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Challenges in Southern Ocean oceanographic research: Indian efforts and preliminary results

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The Indian pilot expedition to Southern Ocean was launched by the National Centre for Antarctic and Ocean Research, Goa in January 2004. During this expedition a number of studies/experiments such as atmospheric observations, physical oceanographic observations, biological studies and chemical oceanographic observations were undertaken. In addition, to understand and reconstruct palaeoclimatic conditions in this part of the world, a number of surface and sub-surface sediment samples were collected along a north-south transect from 9.69°N to 55.01°S between 80 and 40°E long. The preliminary results of these studies in varied fields are presented here. These efforts of Indian scientists on Southern Ocean oceanography have yielded valuable data. The encouraging results have their bearing on the understanding and reconstruction of the glacial hydrography, sea ice extent and changes (if any) in the position of the palaeo front during the Holocene and the LGM over this sector of the Southern Ocean.

Keywords: Antarctic continent, Indian pilot expedition, Southern Ocean.

THE Antarctic continent with its surrounding Southern Ocean represents one of the major climate engines of the earth[1]. Due to their dynamic nature, the Southern Ocean processes have played a key role in the long-term global palaeo-environmental evolution[2]. Nevertheless, the Southern Ocean has received even less attention than the high northern latitude and the oceanic records are few and sparse[3]. This situation is true in the Indian context as well. Oceanographic research in India has been in existence for more than four decades. However, most of the studies were concentrated on the Arabian Sea, Bay of Bengal or Indian Ocean basin and meagre attention was paid to the southern hemisphere.

The importance of the Southern Ocean for Indian marine geosciences was realized quite late and highlighted in detail by Rajan and Khare[4,5]. It was pointed out that India must be in the Southern Ocean mainly because of palaeoclimatic studies and that a bihemispheric approach needs to be adopted. The millennial-scale climate changes seem to originate in the southern hemisphere[5] and the Southern Ocean governs the global climate system. While the mil-

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lennial-scale climate events are globally manifest, there are perceptible differences as well between the geometry of these fluctuatiuons in both the hemispheres. Therefore, in order to understand the forcing mechanism behind the widely geographically separated climatic changes, identification of well-synchronized millennial-scale climate changes must be gleaned from both hemispheres.

Previously, attempts have been made to understand the palaeohydrography[6–13] from different sectors of the Southern Ocean. However, limited attempts have been made in the Indian Ocean sector of the Southern Ocean. Dedicated oceanographic expeditions that would enable expanded spatial and temporal coverage are therefore necessary for a better understanding of oceanographic processes in the Southern Ocean.

Accordingly, the National Centre for Antarctic and Ocean Research (NCAOR), Goa started planning an ambitious research programme in the Southern Ocean. As a beginning in this direction, in September 2001, a pilot cruise to the Southern Ocean utilizing the services of our own research vessel *ORV Sagar Kanya* was planned. This world-class oceanographic research vessel well-equipped with latest analytical instruments belongs to the Department of Ocean Development (DOD) and is managed by the NCAOR. Subsequently, a detailed scientific plan was drawn for a multidisciplinary and multi-institutional cruise to the Indian Ocean sector of the Southern Ocean (up to 55°S). The implementation meeting was held in August 2003 at NCAOR involving about 12 national institutes/ laboratories that discussed and prepared the comprehensive scientific plan of the pilot expedition, addressing the interests of scientists from different disciplines. These discussions culminated in preparing a comprehensive scientific plan covering the major scientific interests and disciplines. Finally the long-awaited event became a reality when the Pilot Expedition to the Southern Ocean, also called as PESO, was flagged-off from the port of Cochin (India) for Southern Ocean voyage via Port Louis (Mauritius), from where PESO was finally launched on 23 January 2004.

Earlier studies have proposed various definitions to determine the latitudinal extent of the Southern Ocean, which extends south of 30–45°S lat. from oceanography perspectives. However, from a geopolitical angle, the International Hydrographic Organization (IHO) in 2000 agreed that the Southern Ocean should be formally recognized and accordingly as per the SCAR report, the IHO delimited a fifth world ocean from the southern portion of the Atlantic Ocean, Indian Ocean and Pacific Ocean, termed as the Southern Ocean. This newly defined ocean extends from the coast of Antarctica north to 60°S lat., which coincides with the Antarctic Treaty limit.

The part of the study area is an integral region of the Southern Ocean and is influenced by many important processes taking place in and around. Pronounced meridional gradients in surface properties separate waters of the Southern Ocean from the warmer and saltier waters of the subtropical circulations. Deacon[14,15] called this hydrographic boundary the Subtropical Convergence, a term replaced by the Subtropical Front (STF) in recent years (M. A. Clifford, unpublished; ref. 16). According to Deacon, the transition from warm, light subtropical water in the north to cold, dense Antarctic water in the south occurred in a step-like manner rather than as a gradual change across the breadth of the Southern Ocean. Detailed mapping of the Southern Ocean fronts was attempted by earlier workers[12,17]. The fronts coincide with currents which carry most of the transport of the Antarctic Circumpolar Current (ACC)[18]. It is significant to note that between the fronts lie zones of relatively uniform water-mass properties. From north to south, the fronts and zones of the Southern Ocean are: the STF, Subantarctic Zone (SAZ), Subantarctic Front (SAF), Polar Frontal Zone (PFZ), Polar Front (PF) and Antarctic Zone (AZ)[19].

South of the STF is the eastward flow of the ACC, extending unbroken around the globe. It is driven by the world's mightiest westerly winds[20], found approximately between 45° and 55°S. Because of the land mass distribution, the ACC is a unique global link that connects all major oceans. Specific water masses shoal dramatically southward across the Circumpolar Current, so that deep waters originating farther to the north are able to enter the subpolar regime and mix laterally with Antarctic shelf waters[17].

In contrast to the long-established demarcation between the subtropical regime and the ACC, there is yet no well-defined boundary between this current and the subpolar regime. Deacon[15] recognized a westward flow adjacent to Antarctica, which is driven by the prevailing easterly winds found to the south of about 65°S. Isotherms and isohalines shoal at the transition between west and east winds, inducing clockwise flow under geostrophic balance[15,21]. The proximity of Subantarctic Surface Water (SASW) to the much warmer and saltier Subtropical Surface Waters (STSW) produces large property gradients, the original indicators of the STF. Deacon[15] gave the first global description of this upper water front. He noted that regardless of the season or ocean basin, surface temperature (salinity) changes as large as 4–5°C (0.5) mark the location of the STF; its northern side is generally warmer (saltier) than 11.5°C (34.9)[21].

Temperature and salinity distributions at 100 m were examined in lieu of Deacon's surface indicators of the STF. Its approximate location lies within a band across which temperature increases northward from 10 to 12°C, and salinity from 34.6 to 35.0 at 100 m. Since the salinity field shows smaller seasonality than temperatures, the haline gradient is a more reliable indicator[21]; one exception is the southeast Pacific sector[17]. Regions towards higher latitude are associated with one or more oceanic frontal systems. The sea surface expression of most of the frontal systems is a sharp southward temperature drop with consequent changes in planktonic biotic assemblages[22].

The Antarctic Bottom Water (AABW) formation takes place at the continental shelves of the Weddell and Ross seas. The highly bar tropic ACC reaches the ocean floor and is able to mix efficiently the North Atlantic Deep Water (NADW) and deep waters from the Indian and Pacific oceans. The mixture of these deep waters, the Circumpolar Deep Water (CDW), then spreads back into other ocean basins in one form or another. The formation of Antarctic Intermediate Water (AAIW) by Ekman pumping occurs in the convergence zone. The northward advection of temperatures and salinities of AABW, CDW and AAIW from the Southern Ocean to other ocean basins has a profound effect on the global ocean circulation and thus on global climate[6].

The Southern Ocean is one among the most significant parts of the world oceans and comprises several physically and biologically distinct regimes, latitudinally separated by fronts. This region is characterized by high production of nutrients and low chlorophyll (HNLC) zone. There is low utilization of these nutrient-rich waters and therefore, this aspect needs further studies. The Southern Ocean is one of the primary sites of intermediate, deep and Antarctic bottom water formation. Geochemical and climatic signals of the Southern Ocean processes are transmitted throughout the world's oceans. Upwelling-linked primary productivity in the Southern Ocean constitutes nearly a third of the oceanic total. The sea-ice distribution and nutrient structure within the cold water ACC control biogenic sedimentary provinces of the ocean. About two-thirds of the silica flux into the ocean is removed by siliceous microorganisms in the Southern Ocean. Little is known about the Southern Ocean circulation response or hydrographic changes to both increasing sea-ice cover and changes in atmospheric circulation during the glacial.

Further, this is also the region of major wind stress and in turn the mixed layer gets deepened, specially during winter. Lastly, the waters of the Southern Ocean directly or indirectly affect the Indian Ocean and thereby the Indian climatic regime. Also the Indian Ocean is land-locked on its northern extremity and therefore, there is no exchange with the north-pole waters. Therefore, the Southern Ocean and its waters need to be studied in detail and the need to have such a cruise in this part of the world is justified. As mentioned by earlier workers, the possibility of asynchronous coupling of the inter-hemispheric climate record necessitates a second look at the high latitudes of the southern hemisphere. It was further postulated that the interactions between the surface ocean, ice and atmosphere should be easier to model in the southern than in the northern hemisphere[5].

The Southern Ocean is also extremely important in the context of global biogeochemical cycling and climate, because it contains sites of deep water convection and also because its surface waters contain a large pool of unutilized nutrients, presumably due to the limitation of biological productivity by low dissolved iron levels.

Another significance of the Southern Ocean lies in its living resources. Antarctic krill is the pivotal species in the food web of the Southern Ocean. The huge abundance of these krill has attracted the attention of the world's fishing fleet. During the initial Indian Antarctic voyages (1981–87), krill and zooplankton samples were collected and analysed to estimate the krill abundance in the Indian Ocean sector of the Southern Ocean. In addition to krill larger animals like squids, seals, toothfish, birds and whales are also present in this region. There was no regulation on early commercial development of Antarctic fisheries till the establishment of the CCAMLR in 1980, which provided an international mechanism for collecting and synthesizing data on the fisheries. It also laid guidelines for managing and regulating the catches. CCAMLR is committed to evolve ways in which the annual ecosystem assessments could be parameterized to produce an index useful in fishing management.

The Southern Ocean also offers a unique opportunity to study animal physiological adaptation to low temperatures and high ultraviolet levels and biogeochemical/ecological research on processes controlling productivity, food web, carbon export, trace-gas cycling, and subsurface water formation. It also offers a unique sedimentary environment to reconstruct past climate and study the role of high-latitude processes in modulating global budgets of carbon and nitrogen.

Our work to date in the Southern Ocean has been restricted largely to the region traversed by the ice breakers chartered annually for our scientific expeditions to Antarctica. Therefore, there has been a pressing need to launch a dedicated oceanographic expedition to the Southern Ocean. Such a specialized expedition would definitely provide a platform to understand oceanographic processes of this region.

Thus a modest beginning was made with the planning of collection of a large number of surface and sub-surface (sediment cores) sediment samples from the Indian Ocean sector of the Southern Ocean along a north–south transect from 9.69°N to 55.01°S lat. and between 80 and 40°E long. during the PESO.

A multi-institutional and multidisciplinary scientific expedition to the Southern Ocean was initially flagged off from the port of Cochin (India) and finally from the Port Luis (Mauritius) on 23 January 2004 with a dedicated team of 30 scientists drawn from various R&D institutions/universities. Figure 1 shows the cruise track of the PESO. A number of scientific experiments/programmes were executed during the PESO. In the following paragraphs a brief account of some of the preliminary results of various studies/observations/experiments (for which inputs have been provided by the respective participating scientists) will be highlighted.

Under the atmospheric science programme of PESO, the following studies were carried out by the representatives of IMD (New Delhi), IITM (Pune), IISc (Bangalore) and SPL (Thiruvananthapuram).

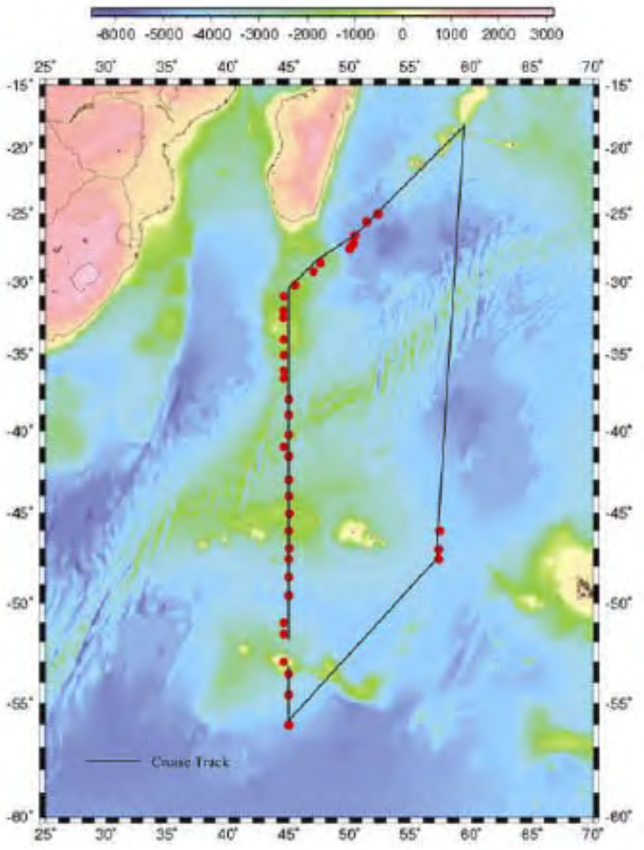

Figure 1. Cruise track of the Pilot Expedition to Southern Ocean and location of stations (•) selected for CTD observations.

Aerosol black carbon: Black carbon (BC) affects the climate by absorbing solar energy that in turn heats up the atmosphere. The magnitude of this effect may depend on how BC is mixed with other aerosol components. Continuous measurements of BC mass concentration were made on-board using an aethalometer. Air intake was at a height of about 12 m from the sea level. From the preliminary assessment of measurements, it is clear that the BC mass concentration over the Southern Ocean is low compared to tropical oceanic regions. This is due to the pristine nature of the air mass prevailing over the Southern Ocean. Because of the anthropogenic nature of the origin of BC, the low BC concentration observed is surprising, and can be due to long-range transport.

Aerosol optical depth: Optical depth is a measure of the transmittance of a vertical atmospheric column of unit cross-sectional area. Aerosol optical depth (AOD) is an important parameter controlling the aerosol radiative forcing. Spectral AOD measurements were made on-board using a hand-held Microtops sunphotometer at wavelengths 380, 500, 675 and 870 nm. The instrument manually aimed at the sun, makes measurements of the direct solar irradiance and derives AOD based on its calibration, and the observation co-ordinates and time as recorded using a GPS receiver attached to it.

Automatic weather station and radiosonde: In order to measure surface-met and upper atmospheric parameters over the Southern Ocean using automatic weather station and radiosondes respectively, various meteorological parameters like air temperature, pressure, relative humidity, rainfall, solar radiation, wind speed and wind direction were continuously measured and stored as one minute average interval.

Radiosonde: Upper atmospheric parameters were measured using high precision Vaisala GPS radiosondes. Radiosondes measure parameters like air temperature, relative humidity, pressure, wind speed and wind direction. As proposed, radiosondes (about 13) were launched at every 2.5°S lat.

Under the physical oceanography programme of PESO, the following studies were carried out by representatives of NCAOR (Goa), SAC (Ahmedabad) and NIO (Goa). In order to understand the *T–S* structures, morphology of circumpolar fronts, circulation regimes in the water column and air–sea interaction processes pertaining to the Indian Ocean sector of the Southern Ocean, CTD (38 stations) and XBT systems (78 locations) were used on-board. Apart from obtaining the *T–S* profiles, a hull-mounted ADCP was operated along the ship's track in the study area. A ship-borne wave recorder was operated at CTD stations to record wave data for a 15-min period. Preliminary results of CTD data analysis indicate the presence of different water-mass regimes in the study area. It is clearly seen that the STF around 41°S separates the high saline sub-tropical waters of the north from the fresh waters of the sub-Antarctic region (N. Anil Kumar, pers. commun.).

Under the biological programme of PESO, the following studies were carried out by the representatives of CMLRE (Cochin), NIO (RC-Cochin), Annamali University, CUSAT (Cochin) and CMFRI (Cochin).

Primary productivity studies: Estimation of primary production using ^{14}C technique, estimation of chlorophyll pigments by fluorometric analysis and qualitative and quantitative study of phytoplankton composition were attempted. A total of 18 stations were included for primary productivity studies along latitudes 45°E and 57°30′E.

Secondary productivity studies: Microzooplankton was collected from 15 stations along the 45°E longitude starting from 31 to 55°S lat. Samples were collected from seven depths, surface, 10, 25, 50, 75, 100 and 120 using CTD rosette. Five litres of sea water was initially filtered through a 200 μm bolting net and later through a 20 μm sieve. The concentrated microzooplankton sample was transferred to 100 ml of filtered sea water and preserved in dark.

Mesozooplankton was collected from 18 stations along the 45°E longitude starting from 31 to 55°S lat. Horizontal hauling was made by Bongo net (300 μm) and vertical hauling by multiple plankton net (MPN; 200 μm). Samples were collected from four different depth strata up to 1000 m (viz. 0–TT, TT–BT, BT–500, 500–1000) using

MPN. After the measurement of live biomass, zooplankton samples were preserved in 4% formalin for further qualitative and quantitative studies. Preliminary analysis of data gave biomass in the range of 20 to 4910 ml/1000 m^3 for Bongo and between 11 and 3571 ml/1000 m^3 for MPN collection at 45°E transect. Along the 57°30′E transect, the values ranged from 120 to 500 ml/1000 m for Bongo and 228 to 246 ml/1000 m^3 for MPN collections. The mixed layer shows higher biomass in comparison with other strata, with an increasing trend in the biomass from north to south of the transect.

Benthic productivity studies: Sediment samples were collected using Van Veen Grab and Gravity corer from seven stations along 45°E, starting from 32 to 53°S lat. Approximately 5–10 g of sediment from the sampler was aseptically transferred using a sterile stainless-steel spatula into a sterile container and kept at –18°C for molecular analysis. Preliminary observations indicate predominance of polycheates in the sediment samples.

Studies on bacterioplankton: About 500 ml of sea water from depths immediately below the euphotic zone and off the sea bottom was collected and kept in the dark at –10°C. Bacterial abundance was determined following diamidino-2-phenylnidole (DAPI) assay at the on-shore laboratory using fluorescence microscope.

Harmful algae in the Indian Ocean sector of southern Ocean: Water samples (1 l each) from surface to 150 m were collected. The samples were stained in Lugol's iodine solution and preserved in 4% formalin for on-shore laboratory analysis.

Bloom: An extensive bloom of the Cyanobacteria, *Trichodesmium erythraeum* was detected on 27 January 2004 at 27°14′S, 50°32′E. SST and SSS at the location were 27.11°C and 34.84 ppt respectively. Dissolved oxygen values were 3.8 ml/l at the surface, 4.4 ml/l at 50 m and 4.1 ml/l at 100 m depths.

Avian fauna: Avian fauna along the ship route was monitored by visual observations using binoculars. The objectives were to identify the major species, assess their latitudinal distribution and prepare a report, including occurrence of juvenile birds. White-chinned petrels were observed throughout the ship route from 31 to 56°S along with a few wandering albatrosses. Yellow-nosed albatrosses were dominant from 40 and 53°S. Black-browed albatrosses and giant petrels were sighted between 43 and 56°S. Bird density and the occurrence of juveniles were maximum near Walters's shoal, Melville Bank, Danilevskij sea mount, Galliieni knoll, Prince Edward and Marion Islands, Crozet Islands along the 45°E transect and near Kerguelen Island close to the 57°E transect (P. Jayashankar, pers. commun.).

Sighting of marine mammals: A total of 21 whales and dolphins were sighted in the area between 22 and 53°S lat. during the present cruise. On-board identification of cetaceans is a tricky affair, since it has to be done based on occasional appearance of certain body parts as well as spouts from the blow-holes in the case of whales. Under these circumstances, it was most desirable to make a detailed description of the features noticed during the sightings for later use. During the present cruise, only 10% of the sighted marine mammals could be unmistakably identified. While 38% fell in the category of 'possible', 52% were 'unidentified'. It is hoped that this picture would certainly improve once expert consultancy is sought for ratification of species identity based on the present detailed descriptions. Eighty-six per cent of the sighted cetaceans were whales, while the remaining were dolphins. Species encountered during the present cruise (identified and 'possible') include sei whale (*Balaenoptera borealis*), minke whale (*B. acutorostrata*) and blue whale (*B. musculus*) (P. Jayshankar, pers. commun.).

Under the chemical oceanography programme of PESO, the following studies were carried out by the representatives of NCAOR and NIO.

Dissolved oxygen: Sea-water samples were collected for analyses of dissolved oxygen (DO) in 32 stations from surface to near bottom extending up to ~ 4000 m water depth. Preliminary results of the analysis indicated that the concentration of DO in the surface layer ranged from ~ 180 to 360 μM. There was a significant increase in DO concentration in the surface layer between station 19 (41°S lat.) and 20 (42°S lat.), suggesting a boundary between two distinct water-masses, viz. Sub-Tropical water-mass and Sub-Antarctic water-mass. There was an inverse relationship ($r = 0.98$) with SST. North of the STF, DO concentration decreases in general with depth, reaching a minimum at intermediate depths (1000–2000 m) and then slowly increases to ~ 200 μM in the near-bottom depths. South of the STF, depth of intermediate oxygen minimum is somewhat decreasing ~ 500 m (Rajkumar, pers. commun.).

pH determination: pH of the water samples was determined immediately after collection using a digital pH meter with automatic temperature compensation probe. Figure 2 shows the pH values at various stations along the cruise track in the Southern Ocean (Rajkumar, pers. commun.).

Nutrient analysis: The well-proven method of continuous analysis of numerous water samples has been achieved

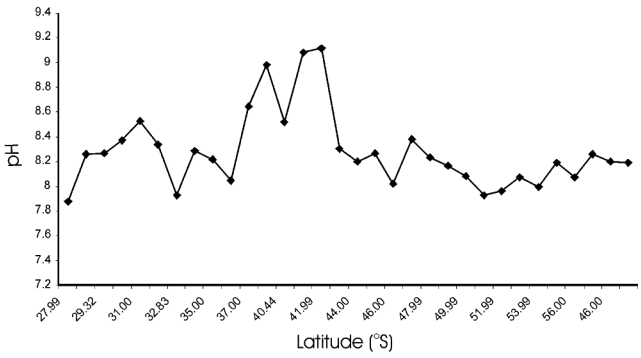

Figure 2. Latitudinal variations in pH values at various stations along the cruise track in the Southern Ocean.

using the Autoanalyser (Skalar) instrument. The nutrient values calculated in the cold region had unique signatures of the water mass circulations and biogeochemical activities in the region of the study. The nutrient data observed show correlation with other oceanographic observations like salinity, temperature and also with pH of the corresponding samples measured (Rajkumar, pers. commun.).

Under the palaeoclimates studies programme of PESO, the following studies were carried out by representatives of NCAOR.

Geological investigations of surface and sub-surface marine sediments and water masses: The prerequisite for any palaeoclimatic reconstruction is the assessment of the response of the used proxy in modern marine environment. To understand the modern-day microfaunal assemblage, plankton net vertical hauls were carried out at two depths (surface and 200/100 m) to decipher the changes from surface with depth at nearly all locations. At all these locations, simultaneously collected data on various hydrographic parameters (DO, SST, salinity, nutrients, etc.) were compared with the microfaunal assemblages.

To undertake palaeoclimatic studies, a number of surface and sub-surface sediment samples were collected along the north-south transect in the study area using various techniques like Van Veen Grab, gravity and piston corer. The sediment collected varied from sandy silt to silty sand, with large presence of shells/tests. Some cores revealed systematic changes in sediment type and colour with presence of several banded intercalations, suggesting intermittent large-scale environmental variations during the time represented by it. Another piston core collected during PESO at 2730 m water depth, apparently revealed abundance of micro-nodules and occasionally larger nodules (~ 5 cm diameter) distributed throughout the core below 75 cm from the seafloor. This certainly points to some large-scale changes in the bottom water conditions compared to the modern times during their deposition. A gravity core collected from 4389 m water depth revealed excellent variations in sediment type and colour, with alternate layers of dark and light bands. It was found that the darker layers are abundant in rock fragments and debris of various size and shape. Most interestingly, preliminary investigations revealed that the above core consists of layers of siliceous and carbonaceous sediments, indicating dramatic changes in the oceanic chemistry during the past.

In view of the foregoing account, it may be surmised that the Southern Ocean region is one of the best known HNLC zones. It is of interest how different microfauna, one at nano level (coccolithophorids; size ~ 10^{-9} m) and the other at microscopic (foraminifera) level behave under the prevailing ambient conditions across the oceanic fronts. Attempts must be made to understand as to how the carbonate flux is changing with depth and also with changing SST pattern in this region. It would be an interesting attempt to develop a cause–factor relationship between the different microfaunal groups and their influence on the oceanic carbon and silica cycle.

In order to reconstruct a regional picture of climates in the Southern Ocean, many transects have been proposed to be undertaken with multidisciplinary and multi-institutional approach. Data thus obtained will be compared with those obtained through ice core and lake-sediment core collected from the icy continent of Antarctica. Such a comparison may help in understanding the climate system of this area in particular and globally, in general. Many such specialized cruises to the Southern Ocean have been planned in the near future, when the following scientific activities shall be taken up in a phased manner as a follow-up of NCAOR's ambitious programme on the Southern Ocean.

- Influence of Southern Ocean and Antarctica on the performance of the Indian summer monsoon.
- Role of high-latitude chemical processes in modulating global budgets of trace gases and their relation to climate.
- Circulation, air–sea exchange and sea–ice dynamics in the Southern Ocean and their contribution to global climate using remote sensing technology.
- Spatial and temporal changes in biological productivity, diversity and resource potential in relation to the controlling physical and chemical processes.
- Integrated geophysical–geological studies: Reconstruction of palaeomargins, palaeoceanography/productivity and palaeoclimate.
- Modelling of Southern Ocean wind-driven circulation, thermocline circulation, AABW formation and biogeochemical cycles of carbon, nitrogen and sulphur.
- Inter-comparison of palaeoclimate obtained from ice-core analysis with that from marine sediments.
- Tele-connection with monsoons and other phenomena.
- Systematic exploitation of living resources of the Southern Ocean.

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Marine and estuarine methylotrophs: their abundance, activity and identity

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Methanotrophs were up to 1 and 0.65% of the total counts in estuarine waters and offshore sediments respectively. Experimental tests on methanol utilization showed that the estuarine isolates grew best at 4% methanol whereas offshore ones grew at 5% at an optimum pH of 6 or 7. Methanol, when used as an additional carbon source, in the presence of nutrient broth concentration ranging from 0.08 to 0.4%, enhanced growth by 129% and respiration by 177% in estuarine isolates. Biochemical and physiological characteristics showed that estuarine methylotrophs exhibited taxonomic affinities to *Pseudomonas* I or II sp. The offshore genera were more varied and belonged to *Flavobacterium* and *Pseudomonas* I or II sp. The abundance, activity and identity suggest that these physiological groups could be widespread and therefore could perhaps contribute significantly to the changes in C_1 compounds and even their derivatives in marine and estuarine environments.

Keywords: Adaptation, estuarine, methylotrophs, marine, methanol.

METHYLOTROPHIC bacteria (MTB) are obligate aerobic microorganisms recognized by their ability to grow on carbon compounds more reduced than CO_2, without any C–C bonds. They are even able to assimilate compounds such as HCHO or a mixture of HCHO and CO_2. MTB capable of oxidizing methane are methanotrophs (MOB). They play an important role in the geochemical cycling of methane and its derivatives. The oxidation of methane can have major implications on the structure of food webs and climate, especially in the current global scenario. Hence, a study on their ecology would be pertinent to understand the dynamics of methane and methane-derived compounds, especially in marine and estuarine systems.

Though much work has been carried out on the molecular[1–3] and taxonomic aspects[4] of methanotrophs, the study is either restricted to lacustrine environment[5,6] or terrestrial regions[7–9]. Work on the marine environment is limited[10]. Hence, the present study assesses the retrievable abundance and distribution of methylotrophs and methanotrophs. It also examines the activity of methylotrophs from estuarine beach and offshore regions.

Sampling was carried out during low tide in September, representing the end of the southwest monsoon season at Dona Paula beach (15°27′N, 73°48′E), a sheltered

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