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OCEANOGRAPHY OF THE ARABIAN SEA DURING THE SOUTHWEST MONSOON SEASON. PART IV: DISSOLVED OXYGEN*

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ABSTRACT

The distributions of dissolved oxygen content in the Arabian Sea during the southwest monsoon season, 1963 are presented through vertical sections and horizontal charts. The surface oxyty variations are considerable and these have been attributed to large variations of surface temperature and salinity, circulation, photosynthesis, etc. The surface waters are found to be supersaturated with oxygen throughout the Arabian Sea, except in regions of intense upwelling. The oxyty in the surface layer is nearly uniform, indicating effective mixing in this layer. Below the surface layer, a strong oxycline (layer in which oxygen decreases with depth) which coinci des with the thermocline has been observed. The oxypleths in the oxycline tended to rise towards the Indian coast. The oxygen minimum intermediate layer could only be observed clearly in the northern Arabian Sea. Across the Gulf of Aden and in the southern latitudes. subsurface oxygen maxima at different steric levels are found. The studies revealed that these oxygen maxima are due to the transport of oxygen rich Subtropical Subsurface Waters across the equator. The high oxyty of the deep waters has been attributed to the penetration of the water mass originating in circumpolar regions.

INTRODUCTION

DISSOLVED oxygen in the Ocean, a non-conservative parameter, is influenced both by physical and biological processes. Based on the dissolved oxygen concentration or oxyty (Montgomery, 1969), the Ocean may be divided into three layers; the upper and bottom layers of high oxyty separated by a layer of low oxyty. The upper layer, being in contact with the atmosphere, is maintained at higher oxyty levels depending upon the oxygen solubility while the bottom water whose origins could be traced to the sea surface at high latitudes (and hence rich in oxyty at the time of formation of the deep and bottom waters) retains most of its oxygen as the consumption of oxygen by the biological processes is very small at these levels. The intermediate layer of low oxyty, often referred as the oxygen minimum layer, is thought to be the result of weak motion by some investigators and as such it has been regarded by them as the layer of no motion. Some others, however, believe that a combination of both physical and biological processes is responsible for the formation of the intermediate low oxyty layer.

The present paper on the distribution of oxyty in the Arabian Sea during the southwest monsoon season forms a continuation of the earlier studies by the authors (Sastry and D'Souza, 1970 a, b and Sastry and D'Souza**, 1971) to understand the ocenography of the region. Earlier studies on the oxygen distribution in the Indian Ocean in general and in the Arabian Sea in particular are few compared to the more comprehensive studies in the Atlantic and Pacific Oceans. Exceptions are those of Rochford (1964), Taft (1963), Wooster, Schaefer and Robinson (1967) and others.

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** These three papers hereafter are referred as SD1, SD2, and SD3 respectively.

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DATA AND ANALYSIS*

During August-September 1963, Atlantis occupied several stations in the Arabian Sea along five sections, one across the Gulf of Aden and the others along 5°, 10°, 15° and 20°N approximately. Fig. 1 is the station location map. For each of the stations, depth, salinity and oxyty are plotted against temperature on a grid showing thermosteric anomaly as a function of temperature and salinity. Smooth curves are drawn and necessary adjustments are made for missing and doubtful observations.

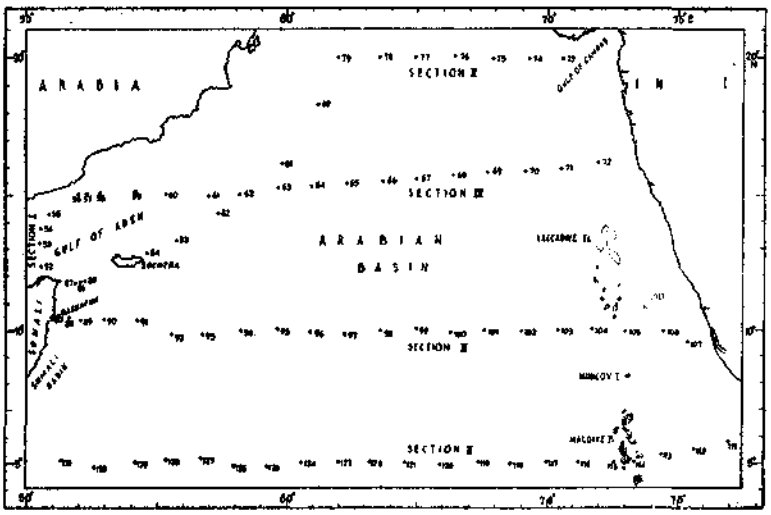

Fig. 1. Station location map.

For the construction of vertical sections (Figs. 2 through 6), the depths are read for the chosen oxypleths. In these figures, the dotted line near the surface marks the bottom of the surface layer which, as defined earlier in SD1, is the layer extending from the surface to a depth where the temperature is less by 1°C to that at the surface. Further, the maxima and minima in oxyty wherever these could be distinguished in the T-O curves are also noted in these figures.

For presenting the spatial distributions at 0, 100, 200, 500, 1000 and 1500 m (Figs. 7 and 9 through 13), the oxyty values at the corresponding depths are read from the station curves. The percentage saturation of oxygen solubility at the sea surface (Fig. 8) is calculated on the basis of data reported by Truesdale, Downing and Lowden (1955). In Fig. 8, the barred values indicate the oxygen solubility while the others show the excess in percentage over saturation solubility.

*The station data presented in this report has been kindly supplied by N. O. D. C., Washington D. C.

DISTRIBUTION OF OXYTY IN THE ARABIAN SEA

Before we present the water mass structure in relation to oxyty, a brief summary of the main features in the oxyty distributions are given below.

Surface Layer

The surface oxyty has been found to vary from 3.45 to 5.13 ml/l. This large variation will be discussed later in relation to several factors such as variations in surface temperature and salinity, circulation and photosynthesis, etc. In the surface layer, the oxyty remains more or less uniform indicating effective mixing in this layer. Below this layer, a strong oxycline (a layer in which oxyty decreases rapidly with depth) develops and this coincides with the zone of rapidly decreasing temperature indicating minimal exchange of oxyty between the surface layer and the subsurface water below. A comparison of the four zonal sections (Figs. 3 through 6) shows that the oxypleths in the oxycline tend to rise to shallower depths both in the northern and eastern Arabian Sea.

Intermediate Layer

The oxyty in the intermediate layer presents a rather complex picture. While the oxygen minimum layer could clearly be demarcated only in the northern Arabian Sea, elsewhere the intermediate layer is characterised by subsurface oxyty maxima. Along section V (Fig. 6) at 20°N, the oxygen minimum layer is bounded by the 0.25 ml/l oxypleths at depths of 150 and 1200 m.

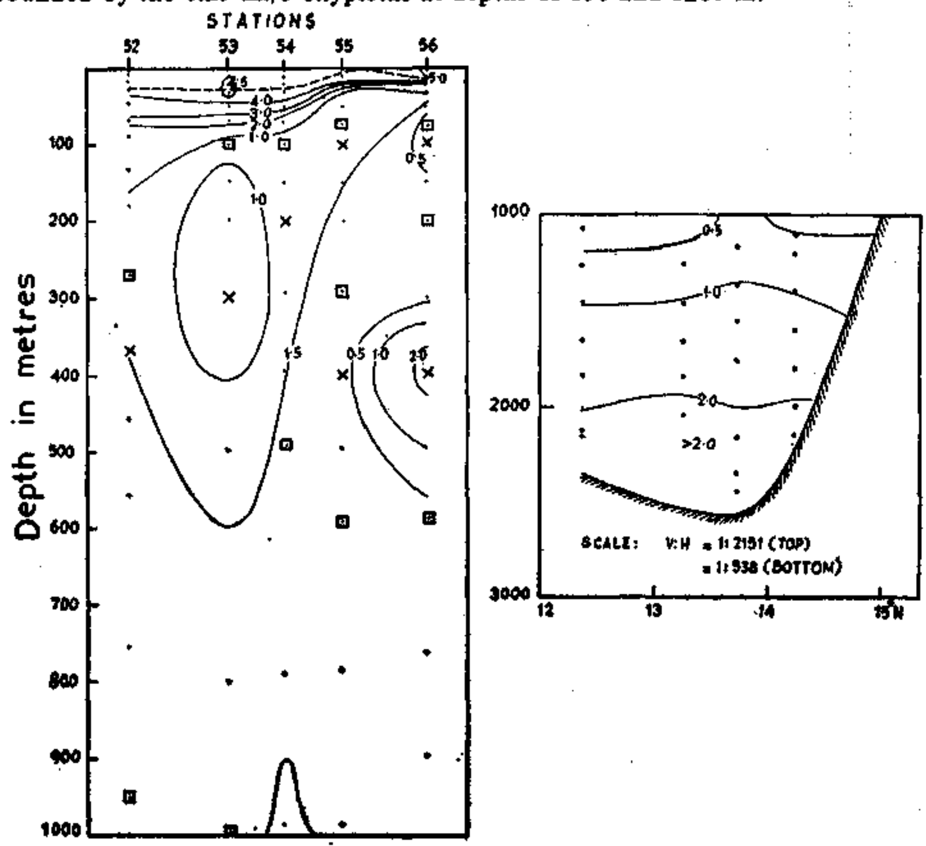

Fig. 2. Dissolved oxygen (ml/l) along approximately 50°E (Section-I).

South of 15°N, oxyty maxima are frequently observed in the intermediate layer. Since any explanation of the water mass structure should take into account these maxima, we shall describe the characteristics of these maxima in greater detail.

Across the Gulf of Aden (Section I, Fig. 2), at station 53, the intermediate oxyty maximum (1.75 ml/l) coincides with the salinity minimum (35.22‰)

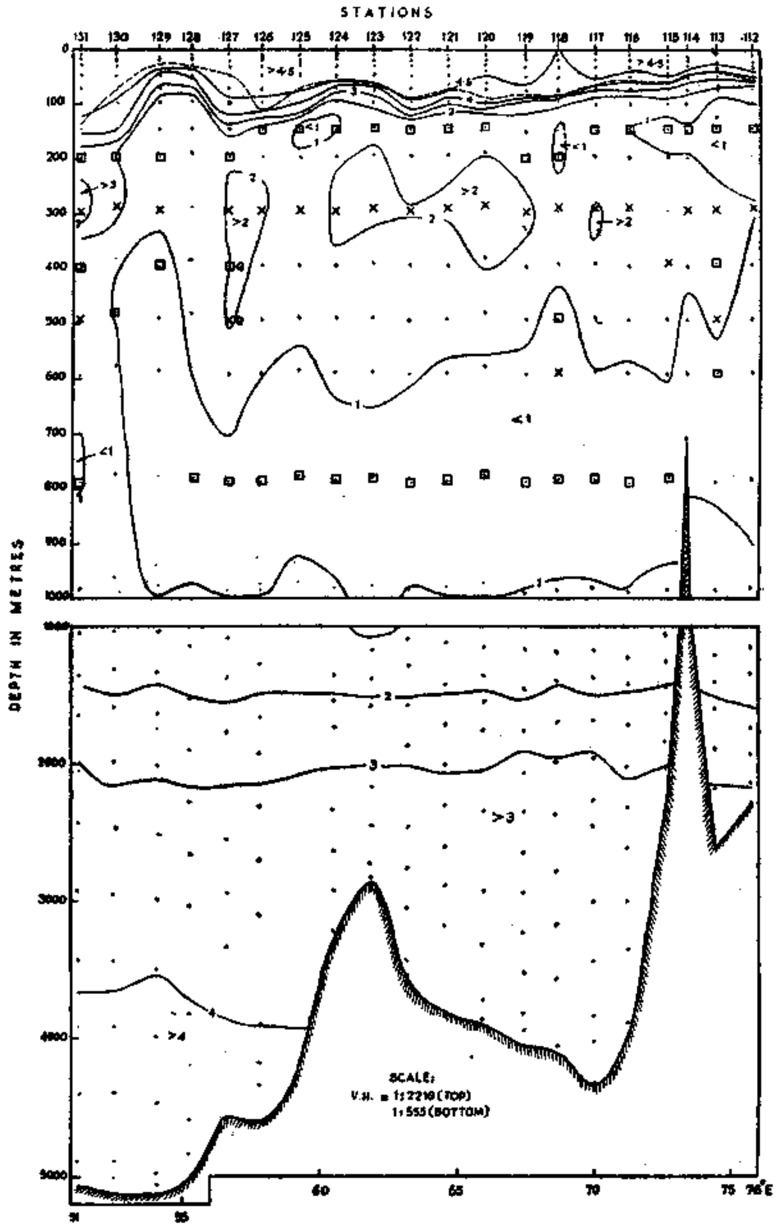

Fig. 3. Dissolved oxygen (ml/l) along approximately 5°N (Section-II).

on the 130 cl/t surface. At station 56, the oxyty maximum (2.30 ml/l) and the salinity minimum (35.23 ‰) are found on the 110 cl/t surface at a depth of 400 m. Elsewhere along this section, the subsurface oxyty maxima shown by X's in Fig. 2 occur at varying depths and steric levels. Further, these maxima are some times located in a layer of decreasing salinity.

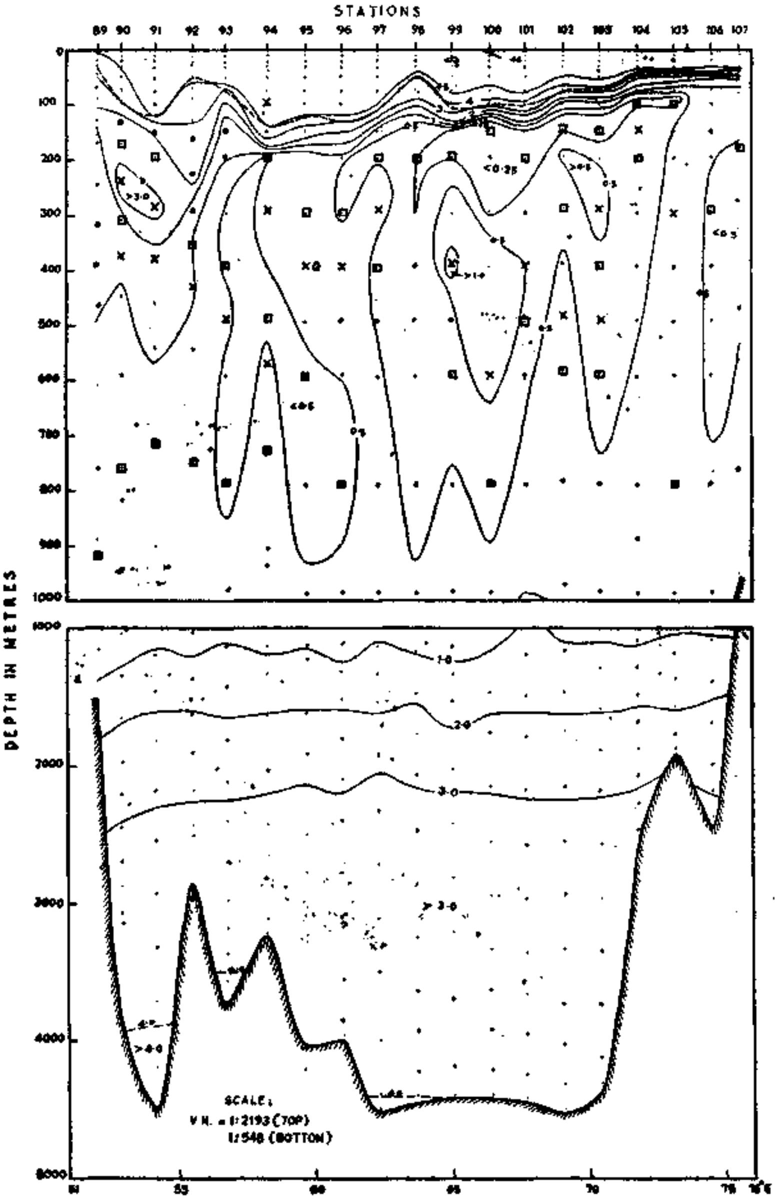

Fig. 4. Dissolved oxygen (ml/l) along approximately 10°N (Section-III).

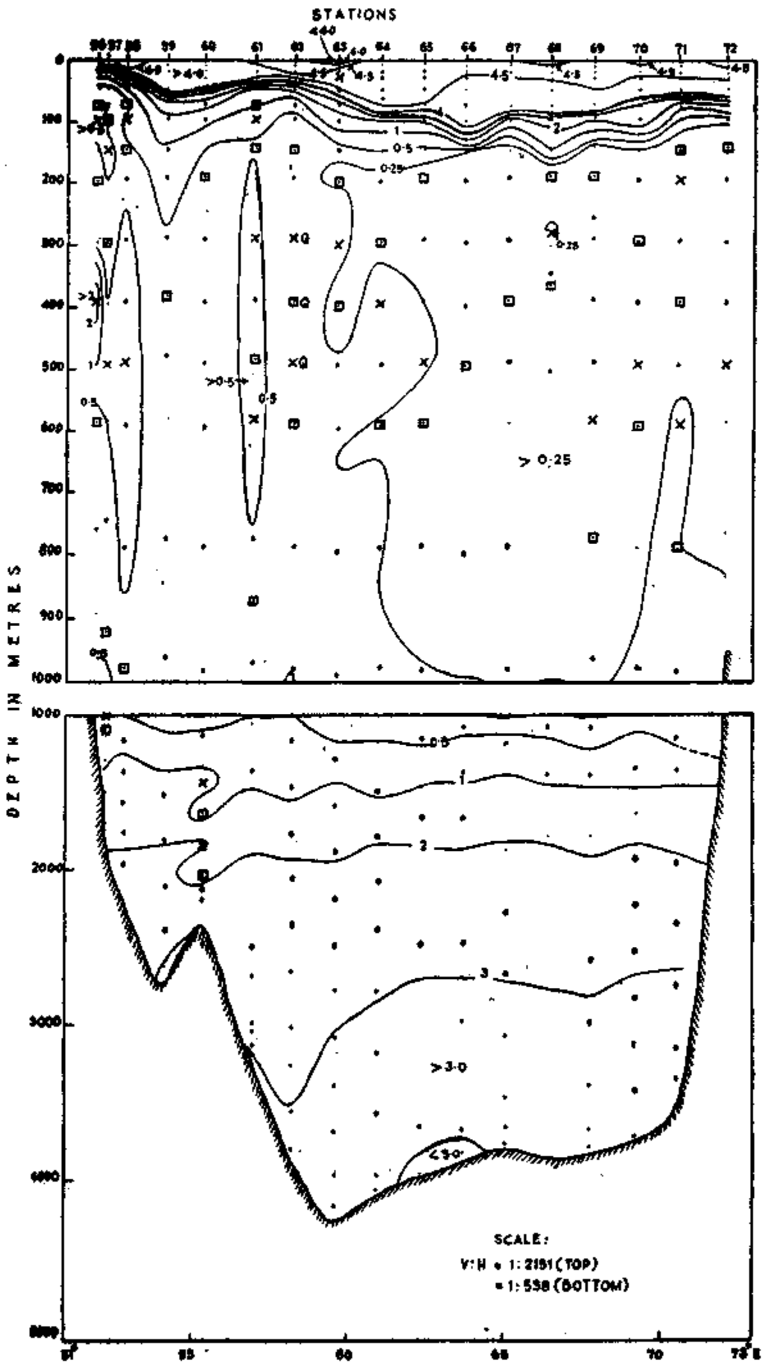

Fig. 5. Dissolved oxygen (ml/1) along approximately 15° N (Section-IV).

At 5°N, subsurface oxyty maxima are seen at almost all the stations at a depth of about 300 m at an average steric level of 130 cl/t (Fig. 3). These maxima vary over a considerable range of values with a tendency to decrease to east, from 3.3 ml/l at station 131 to 1.1 ml/l at station 112. In the western regions, the oxyty maxima at a few stations coincides with the salinity minima. However, along most of the section, the oxyty maxima are found at shallower depths than those of salinity minima and are located in a layer of decreasing salinity.

Along section III (Fig. 4), vast regions of the intermediate layer have oxyty less than 0.5 ml/l and within these zones are located relatively oxygenated waters. These subsurface oxyty maxima are found at varying depths and steric levels. Off the Somali Coast, the oxyty exceeds 3.2 ml/l at depths of 200 to 300 m.

Along 15°N in the oxygen minimum layer (shown by the 0.5 ml/l oxypleths in Fig. 5) the oxyty shows a general increase to the west. East of 60°E, the oxyty is less than 0.2 ml/l. Subsurface oxyty maxima are observed at several stations in the oxygen minimum layer. In the western regions, these maxima tend to coincide with the salinity minima. Elsewhere along this section, though these maxima are not quite conspicuous as in the southern sections, they occur at shallower depths than those of salinity minima.

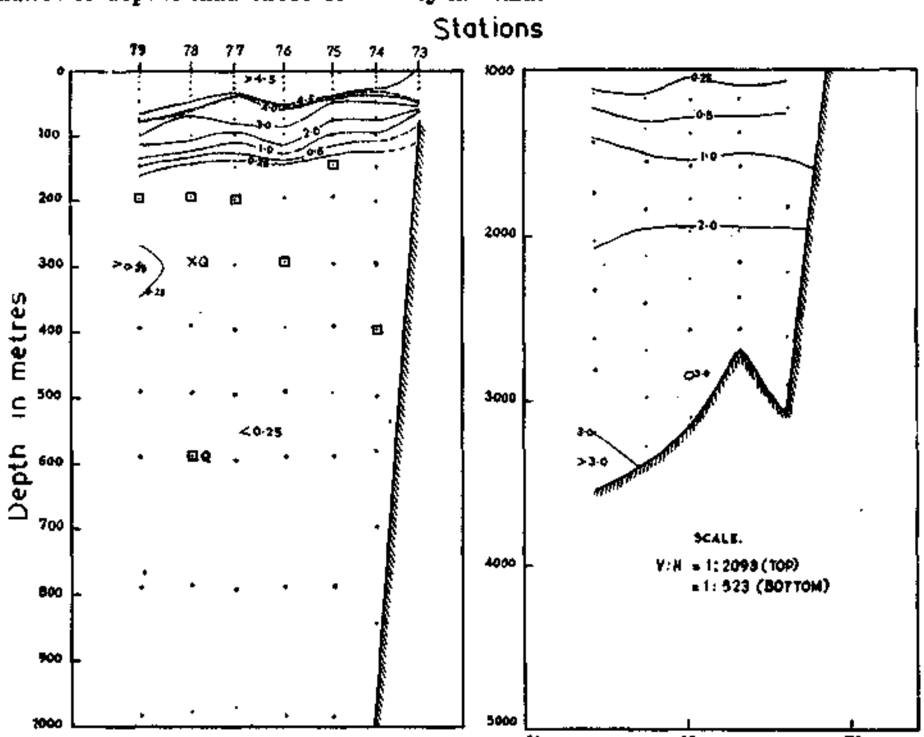

Fig. 6. Dissolved oxygen (ml/l) along approximately 20°N (Section - V).

Thus with the location of the subsurface oxyty maxima well below the oxycline in the southern Arabian Sea, the intermediate layer may be characterised as having poorly oxygenated layers at the top and bottom separated by a layer of oxygen-rich water. In both of the oxygen minimum layers, the oxyty decreases from south to north as well as from west to east and a similar tendency exists in the intermediate oxygen-rich layer.

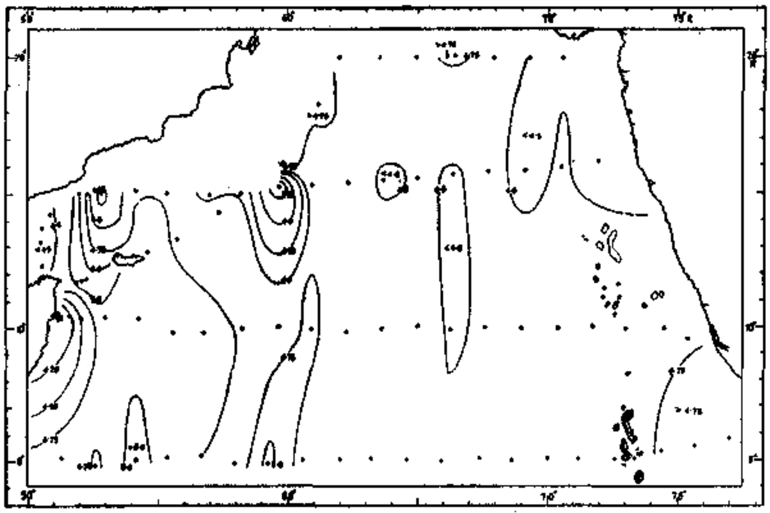

Fig. 7. Dissolved oxygen (ml/l) at surface.

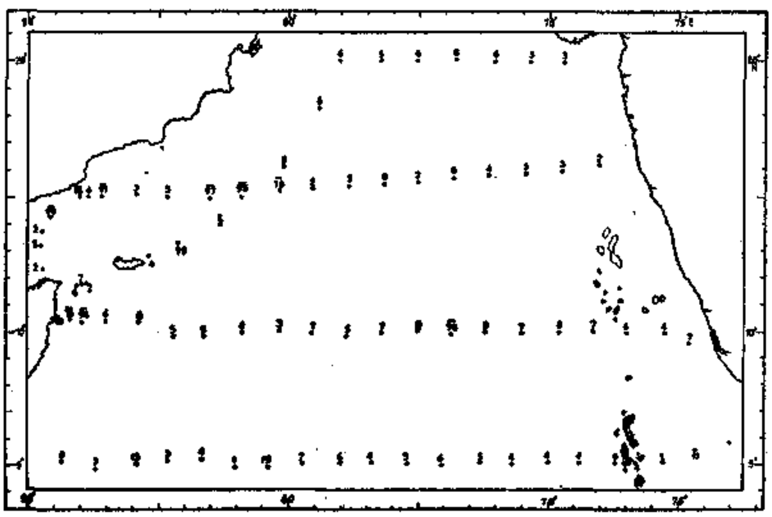

Fig. 8. Percentage saturation of oxyty at surface.

Deep and bottom water

Below the intermediate layer, the oxyty gradually increases with depth. Across the Gulf of Aden, the oxyty of the bottom water exceeds 2.0 ml/l. The oxyty of the bottom water exceeds 4.0 ml/l in the Somali Basin (Fig. 3 and 4) while the bottom oxyty in the Arabian Basin lies in general between 3.0 and 4.0 ml/l. The bottom oxyty also shows a tendency to decrease to the north.

Spatial distribution of oxyty

Figs. 7 and 8 show the oxyty and the percentage saturation of oxygen solubility at the sea surface respectively. It may be mentioned that the estimates of oxygen solubility based on data given by Truesdale, Downing and Lowden (1955) are appreciably lower than those earlier reported by Fox (1909) (see also Richards, 1957).

The oxyty at surface (Fig.7), as mentioned earlier, varies from 3.45 to 5.13 ml/l. Except at station 63 where the oxyty is lowest, it exceeds 4.0 ml/l in the entire region. Fig. 8 shows, however, that the surface waters are mostly supersaturated except at a few stations where undersaturation is observed. At stations 63 and 88, the percentage saturation is 76, the lowest that has been observed anywhere in the Arabian Sea. These stations are located in regions of intense upwelling. Thus it appears that the poorly oxygenated subsurface water rising to the sea surface in the process of upwelling may not have reached equilibrium with the atmosphere. On the other hand, supersaturation may result by the processes of mixing of water masses of different temperatures which were previously saturated with oxygen as well as by photosynthetic process (Richards, 1957). The surface circulation patterns in the Arabian Sea (SD2) suggest complex intermingling of water masses. While it is not possible to assess the amount of photosynthetic oxygen at surface with the data at hand, the supersaturation of oxygen at surface seems to be a net result of both the mixing processes and photosynthetic effects.

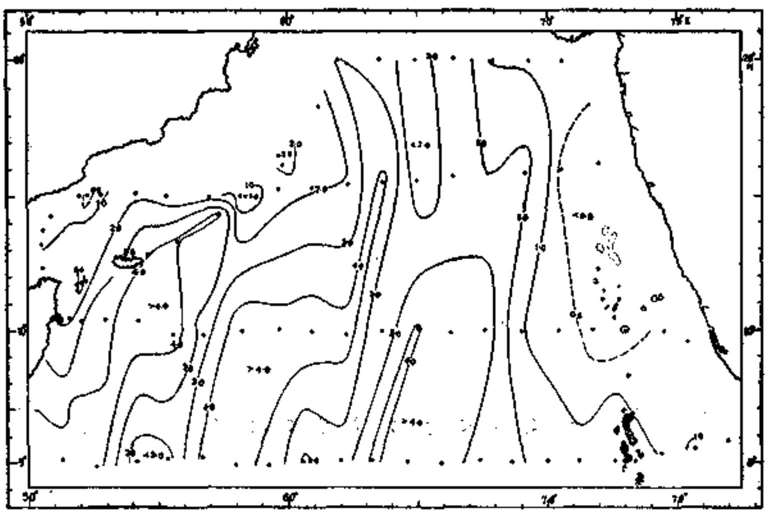

Fig. 9. Dissolved oxygen (ml/l) at 200 m.

The 100 m oxyty (Fig. 9) varies over a wide range of values (0.23 to 4.95 ml/l). These variations are closely related to the location of this surface which appears in the homogeneous surface layer in some regions and in the thermocline in other regions (SD1). Pockets of water with oxyty greater than 4.0 ml/l are found in the central regions of the Arabian Sea. These pockets coincide with regions where the surface layer is well developed often exceeding 100 m. As any material introduced into the surface layer is well mixed in a short time, properties, like dissolved oxygen whose input is at the surface, show very little variation within the surface layer. The nearly homogeneous character of oxyty in the surface layer, as mentioned earlier, is very well demonstrated in Figs. 2 through 6.

Off the west coast of India, the oxyty on this surface is less than 0.5 ml/l. The surface layer in this region is not well developed and has depths of less than 60 m. Along 20°N, the thickness of the surface layer increases from about 40 m at station 74 to 80 m at station 79. The oxyty along this section is moderately high varying from 0.8 to 3.0 ml/l. The variation in oxyty closely correspond to the depth variations in the surface layer. Further, it has been pointed out earlier in SD1, that the gradients of temperature in the thermocline (along 20°N) are weak compared to those along the southern sections and consequently the vertical exchange between the surface and subsurface layers could be more effective along this section. Thus the relatively higher oxyty along this section appears to be governed partly by the greater vertical exchange between the surface and subsurface layer and partly by the variations in the thickness of the surface layer.

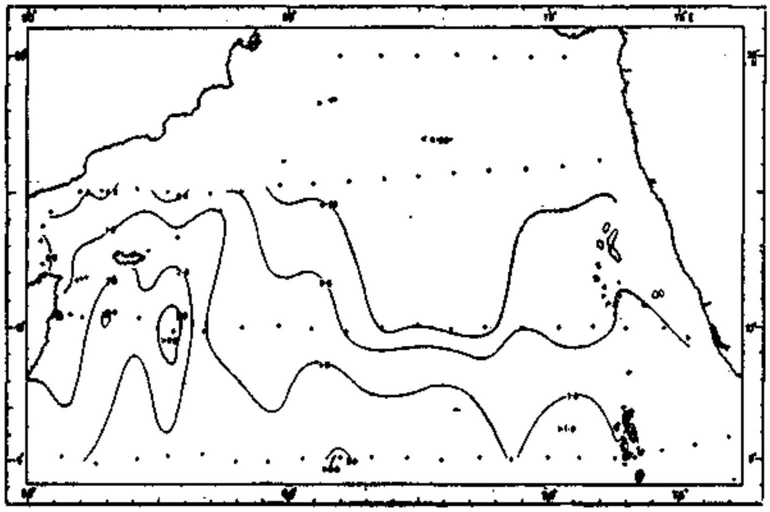

Fig. 10. Dissolved oxygen (ml/l) at 200 m.

However, across the Gulf of Aden the surface layer is only a few metres thick and where the strong temperature gradients below the surface layer limit the vertical exchange, the oxyty on this surface varies from 0.66 to 1.28 ml/l, higher oxyty being found in the southern Gulf. Further, higher oxyty is, in general, observed off the Somali Coast. While a discussion on the origin of the high oxyty water will be presented in the next section, it may be pointed out that the relatively high oxyty at this level off the Somali coast and in the southern regions of the Gulf of Aden appears to be the result of transport of oxygen rich water across the equator through the Somali current. As mentioned earlier in SD2 the flow patterns indicate that the Somali current turns east at about 5° to 8°N and whereafter it branches; one branch flows south and the other north. The northern branch splits again with one branch flowing along the coast enters into the southern Gulf while the other turns northeast off Socotra. In the northern Gulf, the flow is into the Arabian Sea. These features explain the distribution of oxyty along section I.

An isolated pocket with oxyty of 0.44 ml/l is observed at station 62. The isotherms as well as the oxypleths suggest subsurface upwelling, thereby bringing oxygen poor subsurface water to this level.

Thus it is seen that the complex distribution of oxyty at 100 m is governed by the development of surface layer, vertical exchange, circulation and upwelling.

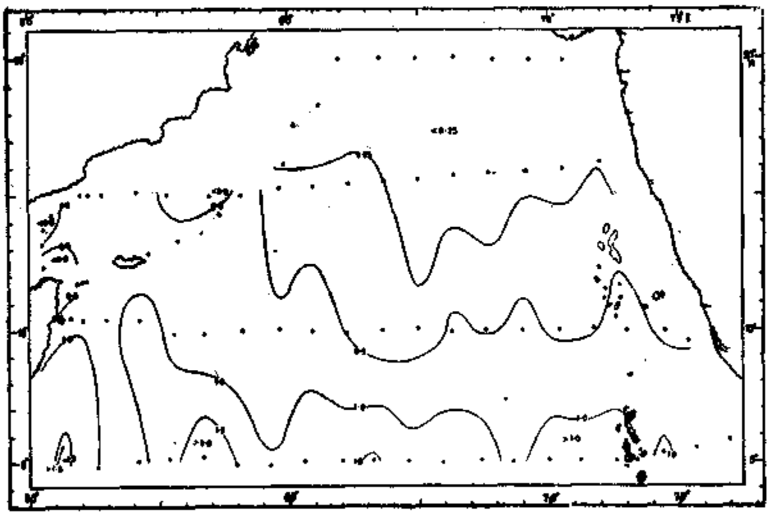

Fig. 11. Dissolved oxygen (ml/l) at 500 m.

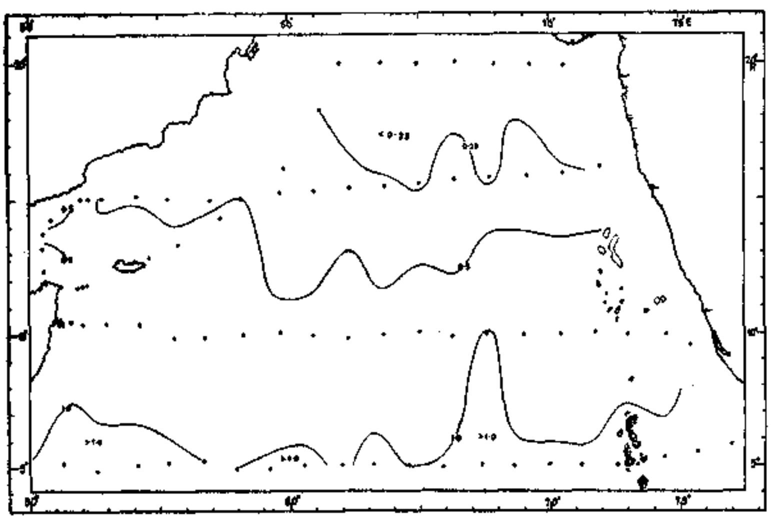

Fig. 12. Dissolved oxygen (ml/l) at 1000 m.

Fig. 10 shows the distribution of oxyty at 200 m. The distribution is relatively simple compared to that at 100 m. The oxyty varies from 0.08 ml/l to 3.56 ml/l on this surface. East of 60°E, the oxyty decreases toward north. In the central and northern Arabian Sea, the oxyty is less than 0.25 ml/l and is quite often as low as 0.1 ml/l. However, in the Somali Basin and along 5°N, the oxyty is generally high and the highest values occur at stations 90 and 92 where it exeeds 3.9 ml/l. At station 90, at this level, the water mass is characterised by an oxygen maximum and a salinity minimum while at station 92, the oxygen is found to decrease and is not associated with any salinity minimum.

As is seen in Fig. 4, the oxycline at these stations is not strongly developed and extends over a considerable thickness of the watermass. While it is not clear why such high oxyty is observed at this level at station 92, it appears that the high oxyty at station 90 is a result of the inflow of water of southern origin.

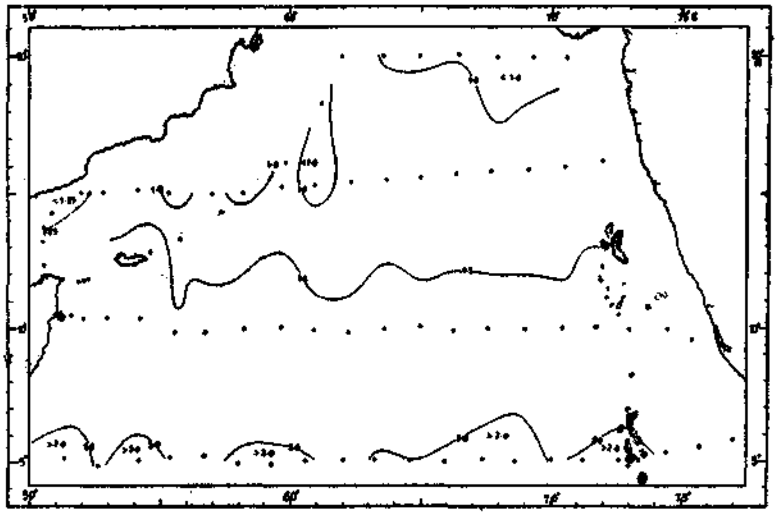

Fig. 13. Dissolved oxygen (ml/l) at 1500 m.

Figs. 11, 12 and 13 show the distribution of oxyty at 500, 1000 and 1500 m respectively. On all these surfaces, the oxyty decreases from south to north. The oxypleths, though wavy, are mostly zonal in similarity with the isotherms and isohalines presented earlier. These features suggest that the oxyty distribution is mostly governed by the advection and diffusion processes. A comparison with Fig. 10 shows that these levels are located in the zone of increasing oxyty below the oxygen minimum layer.

ORIGIN OF THE HIGH OXYTY LAYERS

While presenting the oxyty distribution in the Arabian Sea, we have observed that, south of about 15°N, the intermediate layer is characterised by oxyty maxima at different depths and steric levels. Further the deep and bottom water has been found to be oxygen-rich exceeding 3.0 ml/l. In this section, we present an analysis of the origins of these subsurface oxyty-rich water layers.

Oxyty maxima in the intermediate layer

We have seen that the distribution of the intermediate oxyty maxima are somewhat anomalous in that they appear at about 130 cl/t steric level in the southern Arabian Sea while they are seen irregularly at different steric levels further north. These maxima are found to coincide with the salinity minima in the western Arabian Sea and elsewhere in the region they are found at shallower depths than those of salinity minima. Further, the values of these maxima are found to decrease to the north and to the east.

The above considerations suggest that these maxima do not orginate in the northern Arabian Sea. Further, the Red Sea Water enters the Arabian Sea in the depth range of 500-800 m and as such this water can neither contribute to the subsurface oxyty maxima which are at comparatively shallower depths. Thus we are forced to think of a southern origin for these maxima.

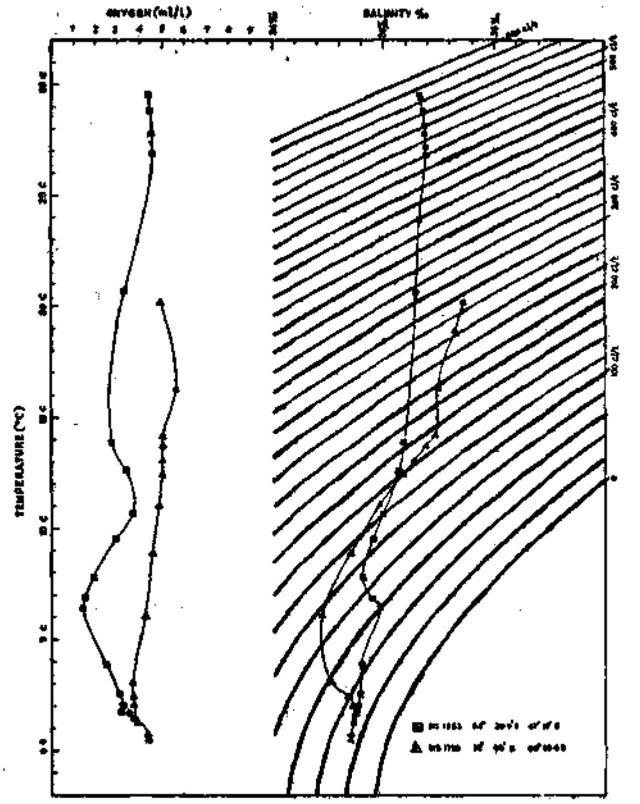

Fig. 14. Temperature - salinity oxygen relations in the South Indian Ocean.

Warren, Stommel and Swallow (1966), while discussing the water mass structure in the Somali Basin, suggest that the Subtropical Subsurface Water, a layer of decreasing salinity and an oxygen maximum, overlying the high salinity core of the North Indian Water penetrates into the Somali Basin. Thus they explain the occurrence of salinity minimum as well as an oxyty maximum in the intermediate layers of the Somali Basin. However, it is felt that the association of an oxygen maximum with the Subtropical Subsurface Water requires further analysis. In Fig. 14, the T-S and T-O curves for two Discovery stations 1756 and 1583 are presented. (These stations were taken from Discovery Reports 1935-1937). At Discovery station 1755 (or at Discovery station 1758 discussed by Warren, Stommel and Swallow, 1966), the layer of Subtropical Subsurface Water overlying the salinity minimum of the Antarctic Intermediate Water does not show any oxygen maximum. On the other hand, the oxyty also decreases with depth in that layer. However, at Discovery station 1583, a pronounced oxygen maximum is seen at about 120 cl/t steric level within the layer of decreasing salinity. At this station, a deep salinity maximum at about 60 cl/t is observed. According to Taft (1963), this deep salinity maximum results because of advection of the high salinity water from north. It is possible that the Red Sea Water penetrates south giving rise to a salinity maximum at this level.

Associated with this salinity maximum, the oxyty is found to be a minimum. This oxyty minimum results when the oxygen-poor Red Sea water mixes with the relatively oxygen-rich Subtropical Subsurface water. Similarly, we explain the oxygen minimum at about 150 cl/t at Discovery station 1583 due to the penetration of the Persian Gulf Water. Thus the oxyty maximum within the Subtropical Subsurface Water develops in the northern regions of the South Indian Ocean. We attribute (following Warren, Stommel and Swallow, 1966) the subsurface oxyty maximum around 130 cl/t in the southern Arabian Sea primarily due to the penetration of the Subtropical Subsurface Water considerably transformed by mixing with the North Indian Water masses. Further northward penetration of this Subtropical Subsurface Water is accompanied by mixing of the oxygen-poor waters of the Arabian Sea whereby the oxyty maximum is progressively eroded. The anomalous behaviour of salinity minima and oxygen maxima coinciding at a few stations and distinctly separated at several other stations may be viewed as a process of transformation that the Antarctic Intermediate water defined by its salinity minimum undergoes when this water type mixes with the other water types in the Arabian Sea (Sastry, 1971). As the main transfer of water across the equator takes place through the Somali current during this season, it is but natural that we find the oxyty maxima to be high in the southwestern regions of the Arabian Sea and in the Somali Basin.

Deep and bottom water

The potential temperatures of the bottom water range from 0.89° to 0.97°C in the Somali Basin, 1.20° to 1.57°C in the Arabian Basin and 1.79° to 2.01°C in the Laccadive Sea (SD1). The bottom oxyty in the Somali Basin exceeds 4.0 ml/l while it varies between 3.0 to 4.0 ml/l in the rest of the region except at a couple of stations where it exceeds 4.0 ml/l. Thus the difference in the bottom oxyty between the Somali Basin and the rest of the region is considerable and needs an explanation.

In SD3, we have pointed out that on the basis of potential temperature and salinity relationships, the watermass at depths exceeding 2500 m in the Arabian Sea is of circumpolar origin (Warren, Stommel and Swallow, 1966). In the Circumpolar Water Mass, the oxyty is between 4.0 and 5.0 ml/l (see the T-O curve for Discovery station 1756 in Fig. 14) and we attribute the high oxyty of the bottom water in the Somali Basin to be of circumpolar origin. As the Circumpolar Water spreads north, its passage is obstructed by the midoceanic ridges and the connecting passage between the Somali Basin and the Arabian Basin lies at depths of 2800-3400 m. Within this depth range, the T-O curve for Discovery station 1756, shows the oxyty between 3.5 and 4.0 ml/l. This water after entering the Arabian Basin sinks to greater depths and thus we explain the lower oxyty in the Arabian Basin compared to that in the Somali Basin.

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