—研究論文—
Scientific Papers

Fine Scale Distribution of Phytoplankton Abundance along the Cruise Track of the Icebreaker SHIRASE, from Tokyo to Fremantle, Australia in the 1991 Season

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「しらせ」航路上における植物プランクトン量の微細分布
(東京～フリマントル，オーストラリア，1991年)

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要旨: 1991年11月14日～28日の砕氷艦「しらせ」の第一レグ航路上(東京～フリマントル)で，表面水モニタリングシステム(SWMS)を用い，水温，塩分，クロロフィル現場蛍光値を5分間隔で調べた．この間，現場蛍光の急激な増加が5カ所においてみられた．その内4カ所は東南アジア沿岸水の島嶼間でみられ，いずれも低水温水塊と関連しており，海岸線や海底地形の変化により引き起こされる底層水の湧昇を示唆した．現場蛍光より見積ったクロロフィル*a*濃度は，過去の観測結果と平均的には一致した．しかしながら，ロンボク海峡でSWMSによって検出された最高濃度は，1日2～3回の観測にもとづく今までの結果よりかなり高かった．SWMSを用いた微細観測では，植物プランクトン群集の局所的増加における空間的規模やその最大量を容易に明らかにすることができる．沿岸域で起こる局所的現象の調査にはSWMSが威力を発揮することが確かめられた．

Abstract: Water temperature, salinity, and *in vivo* fluorescence intensity were investigated using the Surface Water Monitoring System (SWMS) with five minute intervals along the first leg of the icebreaker SHIRASE cruise (Tokyo–Fremantle) from November 14 to 28, 1991 (JARE-33). Five prominent increases of *in vivo* fluorescence occurred during the period. Among them four were observed between islands in the coastal area of Southeast Asia, and were related to occurrence of low temperature water, suggesting local upwelling caused by the coast line and/or submarine topography. Average concentrations of chlorophyll *a* estimated from the *in vivo* fluorescence were consistent with those of previous observations based on sampling two to three times a day. However, the highest concentration detected by the SWMS in Lombok Strait was considerably more than the previous values. High resolution survey by the SWMS can easily reveal local increases of phytoplankton on a finer spatial scale than those with conventional observations. It is confirmed that the SWMS is a powerful tool to investigate local events in coastal waters.

1. Introduction

Since 1983 members of the Japanese Antarctic Research Expedition and their supplies have been transported by the icebreaker SHIRASE (19000 t, Japan Maritime Self-Defense Force), which departs Japan in the middle of every November. She

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cruises in the subtropical waters of both hemispheres, equatorial water, subantarctic water, and Antarctic water. She also crosses the Celebes Sea, Makassar Strait, and the west part of the Flores Sea. Phytoplankton chlorophyll stocks along the JARE cruise tracks have been reviewed in relation to oceanographic fronts in the Southern Ocean (FUKUCHI, 1980). Detailed distribution of chlorophyll, however, has not been reported in the Southeast Asian seas.

Since hydrographic environments are more complicated and tempo-spatial variation of phytoplankton abundance is larger in coastal waters than in open waters (PARSONS *et al.*, 1984a and references therein), fine scale observations are required to evaluate phytoplankton dynamics in coastal waters. The Surface Water Monitoring System (SWMS) has been installed on the icebreaker SHIRASE since 1985 (FUKUCHI and HATTORI, 1987). The system automatically collects data on physical, chemical and biological variables every five minutes during a cruise. Then, the SWMS is a suitable tool to detect oceanographic fronts and local events. This paper represents the fine scale distribution of phytoplankton and environmental variables observed using the SWMS in the open waters of the western North Pacific Ocean and the eastern Indian Ocean, and the coastal waters of Southeast Asia along the first leg of the icebreaker SHIRASE cruise (JARE-33).

2. Materials and Methods

The icebreaker SHIRASE departed Japan on November 14 and arrived at Fremantle, Australia, on November 28, 1991 (JARE-33) (Fig. 1). The present data include surface water temperature, salinity, *in vivo* fluorescence intensity, and depth, collected from 1100 November 17 (GMT) (17°06.0′N, 131°47.7′E) to 0155 November 25 (GMT) (22°36.7′S, 112°44.1′E). Since the mean ship speed was 15.5 knots and the data were collected every five minutes, the interval was estimated as *ca.* 1.3 nautical miles.

To compare the value of *in vivo* fluorescence intensity with extracted chlorophyll *a* concentration, seawater (200 m*l*) from the outlet of the SWMS was taken at the same time as the data output and the water was filltered through a Whatman GF/F filter. The filter was put into a glass vial filled with 6 m*l* of N,N-dimethylformamide (DMF) (SUZUKI and ISHIMARU, 1990), and was stored at −20°C for 24 hours in the dark to extract algal pigments. Concentrations of chlorophyll *a* were determined by a fluorometer (Turner Designs Model 10R), which was calibrated with pure chlorophyll *a* (Sigma Chemical Co.) (PARSONS *et al.*, 1984b). Although the DMF for the extraction of chlorophyllous pigments has not been used by previous JARE investigators, no marked difference between DMF and 90% acetone was found (SUZUKI and ISHIMARU 1990; ODATE *et al.*, 1993).

3. Results

Surface water temperature and salinity, *in vivo* fluorescence intensity, and sea depth recorded using the SWMS are shown in Fig. 2. Five prominent increases of *in vivo* fluorescence were observed in the area along the cruise track. The first increase occurred in the area north-east of the Celebes Sea (Area A), where sea depth decreases from >*ca.* 5000 m to 1300 m. The second and the third increases were

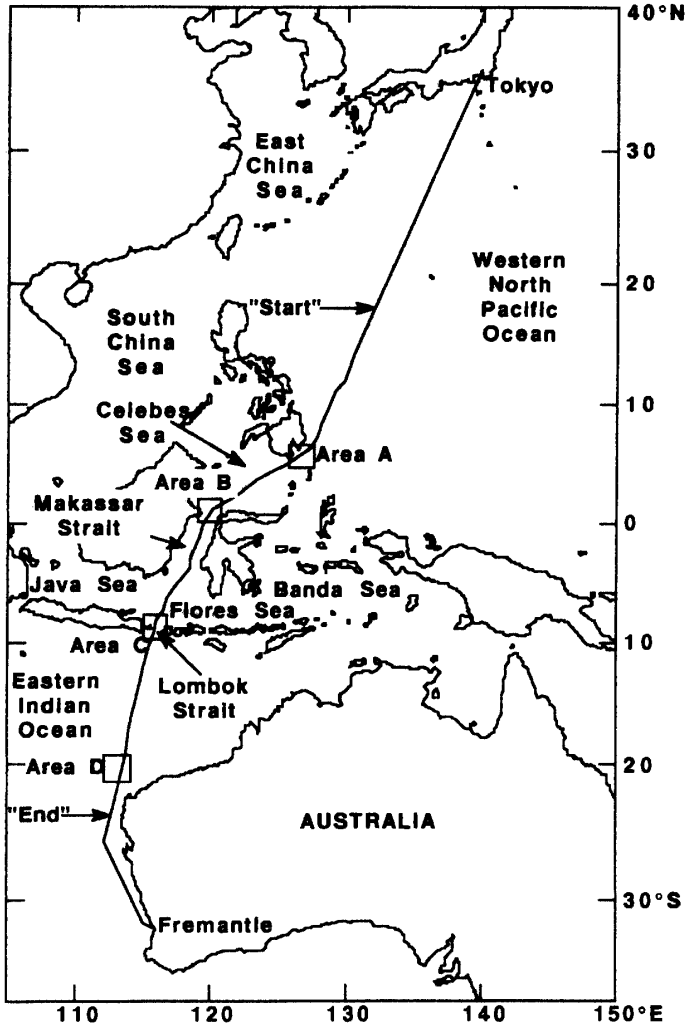

Fig. 1. Cruise track of the icebreaker SHIRASE *from Tokyo to Fremantle, Australia (JARE-33). In the present study data collected from "Start" to "End" are used. In Areas A, B, C, and D, steep increases of* in vivo *fluorescence occurred.*

observed between the Celebes Sea and Makassar Strait (Area B). The ocean depth decreases from ca. 5000 m in the Celebes Sea to 2000 m in Makassar Strait. The highest *in vivo* fluorescence occurred in Lombok Strait (sea depth, <300 m) (Area C). The last increase was recorded in the eastern Indian Ocean off the west coast of Australia (Area D). The four increases of *in vivo* fluorescence in Areas A, B and C seem to be related to the low temperature of surface water, while the increase in Area D is unlikely to be related to low water temperature. Detailed distributions of the same parameters in Areas A, B, C and D are in Figs. 3, 4, 5, and 6, respectively.

In Area A, relatively low temperature water was observed from 1500 to 1700 on November 20 (GMT), although salinity was fairly constant (33.65–33.69) and was intermediate between the western North Pacific and the Celebes Sea (Fig. 3). During this time high values of *in vivo* fluorescence were detected with two major peaks at a distance of *ca.* 31 nautical miles.

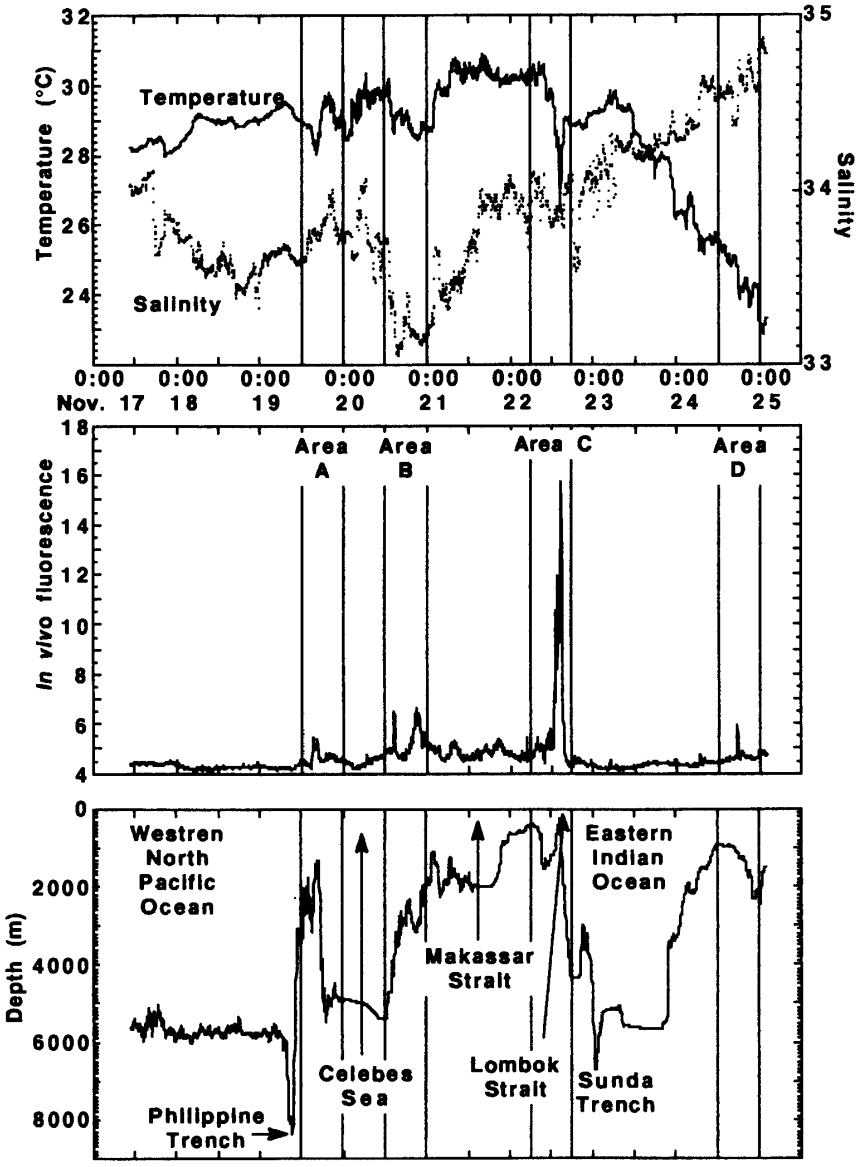

Fig. 2. Fine scale distributions of seawater temperature, salinity, in vivo *fluorescence intensity, and sea depth recorded by the Surface Water Monitoring System.*

The second and third steep increases of *in vivo* fluorescence in Area B were observed from 1400 to 1500 (*ca.* 16 nautical miles) and 1900 to 2230 (*ca.* 54 nautical miles) on November 21 (GMT), respectively (Fig. 4). These increases also coincided with the occurrence of low temperature water. Relatively low salinity was recorded from 1500 to 1600, when *in vivo* fluorescence intensity was at a low level, as observed in the Celebes Sea.

In Area C *in vivo* fluorescence increased from 1300 on November 22 (GMT) when water temperature dropped (Fig. 5). The fluorescence further increased between 1400 and 1500 when rapid decrease of water temperature was recorded. The distance of the high fluorescence area was about 40 nautical miles. The low

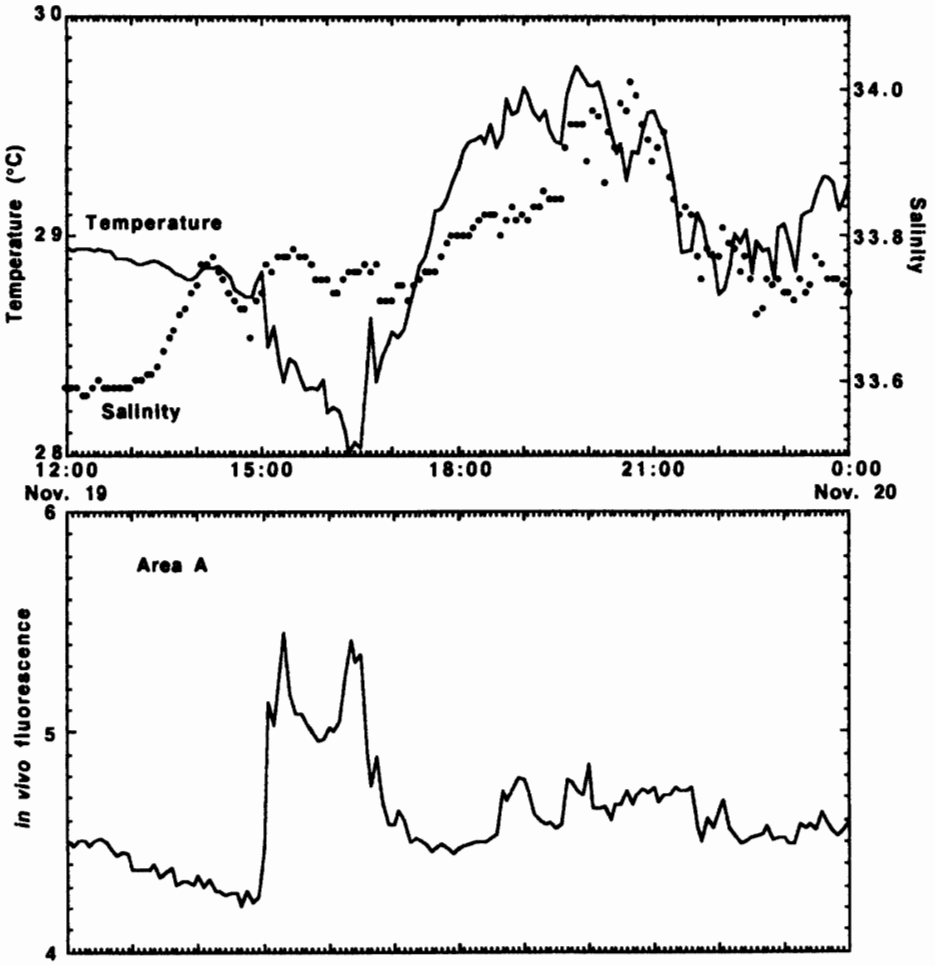

Fig. 3. Enlarged distributions of water temperature, salinity, and in vivo *fluorescence intensity in Area A.*

temperature was likely to be related to the high salinity as observed between 1400 and 1500.

In open waters of the Indian Ocean, a steep increase of *in vivo* fluorescence also occurred from 1710 to 1740 on November 25 (Area D) (Fig. 6) at a distance of *ca.* 8 nautical miles. No marked decrease of surface water temperature was observed during this time, although lowered salinity was recorded. The decrease of salinity began from 1600, but *in vivo* fluorescence was still low between 1600 and 1700.

An inverse relationship between *in vivo* fluorescence intensity and water temperature has been recognized in Areas A, B, and C (Figs. 3, 4, and 5, respectively). Here we further analyze the relationship between change rates of *in vivo* fluorescence intensity and physical variables (Figs. 7 and 8). In these figures, running means of increment for five minutes were calculated based on twelve sequential data, and were used as a measure of the variations of parameters. In Areas A, B, and C, rapid increase and decrease of *in vivo* fluorescence coincided with sharp decrease and increase of water temperature, respectively (Fig. 7). The increment of 1°C/h of temperature corresponded with decreases of about 1, 2, and 5 mV/h of *in*

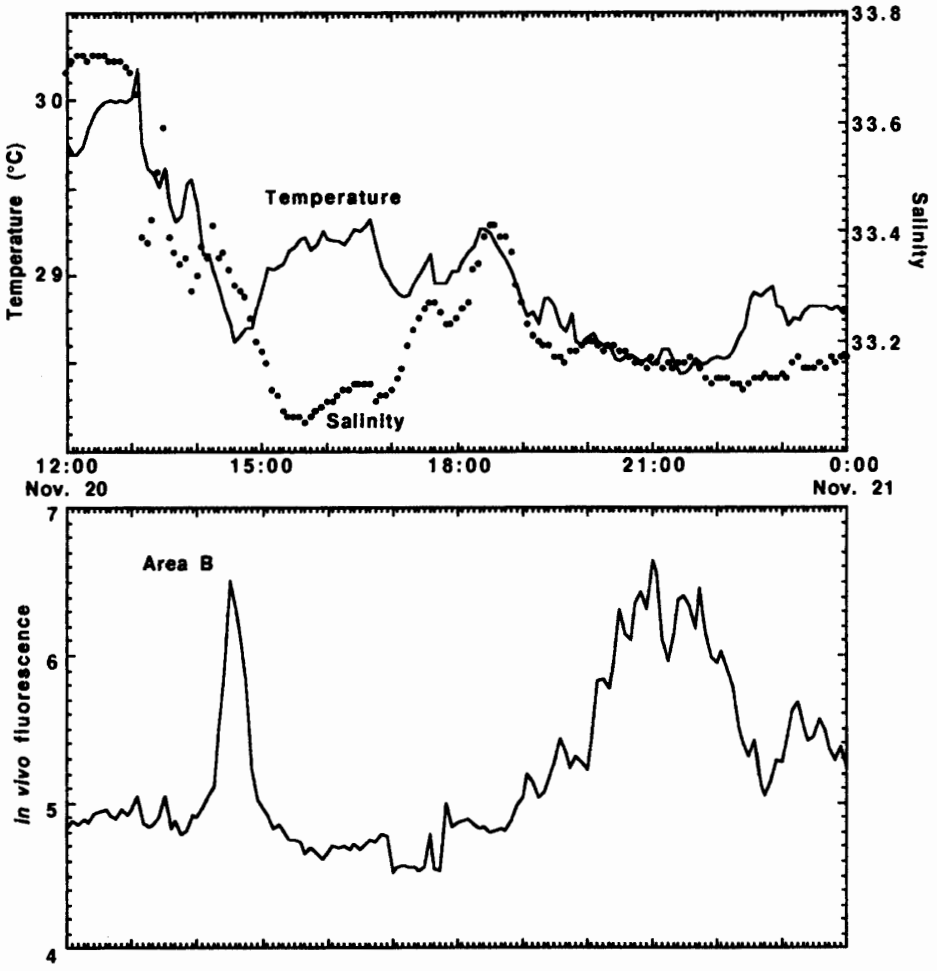

Fig. 4. Same as Fig. 3 but for Area B.

vivo fluorescence in the respective areas. In particular, the decrement reached ±2.5°C/h in Area C, resulting in increments of *in vivo* fluorescence of ±7–9 mV/h. Such a trend is not observed in Area D. In other sea areas water temperature sometimes changed by ±1°C/h, but variation of *in vivo* fluorescence was less than ±0.5 mV/h. On the other hand, *in vivo* fluorescence considerably varied in the surveyed sea areas, although salinity did not change (0 psu/h) (Fig. 8).

The intensity of *in vivo* fluorescence and the extracted chlorophyll *a* concentration of the same seawater has a statistically significant relation ($y=2.831 \log(x)-1.68$, $r=0.981$, $n=32$) ($p<0.001$). The values of *in vivo* fluorescence are converted into chlorophyll *a* concentration and listed with the previous results (Table 1). The mean chlorophyll *a* was lower in the open water of the western North Pacific Ocean and the eastern Indian Ocean (0.11 and 0.15 $\mu g/l$, respectively) than in the coastal water of Southeast Asia. The highest values of *in vivo* fluorescence observed in Areas A, B, C, and D were estimated to be 0.40, 0.65, 1.71, and 0.51 $\mu g/l$, respectively.

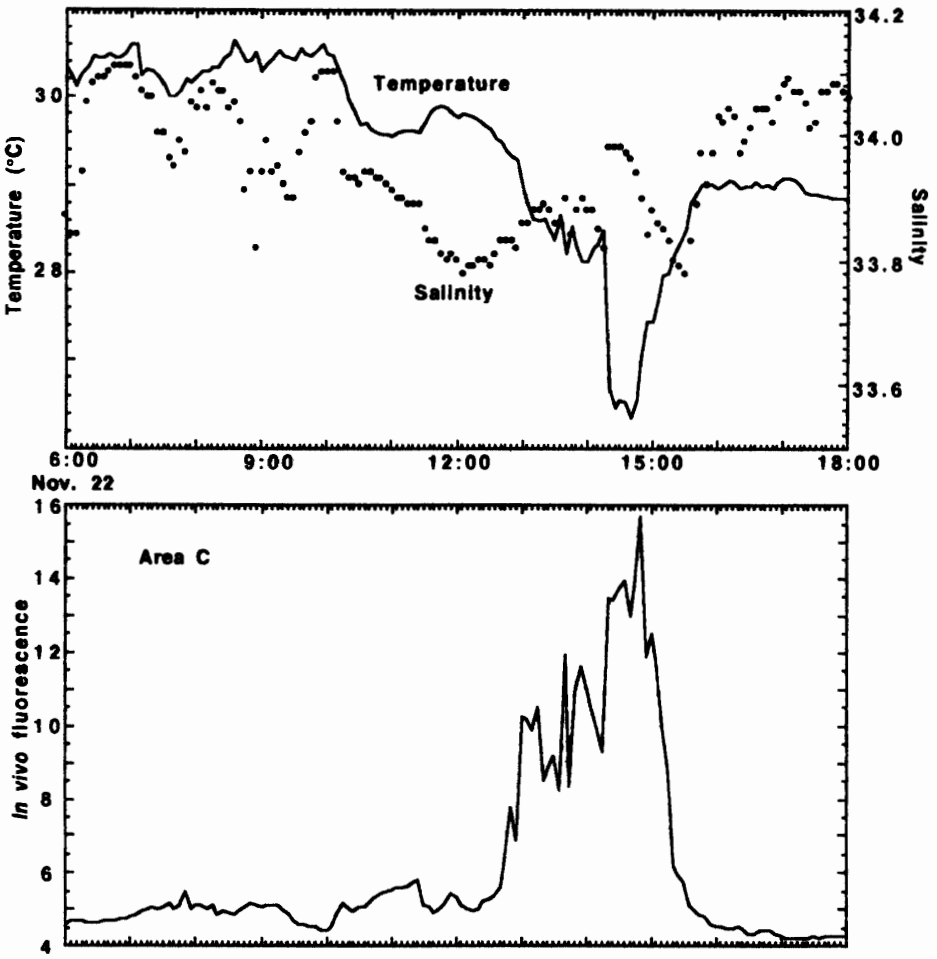

Fig. 5. Same as Fig. 3 but for Area C.

4. Discussion

Surface distribution of chlorophyll *a* has been recorded since 1965 (JARE-7) (HOSHIAI, 1968). Earlier studies showing a fine scale distribution of *in vivo* fluorescence were conducted during the JARE-25 (TANIGUCHI *et al.*, 1986) and JARE-26 cruises (FUKUCHI *et al.*, 1986). These results mainly dealt with the oceanic fronts in the Southern Ocean such as the Subtropical Convergence, the Subantarctic Front, and the Antarctic Polar Front. The present study shows the fine scale distribution of *in vivo* fluorescence as well as water temperature and salinity along the first leg of the JARE-33 cruise, using the SWMS installed on the icebreaker SHIRASE (FUKUCHI and HATTORI, 1987). Prominent increases of *in vivo* fluorescence occurred in the sea area between the western North Pacific Ocean and the Celebes Sea (Area A), between the Celebes Sea and Makassar Strait (Area B), and in Lombok Strait (Area C) (Fig. 2).

Mean standing stocks of the surface chlorophyll *a* concentration based on *in vivo* fluorescence intensity are comparable with previous results (Table 1), which also showed high phytoplankton abundance in the Celebes Sea and Makassar Strait. The

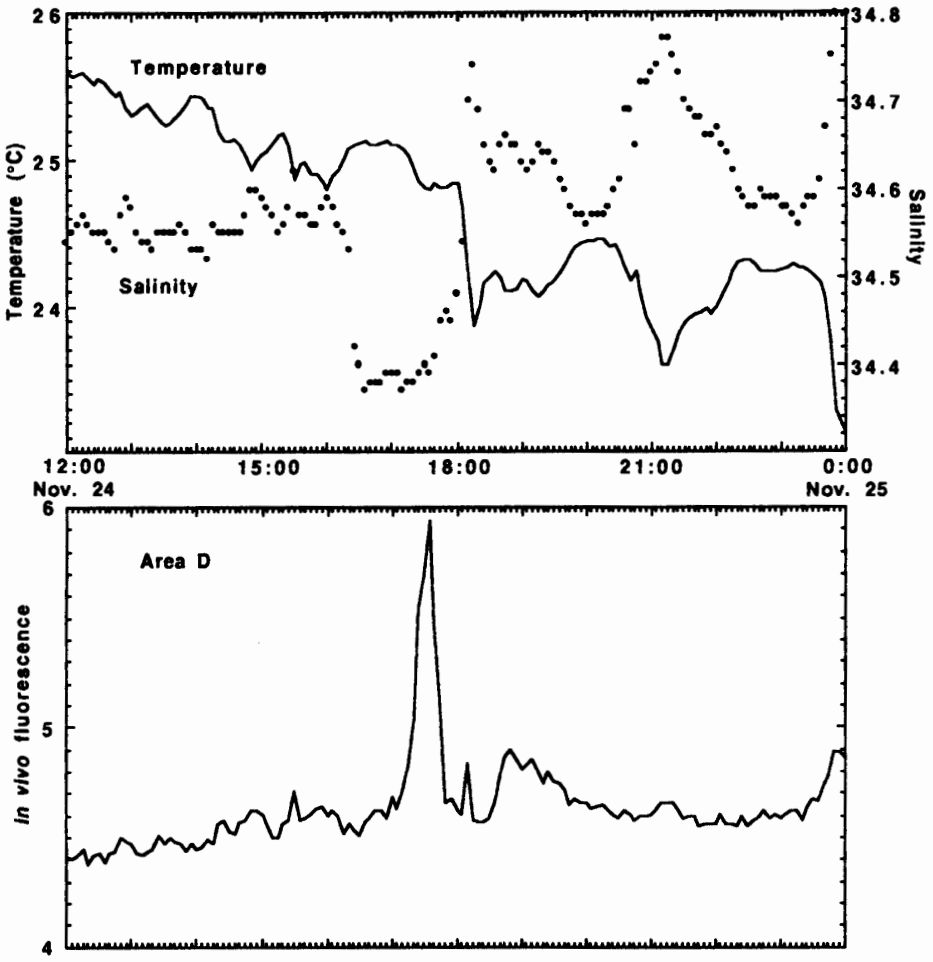

Fig. 6. Same as Fig. 3 but for Area D.

highest concentration of chlorophyll *a* in the present study is 1.71 $\mu g/l$, which is considerably higher than the previously reported maximum, 0.77 $\mu g/l$ (FUKUCHI, 1977). This quantitative difference mainly results from the sampling frequency. The present data were collected every five minutes, while the previous samplings were taken two to three times a day. Marked increases continued within a few hours (within several ten nautical miles) along the cruise track. In addition, the previous JARE investigators failed to collect sample water rich in phytoplankton. Using the SWMS with a computerized and highspeed data processing system for multiple variables, we can easily observe fine scale distribution of phytoplankton abundance.

The present results demonstrate that phytoplankton-rich waters occurred in waters colder than surrounding water masses, usually between islands (Figs. 3, 4, and 5). The high abundance in the coastal waters of Southeast Asia seems to be related to the occurrence of upwelled deep waters, which is affected by the coast line and submarine topography (PARSONS *et al.*, 1984a and references therein). Nutrients contained in the upwelled water are utilized by phytoplankton in the surface layer; then the abundance of phytoplankton is elevated (MACISAAC *et al.*, 1985; TAKAHASHI *et al.*, 1986; WILKERSON and DUGDALE, 1987). Such increase of biological production

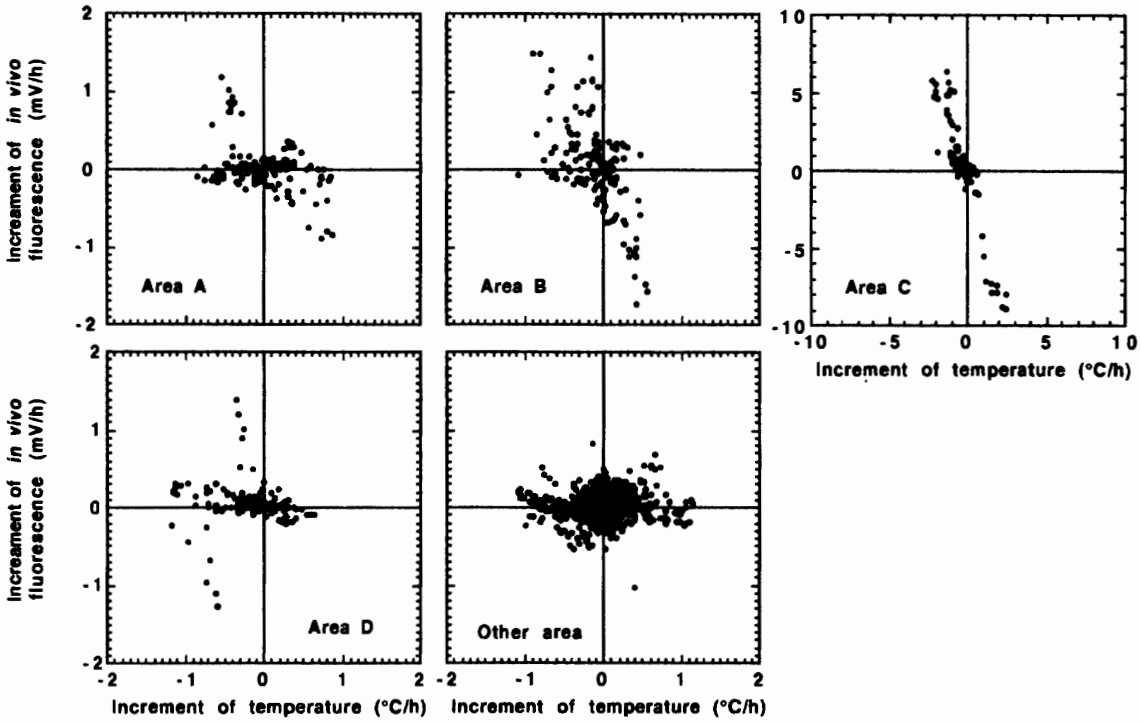

Fig. 7. Relationship between change rates of in vivo *fluorescence intensity and temperature in Areas A to D and the other sea areas. The running means of the increments over five minutes are calculated based on twelve sequential data, and are used as parameters.*

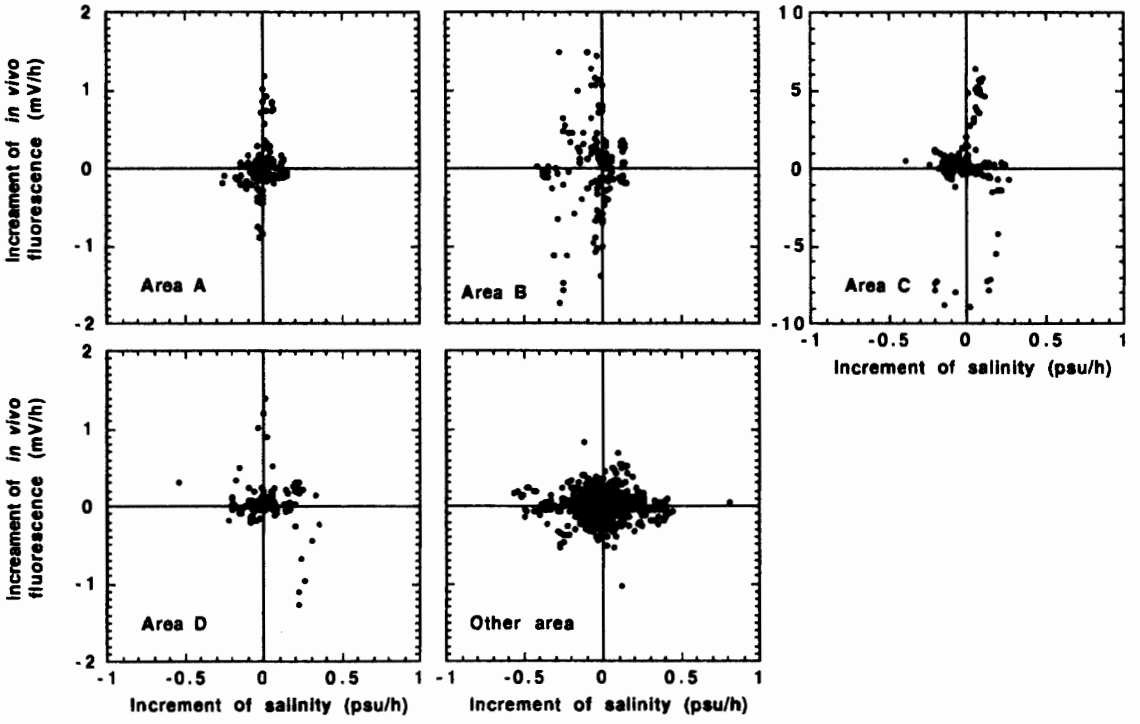

Fig. 8. Relationship between rates of change of in vivo *fluorescence intensity and salinity in Areas A to D and the other sea areas. The running means of the increments for five minutes are calculated based on twelve sequential data, and are used as the parameters.*

Table 1. Chlorophyll a standing stocks (μg/l) [mean ± 1SD (number of data)] in the western North Pacific Ocean, the eastern Indian Ocean, and coastal waters of Southeast Asia observed by several cruises of the JARE in November and December.

Cruise	Western North Pacific Ocean	Eastern Indian Ocean	Coastal waters of Southeast Asia	Reference
JARE-7	0.11 ± 0.046 (12)	0.10 ± 0.028 (9)	0.20 ± 0.118 (7)	HOSHIAI (1968)
JARE-9	0.10 ± 0.028 (9)	0.06 ± 0.013 (4)	0.27 ± 0.168 (3)	TOMINAGA (1971)
JARE-10	0.11 ± 0.075 (12)	0.07 ± 0.025 (9)	0.14 ± 0.039 (6)	TAKAHASHI (1969)
JARE-12	0.05 ± 0.025 (12)	0.11 ± 0.092 (7)	nd	NISHIWAKI (1972)
JARE-14	0.16 ± 0.083 (11)*	0.14 ± 0.059 (10)	0.32 ± 0.189 (7)	KURODA (1978)
JARE-15	0.08 ± 0.040 (11)	0.06 ± 0.020 (11)	0.18 ± 0.056 (8)	HOSHINO (1974)
JARE-16	0.13 ± 0.086 (13)	0.13 ± 0.031 (9)	0.20 ± 0.067 (8)	OHNO (1976)
JARE-17	0.08 (2)	0.15 ± 0.111 (9)	0.19 ± 0.168 (6)	OHYAMA and MAYAMA (1976)
JARE-18	0.07 ± 0.047 (7)	0.13 ± 0.095 (10)	0.34 ± 0.235 (8)	FUKUCHI (1977)
JARE-20	0.14 ± 0.182 (18)	0.11 ± 0.079 (12)	0.28 ± 0.156 (12)	FUKUCHI and TAMURA (1982)
JARE-21	0.05 ± 0.012 (9)	0.08 ± 0.025 (9)	0.26 ± 0.079 (7)	TANIMURA (1981)
JARE-22	0.10 ± 0.080 (12)	0.08 ± 0.059 (10)	0.22 ± 0.095 (7)	WATANABE and NAKAJIMA (1983)
JARE-23	0.04 ± 0.019 (10)	0.09 ± 0.051 (10)	0.29 ± 0.187 (6)	INO and FUKUCHI (1984)
JARE-26	0.09 ± 0.015 (16)	0.17 ± 0.127 (20)	0.28 ± 0.142 (12)	FUKUDA *et al.* (1986)
JARE-33	0.11 ± 0.028 (612)	0.15 ± 0.052 (696)	0.29 ± 0.206 (888)	This study

*One extremely high value has been eliminated.

associated with islands is referred to the 'island mass effect' (PARSONS *et al.*, 1984a).

The highest phytoplankton abundance along the first leg of the JARE-33 cruise occurred in Lombok Strait. The rate of change of *in vivo* fluorescence was more rapid in this strait than in the Celebes Sea and Makassar Strait, even though the rate of change of temperature was the same (Fig. 7). This suggests that the upwelled deep water in Lombok Strait contains a larger amount of nutrients than that in the other areas. Moreover the highest rate of change of temperature occurred in the strait (Fig. 7). Since the ocean depth is shallow in Lombok Strait (Fig. 2), the submarine topography may severely affect phytoplankton dynamics in the surface layer. Inputs of nutrients from land cannot be neglected in coastal waters. Relatively saline waters probably have small contributions in nutrient transports from land, although KURODA (1978) pointed out the possibility of nutrient inputs from land in coastal waters.

A rapid increase of *in vivo* fluorescence in the open water of the eastern Indian Ocean (Fig. 6) was also reported by some of the previous JARE studies (OHYAMA and MAYAMA, 1976; FUKUCHI, 1977; FUKUCHI and TAMURA, 1982; FUKUDA *et al.*, 1986). The increase in open waters did not correlate with the occurrence of low temperature water, in contrast to what was observed in coastal waters. The increase may result from advection of an other water mass, since *in vivo* fluorescence increased after decrease of salinity.

The present study with the high resolution survey of the SWMS can easily reveal local increases of phytoplankton. It is confirmed that the SWMS is a powerful tool to analyze the fine scale distribution of phytoplankton in relation to environmental variables, as recommended by FUKUCHI and HATTORI (1987).

Acknowledgments

The authors are indebted to Captain M. SAITOH of the icebreaker SHIRASE, Japan Maritime Self-Defense Force, and his officers and crew, and to the members of JARE-33 for their cooperation during the cruise. The present study was partially supported by grants from the Ministry of Education, Science and Culture (Grant Nos. 03248208 and 04660204 to T.O.).

References

FUKUCHI, M. (1977): Chlorophyll-*a* contents in the surface water along the course of the FUJI to and from Antarctica in 1976–1977. Nankyoku Shiryô (Antarct. Rec.), **60**, 57–69.

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

FUKUCHI, M., FUKUDA, Y., OHNO, M. and HATTORI, H. (1986): Surface phytoplankton chlorophyll distribution continuously observed in the JARE-26 cruise (1984/1985) to Syowa Station, Antarctica (SIBEX II). Mem. Natl Inst. Polar Res., Spec. Issue, **44**, 15–23.

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. 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.

FUKUDA, Y., OHNO, M., IWANAMI, K. and TOUJU, H. (1986): Chlorophyll *a* content in the surface and subsurface waters along the cruise of the SHIRASE to Antarctica in 1984–1985. Nankyoku Shiryô (Antarct. Rec.), **30**, 103–112.

HOSHIAI, T. (1968): Chlorophyll-a contents in the surface water observed during the cruise of FUJI to the Antarctic in 1965–1966. Nankyoku Shiryô (Antarct. Rec.), **32**, 55–62.

HOSHINO, T. (1974): Surface water chlorophyll-a contents observed during the cruise of the FUJI to Antarctica, November 1973–April 1974. Nankyoku Shiryô (Antarct. Rec.), **51**, 29–38.

INO, Y. and FUKUCHI, M. (1984): Report on chlorophyll *a* distribution along the course of the FUJI in 1981–1982. Nankyoku Shiryô (Antarct. Rec.), **81**, 38–44.

KURODA, K. (1978): Distribution of chlorophyll-*a* contents in the surface water along the cruise of the FUJI to and from Antarctica in 1972–1973. Nankyoku Shiryô (Antarct. Rec.), **61**, 65–74.

MACISAAC, J.J., DUGDALE, R.C., BARBER, T., BLASCO, D. and PACKARD, T.T. (1985): Primary production cycle in an upwelling center. Deep-Sea Res., **32**, 503–529.

NISHIWAKI, S. (1972): Chlorophyll-a content in the surface sea water observed in 1970–1971 during the cruise of FUJI to Antarctica. Nankyoku Shiryô (Antarct. Rec.), **44**, 93–99.

ODATE, T., HARADA, N. and FUKUCHI, M. (1993): Comparisons of N,N-dimethylformamide and 90% acetone as an extraction solvent for fluorometric determination of chlorophyll *a* from natural phytoplankton communities in the Southern Ocean. Nankyoku Shiryô (Antarct. Rec.), **37**, 260–264.

OHNO, M. (1976): Chlorophyll-*a* content in the surface water observed during the cruise of the FUJI to Antarctica in 1974–1975. Nankyoku Shiryô (Antarct. Rec.), **57**, 106–114.

OHYAMA, Y. and MAYAMA, T. (1976): Chlorophyll-*a* contents in the surface water observed during the relief voyage of FUJI to Syowa Station, Antarctica, in 1975–1976. Nankyoku Shiryô (Antarct. Rec.), **57**, 115–122.

PARSONS, T.R., TAKAHASHI, M. and HARGRAVE, B. (1984a): Biological Oceanographic Processes. 3rd ed. Oxford, Pergamon Press, 330 p.

PARSONS, T.R., MAITA, Y. and LALLI, C.M. (1984b): A Manual of Chemical and Biological Methods for Seawater Analysis. Oxford, Pergamon Press, 173 p.

SUZUKI, R. and ISHIMARU, T. (1990): An improved method for the determination of phytoplankton chlorophyll using N,N-dimethylformamide. Nippon Kaiyô Gakkaishi (J. Oceanogr. Soc. Jpn.), **46**, 190–194.

TAKAHASHI, E. (1969): Chlorophyll-a content in the surface water observed in 1968–1969 during the cruise

of FUJI to Antarctica. Nankyoku Shiryô (Antarct. Rec.), **36**, 65–72.

TAKAHASHI, M., ISHIZAKA, J., ISHIMARU, T., ATKINSON, L.P., LEE, T.N., YAMAGUCHI, Y., FUJITA, Y. and ICHIMURA, S. (1986): Temporal change in nutrient concentration and phytoplankton biomass in short time scale local upwelling around the Izu Peninsula, Japan. J. Plankton Res., **8**, 1039–1049.

TANIGUCHI, A., HAMADA, E., OKAZAKI, M. and NAITO, Y. (1986): Distribution of phytoplankton chlorophyll continuously recorded in the JARE-25 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 FUJI to and from Antarctica in 1979–1980. Nankyoku Shiryô (Antarct. Rec.), **72**, 35–48.

TOMINAGA, H. (1971): Chlorophyll *a* and phaeophytin contents in the surface water of the Antarctic Ocean through the Indian Ocean. Nankyoku Shiryô (Antarct. Rec.), **42**, 124–134.

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.

WILKERSON, F.P. and DUGDALE, R.C. (1987): The use of large shipboard barrels and drifters to study the effects of coastal upwelling on phytoplankton dynamics. Limnol. Oceanogr., **32**, 368–382.

(Received December 17, 1993; Revised manuscript received February 7, 1994)