

Reading source and processes from the distribution of suspended particulate matter and its selected elemental chemistry in the Southern and Indian Oceans

Deepti V. G. Dessai¹, Ksh. Tomchou Singh¹, Rahul Mohan², G. N. Nayak^{1,*} and M. Sudhakar²

¹Marine Sciences Department, Goa University, Goa 403 206, India

²National Centre for Antarctic and Ocean Research, Vasco-da-Gama, Goa 403 804, India

Analysis of surface suspended particulate matter (SPM) from 28°S to 69°S at 1° interval reveals a more or less decreasing trend with increasing latitude at two distinct sections in the north and south of 54°S which are marked by relatively steady and a highly fluctuating trends respectively. Vertical as well as horizontal profiles of SPM, temperature and salinity at six selected stations were used in conjunction with associated trace metals to understand their association, distribution and possible source. The southern Antarctic zone is characterized by low salinity and temperature, variable SPM with high Fe and Mn, and the northern Subtropical zone is with high SPM of mainly biogenic material, high salinity and temperature and high Ca, whereas the Sub Antarctic zone in between is of moderate salinity and temperature but low SPM. The terrigenous input through melt water of ice is probably responsible for the high SPM and low salinity near surface waters, and also high SPM waters at 1000 m depth which are with high Fe and Mn in the Antarctic zone. The temperature and salinity controlled primary productivity probably controls the concentration and distribution of near surface high SPM and associated trace metals in the Subtropical zone whereas the primary productivity and the melt water play a role in contributing SPM in the middle convergence zone.

Keywords: Elemental chemistry, processes, source, Southern Ocean, suspended particulate matter.

THE Southern Ocean covers about 15% of the total ocean surface¹ and is considered as a crucial area in the contemporary cycle of matter². The Antarctic convergence surrounds the northern boundary of Southern Ocean between 50°S and 60°S and it is a measure of oceanographic and biological boundary with approximately 50 km width³. The two circumpolar currents affect the upper layers of the Southern Ocean and mark large

changes in temperature and salinity. Southern Ocean is generally a region of low biological productivity, however concentrations of high productivity are associated with the presence of sea ice that surrounds Antarctica for most of the year, particularly at the ice edge^{1,4}.

The present study, which was undertaken during the special expedition to the Southern Ocean and Larsemann Hills in January–April 2006 on board ship *RV Akedemik Boris Petrov*, focuses on the spatial and vertical distribution of suspended particulate matter (SPM) and its chemistry within the Southern Ocean and its relation with SPM of adjoining Subtropical waters.

The study of concentration and distribution of SPM is important in the viewpoint of global material cycling. SPM plays a major role in productivity and helps in tracing the source of materials. Further, it also acts as scavenger for trace metals in water. Therefore, the knowledge of origin, transportation and associated processes of suspended matter is important.

There are various factors contributing to the concentration and distribution of SPM. The atmospheric dust as a factor for SPM in the Southern Ocean has been studied by various workers^{5–8}. Direct atmospheric deposition as a major Fe source was ruled out because of findings of low surface-water dissolved Fe concentrations in the offshore Drake Passage water⁹. The ocean, from about 40°S to the Antarctic circle, has the strongest average wind velocity, which must be playing an important role. The Southern Ocean has great variation in depth although the mean depth is close to 4000 m (ref. 10).

Materials and methods

Thirty-nine surface water samples were collected between 28°S and 69°S. In addition, 36 water samples were collected from six selected stations (Figure 1) at various depths, viz. 0, 10, 50, 100, 200 and 1000 m onboard ship *RV Akedemik Boris Petrov*. Water samples at different depths were collected using a Rosette water sampler

*For correspondence. (e-mail: nayak1006@rediffmail.com)

equipped with CTD and Niskin samplers. Surface water samples were collected using a pre-cleaned bucket.

Collected water samples (2 l) were immediately vacuum-filtered through pre-weighed millipore filters having a pore size of 0.45 μm . Filter papers were then oven dried at 60°C on the shipboard laboratory. Also, 5 l of water sample was filtered at three depths, viz. 0, 200 and 1000 m of six stations to study the SPM chemistry.

SPM concentration was then obtained by re-weighing the filters and subtracting from the original filter paper weights. SPM obtained has been expressed as milligram per litre. A portion of the filter paper was mounted onto a stub coated with platinum in a sputter coater and scanning electron microscope (SEM) photographs of SPM were obtained to understand the various components present. Further, digestion of the filters containing suspended matter was done¹¹ for 17 samples using the following procedure. Filter papers containing suspended matter as well as blank filters were treated with a mixture of concentrated perchloric and nitric acids (each 1 ml) and evaporated almost to dryness. The residue after cooling was dissolved and diluted to 25 ml with 1N nitric acid. Diluted samples were then analysed for five different metals, viz. Fe, Mn, Cu, Zn and Ca using an Atomic Absorption Spectrophotometer (GBC-932 AA model) equipped with deuterium background corrections. Blank

corrections were applied wherever necessary. The accuracy of the analytical method was assessed by the analysis of standard reference materials MAG-1 – marine mud from the United States Geological Survey. Certified and measured values are in general agreement varying the recovery efficiency between 90% and 96% in all the metals analysed for the present study.

Results

Spatial distribution

The concentration of SPM obtained by filtering a fixed quantity of water ranges from 0.70 to 7.05 mg/l. The distribution of SPM in the study area from north (28°S) to south (69°S) shows two distinct sections of pronounced patterns (Figure 2). From 28°S to 54°S, the pattern is comparatively steady with a minimum value of 4.55 mg/l and maximum of 6.70 mg/l (avg. SPM 5.49 mg/l) and shows a more or less decreasing trend with increasing latitude. The highest and lowest concentrations within the studied stretch, however, were located further south in the section between 54°S and 69°S. This section is characterized by a minimum of 0.70 mg/l and a maximum of 7.05 mg/l (avg. SPM 4.02 mg/l) indicating a highly variable pattern. So, 54°S seems to act as the transition point between comparatively steady distributions in the northern side to a highly fluctuating distribution in the southern side. As a whole, SPM decreases from the northern end towards the southern end.

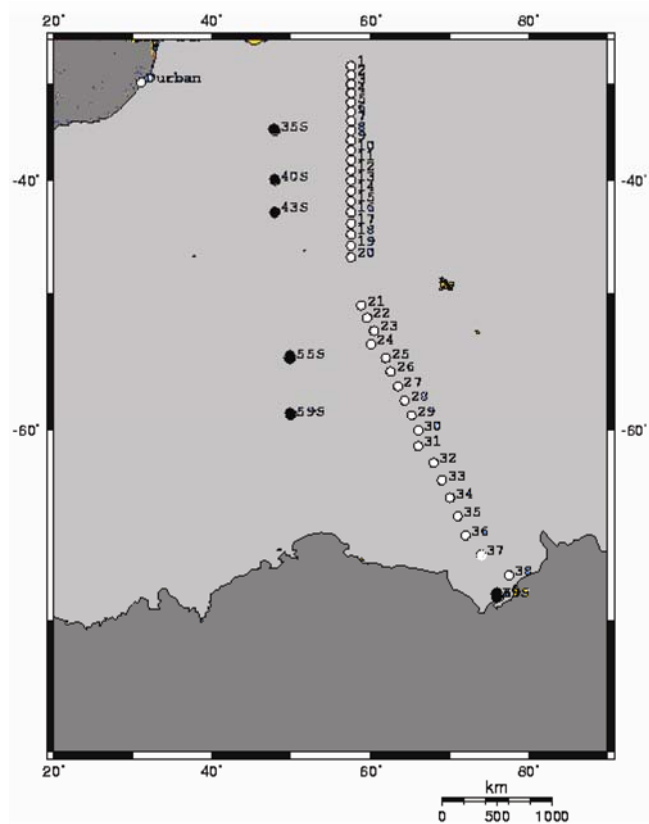


Figure 1. Study area with sample locations.

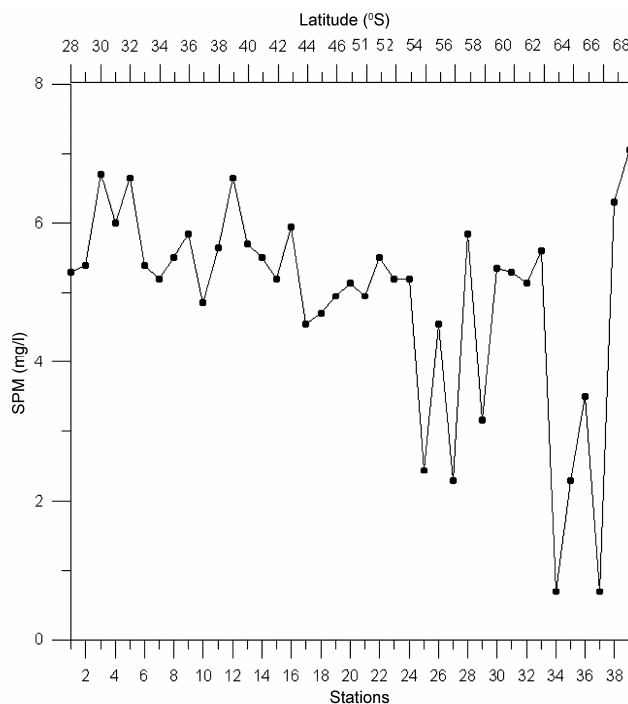


Figure 2. Concentration and distribution of surface SPM along the studied stretch.

Temperature, salinity and SPM of some selected stations:

The temperature and salinity data analysed during the present study are largely in agreement with the published data¹²⁻¹⁴. According to Millero¹², the surface circulation is strongly affected by a number of convergence zones. Going north from Antarctica, in general, the south–north section of water masses in Southern and Indian Oceans are divided into Antarctic zone, Sub Antarctic zone and Subtropical zone. The Antarctic zone is located from continent to Antarctic convergence at 50°S where temperature increases by 2–3°C and salinity is less than 34.5‰. The Sub Antarctic zone is reported from Antarctic convergence to Subtropical convergence at 40°S where temperature rises rapidly by amount of 4°C with a salinity increase of 0.5‰. Vertically, the water column is divided into Antarctic surface water, deep water and bottom water in the Antarctic zone, and into surface, intermediate, deep and bottom waters in the Sub Antarctic zone.

Similarly, Anilkumar *et al.*¹³ have delineated major fronts along 45°E between 40°S and 56°S. The position of Subtropical Front was reported between 41°15'S and 42°15'S with a rapid decrease in temperature and salinity. The Sub Antarctic Front has been located between 42°30'S and 47°S with a decrease in temperature and salinity. Surface Polar Front and Subsurface Polar Front were also identified between 48°S and 52°S. Further, along 57°30'E, the signatures of the Agulhas Return Front and Subtropical Front were identified¹⁴ with a rapid decrease in surface temperature between 43°30'S and 45°S. However, the studies were confined between 35°S and 56°S, and the locations of different fronts vary with longitude and season.

In the present study, considering the area between 28° and 69°S along different longitudes, it is ideal to follow the general classification after Millero¹². With respect to the water depth and latitudes of samples collected, three of the selected stations (69°S, 59°S and 55°S) fall within the surface and deepwater layers of Antarctic zone, two (43°S and 40°S) fall within the surface and intermediate water layers of the Sub Antarctic and one (35°S) falls in the Subtropical zone.

From south to north, temperature gradually increases at all the stations at all the three depths of measurement (Figure 3). The values are relatively low in the Antarctic zone and gradually increase towards the North. However, the values at 200 and 1000 m depths are relatively low at 43°S, whereas the surface value is high probably because of the convergence. The salinity data show a similar trend (Figure 3) at the surface and 200 m with a relatively high value in the Subtropical zone whereas the values at 1000 m depths are more or less constant.

On the other hand, the SPM data do not show any increasing or decreasing trend in any of the three depths. Surface as well as 200 m values are highest at 69°S, whereas that of 1000 m is at 55°S, all of which fall in the Antarctic zone (Figure 3). Interestingly, the value at

1000 m is the highest of the rest of values at 55°S and 59°S, whereas, values at three depths are more or less the same at 35°S. It is also noticed that all the values except at the surface are lowest at 43°S.

Selected elements: Fe and Mn show broadly similar trends (Figure 3) with the highest values (17.47 µg/l, Fe; 0.83 µg/l, Mn) at 200 m water depth at 69°S suggesting the possibility of terrigenous origin, transported by melting ice and wind. Mn maintains almost a constant trend at all depths except at 69°S, whereas Fe shows some variations, more significantly in the Antarctic zone, between stations and water depths. Zn also shows the maximum value (1.82 µg/l) at 200 m water depth at 69°S and high values (1.38 and 1.70 µg/l) at 1000 m water depth at 35°S and 43°S (Figure 3). Ca is highest (115.25 µg/l) at 1000 m water depth at 40°S, whereas Cu is highest (1.31 µg/l) in surface water at 55°S. Interestingly, all the metals except Zn show almost constant value at all the depths at 35°S, whereas the values of all metals are relatively high at 200 m water depth at 69°S and 59°S.

Vertical distribution

SPM is high at 10 m water depth in all the six stations. However, the highest values are recorded at 1000 m, except at 69°S in the Antarctic zone and at 10 m depth in other zones (Figure 4). Temperature profiles largely agree with SPM in vertical distribution in all the stations with a high value at near surface and 1000 m at 59°S and 55°S, whereas values are high in near surface alone at the rest of the stations. Salinity profiles show a relatively low value near the surface and gradually increase with depth at 69°S, 59°S, 55°S and 43°S, on the contrary at 40°S and 35°S, high values are seen near the surface up to 200 m before gradually decreasing with depth (Figure 4). So, the Antarctic zone is characterized by near surface (~100 m) high SPM, less saline and relatively warm water, and down at 1000 m high SPM, warm and high saline water, and in between with less SPM, cold and moderately saline water.

On the other hand, near surface high SPM zone of more saline and warmer water which decreases gradually with depth characterizes at 40°S and 35°S, whereas near surface high SPM, warm but less saline water with depth and a less SPM, cold but high saline water are seen at 43°S.

Selected elements: All the studied elements, viz. Fe, Mn, Zn, Cu and Ca, show increasing trends from surface to 200 m depth at 69°S and 59°S (Table 1). Whereas Fe continues the increasing trend similar to SPM, the rest of the elements show decreasing trends from 200 to 1000 m at 59°S. Except Ca, all the elements show decreasing trends from surface to 200 m depth at 55°S and 43°S

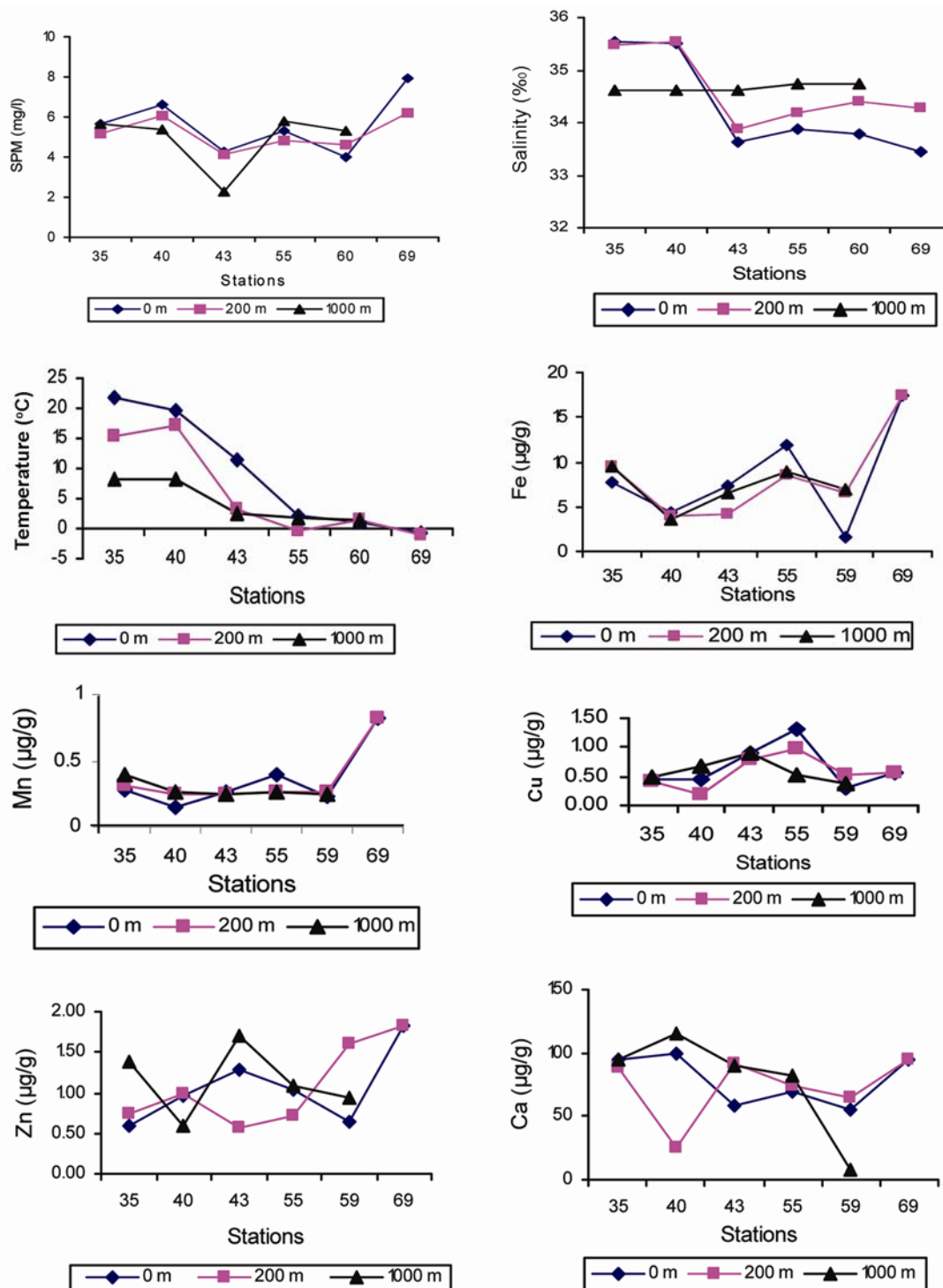


Figure 3. Spatial distribution of SPM, salinity, temperature and selected elements at three depths of selected six stations.

which are similar to SPM, whereas Fe, Mn, Zn and Ca at 55°S, and Fe, Cu and Zn at 43°S show increasing trends from 200 to 1000 m as was with SPM. At 40°S and 35°S, Ca, Cu and Fe (only at 40°S) decrease from surface to 200 m (Table 1) agreeing with SPM, whereas all the elements show increasing trends from 200 to 1000 m which was the case for SPM particularly at 35°S.

Discussion

From the results presented above, it is clear that the surface SPM concentrations as a whole show two sections (northern and southern) of distinct patterns. In the northern section, the particulates studied seems to be mainly of biogenic materials. As a consequence, the horizontal

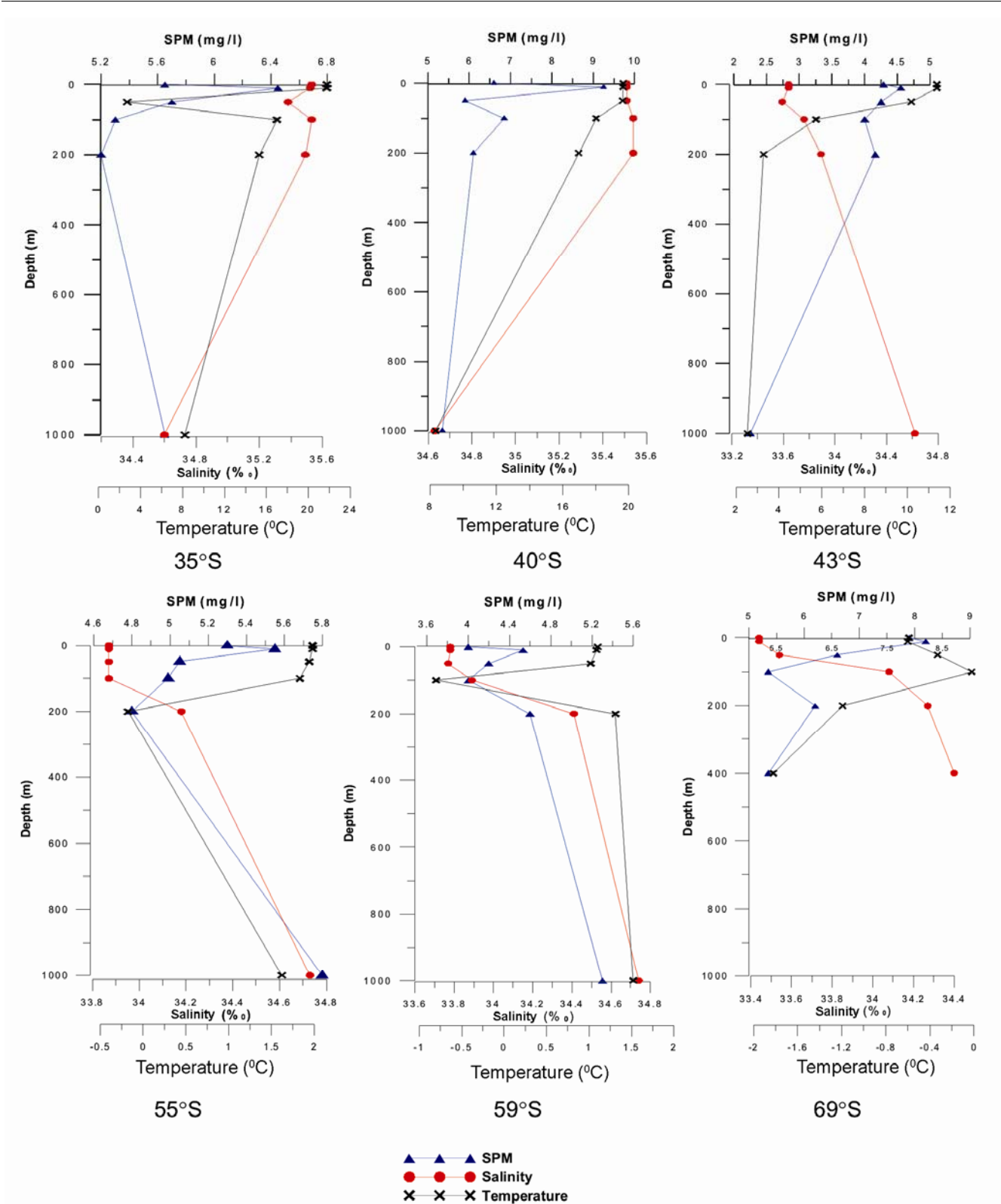


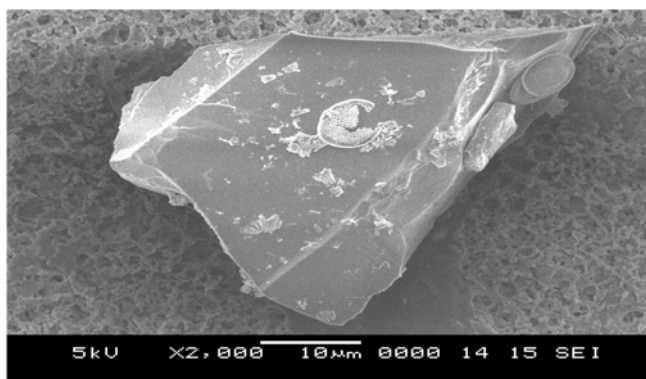
Figure 4. Vertical distribution of SPM, salinity and temperature in the selected six stations.

distribution in this zone is comparatively less fluctuating and is dominantly controlled by temperature and salinity. However, the highest and lowest concentrations are

located in the southern section where terrigenous inputs through melt water seems to play a pivotal role for the concentrations of SPM.

Table 1. Concentration and distribution of selected elements of suspended particulate matter from six selected stations

Stations		Fe ($\mu\text{g/g}$)	Mn ($\mu\text{g/g}$)	Cu ($\mu\text{g/g}$)	Zn ($\mu\text{g/g}$)	Ca ($\mu\text{g/g}$)
Latitude ($^{\circ}\text{S}$)	Depth (m)					
35	0	7.66	0.28	0.45	0.60	94.50
	200	9.44	0.32	0.43	0.75	87.75
	1000	9.46	0.40	0.48	1.38	94.00
40	0	4.45	0.16	0.47	0.96	100.25
	200	3.93	0.25	0.18	1.00	25.00
	1000	3.59	0.26	0.68	0.59	115.25
43	0	7.28	0.26	0.91	1.29	57.75
	200	4.23	0.25	0.80	0.57	91.50
	1000	6.50	0.24	0.90	1.70	89.50
55	0	11.90	0.40	1.31	1.04	69.75
	200	8.46	0.26	0.98	0.73	73.50
	1000	8.85	0.27	0.54	1.09	81.75
59	0	1.66	0.23	0.29	0.65	56.00
	200	6.58	0.27	0.51	1.60	64.75
	1000	6.97	0.24	0.38	0.94	7.28
69	0	8.42	0.34	0.54	0.74	85.75
	200	17.47	0.83	0.56	1.82	95.25

**Figure 5.** SEM photograph of SPM collected at 40°S. SPM consists of angular inorganic particle.

The combination of water column parameters, water sampling and analysis of particulate trace metals allows us to state that the SPM concentrations show different characteristics in three zones of the Southern Ocean. The Antarctic zone (69°S, 59°S and 55°S) is characterized by near surface high SPM, low salinity, indicating development of plumes that resulted from the increase of terrigenous input through melt water. This near surface input of large amounts of melt water results in a sharp salinity gradient which temporarily retains particles settling through the water column and develops a low concentration plume in middle zone¹⁵. The discharge of basal melt water might explain the presence of high SPM zone at 1000 m. Increase in particle concentration within the bottom layer can be partially explained by the breaking of larger flocs into smaller particles¹⁶.

It is observed that all the elements except Fe show a similar trend at 59°S and 69°S though the SPM values are highly fluctuating, which probably reflects the uniform

processes governing their distribution. On the other hand in the northern zone, metals show variations in their distributions probably because of different processes and factors controlling them. When it comes to the middle portion, i.e. in and around the zone of convergence, it seems the two ends of north and south sections play their contributory role as all the elements except Ca characteristics of northern section, maintain similar trends as that of the southern section.

Most of the collected SPM and the enriched metals of northern section are of biogenic nature. Trace metals play an important role in regulating the growth and ecology of marine phytoplankton. Trace metals (Fe, Mo, Zn, Cu and V) are required for the healthy growth of phytoplankton. Krishnaswami *et al.*¹⁷ measured the content of CaCO₃ in SPM and found elevated values in southeastern (around 20°S) and northeastern (around 20°N) Atlantic Ocean surface waters.

On the other hand, high values of Fe and Mn in southern section may be due to terrigenous input and of low productivity as the maxima of Al and Fe concentrations are located where the primary production is very low¹⁸. This can be partially through atmospheric fluxes. Chester *et al.*¹⁹ reported that aerosols in the eastern Atlantic troposphere contain high amounts of montmorillonite and kaolinite with peak concentrations at 5°N. Buat-Menard and Chesselet²⁰ estimated the atmospheric fluxes and stated that the 'deposition of atmospheric particulate matter over open (Atlantic) ocean areas play a significant role in the particulate chemistry of some trace metals, particularly those associated with aluminosilicate minerals' (Al, Fe, Mn).

When the components of SPM, which are mainly of biogenic, are analysed by SEM, diversified species of biogenic materials, particularly in the northern section,

are observed. A few inorganic components are also observed (Figures 5 and 6). Comparatively more diatoms were observed in the southern section. At 69°S, the biogenic constituents are dominated by *Fragilariopsis* sp. (Figure 7) together with *Thalassiosira* sp. (Figure 8). Different types of diatoms such as *Chaetoceros peruvianus*, *Coscinodiscus* sp., *Asteromphalus* sp., *Nitzschia* sp. constitute

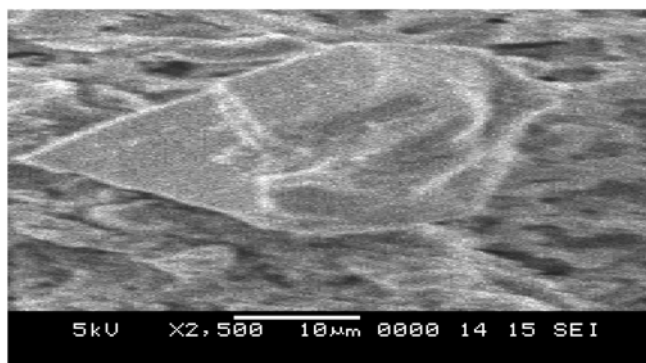


Figure 6. SEM photograph of SPM collected at 35°S. SPM consists of angular inorganic particle.



Figure 7. SEM photograph of SPM collected at 69°S. SPM consists mainly of biogenic components dominated by *Fragilariopsis* sp.

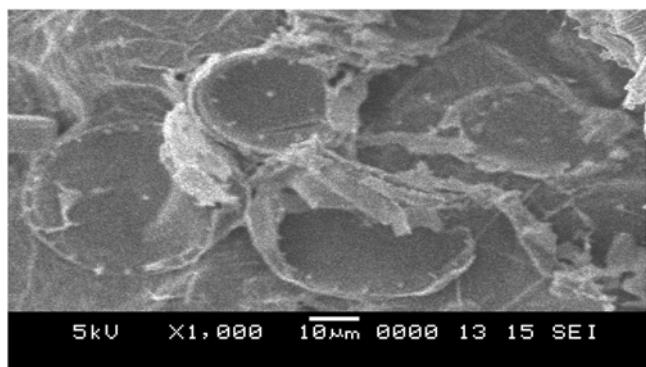


Figure 8. SEM photograph of SPM collected at 69°S. SPM consists mainly of biogenic components dominated by *Thalassiosira* sp.

the biogenic components at 59°S (Figure 9). At 43°S biogenic components include *Dinoflagellates* (*Phalacroma rotundatum*) (Figure 10) and *Fragilariopsis* sp.

Conclusions

Concentrations of SPM in the Southern and Indian Oceans vary spatially and vertically, whereas the minimum and the maximum concentrations fluctuated in the southern section, SPM content in northern section maintained a comparatively steady pattern. There are marked variations in the physical and biological environment in northern and southern sections which affect the distribution of SPM both spatially and vertically. Surface meltwater production is a particularly important phenomenon in the Antarctic regimes that at present lie along the periphery of Antarctic climate and hence the main source as well as the controlling factor for SPM, physical parameters and bound trace metals. On the other hand, the temperature and salinity controlled primary productivity plays a pivotal role in SPM and their bound trace metal distribution in the northern section. In between these two sections, there is a zone of mixed characteristics of both northern and southern signatures

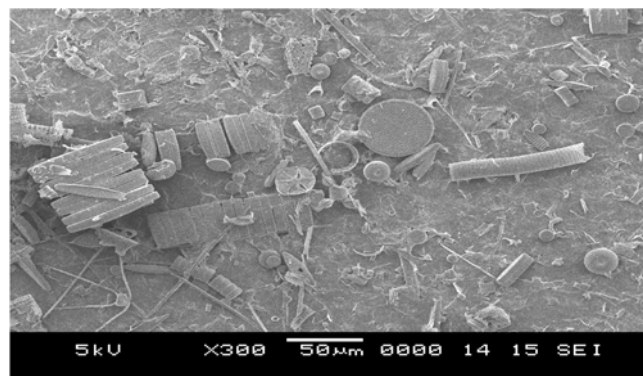


Figure 9. SEM photograph of SPM collected at 59°S. SPM consists of different types of diatoms.

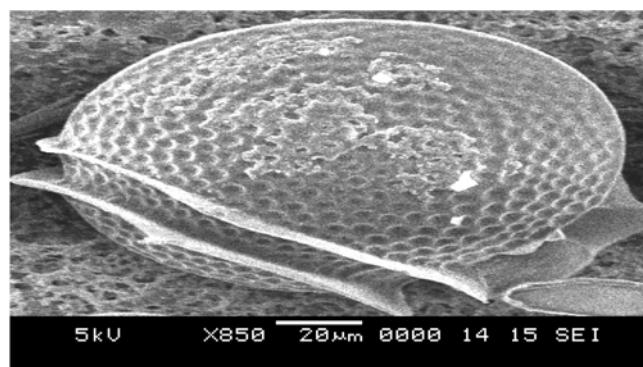


Figure 10. SEM photograph of SPM collected at 43°S. SPM consists of *Dinoflagellate-Phalacroma rotundatum*.

RESEARCH ARTICLES

especially at 43°S which is worth to mention probably because of its location between two convergence points.

1. Miller, D. G., Conservation of Antarctic marine living resources: a review and South African perspective. *S. Afr. J. Antarct. Res.*, 1991, **21**(2), 130–142.
2. Sullivan, C. W., Arrigo, K. R., McClain, C. R., Comiso, J. C. and Firestone, J., Distribution of phytoplankton blooms in the Southern Ocean. *Science*, 1993, **262**, 1832–1837.
3. Scott, J., *Marine Conservation at Macquarie Island*, Tasmanian Parks and Wildlife Service, Hobart, Australia, 1994.
4. El-Sayed, S. Z., Primary production and estimates of potential yields of the Southern Ocean. In *Polar Research: To the Present, and the Future* (ed. McWhinnie, M. A.), AAAS Selective Symposium, West View, New York, 1978, vol. 7, pp. 141–160.
5. Prospero, J. M., Eolian transport to the world ocean. In *The Sea* (ed. Emiliani, C.), John Wiley, New York, 1981, vol. 17, pp. 801–874.
6. Duce, R. A. and Tindale, N. W., Atmospheric transport of iron and its deposition in the ocean. *Limnol. Oceanogr.*, 1991, **36**, 1715–1726.
7. Delmonte, B., Petit, J. R. and Maggi, V., Glacial to Holocene implications of the new 27,000-year dust record from the EPICA Dome C (East Antarctica) ice core. *Clim. Dyn.*, 2002, **18**, 647–660.
8. EPICA Community Members, Eight glacial cycles from an Antarctic ice core. *Nature*, 2004, **429**, 623–628.
9. Martin, J. H., Gordon, R. M. and Frerzwater, S. E., Iron in Antarctic waters. *Nature*, 1990, **345**, 156–158.
10. Stonehouse, B., *Encyclopaedia of Antarctica and the Southern Oceans*, Scott Polar Research Institute, John Wiley, Chichester, UK, 2000.
11. Satyanarayana, D., Rao, I. M. and Prasada Reddy, B. R., Chemical oceanography of harbour and coastal environment of Visakhapatnam (Bay of Bengal): Part I – trace metal in water and particulate matter. *Indian J. Mar. Sci.*, 1985, **14**, 139–146.
12. Millero, F. J., *Chemical Oceanography*, CRC Press, New York, 1996, 2nd edn, p. 469.
13. Anilkumar, N., Dash, M. K., Luis, A. J., Ramesh Babu, V., Somayajulu, Y. K., Sudhakar, M. and Pandey, P. C., Oceanic fronts along 45°E across Antarctic Circumpolar Current during austral summer 2004. *Curr. Sci.*, 2005, **88**, 1669–1673.
14. Anilkumar, N. *et al.*, Fronts, water masses and heat content variability in the Western Indian sector of the Southern Ocean during austral summer 2004. *J. Mar. Sys.*, 2006, **63**, 20–34.
15. Yoon, H. I., Park, B. K., Domack, E. W. and Kim, Y., Distribution and dispersal pattern of suspended particulate matter in Maxwell Bay and its tributary, Marian Cove, in the South Shetland Islands, West Antarctica. *Mar. Geol.*, 1998, **152**, 261–275.
16. Heffler, D., Syvitski, J. P. M. and Asprey, K. W., The flock camera assembly. In *Principles, Methods and Application of Particle Size Analysis* (ed. Syvitski, J. P. M.), Cambridge University Press, Cambridge, 1991, pp. 208–221.
17. Krishnaswami, S., Lal, D. and Somayajulu, B. L. K., Investigations of gram quantities of Atlantic and Pacific surface particulates. *Earth Planet. Sci. Lett.*, 1976, **32**, 403–419.
18. Helmers, E., Trace metals in suspended particulate matter of Atlantic Ocean surface water (40°N to 20°S). *Mar. Chem.*, 1996, **53**, 51–67.
19. Chester, R., Elderfield, H., Griffin, J. J., Johnson, L. R. and Padgham, R. C., Eolian dust along the eastern margins of the Atlantic Ocean. *Mar. Geol.*, 1972, **13**, 91–105.
20. Buat-Menard, P. and Chesselet, R., Variable influence of the atmospheric flux on the trace metal chemistry of oceanic suspended matter. *Earth Planet. Sci. Lett.*, 1979, **42**, 12–22.

ACKNOWLEDGEMENTS. We thank the Ministry of Earth Sciences and Director, NCAOR for the opportunity to participate onboard *RV Akeademik Boris Petrov*, Chief Scientist and team members for their active support during the expedition. Special thanks to Drs Anil Kumar, Anoop Tiwari and Ravi Mishra for their help in sample collection and preliminary onboard analyses. Thanks to Drs B. Ingole, A. C. Anil, Reshma, Shamina, Priya and Ravi of NIO for their help in identification of diatoms and dinoflagellates with SEM photographs. We also thank Dr R. Ramesh, PRL for his valuable suggestions on the manuscript.