

# DISTRIBUTION OF TEMPERATURE AND OXYGEN IN THE ARABIAN SEA AND BAY OF BENGAL DURING THE MONSOON SEASON

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Charts showing the horizontal distribution of temperature and oxygen at seven levels up to 300 m have been prepared using the data collected by INS KISTNA from the Arabian Sea and the Bay of Bengal during the monsoon seasons of 1963 and 1964. The distributions were discussed in relation to upwelling. A tongue of warm water in the surface layers up to 20 m depth off the West Coast of India appeared to be spreading from Gulf of Cambay towards south almost parallel to the coast. The temperature slightly decreased away from the coast in the Bay of Bengal. Temperatures less than 26° C were observed around the southwestern coast south of 9° N. The low temperature water off the southwestern coast had spread both northwards along the coast and further off shore at depths 50 m and more. In the Bay of Bengal, a cell of low temperature in the north central part and another of high temperature in the southwestern part have formed. The pattern of isopleths of oxygen, both in the Arabian Sea and the Bay of Bengal was generally similar to that of the temperature. The concentration of oxygen and the thickness of the oxygen rich surface layer were greater in the Arabian Sea than in the Bay of Bengal.

## INTRODUCTION

The seasonal variations in the distribution of temperature and salinity of the sea water near the coast were studied by several investigators using observational data from limited regions of the Arabian Sea and the Bay of Bengal. But reports on the seasonal variations in the distribution of dissolved oxygen were, however, very limited. Chidambaram and Menon (1945), Jayaraman and Gogate (1957) and Ramasastry (1959) studied the seasonal character of temperature distribution over limited regions near the coast while Ramamritham and Jayaraman (1960) discussed the distribution of oxygen also. The reports by Bal *et al.* (1946) and Jayaraman *et al.* (1961) were confined to temperature and oxygen, respectively, of the Bombay harbour waters.

Ramasastry and Balarama Murty (1957) studied the seasonal variation of temperature along the central part of the east coast of India up to about 300 km from the coast during post-monsoon, winter and hot-weather seasons. The work of Sundara Ramam *et al.* (1963) covered the Arabian Sea during the post-monsoon season only. The investigations of Sewell (1929), though extended over both the Arabian Sea and the Bay of Bengal, were confined to the surface waters only and suffer from paucity of data to present the details of the characteristics in the distribution of temperature. The horizontal distribution of oxygen over extensive areas, similar to the above, had not been studied so far. However, Anand (1965), and Garg *et al.* (1967) discussed the vertical distribution of oxygen, the former in the

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Arabian Sea during the post-monsoon season and the latter in the Bay of Bengal during February-March.

The participation of INS KISTNA in the Indian Programme of the International Indian Ocean Expedition resulted in the extensive study of the oceanographic conditions of the Arabian Sea and the Bay of Bengal. In the present paper the horizontal distribution of temperature and dissolved oxygen in both the Arabian Sea and the Bay of Bengal during monsoon season were discussed. This study had been limited to depths up to 300 m.

### DATA

The area covered by the present study along with the positions of more than 200 hydrographic stations occupied has been indicated in Fig. 1. The observational data were collected during INS KISTNA cruises 8 to 13 (June to August, 1963) in respect of the Arabian Sea and cruises 15 to 17 (June and July, 1964) in respect of the Bay of Bengal. The coverage by these cruises included the sea areas bounded by  $68^{\circ}$  and  $90^{\circ}$ E longitudes between  $9^{\circ}$  and  $21^{\circ}$ N latitudes, and  $70^{\circ}$  and  $78^{\circ}$ E longitudes between  $0^{\circ}$  and  $9^{\circ}$ N latitudes.

In the Arabian Sea, the line of stations along  $72^{\circ}$ E and  $73^{\circ}$ E between  $12^{\circ}$  and  $19^{\circ}$ N and those along  $12^{\circ}$ N and  $13^{\circ}$ N east of  $72^{\circ}$ E were occupied in June '63; all stations along and east of  $70^{\circ}$ E and north of  $10^{\circ}$ N excluding those mentioned above were occupied in July '63 and the line of stations along  $68^{\circ}$ E was occupied in August '63. South of  $10^{\circ}$ N, the line of stations along  $78^{\circ}$ E and off the southern tip of India were occupied in July '63 and the rest in August '63. In the Bay of Bengal, all stations along and south of  $15^{\circ}$ N were occupied in June '64 while those north of  $15^{\circ}$ N were occupied in July '64.

At each of the hydrographic stations temperatures at various depths were measured using reversing thermometers and the sea water samples collected by reversing bottles were analysed for dissolved oxygen concentration following the modified Winkler's method (Strickland and Parsons 1960). Charts (Figures 2 to 15) showing the horizontal distribution of temperature and oxygen in the area mentioned above were prepared for the chosen depths of 0 (surface), 20, 50, 75, 100, 200 and 300 m. These charts were based on the interpolated values (Anonymous 1965, 1967) for the two parameters.

### RESULTS

The salient features of the distribution of temperature and oxygen as they appear on the Figures 2 to 15 are presented below depthwise.

*Surface:*—The most striking feature in the distribution of temperature at the surface (Fig. 2) in the Arabian Sea was a tongue of warm water with temperature higher than  $28^{\circ}$ C (maximum  $29.9^{\circ}$ C) extending parallel to the coast from the Gulf of Cambay southwards to about  $11^{\circ}$ N. The temperature decreased away from the tongue both towards the coast and towards the west with a gradient higher than

elsewhere in the Arabian Sea except off Cape Comorin (the southern tip of India). South of  $10^{\circ}\text{N}$  the presence of cold water of temperature less than  $27^{\circ}\text{C}$  (minimum  $24.6^{\circ}\text{C}$ ) could be identified around the coast. Temperatures higher than  $29^{\circ}\text{C}$  with a maximum of  $30.5^{\circ}\text{C}$  were observed in the equatorial region. The temperatures appeared to be decreasing south of the equator. Most part of the Bay of Bengal was covered by water of temperature around  $29.3^{\circ}\text{C}$  decreasing to  $28.5^{\circ}\text{C}$  towards the eastern part. However, the presence of cold water all along the coast between  $12^{\circ}\text{N}$  and  $20^{\circ}\text{N}$  could be noticed with temperatures as low as  $28.1^{\circ}\text{C}$  and  $26.2^{\circ}\text{C}$  in two separate cells off Madras and Visakhapatnam respectively. The presence of warm water (temperature  $29.5^{\circ}\text{C}$ ) south of  $11^{\circ}\text{N}$  near coast and  $9^{\circ}\text{N}$  in the open sea could only be inferred.

A tongue of high oxygen concentration (maximum 5.78 ml/L) almost coinciding with the tongue of warm water mentioned above could be delineated (Fig. 3) in the Arabian Sea. Over the rest of the Arabian Sea including the equatorial region the oxygen concentration was around 4.5 ml/L. Most part of the Bay of Bengal was characterised by oxygen concentration 4.0 to 4.5 ml/L. Higher oxygen concentrations (maximum 5.60 ml/L) were observed in the north-eastern part of the Bay of Bengal and south of Madras. The cold waters off Madras and Visakhapatnam were characterised by oxygen concentrations less than 4.0 ml/L, the minimum values observed being 3.95 and 2.69 ml/L respectively.

*At 20 m:*—The ranges of temperature and the pattern of its distribution at 20 m (Fig. 4) was generally the same as at the surface both in the Arabian Sea and in the Bay of Bengal. The cold water around the Cape had spread both southward away from the coast and northward along the coast. In the central part of the Bay of Bengal, however, tendency to develop into tongue-like or cellular pattern was noticed. The vertical negative gradient of temperature in the cold water off Madras appeared to be greater than that off Visakhapatnam.

Though the tongues of warm water at surface in the Arabian Sea persisted to 20 m depth, the tongue of high oxygen concentration (maximum 5.6 ml/L) at this depth was limited to a small area off the Gulf of Cambay (Fig. 5). On the contrary, the cold water off the south-western coast and around the Cape was associated with low oxygen concentration with a minimum value of 2.9 ml/L off the Cape. North of  $14^{\circ}\text{N}$ , small cells with alternate high and low extending seawards from the coast have developed. High oxygen concentrations (Fig. 5) in the north-eastern part of the Bay of Bengal and south of Madras as they appeared at the surface persisted to 20 m. Otherwise, over the most part of the Bay, the oxygen concentration was around 4.5 ml/L, this isopleth appearing in a confused pattern across the central Bay. The lowest concentration (3.92 ml/L) near coast was observed north of Visakhapatnam.

*At 50 m:*—The tongue of warm water in the Arabian Sea had disappeared, the isotherms running parallel to the coast at this depth (Fig. 6) with two southwesterly tongues, one from the Gulf of Cambay and the other off south-western coast. Coldest water with temperatures less than  $22^{\circ}\text{C}$  was present near the coast between  $10^{\circ}\text{N}$  and  $14^{\circ}\text{N}$ . Meridional gradients of temperature developed in the equatorial

region while in the central Arabian Sea the temperature was still slightly less than  $28^{\circ}\text{C}$ . In the Bay of Bengal, two cells of cold water with temperatures as low as  $24.5^{\circ}\text{C}$ , one in the southern and the other in the northern Bay have developed. The extent of cold water near coast was confined between  $12^{\circ}\text{N}$  and  $17.5^{\circ}\text{N}$ , the minimum temperatures off Madras and off the mouths of the river Godavari being about  $25^{\circ}\text{C}$ . Strong meridional gradients have developed south of  $10^{\circ}\text{N}$ .

The tongue of high oxygen off the Gulf of Cambay was completely eliminated at 50 m (Fig. 7). The cellular structure with alternate high and low oxygen have persisted all along the coast in the Arabian Sea. The pattern of oxygen distribution south of  $10^{\circ}\text{N}$  was similar to that of the temperature at this depth both in the Arabian Sea and the Bay of Bengal. A cell of low oxygen coinciding with the low temperature cell had developed over the northern Bay of Bengal. Over the rest of the Bay, two areas of oxygen concentration greater than 4 ml/L were separated by a tongue of low (minimum 1.1 ml/L near coast) oxygen extending east-southeast from the mouths of the rivers Godavari and Kistna. South of Madras the concentration was still as high as 5.0 ml/L near coast while low oxygen concentrations prevailed all along the coast north of Madras.

*At 75 m:*—The pattern of temperature distribution at 75 m (Fig. 8) remained essentially the same as at 50 m both in the Arabian Sea and in the Bay of Bengal. The southwesterly tongue off the Gulf of Cambay had disappeared while a cell of low temperature centred at  $1^{\circ}30'\text{N}$  and  $75^{\circ}\text{E}$  had developed. The decrease in temperature from 50 m to 75 m was  $3^{\circ}\text{C}$  near coast in the Arabian Sea while it was  $2^{\circ}\text{C}$  near coast and within the low temperature cells in the Bay of Bengal. The decrease over the rest of the area under investigation was between 1.0 to  $1.5^{\circ}\text{C}$ .

Oxygen sampling north of  $15^{\circ}\text{N}$  and near coast in the Arabian Sea had been poor for depths 75 m and deeper. Over the rest of the area in the Arabian Sea and the Bay of Bengal, the pattern of distribution of oxygen (Fig. 9) also remained essentially the same as at 50 m. However, the two areas of high oxygen concentration in the Bay of Bengal off the coast south of Madras and over the central Bay still retained concentrations greater than 4.0 ml/L while the concentration decreased appreciably over the rest of the Bay.

*At 100 m:*—The pattern of temperature distribution at 100 m (Fig. 10) essentially remained the same as at 75 m in the Arabian Sea and nearly the same in the Bay of Bengal. In the Bay of Bengal, the cold water near coast and the cell of low temperature over the southern Bay at 75 m merged together to appear as a trough of low temperature extending south-eastwards from the mouths of the rivers Godavari and Kistna at 100 m. This resulted in the development of two cells of high temperature off the coast south of Madras and north of  $15^{\circ}\text{N}$  over the central Bay. The temperatures in the colder waters of both the Arabian Sea and the Bay of Bengal decreased by  $5^{\circ}\text{C}$  from those at 75 m while over the rest of the areas the decrease in temperature was about  $2^{\circ}\text{C}$  only.

The pattern of distribution of oxygen at 100 m (Fig. 11) in both the Arabian Sea and the Bay of Bengal remained identically the same as at 75 m. However, the decrease in the concentration of oxygen from 75 m to 100 m was greater in the areas

of low oxygen than in the areas of high oxygen. Further, the patterns of distribution of oxygen and temperature were quite similar.

*At 200 m:*—This depth coincides with the limit of Continental Shelf along both the east and west coasts of India (Fig. 1). An apparently thermal low persisted in the central Arabian Sea west of  $70^{\circ}\text{E}$  from surface down to 50 m. At 100 m (Fig. 10) this thermal low of the shallower depths was replaced by a thermal high. The thermal high at 200 m (Fig. 12) appeared as a tongue extending in NNE to SSE direction. Over the rest of the Arabian Sea and the whole of the Bay of Bengal, the pattern of distribution of temperature again remained the same as at 100 m with the features becoming diffuse. The horizontal gradients and the ranges of temperature at this depth have decreased everywhere compared to those at shallower depths.

The pattern of distribution of oxygen at 200 m (Fig. 13) remained similar to that at 100 m in the Arabian Sea while it became diffuse in the Bay of Bengal. The tongue of low oxygen in the Arabian Sea off the southwest coast persisted while the distinctly cellular structure in the Bay of Bengal broke up into patches. The reduction in the concentration of oxygen from 100 m to 200 m was appreciable both in the Arabian Sea and the Bay of Bengal while it was only marginal in the equatorial region. However, the oxygen concentration remained fairly high in the Arabian Sea and the equatorial region as compared to that in the Bay of Bengal.

*At 300 m:*—The thermal high with temperatures greater than  $14^{\circ}\text{C}$  persisted west of  $70^{\circ}\text{E}$  (Fig. 14) in the Arabian Sea. This thermal high was characterised by appreciably higher gradients of temperature both in the horizontal and in the vertical than anywhere else in the area under investigation. Over the rest of the Arabian Sea and the equatorial region the temperatures were around  $12^{\circ}\text{C}$ . In the Bay of Bengal, the thermal pattern became further diffuse with the temperatures over most of the Bay being around  $11.5^{\circ}\text{C}$ .

The distribution of oxygen at 300 m (Fig. 15) remained almost the same as at 200 m in all the areas. The values for the concentration of oxygen also remained nearly the same. However, the tongue of low oxygen in the Arabian Sea off the southwest coast was apparently disappearing.

#### DISCUSSION

It was mentioned in the Introduction that more of the earlier investigations on the distribution of temperature and oxygen in the seas around India were confined to the coastal areas rather than covering an extensive area in any particular season as in the present study. Thus it was possible to compare the present results with the findings of the earlier investigators only in specific areas near coast.

Jayaraman and Gogate (1957) reported that off Bombay and Saurashtra coasts, the surface temperatures were generally uniform over the area in July, the range being  $28.8$  to  $28.6^{\circ}\text{C}$  only. This was found to agree with the present results in respect of the northern part of the tongue of warm water in the Arabian Sea (Fig. 2). Following the results of Jayaraman and Gogate, it would appear that the tongue of warm water could perhaps be extended farther northeast up to the Gulf of Kutch.

Chidambaram and Menon (1945) found that in an area off Calicut (approximately  $11^{\circ}30'N$ ) minimum temperatures occurred during July-August, the lowest values observed being  $24.85^{\circ}C$ . This could not be substantiated with the available data.

Ramamritham and Jayaraman (1960) analysed data collected during 1958-59 from an area off Cochin and concluded mid-August to be the period of intense upwelling. They recorded oxygen concentrations more than 5.0 ml/L at the surface and stated "The thermal gradient is very sharp below 20 m and except for a thin layer of 10 m at the top the entire shelf is pervaded by cold (below  $22^{\circ}C$ ) highly saline and very poorly oxygenated water. The dissolved oxygen content is less than 0.5 ml/L below 10 m and in some instances values as low as 0.2—0.1 ml/L are recorded." The results of the present investigation in this area showed equally high values for the oxygen content at the surface but values much higher than those recorded by Ramamritham and Jayaraman were found at subsurface depths. Ramasastry (1959) analysed data collected during September-December, 1957 and reported the prevalence of upwelling from 75 to 100 m during September off Cochin. He further found that the salinity values ranged between 34.75 and 35.25‰ and that the frequencies of temperature exhibited bimodal or multimodal character at subsurface depths. The observational data for the present study was collected during July-August in this area. However, the order of magnitude for the salinity values agreed well. The variability in the temperatures with depth as recorded in the present study could only be compared favourably with the multi-modal character of frequency of temperature.

Sewell (1929) and Raghu Prasad (1957) used different sets of temperature observations from the Gulf of Mannar, the former from the offshore area where the depths were greater than 200 fms and the latter from inshore waters off Mandapam. Raghu Prasad obtained a "secondary minimum" of  $25.3$  to  $25.7^{\circ}C$  in July, while Sewell correspondingly obtained  $25.61^{\circ}C$  in June for the monthly averages. The near agreement between these two sets of values would indicate the spread of the upwelled water. Since no observations were made in this area for the present study, it could only be inferred that the area of cold water found off the Cape Comorin possibly extended into the Gulf of Mannar.

It should be possible to explain the character of distribution of properties in the open seas in relation to the atmospheric and oceanic circulations. The effects of surface and river run-off, secondary wind and oceanic circulations and the processes of upwelling and sinking should be taken into account while discussing the distributions near coasts. Even though the winds over the Indian seas are considered as essentially reversible during the year, the surface currents in the Arabian Sea and particularly in the Bay of Bengal exhibit gradual changes from month to month. The mechanism of coupling between the atmospheric and oceanic circulations and particularly the time required for the establishment of stationary or quasi-stationary oceanic conditions has not been clearly understood. Reliable current charts for the Indian seas are not available. Further, it may be stated that investigations into the circulation patterns of the Indian seas have not even been initiated. In view of the fact that observational data for the present study were collected over a period

of three months in respect of the Arabian Sea and two months in respect of the Bay of Bengal, an unsuccessful attempt has been made by the authors to correlate the circulation patterns inferred from the distribution of physical properties and dynamic computations with a composite current chart (for June to August) prepared from the monthly charts of resultant currents in the Indian seas published by the U.S. Hydrographic Office (Pub. No. 566).

The agreement between the results of Jayaraman and Gogate (1957) and those of the present study as discussed earlier in respect of the temperatures in the tongue of warm water in the Arabian Sea suggested that this could possibly be a quasi-stationary feature of the southwest monsoon season. Data west of the area under investigation was lacking to establish the origin of this feature conclusively. However, considering the shallowness of this feature, it could be the result of surface drift due to winds, strong tidal currents near the Gulfs of Cambay and Kutch and circulations near coast. The thermal high associated with strong horizontal gradients at depths greater than 100 m in the central Arabian Sea was probably associated with a watermass boundary. Similarly, the strong horizontal gradients of temperature near the equatorial region and around  $10^{\circ}\text{N}$  in the Bay of Bengal and the thermal high at subsurface depths off Madras could be the result of convergence.

Balarama Murty (1958) and Banse (1959) felt that upwelling off Visakhapatnam and the southwest coast of India, respectively, could have been the result of diverging coastal currents irrespective of the winds. Recent studies by Meteorologists on the structure of the air flow during the monsoon revealed that secondary wind circulations could develop along the west coast of India. Thus, either such secondary wind circulations or diverging coastal currents or both could have resulted in the alternatively high and low oxygen cells associated with upwelling in distinctly separated zones along the central part of the west coast.

La Fond (1954) reported upwelling along the east coast of India during February-April. Balarama Murty (1958) studied the vertical thermal structure along the east coast of India and concluded that upwelling off Visakhapatnam was more intense than off Madras and that the peak intensity in upwelling off Visakhapatnam could take place either in March or April. Both the above studies were in want of data for the monsoon season. It should be expected that low temperature, low oxygen content and strong vertical gradients characterise the upwelled water. Accordingly, the results of the present investigation revealed that upwelling off Madras (in June 1964) persisted while upwelling off Visakhapatnam (in July 1964) was almost waning. It was also found that intense subsurface upwelling was taking place off the mouths of the rivers Godavari and Kistna concealed by the effects of river and coastal run-off at the surface. The cells of low temperature which developed at depths greater than 50 m in the northern and southern Bay of Bengal could also be the result of subsurface upwelling, even though upwelling in the central parts of the Indian seas had not been reported earlier.

The cold waters along the east coast of India and off Cape Comorin were characterised by relatively high oxygen content in the surface layers for the upwelled water. This could have been the result of aeration and possibly phyto-

plankton bloom coupled with reduction in the intensity of upwelling.

The distribution of oxygen at various depths clearly indicated that the Arabian Sea was generally richer in oxygen content. The thickness of the surface oxygen rich water was greatest in the equatorial regions and least in the Bay of Bengal. The oxygen content of the oxygen minimum layer was about 0.3 ml/L over most of the Bay of Bengal, 0.75 ml/L in the Arabian Sea and 1.5 ml/L in the equatorial region.

### CONCLUSIONS

The conclusions arrived at from the results of the present investigation described earlier and the preceding discussion could be enumerated as follows. The patterns of distribution of temperature and oxygen at all levels were generally similar. A quasi-stationary tongue of warm water was present in the surface layers of the Arabian Sea extending from the Gulf of Cambay southwards to 11°N. Upwelling in distinctly separated zones along the central part of the west coast of India was indicated. Upwelling was taking place off Madras while it was waning off Visakhapatnam and further north along the east coast of India. Possibly subsurface upwelling was taking place in the central parts of the northern and southern Bay of Bengal. The thickness of the oxygen rich surface layer was greatest in the equatorial region and least in the Bay of Bengal. The concentration of oxygen in the oxygen minimum layer was highest in the equatorial region and least in the Bay of Bengal.

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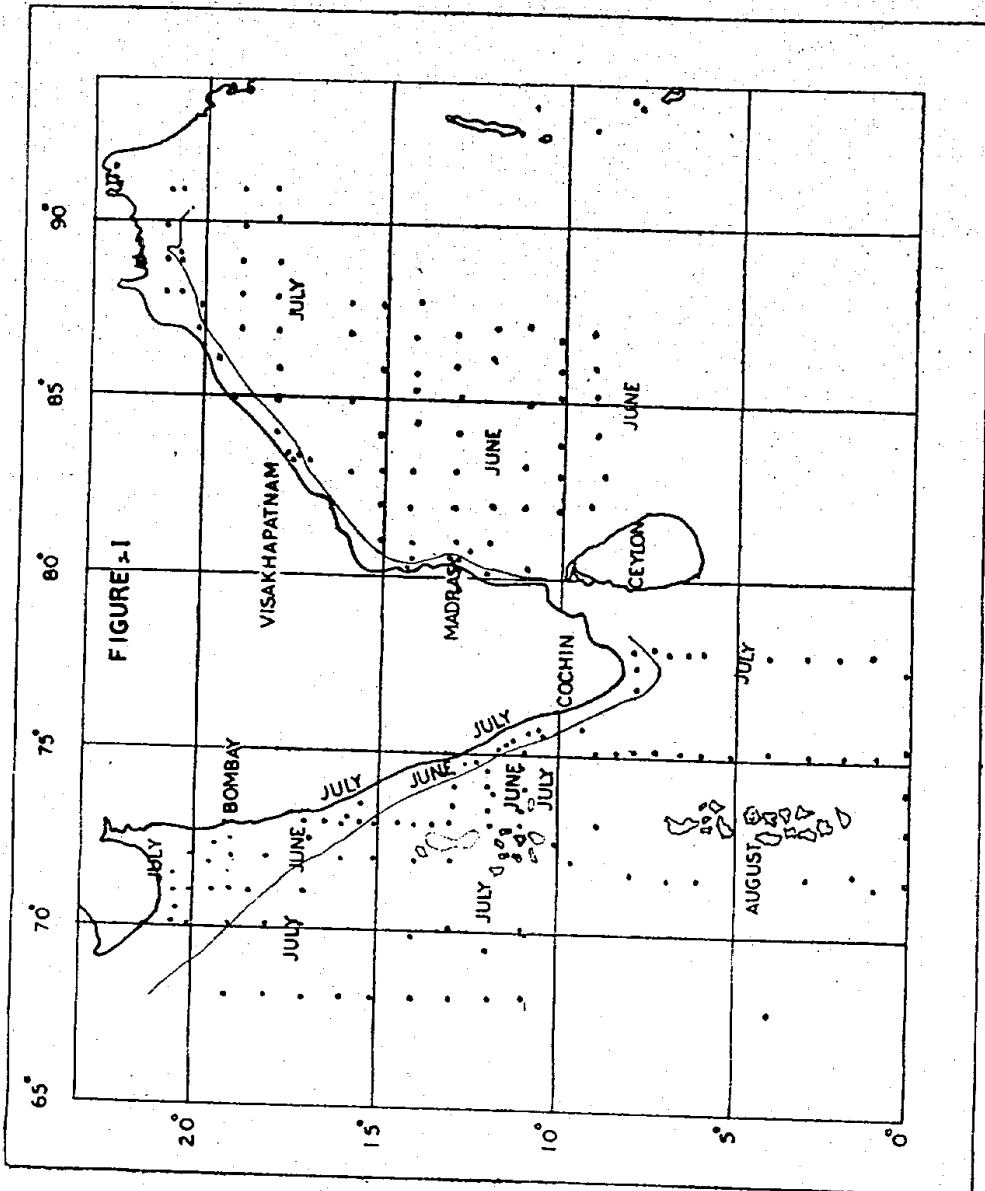


FIG. 1. Area under investigation showing the positions of hydrographic stations and the months in which they were occupied. The approximate limit of the continental shelf is also shown.

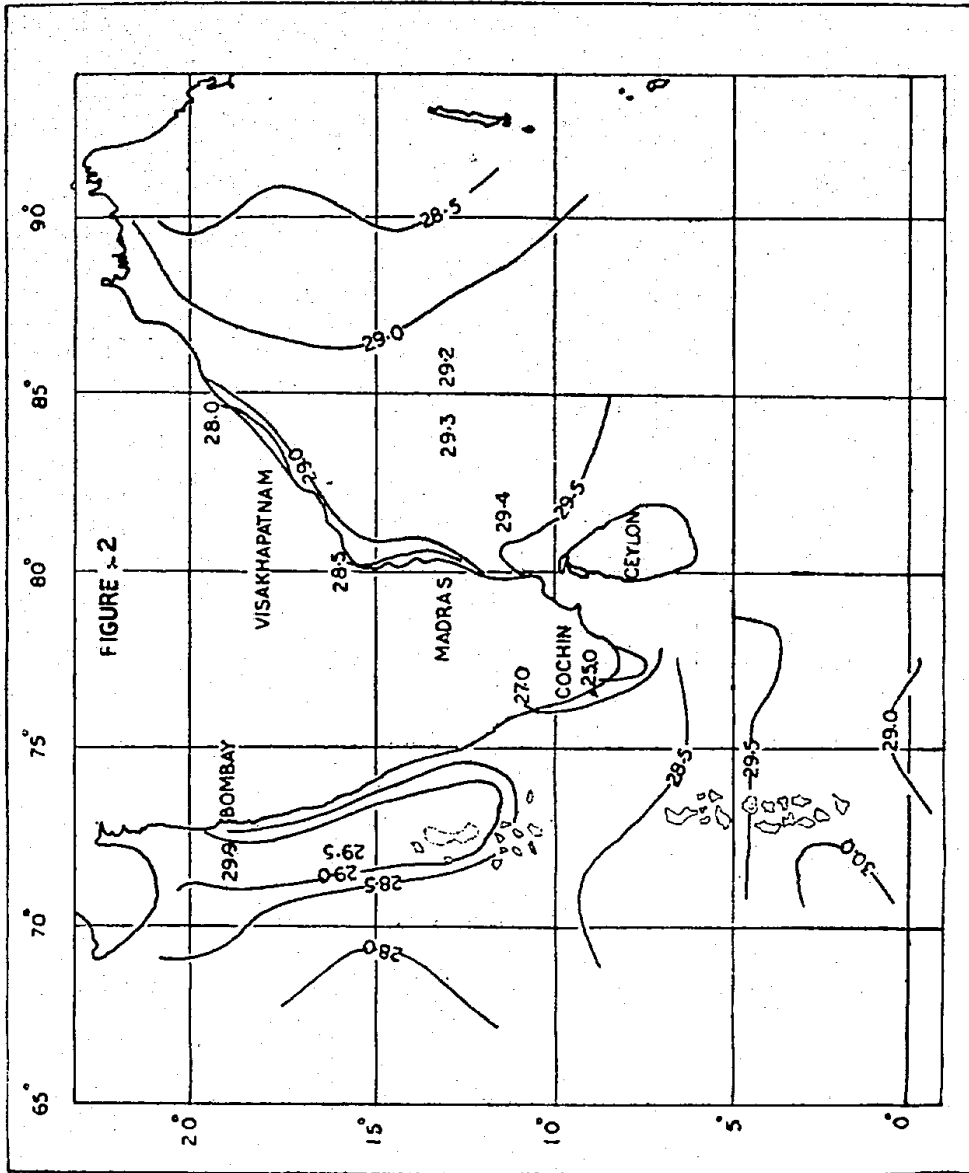


FIG. 2. Horizontal distribution of temperature (°C) at the sea surface.

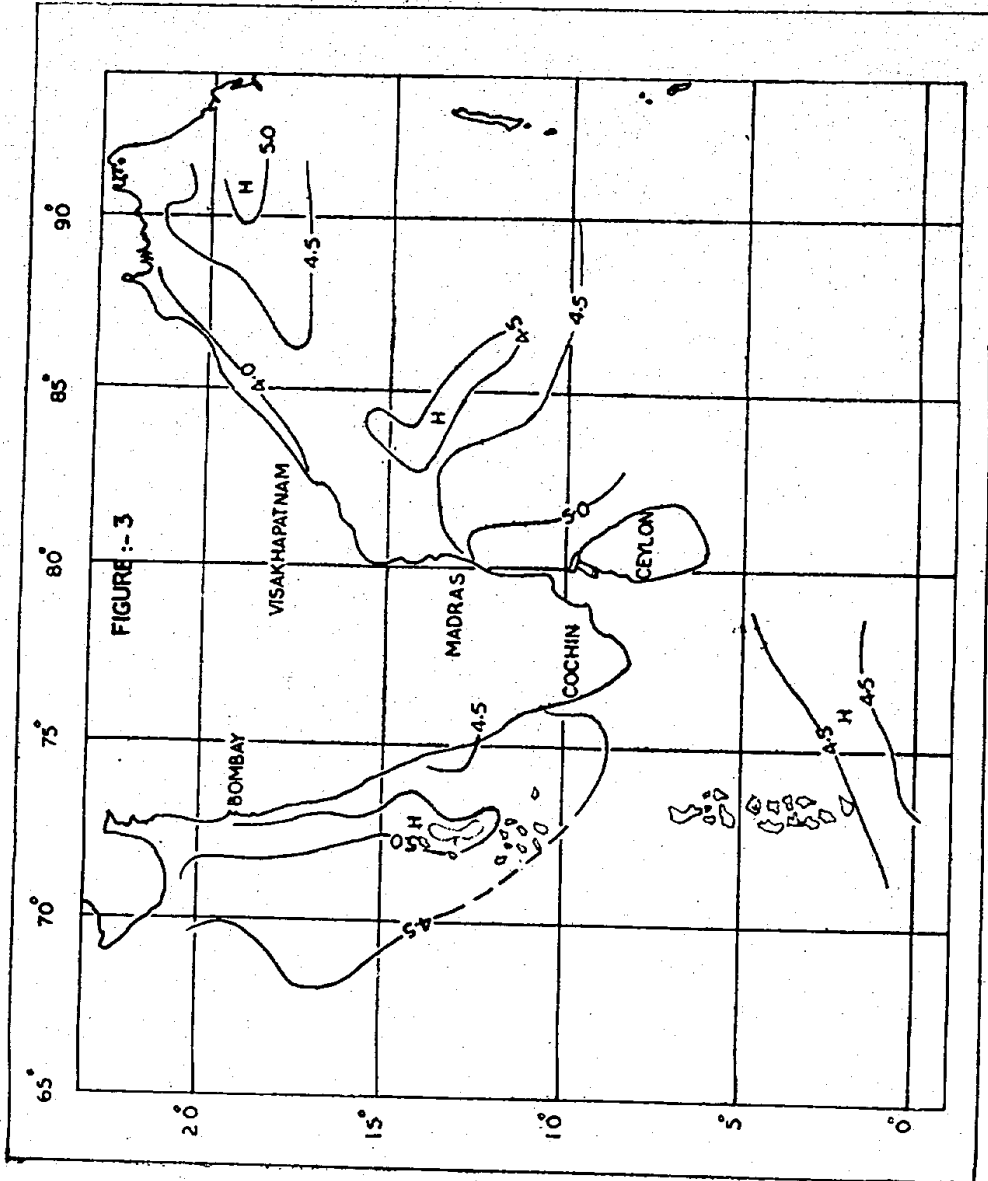


FIG. 3. Horizontal distribution of oxygen (ml/L) at the sea surface.

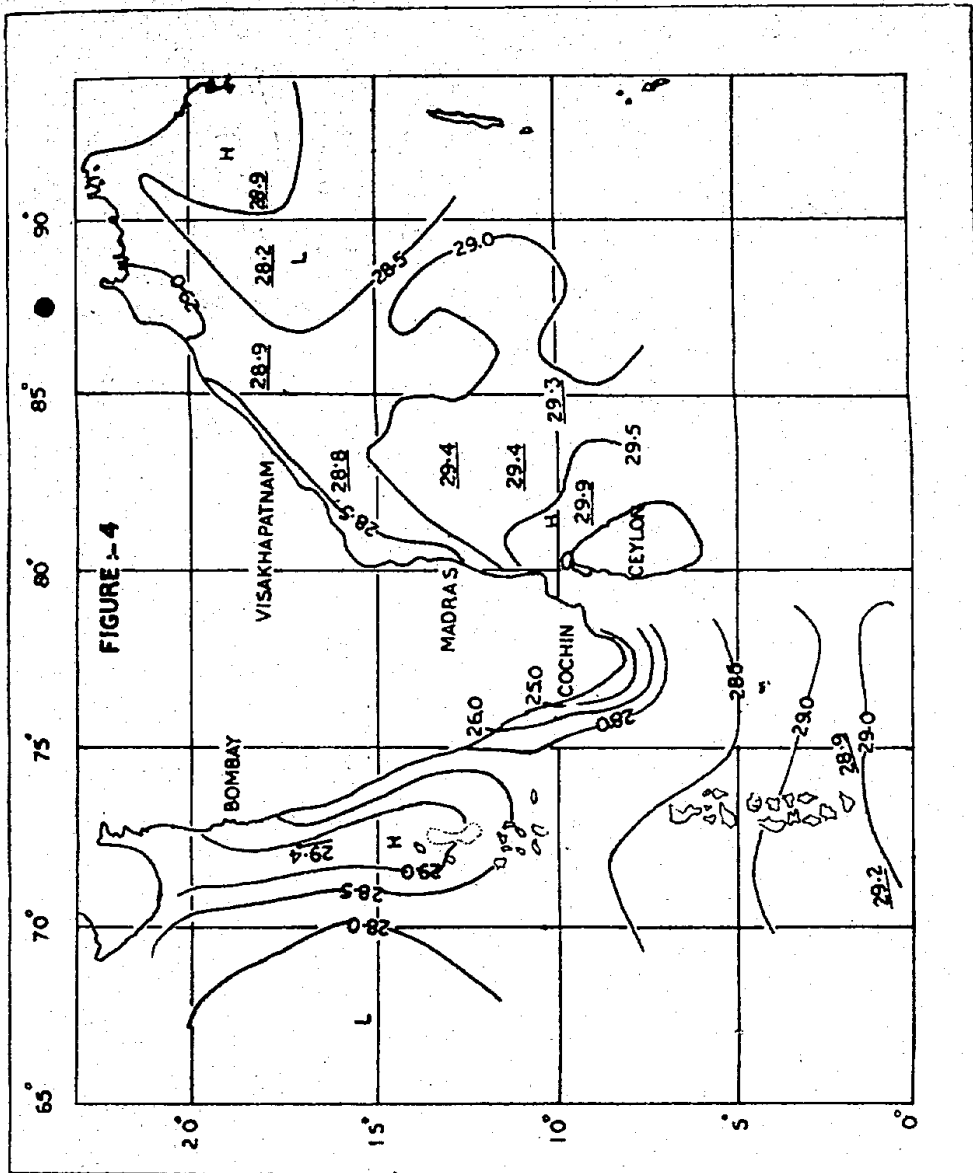


Fig. 4. Horizontal distribution of temperature (°C) at 20 m.

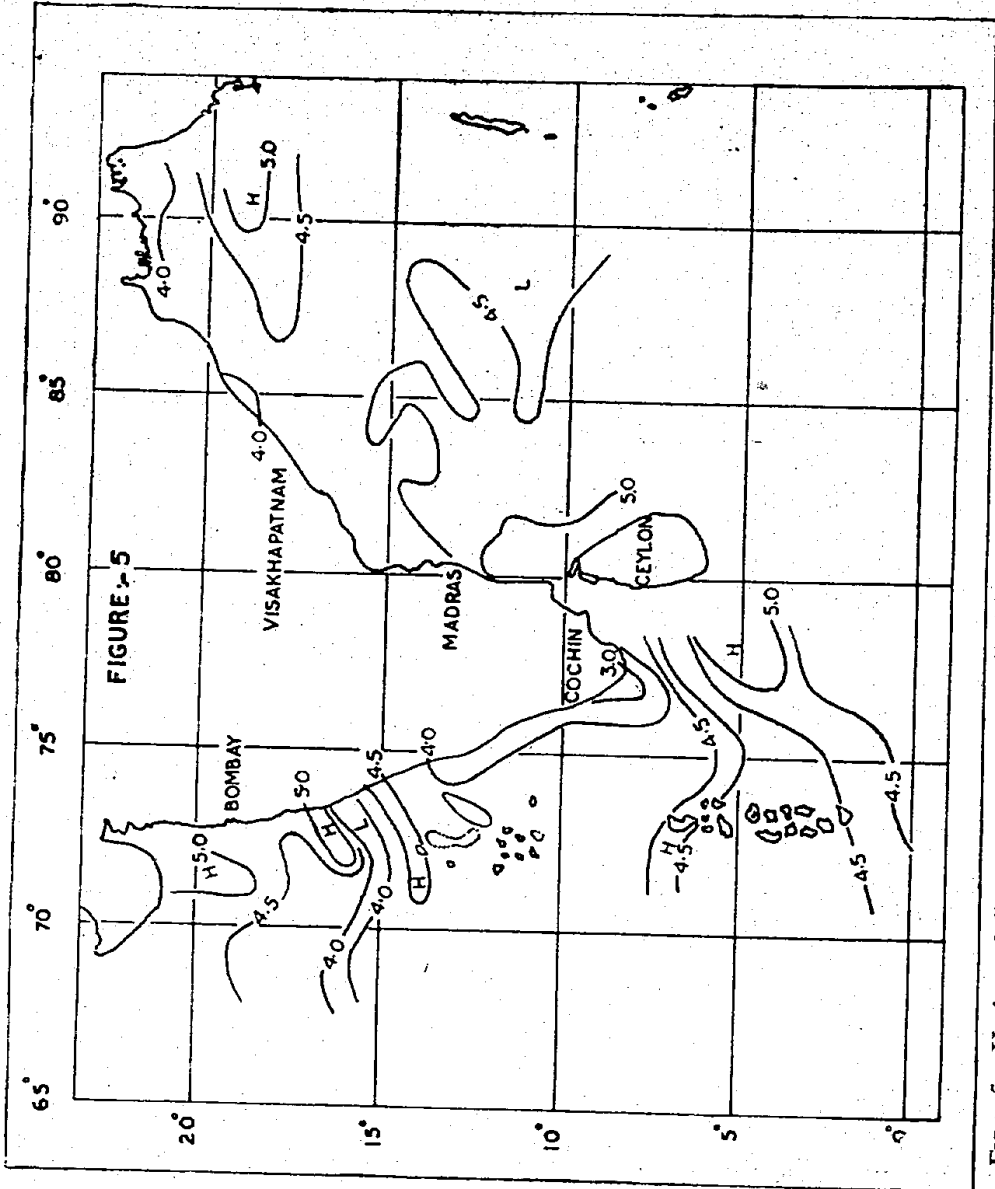


FIG. 5. Horizontal distribution of oxygen (ml/L) at 20 m.

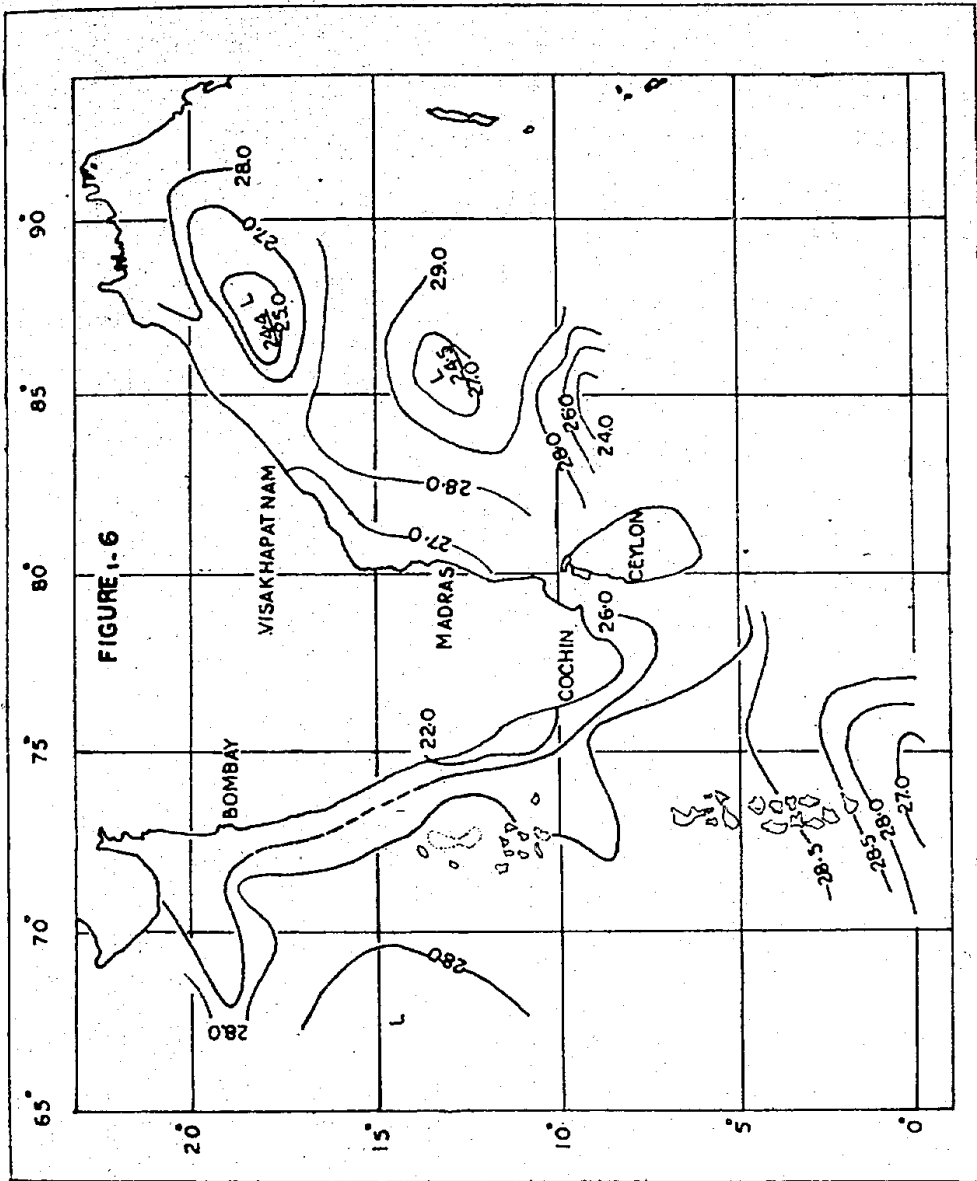


FIG. 6. Horizontal distribution of temperature (°C) at 50 m.

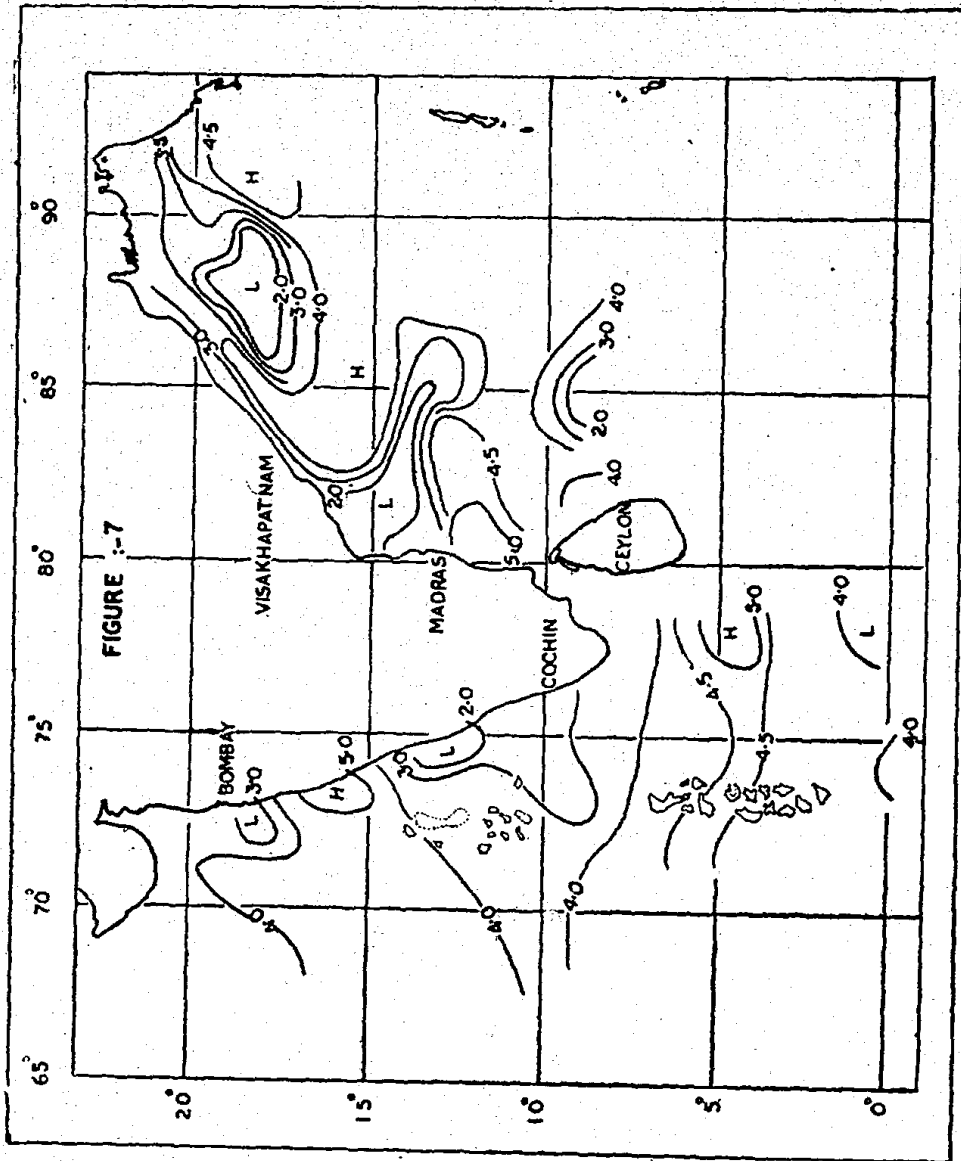


FIG. 7. Horizontal distribution of oxygen (ml/L) at 50 m.



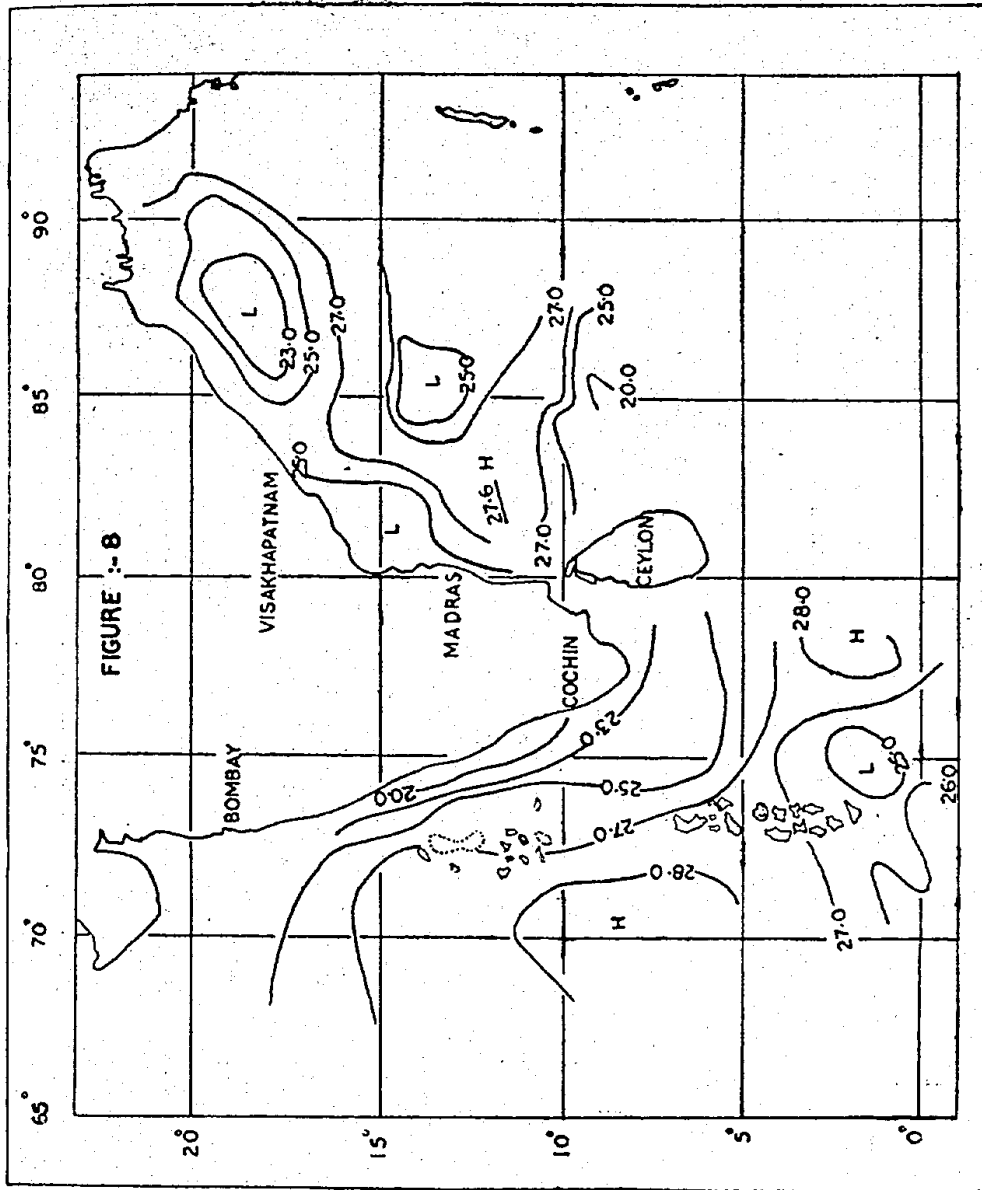


Fig. 8. Horizontal distribution of temperature ( $^{\circ}\text{C}$ ) at 75 m.

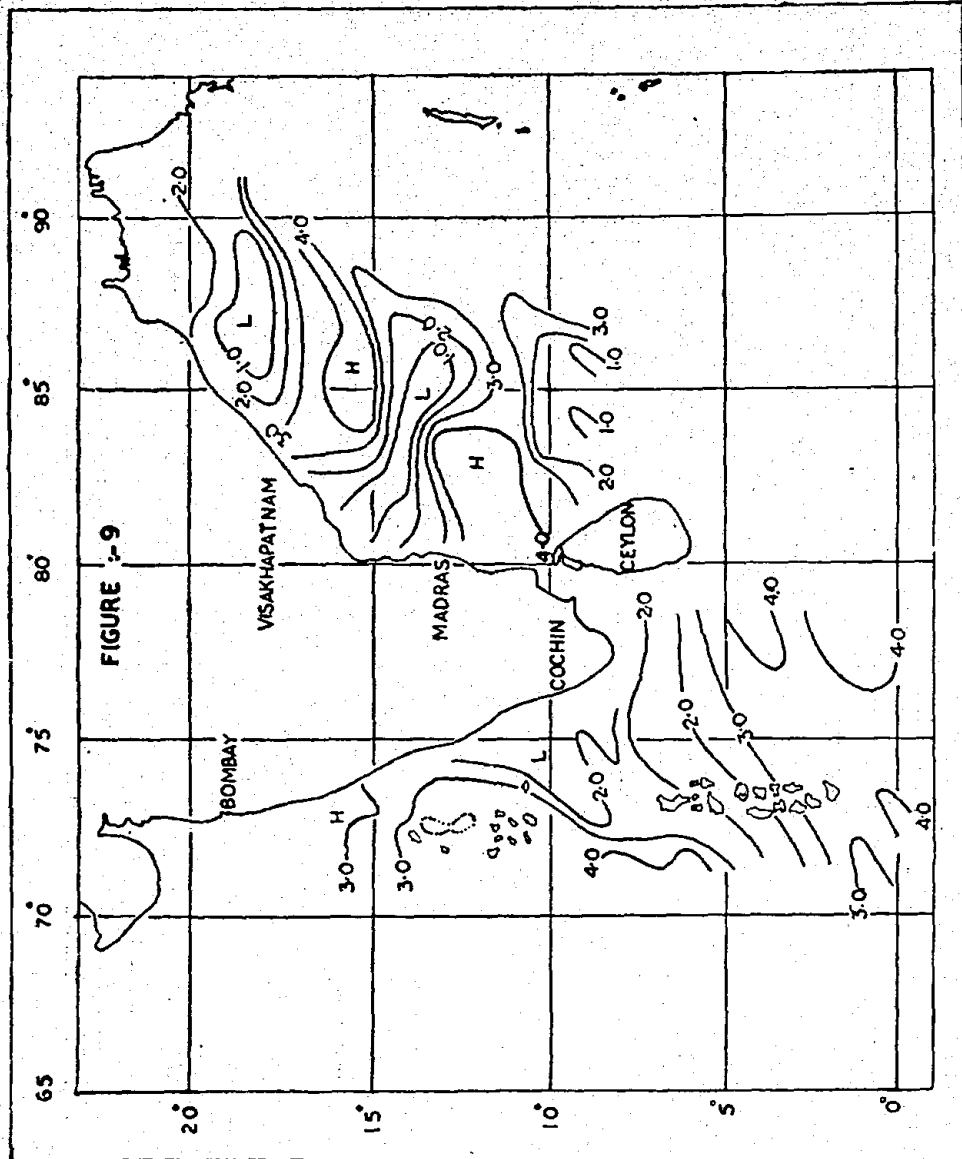


Fig. 9. Horizontal distribution of oxygen (ml/L) at 75 m.

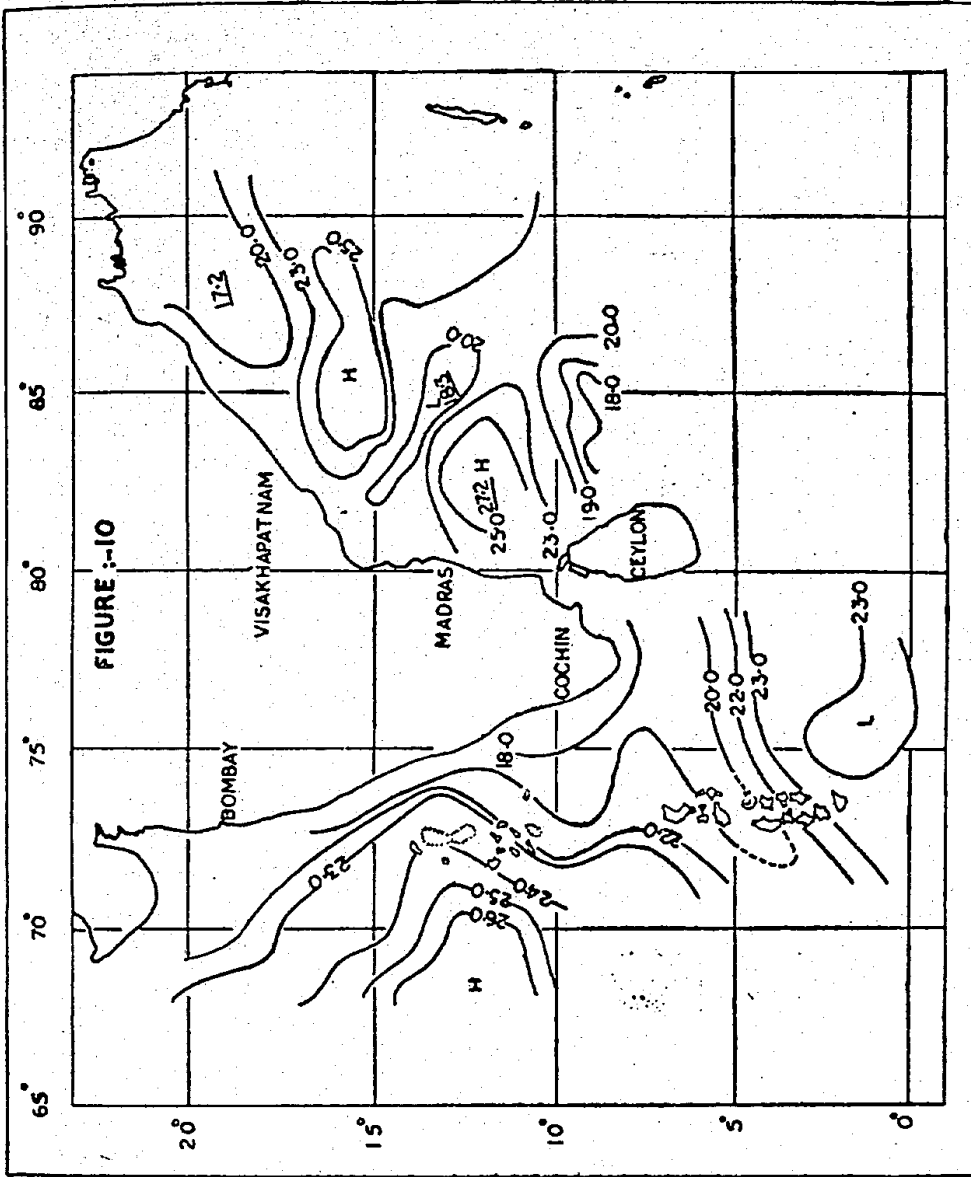


FIG. 10. Horizontal distribution of temperature (°C) at 100 m.

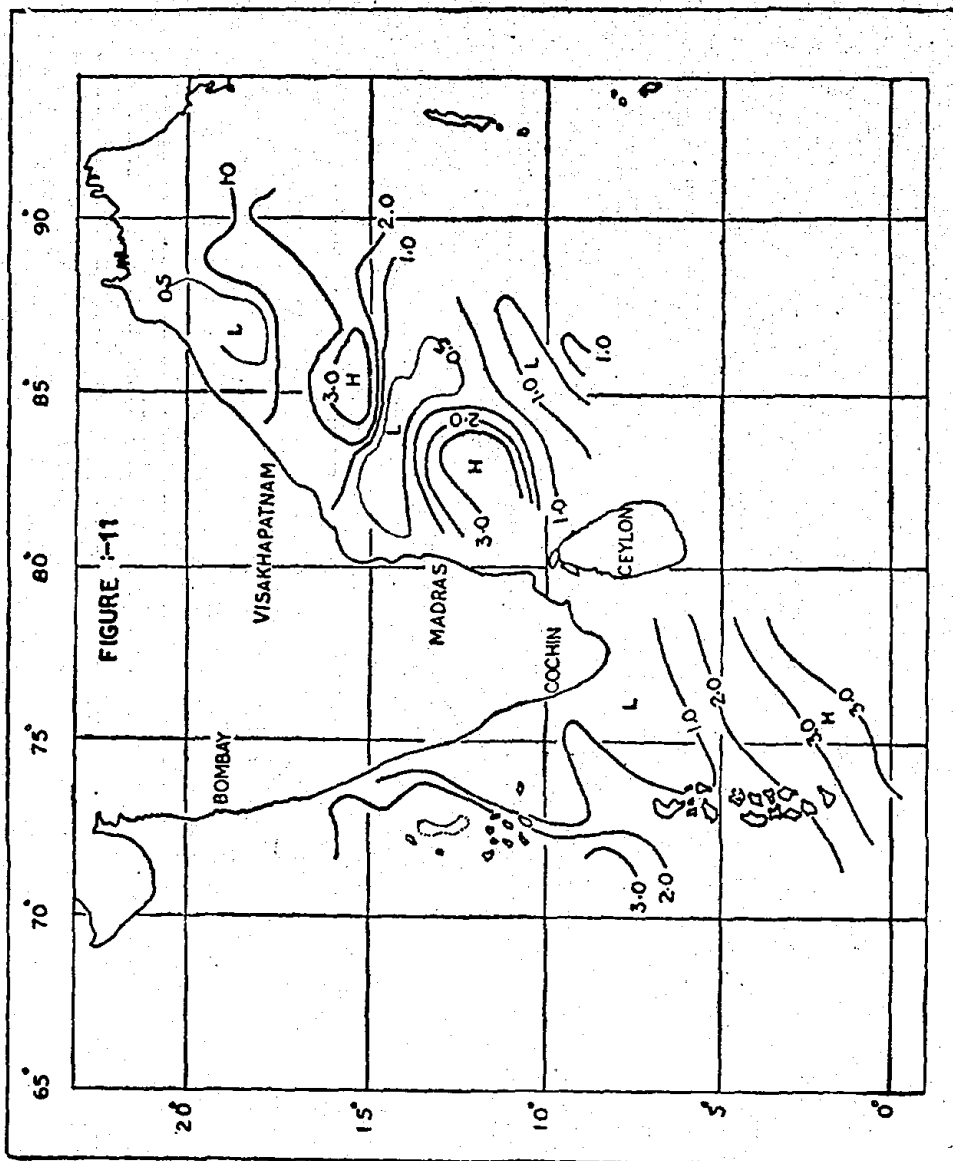


FIG. 11. Horizontal distribution of oxygen (ml/L) at 100 m.

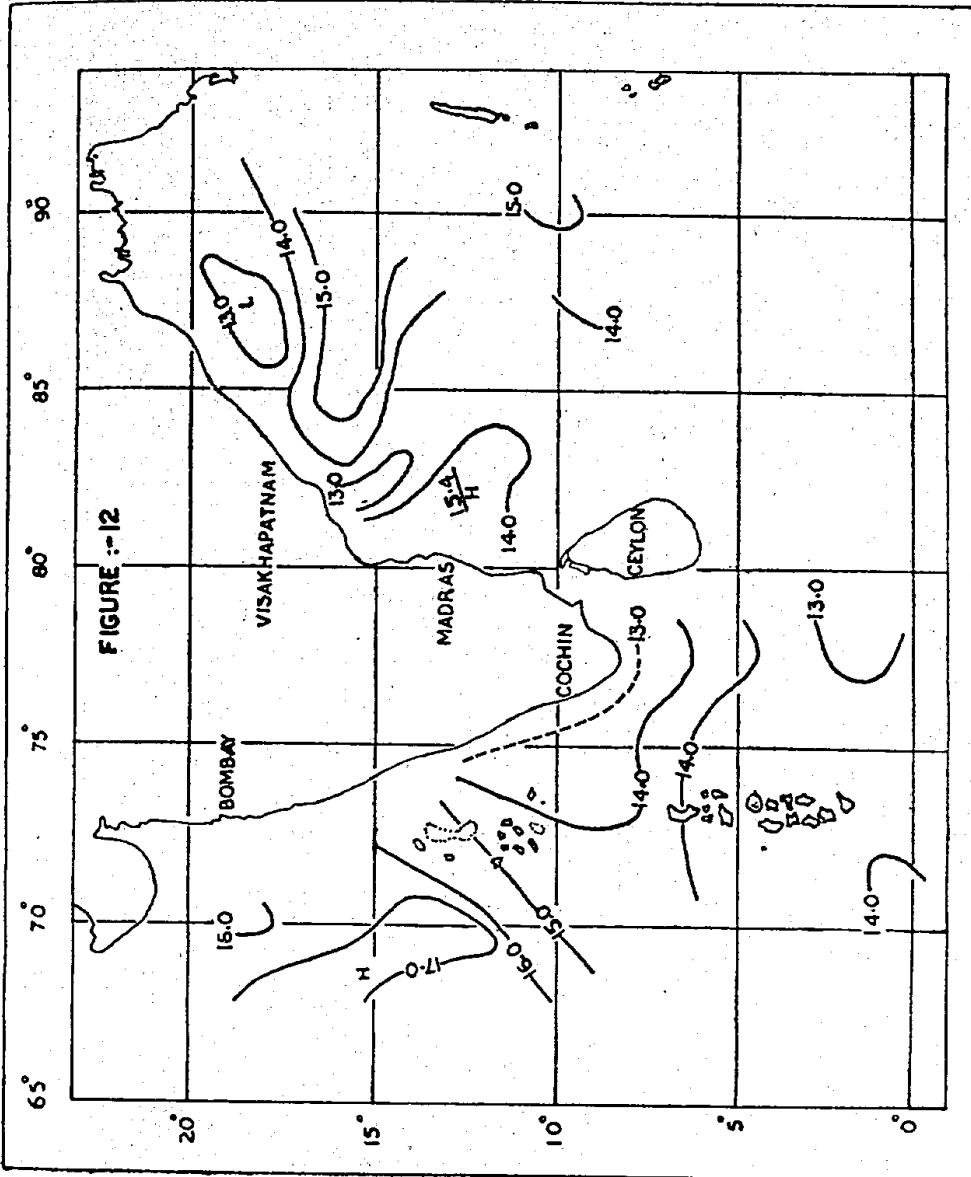


FIG. 12. Horizontal distribution of temperature (°C) at 200 m.

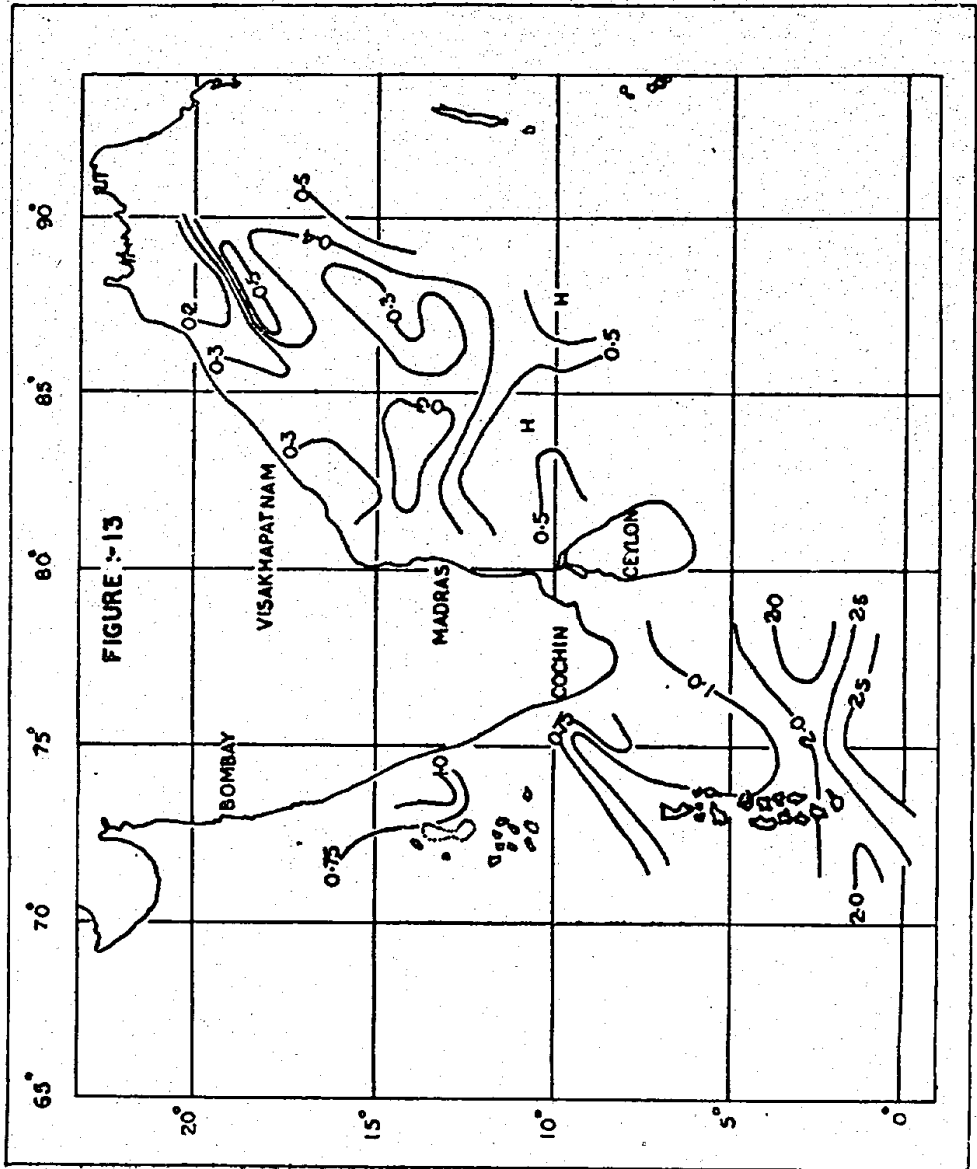


Fig. 13. Horizontal distribution of oxygen (ml/l) at 200 m.

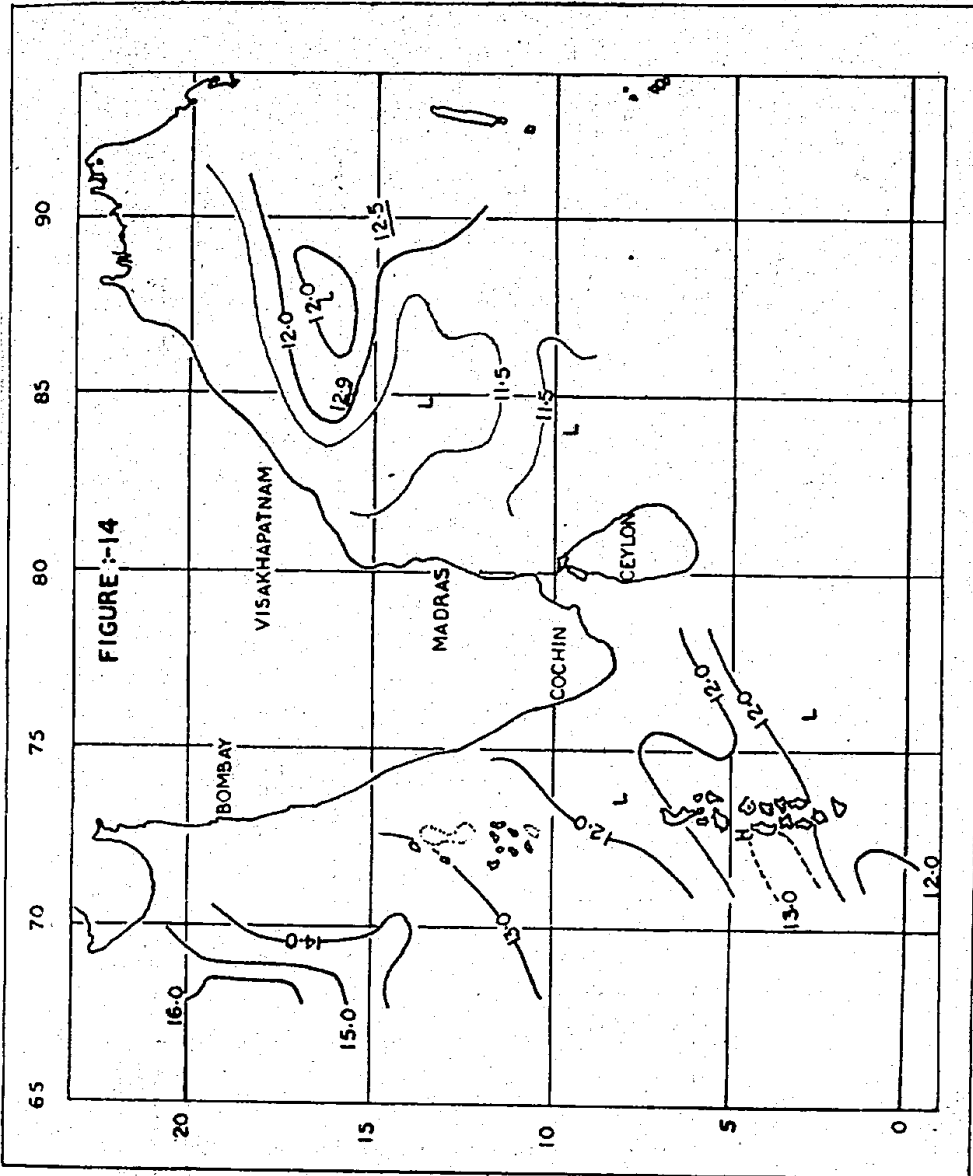


FIG. 14. Horizontal distribution of temperature (°C) at 300 m.

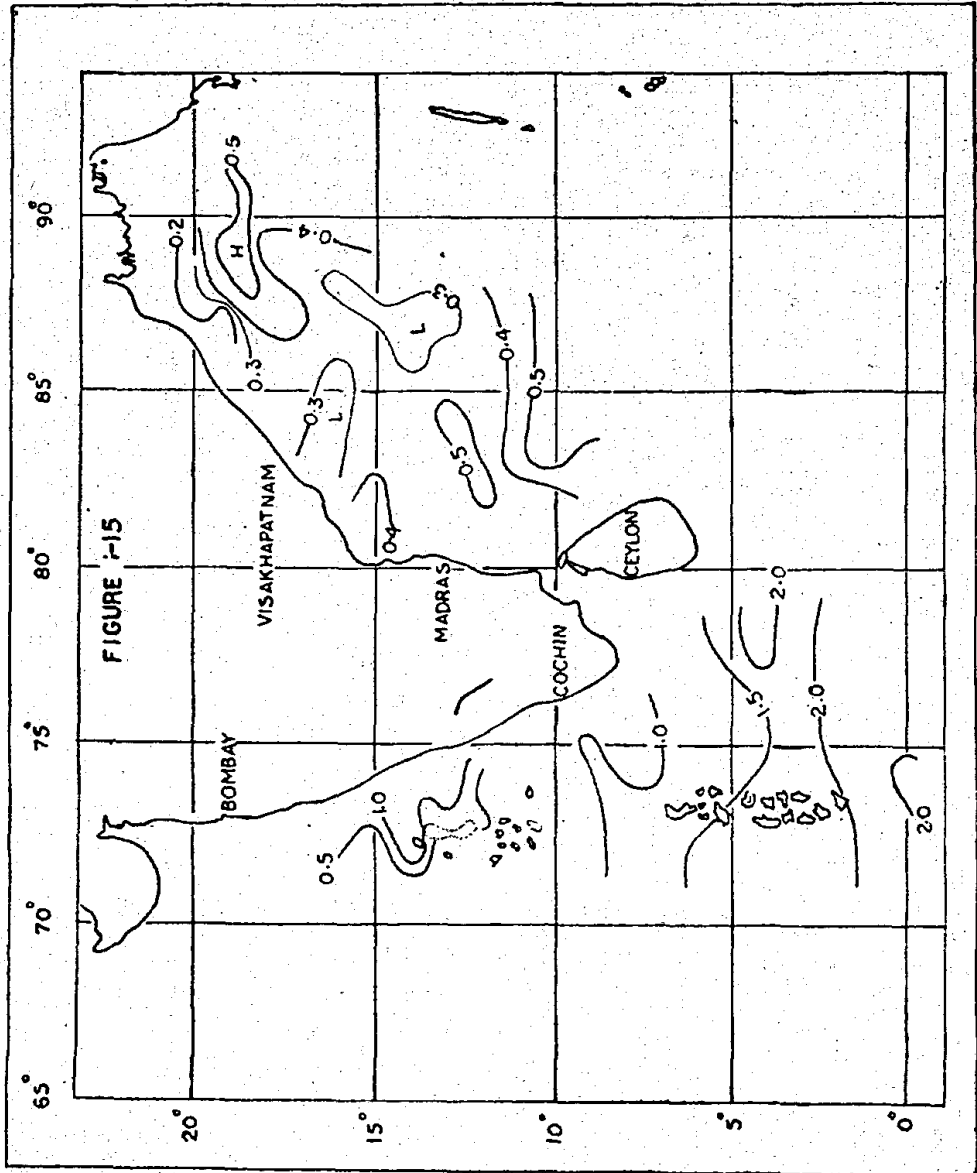


FIG. 15. Horizontal distribution of oxygen (ml/L) at 300 m.