－研究論文－
Scientific Paper

Surface zooplankton communities in the Indian sector of the Antarctic Ocean in early summer 1999/2000 observed with a Continuous Plankton Recorder

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1999/2000年夏季南極海インド洋区にて連続プランクトン採集器により観測された表層動物プランクトン群集

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要旨：1999/2000年夏季，南極海インド洋区において第41次南極地域観測隊による連続プランクトン採集器（Continuous Plankton Recorder: CPR）を用いた動物プランクトン観測が初めて行われた．南極観測船「しらせ」が約14ノットで航走する際，CPRを曳航して約10m水深を水平的に採集した．南極前線を南北に横断した曳航によって採集された5海里あたりの平均現存量は168.1個体であった．採集された動物プランクトンは34分類群に分けられ，なかでもカイアシ類の*Oithona* spp.が動物プランクトン総個体数の59%以上を占めた．二つの異なった動物プランクトン群集がクラスター解析によって見いだされ，これらは水塊の変化に対応していることが示唆された．CPRの観測は表層プランクトン群集の微細分布を捉えることができ，長期的なモニタリング観測に適しているといえる．

Abstract: The first deployment of a Continuous Plankton Recorder (CPR) on board the icebreaker *Shirase* was conducted during the 41st Japanese Antarctic Research Expedition (JARE) in 1999/2000 austral summer in the Indian sector of the Antarctic Ocean. The CPR was towed horizontally at approximately 10 m depth while the *Shirase* was steaming at about 14 knots across the Polar Front (PF). Mean total abundance of zooplankton for horizontal five nautical mile sample units was 168.1(SD: ±117.18) individuals with the maximum of 456 individuals. Zooplanktons were counted for 34 categories of species/taxa. Copepods occupied more than 90% of the total abundance in numbers. *Oithona* spp. was the most dominant group among copepods, representing 59% of the total zooplankton. Other numerically important categories were small-sized calanoids (copepodites and adults;

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18.4%), and copepodites of *Calanoides acutus* and *Calanus simillimus* (8.2%). Latitudinal change of zooplankton abundance coincided with increasing/decreasing tends of temperature and salinity. Two different zooplankton assemblages were identified by cluster analysis and these assemblages seem to be closely related to different water characteristics, such as the of PF and areas of cold water masses. CPR is considered to be an ideal tool for long term monitoring of surface zooplankton communities.

1. Introduction

Among several oceanic currents in the Southern Ocean, there is the eastward flow of the Antarctic Circumpolar Current (ACC) located between the subtropical front and Southern ACC front (SACCF; Orsi *et al.*, 1995). The ACC flows uninterrupted around Antarctica and is thus a unique global link that connects all major oceans. The Polar Front (PF) is also one of the major fronts within the ACC. On the surface, the PF is often marked by a steep latitudinal gradients in temperature, silicate, and other nutrients, from north to south, which contributes to the enhancement of the biological productivity around the PF (Ishino *et al.*, 1968; Lutjeharms *et al.*, 1985). Distribution and community structure of plankton around the frontal zones in the Southern Ocean have been reported by several authors (*e.g.* Andrews, 1966; Errhif *et al.*, 1997; Pakhomov *et al.*, 2000). However, most of these studies provide only information on the composition, and dynamics of macro scale epipelagic zooplankton communities in the Antarctic Ocean.

In the Indian Ocean sector of the Antarctic Ocean, the Japanese Antarctic Research Expedition (JARE) has been conducting routine zooplankton observations with a NORPAC standard net every austral summer since 1972. Takahashi *et al.* (1998) analyzed zooplankton biomass data obtained during the JARE cruises over 22 years, and they showed that the zooplankton biomass was higher in Polar Frontal Zone (PFZ) and Antarctic Zone (AZ). They also suggested the existence of a 4–6 years cyclic fluctuation in zooplankton biomass in PFZ and AZ. These fluctuations seem to be influenced by the so-called Antarctic Circumpolar Wave (White and Petersen, 1996).

Tanimura *et al.* (1999) analyzed the NORPAC samples and reported a positive correlation between zooplankton biomass and water temperature in the Antarctic water off Syowa Station, Antarctica. The NORPAC standard net method seems to be suitable for analyzing macroscale distributions. However, it is difficult to describe a fine scale spatio-temporal variation in the zooplankton communities.

Microscale and successive information can be acquired easily using the Continuous Plankton Recorder (CPR). For instance, Sir Alister Hardy Foundation for Ocean Science (SAHFOS) have been investigating the long-term variability of zooplankton using the CPR, and have reported long term fluctuations of zooplankton abundance and distribution patterns (Colebrook *et al.*, 1984; Fromentin and Planque, 1996; Beaugrand *et al.*, 2001, 2002; Reid *et al.*, 2001). The CPR methodology is considered to be a good tool for the long-term monitoring of zooplankton community.

As a part of monitoring program in Antarctica the JARE has initiated a long-term CPR survey since 1999. The present paper provides the result of the fine scale distributional pattern of zooplankton obtained by the first trial of CPR tow in the JARE zooplankton observations and also assess the abilities of CPR as a tool of long-term monitoring program in the Southern Ocean.

2. Material and methods

CPR sampling was conducted on board the icebreaker *Shirase* during the 41st Japanese Antarctic Research Expedition (JARE-41) from Fremantle, Australia, toward Syowa Station, Antarctica. The CPR was towed three times along 110° E from 50° 27′S to 59° 44′S during 7 and 9 December 1999 (Fig. 1 and Table 1). Ship position data was

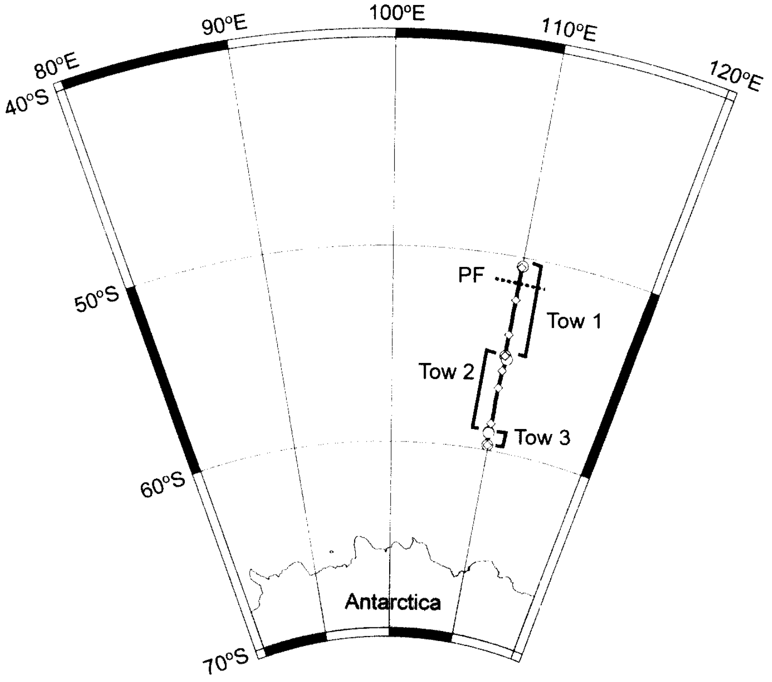

Fig. 1. Transect of the CPR tows conducted on board the icebreaker Shirase *during the 41st Japanese Antarctic Research Expedition (JARE-41) from 7 to 9 December 1999. PF indicates the approximate locations of Polar Front. Open circles, and open diamonds indicate CTD and XCTD positions, respectively.*

Table 1. CPR tows along 110° E longitude on board the icebreaker Shirase *during the JARE-41 cruise.*

Tow	CPR in or out	CPR				Sample Segment No.
		Date (GMT)		Position		
		Date	GMT	Latitude	Longitude	
Tow 1	in	Dec. 7 1999	8:55	50°26.423'S	110°02.038'E	1-56
	out	Dec. 8 1999	6:00	55°03.738'S	109°59.643'E	
Tow 2	in	Dec. 8 1999	9:54	55°13.730'S	110°12.360'E	57-103
	out	Dec. 9 1999	2:55	59°02.767'S	109°45.633'E	
Tow 3	in	Dec. 9 1999	3:05	59°04.520'S	109°45.443'E	104-111
	out	Dec. 9 1999	6:00	59°44.269'S	109°52.320'E	

recorded every minute by GPS navigation system. Concurrently, surface temperature, salinity, and fluorescence intensity were measured continuously with a surface monitoring system installed on board (Fukuchi and Hattori, 1987), which pumps up seawater from about 8 m depth. Vertical observations using CTD and XCTD were also carried out at 13 fixed stations along the cruise track (Shimazaki and Nakauchi, 2002).

The CPR was towed horizontally at a ship speed of about 14 knots, from the stern with a wire cable paid out to 100 m. Depth of CPR tow was about 10 m. The CPR has a square mouth area of 1.25×1.25 cm, which then expands into a tunnel 10×5 cm. The water then passes through a 270μm filtering silk mesh inside the CPR. The 6 m long silk is advanced across the tunnel at a rate of approximately 1 cm per 1 nautical mile, regardless of the towing speed, by water passing over an external propeller. The 6 m long silk is sufficient to sample 450 nautical miles as a normal towing distance. Zooplankton retained on the silk were then sandwiched with a cover silk. The two sheets of silk with zooplankton were rolled into and then are preserved in a borax-buffered formaldehyde bath inside the CPR and contained there (see details in Hardy, 1936; Warner and Hays 1994; SAHFOS website: http://www.sahfos.org). After sampling, zooplankton samples retained between silk meshes were preserved in a 10% v/v buffered formalin solution. The start and end of each towing were marked on the silk before and after towing. In laboratory, the silk was cut into segments that represented exact 5 nautical miles of towing. A total of 111 segments were obtained from three tows. Zooplankton were identified to the lowest possible taxa and counted for each segment. In the present study, zooplankton individual numbers are counted for 34 different categories of species/taxa (see Table 2).

Zooplankton abundances expressed as numbers per 5 nautical mile segment were analyzed by cluster analysis, using Bray-Curtis dissimilarity and UPGMA linkage, in order to compare species/taxa composition between areas, following the procedures described by Field *et al.* (1982), Hosie (1994) and Hosie and Cochran (1994). In order to compare the different sample community, data were transformed using the $\log_{10}(x+1)$ function so as to reduce the bias caused by very high abundant taxa. A total of 16 taxa, which represented more than 4% of total individuals in at least one segment among the 111 segments, were selected as dominant for further ANOVA to define indicator species characterizing the various cluster groups by their higher abundances (Sokal and Rohlf, 1995). Multivariate analysis for cluster analysis were carried out using SYSTAT® 7.0 for windows.

3. Results and discussion

3.1. *Hydrographical conditions*

Continuous record of surface temperature and salinity observed with the ship's surface water monitoring system along the CPR tows is shown in Fig. 2a. Temperature dropped from 4.5°C going south to below 1.0°C, while abrupt changes were observed at several sites, such as around 53°20′S (between segments 34 and 37), around 54°50′S (between segments 51 and 54), around 56°00′S (between segments 65 and 69), around 58°30′S (between segments 93 and 97) and around 59°02′S (between segments 103 and 105). In contrast, salinity increased from north to south (33.85–33.97) and these

Table 2. Category of zooplankton species/taxa employed in the present study. Individual numbers are counted for these 34 categories and a total individual number counted from three CPR tows is listed.

Class (subclass)	Order	Species	Developmental stage	Individual number	Percentage	4% rule*
Appendicularia	Appendicularia	*Oikopleura* spp.		203	1.1	*
		Fritillaria spp.		245	1.3	*
Foraminiferida				123	0.7	*
Gastropoda	Thecosomata	*Limacina retroversa*		1	0.0	
Polychaeta	Errantia	*Tomopteris* indet.		3	0.0	
Malacostraca	Ampipoda	*Themisto gaudichaudi*		32	0.2	
	Euphausiacea	*Euphausia frigida*	Calyptopis	4	0.0	
			Furcilia	2	0.0	
		Thysanoessa macrura	Adult	33	0.2	*
			Calyptopis	12	0.1	
			Furcilia	144	0.8	*
		Euphausia triacantha	Calyptopis	1	0.0	
			Furcilia	2	0.0	
		Euphausia vallentini	Adult	2	0.0	
		Unidentified *Euphausiid*	Adult	2	0.0	
			Furcilia	1	0.0	
Maxillopoda						
(Ostracoda)				4	0.0	
(Copepoda)	Calanoida	*Calanoides acutus*	Adult	37	0.2	
		Calanus simillimus	Adult	98	0.5	*
		C. acutus and *C.*	Copepodite (I-V)	1535	8.2	*
		Euchaeta spp.	Copepodite (I-V)	56	0.3	*
		Haloptilus oxycephalus	All stages	3	0.0	
		Metridia lucens	All stages	1	0.0	
		Pleuromamma robusta	All stages	8	0.0	
		Rhincalanus gigas	Adult and copepodite (I-V)	40	0.2	*
			Nauplius	813	4.4	*
		Calanoid nauplius other than *R. gigas*	Nauplius	683	3.7	*
		Other calanoids	Adult and copepodite (I-V)	3435	18.4	*
	Cyclopoida	*Oithona* spp.	Adult and copepodite (I-V)	11076	59.3	*
	Poecilostomatoida	*Oncaea* spp.	Adult and copepodite (I-V)	6	0.0	
Sagittoidea	Phragmophora	*Eukrohnia hamata*		32	0.2	*
	Sagittidae	*Sagitta gazellae*		1	0.0	
Others		Egg mass		9	0.1	*
		Fish egg		17	0.1	*
Total				18664		16

* Asterisk mark shows categories with more than 4% numerical abundance in segment to determine the dominant zooplankton (see text).

abrupt changes of salinity had correspondence with changes of temperature. A sudden decrease in the surface salinity with temperature was found south of 59°05′S. It is considered that was sea-ice melt water.

The vertical temperature profile observed by XCTD and CTD as shown in Fig. 2b,

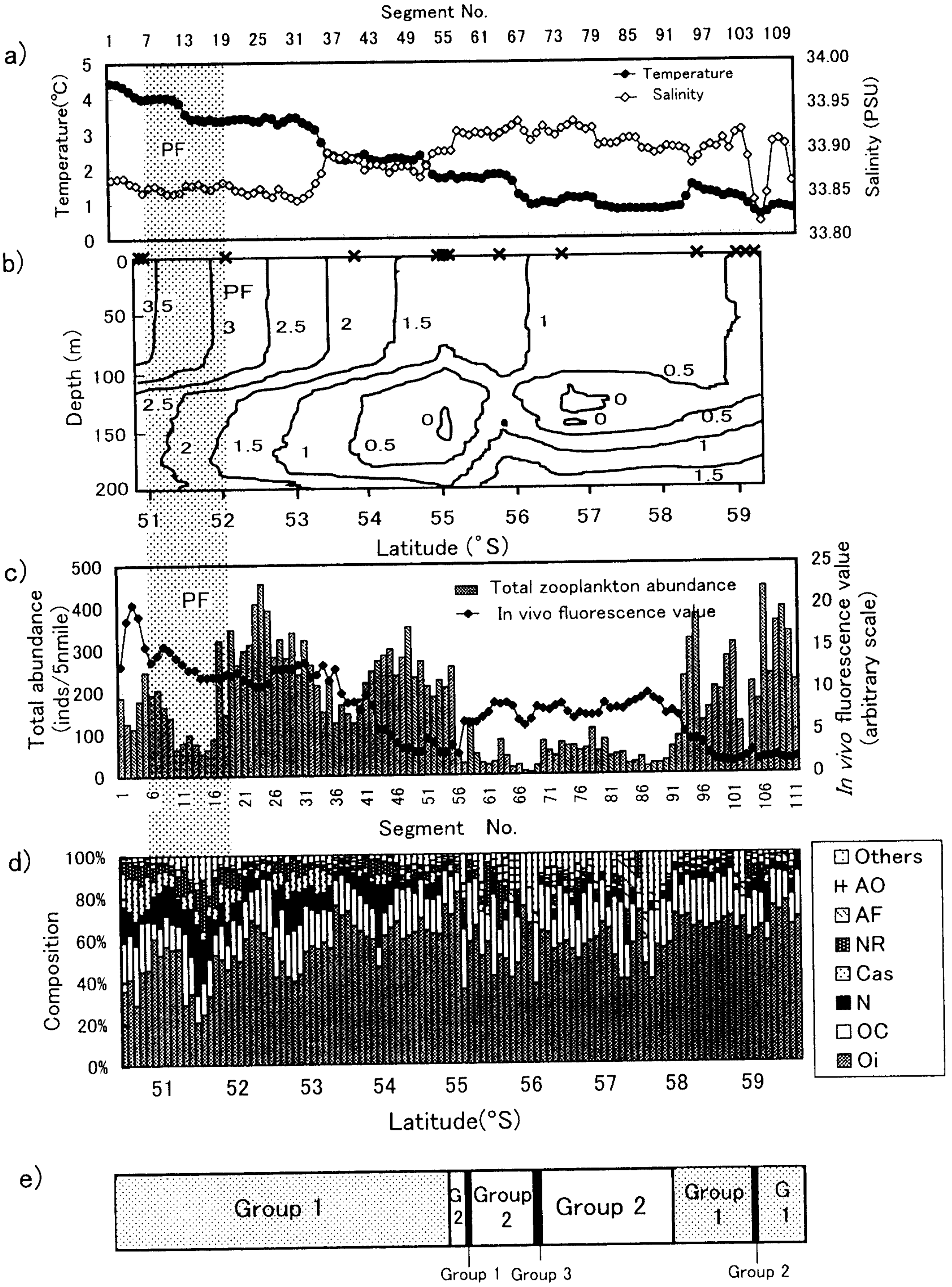

Fig. 2. a) Latitudinal changes of surface temperature and salinity averaged for 5 nautical miles segment of CPR. b) Vertical profile of water temperature (℃) observed with CTD and along 110°E. × indicates CTD and XCTD position; broken lines indicate an approximate location of Polar Front (PF), respectively. c) Latitudinal changes of zooplankton abundance per 5 nautical mile segments and averaged in vivo *fluorescence value of each segment. d) Composition of zooplankton categories of each segment (Oi:* Oithona *spp., OC: Other calanoid copepods, Cas: Copepodite stage of* C. acutus *and* C. simillimus, *NR: Nauplii of* Rhincalanus gigas, *N: Nauplius other than* R. gigas, *AF:* Fritillaria spp., *AO:* Oikopleura *spp.). e) Latitudinal separation of zooplankton groups identified by cluster analysis. See text and Fig. 3.*

could not show such abrupt surface changes, because of the sparse spacing of the observation stations as expressed by the crosses in the Fig. 2b. On the other hand, the vertical profile clearly indicated water structure in the top 200 m (Fig. 2b). The Antarctic Polar Front (PF) was determined based on a vertical temperature profile of 2°C isotherm at 200 m depths. PF located between 50° 52′S and 52° 11′S which were two nearest XCTD position (Fig. 2b), and Southern Antarctic Circumpolar Current Front (SACCF) was not observed along the present transect. The SACCF was expected to be located further south (Orsi *et al.*, 1995). Most of transect in the present study coincided with the AZ.

3.2. Zooplankton identification and category for counting

Table 2 lists the 34 taxa collected by the CPR and used in this study. Sixteen of these taxa were classed as dominant groups and selected for further ANOVA analysis of the cluster groups.

The CPR sample is preserved between two silks and almost all zooplanktons are pressed. Therefore, some zooplankton samples are very difficult to be identified to a species level. In the present study, 34 categories were used.

3.3. Zooplankton composition

Throughout the present study, copepods were the most dominant zooplankton component, representing >90% of the total abundance (including nauplii). The most dominant zooplankton taxa was the cyclopoid copepod *Oithona* spp., accounting for 59.3% of the total abundance. Other abundant categories were small-sized calanoid copepods (mainly *Microcalanus pygmaeus*, *Ctenocalanus citer*, *Clausocalanus* spp., and *Scolecithricella* spp.) (18.4%) and copepodites of *Calanoides acutus* and *Calanus simillimus* (8.2%). Nauplii of *Rhincalanus gigas* (4.4%) were the next most abundant, followed by calanoid nauplii of copepods other than *R. gigas* (3.7%), *Fritillaria* spp. (appendicularians; 1.3%), and *Oikopleura* spp. (appendicularians; 1.1%) (Table 2). The contribution of copepods to the total zooplankton is similar to that observed by Foxton (1956), Yamada *et al.* (1991), Atkinson and Sinclair (2000) and Pakhomov *et al.* (2000). These four papers reported that copepod accounted for >70% of the Antarctic zooplankton. Takahashi *et al.* (2002) reported a very similar composition based on the CPR data in the western Indian sector between South Africa and Antarctica along 25° 30′E two weeks earlier than the present observation.

3.4. Zooplankton abundance and fine scale distribution

Mean total abundance of zooplankton was 168 individuals per segment (SD: ±117.2). Total zooplankton abundance along the transect varied considerably from 6 (segment 68) to 456 individuals (segment 24). Low zooplankton abundances less than 100 individuals per segment were seen in the center of PF and between 55° 04′ to 58° 12′S (Fig. 2c). Percentages of *Oithona* spp. decreased in the center of the PF, and percentages of nauplii of *R. gigas* also decreased in 55°04′ to 58° 12′S (Fig. 2d). The percentage of other calanoids, nauplii of copepod, and nauplii of *R. gigas* were higher in 55°04′ to 58° 12′S than in the south, although *Fritillaria* spp. and *Oikopleura* spp. occurred frequently (Fig. 2d). There was no change in the percentage dominance of

Oithona spp. between 55°04′ and 58°12′S.

The low abundance area of PF is explained by the decrease of *Oithona* spp., and the low abundance area between 55°04′ and 58°12′S was caused not only by the decrease of *Oithona* spp. but decreases of nauplii of copepods, and copepodites of *Calanoides acutus* and *Calanus simillimus*. Previous reports have shown that the PF can act as a boundary to *C. acutus* (Andrews, 1966), and that biomass and abundances of some zooplankton species increased in the PF area (e.g. Andrews, 1966; Yamada and Kawamura, 1986; Errhif *et al.*, 1997). Results of the present study also showed decreased proportion of other small-sized calanoid copepods, *Oithona* spp., and *R. gigas* nauplii (Fig. 2d). Although zooplankton abundance and composition at the PF was different from other areas, no differences could be found north and south of the PF.

Takahashi *et al.* (1998) showed that the zooplankton biomass was higher in the PFZ and AZ, in particular in the northern oceanic community area that corresponds to the present transect. Hosie *et al.* (2002) also showed high abundances across the PFZ and AZ. The present CPR revealed a relatively less abundant area between 55–58 among the northern oceanic community area. In this study, high zooplankton abundance mainly occurred between the PF and 55°S and south of 58°S.

The CPR sampling could reveal the fine scale (about 5 nautical miles) latitudinal variability of zooplankton abundance (Fig. 2c). The hydrographical condition indicates relatively uniform surface temperature structure in top 100 m, while surface temperature decreased from 3 to 1°C south of PF. On the other hand, the zooplankton abundance per segment fluctuated largely and several peaks of abundance were observed at segments 25, 48, 94 and 107. Throughout the fluctuation, an interesting change of abundance and *in vivo* fluorescence was clearly seen from segment around 40 to 96. A mirror image like changes of abundance and fluorescence is seen there; zooplankton abundance fluctuates oppositely to fluorescence. This might be related to grazing pressure by zooplankton on phytoplankton. Further analysis is needed for clear understanding.

3.5. *Zooplankton assemblage*

Cluster analysis was employed to find similarities in the zooplankton composition among the segments. This analysis revealed two major clusters (Groups 1 and 2) and smaller group composed of two segments (Group 3) as identified at the 46% dissimilarity level (Fig. 3). This indicates that there are three different zooplankton assemblages on this transect.

Group 1 was widely distributed over the transect and distributed from 50°30′ to 55°03′S (Segment 1–55) and from 55°04′ to 58°12′S (Segment 92–111; Fig. 2c and 3). Figures 2c and 2e showed Group 1 had higher abundances (mean±SD=229.4±95.16 individuals) than that of Group 2 (mean±SD=48.6±25.47 individuals). *C. simillimus* and *C. acutus* (CI-CV), *Euchaeta* spp. copepodites, *Oithona* spp., *R. gigas* nauplius, other calanoids, calanoid nauplius other than *R. gigas*, and *Thysanoessa macrura* furcilia distinguished significantly higher abundance than Group 2.

Group 2 occurred from 55.0°S to 58.1°S (Segments 56–92) and 59.0°S (Segments 102–103; Fig. 2e), and coincided with the low abundances between 55°04′ to 58°12′S (Figs. 2c and 2e). Group 2 was dominated by *Oithona* spp. and other calanoid

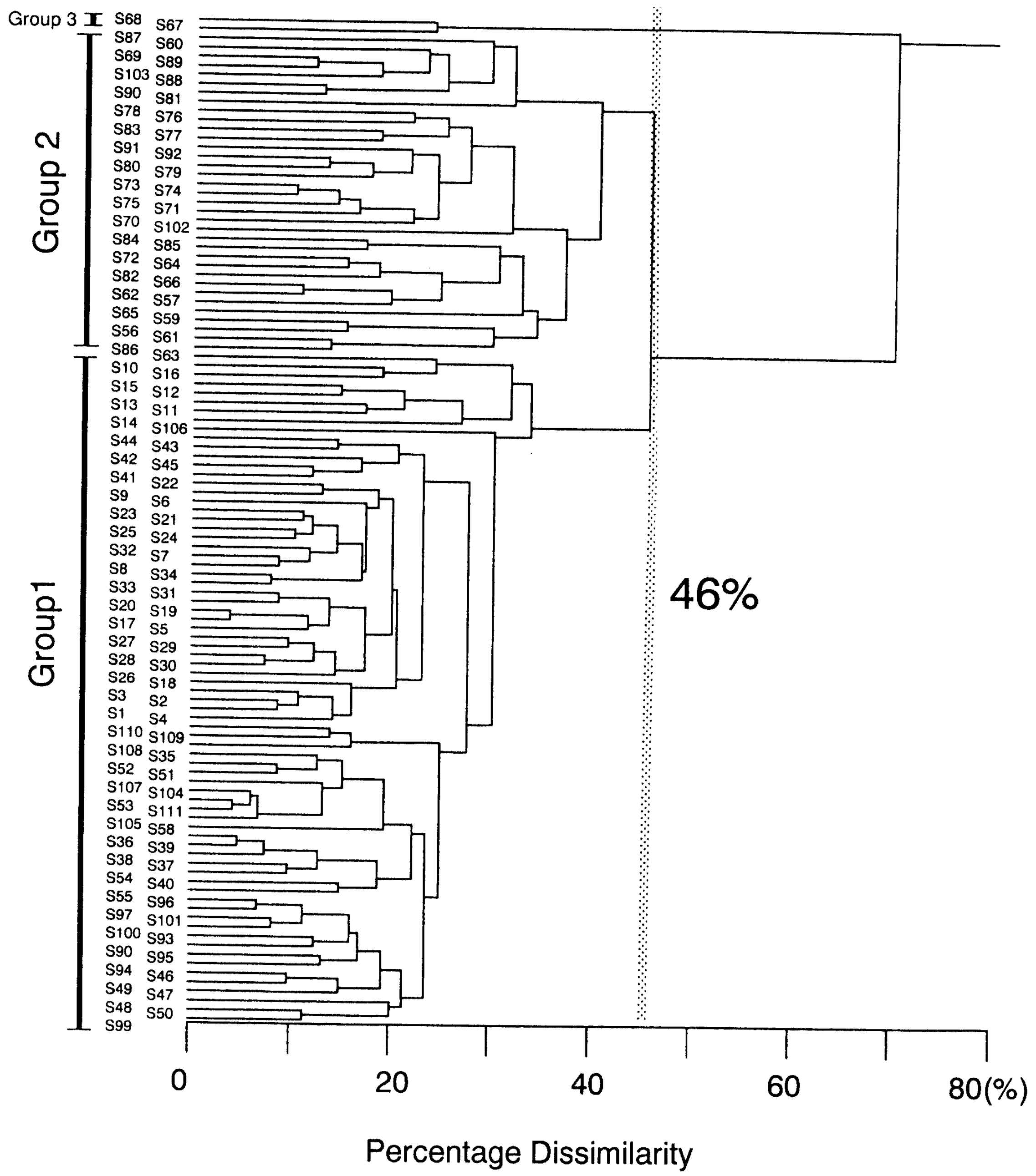

Fig. 3. Dendrogram of cluster analysis comparing among 111 segments. The Bray-Curtis dissimilarity index was used for the comparison with UPGMA linkage, after $\log_{10}(x+1)$ *transformation of species abundance data.*

copepods (Fig. 2d), comprising 36–83% and 8–39% of the total abundance, respectively. *Euchaeta* spp. was not found in Group 2. In contrast to Group 1, the area of Group 2 showed low temperature and high salinity (Fig. 2c), and this group coincided with the position of the increased Chl *a* fluorescence area in the south (58° 12′S to 59° 06′ S, Table 3). As noted above, Group 2 had a relatively low abundance, and dominant species other than Foraminifera were significantly lower than those in Group 1 (Table

Table 3. Mean composition, ANOVA of dominant zooplankton abundances between Group 1 and Grop 2. Numerals in parenthesis are number of segments.

Species	Group 1 (74)	Group 2 (35)	*F*	*P*-value	
Calanus simillimus	0.73	0.45	3.22	0.076	NS
***C. simillimus* and *Calanoides acutus* (CI-CV)**	15.11	1.43	202.07	<0.001	
Egg mass	0.06	0.04	0.19	0.667	NS
***Euchaeta* spp. copepodites**	0.44	0	13.53	<0.001	
Eukrohnai hamata	0.14	0.32	3.63	0.059	NS
Fish egg	0.14	0.04	2.66	0.106	
Foraminifera	0.34	1.19	11.30	0.001	
Fritillaria spp.	1.75	1.14	3.49	0.065	NS
Oikopleura spp.	1.50	0.84	5.37	<0.05	
***Oithona* spp.**	113.67	23.05	137.16	<0.001	
Rhincalanus gigas	0.30	0.12	3.91	0.051	NS
***R. gigas* nauplius**	7.03	0.37	122.82	<0.001	
Other calanoids	34.71	8.65	125.64	<0.001	
Calanoid nauplius other than *R. gigas*	6.59	0.78	122.16	<0.001	
Thysanoessa macrura	0.26	0.08	4.99	<0.05	
***Thysanoessa macrura* furcilia**	0.96	0.36	7.84	<0.01	

Analysis were carried out on $\log_{10}(x+1)$ transformed abundances; values shown are number of individuals per segment. Species with significant differences in mean abundance by ANOVA are shown in bold text. NS=not significant.

3). Foraminifera of Group 2 have significantly higher abundance than that of Group 1.

Group 3 consisted of two segments (S67 and S68) from 56.1°S to 56.2°S (Fig. 3). Zooplankton abundances in this group were very low (mean±SD; 7.0±1.41 individuals), and the community only comprised four copepod taxa; *Oithona* spp., *C. simillimus* and *C. acutus* (CI-CV), and other calanoid copepods (Fig. 2c). This area coincided with the decrease in the surface temperature and Chl. *a* (Fig. 2a and 2c), which may have influenced the zooplankton composition.

There were the same components of Group 1 both north and south on this transect —low abundance assemblages Group 2 and Group 3 were distributed between Group 1 (Fig. 2e). This suggests no latitudinal zonation of zooplankton assemblages (Fig. 2d and e). Low zooplankton abundances were seen around the PF and between 55°04′ to 58°12′S (Fig. 2c), which belong to Group 1 and Group 2, respectively. This indicates different assemblages. Atkinson *et al.* (1990) suggested that there were warm and cold core rings or similar intrusions near the PF, and that the distribution of some zooplankton species was influenced by cyclonic eddies. The water temperature and salinity decreased and increased respectively at 55°S coincident with decreased zooplankton abundance. Cold core rings or similar intrusions could influence the abundance. It is considered that while zooplankton abundance fluctuated, the zooplankton composition has not changed dramatically in the ACC, although it seems that zooplankton maybe influenced by melt ice waters and core rings or similar intrusions.

The previous studies of NORPAC routine observation lacked the resolution to identify small fluctuations of zooplankton communities in relation to small scale changes in water mass. The CPR observation could investigate such fine scale fluctuations of zooplankton abundance and composition that maybe influenced by melt ice waters and core rings or similar intrusions.

4. Conclusion

The first use of the CPR on board the icebreaker *Shirase* was successful and the data obtained from the CPR samples revealed new findings on zooplankton communities structure in the Indian sector of the Antarctic Ocean. The previous JARE routine observation of zooplankton distribution has been employing the NORPAC standard sampling. The NORPAC data has been used to study macro scale distribution patterns (see Takahashi *et al.*, 1998; Tanimura *et al.*, 1999; Yamada *et al.*, 1991). However, the NORPAC methodology needs a certain amount of ship time on station for sampling, but sometimes it is difficult to find sampling time, on board *Shirase*, because the major mission of the ship is to resupply the Japanese Antarctic station and exchange expeditioners during the limited summer time. Sea or weather conditions can also prevent sampling. By comparison, the CPR does not need any ship-time for sampling and continuous sampling could be carried out while the ship is steaming. Only a short ship time for deployment and recovery over several hundred miles of sea surface is required. Further, the CPR samples provide a finer scale resolution in spatial expansion compared with the NORPAC samplings. The present study employed a five nautical mile sample resolution. As a result, a very fine structure of surface zooplankton assemblages could be investigated in relation to small scale changes in water mass through combining CPR data with other simultaneous observations, such as a surface water monitoring system. The combination of CPR and monitoring system data is an ideal methodology to detect fine structures of frontal positions, and to monitor zooplankton communities as part of a long-term monitoring program.

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