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Distribution of Microzooplankton across the Frontal Systems of the Southern Ocean

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Microzooplankton was analysed between 40°S to 53°S and 140°E to 146°E of the Southern Ocean from November 18 to November 30, 1995 to investigate the influence of frontal systems. The density and carbon biomass of microzooplankton were clearly associated with frontal systems, and at least 4 different communities were identified. The Subtropical Convergence Zone and Antarctic Polar Front Zone were the major biological boundaries recognized in the Southern Ocean. Ciliates predominated other microzooplankton in density and carbon biomass. Non-tintinnid ciliates occupied more than 70% of the total microzooplankton, and *Laboea* spp. was the major component of the non-tintinnid ciliates. The density and carbon biomass showed a decreasing tendency toward south from 40°S to the 53°S transect. The ecological importance of a frontal zone is confirmed by the microzooplanktonic data obtained from this study.

Key words : microzooplankton, density, carbon biomass, frontal systems

1. Introduction

The Southern Ocean, which is known to be an important global sink of atmospheric CO_2, has a circumpolar zonation with different physical characters due to strong frontal systems.[1,2] This circumpolar zonation with varying physical characteristics divides the Southern Ocean with several different zones, and this circumpolarity influences the distribution, abundance, and behavior of marine organisms.[3,4]

Early investigations suggested the Southern Ocean as an extremely productive region.[5] However, recent studies have shown that, in general, large areas of the Southern Ocean have a biomass and productivity more typical of oligotrophic waters.[2,4,6]

The abundance and distribution of zooplankton species may have an effect on the biomass and productivity of the Southern Ocean[4,6]. Accordingly, the study of zooplankton is of key importance in understanding the Southern Ocean ecosystem.[7] Microzooplankton have been observed to be the direct consumers of nanoplankton in most zooplankton communities.[8] They can grow rapidly, occur abundantly, and feed efficiently on nanoplankton in various ocean ecosystems.[8,9,10] An abundance of microzooplankton may play an important role not only as a consumer of nanoplankton but also as a promoter of nutrient cycling.[11]

Although research on the distribution of zooplankton across the frontal systems of the Southern Ocean has already been carried out during the Japanese BIOMASS SIBEX[12], other studies dealing with changes in the microzooplankton communities across the Southern Ocean are rare and still required.[13]

The main objective of this paper is to provide information on microzooplankton abundance and biomass in conjunction with the oceanographic features along the west Pacific Sector of the Southern Ocean.

2. Materials and Methods

Sampling for this study was carried out from November 18 to November 30, 1995 from the west Pacific Sector of the Southern Ocean in the region between 40°S to 53°S and 140°E to 146°E aboard the RV *Southern Surveyer* (Table 1). Station locations were based on the zonal systems across the Southern Ocean. Stations 1 and 2 were located in Subtropical Water (STW), stations 3, 4, 5, and 6 were in a Subtropical Convergence Zone (STCZ), stations 7, 8, 9, and 10 were in Subantarctic Water (SAW), station 11 was in an Antarctic Polar Front Zone (APFZ), and station 12 was in Polar Water (PW).

Surface water temperature and salinity were monitored using a SeaBird thermosalinograph, and chlorophyll *a* fluorescence was monitored using a WetLab's WetStar mini-fluorometer.

Water samples were collected from 5 or 6 depths(0, 20, 40, 60, 80, and 100 m) within the upper 100 m of the water column using 10 L Niskin bottles attached to a CTD rosette. One liter of the seawater was immediately preserved with 3% $NaHCO_3$-buffered formaldehyde for a microzooplankton study. Each 1L sample was settled for at least 3 days, then the upper 900 ml was removed with a small siphon tube. The remnant was settled in a 50 ml settling chamber for 2 days for microscope work.

Identification and counting were conducted under an inverted microscope (Zeiss ICM 405) at a magnification of 200 or 400x with phase contrast illumination.

Oligotrichia ciliate cell volumes were calculated using the nearest geometric formula for their size and shape, and the cell volumes of tintinnids were considered as half of their lorica volume.[14] Empty

Table 1. Station locations, sampling dates, and sampling depths in the west Pacific Sector of the Southern Ocean from November 18 to November 30, 1995 aboard RV Southern Surveyor.

Station	Latitude(South)	Longitude(East)	Date (GMT) (1995)	Depths (m)
1	40 45.09	143 25.93	18 Nov.	8, 18, 25, 42, 63, 84
2	41 23.03	142 07.59	19 Nov.	10, 22, 46, 65, 85, 107
3	41 59.27	139 56.49	20 Nov.	7, 19, 29, 45, 66, 87
4	43 00.03	140 53.82	21 Nov.	10, 23, 45, 65, 84, 104
5	43 59.94	141 49.66	21 Nov.	9, 25, 45, 66, 86, 107
6	44 58.87	143 43.72	22 Nov.	9, 27, 46, 64, 75, 91
7	45 59.87	143 37.65	23 Nov.	11, 24, 46, 61, 78, 89
8	47 58.97	145 31.90	24 Nov.	11, 24, 46, 66, 86, 108
9	49 02.27	145 24.31	26 Nov.	10, 27, 56, 79, 105
10	49 57.88	145 45.88	30 Nov.	11, 27, 45, 66, 86, 110
11	52 25.18	145 27.80	28 Nov.	11, 24, 46, 64, 83, 110
12	53 12.96	145 28.53	27 Nov.	9, 24, 46, 66, 86, 107

lorica were not differentiated from filled lorica because tintinnid protoplasts were attached to the shell by fragile strands which detached easily during the collection and handling of the samples.[15] Many empty lorica and naked protoplasts were also found in the samples. The volumes of ciliates were then converted to a carbon biomass using the formula of Putt and Stoecker (1989). The volumes of copepods were calculated using length-dry weight regressions[16], and converted to a carbon biomass as 32% of their dry weight.[17] In the case of other microzooplankton, their volumes were calculated from their geometric dimensions, which were converted to a dry weight and then to a carbon biomass as 50% of their dry weight.[18]

In order to compare zonal distributions, the density and carbon biomass of microzooplankton at each station were integrated throughout the sampled stratum.

3. Results

3.1. Hydrography and chlorophyll *a*

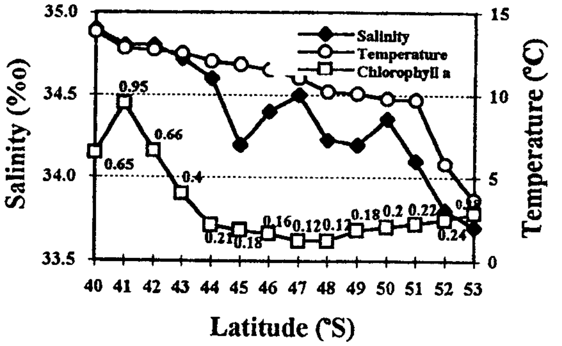

Fig. 1. Latitudinal variation of surface temperature, salinity, and chlorophyll a concentration from the west Pacific Sector of the Southern Ocean. Numbers in plot of chlorophyll a are concentrations (μg/L)

Salinity and Sea surface temperature (SST) showed a decreasing tendency from the STW to PW in the west Pacific Sector of the Southern Ocean (Fig 1). The salinity and SST of the STW and STCZ were similar north of 44°S. However, salinity dropped from 34.6 to 34.2‰ at 45°S, where the southern branch of the Subtropical Front (STF) flowed.[1]

The concentration of chlorophyll *a* changed considerably across the STW and STCZ. The maximum concentration of chlorophyll *a* was observed at St. 2 (0.95 μg/L), and showed a decreasing tendency southward towards the STCZ. Salinity and SST decreased across the STCZ from 34.8 to 34.2‰ and 13.3 to 12.6°C, respectively. The position of this zone is consistent with previous studies during austral summer which identified the STCZ as across 41-45.5°S along 140°E.[19]

In the SAW, the SST decreased from 12.6 to 10.5°C. Salinity, however, fluctuated across the SAW, and showed a minor peak along 47°S. The concentration of chlorophyll *a* was fairly low south of 44°S with an average of 0.19 (± 0.05) μg/L. Salinity increased between the SAW and APFZ from 34.2 to 34.4‰, and decreased again southward. The PW was identified south of 51°S based on a decrease in the SST (from 9.7 to 5.8°C) and salinity (from 34.1 to 33.8‰).

3.2. Microzooplankton

The density of microzooplankton ranged from $1.2x10^8$ ind./m^2 to $5.1x10^8$ ind./m^2 in the west Pacific Sector of the Southern Ocean (Fig. 2). The highest density was observed at St. 4, and the least at St. 11. The density increased in the vicinities of the STW, STCZ, and APFZ. Major peaks of density were observed at St. 2 and St. 4-5, and minor peaks at St. 8 and St. 10. The changes of density between the STCZ and SAW, and the APFZ and PW were dramatic. The density of microzooplankton dropped to half of the STCZ level in the northern end of the SAW, and the density in the southern APFZ was half that of the northern APFZ.

In general, the density of microzooplankton showed a decreasing tendency toward the Polar region. The maximum density was observed in the STW and STCZ, and the minimum was found south of the APFZ.

Ciliates were the major component of microzooplankton which accounted for 95 (± 4.2)% of the total microzooplankton density. They dominated other microzooplankton at all the stations, and the distributional pattern of microzooplankton was determined by their density. Ciliates showed a maximum density in the STW and STCZ, a medium density in the SAW, and a minimum density south of the APFZ.

Oligotrichia ciliates comprised 71.5 (± 8.9)% of the total microzooplankton and 75 (± 10.5)% of the total ciliates. The maximum density of oligotrichia ciliates was observed from St. 4-5 with 3.9×10^8 ind./m^2. South of the APFZ, however, the density of oligotrichia ciliates decreased and showed a minimum at St. 11 with 0.25×10^8 ind./m^2. The density of oligotrichia ciliates in the SAW increased southward and showed a minor peak at the northern end of the APFZ.

Tintinnids were the second dominant microzooplankton except in the PW where the density of tintinnids dominated other microzooplankton. The density of tintinnids was particularly high north of the SAW and south of the APFZ. From St. 6 to St. 11, tintinnids showed a fairly constant density at an of 0.35×10^8 ind./m^2.

Except for ciliates, microzooplankton occurred less than 0.5×10^8 ind./m^2 throughout the surveyed latitudes. The density of copepods increased further south with the highest density at St. 12 and a maximum relative density of 17% of the total microzooplankton. Rotatoria showed a maximum density at St. 4 with 0.23×10^8 ind./m^2. Actinopoda and Foraminifera were minor components of microzooplankton at all the stations. In deed, most species of copepods, Rotatoria, Actinopoda, and Foraminifera exceeded the size ranges of

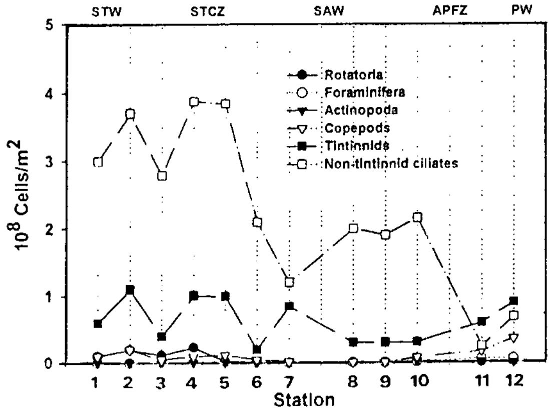

Fig. 2. Latitudinal variation of the density of microzooplankton from the west Pacific Sector of the Southern Ocean.

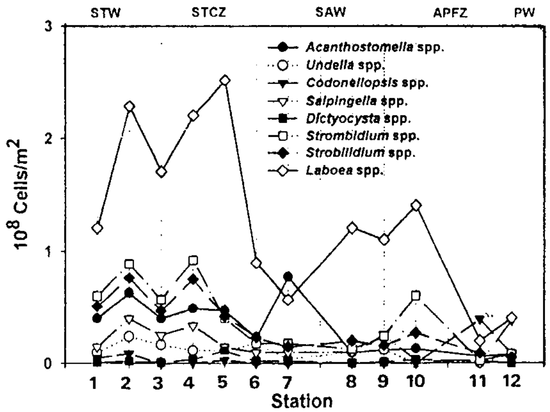

Fig. 3. Latitudinal variation of the density of major microzooplankton species from the west Pacific Sector of the Southern Ocean.

microzooplankton, i.e., >200 μm.

Four taxa of microzooplankton were the major components of the total density in this study (Fig. 3). Among them, the oligotrichia ciliate *Laboea* spp. dominated the other microzooplankton species except at St. 7 and St. 11. It occupied 49.5 (± 7.5)% of the total density of microzooplankton, and, similar to the density results of the total microzooplankton and oligotrichia ciliates, its maximum density was observed at St. 5 with $2.52\text{x}10^8$ ind./m^2 and minimum at St. 11 with $0.2\text{x}10^8$ ind./m^2.

Two taxa of oligotrichia ciliates, *Strombidium* spp. and *Strobilidium* spp. were the second and third dominant microzooplankton species in this study. They occurred with high densities north of the SAW, and showed a maximum density at St. 2 and St. 4. The distributional patterns of *Strombidium* spp. and *Strobilidium* spp. were also similar north of the APFZ.

Five taxa of tintinnids followed the densities of the above species. They were *Acanthostomella* spp., *Undella* spp., *Codonellopsis* spp., *Salpingella* spp., and *Dictyocysta* spp. Among them, *Acanthostomella* spp. showed a relatively high density north of St. 7, and they were the most abundant group of microzooplankton at St. 7. *Codonellopsis* spp. dominated other microzooplankton at St. 11. However, its density was low. At St. 12, *Salpingella* spp. co-dominated the microzooplankton along with *Laboea* spp.

The composition and density of microzooplankton changed dramatically at St. 11. The density of oligotrichia ciliate microzooplankton in that region was the lowest out of all the stations, and instead it was *Codonellopsis* spp. that dominated the microzooplankton.

The species of copepods, Rotatoria, Foraminifera, and Actinopoda never exceeded 5% of the total microzooplankton north of the APFZ. However, south of the APFZ, copepod species (mainly copepod nauplii) showed a relatively high density and occupied around 30% of the total microzooplankton.

The carbon biomass (biomass) of microzooplankton showed a similar distributional pattern to the density profile (Fig. 4). The maximum biomass of microzooplankton was observed in the STCZ and STW, and the minimum south of the APFZ. The biomass decreased sharply at St. 3 (between the STW and STCZ), St. 7 (between the

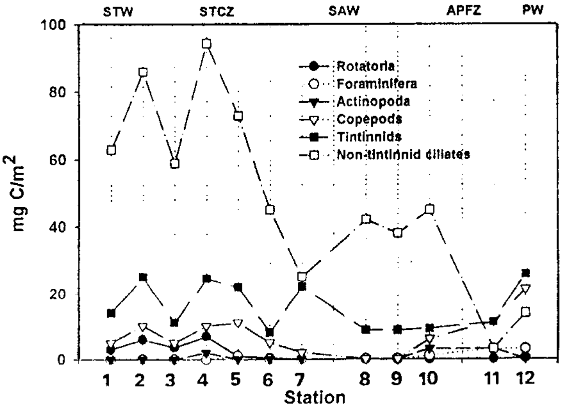

Fig. 4. Latitudinal variation of the biomass of microzooplankton from the west Pacific Sector of the Southern Ocean.

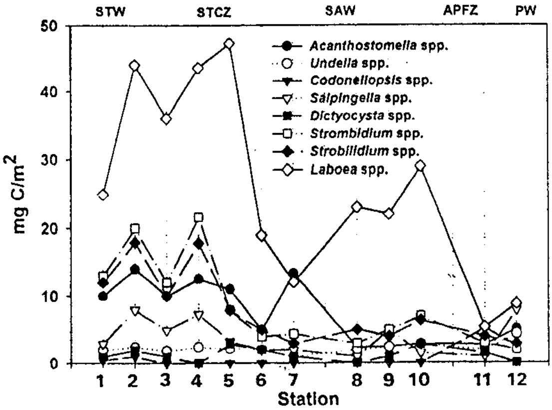

Fig. 5. Latitudinal variation of the biomass of major microzooplankton species from the west Pacific Sector of the Southern Ocean.

STCZ and SAW), and St. 11 (between the APFZ and PW). The biomass in the SAW maintained a fairly constant level, and became more medium both north and south of the SAW.

The biomass of oligotrichia ciliates dominated other microzooplankton groups except for south of the APFZ. They occupied more than 80% of the total biomass of microzooplankton from 9 stations in the STW, STCZ, and SAW. The maximum biomass of oligotrichia ciliates was observed at St. 4 with 94.5 mg C/m^2. The biomass of oligotrichia ciliates, however, decreased south of the STCZ to SAW, and showed a very low level at St. 7. The minimum biomass of oligotrichia ciliates was observed at St. 11 with 3 mg C/m^2, less than 4% of the maximum level.

As in the density distributional profile, tintinnids were the second dominant microzooplankton in the biomass, and showed a high level north of the SAW and south of the APFZ. The mean biomass of tintinnids was 14(± 2.5) mg C/m^2, and the major peaks of the biomass were observed at stations 2, 4, and 12. From St. 6 to St. 11, the tintinnid biomass remained at a fairly constant level of 9.0 (± 0.3) mg C/m^2.

Copepods showed a relatively high biomass south of the APFZ. They occupied around 30% of the total biomass of microzooplankton at Sts. 11-12.

Other microzooplankton taxa were minor components and occupied less than 5% of the total biomass in all the studied latitudes.

Oligotrichia ciliate *Laboea* spp. showed the highest biomass among the sampled microzooplankton except at St. 7 (Fig. 5). It occurred with 26.25 (± 14.09) mg C/m^2. The maximum biomass of *Laboea* spp. was observed at St. 5 with 47.25 mg C/m^2 and the minimum at St. 11 with 5.4 mg C/m^2. Other oligotrichia ciliates such as *Strombidium* spp. and *Strobilidium* spp. also showed a high biomass (around half of *Laboea* spp.) north of the SAW. They maintained a similar biomass at all the latitudes.

The biomass of the tintinnid species was low compared to the non-tintinnid species. At St. 7, however, the tintinnid *Acanthostomella* spp. showed the highest biomass. It occupied 34% of the total biomass of microzooplankton.

Other microzooplankton showed a low biomass. *Salpingella* spp. showed a high biomass at the stations in the STCZ and PW compared to other zones, although it was still less than 10 mg C/m^2. *Codonellopsis* spp. showed the highest biomass at St. 11, yet still occurred at a low level at all latitudes. *Undella* spp. and *Dictyocysta* spp. were minor components of microzooplankton and showed a very low biomass at all the stations.

4. Discussion

The Southern Ocean is known to have two major biogeographical boundaries.[1)] They are the Subtropical Convergence Zone which marks the northern boundary of the Southern Ocean, and the Antarctic Polar Front which separates the Subantarctic and Antarctic Zones of the Southern Ocean. The Subantarctic Water Zone is located between the STCZ and APFZ. South of the APFZ is the Polar Water region where the Antarctic krill is the most important species (El-Sayed and Fryxell, 1993; Knox, 1994). The STCZ and APFZ are known to be important biogeographical boundaries for the distribution of marine organisms in the Southern Ocean.[1,4)] However, the biogeographical importance of the SAW to the distribution of species is less obvious.[20)]

The results obtained in the present study were clearly correlated with the positions of the various circumpolar biogeographical zones that are separated by the main frontal systems of the Southern Ocean.(1) SST and salinity both decreased across these fronts (Fig. 1). The concentrations of chlorophyll *a* were generally low except for in the STW. Low chlorophyll *a* concentrations are typical of Southern Ocean waters(21) and range from 0.05 to 0.31 μg/L in the Australian Sector of the Southern Ocean during austral spring and summer. In addition, Sedwick *et al.*(23) measured such concentrations up to 0.72 μg/L over the continental slope along 140°E during austral summer.

Despite the limited group of zooplankton (microzooplankton) studied, the macroscale geographical positions of the microzooplankton communities were associated with specific water masses or hydrographic features.

A clear shift in the distributional pattern of microzooplankton was observed in the major frontal systems of the Southern Ocean (Figs. 2-5), and at least 4 different communities of microzooplankton were identified.

The STW and STCZ showed a similar composition of the dominant species, density, and biomass of microzooplankton. However, despite the similarity in the dominant species, differences in the composition of the minor species and density of the second and third dominant species were recorded from both sectors (Fig. 3). The density and biomass of microzooplankton decreased sharply between the STW and STCZ. Pakhomov and McQuaid(20) also found differences in the species composition and density of zooplankton between the north and south of the STCZ along the transects between New Zealand and the Ross Sea, and proposed the importance of the STCZ as a strong biogeographical border for the distribution of zooplankton.

The STCZ formed a distinct community characterized by a high density and biomass of microzooplankton (Figs. 2-5). All the microzooplankton species showed a maximum density and biomass in the STCZ. Ciliates were the major component of microzooplankton, and the oligotrichia ciliate *Laboea* spp. predominated the other species in both density and biomass. According to this study, the border between the STW and STCZ seemed to be located at 42°S rather than 41°S(1).

The predominance of *Laboea* spp. was considerably weakened south of the STCZ (Figs. 3 and 5), suggesting a strong biogeographical border between the STCZ and SAW in the distribution of microzooplankton. Other microzooplankton also decreased in density and biomass south of the STCZ except for *Acanthostomella* spp. which showed a maximum density at the border of the STCZ and SAW.

The SAW showed a different density and biomass of microzooplankton compared to other zones (Figs. 2-5). The density and biomass of *Laboea* spp. increased southward of this zone, and the maximum levels were recorded at the north end of the APFZ. However, other microzooplankton showed a fairly constant density and biomass. This result suggests that the SAW has a distinct environmental feature for microzooplankton. Pakhomov and McQuaid(20) also identified this zone as a distinct community in the distribution of zooplankton and seabirds in the Southern Ocean.

The ranges of the APFZ and PW were uncertain from this region. However, the composition of species, density and biomass of microzooplankton changed dramatically along 51-52°S which suggests that this latitude as a strong border in the distribution of microzooplankton. Furthermore, the species composition, density and biomass at 53°S were quite different from other zones. Accordingly, it can be concluded that the regions south and north of 51-52°S have different communities.

Although only microzooplankton was analyzed in this study, the data suggests that microzooplankton distribution is determined by the frontal systems of the Southern Ocean.

Pakhomov and McQuaid[20)] observed a clear delineation in both the Atlantic and Pacific Sectors of the Southern Ocean for seabirds and zooplankton distribution. This study confirmed this macroscale delineation of the Southern Ocean.

From an oceanographic point of view the existence of frontal systems in the Southern Ocean is still unclear.[24)] However, the biological data presented here and previous studies[2,20)] suggest that there are important ecological zones in the Southern Ocean which influence the distribution of marine organisms.

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