

Influence of ridges on hydrographic parameters in the Southwest Indian Ocean

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Abstract The objective of the paper is to use the data collected along two meridional sections (45° E and $57^{\circ}30'$ E) during the austral summer (January–March) 2004 to understand the influence of seabed topography across the Madagascar and Southwest Indian Ridges on hydrographic parameters. The study was supplemented by World Ocean Circulation Experiment (WOCE) Conductivity–Temperature–Depth data collected during February–March 1996 along 30° E, as well as Levitus climatology. A southward shift of 2° latitude (between 45° E and $57^{\circ}30'$ E) was recorded for the two predominant frontal structures, i.e., the Agulhas Return Front and Southern Subtropical Front, which is attributed to the influence of seabed topography on hydrographic parameters. No significant spatial variation of these fronts was noted between the 30° E and 45° E meridional sections. Between latitudes 31° S and 42° S, the temperature and salinity structures show deepening over the ridges. The Antarctic Circumpolar Current core was detected between $40^{\circ}15'$ S and 43° S.

Keywords Seabed topography · Hydrographic parameters · Thermohaline gradients · Volume transport · Ridges

Introduction

Prominent meridional changes in the water properties separate waters of the Southern Ocean from warmer and saltier waters of the subtropical circulation (Deacon 1937).

This change in water properties was named the Subtropical Front (Hofmann 1985). The Antarctic Circumpolar Current is one of the major surface current systems in the southern Indian Ocean. The Antarctic Circumpolar Current flowing towards the east is embedded with numerous circumpolar fronts and has a key role in the modulation of hydrographic conditions in the Southern Ocean (Nowlin and Klinck 1986). One of the major problems that hamper a comprehensive understanding of the dynamics of the Southern Ocean is the paucity of in-situ data from the western Indian sector of the Southern Ocean. The data coverage in the Indian sector of Southern Ocean is strongly non-uniform, with data sparse areas located west of the Crozet Plateau and east of the Kerguelen–Amsterdam Passage. However, these are the key regions where the fronts converge and then split again. Large-scale detailed, multi-ship, synoptic CTD/SeaSoar surveys of these areas deserve the highest priority in any programme of observational studies of the South Indian/Antarctic Ocean (Belkin and Gordon 1996).

The present paper discusses the results of the physical oceanographic parameters observed along transects 30° E, 45° E and $57^{\circ}30'$ E, where observations are sparse, and aims to understand the influence of seabed topography on the hydrographic parameters across the Madagascar and Southwest Indian Ridges. Because it is not easy to classify each front based on the exact change in its characteristic parameters, the criteria adopted by other researchers were considered (Peterson and Whitworth 1989; Park et al. 1993; Belkin and Gordon 1996; Sparrow et al. 1996; Holliday and Read 1998; Kostianoy et al. 2004). The importance of near-surface property distributions when differentiating the Antarctic Circumpolar Current from subtropical waters is also discussed.

Most of the investigations carried out in the Indian Ocean were concentrated on the central and eastern Indian

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Ocean sector (Rintoul et al. 1997; Rintoul et al. 2002; Rintoul and Bullister 1999; Rintoul and Sokolov 2001; Sokolov and Rintoul 2002; Yuan et al. 2004). The present study employs Conductivity Temperature Depth (CTD) and Expendable bathythermograph (XBT) data sampled at a high spatial resolution along 45° E and 57°30' E during 2004 in order to understand the causes of the spatial variations in the frontal positions in the southwestern Indian Ocean. The significance of this study is in its systematic approach designed to reveal the causes for the spatial variation in frontal positions, particularly the role of Madagascar and Southwest Indian Ridges.

Data and method

In situ oceanographic observations were made along 45° E and 57°30' E (meridional sections) during austral summer (January–March) 2004. Along 57°30' E, XBT (between 35° S and 48° S) and CTD (between 45° S and 48° S) data collections were restricted due to bad weather and high sea state conditions. Sea Surface Temperature (SST) was recorded using outboard bucket thermometer (accuracy: $\pm 0.2^\circ\text{C}$). Rapid vertical temperature profiles were recorded by launching XBT probes (type: T-7; accuracy: $\pm 0.15^\circ\text{C}$; depth resolution: 0.65 m), at 1° latitude (Fig. 1) and 0.65 m depth intervals. XBT profiles were quality controlled by following guidelines of the Commonwealth Scientific and Industrial Research Organisation (CSIRO) Cookbook (CSIRO 1993). When the XBT probes are falling through the water column spikes may occur at some depths in the vertical profiles of the temperature data. Hence in the present study these spikes were removed from the thermal structures made from XBT data. Thadathil et al. (2002) and Ridgway (1995) had used temperature data from the Southern Indian Ocean collected using various instruments (from different sources) and reported that the temperature profiles made from XBT data are compatible with the temperature profiles made from the data collected by other instruments. XBT observations were increased to 20–30 nautical miles intervals in the frontal regions, based on strong SST gradients. Along 45° E temperature and salinity profiles (1 m depth interval up to bottom) were measured at 1° latitude intervals using CTD from 31° S to 56°S (make: SBE 9/11; accuracy: temperature $\pm 0.001^\circ\text{C}$, conductivity $\pm 0.0001\text{ S/m}$ and depth $\pm 0.005\%$ of full scale) during 30th January–17th February 2004 (Fig. 1). Water depth was measured using a single beam deep-sea echo-sounder (Frequency: 12 kHz/30 kHz, Model: Hydrostar 4900 of ELAC-Nautik) along the cruise track. Supplementary World Ocean Circulation Experiment (WOCE) (<http://www.noc.soton.ac.uk/OTHERS/woceipo/>) CTD data that were collected along 30°E during

the period February to March 1996 (Section 106SB; Expedition 35MF103_1 onboard RV Marion Dufresne) and Levitus data (Levitus 1982; Levitus and Boyer 1994a; b) from 30° S to 40° S and 40° E to 50° E were used.

Results and discussion

A compilation of hydrographic data from WOCE along 30° E, together with in situ data collected onboard R/V Sagar Kanya (along 45° E and 57°30' E) and the Levitus data were analysed to identify the influence of seabed topography on hydrographic parameters. Because two ridges, the Madagascar and Southwest Indian Ridges, fall under the 45°E meridional transect, the characteristics of hydrographic parameters along 45°E and along two meridional transects at the western and eastern region of 45°E were compared in order to isolate the influence of topographic steering on oceanic circulation patterns. The results obtained are presented in the following sections.

Fronts

Criteria adopted by other researchers and the property indicators used for identification of fronts in the present

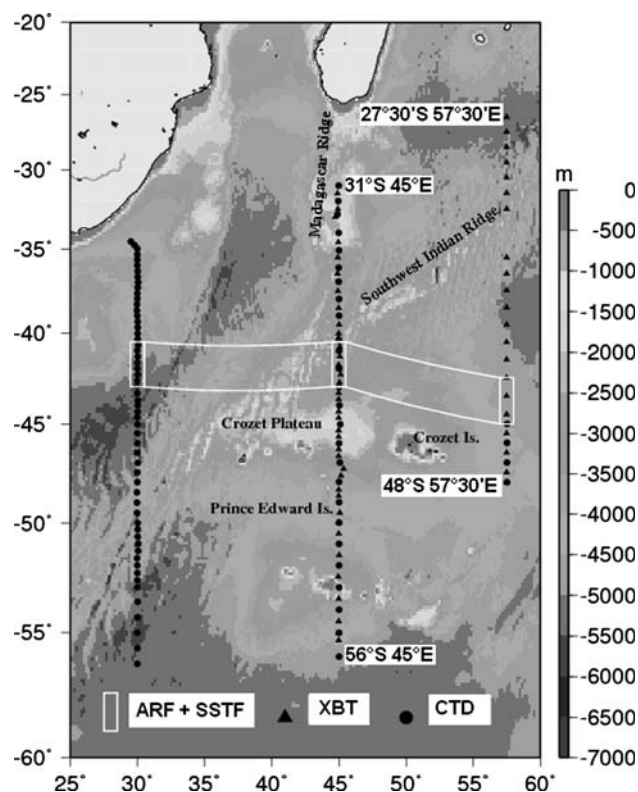


Fig. 1 Represents station locations along 30° E, 45° E and 57°30' E. Southward shift of Agulhas Return Front (Agulhas Return Front) + Southern Subtropical Front (represented by the rectangle) from 45° E to 57°30' E by 2° latitude is exhibited in the Figure

Table 1 Adopted property indicators for identification of fronts

Frontal structure	Adopted property indicators for identification of frontal zones and related references				Reference
	Temperature (°C)	Surface temperature gradient (°C)	Salinity (psu)		
Northern Subtropical Front (NSTF)	21–22°C at surface	$0.027 \pm 0.003^\circ\text{C km}^{-1}$	Consistent value of surface salinity ~ 35.5 psu		Belkin and Gordon (1996); Holliday and Read (1998); Kostianoy et al. (2004)
Agulhas Return Front (ARF)	19–17°C at surface; 10°C isotherm from 300 to 800 m	$0.037 \pm 0.013^\circ\text{C km}^{-1}$	35.54–35.39 psu at surface; 35.57–34.90 psu at 200 m		Holliday and Read (1998); Belkin and Gordon (1996); Sparrow et al. (1996); Kostianoy et al. (2004)
Southern Subtropical Front (SSTF)	17–11°C at surface; 12–10°C at 100 m	$0.035 \pm 0.013^\circ\text{C km}^{-1}$	35.35–34.05 psu at surface; 35–34.6 psu at 100 m; 34.92–34.42 psu at 200 m		Holliday and Read (1998); Belkin and Gordon (1996); Sparrow et al. (1996); Kostianoy et al. (2004)
Subantarctic Front (SAF1)	11–9°C at surface; 8–5°C at 200 m (along 45°E); 11–10°C at surface; 8–5°C at 200 m (along 57°30' E)	$0.030 \pm 0.013^\circ\text{C km}^{-1}$	34.0–33.85 psu at surface; 34.40–34.11 psu at 200 m		Holliday and Read (1998); Belkin and Gordon (1996); Sparrow et al. (1996); Park et al. (1993); Kostianoy et al. (2004)
Subantarctic Front (SAF2)	7–6°C at surface; 4°C isotherm at 200 m depth (along 45°E); 9–8°C at surface; 4°C isotherm at 200 m depth (along 57°30'E)	$0.009 \pm 0.013^\circ\text{C km}^{-1}$	Consistent value of surface salinity ~ 33.85 psu south of SAF		Holliday and Read (1998); Peterson and Whitworth (1989); Kostianoy et al. (2004)
Polar Front (PF1)	5–4°C at surface; northern limit of the 2°C isotherm below 200 m	$0.009 \pm 0.005^\circ\text{C km}^{-1}$	33.8–33.9‰ at surface		Holliday and Read (1998); Belkin and Gordon (1996); Sparrow et al. (1996); Kostianoy et al. (2004)
Polar Front (PF2)	3–2°C at surface	$0.0045 \pm 0.005^\circ\text{C km}^{-1}$	33.8–33.9‰ at surface		Holliday and Read (1998); Kostianoy et al. (2004)

study are given in Table 1. Based on the characteristic property indicators oceanic fronts were identified in the N–S transects along longitudes 30° E, 45° E and 57°30' E.

Temperature, salinity and density structures and the horizontal temperature gradient (at 4 m water depth) are represented in Fig. 2a–d for the 30°E section, in Fig. 3a–d

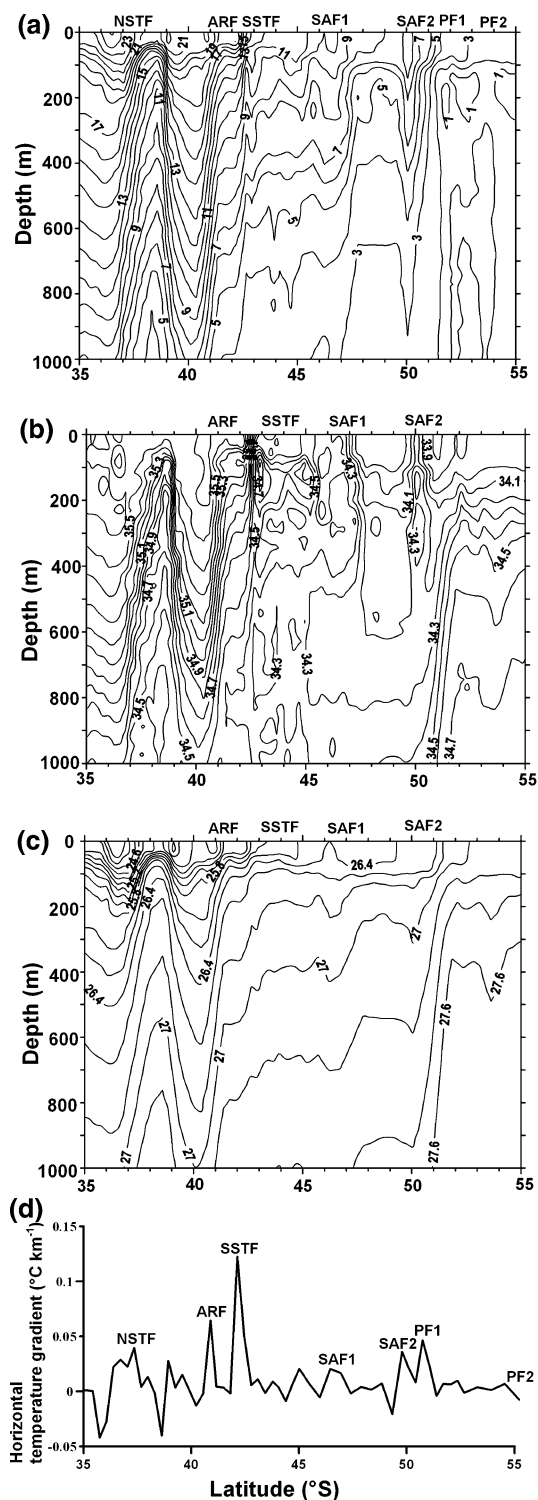


Fig. 2 Vertical structure of (a) potential temperature (°C) (b) salinity (psu) (c) potential density (kg m^{-3}) and (d) horizontal gradient of potential temperature at 4 m depth ($^{\circ}\text{C km}^{-1}$) along 30° E

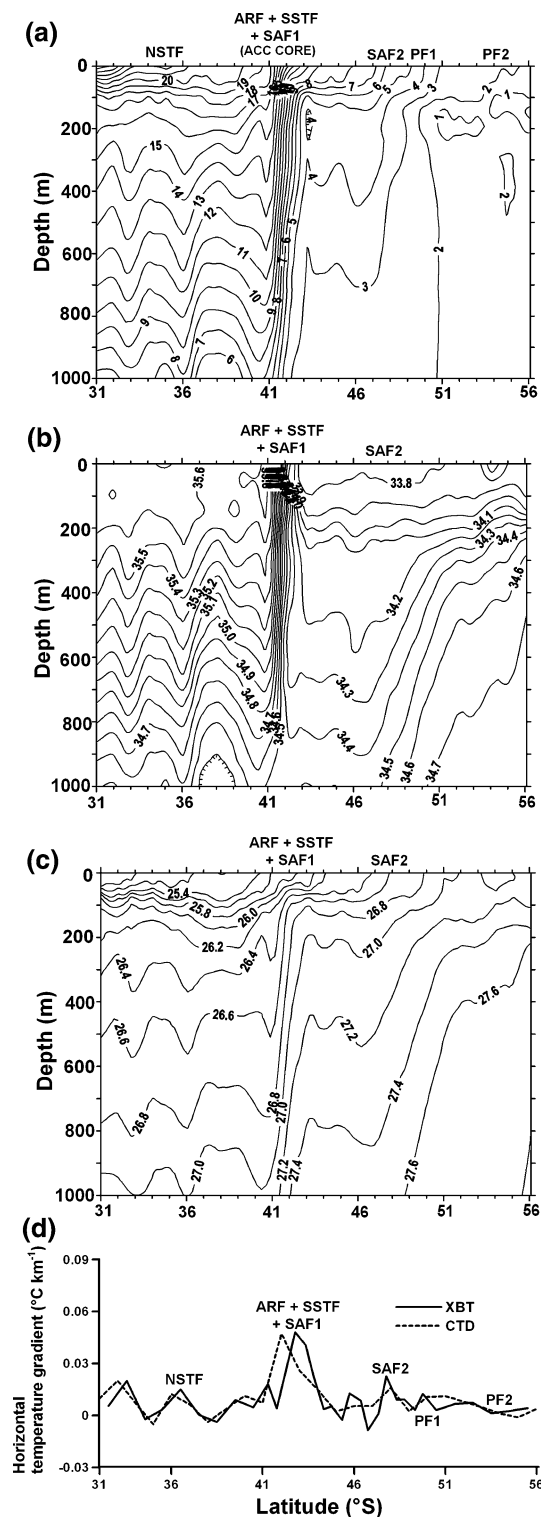


Fig. 3 Vertical structure of (a) potential temperature (°C), (b) salinity (psu), (c) potential density (kg m^{-3}) (d) horizontal gradient of potential temperature at 4 m depth ($^{\circ}\text{C km}^{-1}$) along 45° E

for the transect at 45° E and in Fig. 4a–d for the 57°30' E section. The Northern Subtropical Front, Agulhas Return Front, Southern Subtropical Front, Northern Subantarctic Front, Southern Subantarctic Front, Northern Polar Front and the Southern Polar Front are the oceanic fronts identified along the meridional sections. Variations in latitudinal positions of the oceanic fronts along the meridional sections are presented (Table 2).

Figure 2a–d show the Agulhas Return Front, Southern Subtropical Front as separate fronts along 30° E whereas Fig. 3a–d depict the merged front (Agulhas Return Front + Southern Subtropical Front + Northern

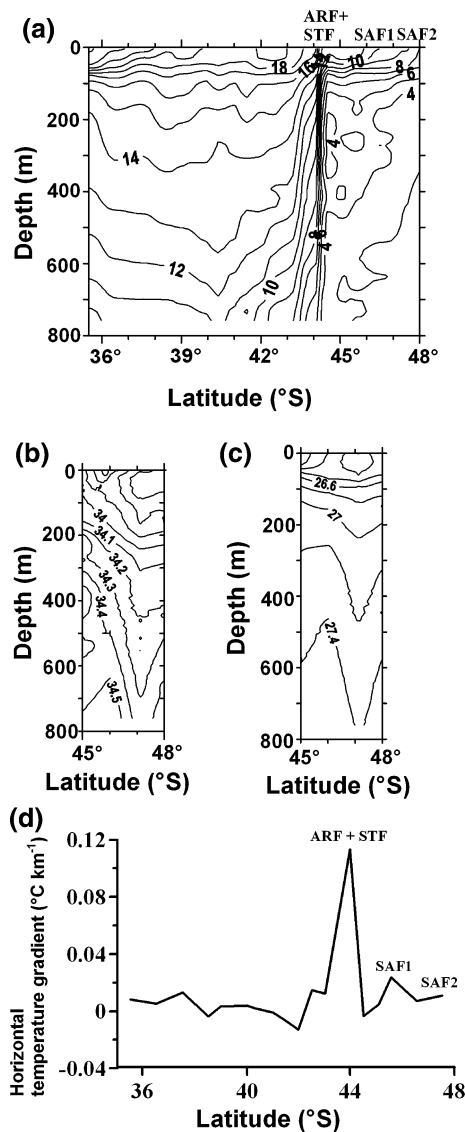


Fig. 4 Vertical structure of (a) potential temperature (°C), (b) salinity (psu), (c) potential density (kg m^{-3}), (d) horizontal gradient of potential temperature at 4 m depth ($^{\circ}\text{C km}^{-1}$) along 57°30' E (XBT and CTD data collection were restricted along 57°30' E due to bad weather and high sea state conditions)

Subantarctic Front) along 45° E. These fronts are located more or less on the same latitude. The results identify the Northern Subantarctic Front as a separate wide front ($\sim 3^{\circ}$ latitude) along 30° E and as a merged front along 45° E (Table 2), which is in contrast with previous studies (Park et al. 1993; Orsi et al. 1995; Belkin and Gordon 1996; Sparrow et al. 1996). Figure 4a and d identify the merged frontal system of Agulhas Return Front + Southern Subtropical Front along 57°30' E and reveal a latitudinal southward shift of two degree from 45° E. Such a shift however, is not observed along the 30° E to 45° E meridional sections. Lutjeharms and Valentine (1984), Lutjeharms (1985), Nagata et al. (1988), Park et al. (1993), Belkin and Gordon (1996), Sparrow et al. (1996), Holliday and Read (1998), and Kostianoy et al. (2004) reported the shifting of hydrographic parameters in the region, but did not attribute these to the influence of the bathymetric ridges. However, in the present study data along three meridional sections were used to illustrate the causes for the spatial variation in frontal positions from west to east in the southwest Indian Ocean. The southward shift of 2° latitude in the frontal positions of Agulhas Return Front + Southern Subtropical Front from 45° E to 57°30' E is attributed to the influence of the ridges predominant in the region.

Geostrophic currents and volume transport along 45° E

Geostrophic currents were computed using 1000 m as the level of no motion along 45° E (Fig. 5). The strongest surface current reaching 0.07 ms^{-1} was coincident with 35° S and Agulhas Return Front + Southern Subtropical Front + Northern Subantarctic Front regions. If not specified otherwise, eastward direction is assumed for the direction of zonal current and transport. The geostrophic current velocity decreases southwards in the Agulhas Return Front + Southern Subtropical Front + Northern Subantarctic Front zone, whereas it changes direction between Agulhas Return Front + Southern Subtropical Front + Northern Subantarctic Front and the Southern Subantarctic Front. A similar reversal in the current pattern was also observed to the north of the Agulhas Return Front + Southern Subtropical Front + Northern Subantarctic Front zone (between 31° S and 36° S) and is compatible with the earlier findings of Park et al. (1993). Therefore, a flow reversal is apparent in the region for the identified fronts.

Shallowing of isolines was observed in the region between Agulhas Return Front + Southern Subtropical Front + Northern Subantarctic Front and the Southern Subantarctic Front (Fig. 3a and b). Closely packed isotherms that suggest large thermal gradients to north of Agulhas

Table 2 Positions of various fronts along 30° E, 45° E and 57°30' E

Longitude	30° E	45° E	57°30' E
Northern Subtropical Front (NSTF)	37°30' S	Between 35°30' S and 36° S	Not identified
Agulhas Return Front (ARF)	Between 41° S and 42° S	Identified as a merged front with SSTF and SAF1 between 40°15' S and 43° S	Identified as a merged front with Subtropical Front (STF) between 43°30' S and 45° S
Southern Subtropical Front (SSTF)	Between 42° S and 43° S	Identified as a merged front with ARF and SAF1 between 40°15' S and 43° S	Identified as Subtropical Front (not as separate fronts like NSTF and SSTF) merged with ARF between 43°30' S and 45° S
Northern Subantarctic Front (SAF1)	Between 45° S and 48° S	Identified as a merged front with ARF and SSTF between 40°15' S and 43° S	Between 45°30' S and 46°30' S
Southern Subantarctic Front (SAF2)	Between 50° S and 51° S	Between 47° S and 48° S	Identified southward of 47° S
Northern Polar Front (PF1)	Between 51° S and 52° S	Between 49° S and 50° S	Not identified due to paucity of data
Southern Polar Front (PF2)	Between 53° S and 55° S	Between 52° S and 54° S	Not identified due to paucity of data

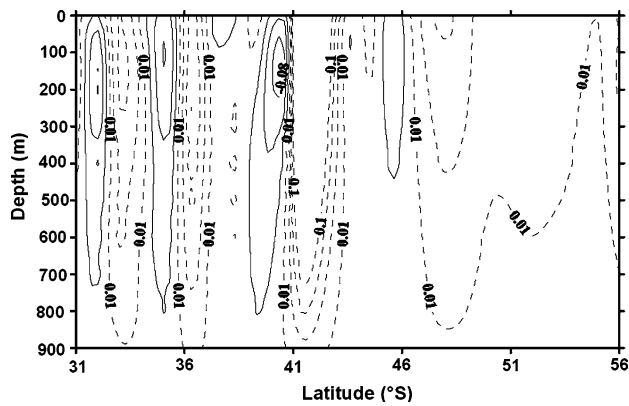


Fig. 5 Vertical structure of geostrophic current (ms^{-1}) along 45°E . Dashed line eastward flow and solid lines westward flow

Return Front + Southern Subtropical Front + Northern Subantarctic Front exhibit a wavy form aligned to the geostrophic currents (Fig. 3a). These alternating eastward and westward components of geostrophic flow perhaps indicate a cyclonic circulation.

The volume transport between station pairs was computed and entered as vectors along the track line in order to decipher the zonal current systems in subtropical to polar regions. The depth integrated volume transport is computed for the upper 1000 m. The zonal volume transports from the subtropical to polar regions (from 31°S to 56°S along 45°E) are exhibited in Fig. 6. Volume transports predominate in the frontal regions along the meridional section. A large volume transport (23 Sv) was exhibited between 40°S and 43°S , whereas it was reported to be $<20 \text{ Sv}$ by the earlier investigations (Park et al. 1993; Orsi et al. 1995). Between 47°S and 48°S (Southern Subantarctic Front region) the volume transport rate is calculated to be 3.78 Sv. It is interesting to note that volume transport

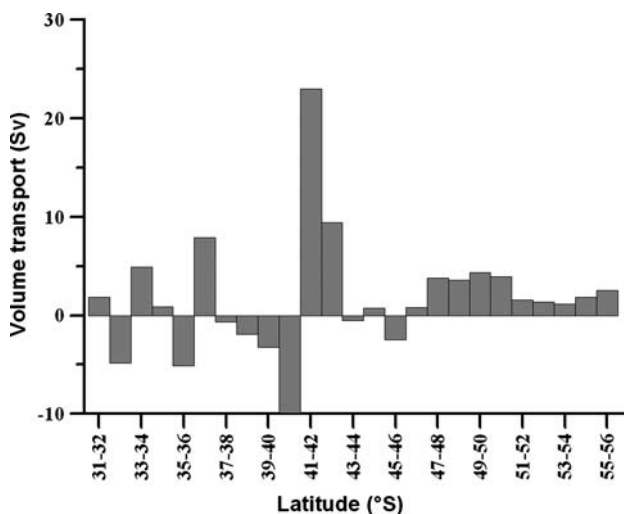


Fig. 6 Volume transport in Sv ($1 \text{ Sv} = 10^6 \text{ m}^3 \text{ s}^{-1}$) along 45°E

also changes direction in the regions where geostrophic flow exhibited a cyclonic circulation (north of 40°S and between 43°S and 47°S). Apart from the previous studies (Sparrow 1996; Park et al. 1993; Orsi et al. 1995) these findings are significant not only for deciphering the strong changes in the characteristic features of hydrographic parameters in the subtropical region but also to illustrate changes in the direction of zonal current and volume transport to the north and south of the merged frontal region, possibly due to the influence of bathymetric ridges.

Hydrographic parameters over the Madagascar and Southwest Indian Ridges

Thermal structures in the water column between the surface and the bottom (including seabed topography) along the 45°E transect are exhibited in Fig. 7. We attribute the shallowing of thermal isolines observed between the Agulhas Return Front + Southern Subtropical Front + Northern Subantarctic Front and the Southern Subantarctic Front (Fig. 3a and b) to the mixing of the warm and saline waters from the north with cold and fresh waters from the south. Closely packed isotherms suggesting large thermal gradients to north of Agulhas Return Front + Southern Subtropical Front + Northern Subantarctic Front exhibit a wavy form. Isotherms show a deepening of 300 m over the seafloor ridges (Figs. 3a and Fig. 7). This deepening of isotherms is clear in Fig. 3a because this figure only plots the shallowest 1,000 m, whereas in Fig. 7 the thermal structure down to 3,000 m water depth is exhibited. A slight bending (wavy structure) of the 3°C isotherm can be

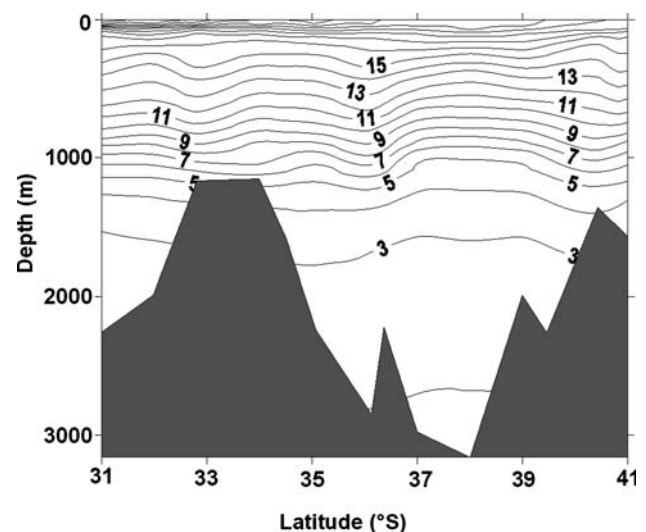


Fig. 7 Vertical structure (including seabed topography) of potential temperature ($^\circ \text{C}$) along 45°E where the influence of ridges on the isotherms are exhibited

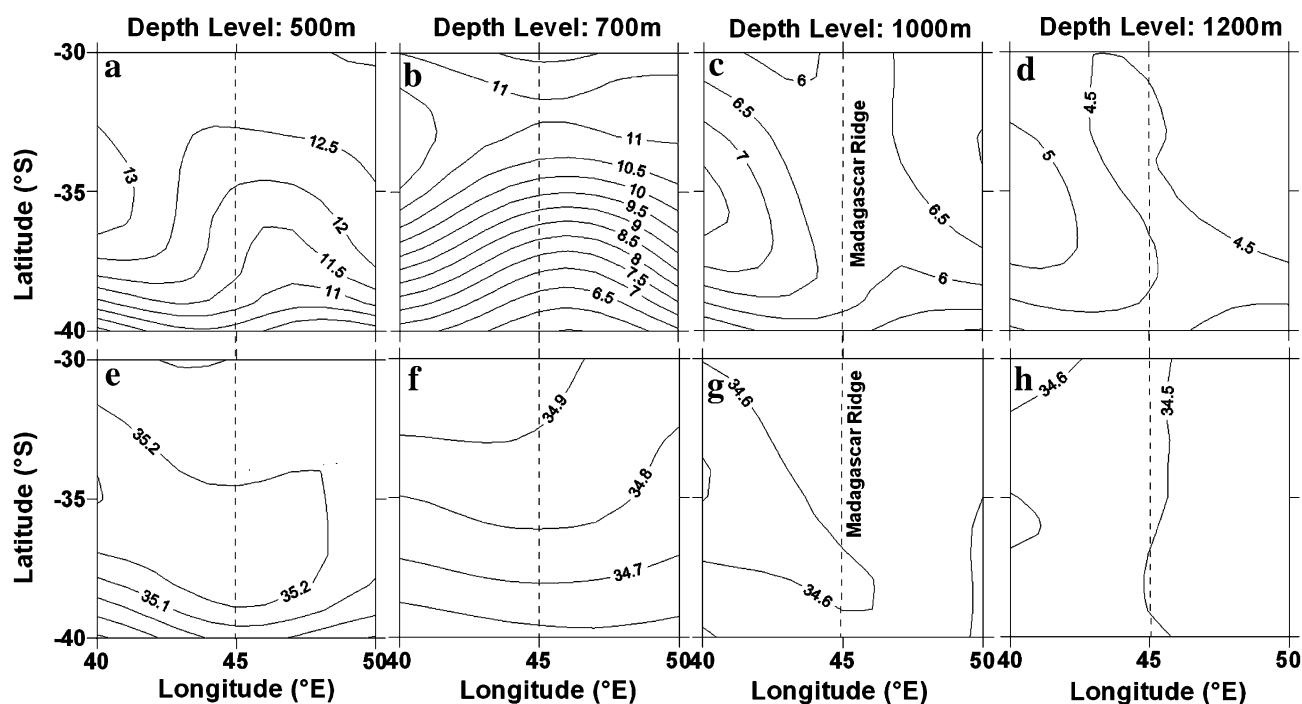


Fig. 8 Structure of potential temperature (°C) and salinity (psu) at depths of (a) and (e) 500 m; (b) and (f) 700 m; (c) and (g) 1000 m; and (d) and (h) 1200 m; respectively based on the Levitus data (area between 30°–40° S and 40°–50° E)

seen on either side of the projected portion of the ridge in Fig. 7. Considering the dynamics there seems to be a convergence zone of water masses above the ridge. Over the ridge crest, the isotherms deepen and form trough patterns, thus suggesting large thermal gradients centered at 32° S and 35° S and extending to the seafloor, perturbing the whole water column stratification.

The influence of the ridges is more obvious in Fig. 8. Based on the Levitus data (area between 30°–40°S and 40°–50°E) isotherms and isohalines exhibit a predominant wavy-like structure at 500 and 700 m water depths. From 31° S to 35° S where the projection of the ridge is more predominant a special distribution of isotherms is observed. The behaviour of the isotherms at 700 m water depth shows a disparity with the isotherms at 1,000 m and 1,200 m. At 700 m water depth (Fig. 8b) the isotherms are closely packed while at 1,000 m (Fig. 8c) and 1,200 m (Fig. 8d) they are separating away from the 45° E meridional section where the ridges are present (Fig. 7). These findings point to the influence of seabed topography in controlling ocean circulation patterns.

The change in direction of the geostrophic current (Fig. 5) between 32° S and 35° S perhaps represents a rotational tendency, which is also observed south of the merged frontal system. This rotational tendency of waters due to topographic steering is perhaps driven by the eastward flowing Antarctic Circumpolar Current resulting in a southward shifting of frontal structures.

A narrow zone of low salinity is observed immediately south of the zone where the maximum drop in hydrographic parameters was identified, and which can be observed as a narrow belt of minimum surface salinity immediately south of the core of the Antarctic Circumpolar Current (Park et al. 1993; Gordon 1975; Whitworth and Nowlin 1987). The Antarctic Circumpolar Current in the Crozet Basin area seems to be shifted to its northernmost position and concentrating in a narrow zone where the subtropical and subantarctic waters are strongly merged (Park et al. 1993). Park et al. (1993) infer that the core of the Antarctic Circumpolar Current is immediately north of the minimum surface salinity layer where the subtropical and subantarctic waters merge. Hence in the present investigation the Antarctic Circumpolar Current core, around the Crozet Plateau is identified as lying between 40°15' S and 43° S along 45° E (Fig. 3a and b).

Conclusion

This study delineates the spatial variation in the position of fronts and the influence of seabed topography in controlling hydrographic parameters across the Madagascar and the Southwest Indian Ridges. The results were obtained in the Frontal Zones using the WOCE CTD data sets along a transect at 30° E between 35° S and 56° S, combined with CTD data sets collected along a transect at 45° E between

31° S and 56° S and XBT data collected along a transect at 57°30' E. Levitus data for an area from 30°–40° S and 40°–50° E were also integrated. The Agulhas Return Front, Southern Subtropical Front and Northern Subantarctic Front are identified as separate fronts along longitude 30° E, whereas these fronts are seen to be merged along longitude 45°E. The southward shift of 2° latitude in the frontal positions of Agulhas Return Front + Southern Subtropical Front from 45° E to 57°30' E is attributed to the influence of the ridges that dominate the seafloor topography in that region.

The present study identified the Northern Subantarctic Front as merging with the Agulhas Return Front and the Southern Subtropical Front along 45° E, whereas it was identified as a wide front (~3° latitude) along 30°E. The geostrophic currents and volume transport exhibited a change in direction both north and south of the merged frontal region. The Antarctic Circumpolar Current core was detected between 40°15' S and 43° S. The rotational tendency of waters in the study area (attributed to the seabed topography) is perhaps driven by the eastward flowing Antarctic Circumpolar Current resulting in a southward shifting of frontal structures.

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