Contrasting pattern in chlorophyll *a* distribution within the Polar Front of the Indian sector of Southern Ocean during austral summer 2010

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A contrasting pattern in chlorophyll *a* (Chl *a*) distribution observed within the Polar Front (52°S and 56°S along 57°30′E) in the Indian sector of the Southern Ocean during the 2010 austral summer is reported here. At 52°S, Chl *a* concentration ranged from 0.08 (30 m) to 0.69 mg m^{-3} (70 m), whereas at 56°S it was below detection level at all depths. Nutrients and light intensity were not found to be limiting the primary production at both stations. It appears that different types of food webs operating in the two locations within the front might have been responsible for causing the contrasting pattern in Chl *a* distribution. At 56°S, large adult copepods and salps were abundant in the mesozooplankton community, which might have been exerting high grazing pressure on the phytoplankton community (conventional food web), thereby lowering the Chl *a* concentration. At 52°S, on the other hand, Chl *a* concentration was relatively high because the small-sized copepods and copepodites which were more abundant here, might have preferred feeding on microzooplankton (20–200 µm size) over phytoplankton (microbial food web). The high total bacterial count observed at this station is also in support of the prevalence of the microbial food web. It could be deduced from the study that distinct biological regimes may be existing within the same frontal regions in the Southern Ocean, depending on the type of food-web dynamics prevailing. More intensive sampling within the frontal regions is imperative in understanding the various biological processes so as to evaluate the productivity potential of the Southern Ocean.

Keywords: Austral summer, chlorophyll *a*, mesozooplankton, Polar Front.

THE Southern Ocean (SO) experiences extreme environmental conditions, where the water is permanently cold and solar energy for photosynthesis is severely restricted[1]. The Polar Front (PF) is one of the strong fronts within the Antarctic Circumpolar Current (ACC)[2]. Regardless of high nitrate and phosphate concentrations, chlorophyll production remains very low in the open waters of the SO[3]. The role of micronutrients in SO has been fairly well studied and their non-availability is known to limit the phytoplankton growth, leading to the formation of the high nutrient–low chlorophyll (HNLC) regions[4]. The low productivity in HNLC regions has been attributed to the low bioavailable iron concentration in surface waters[5], as iron is an essential micronutrient required for the growth of many phytoplankton species. But, fairly high mesozooplankton biomass sustains in the fronts and zones of the SO, despite the low phytoplankton production (low Chl *a*) to support the conventional food web, and this points to the effective functioning of a microbial food[6].

Although studies on biological productivity and biogeochemistry have been carried out in the Pacific Ocean and Atlantic Ocean sectors of the SO, very few studies have been made in this direction from the Indian sector[6–10]. In the present communication, a contrasting feature observed in Chl *a* distribution at stations 52°S and 56°S, located within the PF is presented. Although such features have been reported in the biological productivity between the frontal regions and zones in the SO[6], a dissimilar pattern in the Chl *a* distribution has not been observed within the same frontal region and in this communication, we have attempt to analyse the probable reasons for this behaviour.

During the austral summer 2010 (February), samples for hydrographical and biological parameters were collected along a meridional transect (57°30′E) from 39°S to 56°S on-board *ORV Sagar Nidhi*. The transect runs along the major fronts and zones extending from the Agulhas Retroflection Front (ARF) to PF. Two stations in PF (52°S and 56°S) were sampled during the cruise. PF was identified (Figure 1) by the sea surface temperature (SST)[11]. Vertical profiles of temperature and salinity were recorded up to 120 m using portable CTD (SBE 9/11 plus, Sea-Bird Electronics, USA). SST was measured using a bucket thermometer (Theodoere Friedrich, Germany; accuracy ± 0.2°C).

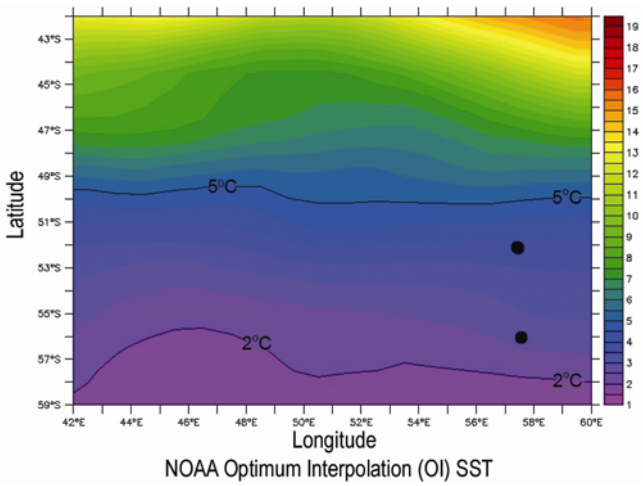

Figure 1. Location of sampling stations in the Polar Front (PF) (bold black lines represent the boundaries of the PF and the contours depict sea surface temperature).

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Water samples were collected from both stations with a rosette sampler from standard depths (0, 10, 30, 50, 70, 100, 120 m) using the INDRONAUT CTD system. Dissolved nitrate, phosphate and silicate were estimated spectrophotometrically, using standard protocols[12]. Dissolved oxygen was estimated by the Winkler method[13]. Photosynthetically available surface radiation (PAR) data were extracted for both the locations from the Sea-viewing Wide Field-of-view Sensor (SeaWifs-daily data). Chl *a* samples were collected from standard depths. Samples were filtered through GF/F filter (pore size 0.7 μm), extracted with 90% acetone overnight and estimated using a spectrophotometer[14]. Column Chl *a* (mg m^{-2}) and column primary productivity (mg C m^{-2} d^{-1}) were also estimated by integrating the depth values. Water samples for primary productivity (PP) were collected from four depths (0, 30, 70 and 120 m). After adding 1 ml of ^{14}C [$Na(^{14}H)Co_3$] in each sample (5 μCi per 300 ml of sea water in Nalgene bottles), the samples were incubated on deck with continuous flow of sea water for 8–12 h, depending on the availability of sunlight. Two light and one dark bottle from each depth were incubated using appropriate density filters to compensate for light intensity. After incubation, samples were filtered through 25 mm GF/F filters (pore size 0.7 μm). The filters were then exposed to HCL fumes to remove excess inorganic carbon and stored individually in scintillation vials. The activity was counted on a liquid scintillation counter (Packard 2500 TR) after addition of scintillation cocktail. Disintegration per minute (dpm) values were converted into daily production rates (mg C m^{-3} d^{-1})[14].

For total bacterial count (TC), water samples (10 ml) from standard depths were stained with 4,6-diamidino-2-phenylindole (DAPI)[15] before enumeration. Cells stained with DAPI were first fixed with formaldehyde (final concentration, 3.7%) to preserve the cell morphology and improve the staining efficiency. Stained cells were filtered onto a black polycarbonate membrane (2 μm Nucleopore, Whatman) and counted under an Olympus epifluorescence microscope (BX 51). The filters used for DAPI were Olympus U-MWU2 (excitation 330–385 nm and emission 420 nm). Counting was done using a Whipple grid with 60× objective (Olympus UPLNFLN).

Mesozooplankton samples were collected with multiple plankton net (MPN, Hydrobios, Germany; mouth area 0.25 sq. m and mesh size 200 μm). Vertical hauls were made from three depth strata, viz. 500 to 300 m; 300 to base of mixed layer depth (MLD), and MLD (MLD at 52°S was 20 m and at 56°S was 75 m). Samples were fixed in 5% formaldehyde. Biomass was estimated by volume displacement method and converted to gram carbon (gC)[16]. Zooplankton taxa were sorted and identified from 25% aliquots and abundance of individual taxa [ind. $(100\ m)^{-3}$] was calculated for the whole sample.

PF during this period extended between 51°S and 58°S. SST and sea surface salinity (SSS) were 4.46°C and 2.97°C (Figure 2 *a*), and 33.84 and 33.92 (Figure 2 *b*) at 52°S and 56°S respectively.

PAR was generally low at both stations, but showed a slightly higher value at 56°S (31.78 E m^{-2} d^{-1} at 52°S and 49.8 E m^{-2} d^{-1} at 56°S). However, phytoplankton biomass (Chl *a*) showed a contrasting pattern at these stations (Figure 2 *c*). At 52°S, the vertical distribution ranged from 0.08 (30 m) to 0.69 mg m^{-3} (70 m) with a column integrated value of 52.5 mg m^{-2}. On the contrary, at 56°S, it was below the detection level in the entire water column up to 120 m. PP (Figure 2 *d*) ranged from 4.3 (120 m) to 166 mg C m^{-3} d^{-1} (70 m) at 52°S. The respective values at 56°S were 1.2 (120 m) and 17 mg C m^{-3} d^{-1} (30 m), indicating a poor phytoplankton density at this station, which is also in support of the non-detection level of Chl *a* at this station. The PP values integrated for the upper 120 m column were 9068.5 mg C m^{-2} d^{-1} at 52°S and 1299.6 mg C m^{-2} d^{-1} at 56°S.

Contrary to the Chl *a* distribution, the overall mesozooplankton abundance was high in the upper 300 m water column at both stations. But, in MLD, the abundance [124032 no. $(100\ m)^{-3}$] and corresponding biomass [0.62 gC $(100\ m)^{-3}$] were relatively high at 56°S compared to that at 52°S [20,160 no. $(100\ m)^{-3}$ and (0.51 gC $(100\ m)^{-3}$ respectively; Figure 3]. In the MLD – 300 m stratum, on the other hand, a reverse trend was noticed where the abundance was relatively high [51,954 no. $(100\ m)^{-3}$ at 52°S compared to 56°S [7481 no. $(100\ m)^{-3}$], but the corresponding biomass values [0.11 and 0.32 gC $(100\ m)^{-3}$ respectively] recorded a three-fold increase at 56°S, indicating the occurrence of large-sized organisms, although Chl *a* was not detectable at this station.

Total bacteria counts (TC) were generally high at both stations and ranged from 1.80×10^8 (100 m) to 6.80×10^9 l^{-1} (30 m) at 52°S and 1.28×10^9 (50 m) to 8.45×10^9 l^{-1} (30 m) at 56°S (Figure 2 *e*). Dissolved oxygen (DO) values were also high at these stations, ranging from 7.1 to 7.4 ml l^{-1} (Figure 2 *f*). Nitrate, silicate and phosphate values (Figure 2 *g–i*) showed that the study area is rich in nutrients, though the values were relatively higher at 56°S. Nitrate concentration ranged from 32.5 (50 m) to 37.0 μM (120 m) at 52°S and 35.9 (10 m) to 39.7 μM at 56°S. The respective ranges for phosphate were 1.95 (10 and 50 m)–2.38 μM (120 m) and 2.22 (0 and 10 m)–2.60 μM (100 and 120 m), and for silicate were 10.20 (0 m)–28.90 μM (120 m) and 17.90 (30 and 50 m)–29.20 μM (120 m) (except for a low value of 4.00 μM recorded at the surface).

Composition of the mesozooplankton community showed considerable variation between the stations. In the MLD at 52°S, copepodites were the most dominant forms (71%), whereas at 56°S adult copepods contributed 95% followed by chaetognaths (1.9%) and salps (1.7%) (Figure 4). It is noteworthy that salps occurred in the upper 300 m water column only at this station (Figure 4 *b*). Relatively more chaetognaths [640 $(100\ m)^{-3}$] and

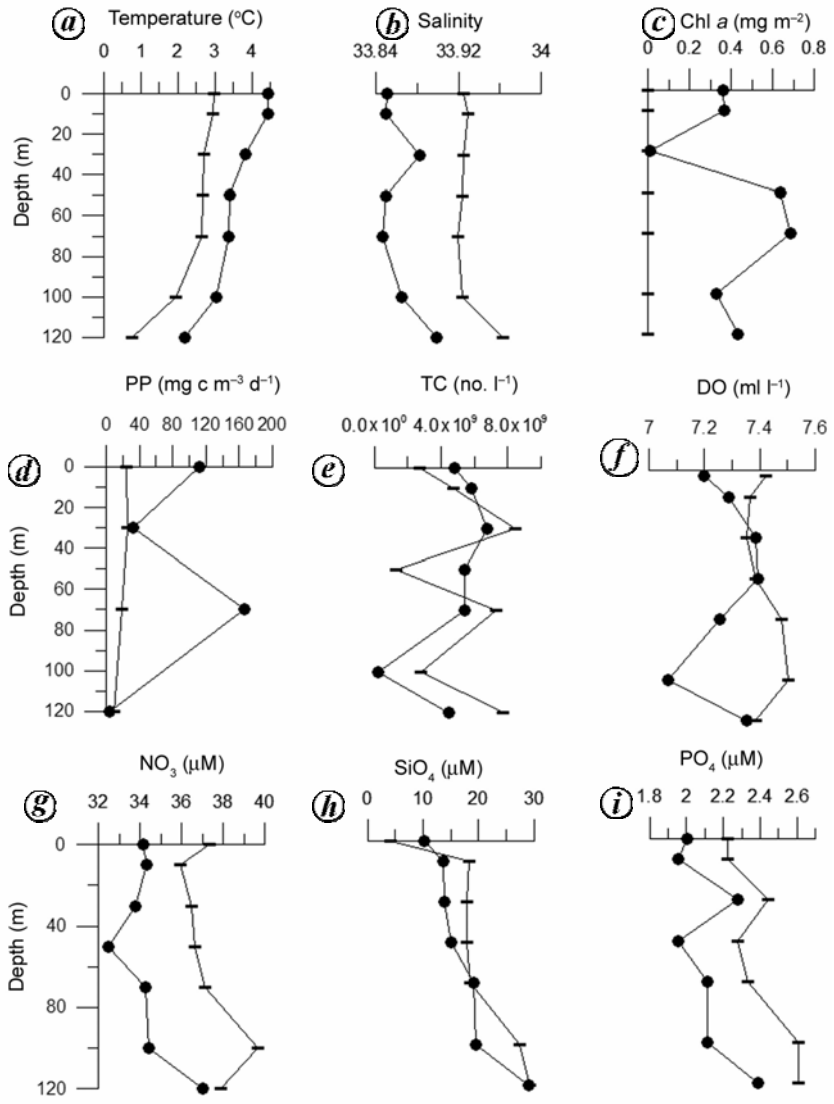

Figure 2. Variation of physico-chemical and biological parameters at (●) 52°S and (–) 56°S along 57°30′E.

euphausiids [160 (100 m)$^{-3}$] were recorded in the MLD at 52°S, whereas chaetognaths occurred in low numbers and euphausiids were absent at 56°S (Figure 4 *b*). In the overall composition, large-sized adult copepods were more abundant at 56°S, whereas copepodites dominated at 52°S (Figure 4 *a*).

Coexistence of multivorous and microbial food webs and also conventional and microbial food webs is known in different locations in SO (ref. 6). Although a clear pattern has not emerged in the present study due to limited number of observations, the results points to the possibility of a combination of multivorous–conventional-microbial food webs coexisting in the two locations within the PF, and such a scenario has not been reported from SO. Multivorous food webs potentially connect secondary production of microorganisms to metazoan consumers[1]. In less productive ocean systems, the multivorous food web could further develop into a microbial food web as nutrients are recycled by the protozoa[17].

High concentration of nutrients is a general feature of the PF[18], which is also known to have high phytoplankton biomass compared to the surrounding area[19]. The increased water-column stability together with high nutrients and trace metal concentrations also resulted in phytoplankton blooms in the vicinity of PF[20,21]. However, Bernard and Froneman[7] did not observe an increase in Chl *a* biomass in the vicinity of PF. All three nutrients were recorded in high concentrations at both the studied locations, although primary production and phytoplankton biomass (Chl *a*) did not show a concurrent increase, particularly at 56°S. Light cannot be considered as a limiting factor for primary production at this station, since PAR value was relatively higher compared to that at 52°S.

Strong signal of an active conventional food web at 56°S and microbial food web at 52°S could be seen in the present study. At 56°S, large-sized copepods and salps were dominant in the zooplankton community and both are efficient feeders of phytoplankton. It is this grazing

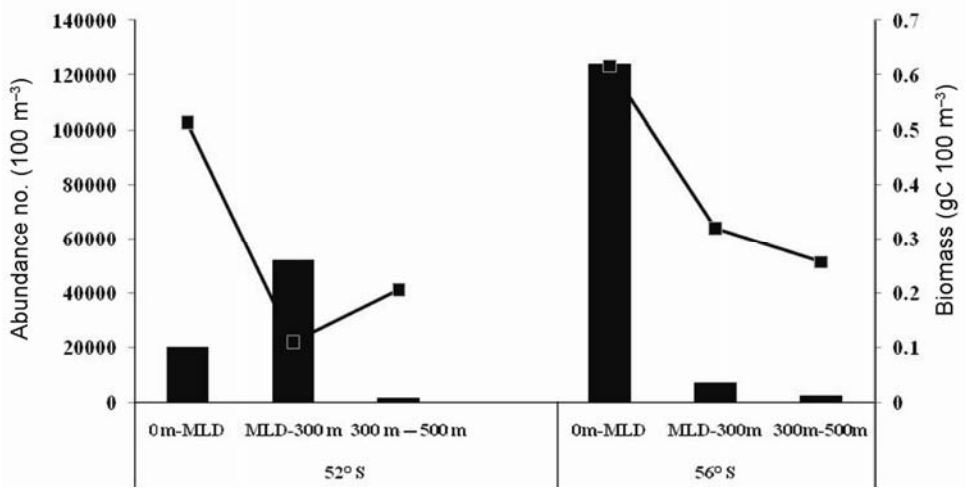

Figure 3. Abundance and biomass of mesozooplankton at 52°S and 56°S along 57°30′E.

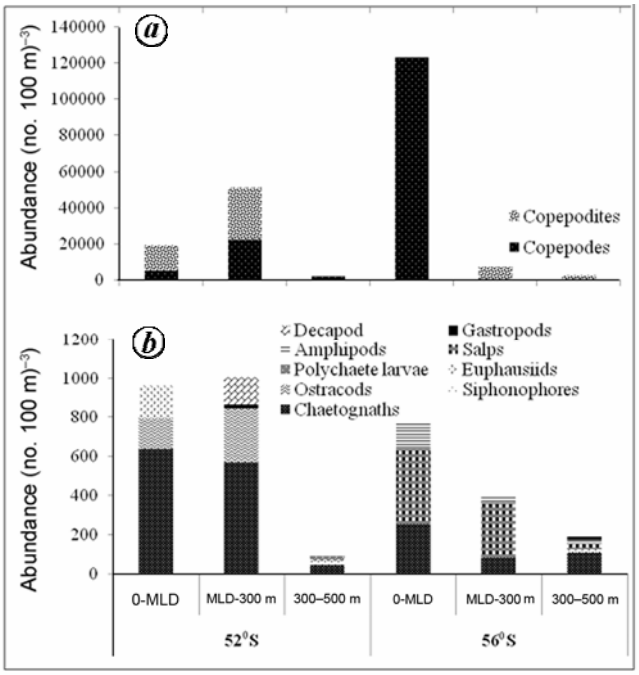

Figure 4. Composition of major mesozooplankton groups in the different depth zones at 52°S and 56°S along 57°30′E: (***a***) Copepodes and copepodites (***b***) Others.

pressure that would have been responsible for bringing down Chl *a* concentration to undetectable levels at this station. A similar situation has also been observed by Jasmine *et al.*[6] in the PF zone. The high total bacterial counts obtained at this station also indicate the possibility of a microbial food web existing, as small-sized mesozooplankton such as copepodites which were present in large numbers, feed on microzooplankton. Conversely, the higher abundance of mesozooplankton at this station, despite the low Chl *a* concentration, might have resulted due to the functioning of multivorous food web since grazing by large and small zooplankton could reduce both phytoplankton and microzooplankton (presently an assumption based on the bacterial counts since no microzooplankton data are available) biomass.

On the contrary, smaller organisms such as small copepods and copepodites were abundant in the zooplankton community at 52°S. Since the phytoplankton biomass (Chl *a*) was fairly high at this station, it is obvious that the grazing pressure by larger zooplankton was not high. Also, since smaller zooplankton were more abundant at this station, an active microbial food web would be a definite possibility. The high total bacterial count at this station is also in support of this proposition.

Small phytoplankton are the potential prey of microzooplankton[22]. There is a weak coupling of bacterial communities with autotrophs in HNLC waters[23]. The bacterial abundance at both stations in the present study suggests that the area (PF) is sustained by high microzooplankton abundance, since microflagellates and ciliates avidly consume bacteria in the Antarctic waters[24]. A possible explanation for the coupling between microbial biomass and mesozooplankton could be the ability of salps to feed on free, particle-bound and aggregated bacteria[24]. As in the present study (56°S), high concentration of salps has been reported earlier from the Indian and Pacific sectors of SO[6,25–27] and these have been known to exert high grazing pressure[4] and unregulated filtration of all particles[1].

The contrasting feature observed in the phytoplankton biomass (Chl *a*) at the two locations within the same front could therefore be due to the variation in feeding habits of the mesozooplankton community. The occurrence of deep MLD at 56°S (75 m) compared to the shallow MLD at 52°S (20 m) could also be an added factor for the low Chl *a* at the former, although Banse[3] could not find any correlation between chlorophyll concentration and MLD in PF. According to Jasmine *et al.*[6] microbial and conventional food webs, either independently or in combination, regulate the food-web dynamics in the SO.

Microphagy is an important characteristic of large zooplankton in the Antarctic waters, and this feeding mode provides an opportunity for the large Antarctic copepods to coexist with salps that have an advantage in oligotrophic waters[1]. This explains the occurrence of high density of copepods and copepodites along with salps at 56°S. Hence in the multivorous food web, both the herbivorous (conventional) and microbial trophic modes may play a significant role[6,28]. From the present data, it could be possible to propose that multivorous food web may be generally operating in the frontal regions, particularly in PF, but depending on the size of the mesozooplankton community prevailing at a given location, either conventional food web (as seen at 56°S) or microbial food web (as seen at 52°S) may become stronger within the front. However, owing to the smaller sample size, the present data can only be treated with some caution. It is, however, suggested that extensive sampling within each frontal region of SO may be required to bring out the variations in the food-web dynamics within each front, which is important for understanding the biogeochemical processes and productivity potential of the SO.

1. LeFèvr, J., Legendre, L. and Rivkin, R. B., Fluxes of biogenic carbon in the Southern Ocean: roles of large microphagous zooplankton. *J. Mar. Syst*., 1998, **17**, 325–345.
2. Belkin, I. M. and Gordon, A. L., Southern Ocean fronts from the Greenwich meridian to Tasmania. *J. Geophys. Res*., 1996, **101**, 3675–3696.
3. Banse, K., Low seasonality of low concentrations of surface chlorophyll in the Subantarctic water ring: underwater irradiance, iron, or grazing? *Prog. Oceanogr*., 1996, **37**, 241–291.
4. Moore, J. K. and Abbott, M. R., Surface chlorophyll concentrations in relation to the Antarctic Polar Front: seasonal and spatial patterns from satellite observations. *J. Mar. Syst*., 2002, **37**, 69–86.
5. Martin, J. H., Glacial–interglacial CO_2 change: the iron hypothesis. *Paleoceanography*, 1990, **5**, 1–13.
6. Jasmine, P. *et al.*, Hydrographic and productivity characteristics along 45 degrees E longitude in the southwestern Indian Ocean and Southern Ocean during austral summer 2004. *Mar. Ecol. Prog. Ser.*, 2009, **389**, 97–116.
7. Bernard, K. S. and Froneman, P. W., Mesozooplankton community structure and grazing impact in the Polar Frontal Zone of the south Indian Ocean during austral autumn 2002. *Polar Biol*., 2003, **26**, 268–275.
8. Bernard, K. S. and Froneman, P. W., Trophodynamics of selected mesozooplankton in the west-Indian sector of the Polar Frontal Zone, Southern Ocean. *Polar Biol*., 2005, **28**, 594–606.
9. Fielding, S. *et al.*, Community structure and grazing impact of mesozooplankton during late spring/early summer 2004/2005 in the vicinity of the Crozet Islands (Southern Ocean). *Deep-Sea Res. II*, 2007, **54**, 2106–2125.
10. Froneman, P. W. *et al.*, Physical and biological processes at the subtropical convergence in the southwest Indian ocean. *S. Afr. J. Sci*., 2007, **103**, 193–195.
11. Ansorge, I. J., Pakhomov, E. A., Kaehler, S., Lutjeharms, J. R. E. and Durgadoo, J. V., Physical and biological coupling in eddies in the lee of the South-West Indian Ridge. *Polar Biol*., 2009, **33**, 747–759.
12. Grasshoff, K., *Methods of Seawater Analysis* (eds Grasshoff, K., Ehrhardt, M. and Kremling, K.), Verlag Chemie, Weinheim, 1983, 2nd edn, p. 419.
13. Carpenter, J. H., The Chesapeake Bay Institute technique for the Winkler dissolved oxygen method. *Limnol. Oceanogr.*, 1965, **10**, 141–143.
14. Strickland, J. D. H. and Parsons, T. R., A practical handbook of seawater analysis. *J. Fish. Res. Bd. Can.*, 1972, **167**, 310.
15. Hicks, R. E., Amann, R. I. and Stahl, D. A., Dual staining of natural bacterioplankton with 4′,6-diamidino-2-phenylindole and fluorescent oligonucleotide probes targeting kingdom-level 16S rRNA sequences. *Appl. Environ. Microbiol*., 1992, **58**, 2158–2163.
16. Madhupratap, M., Nair, V. R., Nair, S. R. S. and Achuthankutty, C. T., Zooplankton abundance of the Andaman Sea. *Indian J. Mar. Sci.*, 1981, **10**, 258–261.
17. delGiorgio, P. A., Prairie, Y. T. and Bird, D. F., Coupling between rates of bacterial production and the abundance of metabolically active bacteria in lakes, counted using CTC reduction and flow cytometry. *Microb. Ecol.*, 1997, **34**, 144–154.
18. Brandini, F. P., Boltovskoy, D., Piola, A., Kocmur, S., Röttgers, R., Abreu, P. C. and Lopes, R. M., Multiannual trends in fronts and distribution of nutrients and chlorophyll in the southwestern Atlantic (30–62 degrees S). *Deep-Sea Res. I*, 2000, **47**, 1015–1033.
19. Landry, M. R. *et al.*, Seasonal dynamics of phytoplankton in the Antarctic Polar Front region at 170°W. *Deep-Sea Res. II*, 2002, **49**, 1843–1865.
20. Dubischar, C. D. and Bathmann, U. V., Grazing impact of copepods and salps on phytoplankton in the Atlantic sector of the Southern Ocean. *Deep-Sea Res. II*, 1997, **44**, 415–433.
21. Perissinotto, R. and Pakhomov, E. A., The trophic role of the tunicate *Salpa thompsoni* in the Antarctic marine ecosystem. *J. Mar. Syst*., 1998, **17**, 361–374.
22. Christaki, U., Obernosterer, I., Van Wambeke, F., Veldhuis, M. J. W., Garcia, N. and Catala, P., Microbial food web structure in a naturally iron fertilized area in the Southern Ocean (Kerguelen Plateau). *Deep-Sea Res. II*, 2008, **55**, 706–719.
23. Gasol, J. M. and Duarte, C. M., Comparative analyses in aquatic microbial ecology: how far do they go? *FEMS Microbiol. Ecol.*, 2000, **31**, 99–106.
24. Azam, F., Smith, D. C. and Hollobaugh, J. T., The role of the microbial loop in Antarctic pelagic ecosystems. *Polar Res.*, 1991, **10**, 239–244.
25. Casareto, B. E. and Nemoto, T., Latitudinal variation of the number of muscle fibres in *Sapla thompsoni* (Tunicata, Thaliacea) in the Southern Ocean: implications for the validity of the species *Salpa gerlachei*. Proceedings of the NIPR Symposium on Polar Biology, Ocean Research Institute, University of Tokyo, 1987, vol. 1, pp. 90–104.
26. Foxton, P., *Salpa fusiformis* CUVIER and related species. *Discovery Rep.*, 1961, **32**, 1–32.
27. Van Der Spoel, S. and Heyman, R. P., *A Comparative Atlas of Zooplankton: Biological Patterns in the Oceans*, Springer-Verlag, Berlin, 1983, p. 186.
28. Mousseau, L., Klein, B., Legendre, L., Dauchez, S., Tamigneaux, E., Tremblay, J.-E. and Ingram, R. G., Assessing the trophic pathways that dominate planktonic food webs: an ecological approach based on simple ecological ratios. *J. Plankton Res.*, 2001, **23**, 765–777.

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