

ON THE OCCURRENCE OF OXYGEN MAXIMA AND MINIMA IN THE UPPER 500 METERS OF THE NORTH-WESTERN INDIAN OCEAN

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ABSTRACT

The depths of occurrence of oxygen maxima and minima have been studied in the upper 500 meters of the north-western Indian Ocean (including Arabian Sea and Laccadive Sea). The data collected by various ships during the International Indian Ocean Expedition were pooled into one degree grids and analysed for getting patterns of distribution—seasonally and regionally.

The studies reveal that there is much variation in the depths of occurrence of oxygen maxima and minima in different areas and different seasons in the north-western Indian Ocean. Along the continental shelf all over the Arabian Sea, biological activity appears to play a predominant role in controlling the oxygen content, while in the open parts of the ocean the depths of occurrence of oxygen maxima and minima mainly appear to be governed by the water movements, circulation and mixing. One of the important observations is the existence of stagnant or near-stagnant conditions in the more central part of the Arabian Sea, restricting the exchange of water masses with the adjoining seas.

INTRODUCTION

DURING the International Indian Ocean Expedition (1960-65) a considerable amount of data has been collected by most of the participating ships on the distribution of dissolved oxygen in the different areas of the Indian Ocean. While these studies involve the general pattern of distribution both in the vertical and horizontal and the occurrence of oxygen minima, no detailed work has yet been undertaken on the occurrence of layers of oxygen maxima and minima and their seasonal variations. This type of study, while giving a general pattern of seasonal and regional variations in oxygen maxima

and minima, will also help in an understanding of water movements and mixing processes, and potential productivity in the different regions of the Indian Ocean, as the oxygen content of the upper layers is intimately related to biological activities. The present paper deals with the surface and sub-surface layers of the north-west Indian Ocean in the upper 500 metres.

The oxygen maxima in the Arabian Sea in the upper layers has been discussed by Rochford (1966) and Khimitsa (1968). The oxygen minimum in the sub-surface layers in the tropical marginal seas of the world oceans was reported in the Pacific and Atlantic Oceans (Wust, 1935; Dietrich, 1937; Seiwell, 1937) and has been attributed to several factors such as limited circulation in the basins and oxidative processes of the organic matter (Sverdrup, 1938; Kawamoto, 1935; Wattenberg, 1939; Redfield, 1942). During the John Murray Expedition of 1933-34 (Gilson, 1937) well-defined oxygen minima were observed in the central and northern Arabian Sea. Clowes and Deacon (1935) reported oxygen minimum between the 300-100 meter layers with oxygen concentration of less than 0.8 ml/L at 8° N and further stated that at 11° S this minimum with oxygen content of 2.0 ml/L is found at 1,200 meters. Schott (1935) pointed out that the sub-surface oxygen minimum is most prominent at about 50 meters off Bombay, while Carruthers *et al.* (1959) found the oxygen minimum at a depth of 18 meters at a distance of 18 nautical miles off Bombay and stated that the oxygen minimum lies below the salinity maxima and occasionally reaches surface layers. Neyman (1961) referring to the presence of oxygen minima along the entire west coast of India states that both the oxygen content and the thickness of the layer are sharply heterogeneous. Vinogradov and Voronina (1961) correlated the minimum values for oxygen in the sub-surface layers with plankton in the Arabian Sea. According to their studies the oxygen below 150 meters dropped suddenly to 0.15 ml/L or sometimes below this value. Further studies by Gallagher (1966), Warren *et al.* (1967), Elizarov (1968), Timofeev (1968) and Khimitsa (1968) confirmed the above results. The sub-surface oxygen minimum was generally correlated with high phosphates (Timofeev, 1968; Reddy and Sankaranarayanan, 1968). Khimitsa (1968) attributed oxygen minimum in the north-western Indian Ocean, especially in the north and north-eastern parts of Arabian Sea to the aging of the Red Sea waters introduced through the Gulf of Aden into the subsurface and intermediate depths and to limited circulation in the area.

Area of investigation; data and analysis.—The observations presented here relate to the depths of occurrence of oxygen maximum and minimum

in the north-western Indian Ocean, including the Arabian Sea and the Laccadive Sea (Special Publication No. 23 of International Hydrographic Bureau) covering the grid between the equator and the northern-most part of the Arabian Sea, *i.e.*, upto Pakistan and Iran coasts and 45°-80° E longitude.

For convenience and ease of interpretation, the following seasonal classification has been adopted:

- (1) Summer or hot weather season—March, April and May;
- (2) South-west monsoon season—June, July and August;
- (3) Post-monsoon season—September, October and November; and
- (4) North-east monsoon season or winter monsoon—December, January and February.

All the available data on oxygen maxima and minima with corresponding depths of occurrence collected by different ships during the IIOE period in the region have been taken into consideration. The data were pooled into one degree squares seasonally and the averages taken as the representative values for that square. In selecting the depths for oxygen maxima and minima certain arbitrary limits were fixed for the maximum and minimum concentrations of oxygen. All values of oxygen which fell between 4.5 and 5.5 ml/L or above have been included as maxima and the values of oxygen which fell between 0 and 1.0 ml/L. were taken as minimum. These limits were chosen because the occurrence of the respective values have the 80-90% probability.

After pooling the data, the depths were plotted on maps for oxygen maxima and minima for each season. Contours were drawn at the intervals of 5-10 meters in the case of maxima and 25-50 metres in the case of minima, depending on the extent of variation of the values (Figs. 1 to 8).

RESULTS

Summer season.—Figures 1 and 2 show the depths of oxygen maximum and minimum respectively during the summer months. In regard to the oxygen maximum it is seen that in the shelf waters along the west coast of India (eastern Arabian Sea) oxygen maximum occurs between 1 and 12 meters except at 9° N latitude where the maximum is seen to exist at 30 meters. Taking the whole of the north Indian Ocean, west of the Indian Peninsula, it is observed that there is a central zone extending north to south

and comprising of a number of cells (A to J in Fig. 1) where the oxygen maxima occur fairly deep at depths exceeding in most of the cases 50 metres and sometimes going down to as much as 86 meters (H). On either side of this central zone extending eastwards to the coast of India and westwards to the coast of Arabia, including the Gulf of Aden, oxygen maxima invariably exist in the upper layers often reaching the surface as the coast is approached. Thus the central part of the Arabian Sea is characterized by having deep oxygen maximum during this season.

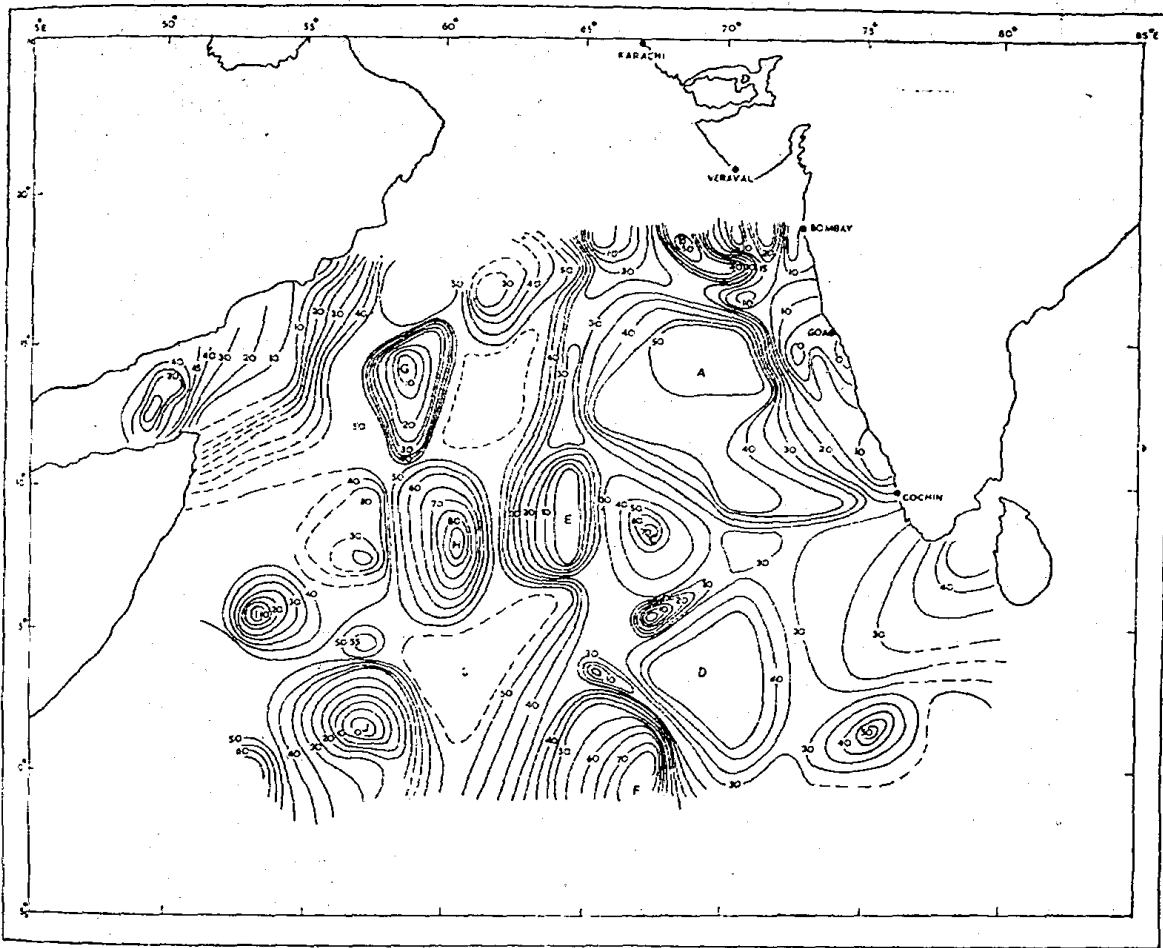


FIG. 1. Depths of occurrence of oxygen maximum during summer season (March, April and May).

'A and B' represent the areas of occurrence of oxygen maxima at about 50 meters. 'C' represents the area of occurrence of oxygen maxima at about 70 meters. 'D' represents the area of occurrence of oxygen maxima below 75 meters. 'E and J' represent the areas of occurrence of oxygen maxima in the surface waters. 'F' represents the area of occurrence of oxygen maxima around 75 meters. 'G and I' represent the areas of occurrence of oxygen maxima in the first 10 meters. 'H' represents the area of occurrence of oxygen maxima around 85 meters.

While the depths of occurrence of oxygen minimum show a similar cellular pattern, the comparison with the depths of oxygen maximum ends here. In general, there is no regularity in the pattern of distribution. The highest value for depth of minimum is 522 meters and that is observed in the area bounded by 14° and 15° N latitude and 72° and 73° E longitude (that is to say in the eastern Arabian Sea nearer the Indian west coast off Goa). North and south of this area oxygen minimum comes up to 200 meters. As the equator is approached in this eastern part, there is shoaling with the oxygen minimum layer reaching up to 120 meters. Proceeding westwards towards western and central parts of the Arabian Sea, the oxygen

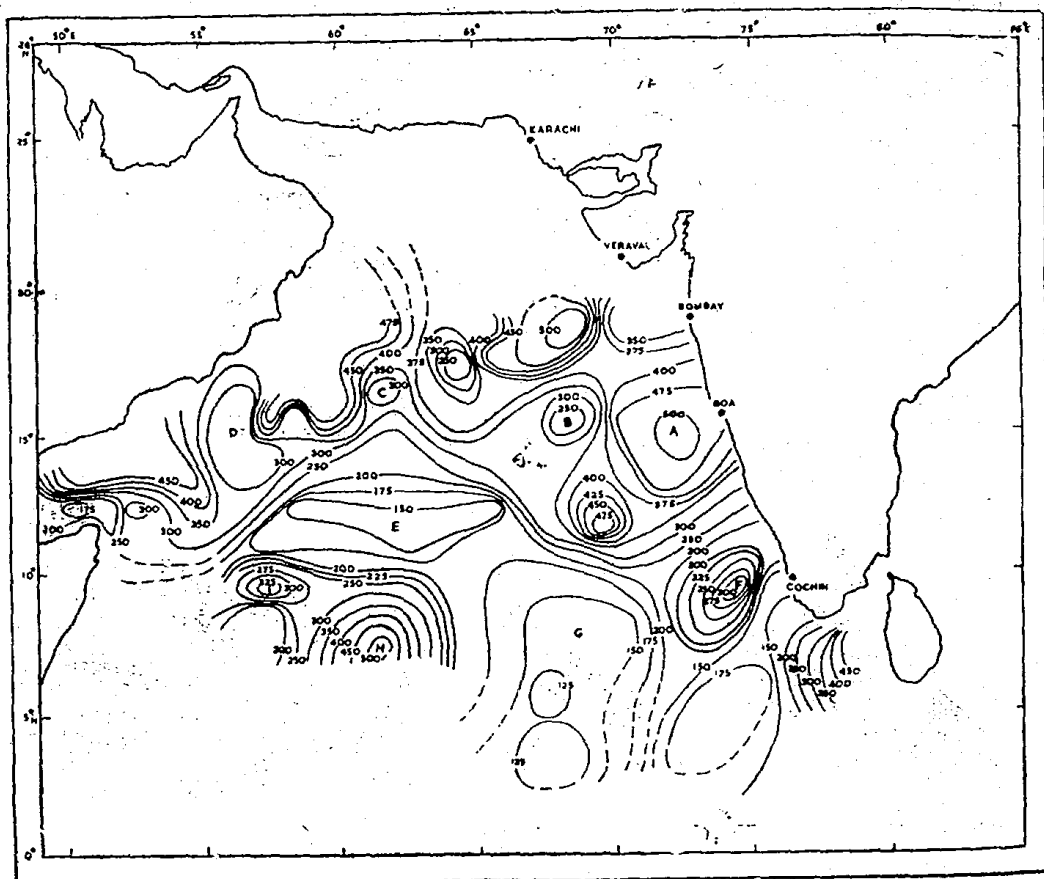


FIG. 2. Depths of occurrence of oxygen minimum during summer season (March, April and May).

'A and H' represent the areas of occurrence of oxygen minimum around 500 meters. 'B' represents the area of occurrence of oxygen minimum at about 250 meters. 'C, D, F and I' represent the areas of occurrence of oxygen minimum at about 300 meters. 'E' represents the area of occurrence of oxygen minimum at about 150 meters. 'G' represents the area of occurrence of oxygen minimum at less than 150 meters.

minimum is seen to exist between 130 and 500 meters; often there is an alternation of deepening and shoaling resembling a sine wave.

South-west monsoon season.—Figure 3 shows the distribution of oxygen maximum during south-west monsoon season. The oxygen maxima in the eastern and western fringes of the Arabian Sea are observed in depths ranging from 0 to 10 metres. In the Central Arabian Sea deep occurrences of oxygen maxima are seen but not to that extent as during summer months.

From the east coast of Arabia down to the Gulf of Aden, maximum values are seen mostly at the surface while at the mouth of the Gulf of Aden

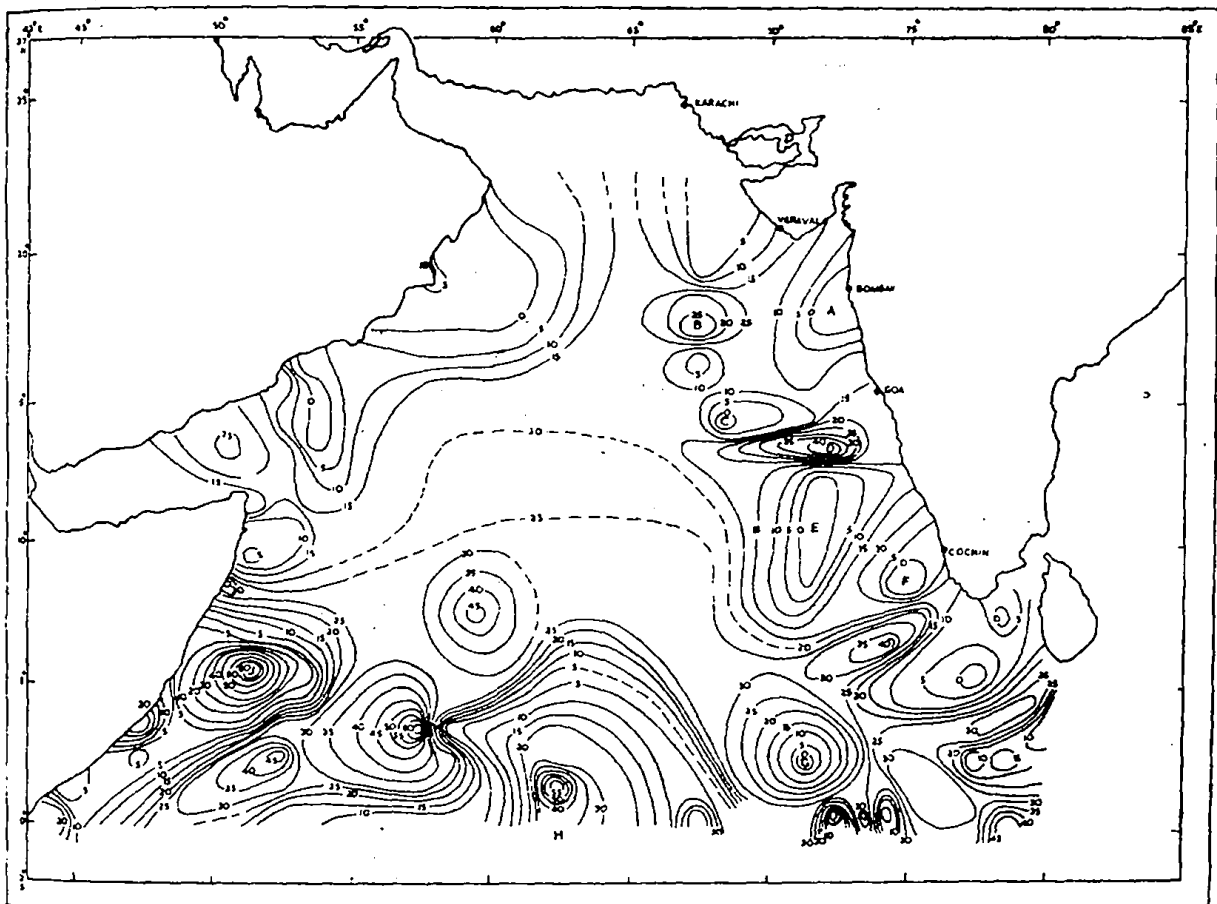


FIG. 3. Depths of occurrence of oxygen maximum during south-west monsoon season (June, July and August).

'A, B, E, F and G' represent the areas of occurrence of oxygen maximum in the surface. 'B' represents the area of occurrence of oxygen maximum at about 25 meters. 'D' represents the area of occurrence of oxygen maximum at about 40 meters. 'H' represents the area of occurrence of oxygen maximum at about 55-60 meters. 'I' represents the area of occurrence of oxygen maximum at about 60 meters. 'J' represents the area of occurrence of oxygen maximum at about 80 meters.

it is at 25 meters. Off the eastern Somali coast at $51-52^{\circ}$ E longitude and $5-6^{\circ}$ N latitude a closed cell (J) is formed where the oxygen maximum is seen to occur at a depth of 83 meters with steep gradients around this grid. In the northern-most and the open regions away from the coastal influences, the depth of oxygen maximum ranges between 20 and 25 meters.

Figure 4 shows the distribution of oxygen minimum. Off Bombay in the northern Arabian Sea, oxygen minimum is seen at 400 meters, but towards west (in the grid $17-18^{\circ}$ N and $67-68^{\circ}$ E) it occurs higher up at 150 meters (cells 'A' and 'B'). In the southern part, off Cape Comorin, the

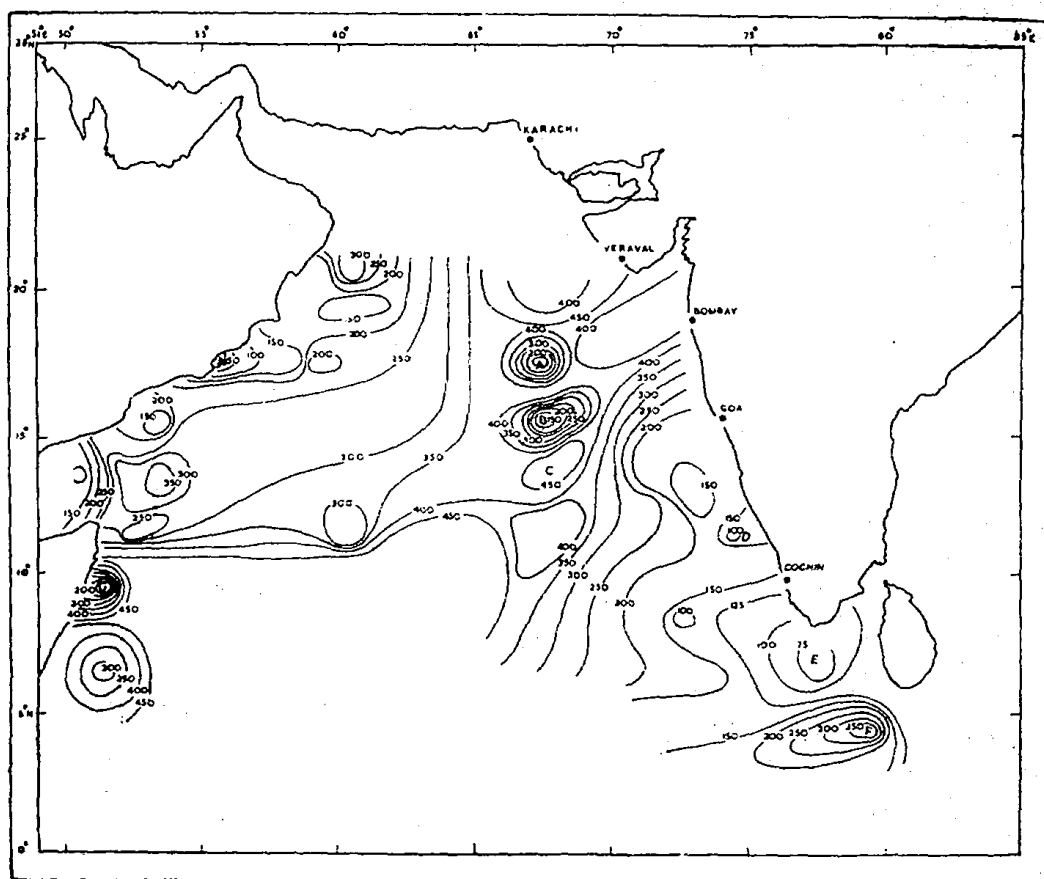


FIG. 4. Depths of occurrence of oxygen minimum during south-west monsoon season (June, July and August).

'A, B and G' represent the areas of occurrence of oxygen minimum at about 150 meters. 'C' represents the area of occurrence of oxygen minimum at about 450 meters. 'D' represents the area of occurrence of oxygen minimum at about 100 meters. 'E' represents the area of occurrence of oxygen minimum at about 75 meters. 'F' represents the area of occurrence of oxygen minimum at about 250 meters.

oxygen minimum layer has come up to 75 meters (Cell E). Further south it deepens and goes down to 370 meters (Cell F).

Off eastern Arabian coast the depths of oxygen minimum vary between 30 and 200 meters, the lowest value being at the south-eastern part of Arabian Peninsula. Towards the Gulf of Aden and around Socotra Island, the depth increases. Off the Somali coast the minimum is found at a depth of 130 meters.

Post-monsoon season.—The distribution of oxygen maxima and minima for the post-monsoon season is shown in Figs. 5 and 6 respectively. In



FIG. 5. Depths of occurrence of oxygen maximum during post-monsoon season (September, October and November).

'A' represents the area of occurrence of oxygen maximum between 0-5 meters. 'B' represents the area of occurrence of oxygen maximum at about 35 meters. 'C' represents the area of occurrence of oxygen maximum at about 25 meters. 'D' represents the area of occurrence of oxygen maximum at about 50 meters. 'F, G, I and K' represents the area of occurrence of oxygen maximum in the surface. 'J' represents the area of occurrence of oxygen maximum at about 30 meters. 'L' represents the area of occurrence of oxygen maximum below 70 meters.

both the cases, the distribution pattern appears to be 'cellular'. The oxygen maxima are present off the west coast of India almost at the surface, the depths of occurrence oscillating in general between zero and 30 meters. Surface oxygen maximum is more common along the east coast of Arabia and southern Arabian Sea, going to deeper layers such as 30 metres along the northern-most parts of the sea and to 50 metres at 'H'. South of 10° N off the Somali coast the maximum exists between 0 and 25 metres with steep-gradients (Cell L).

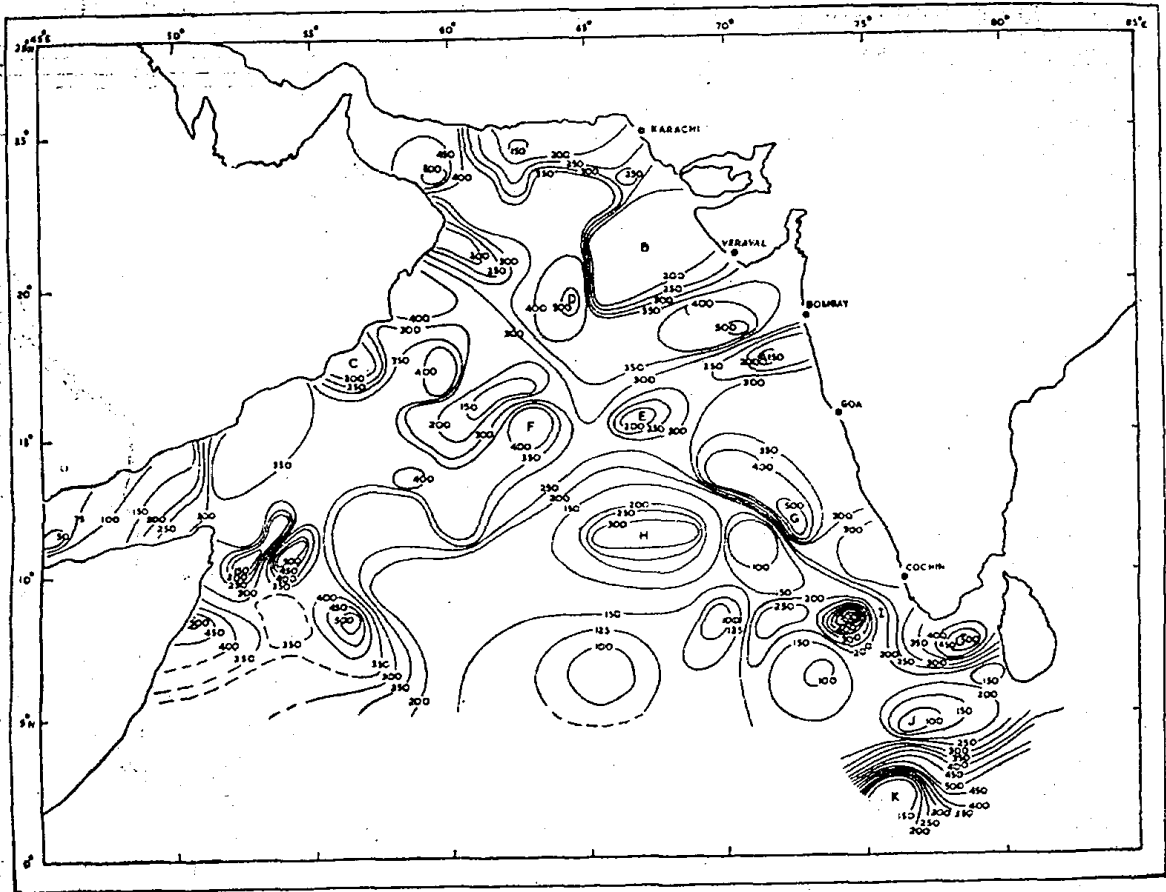


FIG. 6. Depths of occurrence of oxygen minimum during post-monsoon season (September, October and November).

'A, B, C, E and K' represent the areas of occurrence of oxygen minimum between 150-200 meters. 'D, G and I' represent the areas of occurrence of oxygen minimum at about 500 meters. 'F' represents the area of occurrence of oxygen minimum at about 400 meters. 'H' represents the area of occurrence of oxygen minimum at about 300 meters. 'J' represents the area of occurrence of oxygen minimum at less than 100 meters.

North-east monsoon season.—Figures 7 and 8 show the depths of occurrences of oxygen maximum and minimum respectively during north-east monsoon season.

The oxygen maximum is found in the upper layers along the west coast of India between 5–10 meters, sinking to 30 meters at a few places. But in the central Arabian Sea, in the area bounded by 63–64° E longitude and 16–17° N latitude the oxygen maximum sinks to 100 meters (at 'A') and rises to upper levels both in the southern and northern parts of the Arabian Sea. At the mouth of the Gulf of Aden, the oxygen maximum reaches a depth of about 30 meters. South of 5° N, the maximum occurs at 45 meters.

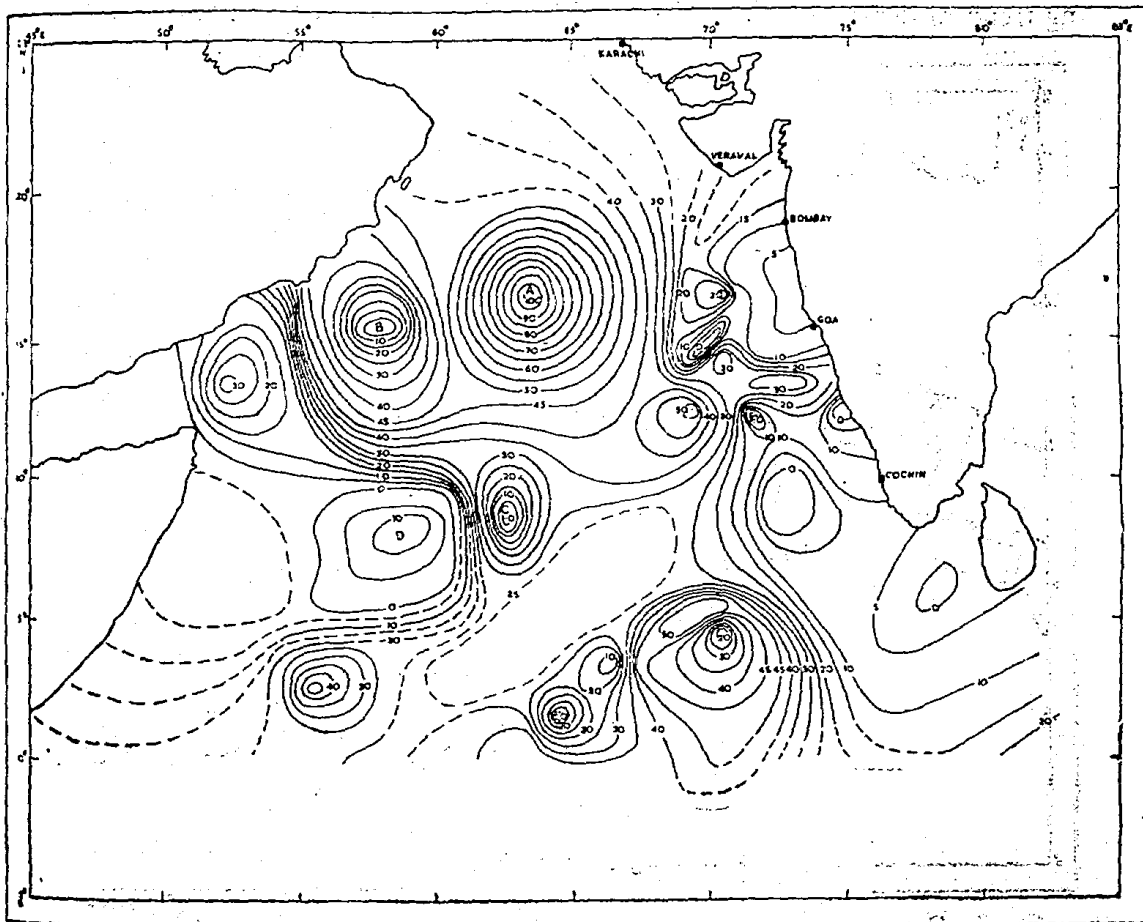


FIG. 7. Depths of occurrence of oxygen maximum during north-east monsoon or winter monsoon (December, January and February).

'A' represents the area of occurrence of oxygen maximum at about 100 meters; 'B, C, E and F' represent the areas of occurrence of oxygen maximum at the surface; 'D' represents the area of occurrence of oxygen maximum at about 10 meters,

The main features (Fig. 8) of the occurrence of oxygen minimum along the west coast of India are that from the southern tip to the Gujarat coast, the minimum occurs in the deeper layers when compared to the south-west monsoon season, occurring between 300–500 meters, but not less than 300 meters deep. In the open Arabian Sea the minimum shoals up and found at depths between 120–150 meters along 70° E longitude (Cells A and B). Off Cochin, it is found to sink to 500 meters (Cell C) and thereafter to shoal to 150 meters towards the open sea (Cell D). South of the Indian Peninsula also the oxygen minimum sinks to 500 meters. In the central Arabian Sea the minimum is found at 400 meters deep shoaling to 150 meters in the southern part of the sea. In the mouth of Gulf of Aden, it reaches to 350 meters and rises up to upper levels towards the Gulf of Aden. Increasing trend of depths of oxygen minimum is also found south of Somali coast.

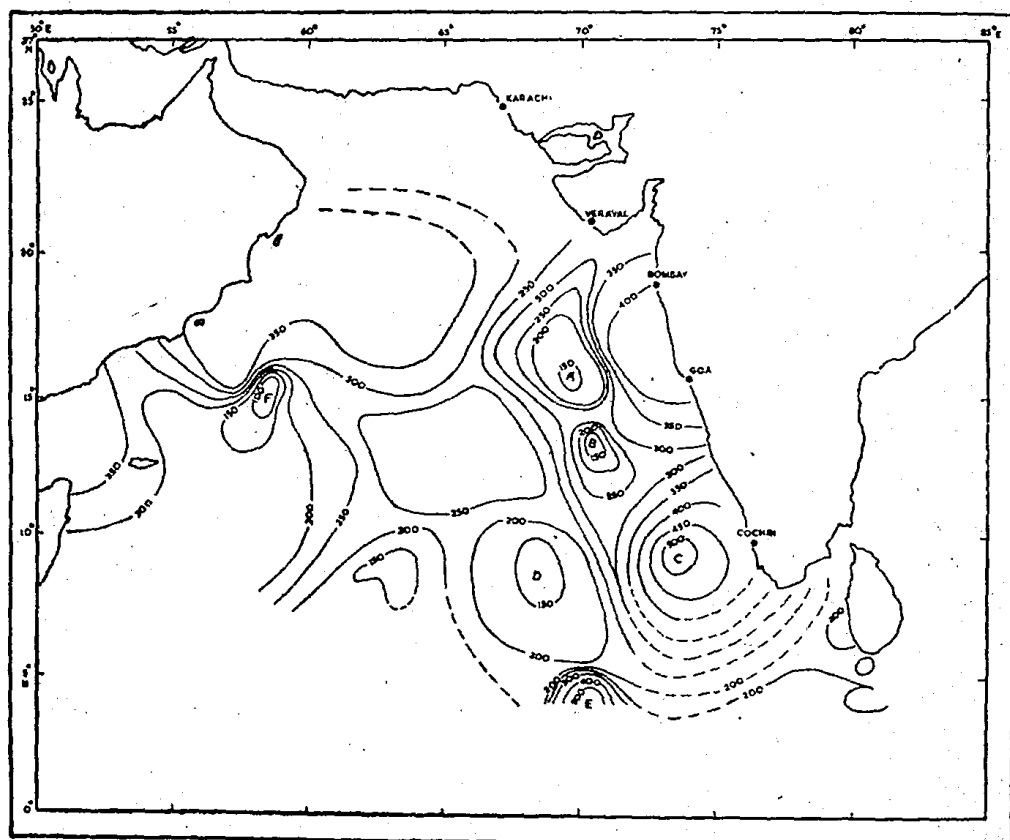


FIG. 8. Depths of occurrence of oxygen minimum during north-east monsoon or winter monsoon (December, January and February).

'A, B and D' represent the areas of occurrence of oxygen minimum at about 150 metres. 'C and E' represent the area of occurrence of oxygen minimum at about 500 metres. 'F' represents the area of occurrence of oxygen minimum at about 100 metres,

DISCUSSION

The results presented in the earlier section make it abundantly clear that there are considerable seasonal and regional variations in the distribution of oxygen in the upper 500 meters of the North-western Indian Ocean, which includes mainly the Arabian Sea, the Laccadive Sea, the Gulf of Aden and the Persian Gulf. The most important factor controlling the distribution of oxygen is physical, such as exchanges across the sea surface, oceanic circulation and water movements, although biological conditions such as photosynthetic production and respiratory activities of the organisms gain importance in certain selected regions, particularly along the coasts. On the other hand, in the open parts of the ocean we have to take into account the circulation pattern and water movements as the major contributing factor.

During the months constituting the south-west monsoon the south-east trades from the southern hemisphere cross the equator and blow as south-westerly winds along the Somali coast. The winds are rather steady in this region and they blow mainly towards north and north-east along the Somali-Arabian coasts, then take an easterly course in the more open parts of the ocean (Swallow, 1965, Swallow and Bruce, 1966, Warren, B., 1965, Warren *et al.*, 1966, Gallagher, 1966). Under the influence of these winds the high speed Somali current crosses the equator bringing with it the oxygen-rich Indian Equatorial waters. The turning of the current away from the coast north of 6° N latitude gives rise to intense upwelling nearer the Somali coast. Thus an 'oxygen front' is created with low oxygen water nearer the coast and a high oxygen water away from the coast, the axis of the Somali current forming some kind of a boundary between these two types of waters. The current travelling away from the coast gives rise to convergence cells north of 5° N and along 60° E. The northern limits of these convergence cells are sometimes seen as far as 10° N. The oxygen maximum sinks here to depths of about 90 meters with values ranging from 4.5 to 4.35 ml/L.

Along the Arabian coast the upwelling processes reduce the oxygen content in the surface layers but soon this is compensated by high organic production-photosynthetic activity leading to oxygen enrichment of the upper layers. The Arabian shelf is narrow and the highly productive waters are carried farther and farther off-shore, where the transparency is high. It is thus possible that the column production is high resulting in deepening of the layers of oxygen maxima. Oxygen maxima are observed at about 50 meters in this area,

Coming nearer the Indian coast, the large influx of river-water, the high degree of turbulence due to monsoonal winds, give rise to increased turbidity of the waters, thereby reducing considerably the thickness of the photic zone. Thus very often, the oxygen maxima are seen in the surface layers only.

One of the noteworthy features during the south-west monsoon is that the circulation and water movements are predominantly meridional and hence a greater part of the north-western Indian Ocean, including the Arabian Sea, is occupied by water spread northwards from the equatorial Indian Ocean. The equatorial Indian Ocean being a region of strong currents and consequently high degree of ventilation, the spreading of these waters to the northern part of the Arabian Sea results in a considerable degree of oxygenation of these waters with the exception of upwelling areas near the Somali-Arabian coast and the south-west coast of India. This factor should therefore determine to a large extent the depths of occurrence of oxygen maxima and minima in the different areas in this part of the Indian Ocean.

When we consider, on the other hand, the conditions during the north-east monsoon, when there is a reversal of winds, oceanic circulation and water movements, it is seen that the predominant flow becomes zonal—the North Equatorial Current system gaining in intensity and becoming important. Due to opposing forces the Somali current becomes insignificant. The coastal current off the west coast of India becomes northerly. Again compared to the southerly drift along this coast during the south-west monsoon months, the northerly drift is somewhat weaker, intensifying perhaps only north of Bombay where this takes a north-westerly turn conforming to the coastal configuration and in line with the general circulation pattern. As a result of this circulation pattern, in a greater part of the central and northern Arabian Sea, there are no appreciable water movements—a near stagnation condition prevailing in certain areas. The sub-surface conditions, however, reflect to some extent the characteristics of Red Sea and Persian Gulf waters.

The southern part of the Arabian Sea is, however, influenced to a considerable extent by the waters brought in by the North Equatorial Current system from the eastern Indian Ocean and the Bay of Bengal. Thus oxygen distribution pattern in the southern Arabian Sea conforms to the conditions prevailing in the eastern Indian Ocean and the Bay of Bengal.

In discussing the depths of occurrence of oxygen minima in the upper 500 metres of the northern Indian Ocean, one has to consider the source of oxygen minima in relation to biochemical cycles as well as the pattern of circulation. Of course the most essential data required for this purpose are the depths of occurrence of oxygen minimum layer, the minimum oxygen concentration and also the thickness of this layer. The last-mentioned parameter will give the necessary clue to the biological and biochemical activities in the upper surface layers. The importance of biological and biochemical activities leading to the oxidation of organic matter with consequent consumption of oxygen as the organic materials sink to deeper levels, has been fully highlighted by earlier workers (Richards, 1957). The respiratory activities of the organisms leading to reduction of oxygen concentration in oxygen-poor layer has also been mentioned by Harvey (Harvey, 1963). The application of these ideas to the conditions in the Arabian Sea and other open parts of the northern Indian Ocean requires a detailed knowledge of the biological productivity and distribution of organisms in this region of the Indian Ocean. A fairly good picture of the plankton biomass has been brought out in the detailed and interesting paper by Prasad (under publication).

One of the most interesting and detailed accounts on the oxygen distribution in the Arabian Sea containing an explanation for the formation of oxygen minimum in the region is that of Khimitsa (1968). This author has summarised the observations of Smetanin (1959) and Neyman (1961) besides stating his own views. Khimitsa mentions that the views of Smetanin are more or less in accord with those of Seiwel (1937). Seiwel has mentioned that the oxygen minimum may appear and re-appear with a continuous decrease in both the horizontal current velocity, or maximum oxygen consumption may, perhaps, coincide with the depth of oxygen minimum layer. He has also noted that the vertical distribution of oxygen results from development history of the water masses and that the effects of infinitely small processes may be considerably increased by their manifold repetitions.

Neyman (1961) relates the formation of oxygen minimum to the regions of formation of deeper water masses in the Arabian Sea. Referring to the Gulf of Aden and the Persian Gulf as the main source regions, Neyman states that 'the surface waters of these regions with high salinity and temperature (with consequent low concentration of oxygen) sink and spread to the sub-surface levels contributing to the oxygen minimum in the whole of the Arabian Sea'. But there is some difficulty in our accepting Neyman's

hypothesis because in the Gulf of Aden, which has been shown to be a very high productive zone where oxygen saturation is known to reach as high as 110-115% and in the Persian Gulf, which is comparatively shallow, thermohaline convection leads to thorough mixing and consequent enrichment of oxygen in the entire column. The sinking and spreading of these waters is more likely to enrich the sub-surface layers rather than deplete them of oxygen. Thus the formation of layer of oxygen minima with extremely low concentrations of oxygen is more likely to be attributed to the near-stagnant conditions in the central and northern parts of the Arabian Sea.

The Soviet oceanographers who had carried out investigations in this region have reported the occurrence of hydrogen sulphide in the intermediate depths in the northern Arabian Sea (Ivanenkov and Rozanov, 1961) which is an indication of stagnant or near-stagnant conditions. In this connection a reference to the interesting paper by Mokievskaya (1961) would be pertinent, as she discusses the hydrochemical conditions at the intermediate layer leading to the formation of hydrogen sulphide.

In concluding this discussion on the occurrence of oxygen minimum, it is particularly emphasized that the studies on the intermediate water masses of the Indian Ocean, with particular reference to occurrence of oxygen minima—sometimes alternating with layers of oxygen maxima—would be a most fruitful line of research and this would solve some of the most complicated problems of circulation and sub-surface water movements in this part of the Indian Ocean.

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REFERENCES

- | | |
|--|---|
| Carruthers, J. N., Gogate, S. S.,
Naidu, J. R. and Laevastu, T. | "Shorewards upwelling of the layer of minimum oxygen off Bombay: Its influence on marine biology, especially fisheries," <i>Nature, London</i> , 1959, 183 (4668), 1084-87. |
| Clowes, A. J. and Deacon,
G. E. R. | "The deep water circulation of the Indian Ocean," <i>Ibid.</i> , 1935, 136 (3450), 936-38. |
| Dietrich, G. | "Über Bewegung und Herkunft des Golfstromwassers inst," <i>Merresk, Univ. Berl. Veroff, N.F. Ser. A</i> , 1937, 33, Tiel 2: 53-91. |

- Elizarov, A. A. .. "Oceanological researches off the west coast of India," (In Russian), *Proc. Sov. Fish Invest. in the Indian Ocean and Adjacent Waters*, 1968, 64(1), 94-101.
- Gallegher, J. F. .. *The Variability of Water Masses in the Indian Ocean*, National Oceanographic Data Centre, General Series, 1966, Publication G-11, pp. 74.
- Gilson, H. C. .. "The nitrogen cycle," John Murray Exped. of 1933-34, *Sci. Repts.*, London, 1937, 2(8), 21-81.
- Harvey, H. W. .. *Chemistry and Fertility of Sea-waters*, Cambridge University Press, 1963, pp. 240.
- Kawamoto, T. .. "On the distribution of the dissolved oxygen in the Pacific Ocean, Part I," *U.M.I. to Gora Kobe Marine Observatory*, 1935, 32, 23-37.
- Khimitsa, V. A. .. "On the vertical and horizontal distribution of oxygen off the western coast of India during the north-eastern monsoon," (In Russian), *Proc. Sov. Fish Invest. in the Indian Ocean and Adjacent Waters*, 1968, 64(1), 162-80.
- Mokievskaya, V. V. .. *Certain Hydrochemical Features of the Northern Part of the Indian Ocean*, Oceanological Research, Publication A.N. SSSR, Moscow, 1961, No. 4.
- Neyman, V. G. .. "Formation of oxygen minima in the surface waters of the Arabian Sea," *Okeanol., Akad Nauk, SSSR*, Moscow, 1961, 4, 62-65.
- Redfield, A. C. .. "The processes determining concentration oxygen, phosphates and other organic derivatives within the depths of the Atlantic Ocean," *Papers in Phy. Oceanogr. Meteorol.*, 1942, 9(2), 1-22.
- Reddy, C. V. G. and Sankaranarayanan, V. N. .. "Distribution of phosphates and silicates in the central, western north Indian Ocean in relation to some hydrographical factors," *Bulletin of the National Institute of Sciences of India*, 1968, 38, 103-22.
- Richards, A. C. .. "Oxygen in the oceans," *Amer. Geol. Soc. Memoirs*, 67, 1957, Vol. I, 185-238.
- Rochford, D. J. .. "Source regions of oxygen maxima in intermediate depths of Arabian Sea," *Aust. J. Mar. Freshwater Res.*, 1966, 16(2), 129-49.
- Schott, G. .. *Geographic des Indischen und stillen Ozeans*, Hamburg-1935, pp. 413.
- Seiwell, D. A. .. "The minimum oxygen concentration in the western basin of the north Atlantic," *Papers in Phy. Oceanogr. Meteorol.*, 1937, 5(3), 24.
- Smetanin, D. A. .. "On the causes of formation of the oxygen minimum layer and the laws of their disposition in the oceans," (In Russian), *Trudy Inst. Okeanol, Akad Nauk, SSSR*, Moscow, 1959, 33.

- Sverdrup, H. U. .. "On the explanation of oxygen minima and maxima in the oceans," *Jour. du conseil.*, 1938, 13, 162-72.
- Swallow, J. C. .. *Some Observations Made Aboard R.R.S. Discovery during August 1964*," *Marine Obsr.*, London, July 1965.
- , and Bruce, J. G. Jr. .. "Current measurements off the Somali coast during the south-west monsoon of 1964," *Deep-Sea Res.*, 1966, 13 (5), 861-88.
- Timofeev, N. A. .. "Distribution of oxygen and phosphorus in the Red Sea," (In Russian), *Proc. Sov. Fish Invest. in the Indian Ocean, and Adjacent Waters*, 1968, 64 (1), 152-61.
- Vinogradov, M. E. and Voronina, M. M. "Influence of the oxygen deficit on plankton distribution in the Arabian Sea (In Russian), *Okeanol.*, Vol I, No. 4, 670-78.
- Warren, B. .. "The Somali Current," *Oceanus*, 12 (1), 2-7.
- , Stommel, H., and Swallow, J. C. "Water masses and pattern of flow in the Somali basin during the south-west monsoon of 1964," *Deep-Sea Res.*, 1966, 13 (5), 825-60.
- Wooster, W. S., Schaefer, M. B. and Robinson, N. K. *Atlas of Arabian Sea for Fishery Oceanography*, University of California, Institute of Marine Resources, IMR Reference No. 67-12, May 1967.
- Wattenberg, H. .. "Die entstchung der sauerstoffarmen zwischenschicht im Ozean," *Ann. Hydrogr. Bul.*, 1939, 67, 257-66.
- Wust, G. .. "Schlichtung und Zirculation des Atlantischen Ozean," Teil 2, Die stratosphere. *Dtsch. Atlant. Expd. Meteorol.*, 1925-27, Wiss., Ergebn., 1935.