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Physico-Chemical Characteristics & Circulation of Waters in the Mauritius-Seychelles Ridge Zone, Southwest Indian Ocean

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Influence of north-south oriented Mauritius-Seychelles ridge on flow patterns in the southwest Indian Ocean has been studied using IIOE data. The ridge affects the zonal flow by causing divergence (upwelling) with a consequent increase in nutrient levels in its leeward side especially during winter. Distributions of physico-chemical parameters together with geostrophic flow patterns for both austral winter (June to August) and summer (December to February) seasons are also presented. The occurrence of 2 general gyres – clockwise and anticlockwise rotations with centres around 12°S and 22°S respectively – is a general characteristic feature of the surface circulation in the southwest Indian Ocean.

Oceanographic studies conducted in the southwest Indian Ocean have focussed mainly on the branching of South Equatorial Current (SEC) near the longitudes of Malagasy[1-3]. East of Malagasy, the circulation pattern and distribution of physico-chemical parameters are known only in broad terms[4]. In this paper, the effect of Mauritius-Seychelles ridge on the flow patterns and consequent redistribution of some physico-chemical water characteristics such as temperature, salinity, oxyty and inorganic phosphate are presented. Comparison of summer and winter spatial distributions of these characteristics together with dynamical topography (geostrophic flow) field is also presented.

Materials and Methods

The study region is characterised by Mauritius-Seychelles ridge (Fig. 1) which orients in north-south direction extending from about 5°S to 20°S and protrudes very close to the sea surface at some places. In some regions, the 200 m isobath is more than 250 km wide and at other places, the sea floor drops steeply on both sides to reach almost 3000 m within a few km distance from the ridge.

Eight oceanographic sections (Fig. 1), covered during the International Indian Ocean Expedition (IIOE) period, were identified for the present study and the appropriate data were retrieved from the data archives. December to February and June to August were considered respectively for summer and winter seasons. Sections II and III on either side of the Mauritius-Seychelles ridge were selected for the study of ridge effect as these were covered by the same ship *RS Discovery* in winter months (June-July 1964) with a time lag of only 9 days. Along these two sections, vertical distributions of temperature, salinity, oxyty and phosphate fields were presented. For the second part of the study on seasonal variability in the region, distributions of temperature and salinity fields along sections V and VI were prepared. Data along sections I, IV, VII and VIII were also considered for preparation of horizontal charts for summer and winter seasons at 0, 50, 100, 200, 500 and 1000 m depths. For geostrophic circulation, 1000 deci-bar (db) surface was choosen as the depth of no motion and charts showing the dynamic topography with reference to this depth were presented for 0, 50, 100, 200, 300 and 500 m depths. It is recalled that the dynamic topography of the sea surface relative to a deeper reference level of least motion gives a good approximation for the circulation in different layers of the ocean[5].

Results and Discussion

Mauritius-Seychelles Ridge Effect

Figs 2A (i) and (ii) show the vertical thermal structure at western (section II) and eastern sides (section III) of the ridge. In both regions, the iso-

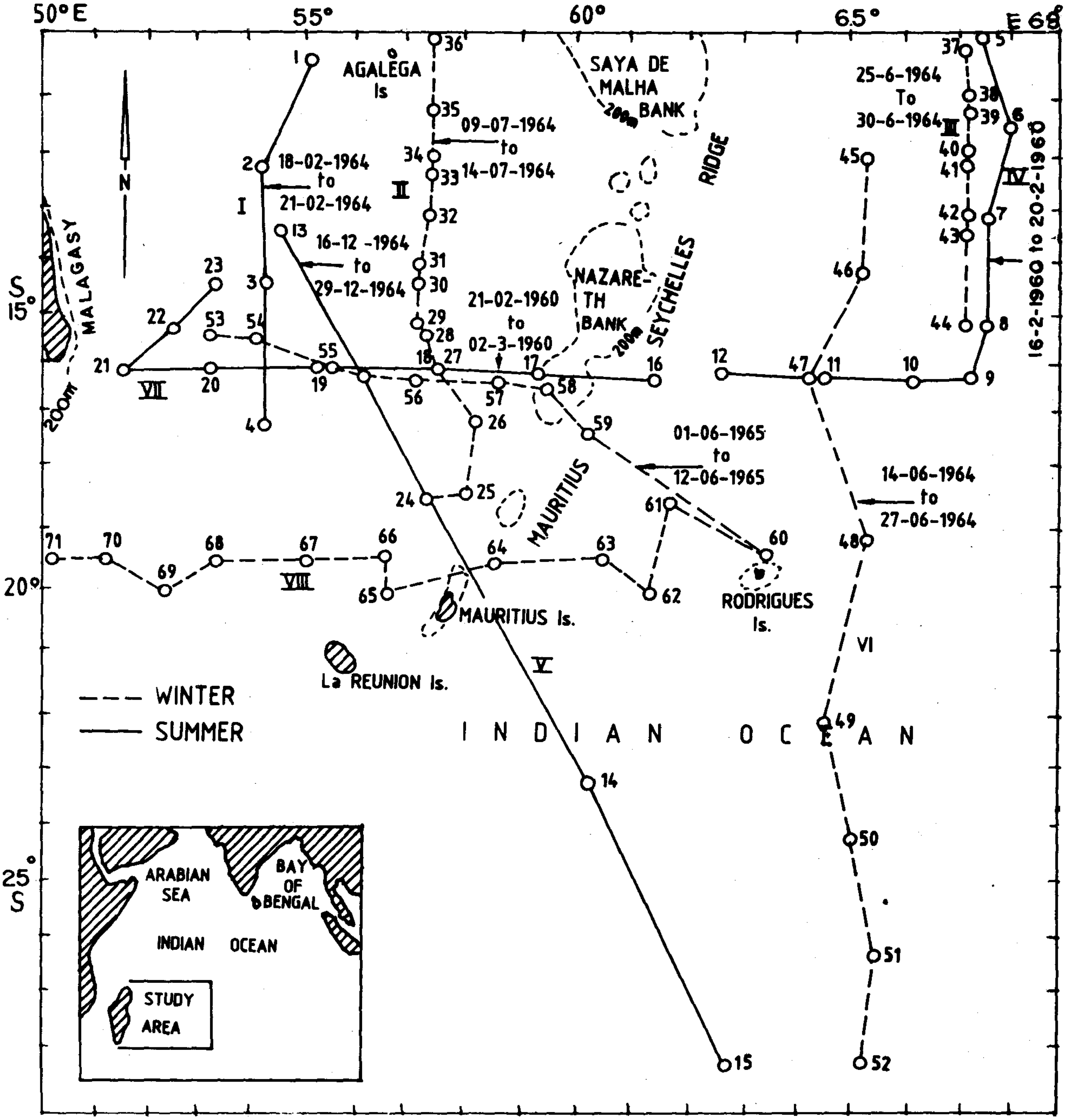

Fig. 1 – Area of study with station locations

therms downslope from north to south especially in upper 700 m where they level off. However, a general rise in the depths of isotherms is observed in upper 100 m layer in the western side of the ridge with a drop in temperature by $>2°C$ at certain depths which could be attributed to upwelling on account of surface divergence. This statement is based on the fact that for potential vorticity to be conserved, the stream lines should tend to be convergent at flow side of an obstacle and divergent at its lee side in the southern hemisphere[6]. The northward upsloping of the isotherms from surface to 700 m gives an indication of a westerly flow impinging on the ridge in its eastern side. However in the west, in the depth range of 400-900 m, the presence of domes and depressions in the thermal structure reflects the disturbance to the smooth flow pattern that is observed in the eastern side of the ridge.

Distribution of salinity in the eastern side of the ridge in [Fig. 2B(ii)] indicates a well defined salinity maximum zone ($>35.4 \times 10^{-3}$) centred around

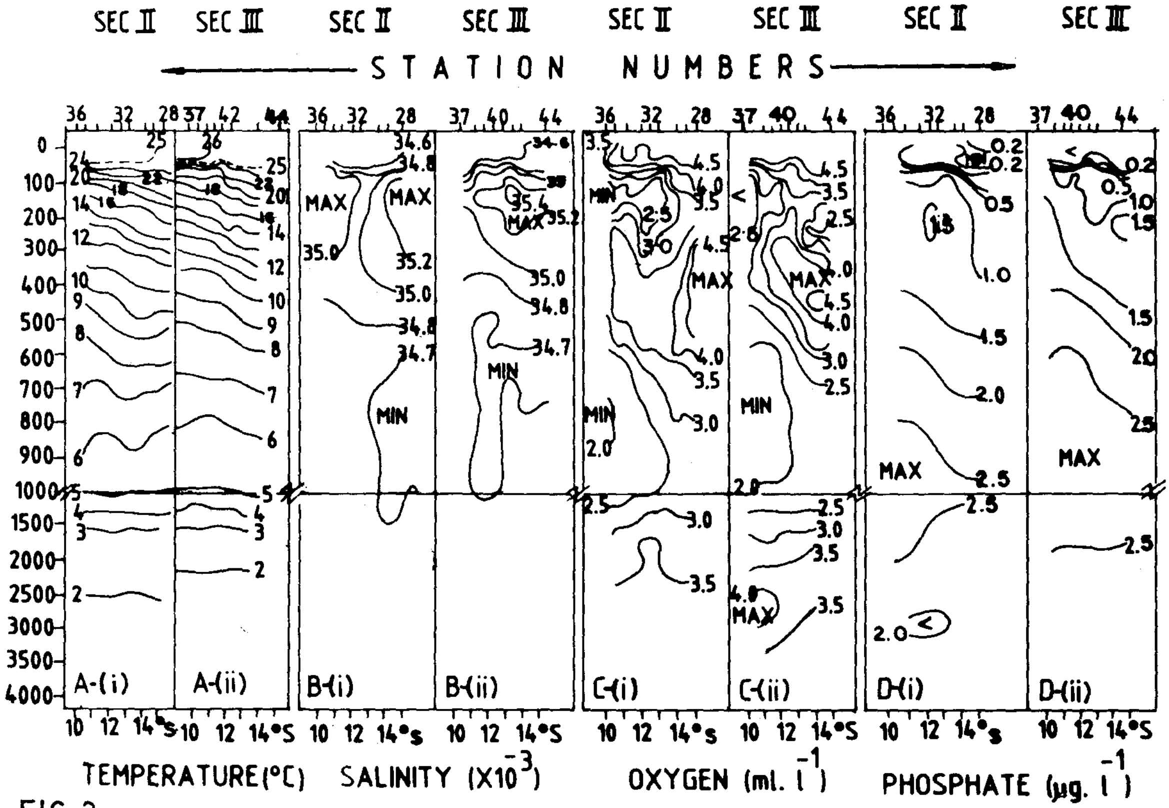

FIG. 2

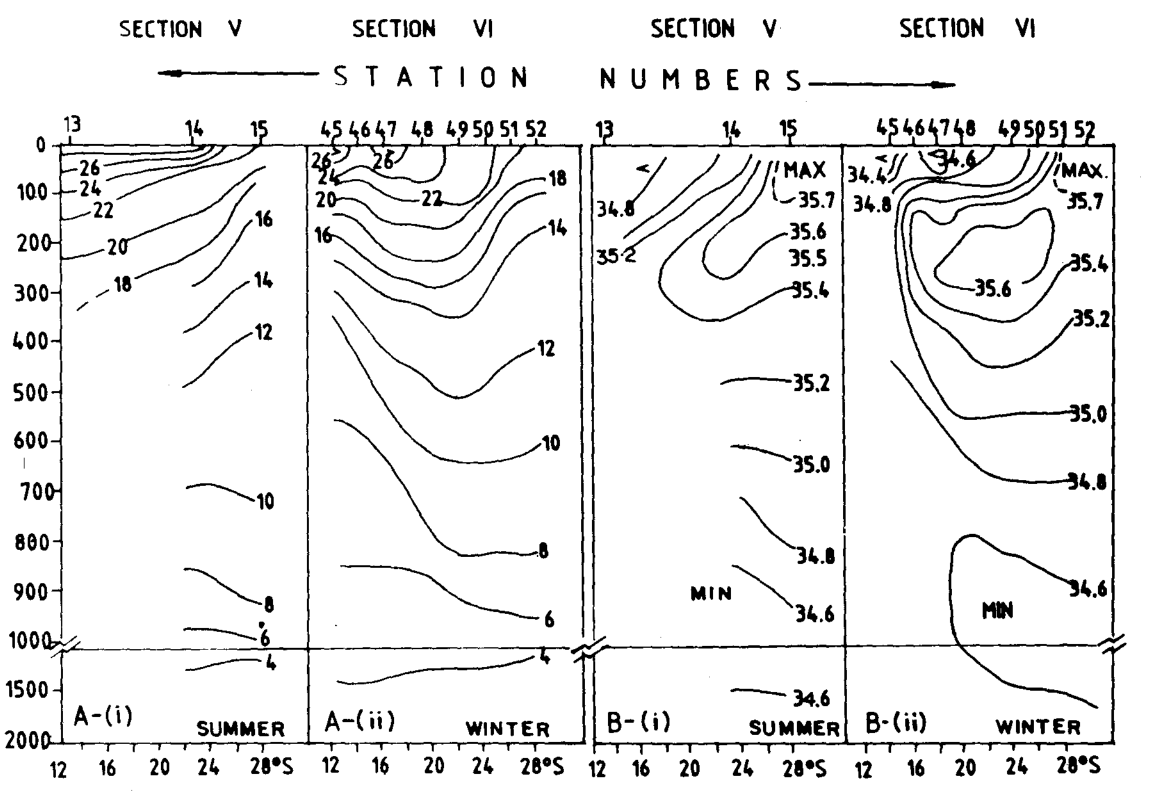

FIG. 3 TEMPERATURE (°C) N→S SALINITY (X 10^{-3})

Fig. 2 – (A) Temperature, (B) salinity (C) oxyty and (D) inorganic phosphate in the west (i) and east (ii) of the Mauritius-Seychelles ridge

Fig. 3 – (A) Temperature and (B) salinity along section V in summer (i) and section VI in winter (ii)

150 m. Below this, the salinity decreases leading to a salinity minimum zone ($<34.7\times10^{-3}$) around 700 m. Premchand and Sastry[1] have also obtained a similar pattern using summer data of 1965 collected on board *Atlantis II* in the southwest Indian Ocean. In the western side of the ridge [Fig. 2B(i)] the shallow salinity maximum zone is also located around 150 m but in a disorganised way as seen from the presence of 2 pockets of high salinity cells at the 2 ends of section II. The upper salinity maximum values, however, are lowered ($>35.2\times10^{-3}$) as compared to those in the eastern side of the ridge. Below the zone of maximum salinity, the salinity distribution remains more or less uniform in both sides of the ridge.

The oxyty vertical profiles in both sections (Fig. 2C) show a maximum zone (>4 ml.1^{-1}) around 400 m sandwitched between 2 minima (<2.5 ml.1^{-1}) centred around 150 and 800 m respectively. A zone of another oxyty maximum exists in the deeper layers around 2750 m depth. Oxyty in the surface layer is >4.5 ml.1^{-1} with slightly low values in the western side of the ridge. The upper oxyty minimum layer almost coincides with the salinity maximum layer in both sections and the oxyty maximum zone with the salinity transition zone.

The phosphate parameter has been selected to represent the productivity levels in the region[7]. At surface and near surface depths, there is a clear evidence that the phosphate level on the western side of the ridge increases from about 0.15 μg.1^{-1} in the east to >0.3 μg.1^{-1} in the west [Figs 2D(i) and (ii)]. The 0.2 μg.1^{-1} phosphate isopleth lies around 80 m in the east of the ridge whereas in its western side, it is almost near the surface. Phosphate values increase steadily with depth in both sections to reach a maximum around 1000 m and the east-west differences are generally small except in the area occupied by the isopleth of 2.5 μg.1^{-1} which is much wider in section III than in section II. The increase in the level of phosphate in the west of the ridge is an indication that upwelling has taken place bringing up nutrient rich waters to the surface layer. It appears that when westward moving SEC encounters with a ridge which is oriented in a north-south direction, change in the circulation pattern takes place with formation of a region of divergence in the lee side of the ridge. The data set is not comprehensive enough, however, to identify the eddies but it is suspected that with a greater resolution of data points, they could be detected. As productivity is closely linked with ocean circulation, the concentration of phosphate is usually high in places where divergence takes place and is less in the regions where convergence is present.

Seasonal Variability

The wind regime in the present area of study undergoes a change from winter to summer[8]. In southern winter, the southeast trade winds extend from 22°S to 5°S blowing persistantly with moderate speeds of about 20 knots whereas in summer, the wind regime is weak (<10 knots), most of the time with variable directions. This seasonal change in wind stress at the ocean surface would affect the circulation patterns and cause redistribution of some physico-chemical parameters.

Vertical distributions—Temperature: During summer, the isotherms slope downward [Fig. 3A(i)] from south to north showing seasonal effect of solar heating in the surface waters in the northern region. Furthermore, the meridional surface temperature gradient, is less in the northern part compared to that in the southern part of section V. In the sub-surface layers during winter (section VI), however, the thermal structure [Fig. 3A(ii)] shows the presence of a trough in the middle of the section around 20°S. The axis of the trough shifts southward with increasing depth. For example, at 500 m, it is located around 22°S while it is around 18°S at 50 m depth. In the southern part of this section, the drop in sea surface temperature from summer to winter is quite remarkable.

The circulation pattern is quite stronger in winter than in summer as the SEC picks up due to increase in the strength of southeast trades. This wind regime on crossing the equator becomes the southwest monsoon which consequently induces an eastward flow north of the equator. Hence a cyclonic gyre is formed with a region of divergence along 10°S which thus explains the marked drop of temperature in the sub-surface layers in the northern part of section VI during winter. However, more southwards, part of the SEC turns south joining the eastward moving current along 35°S to form an anticlockwise gyre (a region of convergence). This explains the formation of trough in the isotherms around 20°S.

Salinity: During summer, the isohalines slope upward from 14°S to 28°S [Fig. 3B-(i)]. A salinity maximum ($>35.2\times10^{-3}$) is observed at about 250 m near 14°S and it reaches the surface further south. There is a pocket of salinity minimum around 1000 m. In winter, the vertical distribution of salinity is not much different from that in summer [Fig. 3B-(ii)] except in the near surface layers of the northern part where relatively low saline waters ($<34.4\times10^{-3}$) could probably be due to local precipitation which results from the southern hemispheric equatorial trough (SHET) – a synoptic weather feature during southern winter.

Horizontal distributions – Temperature: The sea surface temperature has a stronger meridional gradient in winter than in summer [Figs 4A–(i) and (ii)]. The isotherms are rather zonal in the south but they become more or less meridionally oriented north of about 14°S with a warm zone around 63°E. Lack of data and the restriction of the study area north of 10°S, however, precludes the exact location of this warm water core. Around 55°E, the water is colder compared to that in the east especially in the winter. In fact, Vethamony *et al*[9], have indicated, in the Seychelles Islands region, the presence of colder surface waters around 9.5°S between 54° and 59°E longitudes during austral autumn. It is noted that the meandering nature of isotherms west of Seychelles-Mauritius ridge indicates probable presence of some eddies in the region.

At 50 m depth, there is a southward shift of warm core during summer [Fig. 4B-(i)] and a pocket of cold water around 12°S and 68°E. The warm core at 100 m [Fig. 4C-(i)] does not undergo much change in its position. However, the winter temperature distribution at 100 m shows a drastic change as the warm core in the north is replaced by relatively cold waters and another warm core is located around 20°S. This pattern persists at 200 m [Figs 4D-(i) and (ii)]. It is only at 500 m in summer that there is a replacement of the warm core in the northern region by cold waters and no such replacement is seen depthwise during winter [Figs 4E-(ii) and (ii)]. At 1000 m [Figs 4H-(i) and (ii)], the temperature gradient is quite weak and no special inference can be made except that of confinement of warm waters around Mauritius-Seychelles ridge in both the seasons.

Salinity: Surface salinity distribution [Figs 5A-(i) and (ii)] indicates a similar pattern both in summer and winter but with slight differences in individual values. In both seasons, a minimum salinity (summer: $< 34.6 \times 10^{-3}$; winter: $< 34.4 \times 10^{-3}$) is apparent around 12°S and 62°E and a maximum (summer: $> 35.8 \times 10^{-3}$; winter: $> 35.6 \times 10^{-3}$) around 28°S and 64°E. The isohalines north of 14°S look similar to the pattern of the sea surface temeprature in the region. Similar pattern in salinity also exists between summer and winter at 50 m depth [Figs 5B-(i) and (ii)]. At 100 m, the meridional salinity gradient further decreases [Figs 5C-(i) and (ii)]. At 200 m, the salinity minimum zones are still situated north of 14°S but the maximum salinity zone ($> 35.6 \times 10^{-3}$) shifts more northwards with the core located around 22°S [Figs 5D-(i) and (ii)]. The salinity gradient at 500 m becomes very weak [Figs. 5E-(i) and (ii)] whereas at 1000 m, it is reversed with low salinity values towards south [Figs. 5F-(i) and (ii)] indicating the spread of low saline Antarctic Intermediate Water into the region.

Oxyty: The oxyty at surface varies mainly around 4.5 ml.1^{-1} in both seasons [Figs 6A-(i) and (ii)]. However, oxyty decreases significantly at 50 m depth in summer compared to that in winter as observed near 11°S & 67°E [Figs 6B-(i) and (ii)]. At 100 and 200 m also, somewhat higher oxyty values exist during winter. For example, the minimum zone located near 11°S and 62°E in winter is bound by 2.5 ml.1^{-1} isooxyty line whereas in summer, it is characterised with values < 2 ml.1^{-1}. There is not much seasonal variation in oxyty at 500 m and below except in its north-south spatial gradient.

Phosphate: Phosphate values at surface and near-surface (Figs 7A and B) increase with formation of a surface maximum zone (> 0.3 µg.1^{-1}) around the region of Agalega Island in the north during winter. Vertical movement of the waters rich in phosphates from sub-surface as consequence of ridge effect is quite apparent whereas upwelling is not remarkable during summer as seen from the reduced levels in phosphate. However, at 100 m, in both seasons [Figs 7C-(i) and (ii)], the phosphate values increase from south to north with maximum values > 1.4 µg.1^{-1} around 11°S and 68°E in summer and > 1.0 µg.1^{-1} near 12°S and 60°E during winter. At greater depths, the summer nutrient enrichment is seen (Figs 7D to 7F).

During southern winter, as a consequence of an increase in wind stress in the north, SEC strengthens resulting in a zone of stronger divergence (upwelling) in the leeward region of the Mauritius-Seychelles ridge. As a result, an increase in phosphate values is noted in surface layer. In summer, however, the SEC weakens in the north in response to the slackening of the southeast trade winds which are, in fact, replaced by northwest trade winds coming from northern hemisphere. Accordingly the Inter-tropical Convergence Zone (ITCZ) shifts to around 10°S where a divergence zone sets enriching the nutrient level at and below 100 m as compared to that during winter.

Geostrophic circulation – The dynamic topography (Fig. 8) field in the area of study gives clear evidence of 2 large clockwise and anti-clockwise

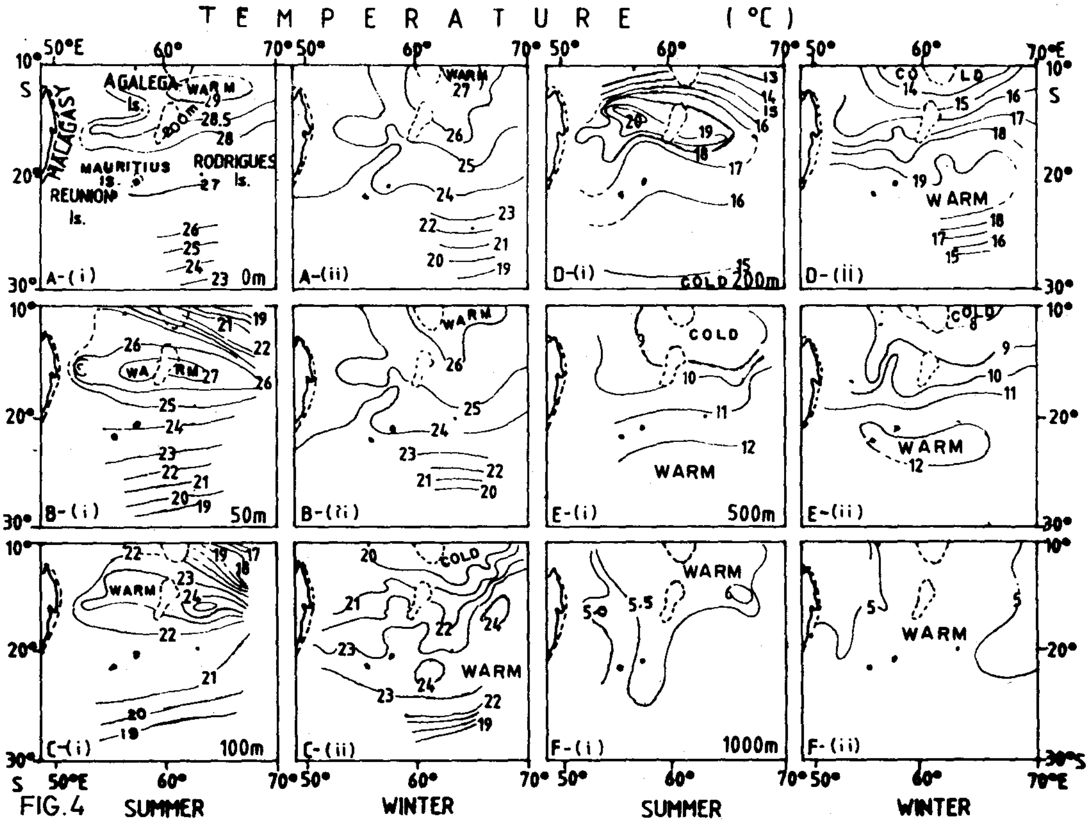

FIG. 4

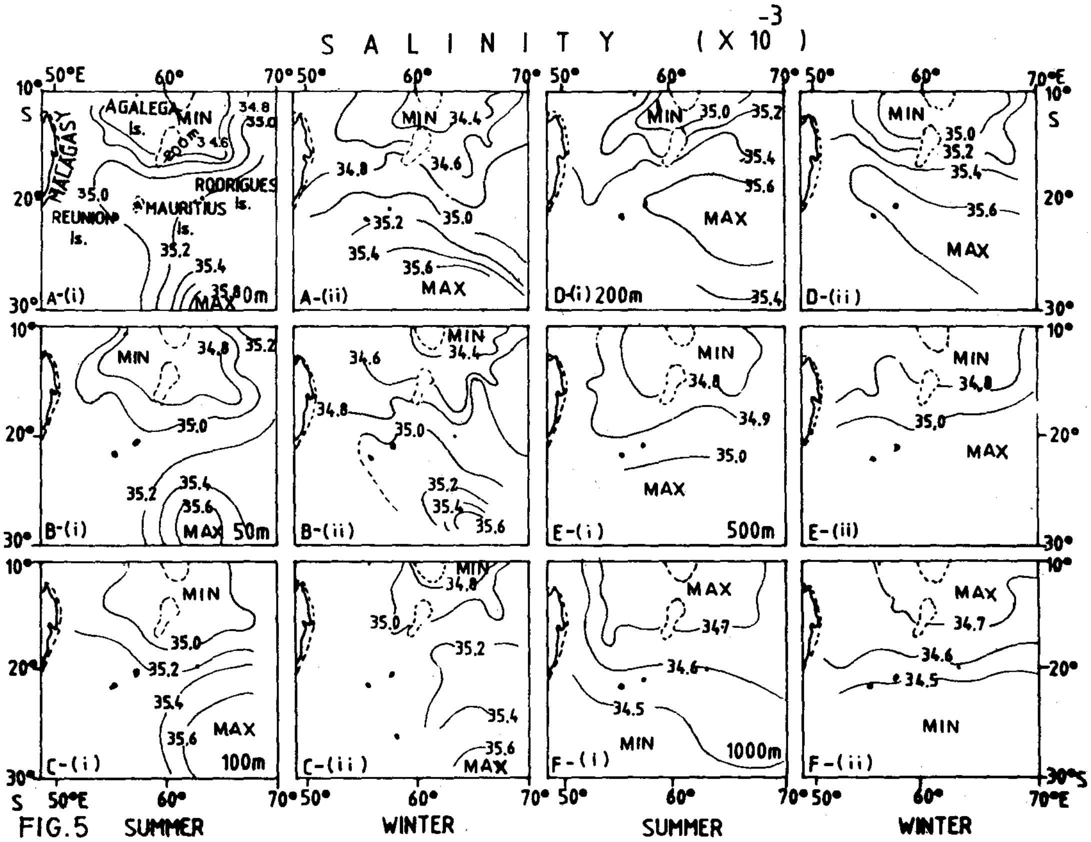

FIG. 5

Fig. 4 – Distribution of temperature at (A) surface (B) 50 (C) 100 (D) 200 (E) 500 and (F) 1000 m during summer (i) and winter (ii)

Fig. 5 – Distribution of salinity at (A) surface (B) 50 (C) 100 (D) 200 (E) 500 and (F) 1000 m during summer (i) and winter (ii)

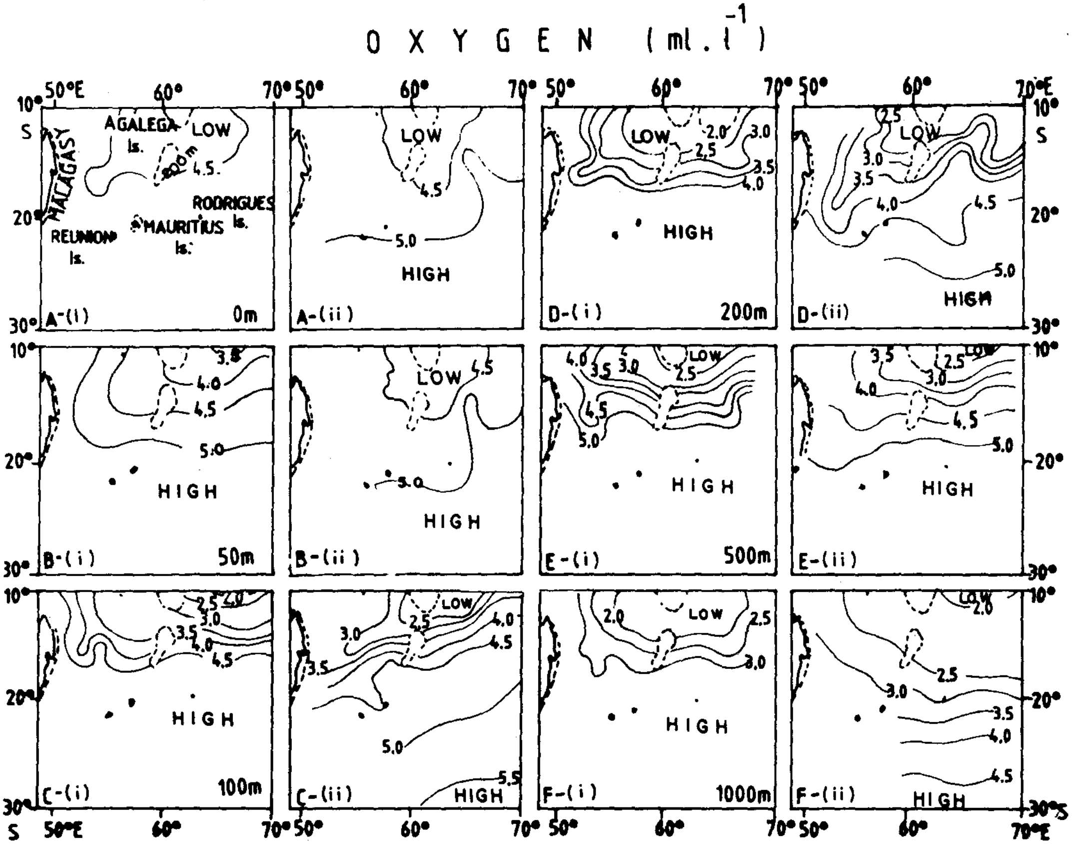

FIG. 6

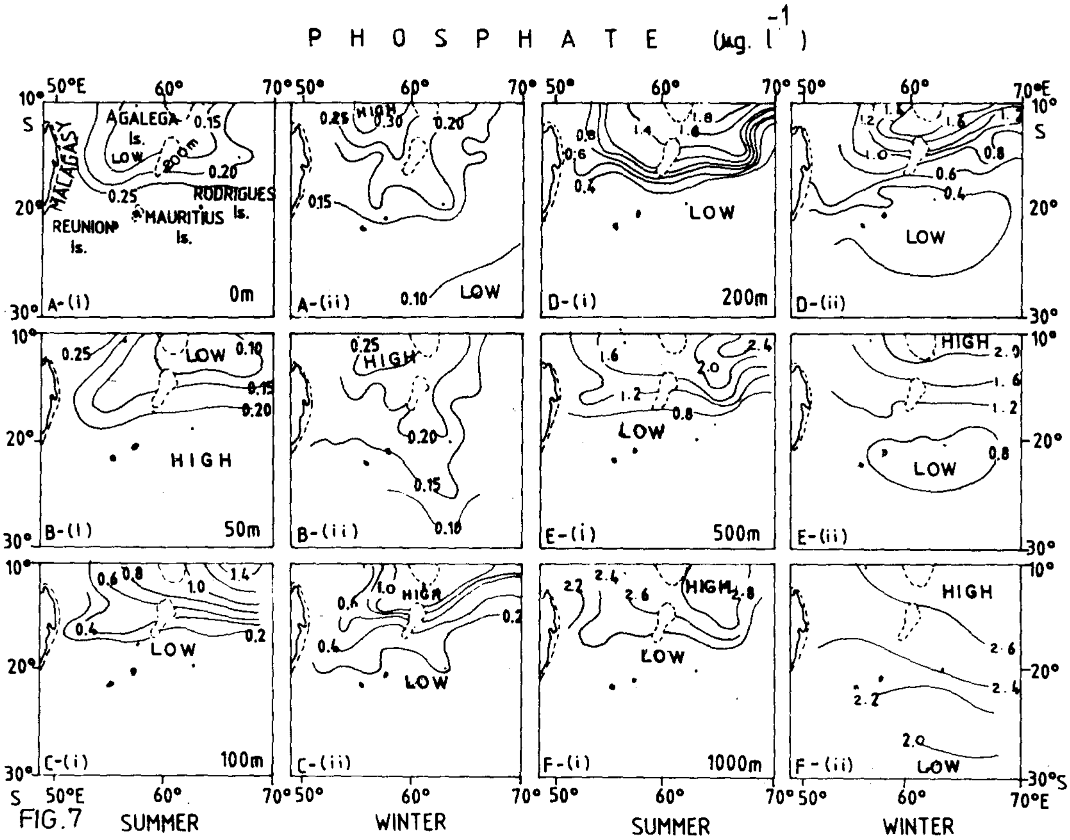

FIG.7

Fig. 6 – Distribution of oxyty at (A) surface (B) 50 (C) 100 (D) 200 (E) 500 and (F) 1000 m during summer (i) and winter (ii)

Fig. 7 – Distribution of inorganic phosphate at (A) surface (B) 50 (C) 100 (D) 200 (E) 500 and (F) 1000 m during summer (i) and winter (ii)

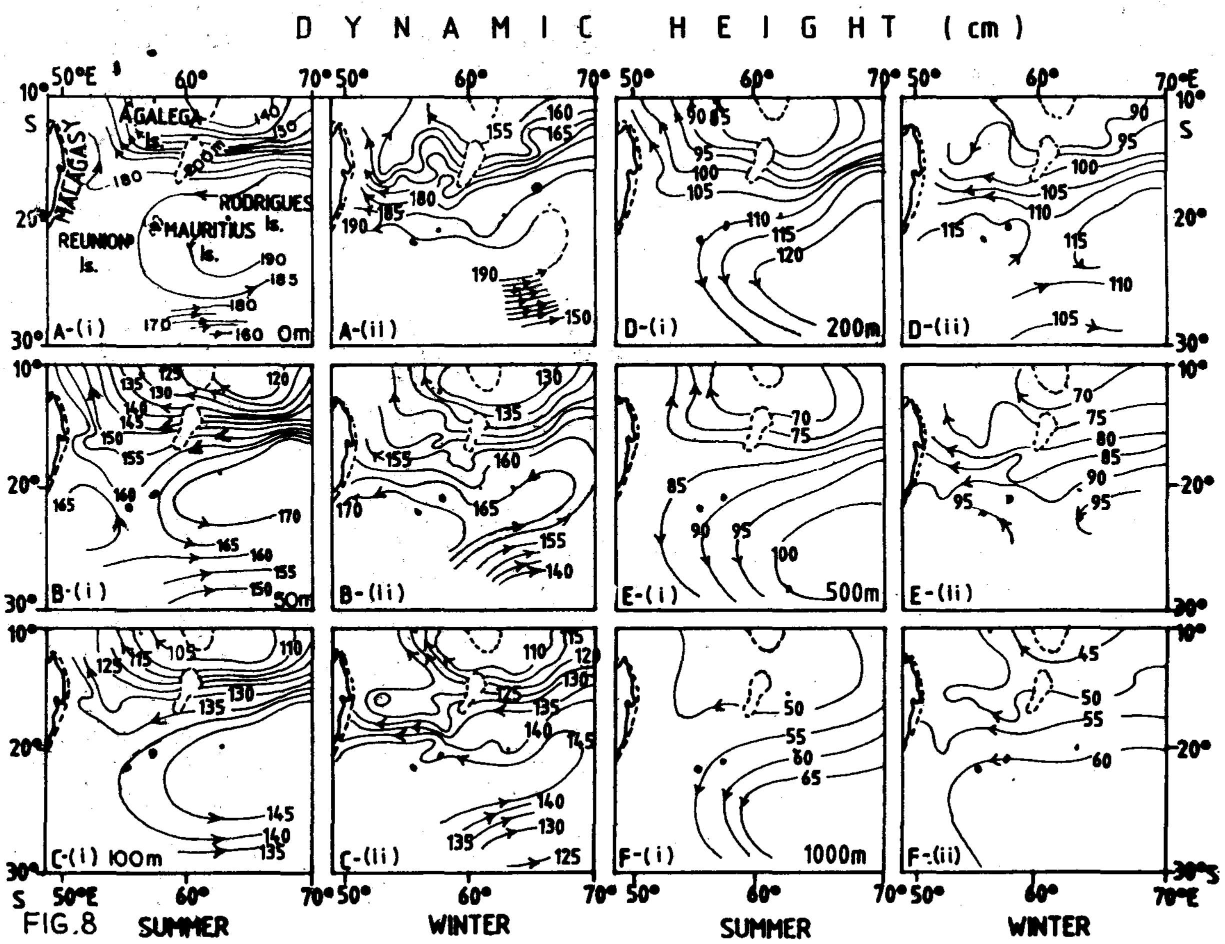

FIG.8

Fig. 8 – Dynamic topography field with reference to 1000 db surface at (A) surface (B) 50 (C) 100 (D) 200 (E) 300 and (F) 500 m during summer (i) and winter (ii)

gyres with their centres around 12°S and 22°S respectively during both winter and summer seasons. This flow pattern is clearly seen up to 1000 m but with a decrease in its intensity. Another interesting feature is presence of circulation of meandering type in upper 100 m layer during winter west of the Mauritius-Seychelles ridge. The summer circulation patterns are similar to those derived by Premchand and Sastry[1]. In between the 2 gyres lies the zonal SEC extending from 12° to 20°S. At surface, its core is around 15°S which itself shifts south with depth. The easterly flow around 30°S indicates the northern periphery of Circumpolar Current.

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