Geostrophic volume transport and eddies in the region of sub-tropical and sub-Antarctic waters south of Madagascar during austral summer (January–February) 2004

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Geostrophic volume transport based on hydrographic data is estimated across two transects that are covered south of Madagascar in the region of the sub-tropical and sub-Antarctic waters as a part of the Indian Pilot Expedition to the Southern Ocean on board *ORV Sagar Kanya* during austral summer 2004. Strong density current shears are encountered in the study area suggesting high potential for the generation of meso-scale eddies. Volume transports with reversing directions are encountered especially in the depth range of 0–1000 m between Madagascar and around Sub-Tropical Convergence (STC) and they reach maximum values of 40 and 80 Sv (1 Sv = 10^6 m^3 s^{-1}) directed towards southeast and east across tracks 1 and 2 respectively. Such reversing flows, however, are not much seen in the sub-Antarctic and Antarctic waters. The sea surface height anomaly (SSHA) field in the southwestern Indian Ocean based on satellite altimetry during January–February 2004 further shows that relatively high meso-scale variability associated with the regions of larger volume transports promotes meandering of East Madagascar current (EMC) and combined Agulhas return current (ARC)/Antarctic circumpolar current (ACC) systems from where eddies are likely to shed out with a developmental tendency of clockwise (anti-clockwise) rotations on right (left) side of these current streams. A positive correlation between SSHA and mixed layer depth (MLD) is confined to the sub-tropical waters, suggesting the influence of eddies on the dynamics of MLD in the study area.

Keywords: Antarctic waters, Austral summer, eddies.

WESTERN boundary currents, viz. the Agulhas current (AC) and East Madagascar current (EMC) in the southwestern part of the Indian Ocean play a crucial role in affecting meridional heat transport from the warm tropical regions to the Southern Ocean. Meso-scale activity in these current systems further strengthens the heat transport mechanisms. Features like eddies, rings, etc. form when AC gets retroflected south of Africa[1]. Rings form periodically with about 100 days period suggesting that the role of bottom topography in the area of retroflection of AC is limited[2]. Further, the meanders in the Agulhas return current (ARC) also help in shedding both cyclonic and anti-cyclonic eddies in the southern part of the sub-tropical gyre of the south Indian Ocean. The south equatorial current (SEC) splits southward on reaching the northern coast of Madagascar and its southern branch flows as EMC which is generally seen with higher eddy kinetic energy[3]. This boundary current further turns southwestward on reaching the southeastern part off the island and joins the Mozambique current to strengthen AC off southeast coast of South Africa. However, Siedler *et al.*[4] and Palastanga *et al.*[5] have recently shown that EMC is partly retroflected eastward moving in a narrow band around 25°S. They have named this retroflected part of EMC as South Indian Ocean Counter Current (SICC) confining to planetary Rossby wave trains and it is characterized with considerable eddy kinetic energy. However, further south in sub-Antarctic waters south of the Sub-Tropical Convergence (STC), there are no significant seasonal and interannual variations in the eddy kinetic energy in association with the Antarctic circumpolar current (ACC)[6,7]. Large topographical influence of Kergulen Plateau on ACC is seen in the formation of two sub-polar gyres on its western and eastern sides[8]. In this study, we have made an attempt to relate the shears in geostrophic volume transports with eddy fields south of Madagascar using both observed hydrographic and satellite altimetry datasets. The relative role of EMC in nourishing SICC and AC is also discussed.

Figure 1 shows the locations of hydrographic stations along two hydrographic sections, viz. track-1 and track-2 with respective orientations of northeast to southwest between 25°S and 31°S and a meridional one along 45°E up to 56°S. The track-1 starts from Madagascar Basin and ends over the Madagascar Ridge from where the track-2 commences and extends up to the Antarctic waters covering both sub-tropical and sub-Antractic regions across the

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southwest Indian Ridge. These tracks were covered during a multi-disciplinary and multi-institutional Indian Pilot Expedition to the Southern Ocean on board *ORV Sagar Kanya* during austral summer (January–February) 2004. Temperature–salinity profiles up to 2000 m depth are obtained by deploying Conductivity–Temperature–Depth (CTD) recorder (model: Sea-Bird 9/11, accuracies: temperature ± 0.001°C; conductivity ± 0.0001 Siemens/m; depth ± 0.005% of full scale) at the distance of about 60 nautical miles along these tracks. All together, 34 CTD stations were occupied. Dynamic topography with reference to an assumed level of no motion at 2000 db has been derived based on the CTD data to estimate the cross-track geostrophic volume transports.

Hydrographic structures of thermal (potential temperature), haline (salinity) and potential density anomaly fields in 0–2000 m water column along the track are presented in Figures 2–4. The oscillatory nature of isotherms, isohalines and isopycnals is witnessed in the stratified waters north of 40°S while south of this latitude, such wavy pattern is absent. Earlier, Anilkumar *et al.*[9,10] have identified various water masses and locations of fronts along track-2 based on data collected during the same pilot expedition. But, their studies have not included the discussion on the hydrographic structures along track-1. From temperature–salinity fields along track-1 (Figures 2 *a* and 3 *a*), one could see the presence of warm fresh waters characterized with sea surface temperature (SST) greater than 27°C and salinity lower than 35.0 psu within a distance of 300 km from station 1, suggesting that these waters are possibly brought by EMC. The central part of track-1 is seen occupied by relatively high saline waters with a sub-surface maximum salinity core of greater than 35.8 psu around 150 m depth (Figure 3 *a*). Earlier, Nauw *et al.*[11] have also observed similar sub-surface high salinity cores southeast of Madagascar terming them as Intra-Thermocline Eddies (ITEs) with a possible eastern source where sub-tropical high salinity watermass is formed. Further, the effects of ITE along track-2 are seen in increasing of salinity in the core of the Antarctic Intermediate Watermass (AIW) in the depth of 900–1600 m through downward salt diffusive processes. Isopycnals generally rise in the central part and sink at both ends of track-1 (Figure 4 *a*) inferring two opposite flow motions of the regimes. Along track-2, three distinct ridges and troughs in all hydrographic fields are generally more or less confined to the sub-tropical waters (Figures 2 *b* and 4 *b*), north of the Sub-Tropical Front (STF), which is a boundary between warm saline sub-tropical and cold fresher sub-Antarctic water regimes situated at 42°S. However, hydrographic structures south of STF show the dominance of sinking processes with much reduced wavy pattern in the isolines that are generally down-sloped northward from the Antarctic waters.

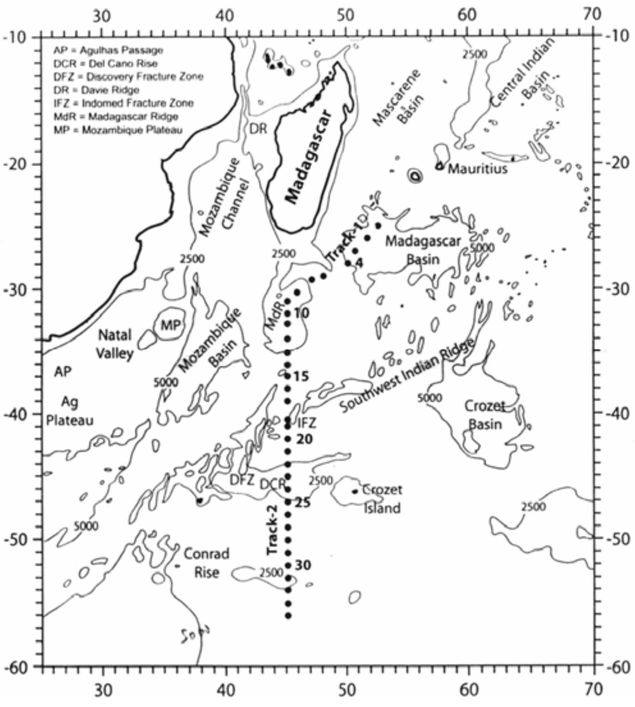

Figure 1. Locations of hydrographic (CTD) stations south of Madagascar during Indian Pilot Expedition to the Southern Ocean during austral summer 2004 on board *ORV Sagar Kanya*.

Geostrophic velocities across tracks-1 and 2, estimated with reference to the assumed level of no motion at 2000 db surface, are presented in Figure 5. Along track-1, the flow structure shows a strong horizontal current shear up to 500 km distance from station 1 in upper 1000 m depth (Figure 5 *a*). A set-up of northwestward flow ($> 0.25\ ms^{-1}$) within 100 km and a southeastward flow ($> 0.35\ ms^{-1}$) at about 400 km distances from station 1 favours formation of a meso-scale eddy with an anti-clockwise circulation. This southeasterly flow is likely intensified when EMC is drawn across the transect 1 off the southeast coast of Madagascar. However, the presence of northwesterly flows near both ends of track-1 suggests development of anti-cyclonic eddies on left side of EMC when it intercepts track-1 twice during its movement into the Mozambique Basin across the Madagascar Ridge. However, Siedler *et al.*[4] show partial retroflection of EMC southeast of Madagascar and the East Madgascar Return Current (EMRC), named as Sub-tropical SICC, meanders in a similar fashion like AC. Along track-2 in the sub-tropical waters north of STF (Figure 5 *b*), the flow is broadly characterized with very weak ($\sim 0.05\ ms^{-1}$) alternating currents, indicating the presence of smaller cells with closed circulation. However, at 41°S, a very strong narrow easterly current jetting with speeds greater than $0.5\ ms^{-1}$ is encountered probably due to merging of northern part of ACC with the southern part of ARC systems at STF. Further south in the sub-Antarctic and Antarctic waters, one could see a broad weak easterly flow with somewhat strengthening seen in ACC in the upper 200 m around 49°S.

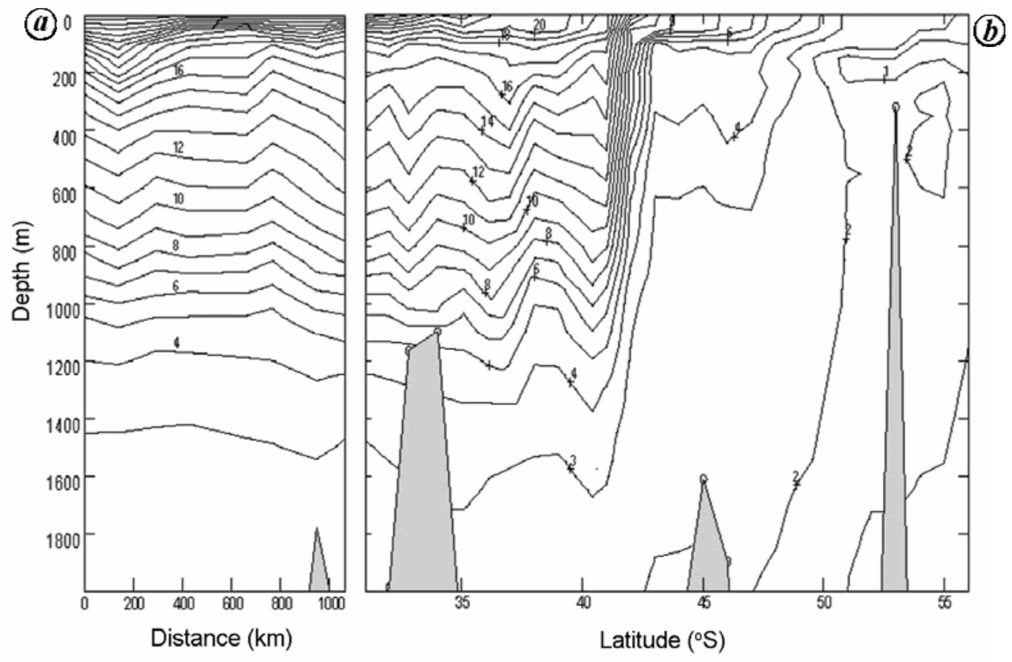

Figure 2. Potential temperature (°C) along (***a***) track-1 and (***b***) track-2.

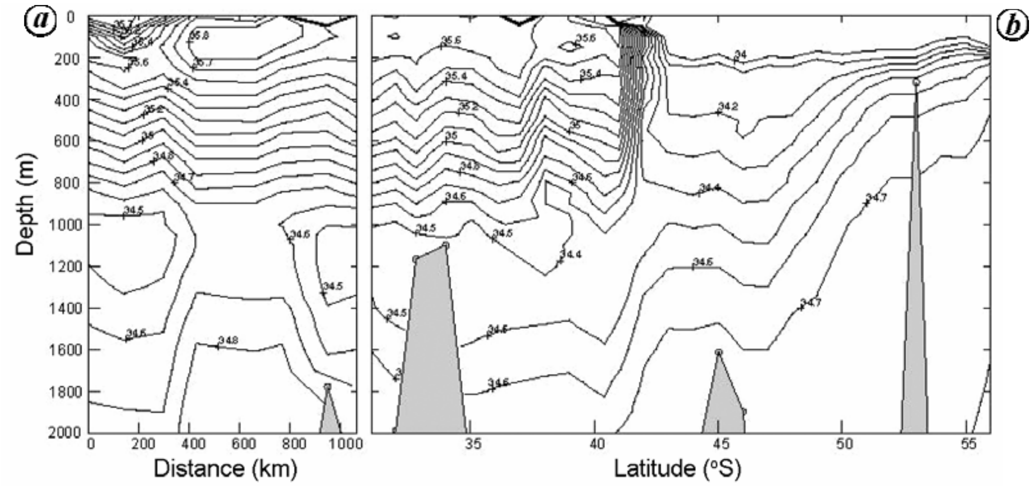

Figure 3. Salinity (psu) along (***a***) track-1 and (***b***) track-2.

Total geostrophic volume transports across tracks-1 and 2 (Figure 6) show the regime of alternate flows seen more prominently in upper 1000 m water column of sub-tropical waters. In the sub-Antarctic waters, the reversals in the transport are not significant. EMC strengthens the transport maximum up to about 50 Sv (1 Sv = 10^6 m^3 s^{-1}) in the upper 2000 m water column (Figure 6 *a*). There seems to be a steady contribution by EMC in feeding anti-cyclonic eddies on its left side as observed from the incidence of same order (~ 30 Sv) in the transport splits at both ends of track-1. Along track-2 (Figure 6 *b*), the transports in upper 1000 m reverse thrice at regular latitudinal distance interval of 2° inferring the presence of three anti-cyclonic cells of about 220 km size interspaced with cyclonic motions north of STF. These cells, on an average, transport waters of about 8 Sv, which is in agreement with the transport by one dipole drawing EMC waters towards the retroflection region of AC[12]. The meandering of combined ARC/ACC systems at STF pave the way for the occurrence of intense cold and warm eddies to the north and south of STF. For the region south off South Africa, Lutjeharms and Valentine[13] have categorized the eddies into a few distinct classes depending on the influences of meridional current shear and bottom topography. The perturbations in STF due to planetary waves cause small pools of warm and cold waters to be detached from combined ACC/ARC and they propagate south and north respectively affecting a rapid heat

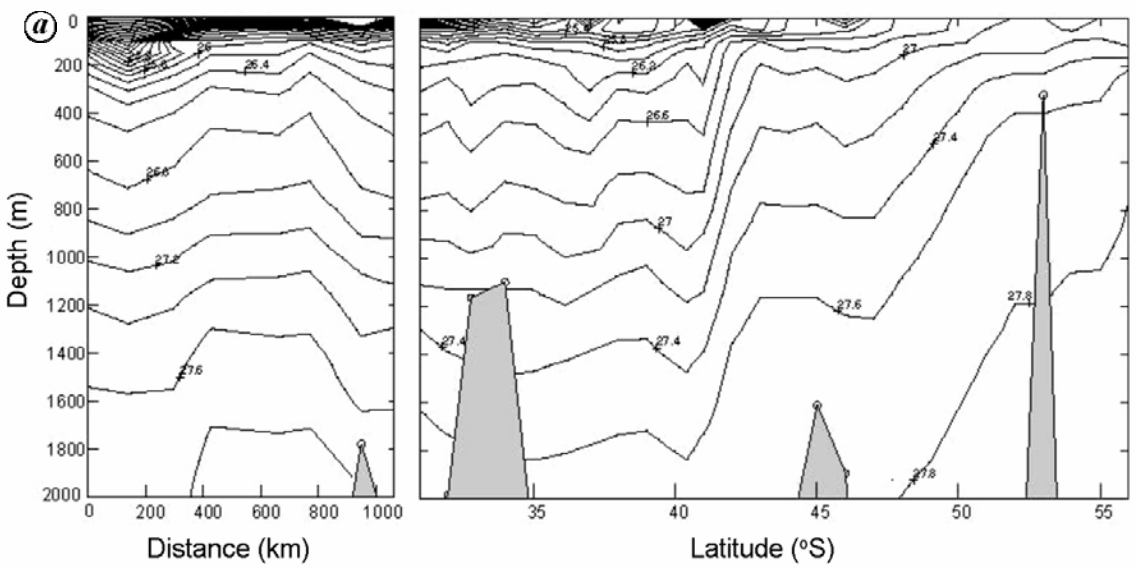

Figure 4. Potential density anomaly (kg m^{-3}) along (***a***) track-1 and (***b***) track-2.

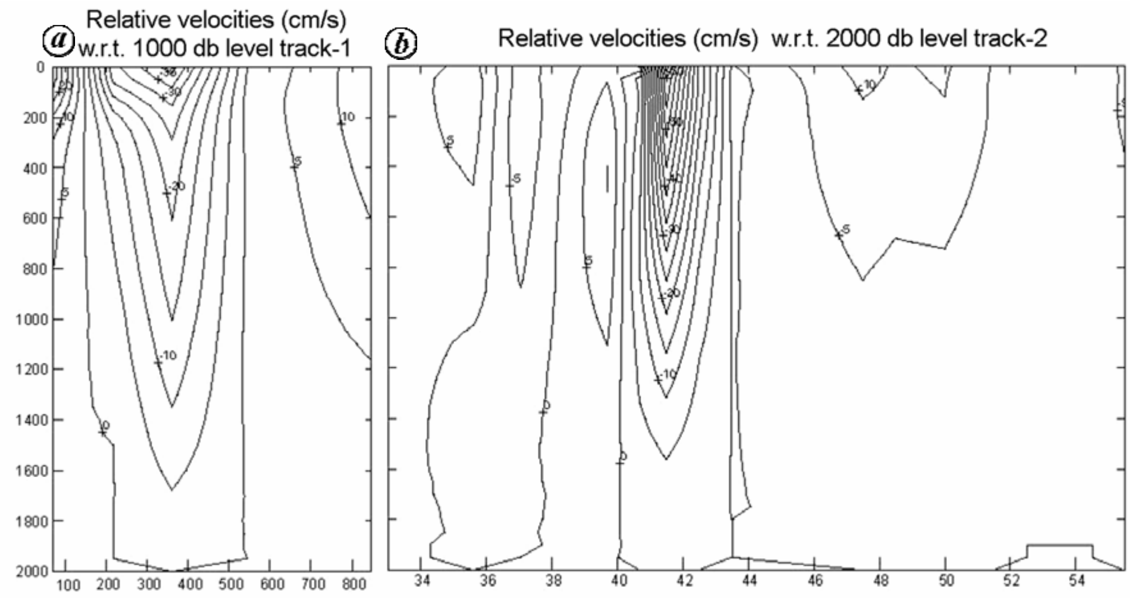

Figure 5. Geostrophic speeds (cm s^{-1}) along (***a***) track-1 and (***b***) track-2.

transport from north to south through eddy diffusion. In general, the comparison of volume transports obtained with 1000 and 2000 db reference levels shows that meso-scale eddies are dominant in the upper 1000 m.

Surface current regimes in southwestern Indian Ocean are also derived from TOPEX/ERS satellite altimetry datasets of Sea Surface Height Anomaly (SSHA) averaged for the period of 28 January–18 February 2004 and presented in Figure 7. Two near zonal regions of moderate to strong shears in SSHA in association with alternating clockwise and anti-clockwise circulation cells (eddies) are identified south of Madagascar between 25°S and 30°S and again between 38°S and 42°S respectively. The latter region is more conspicuous with very high meso-scale variability in SSHA. These regions are associated with westward flowing EMC after its turn at the southeast corner of the Madagascar Island and eastward flowing combined ACC/ARC respectively. Passage of planetary waves causes these currents to meander considerably giving a scope for larger eddy kinetic energy to shed out meso-scale cells. A strong surface current shear along track-2 is also noticed around 41°S from Figure 7 confirming its presence (Figure 5) obtained from CTD observations. The eastward flow due to combined ACC/ARC systems of STF agrees with the volume transport regime as shown earlier. Further, in the Antarctic waters, there is

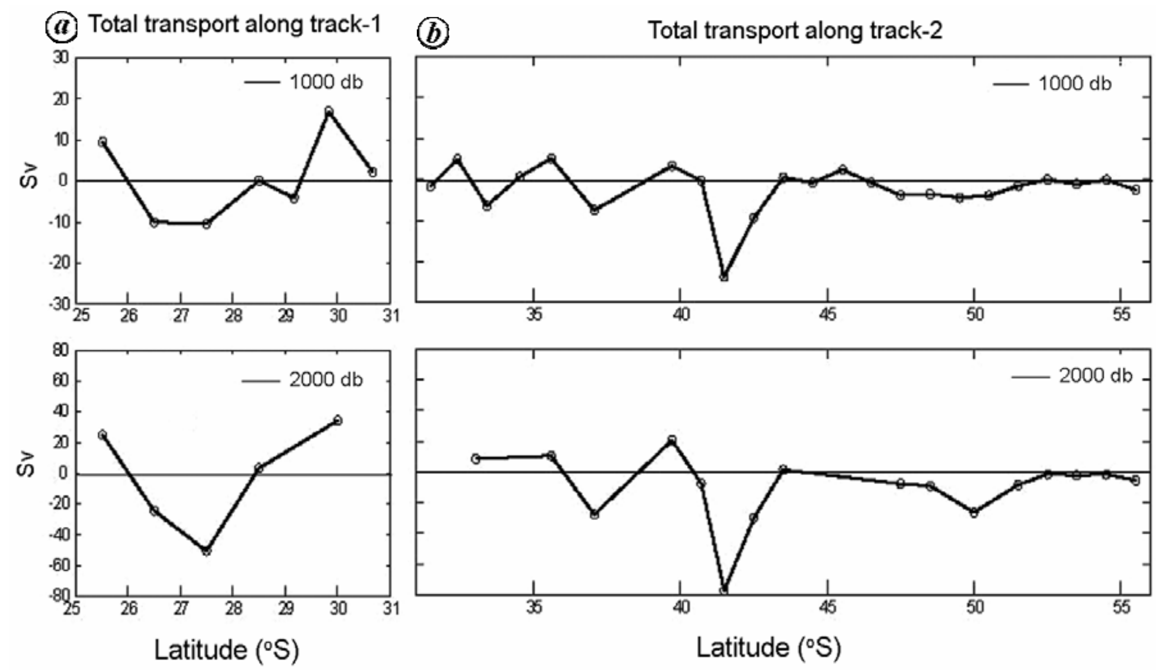

Figure 6. Total geostrophic volume transport ($m^3 s^{-1}$) across (***a***) track-1 and (***b***) track-2. Upper and lower panels represent transport estimates with reference to 1000 and 2000 db surfaces.

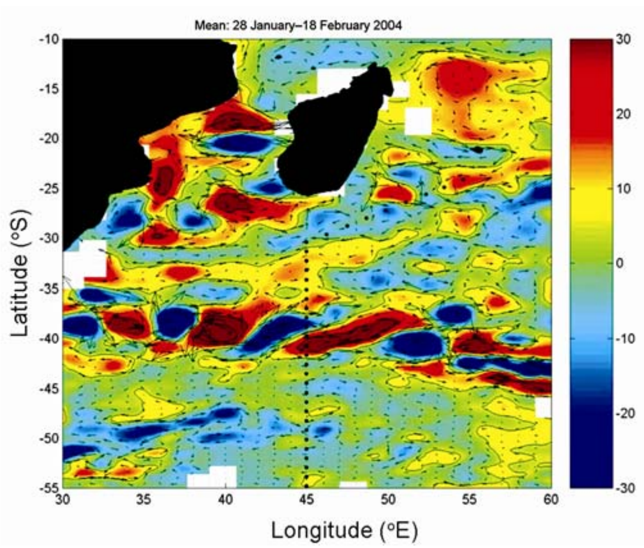

Figure 7. Sea surface height anomaly (cm) and derived surface currents based on TOPEX/ERS altimetry data averaged for the period of 28 January–18 February 2004.

no significant meso-scale variability in the sea surface height except at 49°S where a small increase in the eddy field is indicated along track-2.

The influence of eddies on the Mixed Layer Depth (MLD) is investigated as waters in the upper layers tend to be convergent or divergent associated with them. MLD in the study area varied between 20 and 70 m in the sub-tropical waters wherein SSHA also varied considerably between –0.10 and 0.30 m (Figure 8). South of STF, MLD shows a general southward increasing tendency with values reaching up to 120 m at 53°S in the Antarctic waters though SSHA did not increase correspondingly. However, further south, the surface mixed layer is decreased to about 70 m. Anilkumar *et al.*[10] have also shown maximum summer freshwater input into the surface layer relative to the winter water due to sea ice melting around 53°S. The plot (Figure 9 *a*) between MLD and SSHA values extracted at CTD locations along two tracks shows a wide scatter with almost negligible correlation. However, it is interesting to note a considerable reduction in the scattering nature and a positive correlation (correlation coefficient = 0.49, significant at 0.1 level) established between them if the CTD locations are confined to the sub-tropical waters north of STF. This improved relationship suggests that eddies affect the mixed layer due to horizontal convergences and divergences in field of motion in the regions of higher eddy kinetic energy such as those near STC and south of Madagascar coasts. In the waters of sub-Antarctic and Antarctic regimes, strong sinking processes of cold water masses could easily offset any influence of weak or moderate eddies.

Palastanga *et al.*[5] have attributed that eddies generated around 25°S are due to westward Rossby wave propagation with an annual frequency of about 5 and an average wavelength of about 360 km. EMC is quite strong upstream of the east coast of Madagascar before meeting these wave trains. Cyclonic eddy activity is also occasionally seen with an offshore extension of upwelled waters[14]. Schott *et al.*[15] have observed surface current of ~ 0.7 ms^{-1} EMC at 23°S. It is not clear whether the eddy

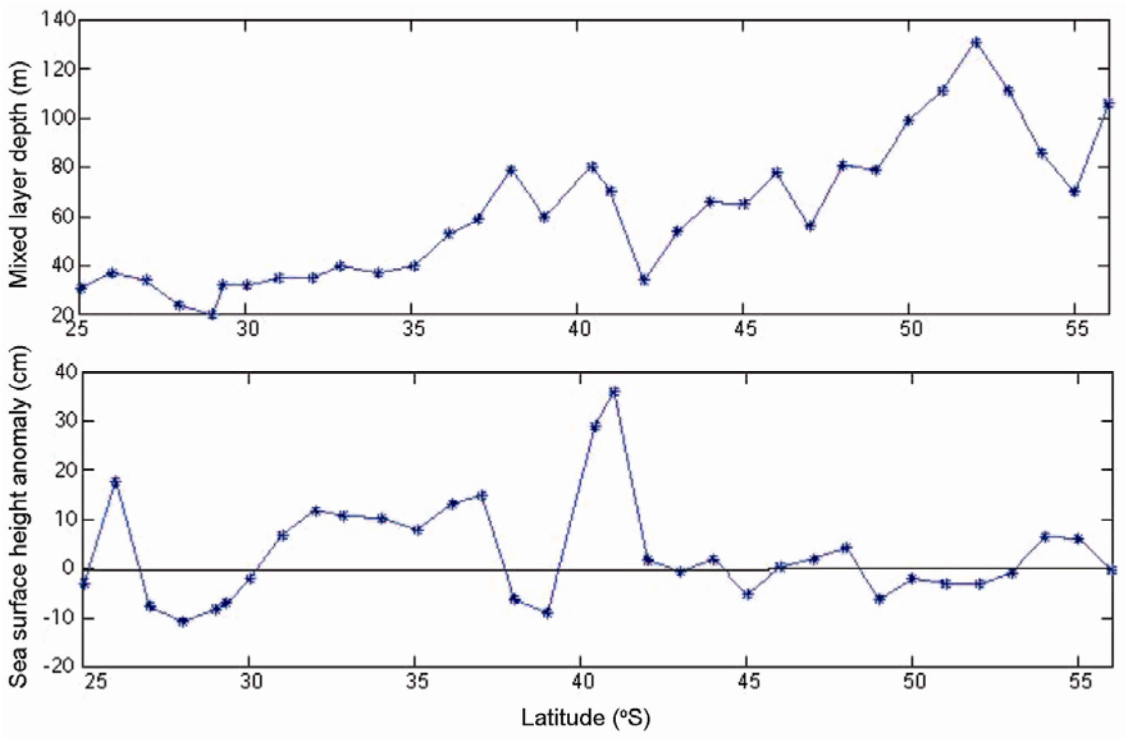

Figure 8. Variability of Mixed Layer Depth (upper panel) and Sea Surface Height Anomaly (lower panel) along two tracks.

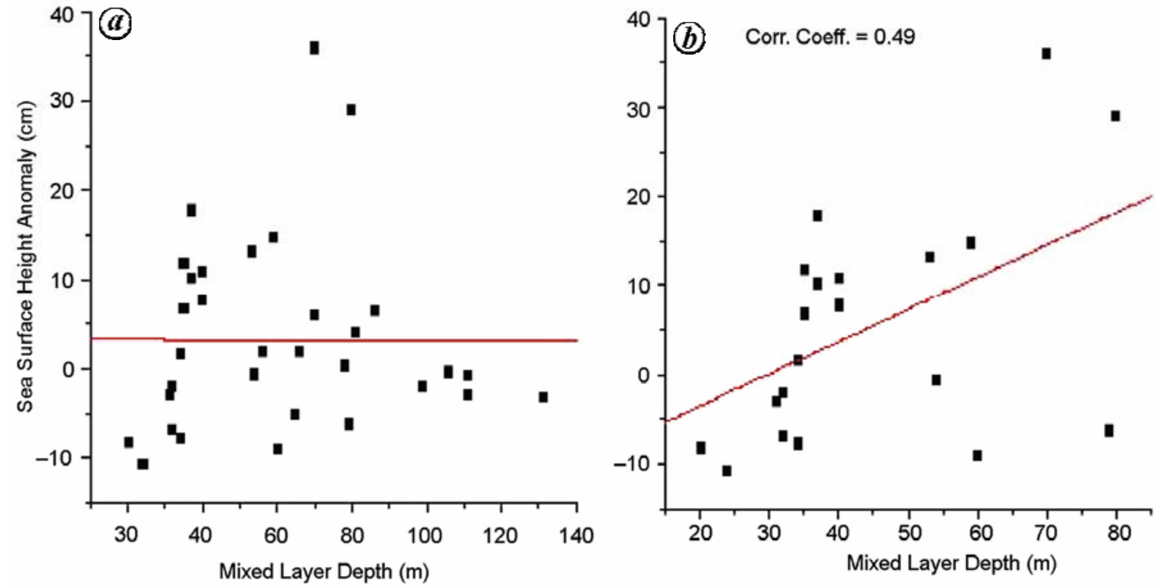

Figure 9. Scatter plot between Mixed Layer Depth and Sea Surface Height Anomaly values extracted at (***a***) all CTD locations, and (***b***) CTD stations north of Sub-Tropical Convergence only.

activity south of Madagascar is the result of baroclinic waves from the east or due to meso-scale variability in the upstream of EMC itself. The phase of planetary wave interacting with EMC is likely to determine the westward turn off the southeast coast of Madagascar. An approaching anti-cyclonic (cyclonic) wave with southerly flow in advance intensifies EMC momentarily giving an apparent retroflection. The retroflection of EMC is not quite evident from the present study. This is in agreement with the recent finding of Quartly *et al.*[16] who have re-examined the retroflection of EMC southeast of Madagascar. A long time-series of current measurements off southeast coast of Madagascar would help understand whether it is a regular feature. The influence of Madagascar Ridge south of the island during the westward movement of eddies is possible since the ridge acts as a barrier with temporary reduction in their propagation speeds. A pair of anti-cyclonic eddies across the Mozambique Channel is seen regularly with a mean size of 250 km and movement speeds[12] between 5 and 10 ms^{-1}. It was further shown that eddy pairs are related to the phases of climate modes, namely the Indian Ocean Dipole and El-Nino/La Nina as EMC is affected inter-annually with about one year lag after peaks in these climate modes appear in the equatorial regions. Eddies are prominently detected at the southeastern corner of Madagascar from TMI images[17,18]. The prominence of anti-cyclone eddies across Mozambique Channel as seen from SSHA map (Figure 7) could be related to high meso-scale variability in the sea surface height due to interaction between northward turned EMC in the eastern part of the channel and southward flowing Mozambique Current in the western part of the channel.

The present study shows that meso-scale activity due to the passage of baroclinic waves in the sub-tropical waters south of Madagascar and just north of STF as inferred from both satellite altimetry (Figure 7) and observed hydrographic structures (Figures 2–4), set-up meanders in EMC and combined ACC/ARC respectively, and moderate to strong eddies are therefore possible to shed out due to barotropic/baroclinic instabilities, whereas the region between these two current systems is characterized with a weaker eddy activity. These eddy motions further help in the rapid transport of excessive heat from the northern parts of the Indian Ocean towards the Southern Ocean and their effects need to be included in global and regional climate modes.

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