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Scientific note

Zooplankton distribution patterns in relation to the Antarctic Polar Front Zones recorded by Continuous Plankton Recorder (CPR) during 1999/2000 *Kaiyo Maru* cruise

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Abstract: During the 8th Antarctic Expedition of the R/V *Kaiyo Maru* of the Japan Fisheries Agency, October 1999 to March 2000, a Continuous Plankton Recorder (CPR) was used to investigate zooplankton composition and abundance in the surface of the Indian sector of Southern Ocean between South Africa and Antarctica. Total zooplankton abundance ranged from 0 to 432 individuals/segment (a 5 nautical miles of the surface towing) (Mean ± SD=69.7 ± 83.5). Zooplankton abundance tended to be higher in the high latitudes than the Sub-Antarctic Front (SAF). Opposite correlations were observed between zooplankton and seawater temperature (negative), salinity (positive) and *in vivo* fluorescence value (positive) reflecting the higher abundance of zooplankton found in the cooler waters south of the SAF, which also have higher salinities and phytoplankton. Among twenty-nine species/taxa identified, cyclopoid copepod *Oithona* spp. were found throughout the transect, and accounted for 53.3% of total zooplankton abundance. Cluster analysis based on seventeen dominant zooplankton species/taxa revealed two groups and three ungrouped individual species/taxa at the 84% dissimilarity level. On the other hand, the cluster analysis based on the samples obtained in a 5 nautical miles indicated two major distinctive zooplankton community groups at 89% dissimilarity level. The main group included most segments in the Polar Frontal Zone (PFZ: region between SAF and the Polar Front) and Antarctic Zone (AZ: south of the Polar Front) with high zooplankton abundance while the second mainly group comprised lower latitude segment with low abundance (<100 individuals/segment).

key words: Continuous Plankton Recorder (CPR), zooplankton, Sub-Antarctic Front (SAF), Polar Frontal Zone (PFZ), Antarctic Zone (AZ)

The Southern Ocean comprises several thermohaline zones separated by four major circumpolar fronts, such as Sub-Tropical Front (STF), Sub-Antarctic Front (SAF), Polar Front (PF) and Antarctic Divergence (AD) (Deacon, 1982; Hempel, 1985; Lutjeharms, 1985; Orsi *et al.*, 1995). Differences in zooplankton composition have been documented in each of these zones (Fukuchi and Tanimura, 1981; Watanabe *et al.*, 1984; Kawamura,

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1986; Pakhomov and McQuaid, 1996; Pakhomov *et al.,* 1996, 2000; Takahashi *et al.,* 1997, 1998), but, net sampling is not ideal for mapping and monitoring in the community because the method is discontinuous. Moreover, abundance estimated with small nets are sometime affected by net avoidance coupled with zooplankton patchiness causing high variation between samples (Tanimura *et al.,* 1999).

The Continuous Plankton Recorder (CPR) has been very successful in the monitoring zooplankton communities in the North Sea and North Atlantic Ocean over the past seventy years (Colebrook *et al.,* 1984; Fromentin and Planque, 1996). The CPR can collect surface plankton continuously for 450 nautical miles (830 km) during a single tow. Therefore in a short period, it is ideal for sampling in large areas and mapping for the distribution of zooplankton in relation to ocean environments such as frontal zones typically found through the Southern Ocean.

In 1999, CPRs were towed on the three transects across the Southern Ocean at around the same year from late November to early December. Three widely spaced transects along 25°E by R/V *Kaiyo Maru* (Japan), along 110°E by icebreaker *Shirase* (Japan) and along 158°E by RSV *Aurora Australis* (Australia), were investigated in order to observe the zooplankton patterns across the frontal zones of the circumpolar current. Comparison of zooplankton data between the three ships will be made in the near future. In this paper, we report more detailed results obtained on the *Kaiyo Maru* cruise and provide information on the composition, distribution and abundance of zooplankton communities in the Indian sector of Southern Ocean between the South Africa and the Antarctica.

Methods of the CPR survey

The Continuous Plankton Recorder (CPR) was towed during the 8th Antarctic Expedition of the R/V *Kaiyo Maru* of the Japan Fisheries Agency from 24 to 25 November 1999 in the Indian sector of Southern Ocean between the South Africa and the Antarctic from 49°S to 55°S (Fig. 1, Table 1). The CPR was towed at 10 m depth and towing speed was between 15 to 17 knots. Water enters the CPR through a 1.27 cm square entrance aperture and passes through a silk filtering mesh (mesh size 270 μm). The movement of the CPR through the water turns an external propeller, which drives the silk across the tunnel at a rate of approximately 1 cm per 1 nautical miles of tow. This silk mesh is preserved in formaldehyde bath after sample collection. Four tows were successively conducted southward cruise from 49°S to 55°S and stopped every two degrees of latitude for the purposes of CTD casts and other sampling (Table 1). After returning to the laboratory, the start and end points of each CPR silk were identified and the silk was cut into a 5 nautical miles (approximately 9.3 km) sampling intervals (segment). There was little difference in number of segments and miles travelled for each 2° latitude segment (Table 1); therefore the CPR was winding on silk at a constant rate. Zooplankton were identified to the lowest taxa as possible, generally species or genus, and counted per segment. Euphausiid larvae were identified to metanauplius, calyptopis, furcilic and adult general stages.

Zooplankton abundance was compared with associated environmental data averaged over the same 5 nautical miles. Sea surface temperature, salinity and *in vivo* fluorescence values as an indicator of phytoplankton biomass were continuously recorded by an

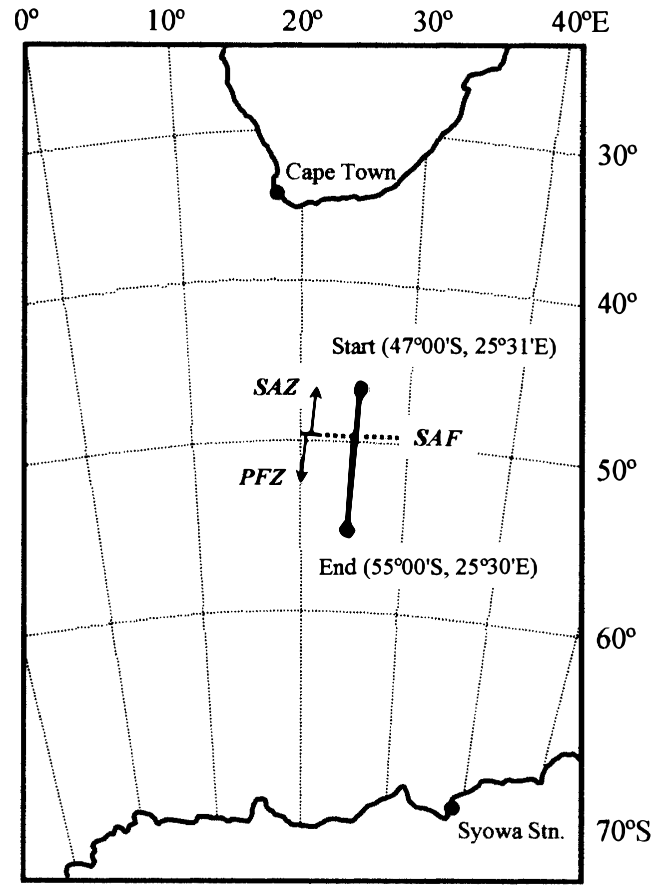

Fig. 1. Location of the CPR survey of *Kaiyo Maru* in November 1999. SAF: Sub-Antarctic Front, SAZ: Sub-Antarctic Zone, PFZ: Polar Frontal Zone.

Table 1. Details of CPR tows conducted on *Kaiyo Maru* in November 1999.

	Start		End			
CPR Run #	Date & Time GMT	Position	Date & Time GMT	Position	*No. of Segments	Distance towed (nautical miles)
1	Nov. 24, 1999; 00:21	47° 00.49'S 25° 31.08'E	Nov. 24, 1999; 07:49	49° 00.14'S 25° 30.37'E	25	122.17
2	Nov. 24, 1999; 09:10	49° 00.48'S 25° 31.09'E	Nov. 24, 1999; 16:50	51° 00.33'S 25° 30.09'E	25	121.99
3	Nov. 24, 1999; 17:52	51° 00.80'S 25° 31.10'E	Nov. 25, 1999; 01:27	53° 00.30'S 25° 30.00'E	25	124.72
4	Nov. 25, 1999; 03:44	53° 00.00'S 25° 29.40'E	Nov. 25, 1999; 11:38	55° 00.20'S 25° 30.30'E	26	126.38

* Each segment of cutted silk corresponds to 5 nautical miles of towing distance.

automated surface water monitoring system which was equipped as a part of an Electronic Plankton Counting and Sizing System (EPCS, Honchigo Co. LTD; see detail Mackas *et al.*, 1981) installed on R/V *Kaiyo Maru*.

Zooplankton data were further analyzed by cluster analysis in order to compare species/taxa composition between areas covered by the segments and species/taxa associations. For the comparison among the areas, data were transformed using a $\log_{10}(x+1)$ function to normalize the areal different of the abundance. Only numerically dominant species/taxa were used in the comparison of species/taxa associations. Dominant species/taxa were defined as those comprising >4% of the total number of individuals for any segments. Table 2 lists the seventeen dominant species/taxa defined. Complete details of the data analysis techniques have been described in Hosie (1994a, b) and Hosie and Cochran (1994). Statistical analyses were performed using SYSTAT® 7.0 for Windows.

Table 2. Dominant species/taxa used in the inverse cluster analysis. Dominant species/taxa were defined as those with a >4% numerical dominance for any segment.

Species/taxa with > 4% numerical dominance	
Thysanoessa macrura	Copepod nauplii
Thysanoessa macrura furcilia	*Themisto gaudichaudi*
Unidentifiable euphausiid	*Eukrohnia hamata*
Calanus simillimus	*Oikopleura* spp.
Metridia lucens	*Fritillaria* spp.
Rhincalanus gigas nauplius	Foraminifera
Small calanoid copepods	*Tomopteris* spp.
Calanoid copepodites	Medusae
Oithona spp.	

Zooplankton abundance and environmental factors

Seawater temperature varied from 7.1 to 0.84°C in the whole transect (Fig. 2). Seawater temperature decreased from low latitude to high latitude and rapidly decreased (about 3°C) around 49°S (segment number 30). Sievers and Emery (1978) defined the Sub-Antarctic Front (SAF) as that front which was found at the most vertically orientated isotherm within a subsurface temperature gradient between 3 and 5°C. Moreover, the average temperature decrease at the sea surface for the SAF is about 4°C (Lutjeharms and Valentine, 1984). Therefore, this location around 49°S (segment number 30) was considered to be the SAF. Temperatures of near 1°C at the end of the tows (53–55°S) would suggest that the Polar Front (PF) had been crossed, and then we stopped sampling within the Antarctic Zone (AZ: south of the PF). CTD data indicate the PF was at 53°S (National Research Institute of Far Seas Fisheries, 2001). The actual position of the PF can only be properly identified by deep oceanographic observation (Orsi *et al.*, 1995). The importance of the SAF as a biogeographic boundary is still unclear (Pakhomov and McQuaid, 1996), although some importance have been pointed out in several studies (Deacon, 1982; Froneman *et al.*, 1995; Pakhomov *et al.*, 1999). Zooplankton abundance tended to be higher in the high latitudes than the Sub-Antarctic Zone (SAZ: region

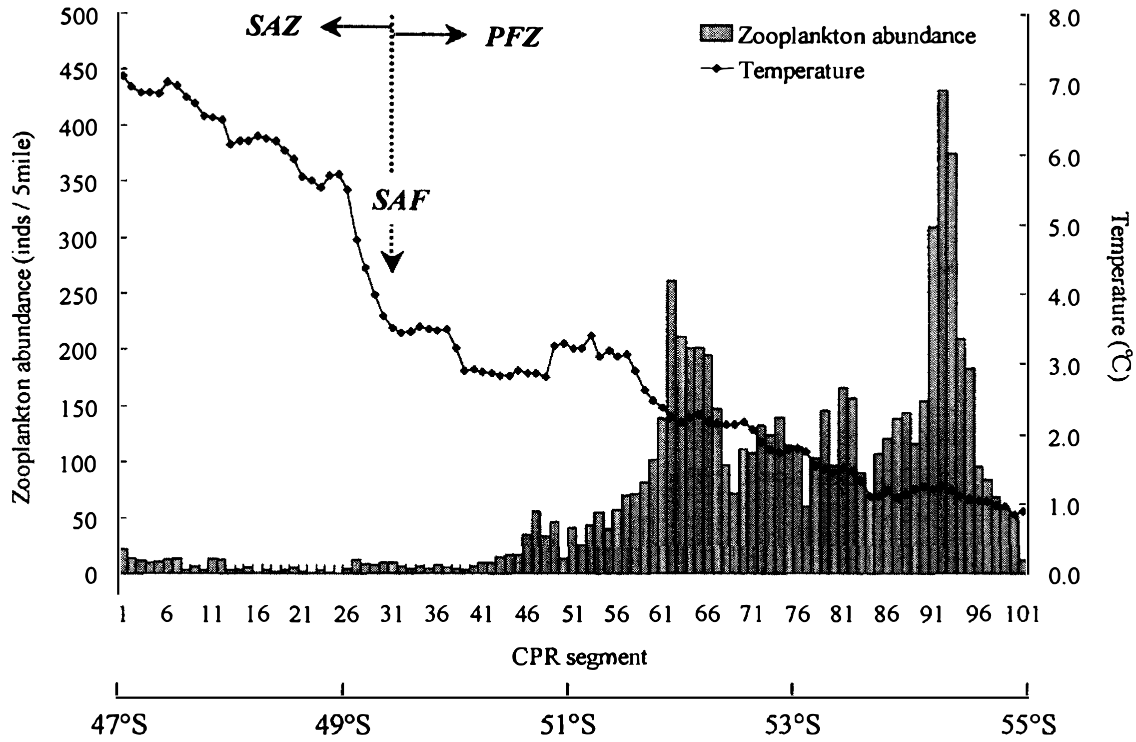

Fig. 2. Latitudinal changes of abundance of zooplankton per 5 nautical mile segments and averaged temperature for the segment.

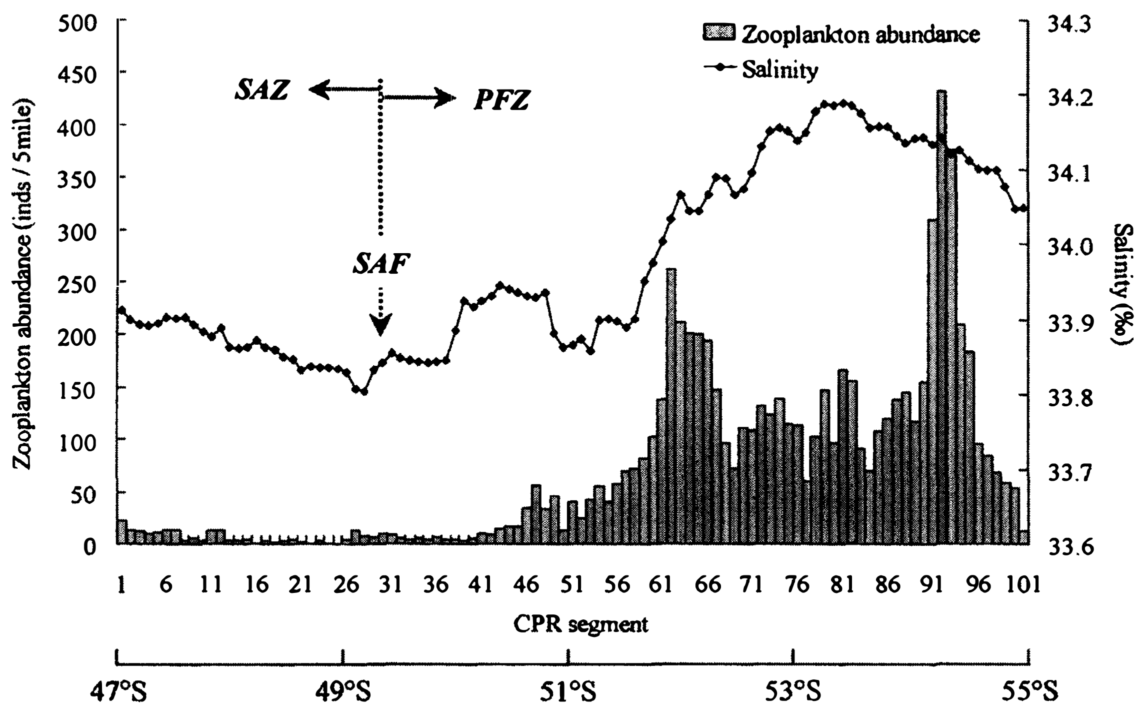

Fig. 3. Latitudinal changes of abundance of zooplankton per 5 nautical mile segments and averaged salinity for the segment.

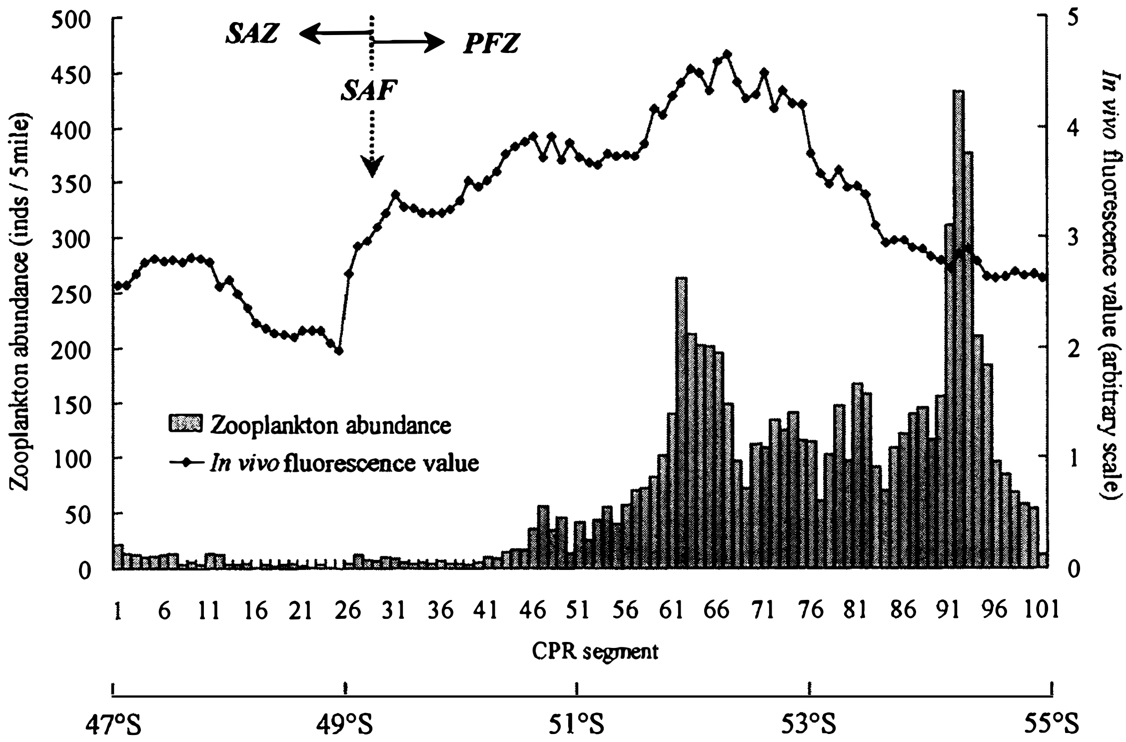

Fig. 4. Latitudinal changes of abundance of zooplankton per 5 nautical mile segments and averaged *in vivo* fluorescence value for the segment.

between SAF and the Sub-Tropical Convergence, see Figs. 2, 3 and 4). Total zooplankton abundance ranged from 0 to 432 individuals/segment (5 nautical miles) (Mean ± SD = 69.7 ± 83.5). A total of 7040 specimens were counted. Overall, there is a negative correlation between surface temperature and zooplankton abundance (F=62.55, DF=1, 99, P<0.0001). Salinity varied from 33.80 to 34.19 psu and increased from low latitude to high latitude (Fig. 3). A strong positive correlation was found between salinity and zooplankton abundance (F=111.5, DF=1, 99, P<0.0001). *In vivo* fluorescence values tended to be higher in the high latitudes than the SAF and were highest, up to 0.047, at 52°36′S (segment number 67) (Fig. 4). The values dropped substantially around 53°S (segment number 75). A significant relationship between zooplankton abundance and *in vivo* fluorescence values was found for the whole transect (F=11.99, DF=1, 99, P=0.0008). However, a similar relationship was not observed within the Polar Frontal Zone (PFZ: region between SAF and the PF) and the AZ. In this study, CPR run started well north of the SAF as seen with the higher temperature and much less zooplankton abundance. Consequently, opposite trends of the correlations were observed between zooplankton and seawater temperature (negative), salinity (positive) and *in vivo* fluorescence value (positive) reflecting the higher abundance of zooplankton found in the cooler waters south of the SAF, which also have higher salinities and phytoplankton biomass. The zooplankton abundance of the SAZ was characterized by low densities. A previous study conducted in the Atlantic sector of the Southern Ocean (0°–10°E) showed that pelagic predators, mainly chaetognaths and euphausiids, virtually controlling secondary production around SAZ (Pakhomov *et al.,* 1999). Therefore, the low zooplankton abundance within the SAZ may appear to be the result of high predation pressure by carnivorous macroplankton, and/or a general low productivity that was caused by the other factor (s).

Species composition and distribution

A total of twenty-nine species/taxa of zooplankton were classified. Cyclopoid copepod *Oithona* spp. were found throughout the transect, and accounted for 53.3% of total zooplankton abundance, followed by small calanoid copepods (*Microcalanus* sp. or

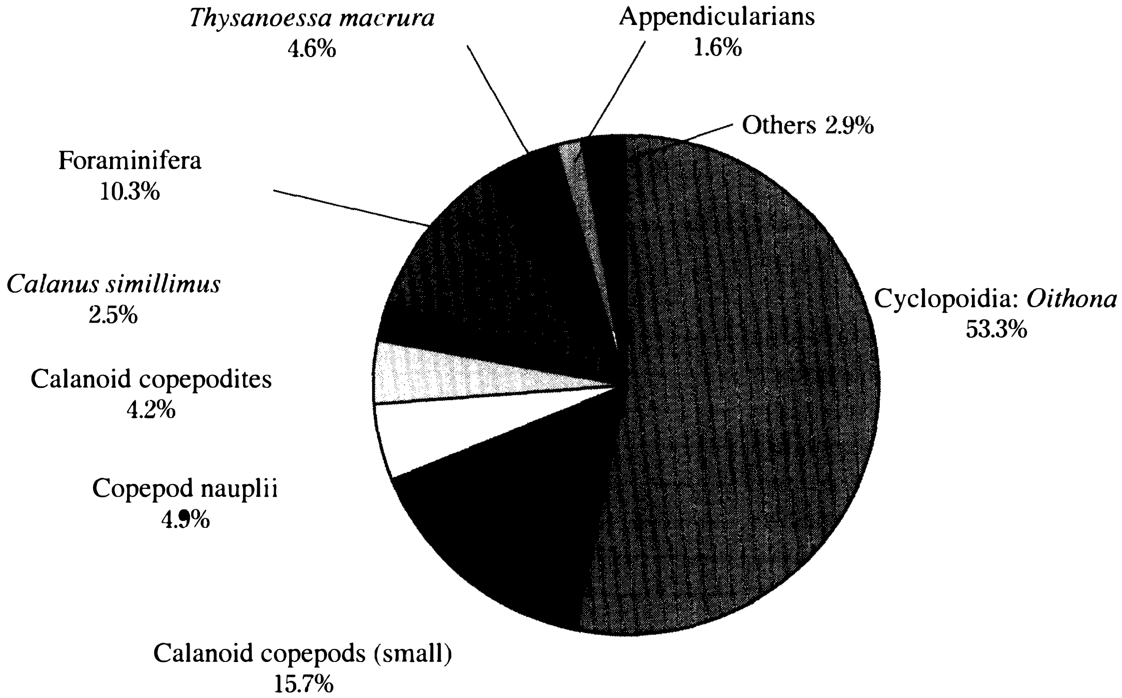

Fig. 5. Major dominant zooplankton species/taxa combine for all segments.

Ctenocalanus sp.) (15.7%), copepod nauplii (4.9%), calanoid copepodites (4.2%), *Calanus simillimus* (2.5%), foraminiferans (10.3%), the euphausiid *Thysanoessa macrura* (4.6%) and appendicularians (*Oikopleura* spp. and *Fritillaria* spp.) (1.6%) (Fig. 5). In this study, copepods were found to be the most important group of zooplankton throughout the transect. This result agrees with previous studies in the Indian sectors of the Southern Ocean (Foxton, 1956; Kawamura, 1986; Yamada and Kawamura, 1986; Voronina, 1998). Pakhomov *et al.* (2000) observed that *C. simillimus* was one of the most important species in the PFZ due to its abundance and biomass. Abundance of *C. simillimus* in this study also increased in the PFZ, but abundance of *Oithona* spp. were higher overall (Fig. 6).

Seventeen species/taxa were classified as numerically dominant (>4%) in the whole study area (Table 2) therefore they were included in the cluster analysis of species/taxa. The cluster analysis revealed two groups and three ungrouped individuals (Unidentifiable

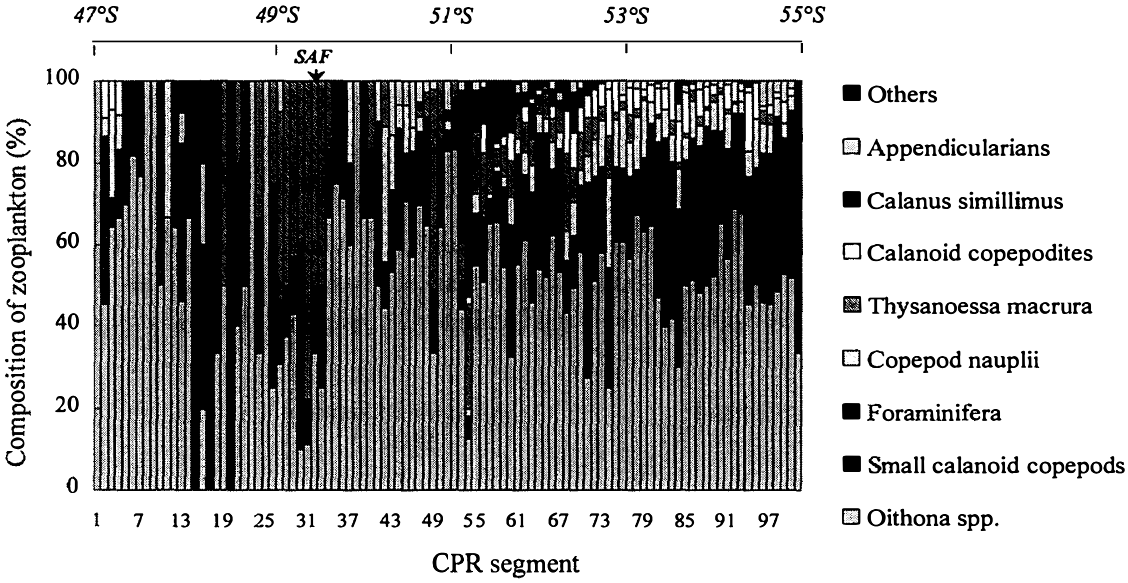

Fig. 6. Composition of dominant zooplankton species/taxa per 5 nautical mile segment.

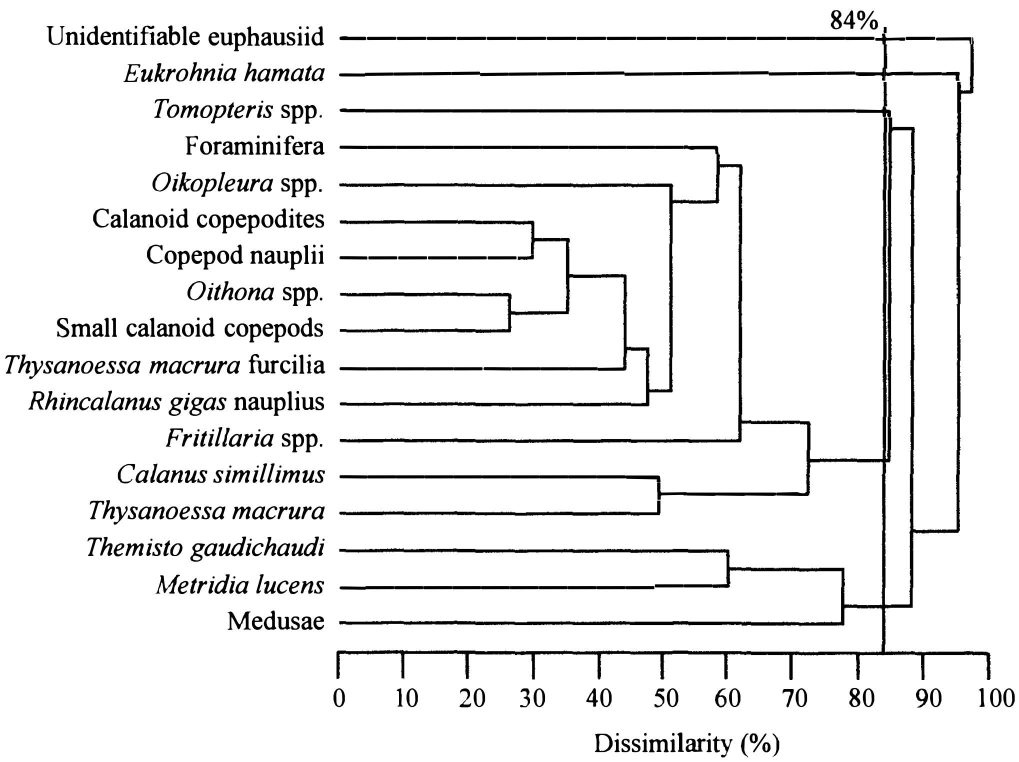

Fig. 7. Cluster analysis of comparison of species/taxa. Seventeen >4% numerically dominant species/taxa common to all transects were used.

eupahusiids, *Eukrohnia hamata* and *Tomopteris* spp.) at the 84% dissimilarity level (Fig. 7). The main group comprised eleven species/taxa, Foraminifera, *Oikopleura* spp., calanoid copepodites, copepod nauplii, *Oithona* spp., small calanoid copepods,

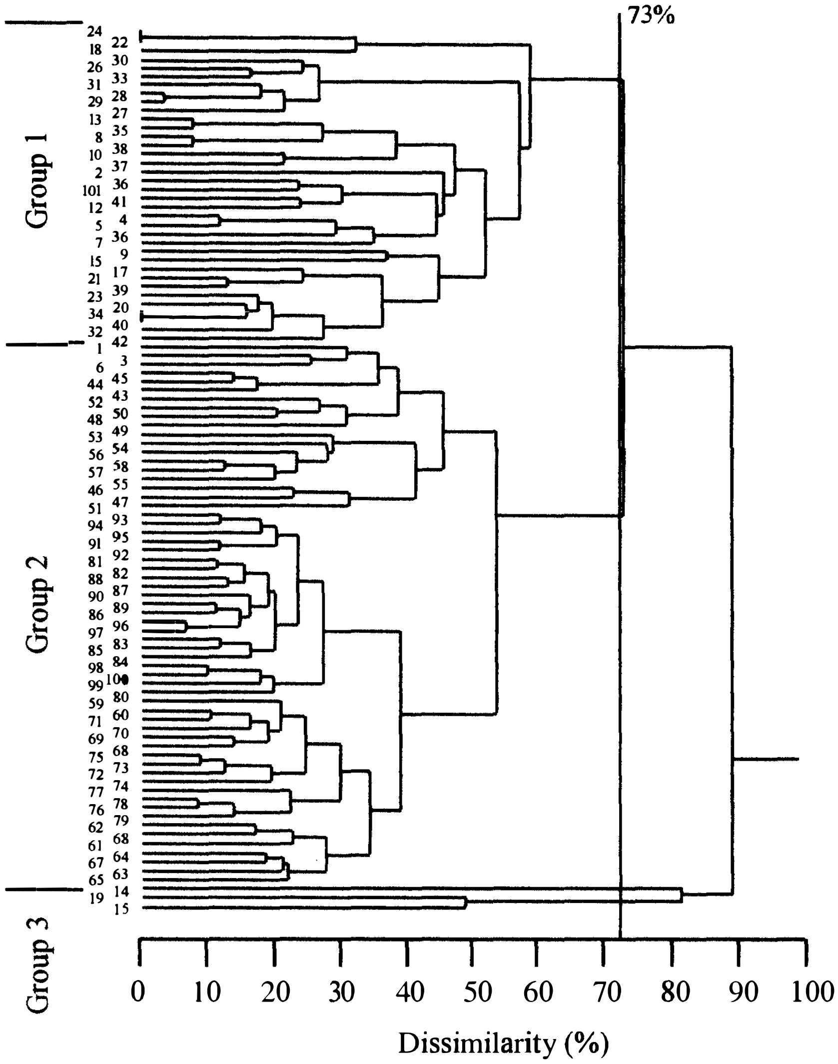

Fig. 8. Cluster analysis of comparison of segments.

Thysanoessa macrura furcilia, *Rhincalanus gigas* nauplius, *Fritillaria* spp., *Calanus simillimus* and *T. macrura*. These results suggest that dominant species/taxa show similar associations throughout the transect (Figs. 5, 7). The second group was consisted of 3 species/taxa, *Themisto gaudichaudi*, *Metridia lucens* and medusae. Unidentifiable eupahusiids, *Eukrohnia hamata* and *Tomopteris* spp. showed no close association with any other species/taxa. On the other hand, the cluster analysis based on the segments indicated two major distinctive zooplankton community groups at 73% dissimilarity level (Fig. 8). The first major group included most segments in the PFZ with high zooplankton abundance while the second group comprised lower latitude segments with low abundance (<100 individuals/segment). Thus, the major separation of segments coincided with the position of the SAF, which clearly distinguished the Antarctic and Sub-Antarctic/Sub-Tropical zooplankton communities. Group three comprised three segments, with low zooplankton abundance and comprising rare species.

The results of this study show that there are distinct zonation patterns in the zooplankton communities of the Southern Ocean, separated by the SAF. For identification of any long term changes and/or evaluation of zooplankton patterns in relation to variation in the SAF position, accumulated CPR data will be necessary. However, in the short term the CPR is valuable for the study of within season intra-annual patterns of zooplankton abundance and for mapping zooplankton patterns in relation to frontal zones.

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