Effect of varying frontal systems on stable oxygen and carbon isotopic compositions of modern planktic foraminifera of Southern Ocean

Manish Tiwari[1,]*, Rahul Mohan[1], Thamban Meloth[1], Sushant S. Naik[1,2] and M. Sudhakar[1,3]

[1]National Centre for Antarctic and Ocean Research, Vasco-da-Gama, Goa 403 804, India
[2]Present address: National Institute of Oceanography, Dona Paula, Goa 403 004, India
[3]Present address: Ministry of Earth Sciences, Mahasagar Bhavan, CGO Complex, New Delhi 110 003, India

Studies have been carried out in the Atlantic and Pacific sectors of the Southern Ocean regarding the movement of its fronts (water-masses boundaries) with changing climate and other oceanic parameters. But the Indian sector of the Southern Ocean has received little attention. To fill in this lacuna, during the first Indian expedition to Southern Ocean in 2004, plankton net samples, sediment cores and other physical oceanographic parameters were collected. Here, we present the isotopic results obtained from planktic foraminifera from the plankton net samples and surface sediments. We find that, in this region too, planktic foraminifera secrete their shells in isotopic equilibrium with seawater and the planktic foraminifera from the core top sediments yield values akin to that obtained from plankton net samples. It implies that planktic foraminifera preserved in sediments record overlying seawater signatures in this sector. Thus, down-core foraminiferal isotopic data from the Indian sector of the Southern Ocean can be used as a proxy for reconstructing the temporal variations of different water masses.

Keywords: Carbon isotopes, foraminifera, oxygen isotopes, Southern Ocean.

PLANKTIC foraminifera thrive in various environments of the upper water column and are sensitive to changes occurring in the temperature, salinity, nutrients, food availability, mixed layer depth, etc.[1,2]. Southern Ocean, which plays an important role in governing the earth's climate, is unique in its water mass distribution that creates distinct fronts. Along these fronts, the physical properties of seawater (e.g. temperature, salinity, etc.) change rapidly resulting in water masses with entirely different characteristics[3]. Attempts have been made earlier to detect seasonal patterns in the frontal water mass structures using isotopic analysis of foraminifera from sediment trap samples in the Pacific sector of the Southern Ocean[4,5]. Thus, down-core variations in the isotopic content of the planktic foraminifera in the sediments of the Indian sector of the Southern Ocean would be an ideal palaeoceanographic tool to delineate the temporal pattern of frontal boundary changes. But before that, we need to establish whether foraminifera preserved in the sediments in this sector of the Southern Ocean faithfully record the overlying seawater characteristics. The present study on the plankton net and surface sediment samples from the Indian sector of the Southern Ocean (where only a few studies have been done till date, e.g. on the terrigenous input[6] and on diatoms from surface sediments[7]) was carried out to evaluate the spatial variability in the isotopic content of foraminifera with changing frontal regimes. Besides, it was also intended to collect preliminary information on the various abiotic parameters such as temperature, salinity, etc., which would probably illuminate the factors governing the planktic foraminiferal isotopic variability in the Indian sector of the Southern Ocean. Thus, this study is an attempt to verify whether the isotopic content of planktic core top foraminifera truly represents the water column planktic foraminiferal isotopic composition by comparing the data acquired from plankton nets with that from the surface sediments.

Oceanographic setup

The hydrography of the Southern Ocean is affected by different frontal regimes as a consequence of different water masses prevailing there. The largest current in the Southern Ocean is the eastward flowing Antarctic Circumpolar Current (ACC) both in terms of the volume and speed[8], and its association with the frontal jets[9] (Figure 1). In view of limitation of the availability of hydrographic data from the Southern Ocean, conductivity, temperature and depth (CTD) data was collected, which helped us map the variations in temperature and salinity for the

*For correspondence. (e-mail: manish@ncaor.org)

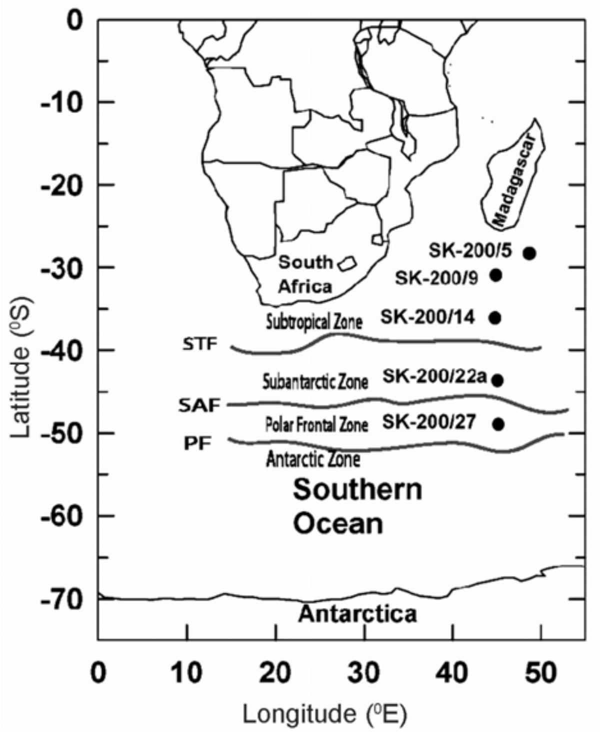

Figure 1. Location map of the core top samples and the frontal structure of the Southern Ocean (STF, SAF and PF denote Subtropical Front, Subantarctic Front and Polar Front respectively). The plankton net samples were collected very near to the core top.

austral summer (Figure 2) and also recognize the frontal boundaries as existed during our observation period during January–March 2004 (Table 1). The four major fronts that were encountered included the Subtropical Front (STF), the Subantarctic Front (SAF) and the Polar Front (PF) in addition to the Agulhas Return Front (ARF)[10]. The temperature plot shows a well-defined surface mixed layer, especially in the tropical region, which is about 80 m thick. But the most prominent feature observed in both the temperature and salinity plots is the clear demarcation at ~42°S, which is the boundary between the Subtropical and Subantarctic zone, i.e. STF. North of this boundary the temperature ranges from 26°C to 15°C, but south of it temperature drops rapidly to 10°C and falls down to 2°C at 55°S latitude. Salinity also exhibits a similar trend with higher salinity (35.8–35 PSU) waters north of STF. Salinity declines considerably beyond STF due to fresh water influx from Antarctica.

Materials and methods

Samples were collected during the Pilot Expedition to Southern Ocean (PESO) onboard *ORV Sagar Kanya* during its 200th expedition and its first to the Southern Ocean. Surface sediments along with plankton net samples were collected along the meridional transect from 28°S to 56°S lat. and 45°E to 48°E long., south of Madagascar (see Figure 2). Plankton samples were collected by means of 0–200 m vertical plankton net tows (net mesh > 150 μm) at nearly the same place where the surface sediments were collected. Sampling depths typically covered 0–5 and 0–200 m. Collected plankton samples were preserved onboard in 5% buffered formaldehyde. Sea-surface temperature (SST) was measured with the help of bucket thermometer and CTD values were also measured. The five plankton net samples collected were numbered as pn# 4, 9, 14, 21 and 26 (Table 1). For isotopic analysis, samples from 0 to 5 m plankton haul were used as they are likely to record sea surface properties.

Core top samples of five sediment cores (SK-200/5, 9, 14, 22a and 27) collected from different water masses were analysed (Figure 2, Table 2). Both the plankton and sediment samples were processed and analysed at the National Centre for Antarctic and Ocean Research (NCAOR), Goa. Sediment samples for analysis were weighed and dried overnight at 45°C, whereas plankton net samples were filtered, dried and individual planktic foraminifera picked. Dried sediment samples were then soaked in water and treated with sodium hexametaphosphate (calgon powder) and hydrogen peroxide (H_2O_2) to dissociate the material and oxidize the organic matter present in the sample respectively. The treated sediment samples were cleaned carefully with a water jet and sieved over 63 μm sieve. Fraction of sample greater than 63 μm in size was dried and transferred to plastic vials. For isotopic analysis, clean samples size range from 250 to 450 μm were chosen and analysed using the GV-Isoprime SIRMS at NCAOR. The reproducibility for both oxygen (δ^{18}O) and carbon (δ^{13}C) is better than 0.1‰ (1σ standard deviation), which is based on repeat measurement of a laboratory standard (Z-Carrara). The isotopic values are reported with respect to V-PDB.

Results and discussion

Samples from both the plankton nets as well as core top sediments were analysed for their isotopic compositions (δ^{18}O and δ^{13}C of planktic foraminifera) to compare values of the surface sediment and the plankton net samples.

Spatial isotopic variability

Figure 3 *a* and *b* show the oxygen and carbon isotopic composition (δ^{18}O and δ^{13}C) of two planktic foraminiferal species, viz. *Globigerinoides ruber* and *Neogloboquadrina pachyderma* (sinistral form) in samples from plankton nets, whereas Figure 3 *c* and *d* show the δ^{18}O and δ^{13}C values of three planktic foraminiferal species, viz. *Globigerinoides ruber*, *N. pachyderma* (sinistral form) and *Globigerina bulloides* in samples from surface sediments. In the Southern Ocean sediments, the amount of a particular species of planktic foraminifera is not

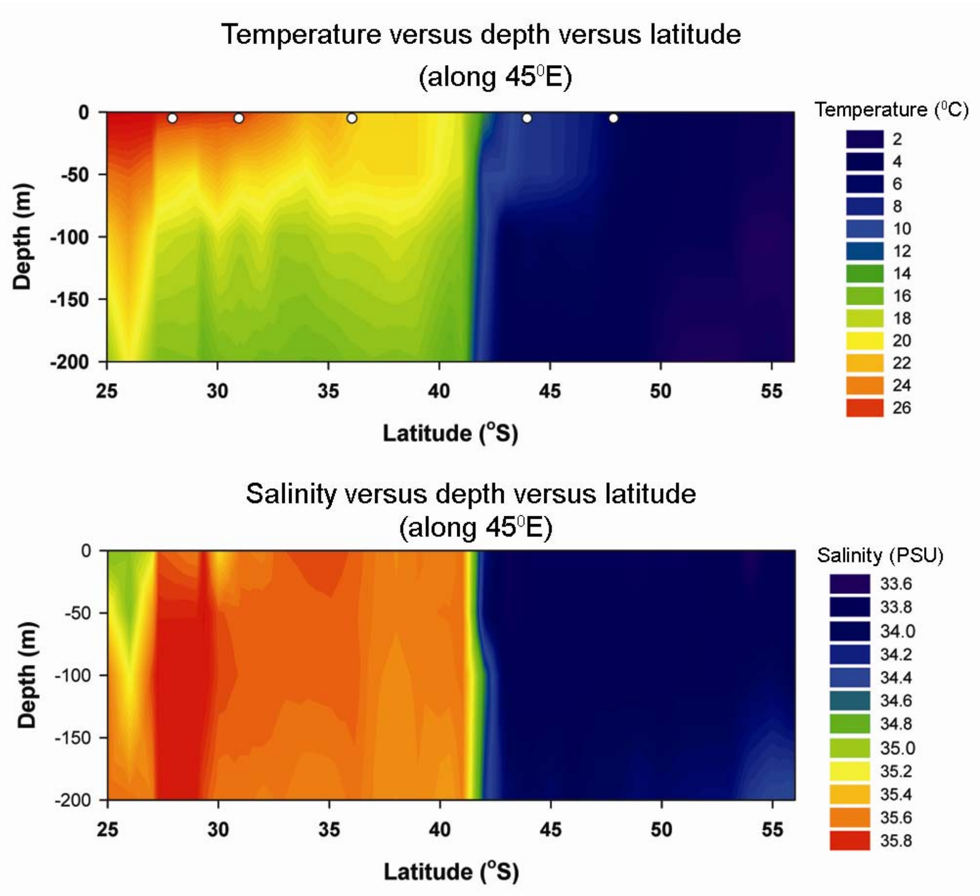

Figure 2. Temperature and salinity profiles along the 45°E. White circles show the location where plankton nets have been collected.

Table 1. Plankton net (>150 μm) samples

Station no.	Depth (m)	Date of collection	Time of collection	Lat. (°S)	Long. (°E)	SST (°C)	Salinity (PSU)
pn# 4	5–0 and 200–0	27 January 2004	9.30 pm	27°59′	49°59′	26.5	35.59
pn# 9	5–0 and 200–0	30 January 2004	5.55 am	31°	44°59′	25.5	35.61
pn# 14	5–0 and 200–0	03 February 2004	9.30 am	36°07′	45°	21.6	35.67
pn# 21	5–0 and 200–0	08 February 2004	5.00 pm	44°	45°	8.6	33.77
pn# 26	5–0 and 200–0	11 February 2004	6.30 am	47°57′	45°60′	5.2	33.77

pn, plankton net.

Table 2. Sediment core locations

Sediment location	Core type	Depth (m)	Location		Oceanic regime
			Latitude (°S)	Longitude (°E)	
SK-200/5	Piston	2296	28°19′	48°44′	Tropical
SK-200/9	Gravity	2256	30°56′	44°52′	Tropical
SK-200/14	Piston	2730	36°07′	44°50′	Subtropical Agulhas Return Front
SK-200/22a	Piston	2720	43°42′	45°04′	Subantarctic
SK-200/27	Gravity	4389	49°00′	45°13′	Polar Front

sufficient in all samples from different latitudes for isotopic analysis. That is why different species were chosen depending on their amount and this is regardless of the depth–habitat relationship.

Plankton net samples

The major factors affecting the oxygen isotopic composition of the planktic foraminifera are temperature as well

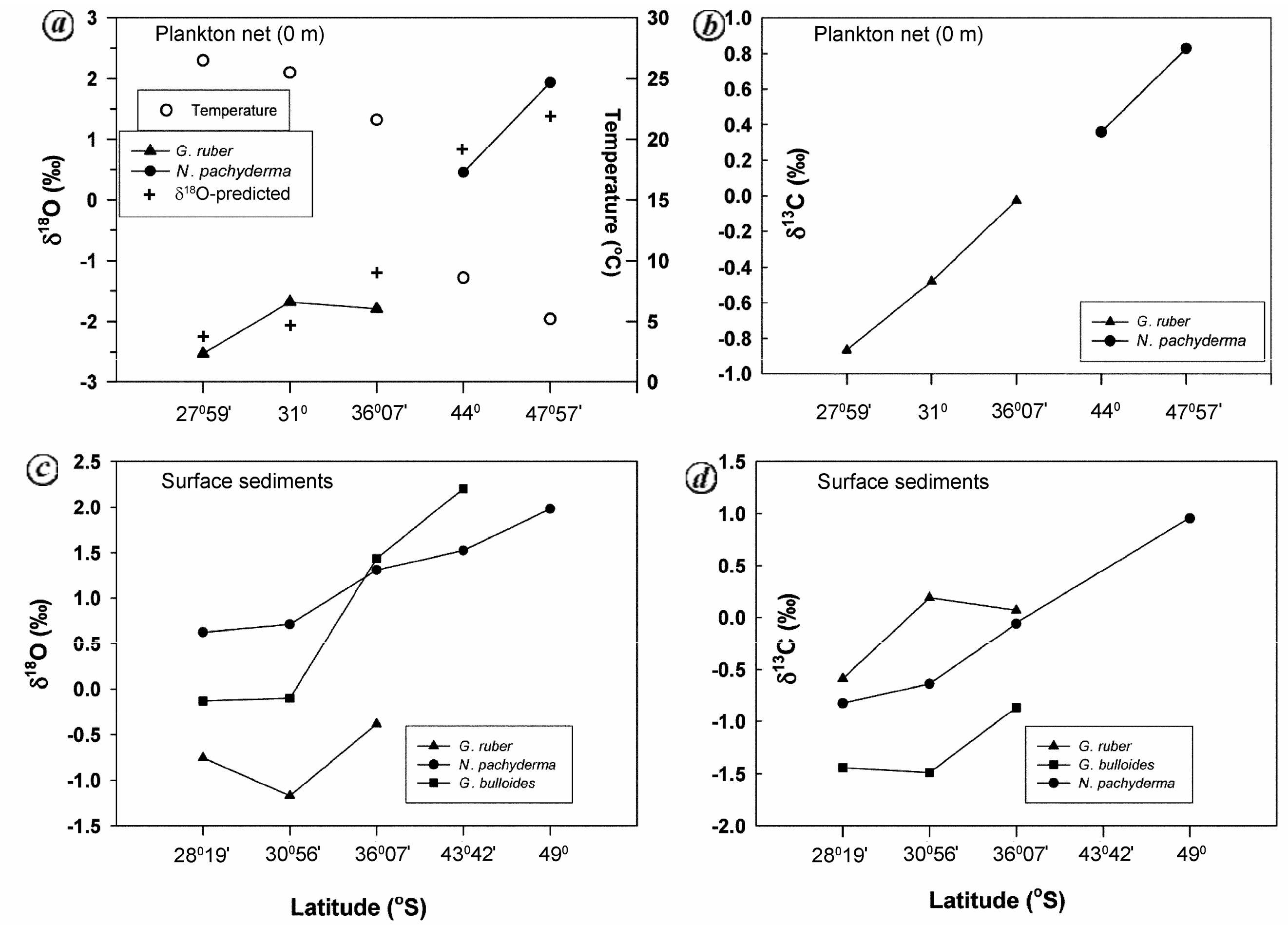

Figure 3. Oxygen (δ^{18}O) and carbon (δ^{13}C) isotopic compositions of foraminifera obtained from plankton nets (***a*** and ***b***) and surface sediments (***c*** and ***b***). Temperature is shown on the right of the figure ***a***; + in the figure ***a*** depict predicted-$\delta^{18}O_{calcite}$ (see text for details).

as the salinity of the seawater in which it precipitates its shell[11]. With decreasing temperature the δ^{18}O values increases (approximately 0.25‰ increase in carbonate δ^{18}O occurs for every 1°C temperature decrease[12]) whereas with decreasing salinity δ^{18}O values also decrease (e.g. in the Southern Ocean, $\delta^{18}O_{seawater}$ changes by 0.66‰ for every per mil change in salinity[13]). It is evident from Figure 3*a* that the δ^{18}O values of the planktic foraminifera from the plankton nets increases with the decreasing SST as we move southwards (SSTs were measured at the same place from where the net samples were collected). In the tropical and subtropical regions (up to ~40°S), the *G. ruber*-δ^{18}O values exhibit a range of –2.6‰ to –1.6‰ with SST falling from 26°C to 21°C. We observe a sharp increase in δ^{18}O values and a major decline in SSTs (from 21.6°C to 8.6°C) in the subantarctic region (~45°S). The species measured is *N. pachyderma* (as *G. ruber* declines drastically beyond the subtropical regions) that dwells in deeper (colder) waters (~130 m)[14] and hence it is isotopically heavier than *G. ruber*. But still the isotopic increase is considerable (the δ^{18}O value increases by ~2‰), which indicates major change in water mass. At the depth where *N. pachyderma* dwells, the salinity increases by 0.5‰ as compared to surface value[10] that will have negligible effect on the foraminiferal isotopic composition (0.5‰ change in salinity will account for only ~0.33‰ change in δ^{18}O value). This indicates that temperature variations with changing water masses mainly govern the isotopic fluctuations recorded in the foraminifera from this region. Further, southwards in the polar zone (~47°S) and the Antarctic zone (~54°S), SSTs decline further and the δ^{18}O of *N. pachyderma* attains a maximum value of 1.93‰.

The carbon isotopic values are governed by the isotopic composition of the dissolved bicarbonate (HCO_3^-), which in turn is modulated by the productivity and mixing with the isotopically depleted waters in the upwelling regions[15]. The δ^{13}C values of the foraminiferal shells from the plankton net show a uniform increasing trend southwards. The value increases from –0.86‰ in tropical region (~27°S) to 0.82‰ in the polar region with a total range of 1.6‰, which is a significant change. There is no signal of isotopically depleted upwelled water influx at the sampling location, as we do not find decline in δ^{13}C values. There are no upwelling zones in the area under study[10,16]. In the Southern Ocean, major region of upwelling is at the 'Antarctic Divergence', which lies at ~65°S (refs 17 and 18). This indicates that the productivity governs the foraminiferal δ^{13}C values and increases polewards. This poleward increase could possibly result because of the melt water from Antarctica, which might supply nutrients that would enhance the productivity. Thus, δ^{13}C variability in this region appears to be governed by the productivity variations with changing water masses. It signifies that the isotopic content of foraminifera dwelling in the seawater is governed by the frontal structure of the Southern Ocean.

Predicted-δ^{18}O of calcite

We also theoretically predict the δ^{18}O of calcite (predicted-$\delta^{18}O_{calcite}$) for the foraminiferal shells from plankton nets for which we already possess the measured δ^{18}O values (measured-$\delta^{18}O_{calcite}$; Figure 3 *a*), and the required SST and salinity data (measured at the sampling site). This will show the extent of deviation exhibited by the precipitated (measured) $\delta^{18}O_{calcite}$ values from the theoretically predicted-$\delta^{18}O_{calcite}$ values, which will help us in better interpreting the isotopic data. Many earlier studies have shown that the planktic foraminifera calcify in isotopic equilibrium with ambient water, but most of them are from Atlantic, Indian or Pacific Ocean[19–23] and few from the Southern Ocean[24] where rapid spatial variations in physical properties of water such as temperature and salinity occur (the Indian sector of the Southern Ocean has received even lesser attention). We use the term 'predicted' instead of 'equilibrium' because the δ^{18}O value of the carbonate species changes with changing pH, i.e. several equilibria for $\delta^{18}O_{calcite}$ might exist depending upon pH[5,25]. The equations used for calculating the predicted-$\delta^{18}O_{calcite}$ values are:

1. For comparison with *G. ruber*, the equation developed by Bemis *et al.*[26] for *Globigerina bulloides* (another planktic species living in similar water depths to *G. ruber*) with a temperature range of 9–24°C has been used:

$$T_{water}\ (°C) = 13.4 - 4.48\ (\delta^{18}O_{calcite} - \delta^{18}O_{water}).$$

2. For comparison with *N. pachyderma*, the equation developed by von Langen *et al.*[27] for *N. pachyderma* with a temperature range from 9°C to 19°C has been used:

$$T_{water}\ (°C) = 17.3 - 6.07\ (\delta^{18}O_{calcite} - \delta^{18}O_{water}).$$

The $\delta^{18}O_{water}$ values have been calculated using the following relationship between $\delta^{18}O_{water}$ and salinity, proposed by Duplessy[13] for Southern Ocean:

$$\delta^{18}O_{water} = 0.66\ (\text{salinity}) - 22.6$$

A correction factor of –0.27‰ has been applied for converting $\delta^{18}O_{water}$ values from V-SMOW to V-PDB[26]. Usually, the temperature : δ^{18}O relationships have been expressed as quadratic equations of the form $T(°C) = a + b(\delta_c - \delta_w) + c(\delta_c - \delta_w)$. But as discussed by Bemis *et al.*[28], linear equations provide an equally good fit and yield temperatures within ±0.2°C of the published quadratic equations, which correspond to a precision of ±0.5‰ in $\delta^{18}O_{calcite}$ measurement.

A comparative analysis of measured-$\delta^{18}O_{calcite}$ and predicted-$\delta^{18}O_{calcite}$ reveals that predicted values show similar trend as exhibited by the measured shell values. Also, the predicted values deviate at most by 0.5‰ from the measured values in both directions, i.e. in some cases they exhibit more positive values and in others, more negative values. This 0.5‰ deviation can be explained if we take into account various uncertainties involved in the measurement and prediction of the $\delta^{18}O_{calcite}$ values. The 1σ (standard deviation) precision of planktic foraminiferal shell measurement is ±0.1‰, which rises to an error of ±0.2‰ in the measured-$\delta^{18}O_{calcite}$ if we take 2σ precision into account. Many assumptions are made in calculating the predicted-$\delta^{18}O_{calcite}$ values. For example, we have not measured $\delta^{18}O_{water}$ values but have estimated it using the δ^{18}O–salinity relationship with inherent errors. Similarly, the paleo-temperature equations used to calculate $\delta^{18}O_{calcite}$ also possess inherent uncertainties. All these together can account for the difference observed between the measured-$\delta^{18}O_{calcite}$ and predicted-$\delta^{18}O_{calcite}$. It appears from the above discussion that planktic foraminifers living in the water column (as obtained from the plankton nets) in the Indian sector of the Southern Ocean precipitate their shells in the isotopic equilibrium with the surrounding waters.

Surface sediment samples

The surface sediments were collected in close proximity to the plankton net sampling locations so as to facilitate the comparison between them. Three planktic foraminiferal species, viz. *G. ruber*, *N. pachyderma* and *Globigerina bulloides* were analysed for oxygen and carbon isotopic composition in five surface sediment samples (Figure 3 *c* and *d*). The δ^{18}O values of all the three species exhibit lower values in the tropical region as compared to the Subantarctic zone and the Polar Frontal Zone. At 28°19′S lat., the δ^{18}O values of *G. ruber*, *G. bulloides* and *N. pachyderma* are –0.75‰, –0.13‰ and 0.63‰ respectively. *N. pachyderma* yields most positive δ^{18}O value as it is the deepest (coldest) water dwelling species, whereas *G. ruber* exhibits the lightest isotopic composition as it dwells in warmer surface waters. In comparison, the Polar Frontal Zone exhibits the heaviest isotopic composition (e.g. δ^{18}O value for *N. pachyderma* is 1.98‰ for the southernmost core top at 49°S latitude) with a sharp increase observed in the subtropical region in all the three species.

Similarly, the δ^{13}C values (Figure 3 *d*) of all the three species from the sediment core tops exhibit an overall increasing trend polewards. For example, δ^{13}C value of *N. pachyderma* increases from –0.82‰ at 28°19′S (tropical region) to 0.95‰ at 49°S (Polar Frontal zone). This variability in the isotopic content of the planktic foraminifera from the sediment samples with the changing water masses indicates that they faithfully preserve the overlying seawater isotopic signature.

Plankton net versus surface sediment samples

The plankton net samples and the surface sediment samples do not match exactly but show a similar trend, i.e. an increasing δ^{18}O and δ^{13}C values southwards. The δ^{18}O values of *G. ruber* in the northernmost plankton net and core top sediment samples are –2.5‰ and –0.7‰, respectively. At the next location (~30°S), the difference reduces to 0.5‰ with exact values being –1.6‰ and –1.1‰ for plankton net and core top sediment samples respectively. At ~36°S, we find values of –1.7‰ (plankton net) and –0.3‰ (core top sediments), i.e. a difference of ~0.4‰. Interestingly, at every location the plankton net values are lower than the sediment sample values. Similarly, for *N. pachyderma*, the δ^{18}O values are 0.4‰ (~44°S), 1.9‰ (~48°S) and 1.5‰ (~44°S), 1.98‰ (~49°S) for plankton nets and surface sediments, respectively. At ~49°S, the δ^{18}O values of plankton net and sediment samples match exactly (~1.9‰ in both the cases). But overall, in the case of *N. pachyderma* species as well, we find lower values for plankton net samples as compared to core top sediment samples.

Similarly, the trends exhibited by δ^{13}C values of plankton net as well as core top sediment samples are alike, i.e. increasing southwards. The northernmost location (~28°S) exhibits a *G. ruber*-δ^{13}C value of –0.86‰ (plankton net) and –0.58‰ (sediment sample), i.e. a difference of 0.3‰. For the samples at ~31°S, we find *G. ruber*-δ^{13}C value of –0.48‰ (plankton net) and 0.2‰ (sediment sample), i.e. plankton net samples are isotopically lighter. Further southwards at ~36°S and 48°S, the δ^{13}C values observed are –0.03‰ (*G. ruber*) and 0.8‰ (*N. pachyderma*) in plankton net samples and 0.07‰ (*G. ruber*) and 0.9‰ (*N. pachyderma*) in surface sediment samples, which are very similar.

A plausible reason for the difference observed between the core top sediments and plankton net samples can be that the former represent the average value whereas the latter reflect only the season-specific value. It is also corroborated by the fact that plankton net samples exhibit lighter isotopic values in each case. The plankton net samples were collected during the austral summer hence record a little warmer SST, which explains the lower δ^{18}O values as compared to surface sediment samples that produce an integrated record of both summer and winter SST. Furthermore, in the southernmost location, where the annual fluctuation in SST is minimal, we find matching isotopic values. Also, the δ^{13}C values exhibit lower values in the plankton net samples from the tropical–subtropical locations only (~28°S and 31°S). This implies that annual productivity fluctuation is much greater in these regions (Subtropical zone) as compared to more poleward locations (Subantarctic zone). In the Subantarctic zone, most of the productivity occurs during austral summer, which is then preserved in the sediments and hence data of plankton net samples collected from the Subantarctic zone during austral summer match very well with those of sediment samples representing integrated productivity.

Conclusion

Stable isotopic studies carried out on planktic foraminiferal samples of plankton net and core top sediments collected during the first Indian expedition to the Southern Ocean provide important insight into the foraminiferal preservation characteristics in the Indian sector of the Southern Ocean. The δ^{18}O value of planktic foraminifera is mainly governed by SST fluctuations: the samples become isotopically heavier polewards. Further, the planktic foraminifera appear to secrete their shells in isotopic equilibrium with seawater as exhibited by comparison between the measured and the predicted-δ^{18}O values. Importantly the isotopic content of planktic foraminifera, from plankton net as well as core top sediment samples, is controlled by the frontal structure of the Southern Ocean. Also, inter-comparison of the plankton net and sediment samples reveals that the latter preserve the signatures of seawater isotopic composition with fidelity. It signifies that foraminifera from sediment samples faithfully record the frontal structures, and in this region the past fluctuations in the extent of various fronts can be reconstructed using down-core foraminiferal isotopic content. The δ^{13}C values appear to be governed mostly by productivity fluctuations, which also increase poleward (both in the plankton net and sediment samples) due to influx of nutrients via melting ice.

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