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Review Article

Paleoclimatic Signals from the Proxy Records of the Southern Ocean : A Review

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Antarctic sea-ice extent and oceanic frontal systems are of primary importance to the marine biota since their marked meridional gradients in physical and chemical properties strongly regulate the phytoplankton contribution to primary productivity.Antarctic sea ice extent along with the Southern Ocean (SO) biological productivity varied considerably during glacial-interglacial periods, and both are known to have played a considerable role in regulating atmospheric CO_2 variations in the past. In the present review paper, we seek to understand the past latitudinal variability of the Southern Ocean frontal systems and Antarctic sea-ice extent based on a multi-proxy approach. The first aspect of this paper concentrates on the diatom based reconstructions of paleo sea-ice and hydrographic changes in the Southern Ocean and its impact on diatom sizes and productivity. Secondly, emphasis would be placed on the studies based on the morphology and isotopic composition of foraminifera and its paleoceanographic implication. The foraminifera shell preserved in the sediments provide unparalleled archives of morphological change, faunal variations, and habitat characteristics as a result of hydrographic changes. To sum up, the advantage of a mulitproxy approach including the magnetic, geochemical and sedimentological parameters have been discussed in understanding the Southern Ocean paleoclimate.

Keywords: Southern Ocean; Sea-ice; Diatoms; Fronts; Productivity; Morphometry; Foraminifera; Magnetic Susceptibility

Introduction

Southern Ocean (SO) is the least understood of the world's oceans, despite its vital role in the present climate system. It exchanges water with the other oceans and partly controls the CO_2 partitioning between the ocean and the atmosphere. In the modern SO, deep ocean waters with high CO_2 and nutrient content are brought to the surface by wind-driven upwelling. However, the scarcity of iron reduces phytoplankton growth (Martin *et al*., 1990; Boyd *et al*., 2000), and major macro nutrients are returned to the sub-surface before they are fully consumed. This incomplete utilization of nutrients allows the escape of the deeply sequestered pCO_2 back to the atmosphere, thereby contributing towards raising atmospheric pCO_2 levels (Sigman *et al*., 2010). Today, this CO_2 "leak" occurs mainly in the polar Antarctic zone as compared to the Subantarctic zone (greater nutrient consumption). However, data and models reveal that a combination of biological and physical processes contributed to lowering the atmospheric CO_2 during glacial times, whereby the Antarctic zone was more strongly stratified (Francois *et al*., 1997; Sigman *et al*., 2010) and productivity was higher in the Subantarctic during ice ages (Kumar *et al*., 1995; Kohfeld *et al*., 2005; Martinez-Garcia *et al*., 2009). Nonetheless it is plausible to presume that the Southern Ocean during different time period could have acted either as a source or a sink of atmospheric CO_2 by changes in the productivity regime or oceanic circulation, or both (Jaccard *et al*., 2013). Most of the SO is a high-nutrient, low-chlorophyll (HNLC) area. There are exceptions to this situation downstream of some of the islands, where surface water productivity is high. The main locations where this occurs are downstream of the Crozet and

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Kerguelen Islands in the Indian sector of the SO. In the recent past quite a few attempts by Indian researchers have been made to understand this phenomenon which would be the prime focus of this paper.

Indian contribution in the field of SO paleoceanography has been largely limited to qualitative climatic reconstructions rather than quantitative studies. Nevertheless, recent advances in the field of SO paleoceanography have taken us a step closer to understanding the past climate variability at millennial and glacial-interglacial timescale. India made its first attempt in understanding the SO diatoms and its paleoceanographic implications by studying the latitudinal variation of diatoms in the surface sediment and nutrient availability in the Indian sector of the SO (Mohan *et al*., 2006). Similarly, planktic foraminifera assemblages preserved in the surface sediment and from water column were studied to understand its paleoceanographic implications (Mohan *et al*., 2015). This study from the Indian sector of the SO revealed higher shell weight of the planktic foraminifera from the sediments and the presence of heavier carbon isotopes in their tests as compared to specimens from water column indicating secondary calcification in foraminifera preserved in the sediments (Mohan *et al*., 2015). It has been suggested that the changes in terrigenous influx to this region were significantly influenced by the rhythmic glacial-interglacial fluctuations in bottom circulation and the position of the Atlantic Antarctic Polar Front (APF) (Thamban *et al*., 2005; Manoj *et al*., 2012). A recent study has also indicated that past changes in terrigenous input from Crozet islands (volcanic) may lead to glacial-interglacial variation in diatom productivity and size (Nair *et al*., 2015). The paleoproductivity records also reveal significant association with shifting nutrient regimes as a consequence of varying frontal zones (Manoj and Thamban, 2015; Nair *et al*., 2015).

An interesting application of the morphology of diatom as a proxy is to analyze if and how it varied over glacial to interglacial transitions at the Polar Front, as this may reflect millennial-scale shifts in the position of this front, and the associated high export of biogenic silica. Changes in the valve size of *F. kerguelensis* in deep-sea sediment cores from the Indian and the Atlantic sectors of SO were recently used to infer changes in diatom productivity, physiology and environmental conditions (Shukla *et al*., 2013; Nair *et al*., 2015). Shukla *et al*. (2013) suggested that variations in circum-polar upwelling were the main controlling factor in opal production during the last ~20,000 years. It was also hypothesized that high nutrient input from the Antarctic Peninsula during the last deglaciation may have exerted a strong control on *F. kerguelensis* valve size and opal export in the Atlantic sector of the Southern Ocean (Shukla *et al*., 2013).

Faithful retrieval and interpretation of high-quality ice-proximal sedimentary sequences from Antarctic margins and the Southern Ocean have made been possible by recent progress in drilling technology and climate proxy methods (Shevenell and Bohaty, 2012). These records provide valuable information about the histories of the East and West Antarctic Ice Sheets and related temperature change in the circum-Antarctic seas. In addition to the recent successes highlighting the value of ice-proximal records, further scientific drilling and climate proxy development are required to improve current understanding of Antarctica's complex paleoenvironmental history (Shevenell and Bohaty, 2012).

This paper provides the review of the work carried out by Indian researchers to understand the paleoclimate history of the Southern Ocean (Indian and Atlantic sector) as well as the applicability of the various proxies in paleoclimatic reconstructions.

Diatoms for Deciphering the Southern Ocean paleoclimate

Diatoms are unicellular algae with a siliceous skeleton called frustules which are found in almost every aquatic environment including fresh and marine waters. Their usefulness in the Southern Ocean paleoceanographic studies is because of their extreme sensitivity to changes in salinity, temperature, nutrient supply and other environmental factors. Diatoms contribute more than 70% of the primary production in the Southern Ocean and play a major role in global silica and carbon cycling. Diatom cell wall is composed of hydrated silica [$Si(H_2O)_n$], and are well preserved in the sediments.

In polar oceans, 1-10% of the diatoms present in surface waters reach the ocean bed (Ragueneau *et al*., 2000). This percentage increases in shallow coastal areas compared to abyssal open ocean zones. Abiotic factors such as lateral transport and dissolution in the water column and at the water-sediment interface and biotic factors such as sedimentation type (single particles vs aggregates or fecal pellets, mass sedimentation events) are the main processes which determine the diatom flux to the sea-floor. These processes support the preservation of highly silicified diatoms as well as alter the geochemical signals embedded into the diatoms. It has however been shown that the residual diatom assemblages in the sediment can still indicate the prevalent surface conditions in different oceanic regions (eg. North Pacific,Sancetta 1992;Southern Ocean, Armand *et al*., 2005; Crosta *et al*., 2005; Romero *et al*., 2005). Diatoms can therefore be used as proxy to infer past oceanographic and climatic changes.

Mohan *et al*., (2006) studied the latitudinal variation of diatom in surface sediments of Southern Ocean (Indian sector) to understand its relationship with the changing nutrient availability and/or supply, and its utility in palaeoceanographic reconstruction. The study indicate that the spatial distribution of diatoms in surface sediments is well correlated with the frontal changes (SST and salinity) and related nutrient availability in the water column (Mohan *et al*., 2006). Similarly, the variation of Antarctic summer and winter sea-ice extent was well recorded in diatom abundance from the surface sediments in the Enderby Basin of Southern Ocean, thereby ascertaining the robustness of diatoms as a proxy for paleo sea-ice estimation (Mohan *et al*., 2011). Understanding the latitudinal variation of Antarctic sea-ice necessitates detailed information on the diatom assemblages preserved in the surface sediments from the sea-ice regime. In this context, a new species (*Trigonium curvatus*) of a diatom *Trigonium arcticum* from the Prydz Bay, East Antarctica has been described which could be possibly used as a sea-ice proxy for paleo sea-ice reconstruction (Nair *et al*., 2015).

Diatoms have been studied in consideration with past climate reconstruction and oceanographic settings from Southern Ocean.One such study by Shukla *et al*., (2013) involves the morphometric analysis of abundant diatom species (*F. kerguelensis*) in the SO (Fig. 1). As per the study, variations in circumpolar upwelling along with nutrient inputs from Antarctic Peninsula have exerted a strong control on *F. kerguelensis* valve size in the Atlantic and Indian sector of the SO. Size records from the Atlantic sector demonstrate larger valve sizes of *F. kerguelensis* during the Last Glacial Period, which is possibly related to greater iron availability through wider sea-ice coverage and higher eolian dust input (Shukla *et al*., 2013). But the scenario is different in the Indian sector

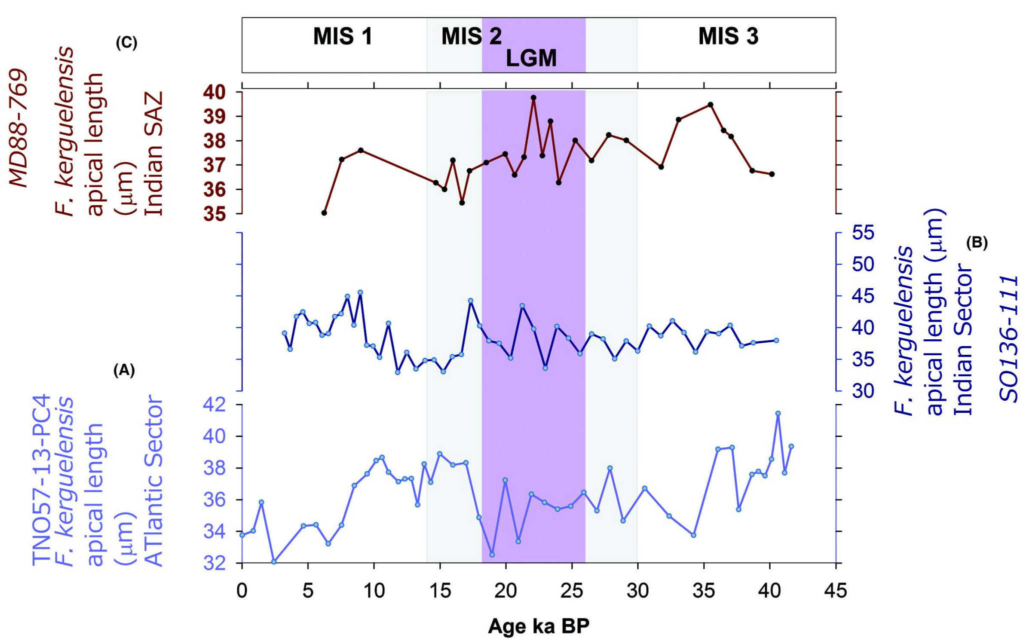

Fig. 1: Size variation of *F. kerguelensis* in the Indian sector vs Atlantic sector

of the SO where larger valve sizes of *F. kerguelensis* have been recorded in the Holocene sediments (Fig. 1). The Indian sector being far away from these iron sources as compared to the Atlantic could be the reason for the probably resultant lower diatom sizes during the last deglaciation. It was hypothesized that high nutrient input in the APF from the Antarctic Peninsula during the last deglaciation had a more important control on *F. kerguelensis* valve size and diatom physiology than the inferred increase in circum-polar upwelling (Shukla *et al*., 2013). During the Holocene period, due to iron limitation smaller *F. kerguelensis* valve size was found in the Atlantic APF and Indian SAF sediment cores, whereas the occurrence of larger *F. kerguelensis* size in the Indian APF core suggests high nutrient availability, especially iron through circum-polar upwelling (Shukla *et al*., 2013).

A recent paleoclimatic study using Southern Ocean (SO) sediment core (diatom records) from the Indian sector suggest a glacial shift in the Antarctic winter sea-ice limit and Polar Front, respectively up to the modern day Polar Frontal Zone (Nair *et al*., 2015). This study has revealed that glacial periods north of the Polar Front were characterised by high diatom productivity and larger *Fragilariopsis kerguelensis* (pennate diatom) and *Thalassiosira lentiginosa* (centric diatom) sizes (Fig. 2). *F. kerguelensis* and *T. lentiginosa* are the dominant components of the diatom assemblages, and most likely the main silica carrier in the iron-limited Southern Ocean. The larger and heavily silicified diatoms such as *F. kerguelensis* and *T. lentiginosa* may have effectively contributed to transporting biogenic silica and organic carbon to the sea bed during the last 42 ka BP. The northward shift in Antarctic winter sea-ice limit during the glacial period (Nair *et al*., 2015) is additionally supported by similar latitudinal changes in APF during the Last Glacial Maximum (LGM) deciphered using silicoflagellate and diatom assemblages (Shetye *et al*., 2013).

Foraminifera as Tracers of Past Oceanic Environments

Paleoceanography has always been closely linked with the study of planktic foraminifera. The high rate of production and excellent preservation of foraminiferal shells in deep sea sediments have produced probably the finest fossil record on earth, providing unparalleled archives of morphological

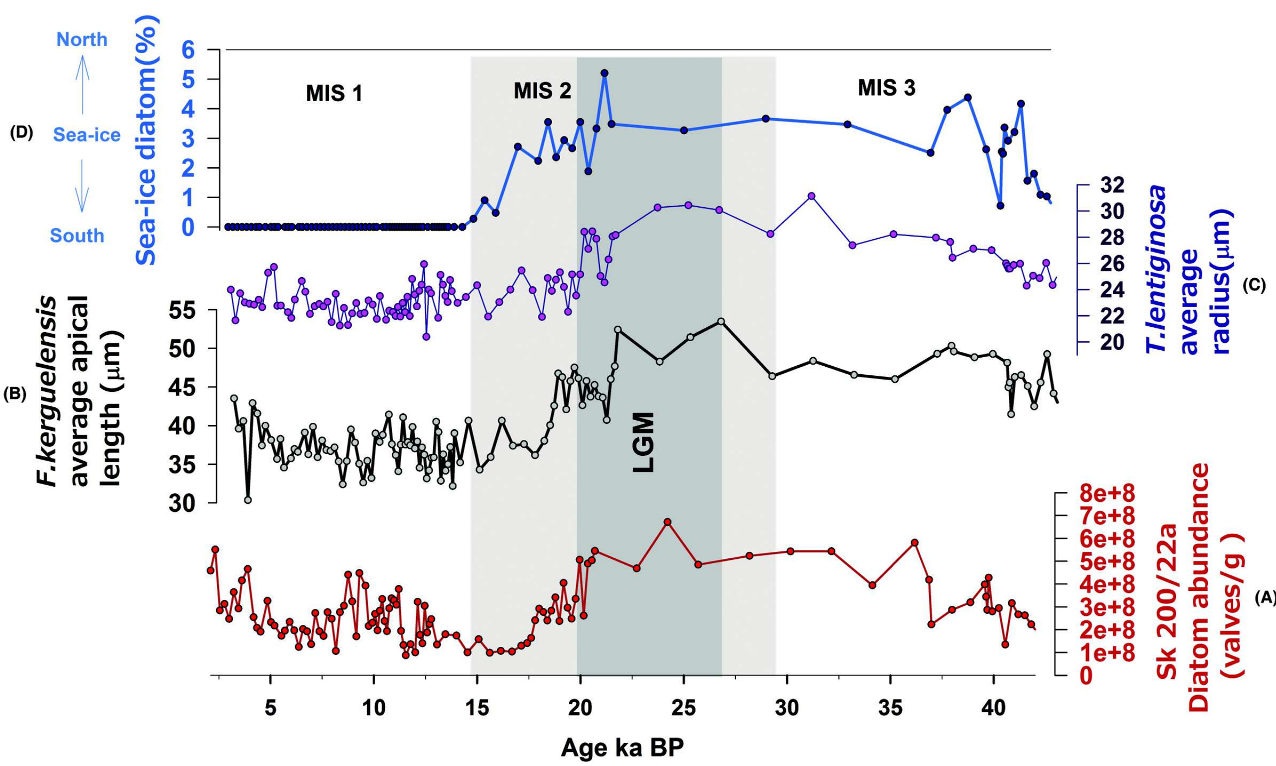

Fig. 2: Abundance and size variation of *F. kerguelensis* vs *T. lentiginosa* in the SO

changes, faunal variations, and habitat characteristics. Planktonic foraminifera are the most commonly used paleoceanographic proxies, be it through the properties of their fossil assemblages or as a substrate for extraction of geochemical signals. The steady flux of foraminiferal shells in the ocean is responsible for the deposition of a large portion of deep sea biogenic carbonate.

The isotopic composition of foraminifera has been used extensively to infer paleoclimatic and paleoceanographic variations (Sen Gupta, 1991; Waelbroeck *et al*., 2005). The seawater temperature for water depths ranging from 0-200 m in the southwestern Indian Ocean was estimated from *G. bulloides* δ^{18}O by using various paleotemperature equations (Saraswat and Khare, 2010). This study showed that the estimated seawater temperature matches well with the sea water temperature during the austral spring season suggesting that *G. bulloides* was abundant at that time (austral spring). The findings will help in paleoclimatic reconstruction studies based on characteristics of *G. bulloides*. Similarly, Khare and Chaturvedi (2012) studied the isotopic variation (δ^{18}O and δ^{13}C) of *Globigerina bulloides* from the surface sedimentsof SO to understand the various frontal systems operating in the Indian sector.

Isotopic studies of *Globigerina bulloides* carried out from the water samples across the Southern Ocean between 10ºN and 60ºS reveals an interesting pattern of increase in the d^{13}C value of the surface water DIC between 35ºS and ~60ºS, with a peak at ~42ºS, matching well with the variation of satellite obtained chlorophyll concentration. Such correlated distribution pattern (of d^{13}C and chlorophyll) has been suggested to have been caused by increased organic matter production and associated removal (of δ^{13}C) (Prasanna *et al*., 2016). Based on the similarities between the estimated and measured δ^{18}O values, the study concludes that the calcification depth of *G. bulloides* is confined to a depth of ~75-200 m between 10ºN and 40ºS latitude (Prasanna *et al*., 2016).

Studies based on the stable isotopic composition of planktic foraminiferal samples of plankton net and core top sediments collected during the first Indian expedition to the Southern Ocean (2004) provide vital insight into the foraminiferal preservation characteristics in the Indian sector of the Southern Ocean. Comparison between the measured and the predicted δ^{18}O values shows that the planktic foraminifera secrete their shells in isotopic equilibrium with seawater (Tiwari *et al*., 2011). Essentially the isotopic content of planktic foraminifera, from plankton net as well as core top sediment samples, is governed by the frontal structure of the Southern Ocean. Foraminifera from sediment samples faithfully record the frontal structures as revealed by the inter-comparison of the plankton net and sediment samples; hence it was suggested that the past fluctuations in the extent of various fronts can be reconstructed using down-core foraminiferal isotopic content in this region (Tiwari *et al*., 2011). It also possible to identify discrete water masses from the SO based on the oxygen isotope and sea-surface salinity and determine the paleosalinity from carbonate fossils from the sediment based on the salinity-oxygen isotope relation (Tiwari *et al*., 2013).

Several aspects of planktic foraminifera (morphology, assemblages, isotopes, elemental composition etc.) are used extensively to understand past oceanography. A study from the Indian sector of SO using planktic foraminifera assemblages from the surface sediment and the overlying water column revealed the dominance of symbiotic foraminiferal species in the subtropical region and non-symbiotic species in sub-Antarctic and polar frontal region (Mohan *et al*., 2015). An indication of secondary calcification in foraminifera preserved in the sediments was observed on the basis of higher shell weight of the planktic foraminifera from the sediments and the presence of heavier isotopes in their tests as compared to specimens from water column (Mohan *et al*., 2015).

Multi Proxy Studies on Late Quaternary Sediments from Southern Ocean

The magnetic parameters (magnetic susceptibility), in combination with other paleoenvironmental proxies such as ice rafted debris (IRD), calcium carbonate content and oxygen isotope records, are useful palaeoceanographic indicators in marine sedimentary records (Bloemendal *et al*., 1988, 1992). The lower and uniform values in magnetic concentration in the sediments of the sub-Antarctic region of the Indian sector of Southern Ocean during interglacial period have been used as a signature for reduced terrigenous input from the nearby volcanic islands (Manoj *et al*., 2012). In contrast, the periods of increased concentration of magnetic minerals in the Southern Ocean sediments have been attributed to enhanced terrigenous input and ice-rafting events. A comparison of the magnetic record with the *N. pachyderma* $\delta^{18}O$, IRD and carbonate records from a marine sediment core from Indian sector of SO reveals that the terrigenous influx, ice rafting, sea-surface temperature and carbonate productivity at the core site are apparently interrelated (Manoj *et al*., 2012). Changes in terrigenous sediment source and transport mechanism have also been investigated using magnetic susceptibility and sedimentological records (Thamban *et al*., 2005).

The records of IRD in the Southern Ocean sediments offer potential as proxy indicators to investigate the dynamic behaviour of Antarctic ice sheets and Antarctic climate (Hayes *et al*., 1975; Grobe and Mackensen 1992; Zachos *et al*., 1992). The concentration of IRD in the sediment core SK200/27 retrieved from Indian sector of SO (south of APF) was nearly twice that in the SK200/22a (north of APF, Fig. 3). Moreover, IRD was more abundant at the LGM in SK200/27 with its peak abundance preceding by nearly two millennia than the abundance in the core SK200/22a (Manoj *et al*., 2013). It seems that an intensification of Antarctic glaciation combined with a northward migration of the Polar Front during LGM promoted high IRD flux at SK200/27 and subsequent deglacial warming could have influenced the IRD supply at SK200/22a (Manoj *et al*., 2013).

To understand the functioning of the Southern Ocean biological pump in the past, it is crucial to reconstruct the paleoproductivity of the Southern Ocean. A high resolution multi-proxy (calcium carbonate, opal, total organic carbon, biogenic barium and planktonic carbon isotope ratios) approach would be ideal for reconstructing the Southern Ocean paleoproductivity. The palaeoproductivity studies carried out by Sruthi *et al*. (2012) and Manoj and Thamban, (2015) on a core from the Indian sector of SO reveal an inverse relationship between the calcium carbonate concentration and opal productivity, indicating the influence of shifting nutrient regimes in the Southern Ocean. To the north of APF, reduced calcite productivity during glacial period suggests an equatorial migration of the frontal regimes. In contrast to the south of APF, increased opal productivity during the interglacial period indicates a southward migration of APF (Manoj and Thamban, 2015). North of APF (Indian sector) was characterised by reduced carbonate productivity as compared to Holocene and the last deglaciation, as indicated by barium concentrations (Sruthi *et al*., 2012). The study also suggests enhanced sub-oxic conditions during LGM and oxygenated condition during the deglaciation and late Holocene. The suboxic conditions during LGM could be attributed to reduced ventilation resulting from a reduction in strength of the global thermohaline circulation at this time interval (Sruthi *et al*., 2012).

Plio-Pleistocene East Antarctic ice sheet dynamics was deciphered using clay mineralogy and carbon content analysis from a marine sediment core (IODP site U1359) off the eastern margin of the Wilkes Land sector (Verma *et al*., 2014). The distribution of clay minerals in the core could be a result of the interplay between illite and chlorite from local source, i.e. cratonic east Antarctic shield and smectite and kaolinite from easternmost sources (Verma *et al*., 2014). Poor crystallinity of illite corroborates the ice retreat condition. The ice retreat

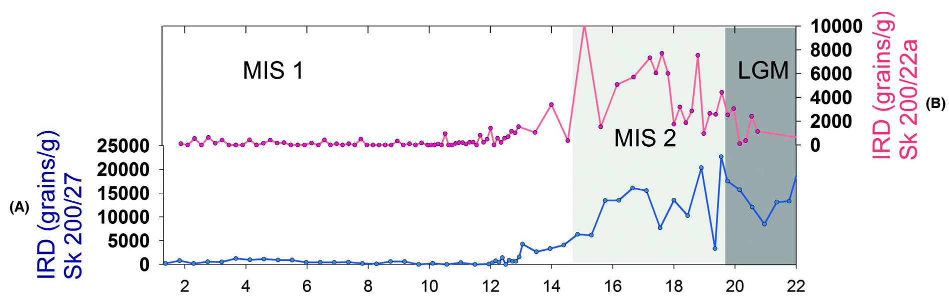

Fig. 3: IRD abandance of sediment core SK200/27 vs SK200/22a in the India sector of SO

condition as deciphered during 5.5-5.8 and 4.5 Ma coincides with the records from Antarctic Peninsula and Prydz bay suggesting continent-wide warming. This study suggests that in the eastern sector of Wilkes Land margin, warming started during late Miocene, i.e., during 6.8-6.2 Ma, much earlier than the other part of east Antarctica (Verma *et al*., 2014).

Scope for Future Research

Most of the Southern Ocean is a high-nutrient, low-chlorophyll (HNLC) area. There are exceptions to this situation downstream of some of the islands, where iron from the islands or surrounding shallow plateau fertilizes the mixed layer and causes a diatom bloom in spring and summer and therefore greater opal fluxes (Blain *et al*., 2007). The main locations where this occurs are downstream of the Crozet and Kerguelen Islands in the Indian sector of Southern Ocean. The oceanic waters around these volcanic islands could have been influenced by changes in terrestrial input during glacial-interglacial periods as a result of changing intensity of ACC (Manoj *et al*., 2012) and sea-level fluctuations, thus adding to the complexities of the oceanic processes. The aim in the future should be to look into such complex regions in order to unravel the local/regional influence from the global changes as lengthily studied in the Atlantic sector of the SO (Anderson *et al*., 2009; Martinez-Garcia *et al*., 2009; Jaccard *et al*., 2013). This will provide some clues on how certain regions of Southern Ocean acted as a sink or a source of atmospheric CO_2 during millennial events of the last glacial-interglacial periods. In addition, improved understanding about the SST and sea-ice variability in the Southern Ocean and northern North Atlantic during the glacial-interglacial timescale is imperative to assess the existence of teleconnections between the two hemispheres. Quantification of the past climate change in place of the earlier qualitative description is the evolving trend in the paleoceanographic research. Quantitative values in terms of sea surface temperature, salinity, sea ice, etc. are also vital for model validations. Such quantitative estimates coupled with accurate chronologies would help to better understand teleconnections between different components of the climate system.

Conclusions

The utility of diatoms, foraminifers, carbonate content, IRD etc. in the sediments has been known to exist since the last century but only in the last few decades the paleoceanographic and palaeoclimatologic studies are fairly well established. This article describes the applicability of different proxies (microfossils, magnetics, sedimentological and geochemical) in Southern Ocean paleoceanography studies. There are still few gaps in our knowledge of the robustness of different proxies used in providing quantitative and qualitative insight into past climatic conditions. From such a point of view, it is clear that none of the proxies can be universal and the simultaneous use of several proxies is necessary for a comprehensive perspective on the past ocean.

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