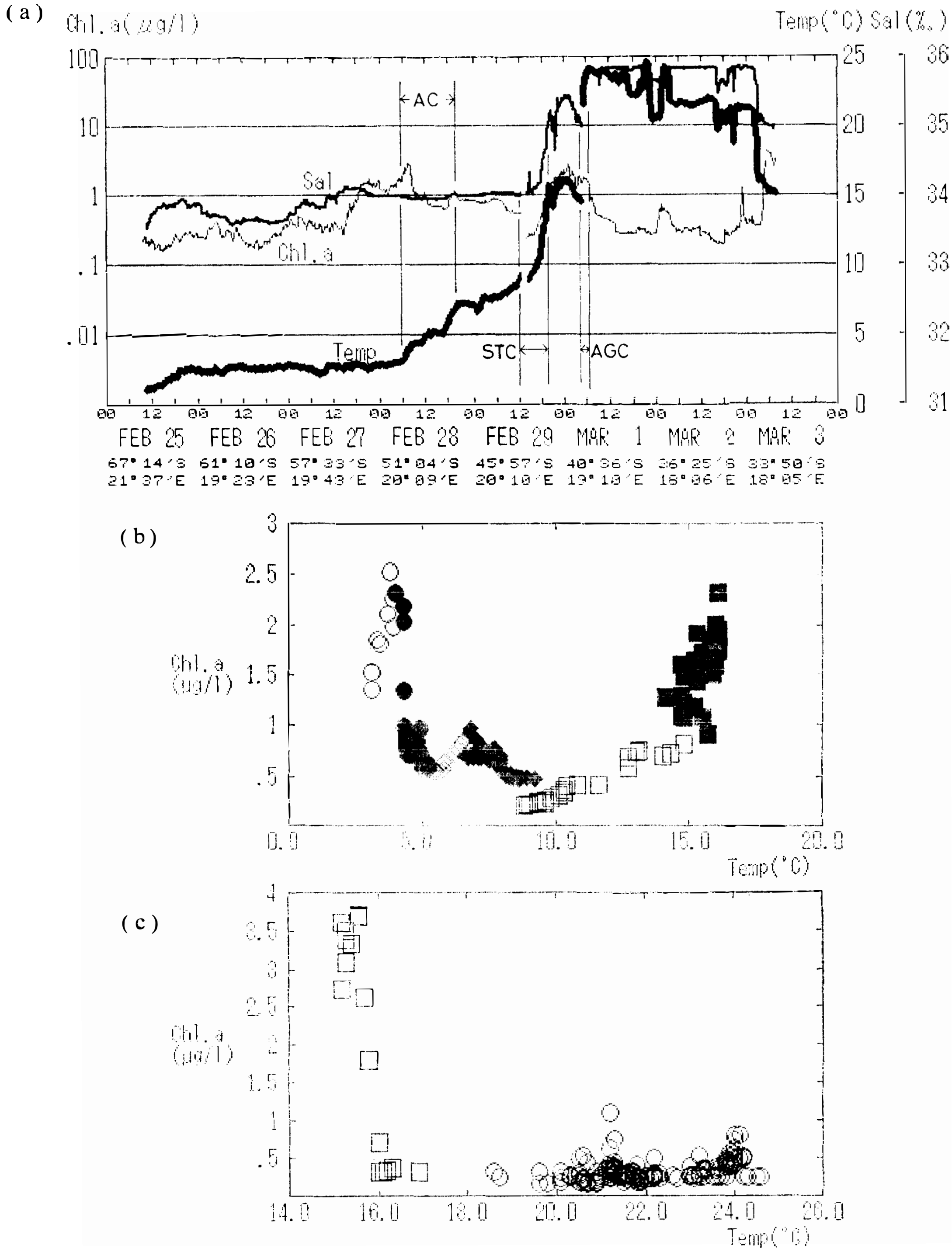

Fig. 5. Variations of chlorophyll a and those of temperature and salinity at 8 m depth in the sea area south of South Africa recorded during February 25–March 3, 1984. (a) Variations in time sequence. AC: Antarctic Convergence, STC: Subtropical Convergence, AGC: Agulhas Convergence. (b) Temperature-chlorophyll diagram between 0600 February 28 and 0345 March 1. Open circle: data obtained between 0600 and 0745 February 28, solid circle: between 0800 and 1645 February 28, open diamond: between 1700 and 1945 February 28, solid diamond: between 2000 February 28 and 1230 February 29, open square: between 1400 and 1945 February 29, solid square: between 2000 February 29 and 0345 March 1. (c) Temperature-chlorophyll diagram between 0700 March 1 and 0700 March 3. Open circle: between 0700 March 1 and 0245 March 3, open square: between 0300 March 1 and 0700 March 3.

productivity such as upwelling existed between two convergences. It is not quite unreasonable that the two convergences are generating a divergence between them, although it could not be supported by the present data on temperature and salinity. Only a positive temperature-chlorophyll relationship was seen over the area between the two convergences (Fig. 5b).

In the Subtropical water north of the Agulhas Convergence, hydrographic conditions were spatially heterogeneous; variability of temperature and salinity is evident in Fig. 5a. This might reflect existing vortices in this area (*cf.* Fig. 7 in FUKASE, 1962). Near the African coast, a low temperature and low salinity water mass which is probably coastal water existed. Chlorophyll also varied irregularly and the phase was not concurrent with those of temperature and salinity (Fig. 5c). The peaks of chlorophyll seemed to be caused by diel periodicity, but their timings were not synchronized in the successive days (Fig. 5a). There might be vortices of various origins and ages which resulted in complicated temperature, salinity and chlorophyll distributions. In the water near the African coast, chlorophyll stock was very large. It increased rapidly as temperature and salinity suddenly decreased approaching to the coast (Figs. 5a, 5c), being under the influence of land drainage.

4. Concluding Remarks

We designed a very simple prototype of continuous measuring-recording system of chlorophyll in the subsurface (8 m) layer. The results obtained confirm general knowledge about the geographical distribution and diel variation of chlorophyll which have been reported by many previous authors. In addition to these, several facts that could be found only by continuous monitoring are also observed. For example, the relationships of chlorophyll to temperature, on smaller and larger scales, are variable among different sea areas, the diel variation becomes lesser in coastal areas where the 12-hour periodicity becomes influential, and the presence of particular hydrographic conditions enhancing phytoplankton productivity is suggested in the area between the Subtropical and the Agulhas Convergences south of South Africa. To discuss these findings thoroughly and make demarcation of sea areas easier in future cruises, the system has to be equipped with the interlocking monitors on temperature, salinity and nutrients. The last is a particularly important clue to determine the age of different water masses occupying narrow geographic ranges (*cf.* LE JEHAN and TREGUER, 1983). Depending on the age of water masses, effects of temperature and of other factors, such as nutrient level and zooplankton biomass as well, are possibly variable.

Acknowledgments

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