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Oceanography of the Arabian Sea during the southwest monsoon season—Part III : Salinity

J. S. SASTRY and R. S. D'SOUZA

Health Physics Division

Bhabha Atomic Research Centre, Bombay

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ABSTRACT. The distribution of salinity in the Arabian Sea during the southwest monsoon season is presented through several vertical sections and spatial distribution charts. The vertical salinity structure has been found to be quite complex and shows several maxima and minima upto depths of about 1000 m. An analysis of the water mass characteristics shows that the Arabian Sea high salinity water forms in the northeastern Arabian Sea as a result of excessive evaporation over precipitation and is located between 300 and 500 cl/t steric levels. The Persian Gulf and Red Sea waters have been identified by their salinity maxima occurring above and below the 100 cl/t surface respectively. In addition, it has been found that, in the depth range of 0-1000 m, the Antarctic intermediate water, subtropical subsurface water and the south equatorial water penetrate into the Arabian Sea at different levels and intermingling of these with the Red Sea, Persian Gulf and Arabian Sea high salinity waters give rise to the observed complexities in the vertical salinity structure. A comparison of the curves of potential temperature *versus* depth, salinity and oxyty in the Somali and Arabian basins with those in the circumpolar regions has shown that the deep and bottom water mass in these basins at depth exceeding 2500 m is of circumpolar origin.

1. Introduction

Of the several property distribution studies of the world oceans, those of salinity are of utmost importance. Salinity, being a conservative property, has been widely used in conjunction with temperature to characterise and to identify the water masses which possess characteristic temperature-salinity relationships. However, comprehensive studies of the distribution of salinity in the Arabian Sea are few, though several workers have analysed these distributions for the near shore regions, especially off the southwest coast of India. Recently, considerable interest in describing these distributions in the region is evident. Of particular interest to the present study are those of Rochford (1964); Warren, Stommel and Swallow (1966); Wooster, Schaefer and Robinson (1967); Sundara Ramam, Balakrishna Kurup and Sreerama Murthy (1968); etc.

This paper is a continuation of the earlier studies by the authors (Sastry and D'Souza 1970, 1971).

2. Data and analysis

A detailed listing of station data used in his paper is given below.

Atlantis stations 49, 51-107 and 112-131, Requisite station REASO4, Anton Bruun station AO 107 are from the data sheets issued by the National Oceanographic Data Center Washington, D. C: Discovery stations DI 1756 and 2113 are from Discovery Investigation Station list of 1935-1937. Albatross station AL 196 is from Swedish Deep-Sea, Expedition Reports.

Fig. 1 (reproduced from Sastry and D'Souza 1970) shows the location of stations where the data had been collected by '*Atlantis*' during the southwest monsoon season of 1963. The methods of preparation of the five vertical sections (Figs. 2 through 6) and of the six spatial distribution charts of salinity (Figs. 7 through 12) at different depths are given in Part I (Sastry and D'Souza 1970).

In Figs. 2 through 6, the isohalines are, in general, drawn at intervals of 0·2 ‰. Intermediate isohalines are introduced wherever they are found necessary. In these figures, Xs and ⊡s indicate the maxima and minima in the salinity distribution respectively. The subscript 'C' associated with either X or ⊡ denotes that the maximum or the minimum values extend over a considerable thickness of the water column and the subscript 'Q' refers to a doubtful point.

3. Distribution of salinity

Prior to a discussion of the water mass structure in the Arabian Sea, the basic features of the salinity variations are summarised in this section. For convenience, the water column is divided arbitrarily into three layers; (*a*) surface layer (0-200 m) (*b*) intermediate layer (200-1000 m) and (*c*) deep and bottom layer (below 1000 m).

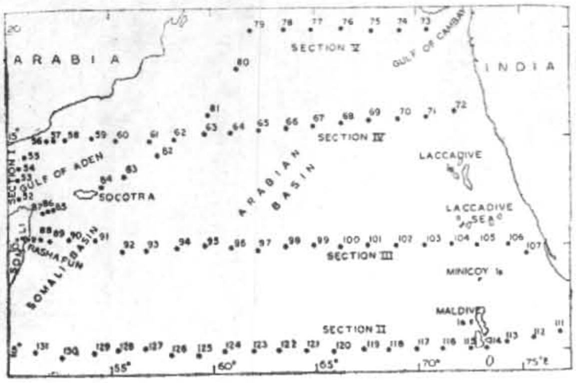

Fig. 1
Station location map

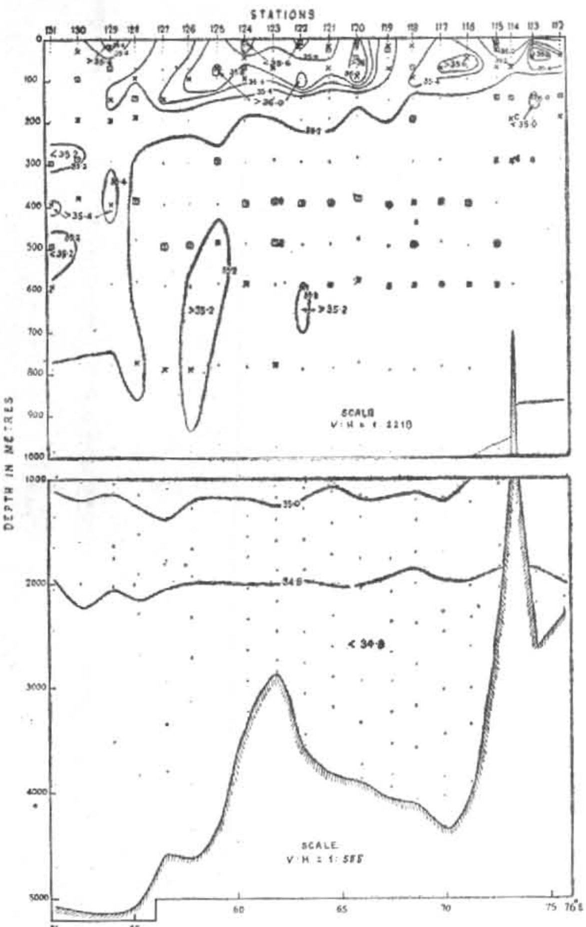

Fig. 3
Salinity (per mil) along approximately 5°N (Section-II)

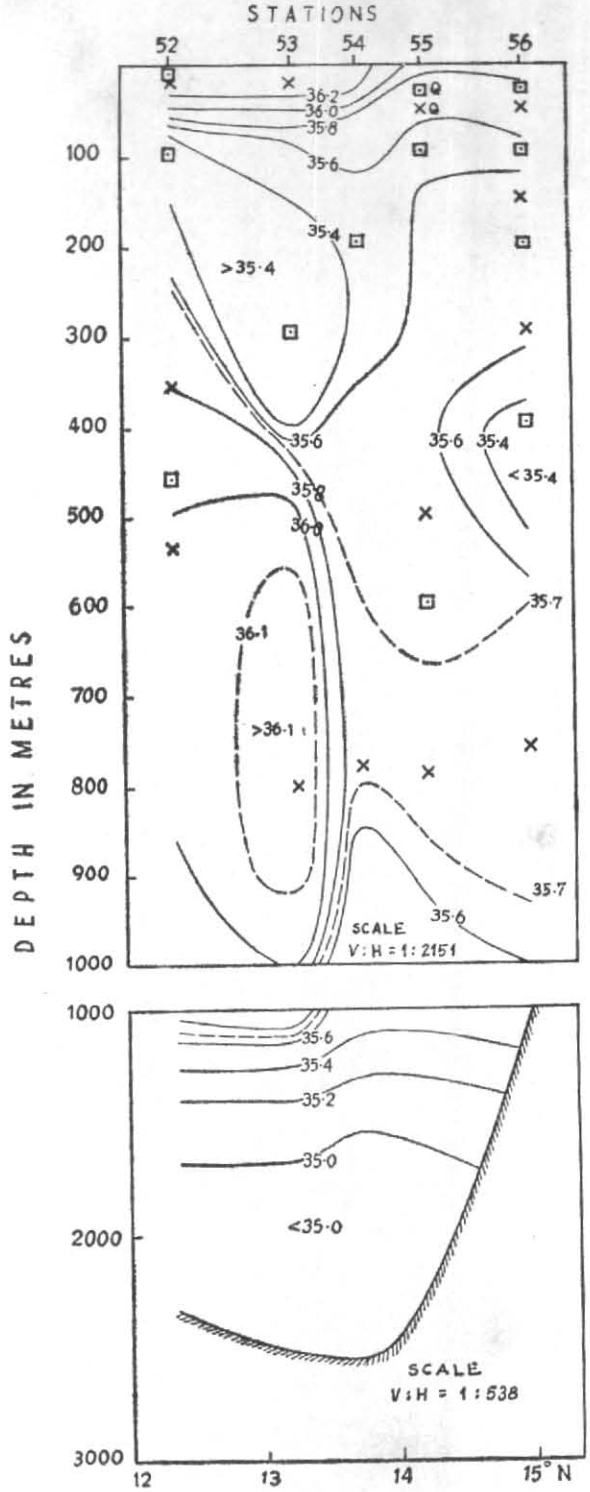

Fig. 2
Salinity (per mil) along approximately 50°E (Section-I)

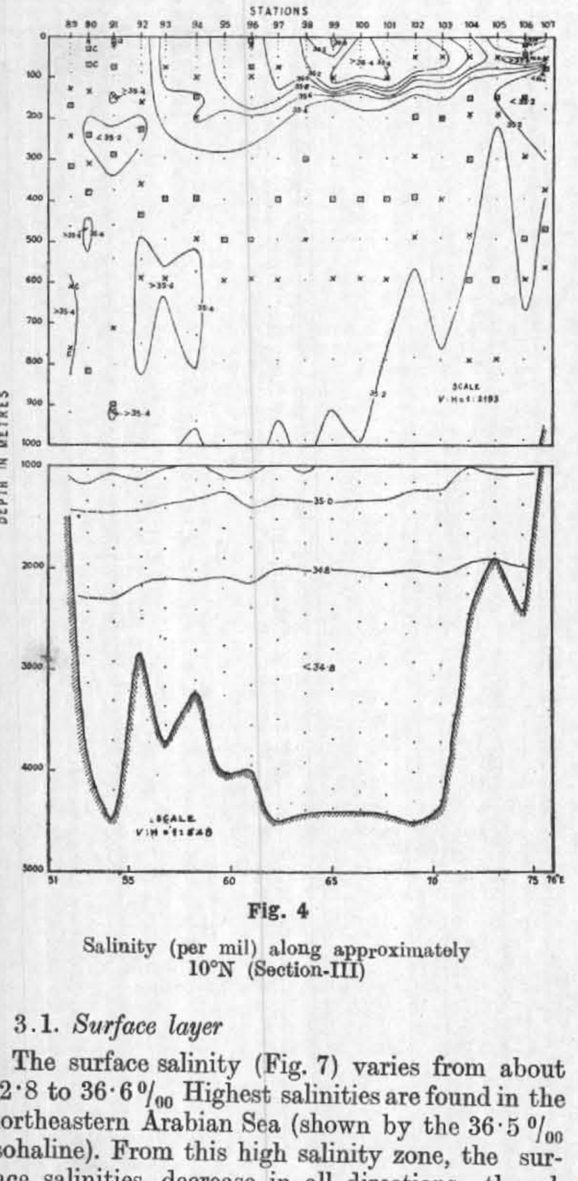

Fig. 4

Salinity (per mil) along approximately 10°N (Section-III)

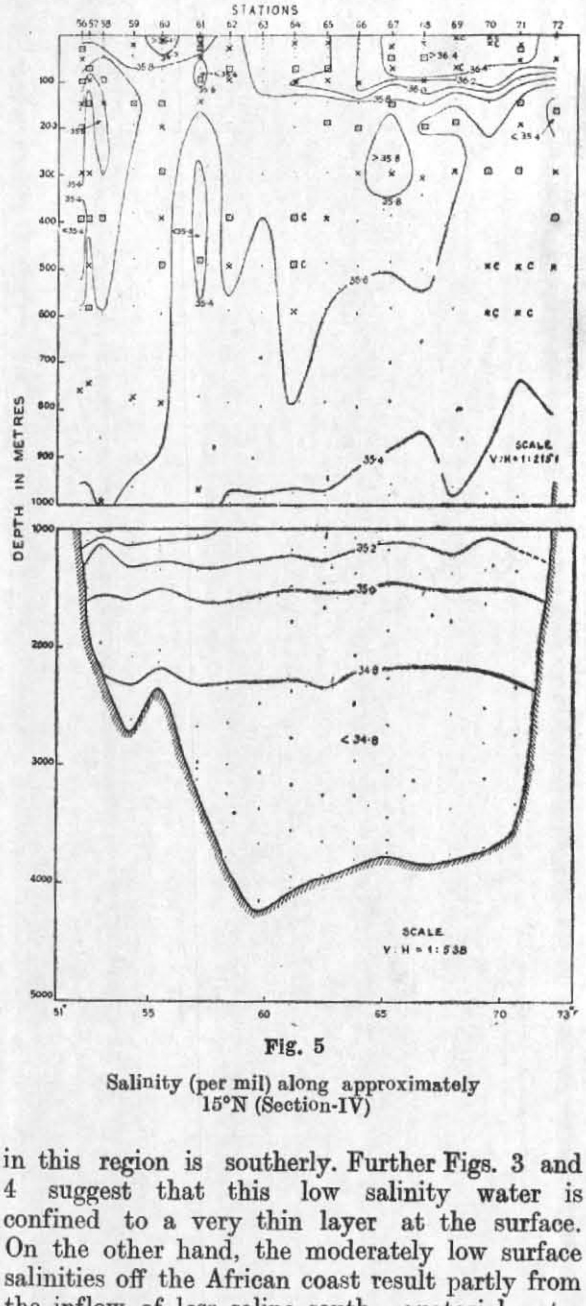

Fig. 5

Salinity (per mil) along approximately 15°N (Section-IV)

3.1. *Surface layer*

The surface salinity (Fig. 7) varies from about 32·8 to 36·6 ‰ Highest salinities are found in the northeastern Arabian Sea (shown by the 36·5 ‰ isohaline). From this high salinity zone, the surface salinities decrease in all directions, though not uniformly. Very low salinities are found off the southwest coast of India. Off the Somali coast, the salinity is moderate (usually less than 35·4 ‰). The salinity exceeds 36·2 ‰ across the Gulf of Aden and is found to decrease to about 35·4 ‰ around Socotra.

The low surface salinities off the southwest coast of India are clearly due to large dilution by heavy precipitation and land drainage during this season. The maximum dilution seems to take place around 10°N. The circulation patterns presented in Pt. II (Sastry and D'Souza 1971) show that the flow in this region is southerly. Further Figs. 3 and 4 suggest that this low salinity water is confined to a very thin layer at the surface. On the other hand, the moderately low surface salinities off the African coast result partly from the inflow of less saline south equatorial water and partly due to intense upwelling off the Somali coast. The south equatorial current after reaching the African coast, turns north and later flows along the coast upto about 8°N (Sastry and D'Souza 1971). The surface salinity in the south equatorial current (as evidenced by the T-S curve for Albatross station 196, 11° 10′S and 96° 15′E in Fig. 13) is low and when this water mixes with the high salinity water in the Arabian Sea, moderate salinities as found in the Somali basin result (*See* also Figs. 3 and 4).

A discussion of the formation of the high salinity

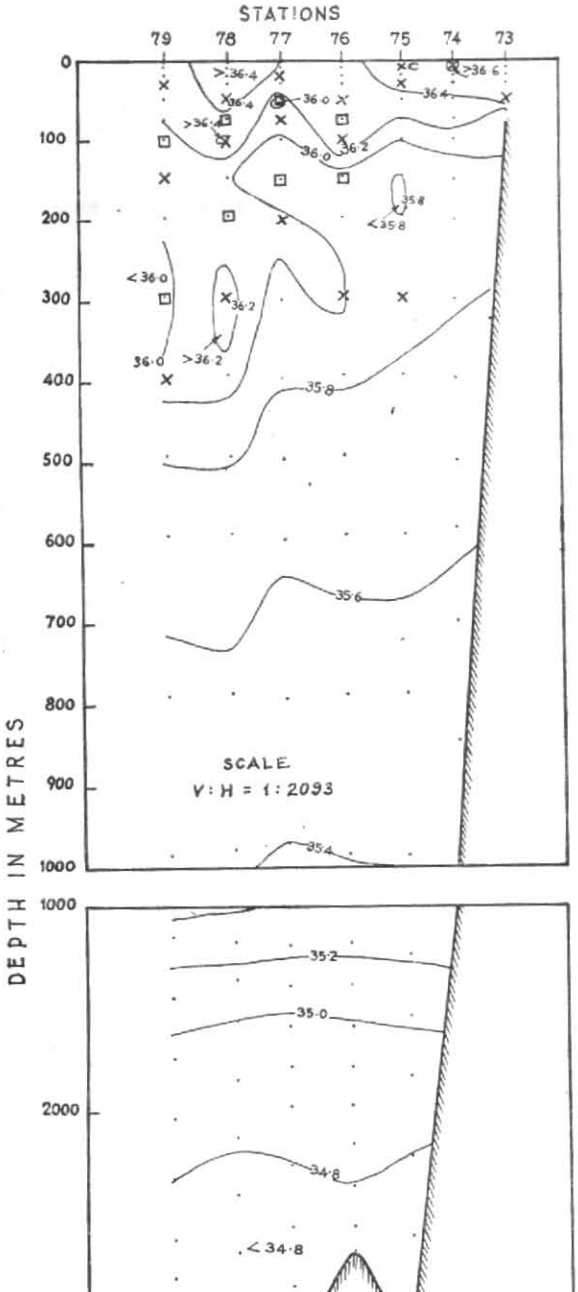

Fig. 6

Salinity (per mil) along approximately 20°N (Section-V)

water in the northern and northeastern Arabian Sea is presented in the next section.

The 100 m salinity (Fig. 8) varies from less than 35·2 to about 36·4 $^{0}/_{00}$. Though high salinities are observed in the northeast Arabian Sea, the region of the highest salinity has shifted to the central regions (shown by the 36·2 $^{0}/_{00}$ isohaline) with an arm extending to the northwestern Arabian Sea. Off the southwest coast of India, the salinities are moderate ($<35·2$ $^{0}/_{00}$) in contrast to the low surface salinities (Fig. 7). In the Somali basin, the 100 m salinity is nearly uniform with a variation from about 35·3 to 35·4 $^{0}/_{00}$ while across the Gulf of Aden, the salinity is found between 35·4 to 35·7 $^{0}/_{00}$.

The distribution of salinity at 200 m (Fig. 9) is relatively simple and the isohalines, showing a pronounced wavy character are oriented in a general westsouthwest-eastnortheast direction. The salinity increases from less than 35·1 $^{0}/_{00}$ in the southeastern Arabian Sea to more than 36·0 $^{0}/_{00}$ in the northwestern regions.

Within this surface layer, salinity maxima are observed at several stations. These maxima occur within the depth range of 50 to 150 m and are located between the 300 and 500 cl/t steric levels. A closer examination of the four zonal sections (Figs. 3 through 6) reveals that these maxima have the highest values in the northeastern Arabian Sea and further they are found at relatively shallower depths in the same region.

3.2. *Intermediate layer*

The salinity distribution at 500 m (Fig. 10) shows that high salinities of about 36·0 $^{0}/_{00}$ are found across the Gulf of Aden. The isohalines are mostly zonal and the salinity increases from south to north. Fig. 11 shows a similar salinity distribution at 1000 m.

In the intermediate layer, the salinity varies rather irregularly marked by maxima and minima in the entire region. Double maxima are frequently observed. Across the Gulf of Aden and in the southern Arabian Sea (Figs. 2, 3 and 4), a prominent salinity maximum is found in the depth range of 500 to 800 m confined to 100 and 80 cl/t steric levels. This salinity maximum is conspicuous by its absence in the northern Arabian Sea (*See* Fig. 6). Another salinity maximum is frequently found at depths of 200-300 m and between 200-120 cl/t steric levels. Between these two zones of salinity maxima, a zone of salinity minimum at about 400 m coinciding with 120 cl/t surface is found in the southern Arabian Sea. At a few stations especially in the western regions the salinity minima are found to coincide with subsurface

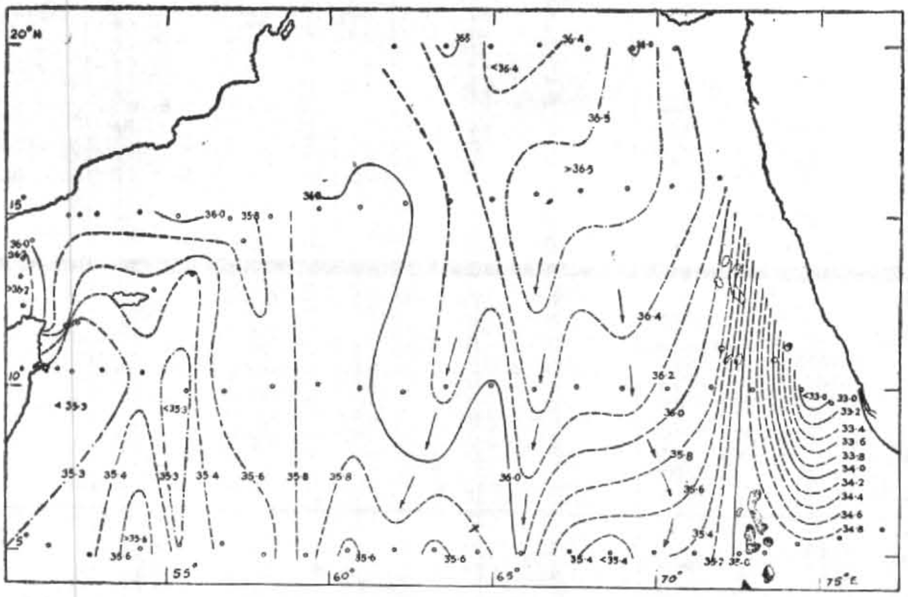

Fig. 7. Salinity (°/₀₀) at surface

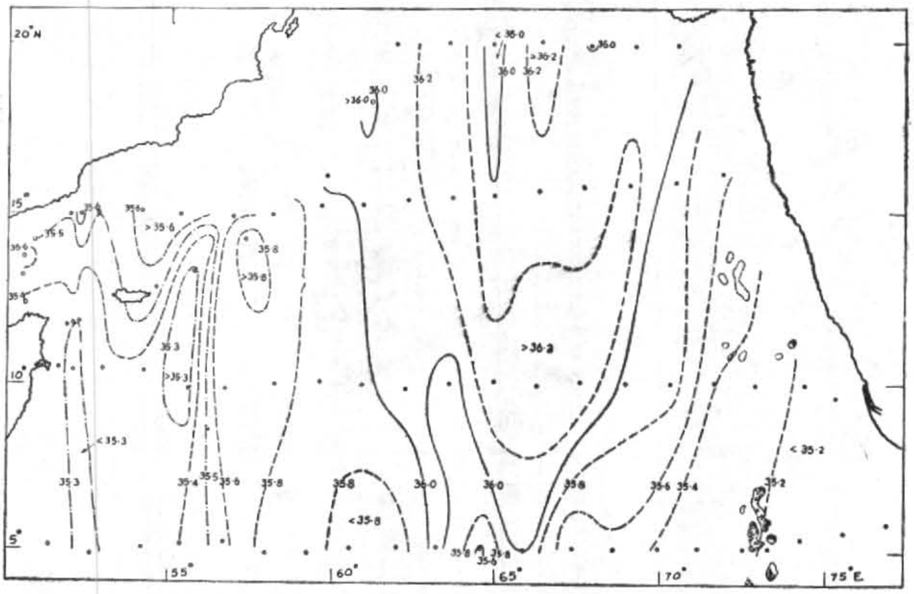

Fig. 8. Salinity (°/₀₀) at 100 m

oxygen maxima (D'Souza and Sastry 1971), while at others, the salinity minimum is located at about 100 m below the oxygen maximum. In the northern Arabian Sea these maxima and minima are found irregularly at different depths and steric levels.

3·3. *Deep and bottom water*

At 1500 m, the salinity varies within narrow limits from less than 34·9 °/₀₀ in the southern regions to more than 35·0 °/₀₀ in the northern regions (Fig. 12). Below a depth of about 2000 m, the salinity decreases to abyssal values (<34·8 °/₀₀).

4. Water masses in the Arabian Sea

Our main concern so far has been to present the three dimensional salinity distribution in the Arabian Sea. The basic feature of the water mass in the upper 1000 m is the occurrence of several maxima and minima in the entire region. The spatial distribution charts have further revealed that high salinity zones are found in different regions at different depths. In this section, we present a study of these maxima and minima in relation to their origin.

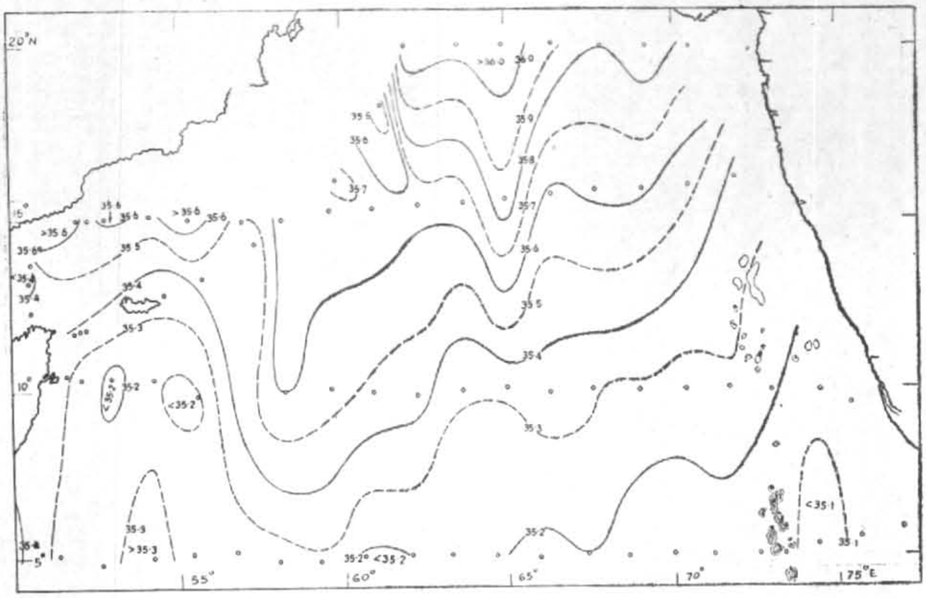

Fig. 9. Salinity (‰) at 200 m

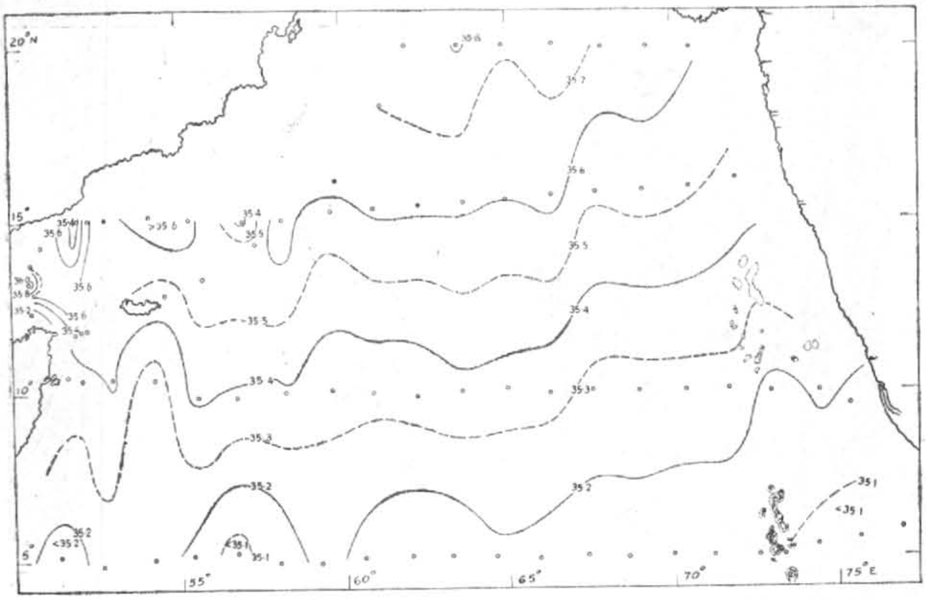

Fig. 10. Salinity (‰) at 500 m

The usefulness of the temperature-salinity diagram to characterise and to identify the water masses is well known. A deeper insight into the water mass structure may be obtained by plotting the temperature-salinity values of the maxima and minima on the T-S diagram on which lines of equal thermosteric anomaly are also drawn. Such a plot is shown in Fig. 14. The basic features of the salinity maxima and minima are summarised below. The salinity minima exhibit a wide scatter. About ninety per cent of the values fall within the temperature range of 9·5 to 20·0°C and the salinity range of 35·0 to 36·0 ‰. The corresponding values of the thermosteric anomaly is from 80 to 260 cl/t. The salinity maxima show a much wider scatter and these may be grouped under three categories :

(1) those located between 300 and 500 cl/t levels,

(2) those located between 100 and 200 cl/t levels, and

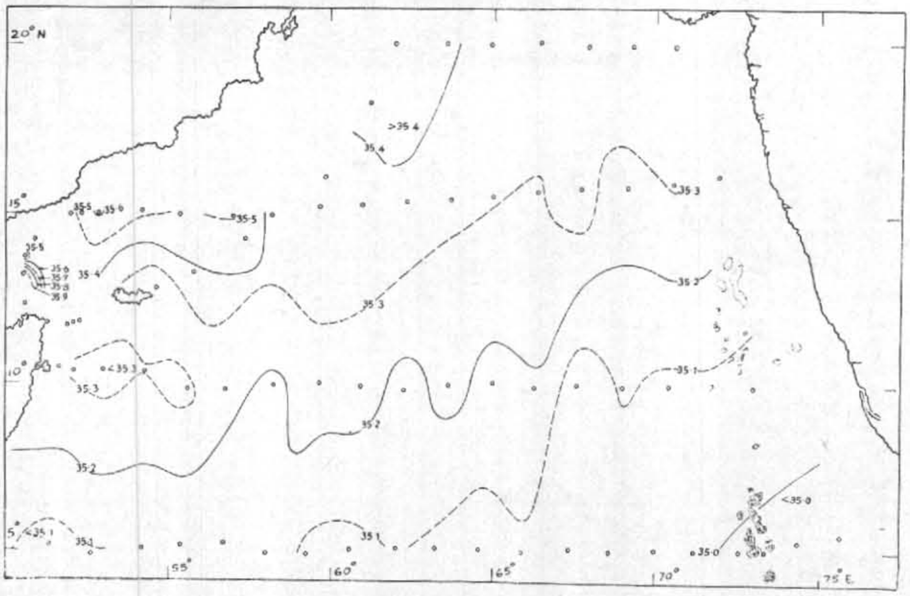

Fig. 11. Salinity (‰) at 1000 m

(3) those located between 60 and 100 cl/t levels.

Any representation of the water mass structure in the Arabian Sea should adequately explain, at least qualitatively, the above features in Fig. 14.

4.1. *Salinity minimum in the Arabian Sea*

The presence of salinity minima over a wide range of steric levels is not immediately clear. We do not have any large fresh water sources, except perhaps the land drainage and the *Indus* discharges into the Arabian Sea, for considerable dilution. Further, there is no evidence of any large scale sinking in the region. Though Sundara Raman, Balakrishna Kurup and Sreerama Murthy (1968) suggest the presence of the *Indus* water in the depth range of 75-150 m, it is doutful whether the *Indus* discharges limited to about 0·02 km³/h (Leopold 1962) have any effect on the subsurface salinity structure whatsoever. At best, these discharges would result in the formation of a thin surface layer. As seen in Figs. 3 and 4, the influx of fresh water off the southwest coast of India is limited to a very thin layer at surface. Thus in order to understand the source of the salinity minima, we should necessarily think of an external origin of low salinity water which penetrates into the Arabian Sea.

The origin of the salinity minimum at intermediate depths in the Arabian Sea has been the subject matter of much discussion. According to Ivanov-Frantskevitch (*See* Taft1963), the salinity minimum may be explained by the spreading of two or more high salinity water masses at different depths to cause salinity minimum at intervening depths. Tchernia, Lacombe and Guibout (1958), tracing the salinity minimum continuously from the south Indian Ocean to the northern Arabian Sea, have concluded that the Antarctic intermediate water (which is characterised by its salinity minimum as seen in Fig. 13) penetrates into the Arabian Sea. However, Taft (1963) points out that these salinity minima are located at different steric levels (Fig. 14) and as such these cannot be represented by a line of flow. Taft's salinity distribution on the 125 cl/t surface shows a zone of salinity minimum which extends from Banda Sea to about 10°S, 60°E. This low salinity water is seen within the depth range of the Somali basin salinity minimum and as such the Somali basin salinity minimum could be connected to the Banda Sea Water. However, Warren, Stommel and Swallow (1966) have shown that the oxyty of the Banda Sea water is appreciably lower than that associated with the Somali basin salinity minimum. Thus they rule out the possibility of the Banda Sea water penetrating into the Arabian Sea in appreciable quantities. They suggest that the subtropical subsurface water, a layer of salinity transition and an oxygen maximum, penetrates into the Arabian Sea overlying the high salinity core of the north Indian Water. Although this scheme looks obvious at first and explains satisfactorily the salinity minimum as well as the oxygen maximum in the Somali basin, it fails to explain the wide scatter of the salinity minima in Fig. 14.

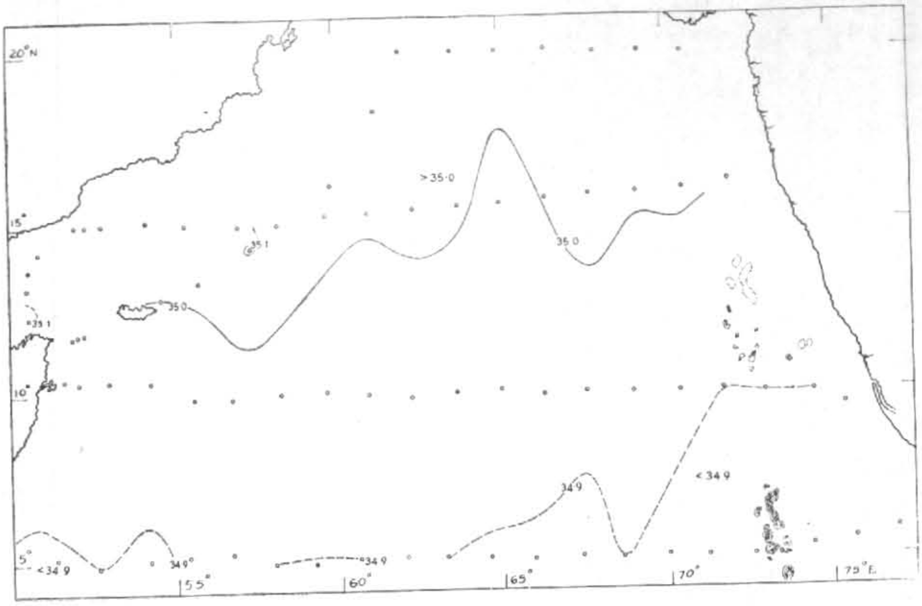

Fig. 12. Salinity ($^0/_{00}$) at 1500 m

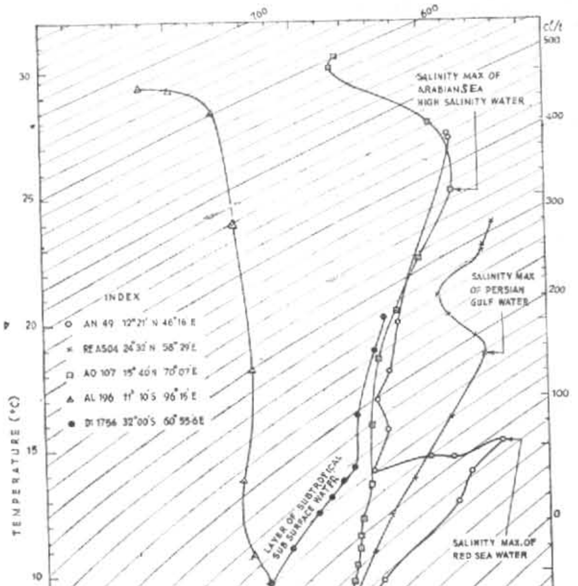

Fig. 13

T-S characteristics of water masses in the Indian Ocean (*after* Sastry[3] 1971)

Sastry (1971) discusses the transformation by mixing of three water types, two of which have the same density but different temperatures and salinities. He shows that when mixing progresses between the three water types, defined by the salinity minimum of the Antarctic intermediate water and salinity maxima of the Red Sea and Persian Gulf waters (Fig. 13) the Antarctic intermediate water type gets transformed such that its salinity increases accompanied by a shift in the salinity minimum to progressively higher steric levels. North of about 12°N, the Red Sea Water ceases to be of significance as discussed in section 4·4 (*See* also Rochford, 1964) and the Arabian Sea High Salinity Water assumes prominence in the mixing processes. Thus further transformation of the Antarctic Intermediate water type is accompanied by a sudden shift of the salinity minimum to still higher steric levels. Sastry, thus, explains the wide scatter of salinity minimum in Fig. 14 and his scheme appears to be in accordance with the salinity distributions in Figs. 3 through 6. However, the assumption of uniform eddy diffusivity and the characterisation of the water mass by a single temperature-salinity values are questionable in Sastry's model.

4·2. *Salinity maximum between 500 and 300 cl/t steric levels*

These salinity maxima are found within the surface layer in the entire region. Rochford (1964) has identified these maxima and calls this water as Arabian Sea high salinity water. As these maxima are located close to the sea surface, the distribution of these maxima will be largely governed by the variations in the wind distribution.

As mentioned earlier, surface salinities exceeding $36 \cdot 5\,^0/_{00}$ are found in the northeast Arabian Sea. Within this zone of high salinity ($>36 \cdot 4\,^0/_{00}$) the thermosteric anomaly varies from about 380 to 440 cl/t (Sastry and D'Souza 1971) and thus we attribute the northeast Arabian Sea as the source region for these salinity maxima.

The mechanism by which the salinity maximum occurs seems to be governed by the air-sea interaction processes. According to Morskoii Atlas (Warren, Stommel and Swallow 1966) the annual excess of evaporation over precipitation is about 100-150 cm in the northwest Arabian Sea. Further, Venkateswaran (1956) has studied the rates of evaporation during the various seasons in the Indian Ocean in some detail. Though his estimates based on several assumptions seem to require a revision with the more recent data obtained during IIOE his annual evapo ation rates and the excess of evaporation over precipitation substantially agree with those given in Morskoii Atlas for the Arabian

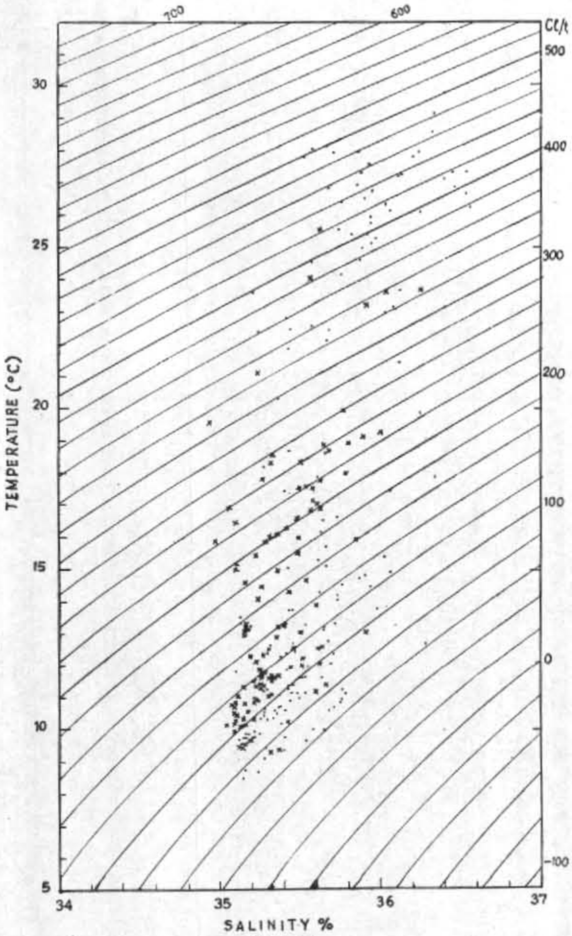

Fig. 14
Temperature and salinity values of salinity maxima and minima
. Maxima × Minima

Sea. His studies further show that maximum evaporation takes place during December-February and June-August. The large evaporation over the Arabian Sea necessarily increases the surface salinity.

During the southwest monsoon season, the low surface salinities between the Somali coast and west of 60°E (Fig. 7) are due to the influx of less saline south equatorial water while the low salinities off the southwest coast of India are due to heavy rainfall and land drainage. Thus the effective increase in surface salinity due to evaporation will be noticeable in the northeastern Arabian Sea where the influence of the above factors is less. During the northeast monsoon season, while the influx of south equatorial water no longer exists, appreciable quantities of less saline Bay of Bengal water may enter into the southern region of the Arabian Sea. Further, during this period, the rainfall over the region is negligible. It might be expected that, over most of the northern Arabian Sea, surface salinity increases with a shift of the high salinity zone to the region of maximum evaporation.

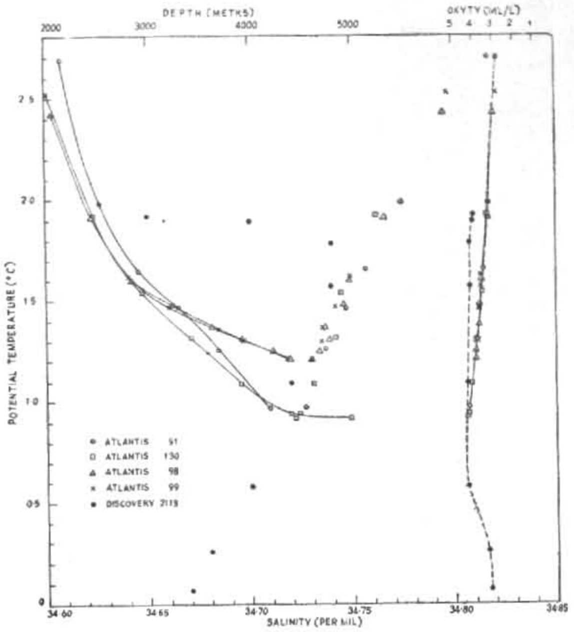

Fig. 15

Relationship showing temperature *versus* depth, salinity and Oxyty

Even though the surface salinity increases considerably, because of high surface temperatures in this region, the water mass formed at the surface does not sink to great depths and this water spreads along the isanosteric surfaces (380 to 440 cl/t). The topography of the 400 and 300 cl/t isanosteric surfaces (Sastry and D'Souza 1971 a) slope downward to the south and thus we find these maxima deeper in the southern Arabian Sea. The arrows in Fig. 7 show the probable flow paths of these maxima during the southwest monsoon season*.

4·3. *Salinity maxima between 100 and 200 cl/t steric levels*

The subsurface salinity maxima appear continuous extending from about 80 to 200 cl/t steric levels. However, they may be grouped into two distinct categories as those falling above and below the 100 cl/t steric level. As is evident from Figs. 3, 4 and 5, at several stations in the southern Arabian Sea, two subsurface salinity maxima (one above and the other below the 100 cl/t surface) are frequently observed. However in the northern and northeastern Arabian Sea, the vertical salinity structure at several stations show only one maximum above the 100 cl/t surface and the deeper salinity maximum is conspicuously absent. Further the values of these maxima show a northward increase. These features in the vertical salinity structure suggest different source regions for these maxima and also a northern origin for the water type with the salinity maximum above the 100 cl/t surface.

As seen in the previous section, the evaporation processes over the Arabian Sea could result in surface salinity maxima limited to the steric levels of 300 to 500 cl/t. As such this water type does not seem to originate in the Arabian Sea. In order to find the source region of this water type, we have analysed the temperature-salinity curves at several stations in the northern Arabian Sea and the adjoining Gulf of Oman. In the Gulf of Oman, the vertical salinity structure shows a pronounced subsurface salinity maximum exceeding $36 \cdot 4^{0}/_{00}$ (*See* the station curve for 'Requisite' station REASO4 in Fig. 13). In this region these salinity maxima are found at a mean steric level of about 165 cl/t with a range of variation from about 135 to 195 cl/t. Further these maxima could be traced to the sea surface in the eastern Persian Gulf. Thus we attribute the Persian Gulf as the source region of these salinity maxima. It appears that the surface water flows into the Persian Gulf and later sinks due to increase in salinity due to the very high rates of evaporation in this region and flows out along the bottom into the Gulf of Oman. As this water flows out into the Arabian Sea, the salinity of these maxima is quickly eroded and

*The authors are preparing a paper on the distribution or properties on the isanosteric surfaces wherein the flow paths of these maxima are better represented.

further distribution of these maxima is governed by the flow patterns at these steric levels.

4.4. *Salinity maxima below the 100 cl/t steric level*

These subsurface salinity maxima have been identified as those of Red Sea water by several workers (Sverdrup, Johnson and Fleming 1942; Rochford, 1964; Warren, Stommel and Swallow, 1966, etc). Across the Gulf of Aden, the Red Sea water could be recognised by its high salinity exceeding 36·0 ‰. Thus at station 53 (Fig. 2), the salinity maximum at a depth of 800 m is clearly of the Red Sea water. As this water flows out of the Gulf, its salinity is quickly reduced. Elsewhere in the Arabian Sea, this water may be identified by the salinity maximum at depth varying from 500 to 800 m.

It is clear, from an examination of Fig. 6 that this water mass is absent in the northern Arabian Sea. Rochford's (1964) studies also indicate a similar feature. Further his studies show that this water could be traced in the Bay of Bengal as well as in the south Indian Ocean as far south as 20°S. Warren, Stommel and Swallow (1966) suggest interfingering of the Red Sea water and the Antarctic intermediate water below 100 cl/t in the Somali basin. Tchernia, Lacombe and Guibout (1958) — as mentioned earlier, conclude that the Antarctic Intermediate Water penetrates into the northern regions of the Arabian Sea. Therefore, it is surprising that while the Antarctic intermediate water, whose salinity minimum occurs at about the same steric level as that of the salinity maximum of the Red Sea water (Fig. 13), penetrates into the northern Arabian Sea, the Red Sea Water flowing into the Arabian Sea, through the Gulf of Aden should be totally absent in the northern Arabian Sea. An explanation for such an anomalous character may be given in terms of the mixing processes. Sastry (1971) suggests that when mixing of the Red Sea, Persian Gulf and Antarctic intermediate waters progresses, the salinity of the salinity maximum of the Red Sea water is eroded to such an extent that the Red Sea water looses its characteristic tracer property.

5. Deep Water

Below a depth of 1000 m, the salinity decreases monotonically to abyssal values of 34·71-34·74‰ in contrast to the rather irregular variations above 1000 m. While the temperature also decreases monotonically the dissolved oxygen increases with depth (D'Souza and Sastry 1971).

The finer details of the water mass structure of the deep and bottom waters may be seen more clearly by plotting the relationships of potential temperature *versus* depth, salinity and oxyty. In Fig. 15, we have presented these relationships of the water mass below 2000 m at two stations in the Somali basin (*Atlantis* stations 91 and 130) and two stations in the Arabian basin (*Atlantis* stations 98 and 99). Also included in this figure are the potential temperature—salinity and potential temperature-oxyty relations at *Discovery* station 2113 (58° 22·9′ S, 57° 10·5′E) in the circumpolar regions.

In the range of potential temperature from 0.9 to 1·7°C the potential temperature—salinity relations at all five stations are similar. However, the salinities in the Somali and Arabian basins are slightly higher than those at Discovery station 2113. On the other hand, the oxyty in the circumpolar regions is slightly more than that in the Somali and Arabian Basins. The depth-potential temperature curves in the Somali and Arabian Basins nearly coincide upto a depth of about 2800 m (*See* station curves for stations 98, 99 and 130) and at greater depths they deviate considerably showing that potential temperature of the deep water in the Arabian basin is slightly more than that in the Somali basin. Taking all the four curves into consideration and the depth of intersection of these curves, it appears that the sill depths connecting the two basins lie between 2800 and 3400 m.

The Indian Ocean Deep and Circumpolar Water has a range of temperature from 0·5 to 2·0°C and a range of salinity from 34·7 to 34·75 ‰ (Defant 1961). Below a depth of about 2500 m the potential temperatures and salinities at all stations are within the above ranges and we conclude that the entire water mass below, 2500 m in the Arabian Sea is of circumpolar origin. The slightly higher salinities in the Arabian Sea are probably due to diffusion of salt from the high salinity of the Red Sea and Persian Gulf waters. The circumpolar water enters into the Somali basin following the western edge of the nearly meridional mid-oceanic ridge (50-65°E). Thereafter the water above the sill depth flows into the Arabian basin. Thus we find the deep and bottom water in the Somali and Arabian basins is of circumpolar origin.

Acknowledgement

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