

Hydrological Characteristics & Trimequatorial Transport in the West Indian Ocean*

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Analysis of distribution of temperature, salinity, thermosteric anomaly and oxyty of the data collected by R. V. Atlantis-II in the southwest Indian Ocean has revealed the following features: Salinity minimum of the Antarctic Intermediate Water progressively increases from <34.5‰ at 26°S to >34.8‰ at about 10°S and the thickness of the salinity minimum layer increases towards north. Salinity minimum is conspicuously absent over most of the equatorial region of the south Indian Ocean. Thickness of the Sub-tropical Subsurface Water decreases towards north. A layer of an oxyty maximum which is very clearly defined in the northern regions, is associated with the Subtropical Subsurface Water. South Equatorial Current, as it approaches Malagasy, splits into 3 branches : northern, central and southern. The northern branch, primarily consisting of water of equatorial Pacific Origin, turns north and merges with a huge clockwise cell. The central branch, consisting of water drawn from the West Australian Current flows towards Africa after bypassing Malagasy and the southern branch flows south along the east coast of Malagasy. After reviewing various theories on the water mass structure in the Somali Basin, it is concluded that salinity minimum and oxyty maximum in the intermediate layers of the Somali Basin occur due to the penetration of the entire water column above salinity minimum of the Antarctic Intermediate water through the central branch of the South Equatorial Current.

SASTRY and D'Souza¹, while investigating factors responsible for higher productivity in the Arabian Sea, have speculated that the processes of thermohaline upwelling partly contribute towards the nutrient enrichment of the surface layer. They point out that (a) excess of evaporation over precipitation over the Arabian Sea is of the order of 100-150 cm/year, (b) net geostrophic mass transport in the upper 200 m across 5°N is directed south and is of the order of 21.0×10^6 m³/sec, and (c) Red Sea and Persian Gulf waters flow out of the Arabian Sea, and in order to compensate for these outflows there should be a net transport into the Arabian Sea.

At depths exceeding 2500 m, the water characteristics in the Somali and the Arabian Basins are of circumpolar origin^{2,3} and thus a positive mass flux into the Arabian Sea at deeper levels is evident. However, the transport mechanisms in the intermediate levels (200-1000 m) are not very clear and studies by several investigators as to the nature of transport at these levels are somewhat confusing.

The purpose of the present investigation is to study the distributions of temperature, salinity, dissolved oxygen and geostrophic circulation in the south-western Indian Ocean to make an assessment of the transquatorial transport characteristics in the intermediate layers.

*All the data reported in this investigation are available in the data files of the Institute's Data Centre. Only representative figures are given in this paper for the understanding of the text, and the detailed figures of various sections discussed are available with the authors.

Analysis of Data

During the International Indian Ocean Expedition, *Atlantis-II* has covered several sections in the south-western Indian Ocean during 25 April to 20 June 1965. For each of the stations (Fig. 1), the station curves showing temperature against depth, salinity and dissolved oxygen were drawn on sheets showing thermosteric anomaly as a function of temperature and salinity. These curves were later smoothed. From these, the depths of isohalines, iso-oxyty lines and isanosteres were read. Vertical sections showing the distribution of these properties along 8 sections (7 zonal and 1 nearly meridional) were prepared. Assuming the level of no motion at 1000 db, the geostrophic currents were computed. Charts showing the dynamic topography at surface, 100, 200 and 500 m were also constructed.

Results

Distribution of parameters — The surface temperature decreases from west (>23°C) to east (<21°C) while salinity increases from 35 to 35.2‰ along section I. The thickness of the surface layer is of the order of 50-75 m. The thermocline or the mass discontinuity layer (extending from the knee of the thermocline to the 15°C isothermal surface) has a thickness of about 250 m and below this layer, the temperature decreases monotonically with depth. Distribution of salinity shows a well-defined salinity maximum zone (>35.5‰) centred around 200 m and is bounded by the 300 and 200 c/t isanosteres. Below the zone of salinity maximum, a

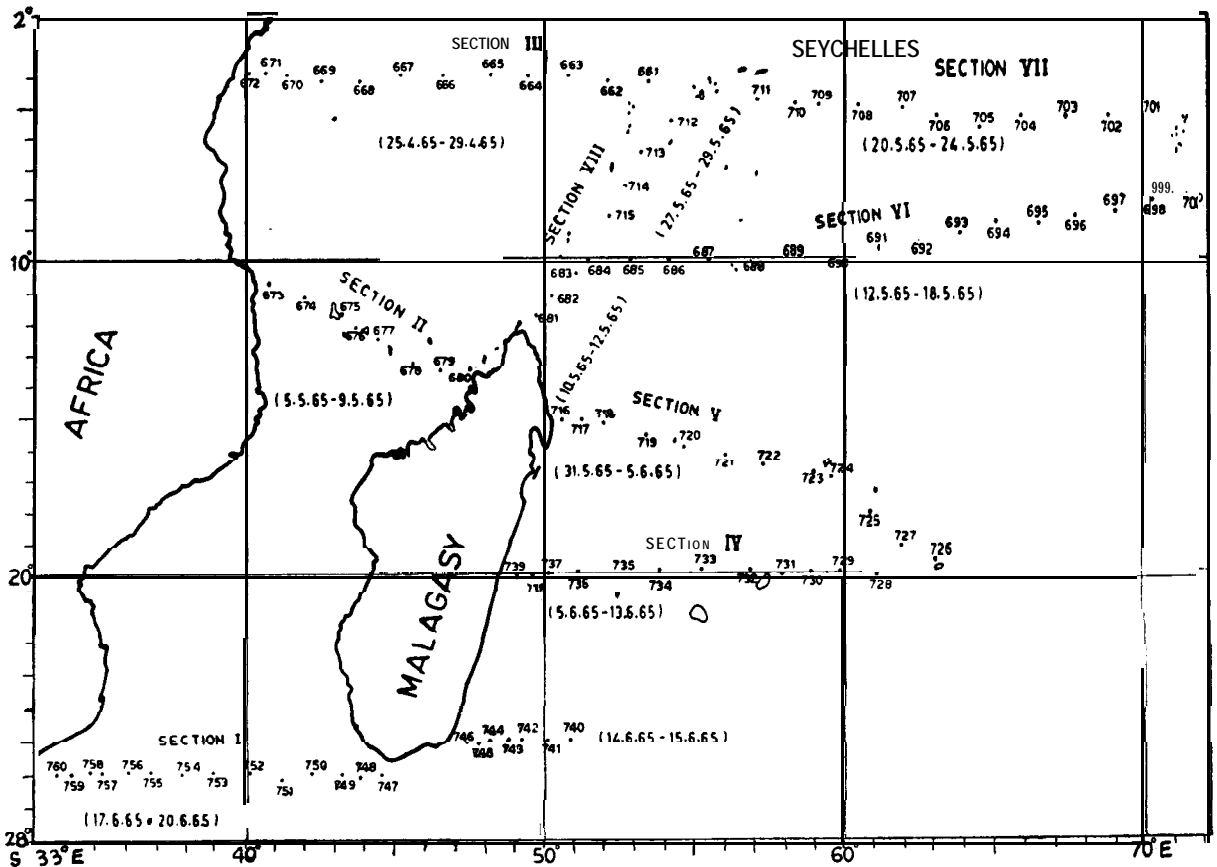


Fig. 1 — Station location map

salinity transition zone, a zone of decreasing salinity extends up to about 800 m. In the depth range of 800-1000 m, a well-defined salinity minimum zone ($<34.5\text{‰}$) bounded by the 100 and 80 cl/t isanosteres is present. Below 1000 m, the salinity shows a gradual increase to reach a maximum of 34.8‰ at depths of 2600-2800 m.

In the depth range of 300-800 m, the isotherms, the isohalines and the isanosteres show domes (stations 759, 751 and 748) and depressions, an indication of fairly strong circulation at those levels.

Oxyt at surface varies from 5 to 6 ml/litre. In contrast to regular patterns of the distributions earlier presented, oxyt distribution is irregular and several subsurface maxima and minima are found up to 2000 m. Coinciding with the shallow salinity maximum layer, an oxyt minimum layer is observed. In the salinity transition zone, oxyt exceeds 5 ml/litre and feeble oxyt maximum exists at these levels. Within the zone of salinity minimum, the oxyt also shows lower values of about 3.5 to 4.5 ml/litre. With increasing depths, the oxyt again increases to about 4.5 ml/litre.

The layer of salinity transition as well as oxyt maximum has been referred to as the Sub-antarctic Intermediate Water by Ivanenkov and Gubin⁴ and as the Subtropical Subsurface Water by Warren *et al.*². The Antarctic Intermediate Water is identified by the salinity minimum.

Distributions of temperature, salinity, thermosteric anomaly and oxyt along section II are basically similar to those along section I. However, there exist some differences and as they are pertinent to the present study, they are briefly summarized below.

Surface waters along this section are about 5°C warmer. Salinity in the shallow salinity maximum layer shown by the 35.3‰ contour is less by about 0.2‰ compared to the southern section. Thickness of the salinity transition zone is very much reduced. On the other hand, salinity minimum zone is not quite conspicuous in section II and salinities are more or less uniform centred around 34.8‰ below about 600 m. The predominant trough-ridge pattern in the structure of isotherms, isohalies and isanosteres along section I are conspicuously absent along this section. However, isolines show a trough-like structure in the central regions of the section from where they slope upwards towards the coasts. At station 679, off the coast of Malagasy, they form a ridge. Distribution of oxyt along this section is fairly simple compared to the complex pattern along section I. Surface oxyt is nearly uniform (4.5 ml/litre). Oxyt distribution shows a well-defined maximum shown by 4 ml/litre contour within the salinity transition zone instead of a feeble one along the southern section. Oxyt maximum zone is centred around 400 m and is primarily located

between the 160 and 120 cl/litre isanosteres. The oxyty minimum (2.5 ml/litre) is located at the base of the salinity minimum zone.

The surface temperature exceeds 28°C all along section III. In the depth range of 100-200 m off the African coast, the isotherms form a ridge (stations 670 and 669) whereas they show a trough at depths of 500-800 m. Surface salinity is maximum (35.3‰) in the central regions and it shows a gradual decrease on both sides. Salinity minimum (34.8‰) occurs at station 664. Salinity increases with depth both in the eastern and western regions and the shallow salinity maximum occurs at about 100-200 m. Below this layer, salinity reaches a minimum as shown by the 34.9‰ contour in the depth range of 400-700 m.

Thermocline anomaly varies between 500 and 600 cl/t at surface. The thickness of the strong mass discontinuity layer is seen to decrease progressively from south to north (Fig. 2c). The peculiarity in the distribution of oxyty along this section is the conspicuous absence of a well-defined oxyty maximum layer except at stations 671 and 672 (close to the African coast).

Sections IV and V are situated off the east coast of Malagasy and the property distributions along these two sections are very much similar to those along sections I and II respectively. Fig. 2 shows the distribution of temperature, salinity, thermocline anomaly and oxyty along section IV.

Distribution of salinity along section VI shows the presence of the shallow salinity maximum layer. Salinity minimum zone is absent. In the depth range of 250-400 m, oxyty shows a maximum. A well-defined oxyty minimum layer is centred around 900 m.

Section VII is virtually a continuation of section III. The basic difference between these two sections is the presence of a definite salinity minimum zone along section III and its absence along section VII. On the other hand, the salinity is rather uniform (between 400 and 900 m) with a slight decreasing tendency with depth all along this section.

Section VIII extends from the northern tip of Malagasy in a north easterly direction on the eastern side of the island chain. Just below the surface layer (Fig. 3a), the isotherms slope upward away from Malagasy. The upward sloping is much more conspicuous in the depth range of 300-1000 m. Between stations 682 and 683 they develop into a ridge and further northward, they form a trough. North of station 715, they are more or less horizontal.

Salinity distribution shows a northward increase from 34.9 to 35.1‰ (Fig. 3b). The shallow salinity maximum layer is shown by the 35.1‰ isohaline and within this, a tongue-like distribution is present, off Malagasy. Close to the coast off Malagasy, salinity decreases rapidly to reach a minimum bounded by the 34.7‰ contour. Along the northern regions, while a layer of decreasing salinity is present, gradients are weak and no salinity minimum layer is evident. Within the salinity transition layer at stations 681 and 682, oxyty shows a maximum (Fig. 3c). In the depth

range of 700-1000 m, coinciding with the salinity minimum, oxyty also shows a minimum. While the salinity minimum is bounded by 100 and 60 cl/t isanosteres, oxyty maximum occurs at about 125 cl/t (Fig. 3d).

The salient features of the distributions along various sections are summarized below:

- (1) Surface temperature increases from south to north.
- (2) Thickness of the thermocline (mass discontinuity layer) progressively diminishes northward.
- (3) Salinity in the shallow salinity maximum progressively erodes towards north.
- (4) Thickness of the salinity transition layer, a layer of decreasing salinity, decreases northward.
- (5) Oxyty maximum layer is located in the salinity transition zone and is found to be well defined in the northern regions.
- (6) Salinity minimum layer widens towards north and salinity in this layer increases. Along sections VI and VII, salinity minimum is conspicuously absent. However, off the African coast and northern tip of Malagasy salinity minima are found.
- (7) Salinity minimum layer, in general, occurs at about 100 to 80 cl/t while oxyty maximum is found at about 100 to 150 m above the salinity minimum and is at about 125 cl/t.

Geostrophic circulation — As mentioned earlier, geostrophic currents have been computed taking the 1000 db surface as the reference level. Across sections I and II, because of the constraints imposed by the African continent on the west and Malagasy on the east, the flow would be mainly meridional.

Across section I, a strong southerly current, about 200 km wide with speeds exceeding 75 cm/sec at its core extends up to about 1000 m. To the east as well as to the west of this feature, weak northerly currents are noticed. In this central regions, weak northerly flow dominate with maximum speeds ranging from 10 to 20 cm/sec. In the eastern regions, north and south components alternate with speeds of the order of 30 cm/sec in their cores.

Along section II, the northerly flow in the central regions is sandwiched by the southerly currents off the coasts of Africa and Malagasy. Below 300 m, the currents are weak.

The circulation pattern is quite complex along section III. The meridional components alternate in direction. It may be assumed that, close to the African coast, the current structure represents the actual field of motion since the zonal flow would be very much reduced near the African continent.

A southerly flow, about 350 km wide, is located between stations 669 and 667, with its core speed exceeding 100 cm/sec near the surface. This broad band is bordered by 2 northerly flows of about the same width on either side. Close to the African coast, the current is directed north in the upper 200 m and the direction is reversed at deeper levels. In the eastern regions along this section, meridional components of currents range between 20 and 30 cm/sec. The field of motion all along this section shows considerable amount of shear both in the vertical and horizontal.

Off the east coast of Malagasy across 20°S, a fairly strong southerly flow near the coast extends up to deeper levels. Further east, the meridional

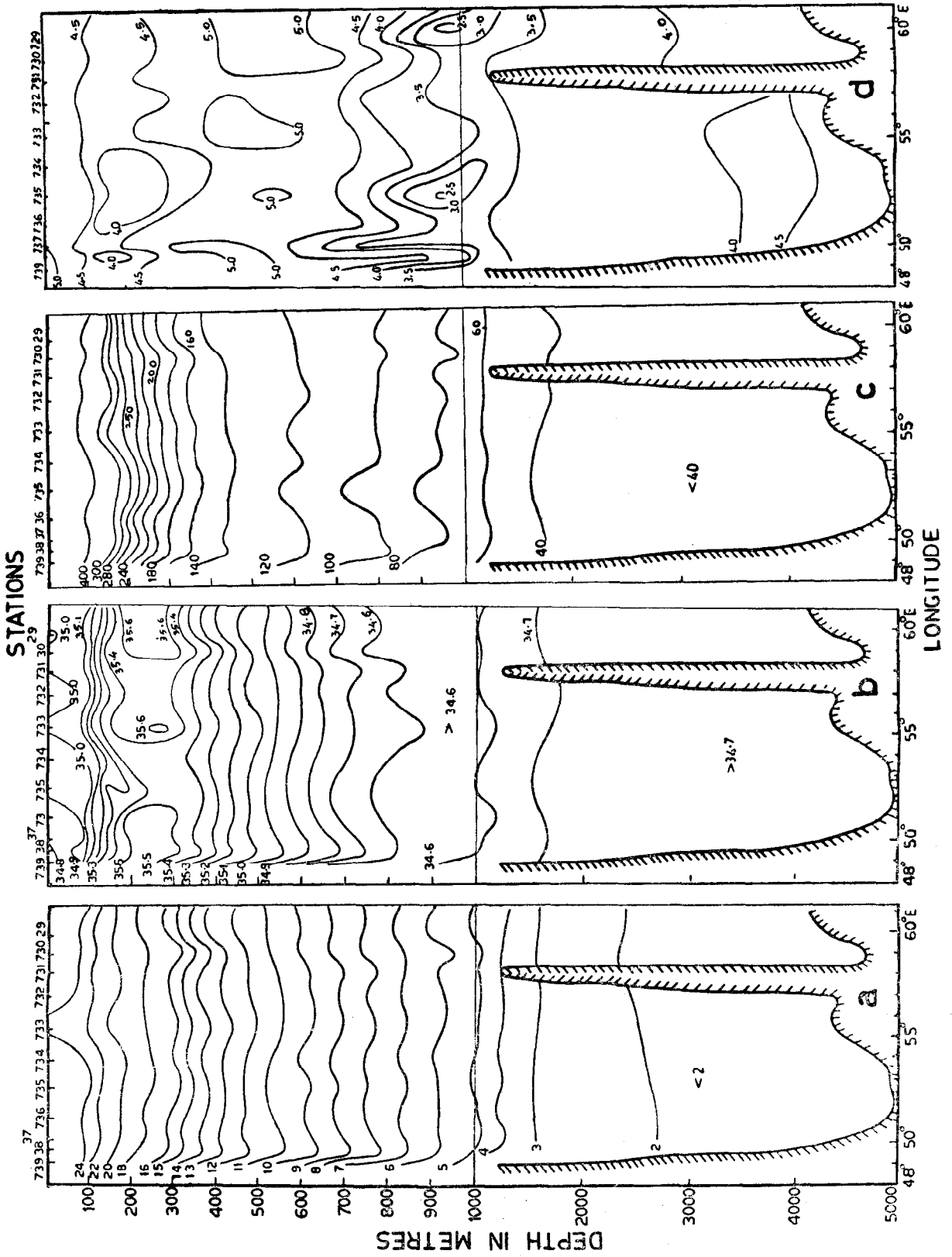


Fig. 2 — Temperature (a), salinity (b), thermocline depth (c) and dissolved oxygen (d) along Section IV

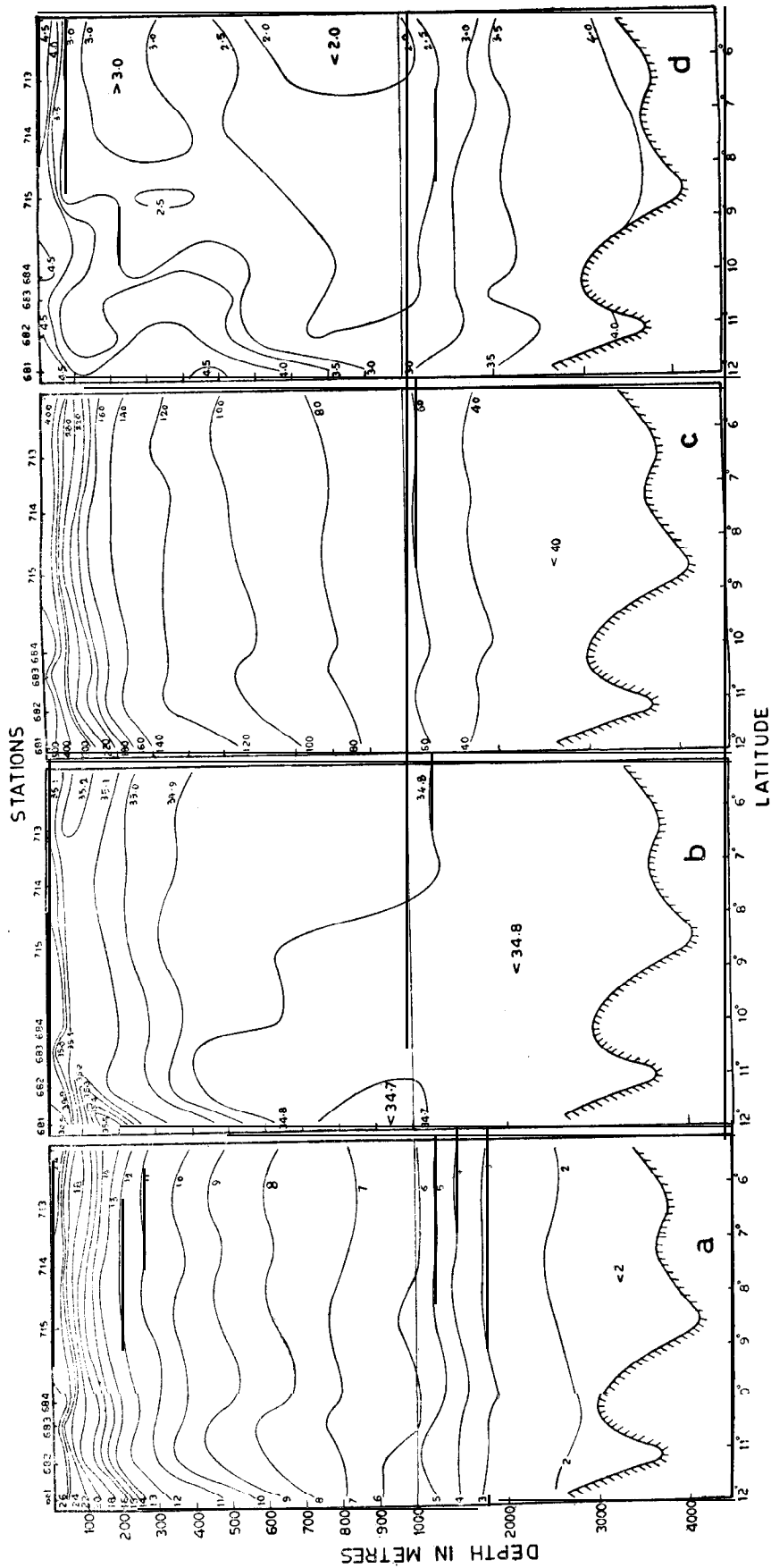
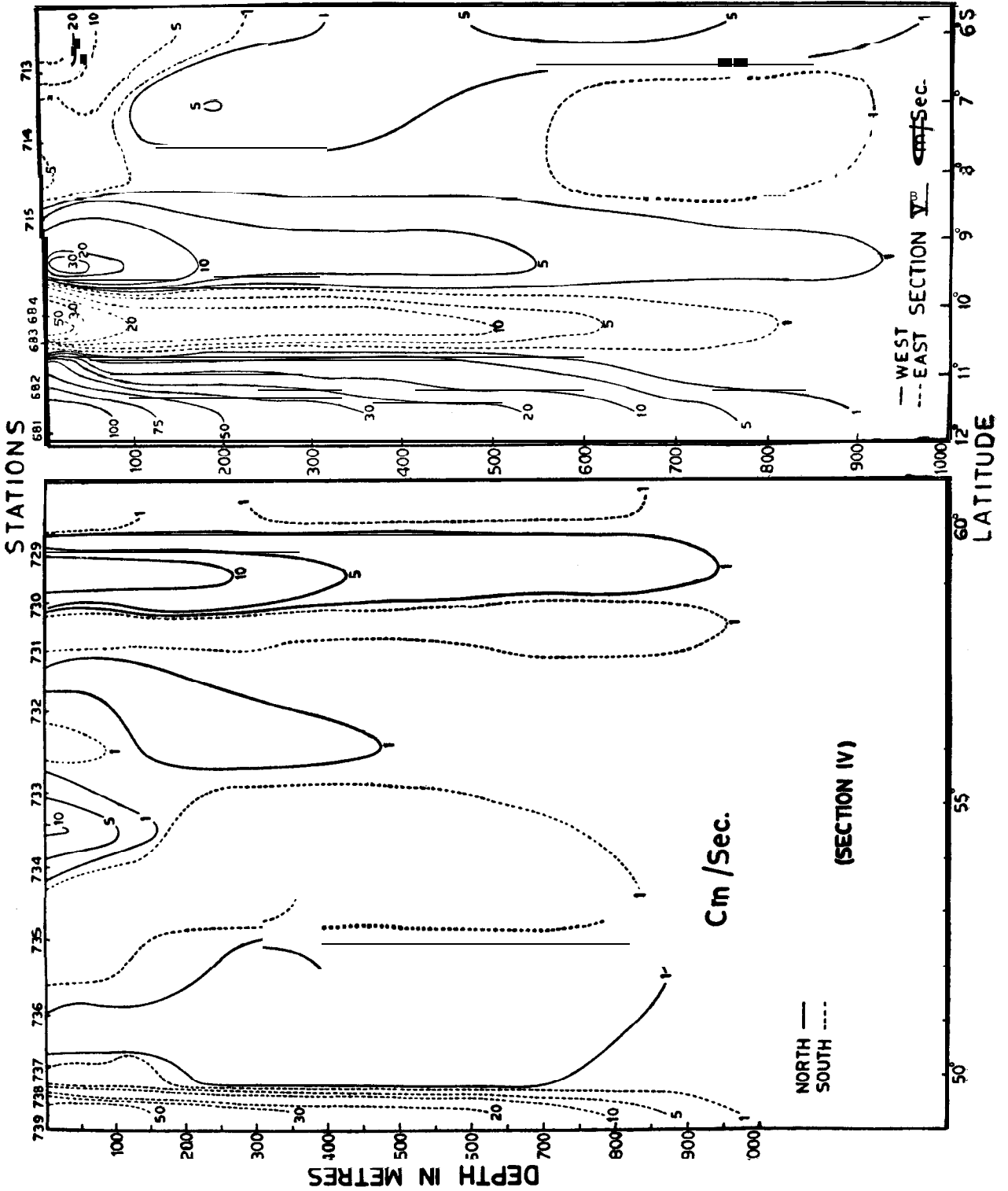


Fig. 3 — Temperature (a), salinity (b), thermosteric anomaly (c) and dissolved oxygen (d) along Section VIII

Fig. 4—Geostrophic currents across Sections IV and VIII



components are weak (Fig. 4a). Section V shows a similar pattern though the strength of the meridional components vary from place to place.

Across sections VI and VII, the basic feature of meridional components of currents is the prevalence of alternate bands, though of varying speeds. With increasing depth, the flow tends to be sluggish.

While similar features are observed in the current structure across section VIII close to the northern tip of Malagasy, a fairly strong zonal flow, about 200 km wide, with speed exceeding 100 cm/sec is directed westward. Further northwards, the flows tend to become weak gradually (Fig. 4b).

So far our main concern has been to study vertical structure of the flow across various sections. These studies have revealed that, except near the coastal boundaries, the meridional components are weak and that considerable amount of shear is present both in the vertical and horizontal. In order to get a precise idea of the field of motion, dynamic topographic charts from surface to 500 m are made (Fig. 5). As sections I and II are separated by 15°, no attempt has been made to present these charts in the Malagasy channel.

The basic feature of circulation in the western Indian Ocean is the formation of 2 huge cells: a clockwise cell centred around 8°S and 55°E and an anticlockwise cell around 22°S and 52°E. Between these two, a fairly strong zonal flow, the South Equatorial Current, is present. The South Equatorial Current, as it approaches Malagasy and the island chain on its north, splits into 3 branches. One of these flows south along the Malagasy coast attaining greater strength in its further course. The 2nd branch turns north and then to east to form the great clockwise cell mentioned above. Located between these 2 systems is the 3rd one which flows in a general north-westerly direction, bypasses the northern tip of Malagasy where it is about 200 km wide and later flows towards the African coast. Close to the African coast, this current shows a pronounced meandering. In fact, alternate bands of meridional components across various sections seem to be the result of the meandering of the South Equatorial Current. Even though the flow tends to be sluggish with increasing depth, these features are clearly seen to extend up to 500 m. Further, the core of the South Equatorial Current shifts southward with depth. The dynamic topographic chart for 500 m (Fig. 5) shows that in the northern regions, east of the island chain, the zonal flow tends to be very small, an indication of strong vertical shear in the zonal flow. These features of the circulation, it may be pointed out, are in general agreement with those of Wyrtki⁵.

Discussion

At intermediate level, the water mass structure in the Somali Basin is quite complex. Broadly, the features consist of a low salinity layer (<35.1‰), overlying a high salinity layer with secondary maxima and minima occurring in both of them^{2,3,6}. The high salinity layer is associated with low oxyty and the low salinity layer with high oxyty (>3.0 ml/litre). Oxyty maximum, in general, is

observed at about 100 m above the salinity minimum.

The mid-depth configuration of the water mass structure in the Somali Basin has been studied by several investigators^{2,3,7}. However, divergent views have been expressed as regards to the origin of the low salinity and high oxyty layers in the region.

The simplest explanation for the occurrence of salinity minima is obviously the spreading of 2 or more high salinity water masses at different steric levels. In the Arabian Sea, 3 high salinity water masses could be identified: (i) the Arabian Sea High Salinity Water (440-360 cl/t), (ii) the Persian Gulf Water (180-120 cl/t), and (iii) the Red Sea Water (100-80 cl/t). When these 3 water masses are present at any locality, occurrence of salinity minima sandwiched between these layers is the obvious result. However, on the basis of the above explanation, mid-depth water mass structure cannot be explained since oxyty both in the Red Sea and the Persian Gulf waters as they flow out and spread into the Somali Basin is very low compared to the observed values in that region.

Tchernia *et al.*⁸, on the basis of salinity minimum, have suggested that the Antarctic Intermediate Water moves across the equator in the western Indian Ocean and to the northern regions of the Arabian Sea, thereby implying a direct trans-equatorial movement of the Antarctic Intermediate Water. Taft⁹ points out that the salinity minimum in the Arabian Sea and that of the Antarctic Intermediate Water are located at different steric levels and he further contends that these minima cannot be connected by a 'line of flow'. He further suggests that the penetration of low salinity water of Equatorial Pacific origin through the Banda Sea into the Somali Basin gives rise to the salinity minimum at about 100 cl/t level. However, oxyty in the eastern Indian Ocean where the Pacific Water penetrates, ranges from 2 to 2.5 ml/litre whereas in the Somali Basin, oxyty exceeds 3 ml/litre in the same depth range. Taft's concept of a 'line of flow' is indeed a useful one and has been widely applied to deduce the flow pattern based on the distribution of properties on steric levels. It derives its importance due to the fact that the change of potential energy and entropy is at a minimum if interchange and mixing takes place along the steric surfaces. However, studies by Mamayev¹⁰ in the Atlantic Ocean and by Sastry¹¹ in the Indian Ocean have shown that when 3 or more water masses come into contact, transformation of water masses takes place and in the process of mixing, steric levels of these water masses are also altered. That, such is the case can clearly be seen from the potential temperature versus salinity plots for the core layers of Red Sea and Persian Gulf Water masses⁵. In the Gulf of Oman, the Persian Gulf Water is found at $\sigma_t = 26.5$ whereas in the Bay of Bengal, the same water mass is located at about $\sigma_t = 26.8$. Similarly, the Red Sea Water in the Gulf of Aden is primarily located between $\sigma_t = 27$ and 27.5 whereas in the Malagasy channel it appears at $\sigma_t = 27.7$. Thus, in our opinion, the concept of a 'line of flow' should be judiciously made use of. This, of course, does not mean that

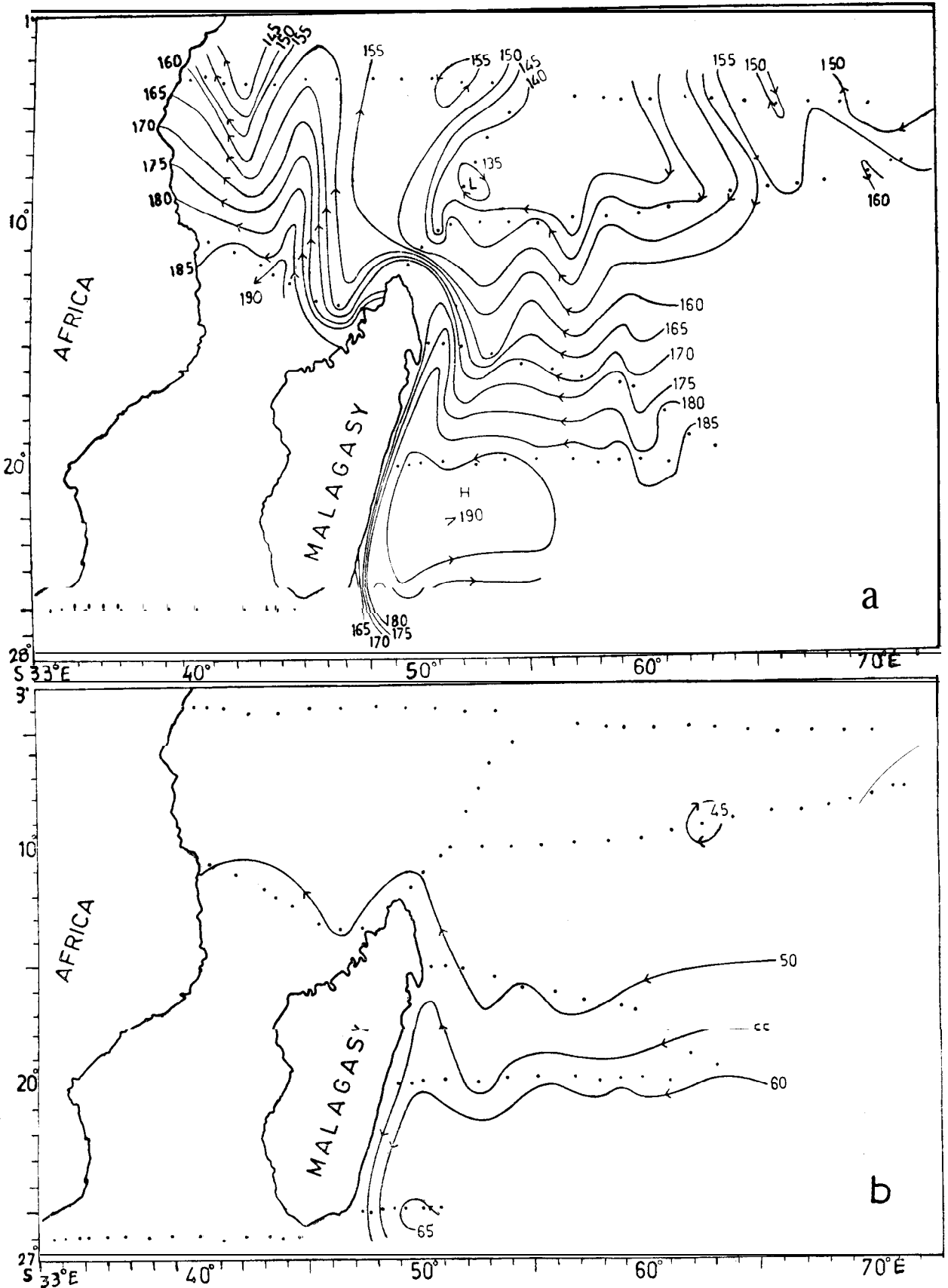


Fig. 5 -Dynamic topography of (a) surface and (b) 500 db surface with reference to 1000 db

the authors support the view of direct penetration of the Antarctic Intermediate Water into the Arabian Sea.

Pointing out that the oxyty in the Somali Basin is substantially higher than that found associated with low salinity Pacific Water, Warren *et al.*² contend that the northward transport of Pacific Water is not appreciable. They suggest that the penetration of the Subtropical Subsurface Water, a layer of salinity transition and oxyty maximum, gives rise to the observed distribution in the Somali Basin. They further opine that the subsurface water (in the depth range of Somali Basin salinity minimum) of Equatorial Pacific origin is perhaps cut off due to the vertical shear in the South Equatorial Current and does not flow west in significant strength. The chart showing the dynamic topography at 500 db shows that at 500 m, the zonal flow due to the South Equatorial Current is cut off near the island chain northward off Malagasy. Further, these authors envisage an elaborate mixing and intermingling of the various water masses in the Somali Basin: Antarctic Intermediate Water, Subtropical Subsurface Water, Red Sea Water, Persian Gulf Water and Equatorial Pacific Water.

Sharma⁷ while studying the water characteristics in the intertropical Indian Ocean arrives at a similar conclusion as that of Taft⁹ and he feels that the

high oxyty found in the Somali Basin is probably a result of mixing of the Pacific Water with higher oxyty water from the south during its flow to the west.

It may, however, be remarked that, if oxyties were to increase from 2.3 ml/litre in the eastern Indian Ocean to 3.3 ml/litre in the Somali Basin by mixing of southern high oxyty waters (say, of oxyty 4 ml/litre) with the waters of Pacific origin in equal volumes, the mixture still possesses lower oxyties than those observed in the Somali Basin. Thus Sharma's argument partly supports the view of Warren *et al.*² that the flow of Equatorial Pacific Water is not significant.

Thus there are 2 basically divergent views as regards the mid-depth water mass structure in the Somali Basin. As far as the authors are aware, there has been no unified approach to bring in these divergent opinions to explain various features of the mass structure in the western Indian Ocean.

The progressive thickening of the salinity minimum layer and the consequent destruction of the salinity transition layer as one moves from south to north in the western Indian Ocean is clearly due to the intense vertical mixing induced by the shear in the field of motion. The absence of the salinity minimum layer either in section VI or section VII is fairly a good indication that neither

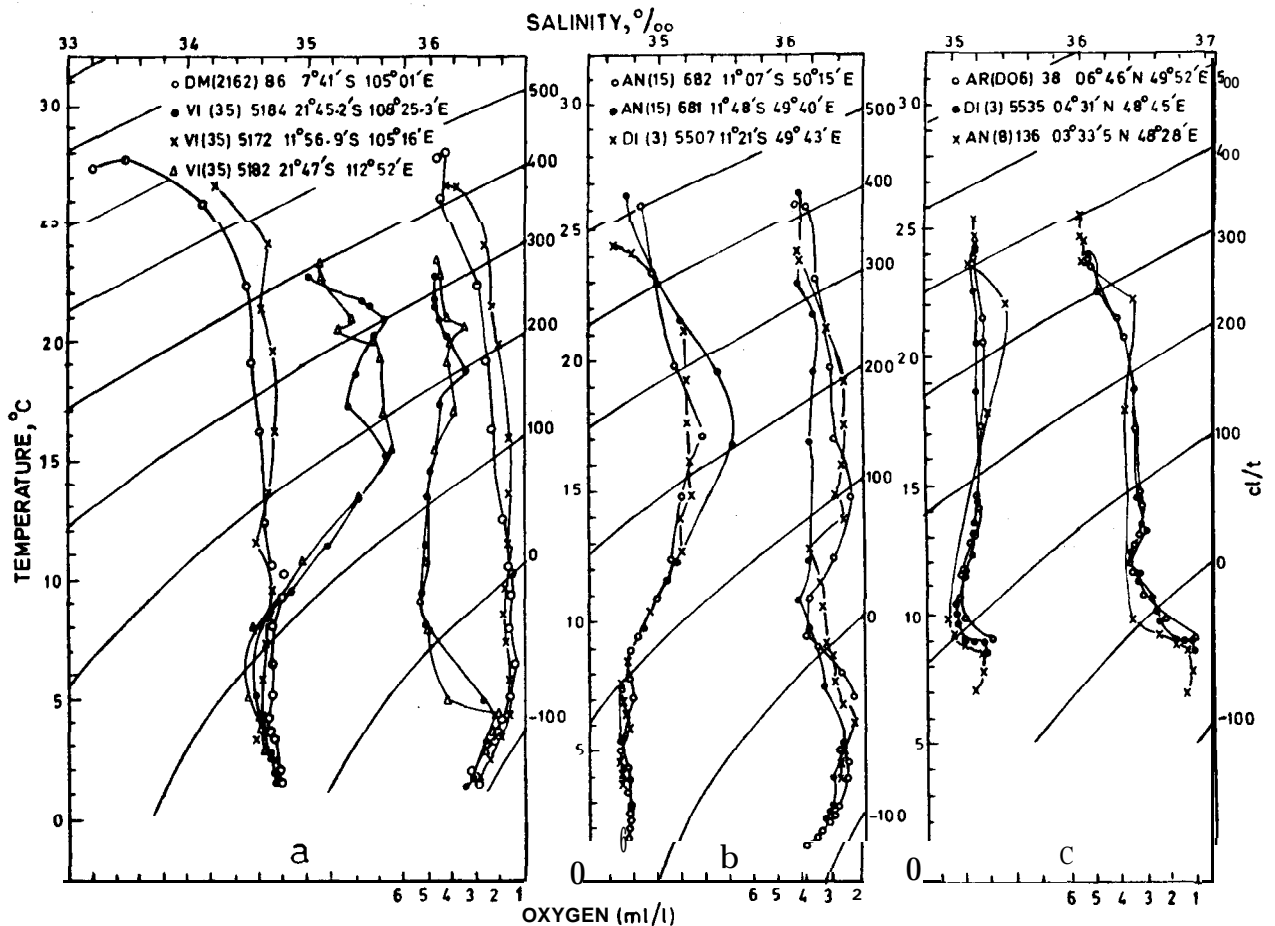


Fig. 6 — Temperature-salinity-oxyty relationships in (a) eastern Indian Ocean, (b) northern tip of Malagasy and (c) Somali Basin

the Antarctic Intermediate Water nor the Subtropical Subsurface Water penetrate directly into the Arabian Sea. Examination of the flow patterns does not suggest a direct line of flow in the west Indian Ocean. Thus we rule out the possibility of any direct movement of either the Antarctic Intermediate Water or the Subtropical Subsurface Water across the equator. This argument does not, of course, preclude a southern origin for the water mass structure in the Somali Basin.

Distribution of salinity along section VIII coupled with the zonal circulation gives a clue for the correct interpretation of the phenomena.

In the eastern Indian Ocean, the South Equatorial Current is fed by the Equatorial Pacific Water on its north and by the water drawn from the West Australian Current on its south. These 2 water masses could easily be identified by their distinct temperature-salinity and temperature-oxyty relationships (Fig. 6a). At the two southern stations (VI 5182 and VI 5184), the shallow salinity maximum, the salinity transition layer and the layer of salinity minimum of the Antarctic Intermediate Water are clearly seen. Salinity minimum of the Antarctic Intermediate Water is found at 100 cl/t. Oxyty at these 2 stations shows a maximum just above the salinity minimum and has values about 5.5 ml/litre. On the other hand, at the 2 northern stations (DM 86 and VI 5172), salinity is more or less uniform over the entire depth and no salinity minimum could be seen at about 100 cl/t. Oxyty is also relatively poor and in the depth range of salinity minimum it has values of about 2 ml/litre. Lateral mixing in the South Equatorial Current appears to be of limited extent and these water masses as they flow west retain their characteristics. As seen earlier, the northern branch of the South Equatorial Current, primarily consisting of the water of Pacific origin, turns north and then east to merge with the great clockwise cell eastward of the island chain north of Malagasy. In the depth range of the salinity minimum, the core of the South Equatorial Current shifts south and the zonal flow north of 15°S is very sluggish. The middle branch of the zonal flow, consisting of water primarily drawn from the West Australian Current, flows north-west as it approaches Malagasy, bypasses the island, flows towards the African coast and finally into the Somali Basin. Similarity of the temperature-salinity-oxyty relationships at stations

681, 682 (section VIII) and DI 5507 (Fig. 6b) located at the northern tip of Malagasy and at stations AR 38, DI 5535 and AN 136 (Fig. 6c) in the Somali Basin is further proof of the above argument. It may be remarked that the salinity in the salinity minimum layer increases while the oxyty in the oxyty maximum layer decreases as the water mass flows from the east Indian Ocean to the west and this is due to its mixing with the high salinity and low oxyty waters of the north Indian Ocean, chiefly the Red Sea and Persian Gulf Waters.

It may be worth noting that the occurrences of *Globigerina pachyderma*, a typical cold water Foraminifera in the slope regions off Bombay, is further indication of the presence of water of south Indian Ocean origin in significant quantities.

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References

- I. SASTRY, J. S. & D'SOUZA, R. S., *Indian J. mar. Sci.*, 1 (1972), 17.
2. WARREN, B., STOMMEL, H. & SWALLOW, J. C., *Deep Sea Res.*, 13 (1966), 825.
3. SASTRY, J. S. & D'SOUZA, R. S., *Indian J. Met. Geophys.*, 23 (1972), 470.
4. IVANENKOV, V. N. & GUBIN, F. A., *Trans. mar. Hydrographis. Inst. Acad. Sci. U.S.S.R.*, 22 (Eng. Trans.) (1960), 27.
5. WYRTKI, K., *Oceanographic atlas of the International Indian Ocean Expedition* (National Science Foundation, Washington DC), 1971, 531.
6. D'SOUZA, R. S. & SASTRY, J. S., *J. mar. Biol. Ass. India*, 15 (1973), 46.
7. SHARMA, G. S., *J. mar. Res.*, 30 (1972), 102.
8. TCHERNIA, P., LACOMBE, H. & GUIBOUT, P., *Bull. Inf. Corn. Cent. Oceanogr. Etudo Cotes*, 10 (1958), 115.
9. TAFT, B. A., *J. mar. Res.*, 21 (1963), 129.
10. MAMAYEV, O. I., *Trans. mar. Hydrophis. Inst. Academy Sci. USSR* (Eng. Trans.), 25 (1963), 42.
- II. SASTRY, J. S., *The salinity minimum in the Arabian Sea*, paper presented at the symposium on Indian Ocean and adjacent seas, their origin, science and resources, Cochin, 1971.
12. GUPTA, M. V. S., *Proc. IV Micropaleontological Colloquium* 1974, Dehra Dun (in press).