Tracing the signature of various frontal systems in stable isotopes (oxygen and carbon) of the planktonic foraminiferal species *Globigerina bulloides* in the Southern Ocean (Indian Sector)

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Abstract

Twenty-five surficial sediment samples, collected on board *ORV Sagar Kanya* during her 199th and 200th cruises along a north-south transect between latitudes 9.69°N and 55.01°S, and longitudes 80°E and 40°E were studied for isotopic variations (values of δ^{18}O and δ^{13}C) of the indicator planktonic species *Globigerina bulloides*. The results indicate that from latitudes 9.69°N to 15°S both these isotopes (δ^{18}O and δ^{13}C) fluctuated significantly. Between latitudes from around 15°S to 30–35°S δ^{18}O values steadily increased, whereas δ^{13}C showed a decreasing trend. However, to the south of latitudes 30–35°S, both isotope values showed a similar response with a gradual increase up to latitude 50°S, beyond which δ^{18}O continued to increase while δ^{13}C declined. The characteristic patterns of the values of both isotopes indicates that the signatures of different water masses

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are associated with various frontal systems and/or water masses across the transect. The signature of the Polar Front at around latitude 50°S shows the specific response of the isotopic values ($\delta^{18}O$ and $\delta^{13}C$) of *G. bulloides*. Such a response beyond 50°S latitude is ascribable to the general decrease in the ambient temperature, resulting in a continuous increase in $\delta^{18}O$ values, while $\delta^{13}C$ values decrease as a result of reduced photosynthesis in regions approaching higher latitudes owing to low light penetration. To further corroborate our results, those of many such transects from geographically distinct regions need to be studied for isotopic variations in the calcareous shells of planktonic foraminiferal species. The results have the potential to be used as a proxy to assess the movement of frontal systems in southern high latitude regions.

1. Introduction

The Southern Ocean accounts for more than 12% of the total area and 50% of the total volume of the world ocean. It links the three major global oceans – the Pacific, Atlantic and Indian Oceans – transferring heat and momentum, and is the major source for the densest deep water in the global ocean. The Southern Ocean, sea ice and the Antarctic ice sheets are integrally linked to form the Antarctic ocean-cryosphere system, which is one of the most important components of the Earth's climate, influencing as it does the atmospheric composition, circulation, global heat budget and ocean circulation. The study area is an integral part of both the Indian and the Southern Oceans. The Indian Ocean exhibits a unique oceanographic characteristic: unlike the Pacific and Atlantic Ocean, which communicate with both the North and South Poles, the Indian Ocean is bounded in the north by a land mass. The northern Indian Ocean experiences seasonal reversal (Wyrtki 1973) with a characteristic change in the equatorial currents. The westward flowing North Equatorial Current (NEC) is prominent in January and March, when the north-east monsoon is fully established. It runs as a narrow current from the Malacca Strait to southern Sri Lanka, where it bends southwards between 2°S and 5°N in the region between 60°E and 75°E. The South Equatorial Current (SEC) occupies the region south of 8°S. Between these westward flows runs the Equatorial Counter Current (ECC).

Likewise, the southern Indian Ocean circulation is characterized by a subtropical anticyclonic gyre (Wyrtki 1971). The poleward flowing Agulhas Current lies in the west, the eastward flowing Antarctic Circumpolar Current (ACC) in the south and the equatorward flowing Western Australian Current in the east. The main feature of the Southern Ocean is the strong eastward flow in the zonally connected Antarctic Circumpolar Current (ACC). The ACC connects the major world oceans and redistributes oceanic properties such as heat, salt and nutrients. The

ACC consists of three major circumpolar fronts which are, from north to south, the Sub-Antarctic Front (SAF), the Antarctic Polar Front (PF) and the Southern Antarctic Circumpolar Current Front (SACCF). The fronts separate distinct surface water masses and are associated with strong currents and strong lateral gradients in temperature, salinity and biological productivity (Nowlin et al. 1977, Moore & Abbott 2002, Pollard et al. 2002, Boyd et al. 2005, Dong et al. 2006). The Subtropical Front (STF) is located at approximately 40°S in the south-central Indian Ocean (Stramma 1992). It is significant to note that between the fronts there lie zones of relatively uniform water mass properties. From north to south, the zones of the Southern Ocean are the Sub-Antarctic Zone (SAZ), the Polar Frontal Zone (PFZ) and the Antarctic Zone (AZ) (Whiteworth 1980). The near-surface property distribution differentiates water of the Southern Ocean from the warmer and more saline water of the sub-tropical circulations (Orsi et al. 1995), giving rise to a hydrographical boundary known as the Sub-Tropical Convergence (STC) or Sub-Tropical Front (STF) (Deacon 1933, 1937, Clifford 1983, Hofmann 1985). Consequently, a number of distinct water masses can be witnessed along a north-south transect in the Indian Ocean sector of the Southern Ocean.

Despite the importance of the Southern Ocean to world climate, its unique ecosystem and associated resources, its role in climate change and the functioning of its ecosystem are poorly understood. Several species of planktonic foraminifera build their tests in isotopic equilibrium with sea water and can therefore be used to trace the variations occurring in a number of distinct different water masses. In view of this, we here study the variations in the values of δ^{18}O and δ^{13}C of the calcareous tests of the planktonic foraminifera *Globigerina bulloides* in surface sediment samples collected along a north-south transect from latitude 9.69°N to 55.01°S in an attempt to understand the influence of the various frontal systems operating in the study area.

2. Material and methods

A total of 25 surface sediment samples (comprising Peterson Grab, Gravity and Piston core top samples) were collected on board *ORV Sagar Kanya* during her 199th and 200th cruises along a N-S transect between latitudes 9.69°N and 55.01°S and longitudes 80°E and 40°E (Figure 1, Table 1) of the Southern Ocean (Indian sector). The study area lies above the general lysocline and Carbonate Compensation Depth (CCD) reported in this region below 4400–4700 m water depth (Banakar et al. 1998), thus the possibility of any dissolution effect on planktonic

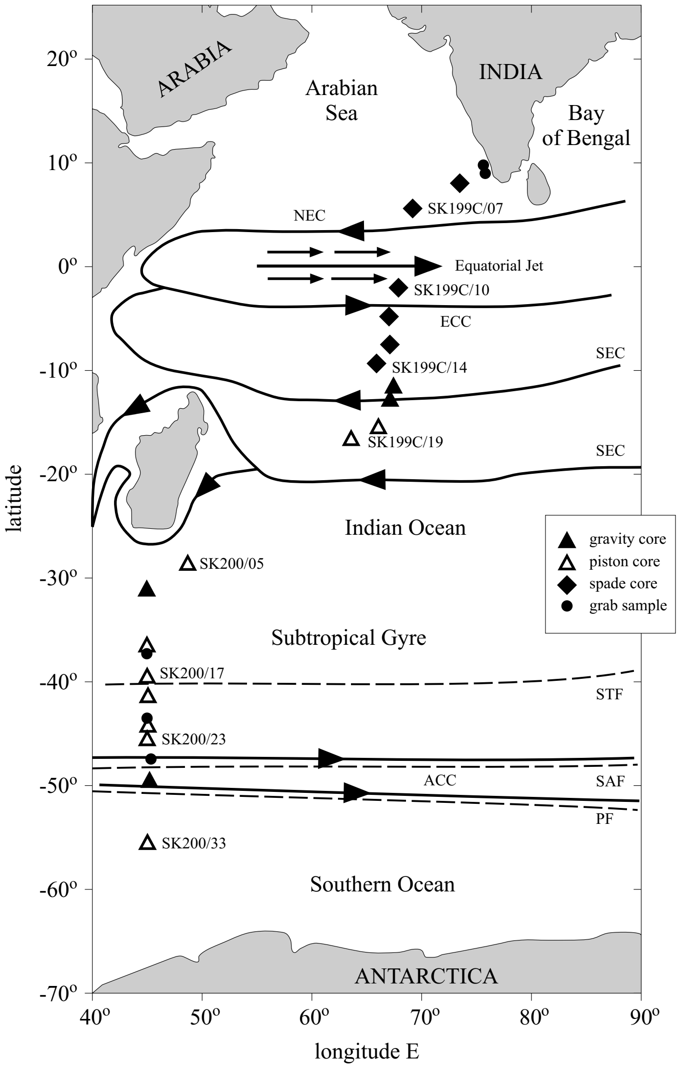

Figure 1. Map showing the details of the sampling locations

foraminifera can be ruled out. The planktonic foraminifera *Globigerina bulloides* has been reported as a thermocline dweller (Bée & Tolderlund 1971). The thermocline in our study area has been reported to vary within the range of 75–150 m (Anilkumar et al. 2005). All the sediment samples (top 1 cm of the sediment core/grab) were immediately stained with Rose Bengal and preserved in 10% formalin to differentiate living specimens of benthic foraminifera. Even though all possible efforts were made to collect surface sediments so as to sample recent sediments, we believe that at a few locations, slightly older sediments may have been collected. Without

Table 1. Details of the sampling stations

Series no.	Sample no.	Location		Water depth [m]	Sampling method	$\delta^{13}C$ [‰]	$\delta^{18}O$ [‰]
		Latitude	Longitude				
1	SK199C/01	09°41.25′N	75°45.15′E	87	Peterson Grab	−1.459	−2.249
2	SK199C/02	09°38.20′N	75°36.19′E	319	Peterson Grab	−1.508	−1.503
3	SK199C/03	09°30.27′N	75°30.31′E	1030	Peterson Grab	−1.284	−0.943
4	SK199C/04	09°24.31′N	75°23.63′E	1516	Peterson Grab	−1.391	−1.536
5	SK199C/05	08°59.50′N	74°49.31′E	2738	Peterson Grab	−1.827	−2.053
6	SK199C/06	08°08.00′N	73°33.86′E	2250	Spade Corer	−0.298	−0.908
7	SK199C/10	01°55.38′S	67°52.85′E	2597	Spade Corer	−1.412	−1.087
8	SK199C/12	04°41.18′S	67°05.75′E	3320	Spade Corer	0.195	−0.745
9	SK199C/13	07°21.89′S	67°10.37′E	3305	Spade Corer	−0.638	−1.114
10	SK199C/14	09°10.74′S	65°57.33′E	3373	Spade Corer	−0.536	−1.534
11	SK199C/15	11°25.46′S	67°24.16′E	3513	Gravity Corer	−1.282	−0.985
12	SK199C/16	12°35.56′S	67°08.59′E	3722	Gravity Corer	−0.446	−1.089
13	SK199C/17	15°16.71′S	66°00.77′E	3368	Piston Corer	−0.961	−1.350
14	SK199C/19	16°16.06′S	63°27.86′E	4003	Piston Corer	−0.836	−0.025
15	SK200/05	28°19.29′S	48°43.56′E	2295	Piston Corer	−1.076	0.632
16	SK200/09	30°54.85′S	44°51.37′E	2227	Gravity Corer	−1.970	−0.037
17	SK200/14	36°07.30′S	44°53.54′E	2805	Piston Corer	−1.697	0.884
18	SK200/15	37°00.00′S	44°59.00′E	2984	Peterson Grab	−1.485	0.447
19	SK200/17	39°01.71′S	44°58.17′E	4022	Piston Corer	−0.814	1.132
20	SK200/19	40°58.88′S	45°03.53′E	2532	Piston Corer	−0.099	2.817
21	SK200/21	43°09.00′S	44°59.00′E	3210	Peterson Grab	0.112	1.714
22	SK200/22A	43°41.47′S	45°04.22′E	2723	Piston Corer	0.011	1.959
23	SK200/23	44°59.82′S	45°00.83′E	1423	Piston Corer	−0.332	2.489
24	SK200/27	49°00.34′S	45°13.11′E	4377	Gravity Corer	0.673	2.935
25	SK200/33	55°00.39′S	45°00.63′E	4185	Piston Corer	−0.243	3.128

the exact dating of these sediment samples, the presence of living benthic foraminiferal specimens at various stations may be considered an indicator of modern ambient conditions. All the sediment samples were processed using standard procedures (Khare & Chaturvedi 2006). *G. bulloides* (a non-symbiotic planktonic species) was selected for oxygen and carbon isotope analyses of its tests because of its ubiquitous presence in all the samples. 10–12 specimens of *G. bulloides* were selected and thoroughly cleaned, then analysed through a Finnigan MAT 251 isotope ratio gas mass spectrometer, which was coupled to an automatic carbonate preparation device (Kiel I) and calibrated via NBS 19 to the PDB scale at the Alfred Wegener Institute for Polar and Marine Research, Germany. The values are given in δ notation versus VPDB (Vienna Pee Dee Belemnite). The precision of the oxygen isotope measurements based on repeated analyses of a laboratory standard over a one-year period was better than 0.09‰ for oxygen. Similarly, the precision of the carbon isotope measurements based on repeated analyses of a laboratory standard over a one-year period was better than 0.06‰. The average annual temperature and salinity data at 75 m water depth across the transect of the study area was obtained from the dataset in Levitus et al. (1994).

3. Results and discussion

The minimum value of δ^{18}O was -2.249‰, recorded at station SK199C/01, the maximum being 3.128‰ at SK200/33 (Figure 2a). Similarly, the minimum value of δ^{13}C was -1.970‰ at SK200/09 and the maximum was 0.673‰ at SK200/27 (Figure 2b). Oxygen and carbon isotope measurements on calcareous tests of foraminifera have been standard tools for reconstructing past oceanographic conditions (Woodruff et al. 1990, Loubere & Bennett 2008). While δ^{18}O in shell carbonate is a function of the ratio in seawater and the calcification temperature (McCrea 1950, Epstein et al. 1953), δ^{13}C is controlled by the ratio of dissolved inorganic carbon (DIC) in seawater and physiological processes like respiration and symbiont photosynthesis (Spero et al. 1997).

Oxygen isotopes (δ^{18}O values) from foraminiferal tests are commonly used as proxies for the temperature (Ariztegui et al. 1996), growth and decay of polar ice caps as well as local changes in temperature and/or salinity (Shackleton 1987, Abreu & Anderson 1998), cyclostratigraphy and sea level changes (Shackleton et al. 1993, Miller et al. 1998, Spezzaferri et al. 2002). In contrast, carbon isotopes (δ^{13}C values) of foraminiferal shells are commonly used as proxies for palaeoproductivity (Shackleton 1977, Broecker & Peng 1982, Curry et al. 1988), the global carbon cycle

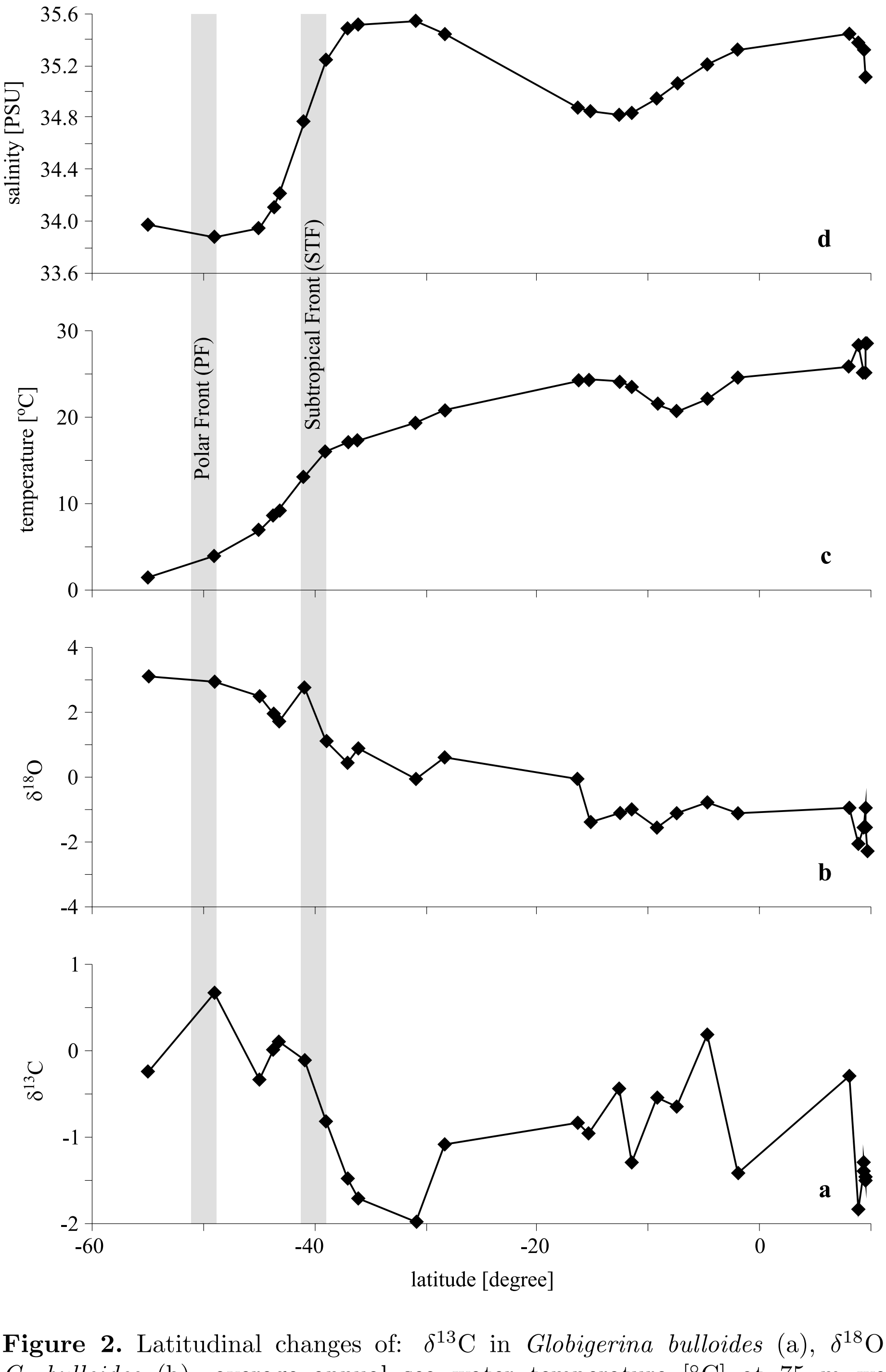

Figure 2. Latitudinal changes of: δ^{13}C in *Globigerina bulloides* (a), δ^{18}O in *G. bulloides* (b), average annual sea water temperature [°C] at 75 m water depth (c), average annual sea water salinity [PSU] at 75 m water depth (d)

(Siegenthaler & Joos 1992, Shaffer 1993, Lassey et al. 1996) and orbitally-driven climate variability (Shackleton 2000).

It is evident from Figures 2a,b that the parameters $\delta^{13}C$ and $\delta^{18}O$ apparently display specific trends in different latitudinal regimes. From latitude 9.69°N to 15°S both isotopes ($\delta^{18}O$ and $\delta^{13}C$ values) fluctuated significantly. From 15°S to around 30–35°S $\delta^{18}O$ continued to increase steadily, but $\delta^{13}C$ tended to decrease. However, south of 30–35°S both isotopes again showed a similar response with a gradual increase to latitude 50°S, beyond which $\delta^{18}O$ continued to increase while $\delta^{13}C$ declined (Figures 2a,b). The temperature profile (Figure 2c) exhibits a general decreasing trend towards higher latitudes. While a decreasing trend in the temperature profile is clearly related to the increase in $\delta^{18}O$ values (Figure 2b), the salinity profile (Figure 2d) indicates that a low salinity appears to favour higher $\delta^{13}C$ values in *Globigerina bulloides* tests.

These characteristic patterns may be attributed to ambient water masses with distinct physicochemical properties, which by and large appear to be influenced by the prevailing frontal system and zones of relatively uniform water mass properties. The region south of latitude 30°S is mostly dynamic owing to the presence of the Agulhas and ACC, the two major current systems. The Agulhas Current (Gordon 1985) is the western boundary current that flows polewards along the east coast of Africa from latitude 27° to ≈ 40°S, and then reverses direction or retroflects eastwards to become the Agulhas Retroflection Current. The retroflection exhibits a quasi-stationary meandering pattern with a wavelength of 500 km between 38° and 40°S (Gordon 1985). The westerlies are largely confined between ~ 40° and ~ 65°S, and drive the eastward surface current, initiating a northward Ekman drift that is critical to the formation of the Antarctic Intermediate Water mass (AIW), subducted below the subantarctic surface water. The strong circumpolar geostrophic currents and weak stratification result in the isopycnals tilting towards the surface in the southern part of ACC. This tilting causes the upwelling of deep water originating from the other oceans and also from the deep Indian Ocean to the surface, where they are modified by atmospheric interactions (Jasmine et al. 2009). This upwelling of nutrient-rich deep water to the surface is triggered by the Antarctic Divergence (Jones et al. 1990). The upwelling deep water not only contains high concentrations of dissolved nutrients that support a rich biological productivity but is also supersaturated with carbon dioxide (CO_2), which is vented to the atmosphere and plays a substantial role in modulating atmospheric CO_2 concentrations. Atmospheric CO_2 concentrations can be drawn down and transferred into the deep ocean through a biological pump mechanism. CO_2 converted into organic matter by photosynthesis is exported to deeper waters from the upper ocean by sedimentation and vertical migrations of organisms. The westerlies have a large impact on Southern Ocean hydrography, exerting a great influence on both the distribution of sea ice and biological productivity. The degree of variability in hydrographic and biological characteristics is high between the zones and the frontal system (Kostianoy et al. 2003, 2004).

It is intriguing to observe that the response of these two isotopes in the latitudinal corridor between 15° and 35°S is not coherent (Figures 2a,b). Does this non-linear response between δ^{18}O and δ^{13}C values have any link with the prevailing sub-tropical gyre in this region? Perhaps the complex dynamics in this latitudinal belt cause the non-linear correspondence between δ^{18}O and δ^{13}C.

The distinct profiles shown in Figures 2a,b apparently reveal the signature of the Sub-Tropical Front (STF). The northern side of the STF is generally more saline (Deacon 1982), whereas south of the STF is the eastward flow of the Antarctic Circumpolar Current (ACC), found approximately between latitudes 45 and 55°S (Trenberth et al. 1990). The near-surface property distribution differentiates the ACC water from the warmer and more saline water of the Sub-Tropical regime.

Similarly, the response beyond latitude 50°S could be ascribed to the general decrease in the ambient temperature, resulting in a continuous increase in δ^{18}O values, while δ^{13}C values decrease due to reduced photosynthesis in the regions close to higher latitudes owing to the low light penetration (Lali & Parsons 1997). This probably reveals the signature of the Polar Front at around latitude 50°S, showing the specific response of the isotopic values (δ^{18}O and δ^{13}C) of *G. bulloides*.

Wilke et al. (2006), while studying the planktonic foraminiferal flux in the Indian Ocean, reported the highest oxygen (lowest temperature) and carbon isotope values associated with frontal zones, i.e. when Atlantic and Agulhas waters mix and upwelling of deeper water masses occurs. The present observations enable the isotopic values of planktonic foraminiferal species associated with the various frontal systems in the study area to be distinguished.

4. Conclusions

The signatures of different water masses associated with various frontal systems across a north-south transect have been traced in stable isotopes (δ^{18}O and δ^{13}C values) in the calcareous shells of the planktonic foraminiferal species *Globigerina bulloides*. The results may have a bearing on understanding past movements in the position of various frontal systems if studied in sub-surface sediments in the study area. However, a larger data set from distinct geographical locations in different sectors of the Southern Ocean is required for further corroboration of our results.

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