

Thermohaline circulation and water characteristics around Mauritius group of islands

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Received 15 June 1989, revised 23 April 1990

Conventional hydrocast data together with XBT soundings, collected during September-October 1987, in the area lying between 10°S to 20°S and 56°E to 62°E encompassing the Seychelles-Mauritius ridge, have been examined to project the thermohaline structure and geostrophic flow fields. In the study area, geostrophic circulation shows a predominant westerly flow. This flow on crossing the ridge zone triggers the meridional rise of isotherms towards the northern latitudes from depths of 300 to 500 m. This type of flow gives rise to possible upwelling in the western region, which is also supported by increased levels of nutrients and biomass.

Physical oceanographic studies in the southwestern Indian Ocean mainly deal with the characteristics of the South Equatorial Current [SEC]. The upper 1000 m layer in this region is characterized by a variety of watermasses of different origins. The hydrographic property distribution in this region has been earlier studied¹⁻⁴. It is well known that the SEC splits in to 2 or 3 branches near Madagascar^{1,3} and these may cause the formation of gyres of different scales. Though some studies have been made on gyres in the southwestern Indian ocean^{2,3,5}, no detailed study is available around Mauritius group of Islands.

The area under investigation is characterized by approximately north-south oriented Mauritius-Seychelles Ridge which extends from about 5° to 20°S. This ridge consists of varying sill depths and several fractures along its length. Meridional sections in this area are extremely useful to understand the influence of this meridional ridge on strong zonal flows. With this aim, 3 meridional sections have been chosen in the present study (Fig. 1). One section falls on the top of the ridge and the other two sections fall on the eastern and western flanks of the ridge. The section on the western flank of the ridge covers the eastern part of the Mascarene Basin. The present investigation is made to describe and discuss the thermohaline circulation and water characteristics in the upper 1000 m of the southwestern Indian Ocean (10° to 20°S and 56° to 62°E).

Materials and Methods

During the 35 cruise of *ORV Sagar Kanya* [15 September to 12 October 1987], hydrographic data (temperature and salinity) up to 1500 m depth using revers-

ing bottles fitted with reversing thermometers and depth - temperature profiles up to 760 m depth using XBT (expendable bathy thermograph; Sippican R-603 G; temperature accuracy; $\pm 0.2^\circ\text{C}$; depth accuracy; $\pm 2\%$), together with surface meteorological

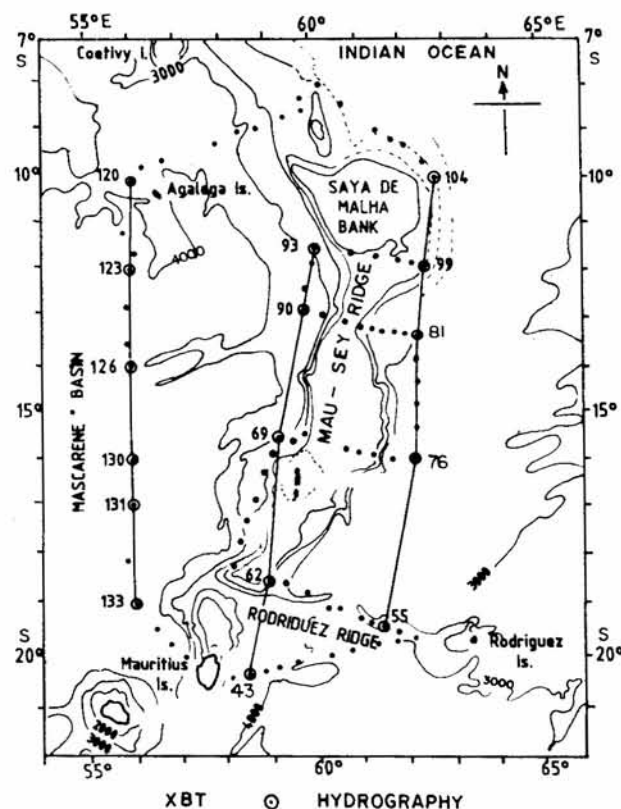


Fig. 1—Study area along with 3 meridional sections hydrography stations and XBT stations

parameters were collected around Mauritius group of Islands. The area covered (Fig. 1) includes Rodriguez ridge, Mauritius-Seychelles ridge, Nazareth bank, Saya de Malha bank and eastern Mascarene basin. Altogether 35 hydrocast and 85 XBT stations were occupied during the survey. Salinity samples were analyzed on a Guildline 8400 A model Autosol salinometer available on board. The salinometer was standardized with IAPSO standard seawater after every 20 samples during the entire cruise. The conductivity ratio so obtained was converted into salinity using practical salinity scale⁶. Temperature readings obtained from reversing protected and unprotected thermometers were corrected. Necessary temperature corrections were applied to XBT data using bucket thermometer readings. Temperature data were digitized at 10 m depth intervals. Following Colborn⁷, the mixed layer thickness is taken as the depth at which the temperature is less by 1°C from the SST and the thickness of thermocline is defined as the layer thickness between bottom of the mixed layer and 13°C isothermal surface. Geostrophic flow fields, were computed using temperature and salinity values digitized at standard depths. Vertical sections showing the distributions of temperature, salinity, sigma-t and geostrophic currents [hatched portion denotes the easterly flow and non-hatched portion denotes westerly flow] were prepared for each section to study the prevailing oceanographic conditions in the upper 1000 m water column. The charts showing the vertical distribution of physical properties were prepared with a vertical scale of 5000:1 for the upper 300 m and 1000:1 for the layer below this depth.

Results

Sea surface temperature (SST) decreases (Fig. 2A) from north to south (i.e. 27°C at 10°S to 23.8°C at 19°S). The mixed layer depth varies from 65 to 145 m with the lowest value at 10°S and highest at 19°S. In the thermocline the isotherms slope downward from north to south. The bottom of the thermocline, taken as the depth of occurrence of 13°C isotherm (Colborn⁷), varies from 260 m in the north to 350 m in the south. The vertical gradients within the thermocline are comparatively stronger in the northern region (sts 99 and 104) between 24° and 18°C isotherms ($0.13^{\circ}\text{C.m}^{-1}$) below which the thermocline itself is very poorly formed. In the layer below 220 m, the isotherms show an upward bulge north of 13°S (st 81). They slope downward towards north in the upper 100 m of this layer and upward in the column below. In the southern region of the section, the vertical gradients are moderate and nearly uniform. At st 55, which falls on the ridge, a nearly isothermal water of temperature

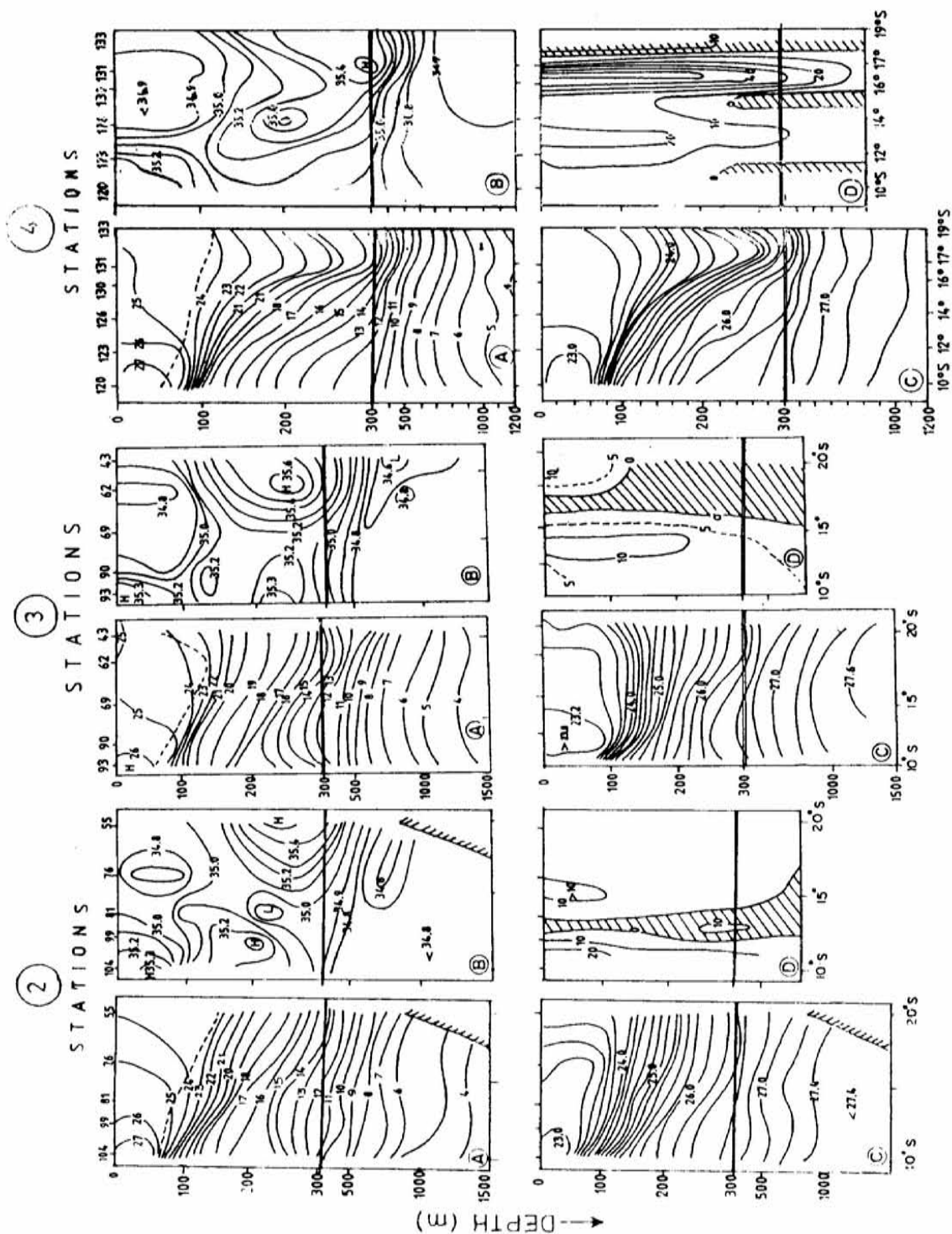
< 24°C extends up to a depth of 150 m from the surface.

The surface salinity decreases from 35.29×10^{-3} at 10°S to 34.8×10^{-3} at 17°S and then increases to 34.99×10^{-3} at 19°S (Fig. 2B). At st 55 the nearly isohaline layer extends to about 100 m from the surface, within this layer the salinity varies by about 0.01×10^{-3} . The salinity of the surface high salinity water in the north is about 35.3×10^{-3} at 50 m depth. This surface high salinity water progresses toward south up to st 81, where after a low salinity water with a value of 34.67×10^{-3} can be observed at st 76. At this station, the surface salinity is 34.81×10^{-3} , but it falls to 34.67×10^{-3} at 20 m depth and remains around that value up to 100 m depth. Below 100 m, the salinity field shows alternate cores of high and low saline water with their axes approximately between 200 and 220 m. The high saline water between 100 and 300 m in the northern region has core value of 35.3×10^{-3} at 200 m and it abuts against a low saline water at the same depth range at st 81 which has only a limited lateral extent with a core value of 34.88×10^{-3} around 220 m. Further south of this low saline water, another high saline water appears to be entering from south with a maximum value of 35.56×10^{-3} at station 55 at a depth of about 240 m. Below 300 m depth, the salinity gradually decreases. In the southern region of the section, low saline water enters from south and has a minimum value of 34.50×10^{-3} around 700 m at st 76. In the north, the salinity is more or less uniform below 500 m depth.

The vertical distribution of density, represented by sigma-t, increases from north to south from about a little < 23 to 23.6 at the southernmost station and it is highest along this section (Fig. 2C). The density in the mixed layer is nearly uniform up to a depth of about 60 m in the north and 100 m in the south. Further the density gradients are also strong in the north than in the south and pycnocline slopes downward towards south up to a depth of 200 m. Below 200 m depth, the isopycnals show a spreading in the northern region. Below 300 m depth, isopycnals slope upward in the north and downward in the south.

The computed geostrophic currents across this section (Fig. 2D) show a weak easterly current between sts 81 and 99. But this current marginally increases and attains a velocity of 10 cm. sec^{-1} between 250 and 400 m depth. Across the rest of the section, the current is predominantly westerly with velocity 20 cm. sec^{-1} in the northern region. The velocity of this westerly current decreases southward.

In section 2, the SST (Fig. 3A) decreases from north to south from 26° to 24.5° C up to st 62 and it increases further south to 25.6° C [st 43]. The near isothermal



Figs. 2 to 4—Vertical distribution of [A] temperature, [B] salinity, [C] sigma-t and [D] geostrophic currents along sections 1, 2 and 3

layer extends to as deep as 130 m at st 62. The mixed layer is 64 m depth at the northern most station and steeply deepens to 135 m at st 62 and further south, the mixed layer shoals back to surface. Below the mixed layer, the isotherms, in general, slope downward towards south. The thickness of the layer between 24° and 18°C isotherms is about 75 m in the north and 180 m in the south. Sloping of the isotherms north of 13°S reverses in the layer below 200 m, but south of this latitude, the slope reverses only below 500 m depth. The isotherms show a gentle ridge in the center of the section below 500 m, which may be due to the fact that this section is passing through the shoals and troughs of the great ridge. The temperature at 1500 m is less than 4°C.

The surface salinity (Fig. 3B) at st 93 is 35.31×10^{-3} and it gradually decreases towards south reaching lowest value (34.77×10^{-3}) along this section at st 62. A low saline water with a nearly homogeneous salinity of 34.77×10^{-3} extending up to a depth of about 90 m is seen centered around st 62. In the layer between 100 and 300 m, 2 high saline water masses, one entering from the north and the other from south can be seen. They abut against each other at st 69. However, as a result of this contact, the whole layer of about 200 m thickness at this station has a uniform salinity of slightly $< 35.2 \times 10^{-3}$. The high saline water entering from the north has a maximum value of 35.3×10^{-3} , while the one entering from the south has a maximum value of 35.64×10^{-3} . Below 500 m, a low saline water with a salinity minimum of 34.58×10^{-3} enters the region at st 43. The water below 500 m depth, north of 15.5°S, has a salinity 34.75×10^{-3} . In this layer the variations in salinity are very small.

The density (Fig. 3C), more or less similar to that of section 1, varies from 23 to 23.6 σ_t at the surface. Below 80 m, sigma-t structure shows a trough like pattern up to a depth of about 150 m and below that the isopycnals show a ridge like structure at the center of the section, probably due to the crossing of the ridge at st 62.

Along section 2 the current is westerly up to south of st 69 with a velocity slightly higher than 10 $\text{cm} \cdot \text{sec}^{-1}$ (Fig. 3D). South of it, the current is eastward with speeds $< 10 \text{ cm} \cdot \text{sec}^{-1}$. Further south, the current is westerly and has a velocity around 10 $\text{cm} \cdot \text{sec}^{-1}$ at the surface. This current persists up to 120 m depth.

The vertical distribution of temperature along section 3 is shown in (Fig. 4A). The distribution shows a strong north-south gradient with a difference of 3°C at the surface. The SST varies from about 27°C at 10°S to 24.8°C at 19°S. The warm water at st 120 extends vertically downwards to a depth of 60 m with a tempe-

perature maximum [$T > 27.2^\circ\text{C}$] at 30 m depth. The mixed layer depth varies from 50 m at 10°S to 125 m at 19°S. Below this layer, the temperature falls gradually to a value of 5°C around 1100 m. Thermocline seems to be poorly formed in this region except at st 120 where the vertical gradients of temperature, typical of thermocline, are strong approximately in the depth range of 80 to 100 m in the northern region. The vertical gradients of temperature progressively become weaker with increasing latitude along this section. The thermocline slopes downward towards south up to st 131, where the isotherms form a trough. This feature is clearly seen up to a depth of 1200 m. Further south of this station, the isotherms rise towards surface.

Fig. 4B shows the distribution of salinity along section 3. The surface salinity shows a gradual decrease southwards from 35.3×10^{-3} to 34.8×10^{-3} at st 126 [14°S]. But south of this station the salinity increases progressively to a value 34.92×10^{-3} . Furthermore the surface high saline water [35.4×10^{-3}] north of 12°S is seen penetrating downward up to 100 m depth. Also in the sub-surface layers, below 100 m depth, a high saline water with a core value of 35.53×10^{-3} is seen entering from south around 200 m depth and extends up to 12°S. Below 600 m depth, a low salinity water with salinity around 34.62×10^{-3} at 1000 m depth enters this region from the south and extends up to 14°S. Except for the layer between 100 and 300 m depth, the salinity pattern shows a general decrease from north to south.

The vertical distribution of density along section 3 is shown in Fig. 4C. The density of the water along this section gradually increases towards south. The isopycnals show a well pronounced shoaling trend in the north and a strong deepening trend at st 131. The vertical gradients of sigma-t show a reverse trend with depth from north to south. However, the vertical gradients are strong in the layer between 60 and 100 m in the north while they are weak at the same level in the south. But the vertical gradients in the pycnocline in the south are stronger in the layer below 200 m, whereas they are weak in the north at the same level. Thus pycnocline inclines almost vertically from north to south.

The structure of the geostrophic currents along section 3 has been shown in (Fig. 4D). The flow is chiefly westerly along the section up to 17°S. South of 17°S, the flow is easterly. The westerly flow between 16° and 17°S is relatively stronger and the speed reaches as high as 50 $\text{cm} \cdot \text{sec}^{-1}$ at the surface. The sub-surface flow below 240 m is easterly between 10°S and 12°S, and 14° and 16°S, i.e., the flow at this depth is in the direction opposite to that at the surface.

Discussion

The surface water in the low latitudes of the southern Indian Ocean is fresher in general than the water in the north or south. SEC brings low saline water from the Timor and Banda Seas^{1,8}, where the salinity varies from $34 - 34.5 \times 10^{-3}$ and this water spreads westwards roughly along 10°S . The low saline water which is seen extending up to 55°E during summer, continues to 65°E during winter and the surface salinity varies between 35 and 35.3×10^{-3} between 10°S and 20°S ^{1,9}. In the present investigation also the surface salinity shows similar features and varies between 35 and 35.3×10^{-3} up to 12°S . This surface high saline water mass is generally associated with a relatively warm temperature in the north. Further, the high saline water which appears around 60 m at st 104 (Fig 2B) can be traced at the surface on the neighboring western section (Fig 4B) almost around the same latitude. This water mass which is present in the upper portion of the thermocline may possibly be of Arabian Sea origin since the Arabian Sea high salinity water mass, which forms in central and northern regions of Arabian Sea, is known to spread with various branches of surface circulation throughout the monsoon gyre north of 10°S and may be seen as a surface high saline water mass in the upper portion of the thermocline¹⁰ between 26° and 22°C .

The salinity distribution suggests a general northward movement of water in this region below 100 m depth (Figs 2B, 3B and 4B). Along the eastern section (Fig. 2B) the northward moving water in the south and southward moving water in the north are separated by a salinity minimum around 13°S . But this feature disappears in the central (Fig. 3B) and western sections (Fig. 4B). The central section shows a direct contact between the 2 high saline waters with the formation of a nearly isohaline layer (250 m) between them and the western section shows only 1 high saline water mass moving northward. This indicates that the westward movement of the low salinity sub-surface water is confined to about 61°E and the salinity progressively increases westwards. The high salinity water mass along 56°E is double cored within itself with salinity values of $> 35.6 \times 10^{-3}$ at the cores between 200 and 300 m depths. This water mass progressively rises towards surface in its course of travel towards north.

The density analysis of the water masses shows that the circulation in this area is affected by the presence of the ridge, which gives rise to several small scale gyres embedded in the broad SEC system^{4,11}. The westward flowing current when confronts with the ridge can produce a strong divergence on the leeward side, which consequently results in the upwelling in the region. Such a feature has been reported earlier by Ragoonaden *et al.*⁴ The mixed layer and the thermocline exhibit a southward tilt in all the 3 sections. This phenomenon is essentially due to the broad westerly current prevailing in this area. Analysis of geostrophic flow field also suggests a broad westerly flow with small pockets of easterly flow at few places. The westerly flow, after crossing the ridge gains strength and exceeds even $50\text{ cm}\cdot\text{sec}^{-1}$ between sts 130 and 131. The easterly flow on the other hand is weak and in general the magnitudes of this flow are $< 10\text{ cm}\cdot\text{sec}^{-1}$.

Acknowledgement

The authors express their gratitude to Dr B.N. Desai, Director for his keen interest and to the Department of Ocean Development, New Delhi for providing financial support.

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