Vertical Distribution of Chlorophyll *a* in the Indian Sector of the Antarctic Ocean in 1972–1973

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1972–1973 年，南極海インド洋区におけるクロロフィル *a* の垂直分布

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要旨： 第14次日本南極地域観測隊の海洋生物調査の一環として，南極海インド洋区において，水深 500 m までのクロロフィル *a* 量の垂直分布を調査した．観測は，1972 年 12 月に「ふじ」南下航路上の東経 105 度線に沿った南緯 38～60 度間の 6 点，および南緯 60 度以南域の 2 点で行われた．1973 年 2～3 月の北上航路上においては東経 15 度線上に沿った南緯 67～35 度間の 9 点で観測を実施した．表面海水中および亜表層極大層におけるクロロフィル *a* 量は，南下航路上の南極海域において顕著に高かった．全観測点を通して，0～250 m 水柱内のクロロフィル *a* 積算値は 17～129 mg/m² であり，特に南下航路上の南極海域において高かった．これは 12 月下旬が南極海域における植物プランクトンの増殖期に相当することによる現象と考えられた．有光層内のクロロフィル *a* 積算値は 8～43 mg/m² であった．有光層より下層における高クロロフィル *a* 量分布が，南極海域において顕著にみられた．表面海水中のクロロフィル *a* 量と亜表層におけるクロロフィル *a* 量およびクロロフィル *a* 積算値との間に正の相関がみられた．

Abstract: In the Indian sector of the Antarctic Ocean, vertical distribution of chlorophyll *a* down to a depth of 500 m was investigated. The observations were carried out as part of the marine biological programs of the 14th Japanese Antarctic Research Expedition at six stations on the southward leg of the FUJI between 38° and 60°S along 105°E, two stations south of 60°S in December 1972, and at nine stations on the northward leg between 67° and 35°S along 15°E in February and March 1973. High surface chlorophyll *a* contents and the remarkable subsurface maximum of chlorophyll *a* were distributed in the Antarctic water on the southward leg. Integrated chlorophyll *a* stocks in a 0–250 m water column were in the range of 17–129 mg/m^2 and high values were found in the Antarctic water on the southward leg. The enhancement of chlorophyll *a* in late December seems to coincide with the blooming season of phytoplankton in the Antarctic water. The integrated stocks of chlorophyll *a* in the euphotic zone were in the range of 8–43 mg/m^2. A large amount of chlorophyll *a* contents below the eupho-

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tic zone were distributed mainly in the Antarctic water. Positive correlations among surface chlorophyll *a* contents, subsurface chlorophyll *a* contents and integrated chlorophyll *a* stocks were found.

1. Introduction

The surface distribution of chlorophyll *a* in the Indian sector of the Antarctic Ocean was investigated as part of the marine biological programs of the 14th Japanese Antarctic Expedition (JARE) in 1972–1973 (KURODA, 1978). Surface distributions of chlorophyll pigments in the present area have been studied by the JARE members since 1965 (FUKUCHI, 1980). However, there were few data about the vertical distribution of chlorophyll *a* pigment that may contribute to the estimation of the primary standing crops and production.

The present paper describes the vertical distribution of chlorophyll *a* pigment obtained on the 14th expedition in order to clarify the distributional properties of chlorophyll *a* in relation to oceanographical structures and to obtain basic data for estimating the standing crops of chlorophyll *a* in the Antarctic Ocean.

2. Materials and Methods

Vertical observations were carried out at six stations between 38° and 60°S along 105°E longitude and two stations in the Antarctic water south of 60°S on the southward and westward legs to Syowa Station (69°00′S, 39°35′E) during a period from December 18 to 28 in 1972. Furthermore, between February 27 and March 7 in 1973 about two months later than the former legs, nine stations were occupied on the northward leg between 67° and 35°S along 15°E longitude (Fig. 1). At each station physical and chemical oceanographic observations were carried out (SUGITA and IWANAGA, 1974). In addition, color of sea (Forel scale) and transparency (Secchi disc readings) were observed (Appendix 1).

Water samples of 250 m*l* at 15 layers down to the 500 m depth excluding the surface water were collected by Nansen bottles. The surface water was sampled by a plastic bucket. The chlorophyll *a* and phaeophytin contents were measured with a fluorometer on board the icebreaker FUJI as described in KURODA (1978). The pigment ratio was calculated as the percentage of chlorophyll *a* to the sum of chlorophyll *a* and phaeophytin. The sampling depths were estimated by wire length and angle (Appendix 1). The integrated chlorophyll *a* stocks in the euphotic zone and in the water column down to 250 m were calculated. Three times the Secchi depth is employed as an estimated value of the euphotic depth.

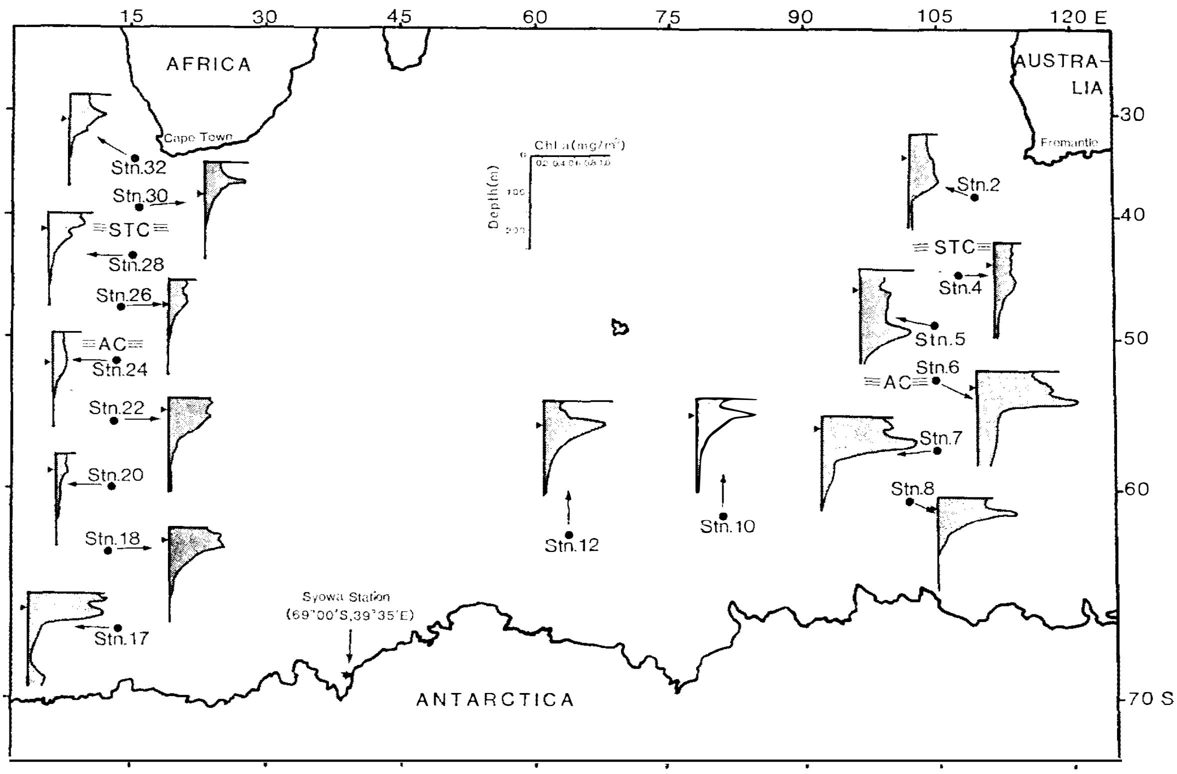

Fig. 1. Vertical profiles of chlorophyll a and euphotic depths (▶) at 17 stations observed during a period from December 1972 to March 1973.

3. Results and Discussion

3.1. Sectional distributions of water temperature, chlorophyll *a* and pigment ratio

3.1.1. Along 105°E on the southward leg in late December

As seen in Fig. 2 (upper), there are two convergence zones, that is, the Subtropical Convergence (STC) and the Antarctic Convergence (AC). Accordingly, there are three typical water masses; the Subtropical water, the Subantarctic water and the Antarctic water. While the Subtropical water was stratified in the upper 100 m layer, vertical mixing of water was developed well in the Subantarctic water. In the Antarctic water, there was a remarkable minimum layer of water temperature between 80 m and 150 m.

A weak subsurface maximum of chlorophyll *a* (0.37 mg/m^3) was found around 120 m at Stn. 2 in the Subtropical water, where the pigment ratio was as less as 31% (Fig. 2, middle and lower). This may show the low activity of phytoplankton. At Stn. 5 in the Subantarctic water, there was a marked subsurface maximum of chlorophyll *a* (0.70 mg/m^3) around 158 m where the pigment ratio was 79%. This may indicate the high activity of phytoplankton. The subsurface chlorophyll *a* maximum there

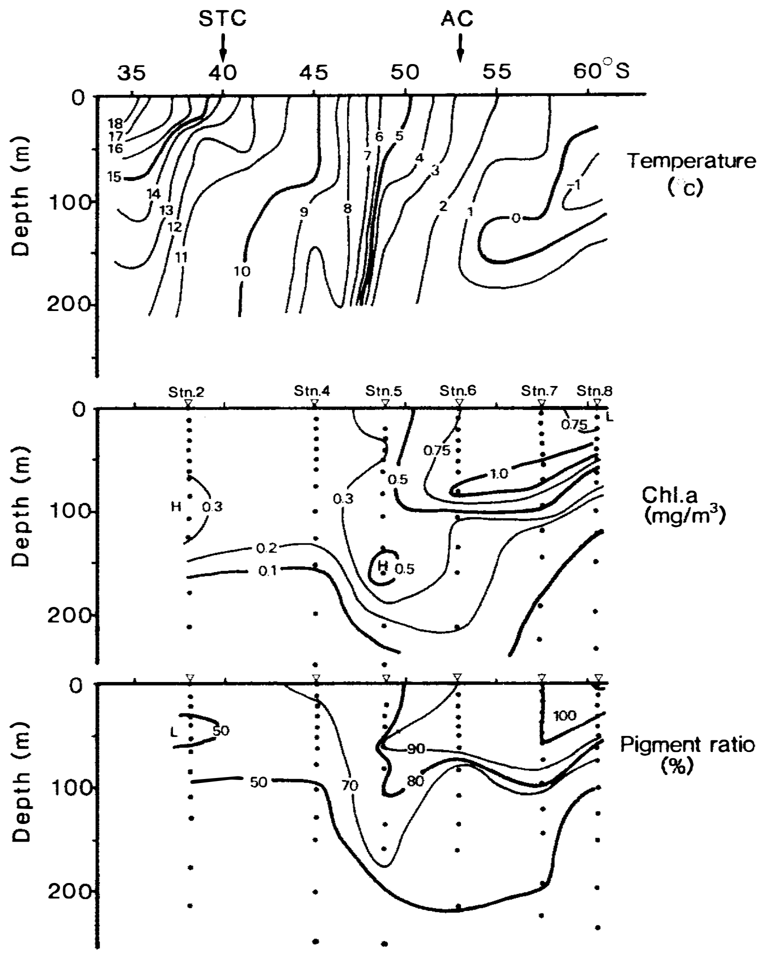

Fig. 2. Sectional distributions of water temperature (°C, upper), chlorophyll a (mg/m³, middle) and pigment ratio (%, lower) along 105°E longitude on the southward leg between 18 and 24 December 1972. STC: Subtropical Convergence, AC: Antarctic Convergence.

appeared deeper than the euphotic depth. This phenomenon may be closely related to the effect of remarkable vertical mixing. From north to south toward AC, the chlorophyll *a* stocks in the upper 100 m layer increased remarkably. A conspicuous subsurface chlorophyll *a* maximum (1.0–1.3 mg/m³) was distributed between 30 and 80 m in the Antarctic water where pigment ratios were high in the range of 67 to 99%. In the upper layer above this subsurface maximum, chlorophyll *a* contents were high in the range of 0.6 to 1.0 mg/m³ and the pigment ratios were also high more than 90%. Phytoplankton may have been in full bloom.

In general, it is clear that the chlorophyll *a* contents as well as the pigment ratios tended to increase from north (Subtropical water) to south (Antarctic water). As one of the characteristics of vertical chlorophyll *a* distribution, a considerable amount of chlorophyll *a* pigments were distributed below 150 m in the Antarctic water, especially at Stn. 6 near the Antarctic Convergence (Figs. 1, 2). This may be a peculiar phenomenon of chlorophyll *a* distribution in the Antarctic water.

3.1.2. Along 15°E on the northward leg in February-March

While the general features of oceanographic structure were similar to those in the 105°E section (Fig. 3, upper), the STC was strongly formed with a notable change of water temperature (KURODA, 1978).

In the Subtropical water, the subsurface chlorophyll *a* maximum (0.45 mg/m^3) was distributed around 50 m at Stns. 30 and 32 and the pigment ratios were in the range of 40 to 50% (Fig. 3, middle and lower). The chlorophyll *a* content of the maximum layer was higher and the depth of the layer was shallower than that in the 105°E sec-

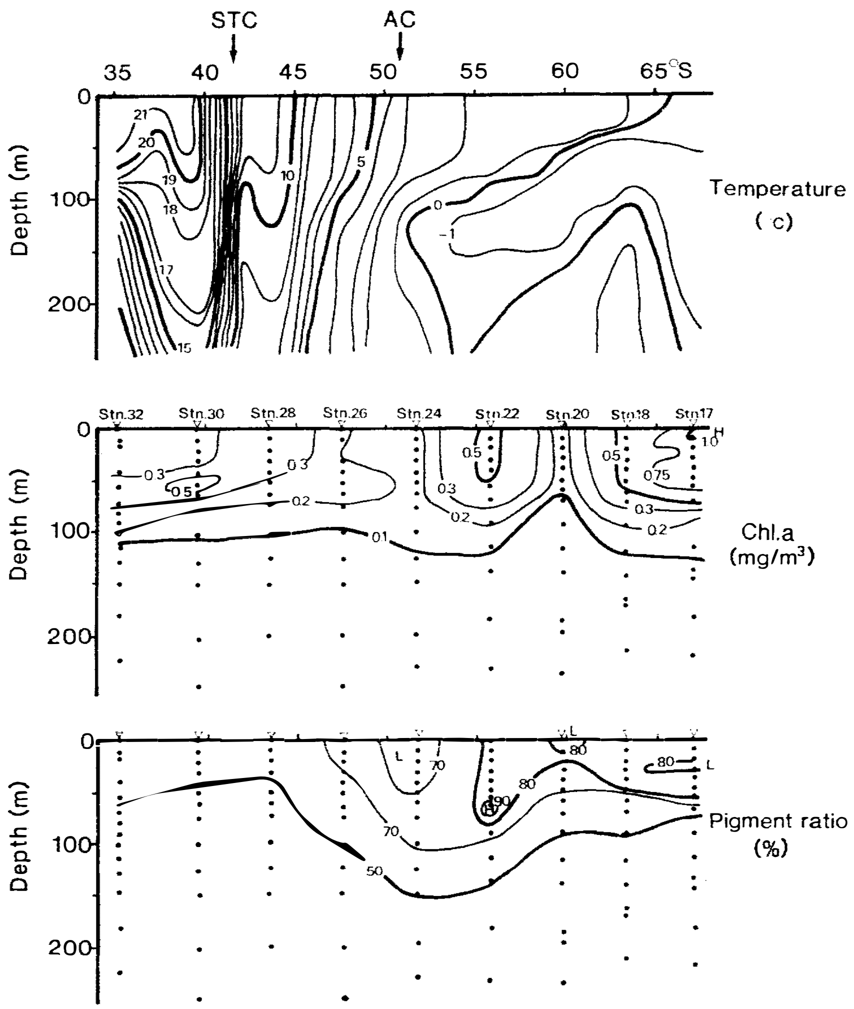

Fig. 3. Sectional distributions of water temperature (°C, upper), chlorophyll a (mg/m^3, middle) and pigment ratio (%, lower) along 15°E longitude on the northward leg between 27 February and 7 March 1973. STC and AC as in Fig. 2.

tion. On the other hand, no subsurface maximum layer was found in the Subantarctic and Antarctic waters. Consequently, the pattern of chlorophyll *a* distribution in the 15°E section was remarkably different from that in the 105°E section (Fig. 2).

The chlorophyll *a* contents in the upper 50 m layer were 0.2 to 0.3 mg/m^3 in the Subtropical water, 0.2 to 0.5 mg/m^3 in the Subantarctic water and 0.1 to 1.0 mg/m^3 in the Antarctic water. Compared with the contents observed in the 105°E section, the contents in the Antarctic water in the 15°E section were remarkably low, and there were only three stations (Stns. 16, 18 and 22) where the contents above 0.5 mg/m^3 appeared. Also, the pigment ratios were lower than 90%. It is considered that this phenomenon is related with the seasonal periodicity of phytoplankton production (HART, 1942; HASTLE, 1969); phytoplankton is in bloom in late December on the southward leg, whereas phytoplankton is decaying in early March on the northward leg as discussed by KURODA (1978) and FUKUCHI (1980).

3.2. Distribution of the integrated chlorophyll *a* stocks

The integrated chlorophyll *a* stocks in the water column between the surface and the 250 m depth varied from station to station in the range of 17 (Stn. 20) to 129 mg/m^2 (Stn. 6). The chlorophyll *a* stocks were generally high in the Antarctic water, especially in late December (Fig. 4).

The chlorophyll *a* stocks in the euphotic zone were in the range of 8 to 43 mg/m^2. The maximum stock was measured at the southernmost station (Stn. 17). In the Subtropical water, the stocks on the northward leg (23 and 24 mg/m^2) were higher than those on the southward leg (17 mg/m^2). In the Subantarctic water, the stocks on the northward leg (17 and 20 mg/m^2) were also higher than those on the southward leg (13 and 15 mg/m^2). On the other hand, in the Antarctic water, the stocks on the northward leg (8 to 43 mg/m^2; mean, 21 mg/m^2) were lower than those on the southward leg (22 to 36 mg/m^2; mean, 28 mg/m^2). Difference between the two legs in the integrated chlorophyll *a* stocks is considered to relate with the seasonal periodicity of phytoplankton as discussed above.

According to EL-SAYED and TURNER (1977), the integrated chlorophyll *a* stocks in the euphotic zone (to the depth where light intensity is 1% of surface intensity) in the Antarctic water were 13 to 15 (mean: 14) mg/m^2 at 150°E longitude in March–May 1969, 11 to 44 (mean: 21) mg/m^2 in November 1970–January 1971 in the same area as the present southward and westward legs and 5 to 21 (mean: 13) mg/m^2 at 170°E longitude north of the Ross Sea in January–February 1972. These values seem to be lower than the present values, while the direct comparison leaves a question in different sampling dates and areas. Therefore, chlorophyll *a* stocks among the three sectors will be estimated in the future.

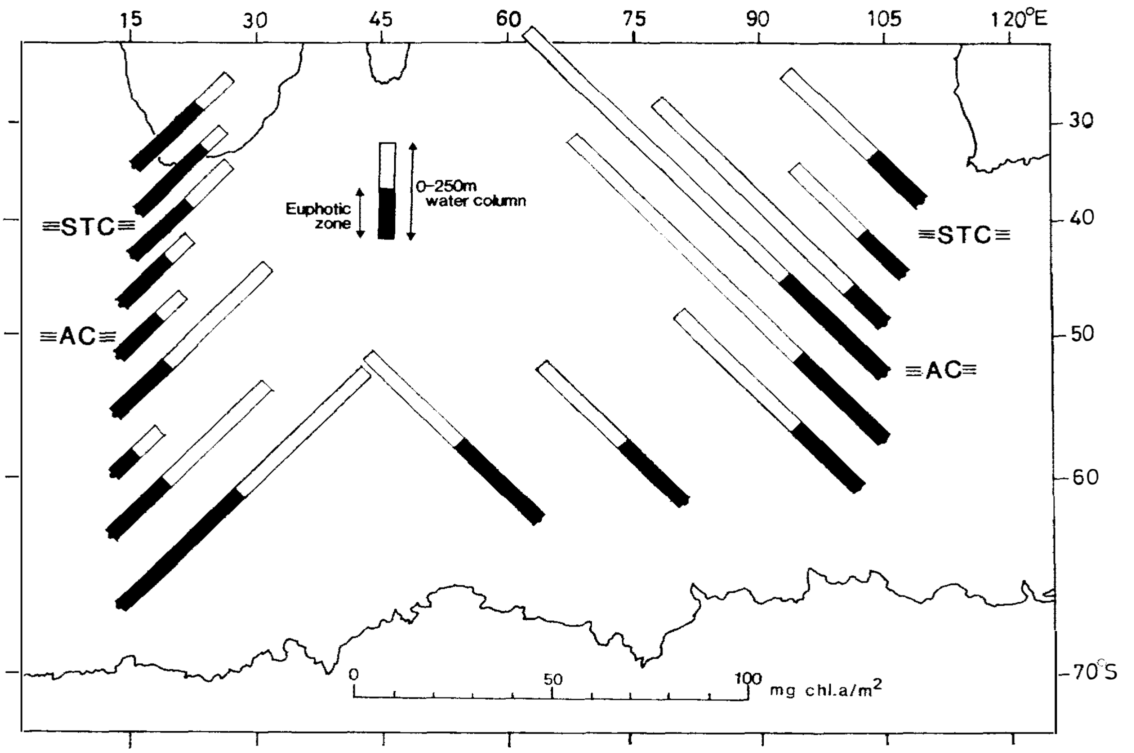

Fig. 4. Distribution of the integrated chlorophyll a stocks in a 0–250 m water column and in the euphotic zone.

The chlorophyll *a* stocks in the euphotic zone as well as in the water column below the euphotic zone are extremely higher in the Antarctic water than those in the Subtropical and Subantarctic waters (Fig. 4). This indicates that a large amount of chlorophyll *a* pigments below the euphotic zone are distributed in the Antarctic water. The chlorophyll *a* pigments in phytoplankton transferred from the euphotic zone may be in an active condition in waters below 2°C in the Antarctic. Generally, the vertical distribution of chlorophyll *a* is under the large influence of the stability of water (OHWADA, 1971). The transferring of chlorophyll *a* from the euphotic zone observed in the present work might be related with high chlorophyll *a* stocks in the euphotic zone, vertical mixing of water above the temperature minimum layer and effect of low temperature on retarding decomposition.

3.3. Correlation between the surface chlorophyll *a* and the sub-surface chlorophyll *a*

The integrated chlorophyll *a* stocks in the euphotic zone and in a 0–250 m water column and the subsurface maximum values are plotted against the surface chlorophyll *a* contents (Fig. 5). Positive correlations among these values can be seen. The surface chlorophyll *a* contents may be a good expedient for evaluating the chlorophyll *a* stocks in the subsurface layer. Therefore, this fact may encourage the routine ob-

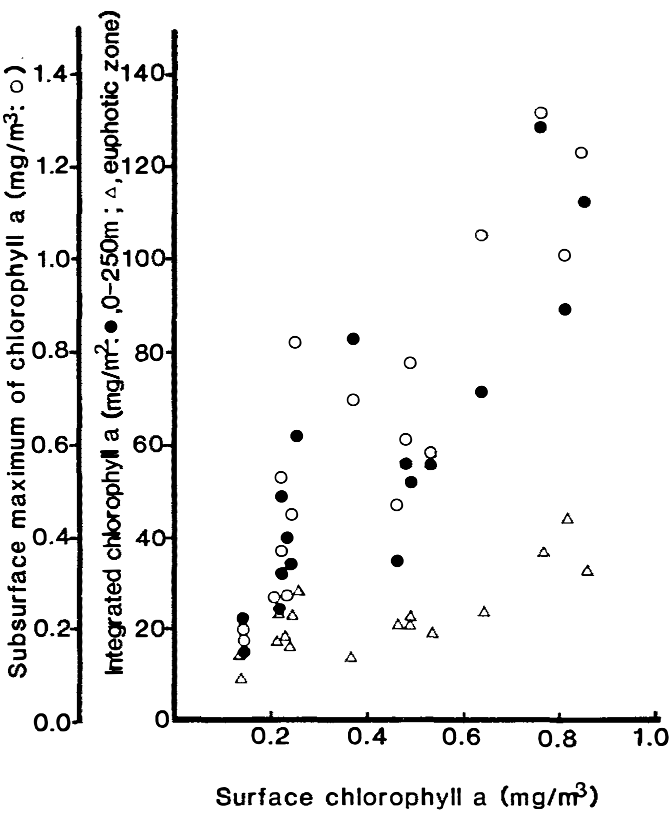

Fig. 5. Relationships of integrated chlorophyll a stocks in 0–250 m water column (●) and in the euphotic zone (△), or subsurface maximum of chlorophyll a (○) against surface chlorophyll a contents.

servation of the surface chlorophyll *a* carried out by the JARE members every year since 1965.

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Appendix 1. Data on chlorophyll a, phaeophytin, pigment ratio, color of sea and transparency observed in the Indian sector of the Antarctic Ocean in 1972–1973.

Station No.	Date and local time	Position	Color of sea	Trans-parency (m)	Depth (m)	Chl. *a* (mg/m^3)	Phaeo. (mg/m^3)	Pigment ratio (%)
2	1972	38°02′S	3	23	0	0.22	0.11	66
	Dec. 18	109°05′E			10	0.23	0.11	68
	1023～1240				20	0.23	0.11	67
					30	0.23	0.12	66
					40	0.24	0.31	44
					50	0.25	0.34	43
					60	0.27	0.42	39
					65	0.30	0.14	68
					84	0.32	0.13	71
					107	0.32	0.36	47
					126	0.37	0.83	31
					177	0.04	0.11	24
					212	0.03	0.08	26
					283	0.01	0.06	14

Appendix 1 (continued).

Station No.	Date and local time	Position	Color of sea	Trans-parency (m)	Depth (m)	Chl. *a* (mg/m³)	Phaeo. (mg/m³)	Pigment ratio (%)
4	1972	45°03′S	3	22	0	0.23	0.10	70
	Dec. 20	107°25′E			10	0.23	0.09	72
	0850～0922				20	0.22	0.10	69
					30	0.24	0.12	67
					39	0.21	0.12	63
					49	0.22	0.12	65
					59	0.21	0.11	66
					77	0.21	0.11	65
					100	0.27	0.27	50
					127	0.22	0.31	41
					150	0.11	0.17	39
					199	0.05	0.06	46
					249	0.04	0.16	20
					299	0.01	0.05	16
					399	0.00	0.05	7
					498	0.01	0.04	18
5	Dec. 21	48°51′S	3	20	20	0.37	0.11	78
	0855～0930	104°47′E			30	0.37	0.15	71
					40	0.26	0.08	77
					50	0.27	0.07	79
					60	0.42	0.05	90
					82	0.37	0.15	72
					106	0.38	0.10	80
					134	0.38	0.12	77
					158	0.70	0.19	79
					212	0.19	0.25	43
					249	0.03	0.08	25
					299	0.02	0.07	23
					399	0.01	0.04	25
					498	0.02	0.05	25
6	Dec. 22	52°56′S	4	15	0	0.76	0.05	94
	0901～0929	104°51′E			10	0.70	0.08	90
					20	0.76	0.05	94
					30	0.86	0.09	91
					39	0.93	0.13	88
					49	0.99	0.09	92
					59	0.93	0.01	99
					82	1.31	0.63	67
					106	0.31	0.25	56

Appendix 1 (continued).

Station No.	Date and local time	Position	Color of sea	Trans-parency (m)	Depth (m)	Chl. *a* (mg/m³)	Phaeo. (mg/m³)	Pigment ratio (%)
6					135	0.25	0.25	50
					159	0.24	0.22	52
					212	0.21	0.20	52
					310	0.04	0.06	44
					414	0.04	0.04	51
					517	0.05	0.06	44
7	1972	57°29′S	5	11	0	0.85	0.00	100
	Dec. 23	104°38′E			5	0.83	0.00	100
	0931～1003				15	0.88	0.00	100
					25	0.93	0.00	100
					35	0.82	0.00	100
					45	0.89	0.00	100
					55	1.20	0.00	100
					71	1.23	0.03	98
					95	0.55	0.07	88
					119	0.17	0.09	64
					143	0.17	0.11	59
					190	0.09	0.06	61
					221	0.04	0.06	38
					265	0.02	0.06	28
					353	0.03	0.05	34
					441	0.01	0.06	18
8	Dec. 24	60°26′S	5	10.5	0	0.64	0.02	97
	0848～0918	101°57′E			10	0.62	0.00	100
					20	0.63	0.00	100
					30	0.94	0.00	100
					40	1.05	0.01	99
					50	0.73	0.04	95
					60	0.49	0.30	63
					74	0.36	0.14	72
					99	0.16	0.15	51
					123	0.10	0.11	47
					148	0.03	0.05	33
					197	0.02	0.05	27
					235	0.02	0.06	24
					282	0.01	0.04	21
					376	0.02	0.04	29
					470	0.01	0.05	13

Appendix 1 (continued).

Station No.	Date and local time	Position	Color of sea	Trans-parency (m)	Depth (m)	Chl. *a* (mg/m³)	Phaeo. (mg/m³)	Pigment ratio (%)
10	1972	61°25′S	4	15	0	0.49	0.06	89
	Dec. 26	81°51′E			10	0.34	0.07	83
	0916～0942				20	0.33	0.04	90
					30	0.55	0.12	83
					40	0.78	0.13	86
					50	0.49	0.27	65
					60	0.45	0.28	62
					75	0.35	0.20	64
					100	0.17	0.07	72
					125	0.09	0.06	59
					150	0.06	0.07	48
					200	0.04	0.05	46
					249	0.03	0.04	39
					299	0.03	0.08	29
					398	0.01	0.04	24
					498	0.02	0.04	27
12	Dec. 28	62°31′S	3	23	0	0.25	0.10	91
	0851～0918	63°29′E			10	0.20	0.05	81
					20	0.21	0.06	78
					30	0.28	0.05	85
					40	0.32	0.09	79
					50	0.62	0.11	84
					60	0.82	0.20	81
					74	0.63	0.58	52
					99	0.32	0.16	66
					124	0.18	0.14	56
					246	0.02	0.10	16
					296	0.03	0.08	25
					394	0.03	0.06	32
					493	0.02	0.07	19
17	1973	67°05′S	5	15	0	0.81	0.14	86
	Feb. 27	13°43′E			9	1.01	0.14	88
	0930～1010				19	0.96	0.18	84
					28	0.77	0.26	75
					38	0.92	0.19	83
					47	0.96	0.12	89
					55	0.93	0.22	81
					69	0.57	0.53	52
					91	0.20	0.28	41

Appendix 1 (*continued*).

Station No.	Date and local time	Position	Color of sea	Trans-parency (m)	Depth (m)	Chl. *a* (mg/m³)	Phaeo. (mg/m³)	Pigment ratio (%)
17					114	0.13	0.18	42
					137	0.08	0.09	47
					145	0.08	0.07	52
					182	0.04	0.06	40
					220	0.22	0.29	43
					294	0.01	0.04	20
					368	0.01	0.04	12
18	1973	63°21′S	4	12	0	0.48	0.08	86
	Feb. 28	12°37′E			10	0.55	0.11	83
	0940～1015				20	0.57	0.12	83
					30	0.56	0.13	82
					39	0.58	0.11	84
					49	0.61	0.15	80
					59	0.50	0.29	63
					70	0.38	0.28	58
					94	0.23	0.22	51
					117	0.12	0.13	47
					141	0.06	0.09	40
					164	0.05	0.08	41
					170	0.04	0.08	36
					212	0.02	0.07	24
					255	0.03	0.07	27
					339	0.02	0.04	29
					424	0.01	0.03	18
20	Mar. 1	59°52′S	3	16	0	0.14	0.05	72
	0906～0940	12°53′E			10	0.17	0.05	78
					19	0.16	0.04	80
					29	0.14	0.07	69
					39	0.15	0.06	72
					48	0.17	0.05	77
					58	0.11	0.06	65
					70	0.08	0.06	58
					93	0.06	0.06	51
					116	0.06	0.07	46
					139	0.05	0.06	45
					185	0.02	0.04	30
					197	0.01	0.04	21
					236	0.01	0.04	24
					315	0.01	0.03	28

Appendix 1 (continued).

Station No.	Date and local time	Position	Color of sea	Trans-parency (m)	Depth (m)	Chl. *a* (mg/m³)	Phaeo. (mg/m)³	Pigment ratio (%)
20					394	0.01	0.03	16
22	1973	55°49′ S	5	11	0	0.53	0.09	85
	Mar. 2	13°07′ E			10	0.58	0.10	85
	0909～0940				19	0.54	0.12	82
					29	0.51	0.06	89
					38	0.50	0.13	80
					48	0.55	0.11	83
					54	0.49	0.10	84
					68	0.44	0.02	97
					91	0.23	0.06	79
					113	0.11	0.10	51
					136	0.09	0.07	55
					181	0.04	0.06	41
					231	0.04	0.05	44
					277	0.02	0.06	26
					369	0.01	0.04	26
					462	0.01	0.04	19
24	Mar. 3	51°46′ S	2	30	0	0.14	0.08	64
	0859～0930	13°29′ E			10	0.15	0.09	63
					20	0.15	0.08	66
					30	0.15	0.09	61
					40	0.16	0.08	67
					50	0.18	0.10	65
					60	0.18	0.07	71
					74	0.19	0.05	79
					99	0.16	0.06	73
					123	0.08	0.04	64
					148	0.04	0.04	51
					197	0.01	0.04	28
					228	0.01	0.04	14
					274	0.00	0.04	9
					366	0.00	0.03	11
					457	0.01	0.03	16
26	Mar. 4	47°37′ S	3	24	0	0.21	0.06	77
	0904～0946	13°43′ E			10	0.26	0.05	83
					20	0.20	0.07	75
					30	0.20	0.09	69
					40	0.24	0.11	68
					50	0.25	0.13	66

Appendix 1 (continued).

Station No.	Date and local time	Position	Color of sea	Trans-parency (m)	Depth (m)	Chl. *a* (mg/m³)	Phaeo. (mg/m³)	Pigment ratio (%)
26					60	0.25	0.12	67
					74	0.20	0.17	54
					99	0.09	0.08	54
					123	0.05	0.08	40
					148	0.03	0.08	24
					197	0.01	0.05	16
					246	0.01	0.04	11
					296	0.01	0.04	11
					391	0.00	0.03	11
					489	0.00	0.03	6
28	1973	43°34′S	4	16	0	0.46	0.40	53
	Mar. 5	15°14′E			10	0.40	0.31	56
	0856～0934				20	0.45	0.39	54
					30	0.47	0.39	55
					40	0.31	0.33	48
					50	0.26	0.36	43
					60	0.29	0.34	46
					74	0.19	0.25	43
					99	0.11	0.24	31
					123	0.06	0.11	33
					148	0.03	0.06	31
					197	0.01	0.04	17
					293	0.00	0.03	11
					391	0.01	0.04	27
					489	0.00	0.03	7
30	Mar. 6	39°33′S	3	30	0	0.22	0.16	58
	0851～0920	15°23′E			10	0.22	0.14	62
					20	0.23	0.15	61
					30	0.26	0.19	58
					40	0.33	0.28	54
					50	0.53	0.87	38
					60	0.31	1.13	22
					75	0.22	1.01	18
					100	0.11	0.58	16
					125	0.06	0.21	21
					149	0.03	0.09	23
					199	0.00	0.03	11
					246	0.00	0.04	5
					295	0.01	0.05	12

Appendix 1 (continued).

Station No.	Date and local time	Position	Color of sea	Trans-parency (m)	Depth (m)	Chl. *a* (mg/m³)	Phaeo. (mg/m³)	Pigment ratio (%)
30					393	0.00	0.03	3
					491	0.00	0.02	8
32	1973	35°10′S	3	27	0	0.24	0.11	69
	Mar. 7	15°14′E			10	0.25	0.11	69
	0857～0925				25	0.24	0.12	66
					40	0.29	0.22	57
					54	0.45	0.40	54
					69	0.32	0.37	47
					79	0.28	0.58	32
					88	0.21	0.32	40
					98	0.22	0.23	49
					112	0.06	0.11	35
					127	0.04	0.09	30
					147	0.03	0.08	31
					177	0.01	0.06	18
					221	0.01	0.07	13
					255	0.02	0.07	21
					353	0.00	0.05	6
					441	0.00	0.04	5