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LONG-TERM OBSERVATION OF ZOOPLANKTON BIOMASS IN THE INDIAN OCEAN SECTOR OF THE SOUTHERN OCEAN

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Abstract: Mean biomass, horizontal distribution and annual fluctuations of zooplankton biomass in the upper layer of the Indian Ocean sector of the Southern Ocean were investigated based on NORPAC standard net samples obtained by the Japanese Antarctic Research Expedition (JARE) for 22 years. The average biomasses in circumpolar areas were 36.4, 79.4, 133.9 and 172.5 mg m^{-3} wet wt in the Subtropical, Sub-Antarctic, Antarctic, and Polar Frontal Zone, respectively. Mean zooplankton biomasses obtained in this study were slightly higher than those previously reported from Indian and other ocean sectors. In the Antarctic Zone, the average biomass decreased from north toward south. Horizontal distribution of surface zooplankton biomass showed high abundance over a relatively extensive area east of Prydz Bay, including the Polar Frontal Zone and Antarctic Zone (90–110°E, 45–65° S). The mean biomass of the Antarctic Zone varied annually. In the Antarctic Zone, the range of the variation was larger in the Northern Oceanic Community area than that in the Main Oceanic Community area, but no similarity in the patterns for the 22 years in the two areas was observed. In the Northern Oceanic community area, cyclic fluctuation of zooplankton biomass every 4–6 years were observed. This periodicity may relate to the physical process, *i.e.* ice-ocean-atmosphere system of the Southern Ocean.

1. Introduction

During every austral summer season (December–March) from 1972/73 to 1995/96 (except 1973/74 and 1974/75), plankton samplings have been carried out in the Indian Ocean sector of the Southern Ocean as part of the Japanese Antarctic Research Expedition (JARE). The sampling was done on board the icebreaker FUJI from 1972/73 to 1982/83 as described by FUKUCHI and TANIMURA (1981) and WATANABE *et al.* (1984). The icebreaker SHIRASE was launched in 1983 and the sampling has been continued since then (TAKAHASHI *et al.*, 1997). Although several kinds of plankton nets have been employed on board the icebreakers, vertical hauls by a NORPAC standard net (North Pacific standard net) have been routinely and frequently carried out in order to estimate the mean biomass of surface zooplankton and its time-spatial variability in the upper layer of the Indian Ocean sector of the Southern Ocean. The

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present paper describes preliminary results for the mean biomass, horizontal distribution and annual fluctuations from zooplankton data obtained over 22 years of observations within JARE.

2. Materials and Methods

Zooplankton samples were obtained by vertical hauls of a NORPAC standard net (NGG 54, 0.33 mm mesh openings) on board the icebreakers during JARE-14 to JARE-37 (except JARE-15 and JARE-16), over a period of 22 years. The use of this net for the purpose of collecting macrozooplankton in international cooperative surveys was established at the international meeting for NORPAC oceanographic investigations held at Honolulu in February 1956 (MOTODA, 1957). Details concerning sampling methods and analysis can be found in FUKUCHI and TANIMURA (1981), WATANABE *et al.* (1984) and TAKAHASHI *et al.* (1997). As a rule, the majority of samples used in this study were collected from 150 m depth to the surface, as estimated by wire length and angle. However, sea conditions sometimes affected sampling, with hauls starting from 100 m or down to 250 m. Moreover, 10 samples (2.7% of the total samples) which showed extremely high biomass (>1000 mg m^{-3} wet wt) were excluded from the analysis in order to estimate averaged zooplankton biomass of the Indian Ocean sector of the Southern Ocean (Table 1). As a result, 351 out of 392 NORPAC standard net samples were used for this study (Table 2). The average sampling depth of 351 samples was 155 (±25) m.

Table 1. The sampling stations excluded from analysis due to their extreamly high biomass (>1000 mg m^{-3} wet wt).

JARE No.	Sample No.	Position		Biomass (mg m^{-3} wwt)
		Latitude	Longitude	
14	14N006	55°26′N	104°51′E	1402
14	14N007	57°29′N	104°38′E	1375
18	18N007	64°50′N	39°59′E	1779
19	19N001	34°06′N	111°41′E	1827
19	19N002	37°17′N	108°58′E	3454
19	19N003	57°40′N	99°49′E	1060
29	29N029	64°02′N	116°26′E	3277
34	34N005	55°00′N	107°37′E	1300
35	35N025	65°00′N	150°18′E	2474
37	37N029	55°56′N	144°30′E	5604

3. Setting of Area Division

Since the Southern Ocean is not ecologically uniform and is subdivided into several distinct circumpolar zones by strong frontal systems (DEACON, 1982; HEMPEL, 1985), all sampling stations were subdivided as follows: Subtropical Zone (STZ: north of Subtropical Front), Sub-Antarctic Zone (SAZ: between Subtropical Front and Sub-Antarctic

Table 2. Number of NORPAC standard net samples used for analysis in the present study. Abbrevations under AZ indicate the area characterized by the specific zooplankton community structure (HOSIE et al., 1997; See text).

JARE No.	Year	Sampling zone						Total
		STZ	SAZ	PFZ	AZ			
					NOC-area	MOC-area	NC-area	
14	1972/73	5	5	3	11	6	–	30
17	1975/76	2	3	2	5	4	–	16
18	1976/77	7	2	1	5	5	–	20
19	1977/78	–	–	–	6	2	–	8
20	1978/79	–	–	–	5	1	–	6
21	1979/80	11	3	2	9	8	–	33
22	1980/81	–	–	2	8	4	9	23
23	1981/82	–	–	2	2	3	–	7
24	1982/83	1	–	2	4	3	–	10
25	1983/84	–	–	–	–	10	4	14
26	1984/85	–	–	2	3	4	10	19
27	1985/86	2	–	1	1	9	14	27
28	1986/87	3	–	2	4	3	2	14
29	1987/88	–	2	–	3	14	–	19
30	1988/89	–	2	3	2	1	–	8
31	1989/90	–	–	1	11	1	–	13
32	1990/91	2	1	2	1	–	–	6
33	1991/92	–	2	1	1	11	–	15
34	1992/93	–	4	–	2	11	–	17
35	1993/94	1	–	1	7	4	–	13
36	1994/95	–	2	3	4	9	–	18
37	1995/96	–	1	1	5	8	–	15
Total		34	27	31	99	121	39	351

NOC: Northern Oceanic Community, MOC: Main Oceanic Community and NC: Neritic Community.

Front); Polar Frontal Zone (PFZ: between Sub-Antarctic Front and Polar Front) and Antarctic Zone (AZ: south of Polar Front). The positions of each front were after NAGATA *et al.* (1983), but the positions of the fronts along 150°E were determined according to ORSI *et al.* (1995), and these are shown in Fig. 1.

Recently, different zooplankton communities separated by the Antarctic Divergence have been recognized in the Antarctic Zone (SIEGEL and PIATKOWSKI, 1990; BOYSEN-ENNEN *et al.*, 1991). HOSIE and co-workers (HOSIE, 1994; HOSIE *et al.*, 1997) intensively studied zooplankton community structure around Prydz Bay, located in the center of the Indian Ocean sector (Fig. 1) and recognized that the zooplankton community changes at 62–63°S, the approximate position of the Antarctic Divergence in the Indian Ocean sector (DEACON, 1982). Yet another community is found on the continental shelf, shallower than 1000 m (HOSIE, 1994; HOSIE and COCHRAN, 1994; HOSIE *et al.*, 1997). Therefore, the Antarctic Zone was subdivided into the three zooplankton

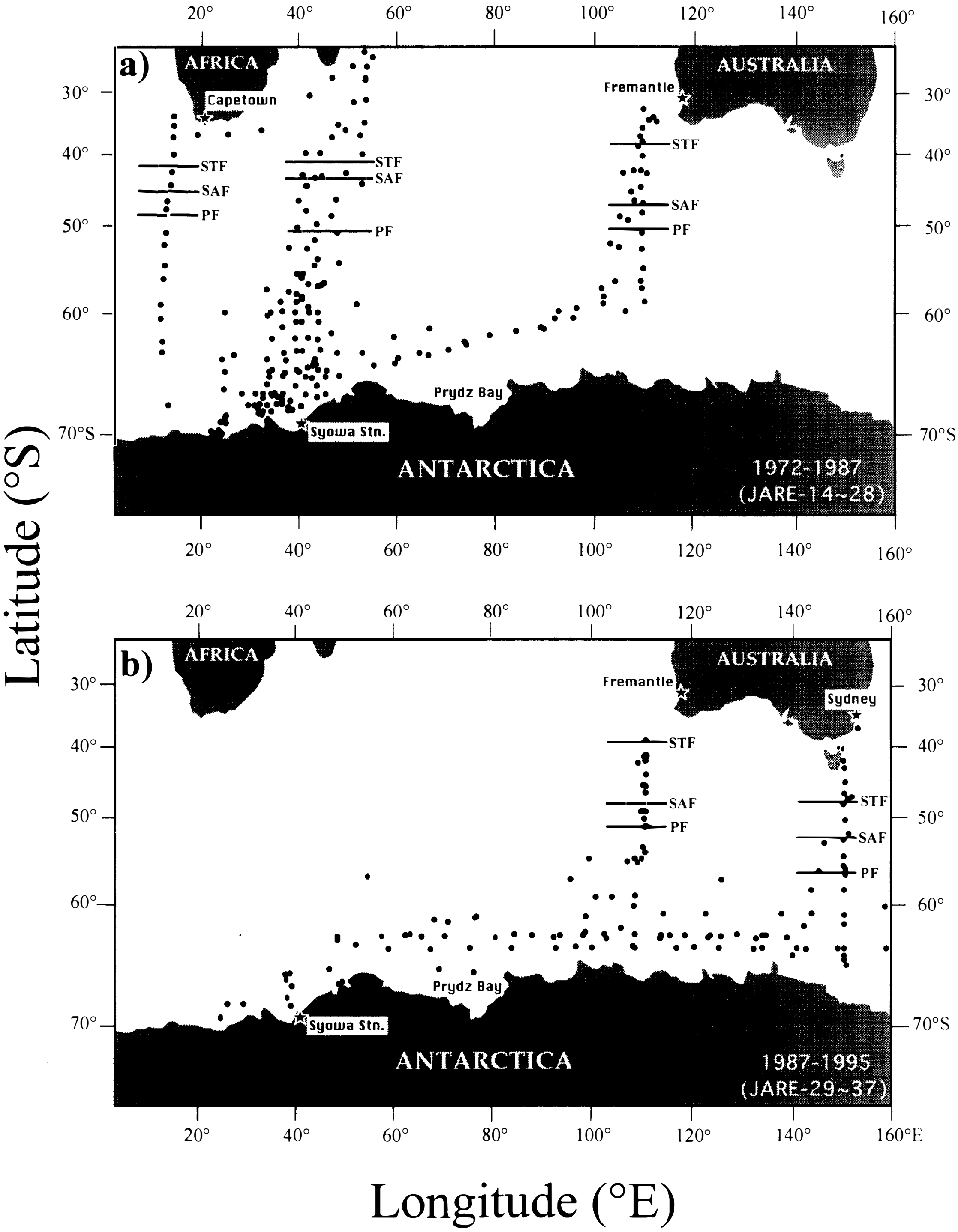

Fig. 1. Stations of NORPAC standard net sapling during cruises of the JARE-14 to JARE-28 (a) and JARE-29 to JARE-37 (b). Solid lines in the figures indicate mean position of the fronts of the Antarctic circumpolar current (NAGATA et al., 1983; ORSI et al., 1995); STF: Subtropical front, SAF: Sub-Antarctic front, PF: Polar front.

communities in this study, *i.e.* the Northern Oceanic community area (NOC-area: between Polar Front and 62.5° S), Main Oceanic Community area (MOC-area: between 62.5° S and shelf edge, 1000 m depth) and Neritic Community area (NC-area: shallower area than 1000 m) (Table 2). A Krill Dominated Community, which was also recognized as a distinct zooplankton community in the Antarctic Zone by Hosie and co-workers, was not distinguished in this study because of its inconsistent occurrence pattern (Hosie and Cochran, 1994; Hosie *et al.*, 1997).

4. Results and Discussion

4.1. Sampling area and date

The locations of sampling stations are presented in Fig. 1. During JARE-14 to JARE-28, sampling was mainly conducted in the western part of the Indian Ocean sector of the Southern Ocean (Fig. 1a); thereafter, sampling stations were shifted toward the eastern area of the Indian Ocean sector of the Southern Ocean (Fig. 1b)

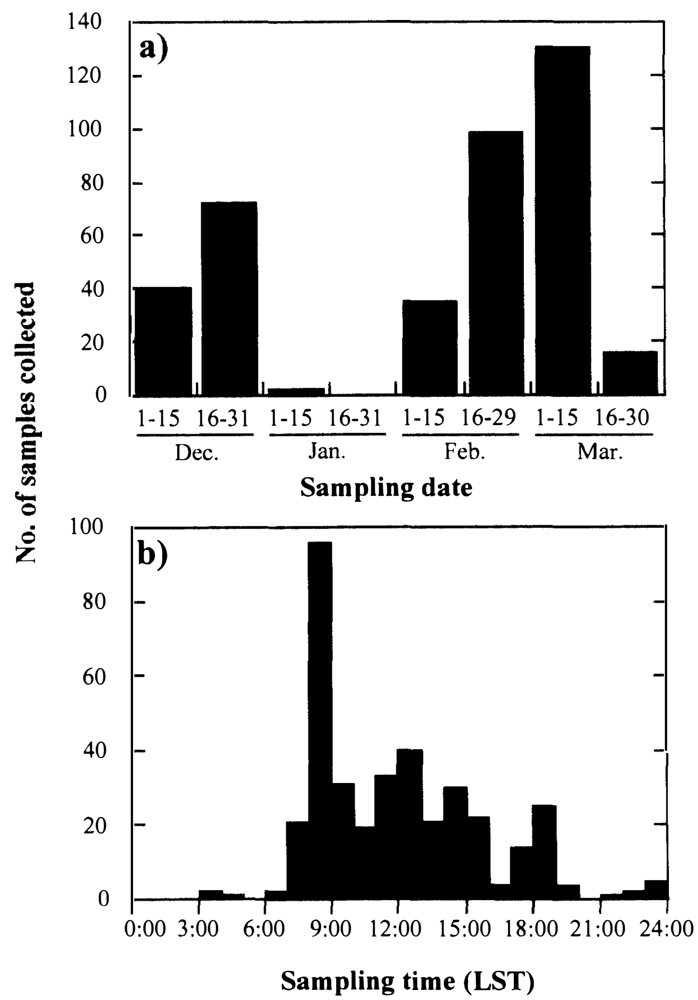

Fig. 2. Date and time of zooplankton sampling with NORPAC standard net during JARE-14 to JARE-37.

because the cruise tracks of the SHIRASE changed from JARE-29. Dates of sampling are roughly divided into 2 seasons (Fig. 2a), *i.e.* early summer (December) when the icebreakers travel southwest ward from Fremantle to Syowa Station and late summer (February to March) when the icebreakers return north- or northeast ward from Syowa Station to Port Louis or to Sydney. Most of the samples used in this study were obtained during the day (Fig. 2b) and hence the effect of diel vertical migrating zooplankton to the biomass in this study would be small.

4.2. Mean biomass

The mean zooplankton biomass, between 30–70°S and between 15–160°E, was estimated to have 124.0 mg m^{-3} wet wt. The average biomasses in circumpolar areas were 36.4, 79.4, 133.9 and 172.5 mg m^{-3} wet wt in the Subtropical, Sub-Antarctic, Antarctic, and Polar Frontal Zone, respectively (Table 3). In the Antarctic Zone, the Northern Oceanic Community area showed higher biomass than the Main Oceanic and Neritic Community area (Table 3). Decreasing of zooplankton biomass toward the south in the Antarctic Zone was also observed by several authors (FOXTON, 1956; HOSIE *et al.*, 1997). Mean zooplankton biomasses obtained in this study were slightly higher than those previously reported in the Indian and other Ocean sectors except for the value of KAWAMURA (1986) (Table 4). According to FOXTON (1956) two seasonal maxima of zooplankton abundance exist in the 0–100 m layer, *i.e.* November–December and February–April, and it is believed that the first maximum of zooplankton biomass is associated with the upward migration of wintering organisms into the surface layer, but the second one is due to the development of new generations (VINOGRADOV and NAUMOV, 1964). In fact YAMADA and KAWAMURA (1986) report considerable decrease of zooplankton biomass in the 0–100 m layer in the Prydz Bay region from December to January. JARE sampling data indicate that almost all NORPAC net samplings have been conducted during the two maximal seasons of zooplankton abundance, *i.e.* December and February–March (Fig. 2a), and this would result in relatively high estimates of the biomass. Another possibility is phytoplankton contamination of the zooplankton samples, which is often reported in the Southern Ocean (FOXTON, 1956; KAWAMURA,

Table 3. Mean zooplankton biomass in the upper layer of the Indian Ocean sector of the Southern Ocean, for all years from 1973/74 to 1995/1996, except 1973/74 and 1974/75.

Area and zooplankton community	Mean biomass (mg m^{-3} wwt)	Standard deviation	Number of samples
Subtropical Zone	36.4	± 45.1	34
Sub-Antarctic Zone	79.4	± 75.9	27
Polar Frontal Zone	172.5	±200.5	31
Antarctic Zone			
Northern Oceanic Community	194.9	±206.1	99
Main Oceanic Community	110.0	±155.3	121
Neritic Community	55.2	± 63.0	39
Total	133.9	±174.6	259
Total	124.0	±167.4	351

Table 4. Summary of literature values of surface zooplankton biomass in the Southern Ocean estimates from net catches in summer.

Region	Latitude (°S)	Period or months	Depth (m)	Biomass (mg wet wt m⁻³)	References
Pacific Ocean sector	56–70	12–1	0–100	88.5	HOPKINS (1971)*†
Pacific Ocean sector	58–69	12–3	0–100	95.5	FOXTON (1956)§†
Pacific Ocean sector	63–68	1–2	1–5	56.7	PAKHOMOV and MCQUAID (1996)
Pacific, Indian Ocean sector	50–70	1–4	0–100	73.6	VORONINA and NAUMOV (1968)
Pacific, Indian Ocean sector	60–65	12–1	0–100	296.7	KAWAMURA (1986)
Indian Ocean sector	51–70	12–3	0–155	133.9	Present study
Indian Ocean sector	50–63	1–3	0–100	69.1	FOXTON (1956)§†
Indian Ocean sector	46–64	12	0–100	51.6	YAMADA and KAWAMURA (1986)
Indian Ocean sector	62–69	1	0–100	20.0	YAMADA and KAWAMURA (1986)
Atlantic Ocean sector	52–65	12–1	1–5	7.4	PAKHOMOV and MCQUAID (1996)
Atlantic Ocean sector	48–69	12–3	0–100	59.5	FOXTON (1956)§†
Northern Weddell Sea	65–70	summer	0–200	30	EL-SAYED and TAGUCHI (1981)
Southern Weddell Sea shelf	75–77	3	0–200	100	EL-SAYED and TAGUCHI (1981)
Oceanic Weddell Sea	66–73	1–3	0–300	62.4	BOYSEN-ENNEN *et al.* (1990)*
NE Weddell Sea shelf	70–74	1–2	0–300	57.6	BOYSEN-ENNEN *et al.* (1990)*
Southern Weddell Sea shelf	75–78	1–2	0–300	23.2	BOYSEN-ENNEN *et al.* (1990)*

* Original data in dry weight were converted to wet weight using the ratio DW:WW = 1:10 (HOPKINS, 1971).

§ Original data expressed in displacement volume were compared directly with wet weight data (KAWAMURA, 1986).

† Recalculated based on appendix.

1986). Further investigation would provide more accurate estimation of zooplankton biomass.

4.3. Horizontal distribution

Horizontal distribution of zooplankton biomass, expressed as means over 5-degree quadrangles is presented in Fig. 3. The highest zooplankton biomass (544.2 mg m^{-3} wet wt) was observed off Terre Adélie (150–155°E, 65–70°S) and the lowest biomass (7.9 mg m^{-3} wet wt) was south of Madagascar (50–55°E, 35–40°S). Particularly, high biomass values were always observed in the area east of Prydz Bay, including the Polar Frontal Zone and the Antarctic Zone between 45–65°S and between 90–110°E. The mean biomass east of Prydz Bay was consistently higher than that in other regions regardless of month (Table 5). High abundance of zooplankton biomass in this area was also reported by VORONINA (1966). According to the JARE oceanographic observation data, the region between 100–110°E is an upwelling region. High chlorophyll *a* concentrations are often found in this area, indicating high primary productivity (SUZUKI and FUKUCHI, 1997). The high zooplankton biomass in this area may be attributed to the high chlorophyll *a* concentration.

In this study, some stations which showed extremely high biomass (>1000 mg m^{-3}

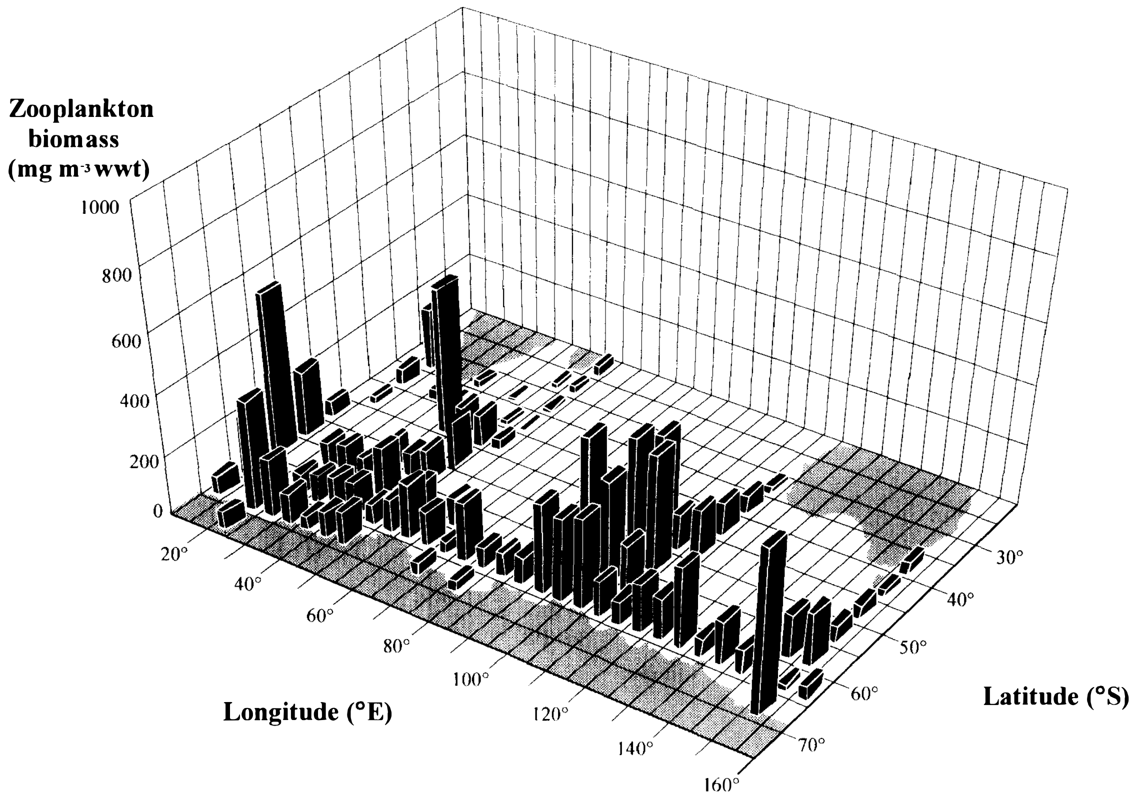

Fig. 3. Horizontal distribution of zooplankton biomass in the upper layer of the Indian sector of the Southern Ocean. Zooplankton biomass (mg m^{-3} wet wt) is expressed as the mean over 5-degree quadrangles.

Table 5. Mean zooplankton biomass (mg m^{-3} wet wt) in the range of 45–65°S, east of Prydz Bay and in other areas in December and February–March.

Month	East of Prydz Bay (90–110°E)		Other areas (15–90°E and 110–150°E)	
	Biomass (±SD)	Number of sample	Biomass (±SD)	Number of sample
December	263.5 (±208.6)	39	142.7 (±159.1)	22
February–March	236.4 (±267.7)	15	116.2 (±159.2)	138

wet wt) were excluded from the analysis (see Materials and Methods, Table 1), but these stations occurred along certain latitudes, namely *ca.* 35°, 55° and 65°S. These latitudes were slightly different from mean positions of circumpolar frontal systems derived from many previous observations (DEACON, 1982; NAGATA *et al.*, 1983, ORSI *et al.*, 1995), but specific oceanographical conditions may also affect the extremely high biomasses.

4.4. *Annual fluctuations*

The annual fluctuation of the surface zooplankton biomass in the Antarctic Zone is presented in Fig. 4. The mean biomass of each year in the Antarctic Zone varied

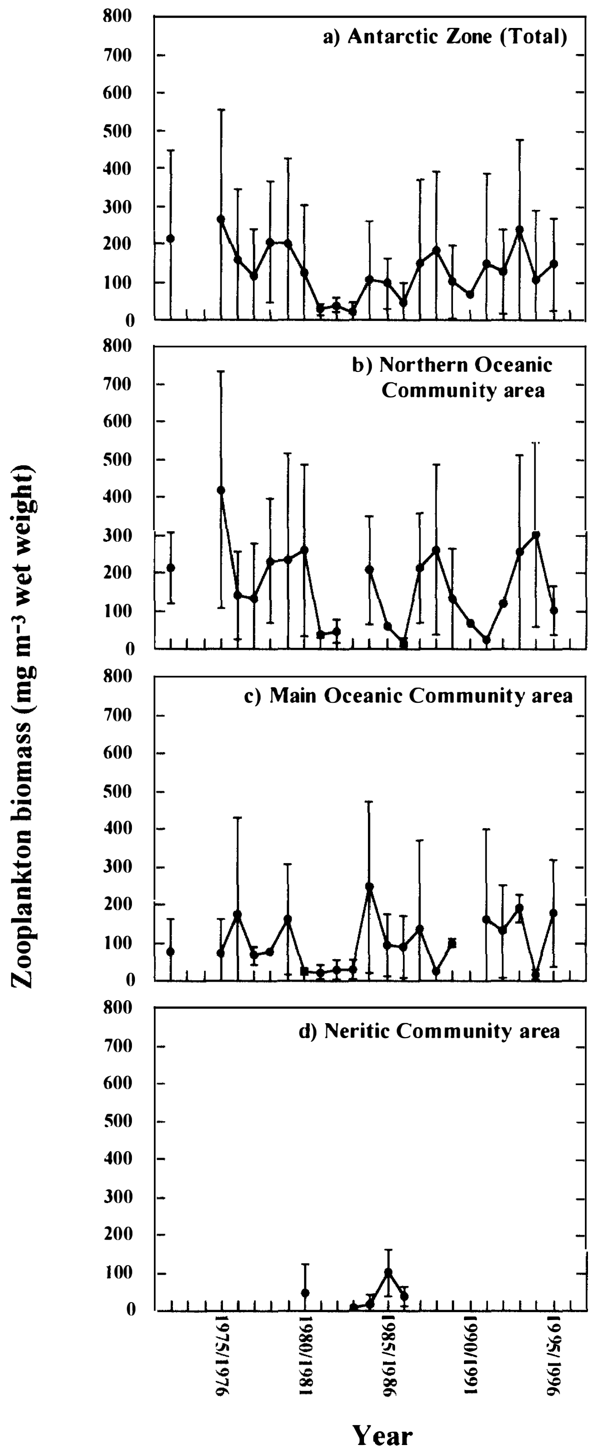

Fig. 4. Annual fluctuations of the zooplankton biomass in the upper layer of the Antarctic Zone. Total of Antarctic Zone (a), Northern Oceanic Community area (b), Main Oceanic Community area (c), Neritic Community area (d). Vertical bars indicate standard deviations.

annually (Fig. 4a). The highest biomass (265.7 mg m^{-3} wet wt) was observed in 1975/76 and very low biomasses (23.2–40.4 mg m^{-3} wet wt) were observed from 1981/82 to 1983/84. The range of the variation was larger in the Northern Oceanic Community area than that in the Main Oceanic Community area, but there is no evident similarity in the patterns for 22 years between the two areas (Fig. 4b, c). Throughout the sampling period, cyclic fluctuations every 4–6 years were observed in the total of the

Antarctic Zone (Fig. 4a). This fluctuation may result from samples of the Northern Oceanic Community (*i.e.* West Wind Drift Community; HOSIE, 1994) area since the fluctuation pattern of this area showed a more clear cyclic pattern than that of the total of the Antarctic Zone (Fig. 4b). Recently a relationship between sea-ice extent and zooplankton abundance has been reported (KAWAGUCHI and SATAKE, 1994; SIEGEL and LOEB, 1995; LOEB *et al.*, 1997). MURPHY *et al.* (1995) reported that anomalies in sea-ice extent appear to show a clockwise circumpolar precession with period of 7-9 years and indicate that the ice-ocean-atmosphere system of the Southern Ocean has the potential to transfer anomalies spatially and temporally. Moreover, recent satellite image analysis has revealed an eastward propagating Antarctic Circumpolar Wave in variations of ice edge extent along the entire Antarctic continent with a period of about 4-5 years and wave length of 180 degrees in longitude (JACOBS and MICHELL, 1996; WHITE and PETERSON, 1996). In these contexts, the cyclic fluctuation of zooplankton biomass may be relate to physical processes, *i.e.* the ice-ocean-atmosphere system of the Southern Ocean.

In the Southern Ocean, continuous zooplankton sampling over the long term (more than 20 years), has not been done as far as we know except for JARE. Further continuation of this sampling and detailed investigation at the species levels of the samples will provide important information for understanding the Antarctic ecosystem.

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