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ON UPWELLING ALONG THE WEST COAST OF INDIA*

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ABSTRACT

The Oceanographic features prevailing along the west coast of India from Ratnagiri to Cape Comorin during the monsoon season of 1962 are presented and discussed. Nineteen hydrographic sections were investigated out of which twelve have been taken up for consideration. It was found that upwelling was noticeable to a marked extent in the region Calicut to Karwar and during this period a strong southward flow existed along the west coast. The topography of the bottom of the convection layer was also studied to have additional information regarding the monsoon features. In this connection the associated vertical migration of the thermocline during this period is shown and the probable causes of upwelling along this coast are discussed.

INTRODUCTION

THE hydrographic conditions along the west coast of India during the southwest monsoon period differ markedly from those during the other seasons. During the period of the southwest monsoon (June, July and August), upwelling is established along the west coast, especially from the month of July onwards, and there is reason to believe that the magnitude of the phenomenon varies along the coast and also from year to year. Many of the accounts already published (Rama Sastry and Myrland, 1959; Varadachari, 1961; Varadachari and Sharma, 1964; Sankaranarayanan and Qasim, 1967) clearly indicate that the Arabian Sea is characterised by relatively lower temperature, higher salinity, higher nutrient content, greater primary productivity, richer phytoplankton and zooplankton biomass and a greater fish yield than those of the Bay of Bengal. The increase in primary productivity along some of the coastal areas has been attributed to the high nutrient content brought to the euphotic zone by upwelling (Sankaranarayanan and Qasim, 1967).

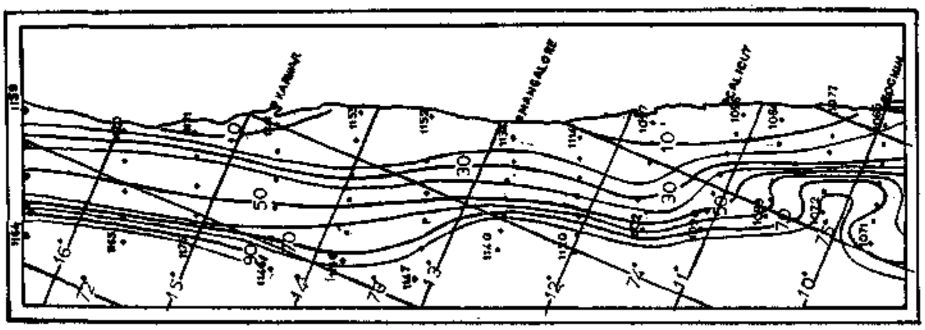

Fig. 1. Geographical positions of the hydrographic stations investigated during the monsoon period. Also given the depth of the convection layer along the west coast.

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Detailed hydrographic studies to ascertain the monsoon conditions existing along the west coast of India were conducted during June-August 1962 in seven cruises of R.V. *VARUNA*. Nineteen sections in the region Cape Comorin to Ratnagiri which were mostly normal to the coastline were occupied. Twelve hydrographic sections (Fig. 1) have been considered for interpretation since the typical southwest monsoon features had not developed when an additional set of seven sections were occupied south of Cochin.

The methods of collection and analysis of the data are the same as has been reported earlier(Ramamirtham and Jayaraman, 1960; Rama Sastry and Myrland,1959) The distribution of the various parameters such as temperature, salinity, density and dissolved oxygen content in the vertical plane in seven representative sections is given. Also the lateral distribution of the above parameters in the isobaric levels along the 10 m, 30 m, and 50 m depths are given, taking into consideration all the twelve hydrographic sections. An additional bathymetric chart representing the slope of the bottom of the convection layer (more or less the top of the thermocline) is included here to have a better idea of the shoreward migration of the offshore subsurface waters.

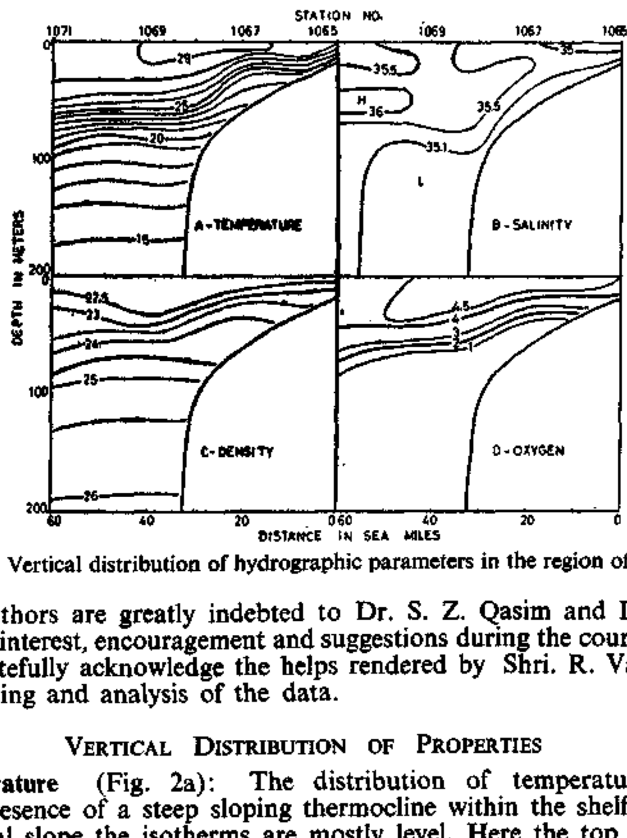

Fig. 2. Vertical distribution of hydrographic parameters in the region off Cochin.

The authors are greatly indebted to Dr. S. Z. Qasim and Dr. E. G. Silas for their keen interest, encouragement and suggestions during the course of this work. They also gratefully acknowledge the helps rendered by Shri. R. Vasantha Kumar in the processing and analysis of the data.

VERTICAL DISTRIBUTION OF PROPERTIES

Temperature (Fig. 2a): The distribution of temperature off Cochin reveals the presence of a steep sloping thermocline within the shelf, while beyond the continental slope the isotherms are mostly level. Here the top of the thermocline occurs at about 45 m depth in the deepest station and reaches the surface in the near coastal area. An overall uplift of the temperature discontinuity layer by about 50 metre than what occurs during the pre-monsoon season is seen off Cochin. In the offshore area, the two layered nature of the thermocline is noticeable.

Off Calicut (Fig. 3a), the intrusion of offshore cold sub-surface waters into the shelf is conspicuous in the form of a tongue. In this section also the top of the thermocline touches the very surface areas in the inshore region and an eastward gradient of temperature is observed in the surface layers. This intrusion thus obliterates the mixed layer in the coastal regions. In the deeper layers the distribution is comparable to that seen off Cochin.

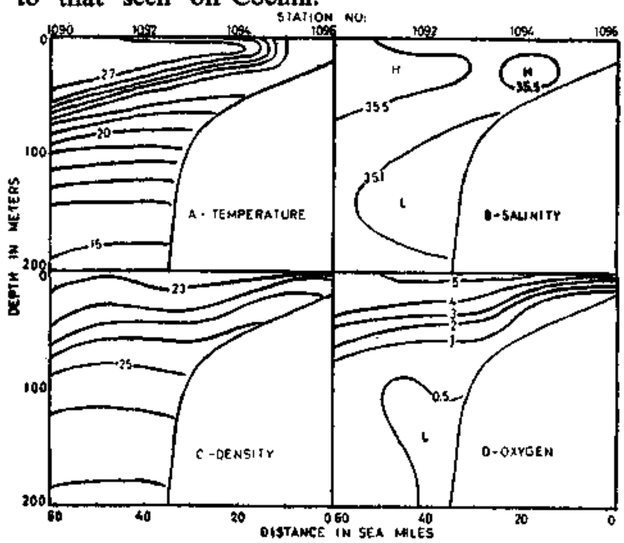

Fig. 3. Vertical distribution of hydrographic parameters in the region off Calicut.

Similar features are observed off Cannanore (Fig. 4a), but off Mangalore (Fig. 5a) the features are noticeably different. Thus, the thermocline off Mangalore has an upslope from 100 to 0 metre indicating a greater intensity of upwelling. The

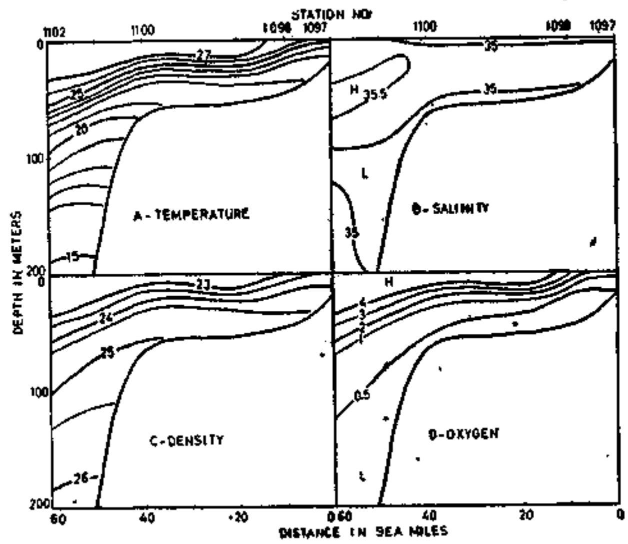

Fig. 4. Vertical distribution of hydrographic parameters in the region off Cannanore.

waters over the whole of the continental shelf have temperatures less than 26°C. The mixed layer is not conspicuous over the shelf and even at 200 m depth the isotherms show an eastward upslope. The wavy pattern in the thermal structure, especially in the offshore regions are indicative of the presence of internal waves. Similar to the previous sections, lateral thermal gradients can be observed over the shelf, but with higher intensity.

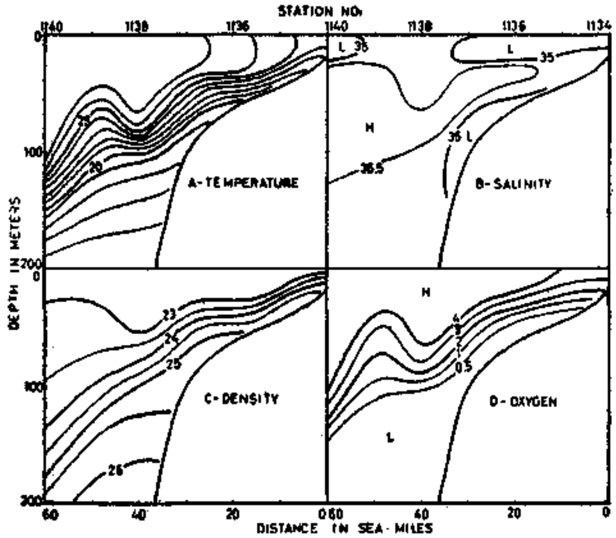

Fig. 5. Vertical distribution of hydrographic parameters in the region off Mangalore.

Off Coondapur (Fig. 6a), the influx of sub-surface offshore cold waters is not so intense as off Mangalore. Thus, the steep eastward upslope of the temperature discontinuity layer beyond the continental slope is not so conspicuous, although within the shelf the isotherms have visible upslope. Unlike the regions off Calicut and Mangalore, the isotherms of lower temperatures do not reach the surface, as a comparison of the 25 °C isotherm in the three sections would show. The thermocline in this section does not reach the surface and the mixed layer having a temperature between 27-28°C is well formed in the offshore region and the lateral thermal gradients in the surface layer are absent.

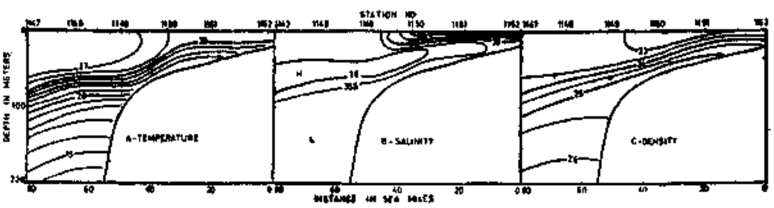

Fig. 6. Vertical distribution of hydrographic parameters in the region off Coondapur.

Off Karwar (Fig. 7a), the thermal features are comparable to those off Mangalore. In this section also the sloping nature of the isotherms over the shelf results in the absence of the mixed layer. The intensity of the incursion of colder waters into the shelf is more pronounced than that off Coondapur. In the offshore region, the mixed layer is well formed and unlike the Coondapur section it extends up to a depth of 100 m in the westernmost station. Similar features prevail in the section off Ratnagiri (Fig. 8a) except that the upward tilt of the temperature discontinuity layer is more than in the previous section. Even at depths of 100 m or so, the slope of the discontinuity layer is pronounced.

Thus, the vertical distribution of temperature is mostly of the same pattern along the entire coast during the period of investigation. In most of the cases the vertical extent of the surface mixed layer is reduced in the near shore region, and in a few cases it can be observed that the mixed layer is mostly absent over the shelf. This feature is produced mostly by the upsloping nature of the isotherms. A strong, though comparatively thin, thermocline is evident over the shelf, a feature which is quite contrary to that observed during the other seasons.

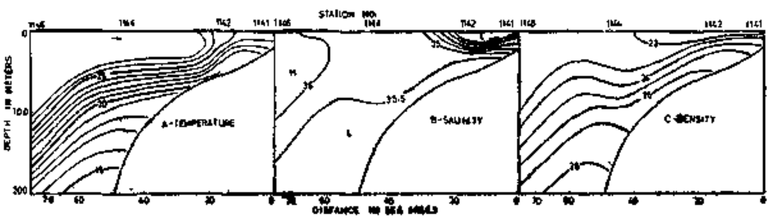

Fig. 7. Vertical distribution of hydrographic parameters in the region off Karwar.

Salinity (Fig. 2b): The vertical distribution of salinity in the Cochin section (Fig. 2b).) reveals the presence of a high saline cell at about 50 m depth in the offshore regions. The salinity is found to slightly decrease towards the coast, and is less than 35‰ very near the coast. The high saline cell is observed within the thermocline. Over the bottom of the continental shelf and the slope the values are less than 35.1‰ and below 100 m depth the distribution in the offshore region is fairly uniform. The incursion of high saline tongue into the continental shelf region can be observed.

The intensity of the salinity maximum is reduced off Calicut (Fig. 3b) and the isohaline zone is found within the mixed layer. The distribution in the deeper layers is comparable with that off Cochin. The tongue-like structure is not so conspicuous and the salinity values of the continental shelf waters are, in general, higher than off Cochin. This is evident from the occurrence in these waters of the high saline cell with a core value greater than 35.5‰.

Further north, off Cannanore (Fig. 4b) the entire continental shelf is pervaded by a water mass of salinity between 35‰ and 35.5‰. Again, this region coincides with the temperature discontinuity layer over the shelf and as in the Cochin section the salinity maximum zone is observed within the thermocline. In the deeper layers (below 100 meters) the distribution is comparable to that in the previous sections. It may be noticed that, in the above three sections, precipitation and run off from land drainages has not affected the salinity distribution to any marked degree.

A similar pattern exists off Mangalore (Fig. 5b), although the vertical extent of the salinity maximum zone has widened in the offshore region. But a remarkably different pattern of salinity distribution exists off Coondapur (Fig. 6b) and in the sections north of this (Fig. 7b & 8b). Thus, off Coondapur the precipitation and run off from land drainage have affected the salinity in the surface layers to a great extent. Although a tongue like intrusion of offshore high saline waters into the continental shelf is conspicuous, the salinity in the surface layers is less than 34‰ producing a strong well defined halocline over the shelf. This halocline consequently coincides with the stably stratified thermocline already mentioned. Unlike off Cochin, Calicut, Cannanore and Mangalore, the salinity values in the deeper layers are high.

The effect of rain and fresh water influx in reducing the surface salinity values over the shelf is much more pronounced off Karwar (Fig. 7b), resulting in a well defined vertical stratification of the halocline. But an extension of the high saline tongue into the shelf is not observed although the salinity maximum zone occurs in the offshore regions off Karwar. Off Ratnagiri (Fig. 8b), the spacial extent of the salinity maximum zone is found to be increased much and the intrusion of high saline waters into the shelf is noticeable. The effects of external factors such as rain and fresh water influx are not visible over the shelf.

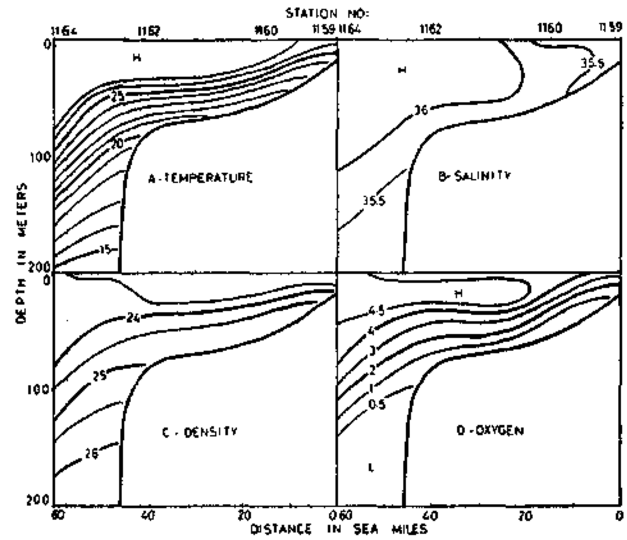

Fig. 8. Vertical distribution of hydrographic parameters in the region off Ratnagiri.

Thus the distribution of salinity during the monsoon season presents quite dissimilar features compared to the other seasons. The presence of a halocline in some of the sections due to the influence of fresh water influx from the shore is considerable and is perceptible to a distance of 16 to 24 kilometres from the coast. The salinity maximum is, in general, weak compared to the other seasons.

Density: The distribution of density, in general, resembles that of temperature. Thus, near the continental slope off Cochin (Fig. 2c), the isopycnals show an eastward upslope, and a general southward drift over the shelf is observed. The pycnocline, like the thermocline, is well developed over the shelf, and at 100 m and below, stable stratification in the horizontal is observed.

Off Calicut (Fig. 3c), the close resemblance between the thermocline and the pycnocline is not so conspicuous as off Cochin. The pycnocline is rather diffused and the southward drift over the shelf is not so strong. The more or less horizontal nature of the pycnocline over the shelf is indicative of the absence of noticeable meridional movements in the region off Cannanore (Fig. 4c). The sloping nature of isopycnals is observed only in the region of the continental slope. But unlike off Calicut, the vertically stable stratification of the thermocline is reflected in the pycnocline. Thus, meridional movements are restricted to the offshore regions.

The strong upsloping nature of the isopycnals is indicative of the intense southward drift in the region off Mangalore (Fig. 5c). The currents are stronger in the offshore regions and convergence of the isopycnals over the shelf is noticed. The wavy nature of the isopycnals in this region considerably modifies the thickness of the surface mixed layer which is comparatively thicker in the offshore regions and nearly absent very near the coast. Unlike the southern sections, off Mangalore lateral movements are perceptible even below 150 m.

In the shelf waters off Coondapur (Fig. 6c) the vertical stratification of the thermocline, the halocline and pycnocline are similar. The discontinuity in the density distribution starts from the surface and this can be attributed to the peculiar pattern of the salinity distribution rather than the effect of the thermocline which starts only at about 20 m depth. The eastward upslope of the isopycnals is indicative of a noticeable southward drift along the entire section normal to the vertical plane. Similar features are also predominant in the region off Karwar (Fig. 7c), where the southward drift has a higher intensity. Off Ratnagiri (Fig. 8c), the salinity distribution appears to modify the density structure considerably, although the temperature distribution in this section appears to be similar to that observed in the other sections. Consequently a strong pycnocline is absent over the shelf off Ratnagiri and the southward drift appears to be weak, although in the offshore regions this drift is still conspicuous.

Oxygen: The distribution of dissolved oxygen during the monsoon season presents noticeably different features from that occurring during the other seasons. Thus off Cochin (Fig. 2d), considerable decrease in the values occur in the vertical within the shelf and values less than 1 ml/L occur over the bottom of the continental shelf. This feature is totally different from those observed during the premonsoon and postmonsoon periods when these waters are saturated upto 80 to 90% with oxygen. This feature occurs due to the effect of an influx of offshore subsurface waters on to the shelf. The oxygen deficit water starts even from 80 m depth in the offshore regions, unlike other seasons when the top of the oxygen deficit layer coincides mostly with the bottom strata of the thermocline at about 150 to 200 m.

Comparable features exist off Calicut. The shoreward upslope of the isolines of oxygen are observed with a more compact packing of the isolines in the surface layers. The oxygen deficit layer, as can be observed is more intense than that off Cochin. The shoreward upslope of the oxygen deficit layer is still conspicuous in the sections off Cannanore, Mangalore and Ratnagiri. Off Mangalore the thickness of the high oxygen layer is more in the offshore regions compared to the other sections, but the general trend in the distribution pattern is the same in all the sections.

HORIZONTAL DISTRIBUTION OF PARAMETERS

For representing the distribution of parameters in the lateral plane three representative isobaric surfaces at 10 m, 30m, and 50 m are chosen. In view of the effects of precipitation and run off, the surface layer has not been considered for horizontal studies. Thus, at 10 m depth two cold water pockets one off Mangalore and another off Karwar are observed (Fig. 9). There is a decrease of 6°C to 7°C in temperature compared to the other seasons. It is at these two regions that the maximum intensity of the eastward temperature gradients are observed. As has been indicated in the vertical distribution patterns, these temperature gradients are again confined to the shelf region. The more or less continuous nature of the isotherms from Calicut to Ratnagiri in the meridional direction is indicative of the uniform effect of the colder waters over the shelf.

The effect of rain and land drainage which has been observed in the sections from Mangalore to Karwar, is again reflected in the horizontal distribution patterns of salinity at 10 m depth. Towards the north of 15°N and south of 12°N, the distribution in the lateral plane is more or less uniform. As far as the distribution of the dissolved oxygen content is concerned, totally different features are observed from those existing in the other seasons. In the regions where low temperature values are observed (Calicut to Karwar) dissolved oxygen values are less than 1 ml/L. During the premonsoon and post-monsoon seasons these regions usually

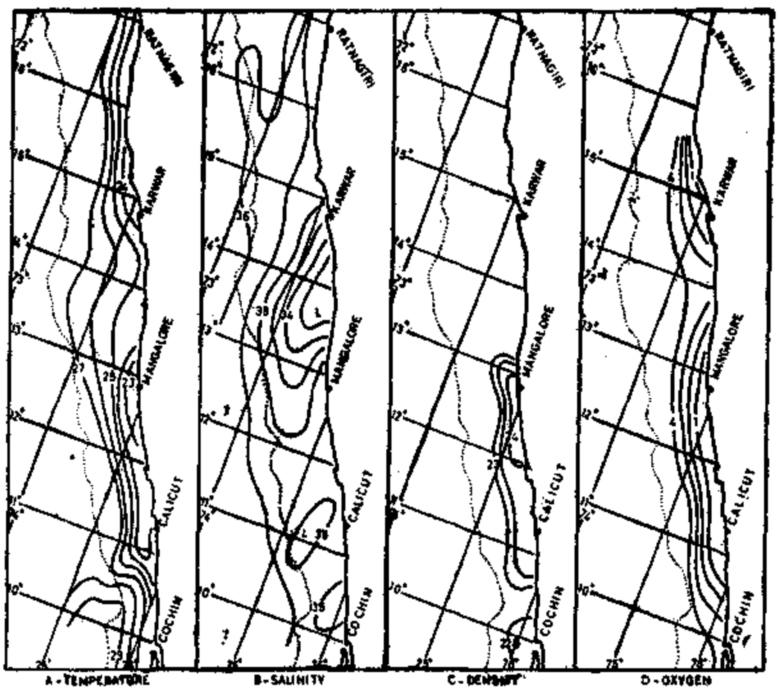

Fig. 9. Distribution of hydrographic parameters at 10 m level.

exhibit values as high as 4 to 4.5 ml/L. Again, the nature of the isolines of oxygen indicates a uniform effect of the cold water intrusion. Due to the effect of rain and fresh water influx the values of density are peculiar in the regions north of Mangalore and isopycnal studies may not be accurate. Hence, only the region between Cochin and Mangalore has been considered for these studies. Here the expected westward gradient in the density distribution can be observed and the southward drifts too.

At 30 m depth (Fig. 10), the eastward temperature gradients in the horizontal are stronger than those at 10 m depth. The horizontal temperature discontinuity zone is confined over the edge of the continental shelf. Between Calicut and Karwar it can be observed that the major portion of the continental shelf is occupied by waters of temperature below 22°C and this region seems to be affected to the maximum by the cold water intrusion. In the region north of Karwar the temperature gradients are weaker. Unlike the features observed at 10 m depth the salinity values at 30 m depth are not found to be affected by the land drainage and rain. The salinity distribution is mostly uniform as can be observed from the nature of the 35.5‰ isohaline. North of Mangalore, salinity values are higher. As observed in the 10 m level, there occurs a drastic decrease in oxygen content towards the coast, at 30 m level also. The effect of extraneous fresh water is considerably reduced at 30 m than at 10 m. This feature can be observed from the continuous nature of the isolines of oxygen. The more or less uniform intrusion of cold waters, thus seen results in a long belt of low oxygenated waters along the coast. Isopycnals too are continuous in the meridional direction resulting in a regular southward drift roughly parallel to the coastline.

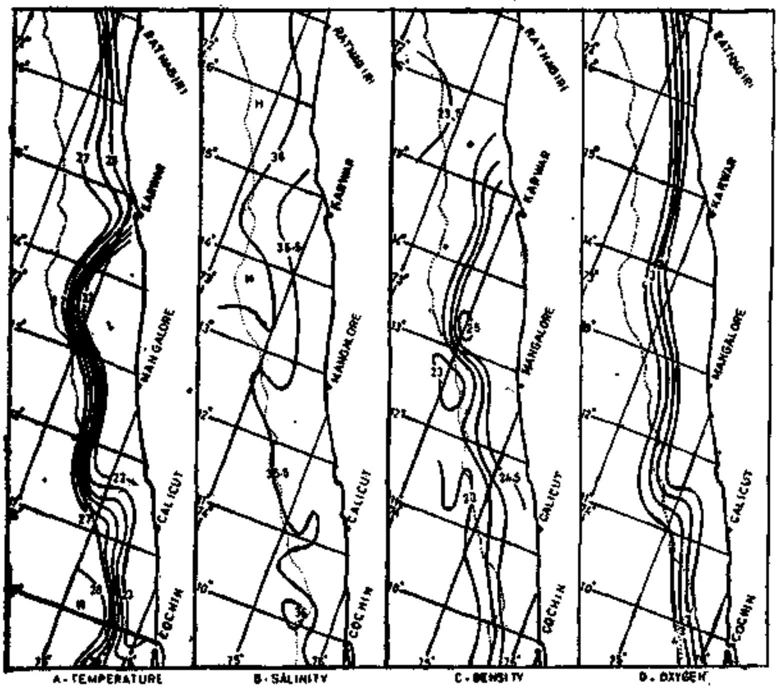

Fig. 10. Distribution of hydrographic parameters at 30 m level.

The eastward temperature gradients appear to be diffused in the region north of 14°N at 50 m level (Fig. 11). A convergence of isotherms occur off Mangalore and south of 12°N the gradients are again weak. Considering all the three lateral distribution patterns it can be observed that the region between Mangalore and Karwar is maximum affected during the monsoon period. The maximum temperature of 27°C -28°C being same in all the levels, the minimum temperature of 20°C occurs at 50 m level, thus increasing the intensity of the eastward temperature gradients depthwise. The salinity distribution at 50 m level is more or less uniform and the distribution of the dissolved oxygen is mostly identical as at the 30 m level. Density gradients are again strongest between Mangalore and Karwar and the southward drift is maximum developed in this region.

DISCUSSION

It is evident from the distribution of properties in both vertical and horizontal planes, and the pattern of circulation, that a proper knowledge of the conditions during the monsoon period along the west coast form an essential pre-requisite. The reduced thickness of surface mixed layer, the occurrence of the thermocline over the continental shelf and the comparatively very low content of dissolved oxygen in the shelf waters, are some of the major features. During this period, the circulation in general, shows a strong southward flow along the entire west coast. Further, the lateral gradients in temperature and density are well developed during the active period of monsoon, when the region north of 11°N were investigated. The resulting drifts are also strongest in these regions.

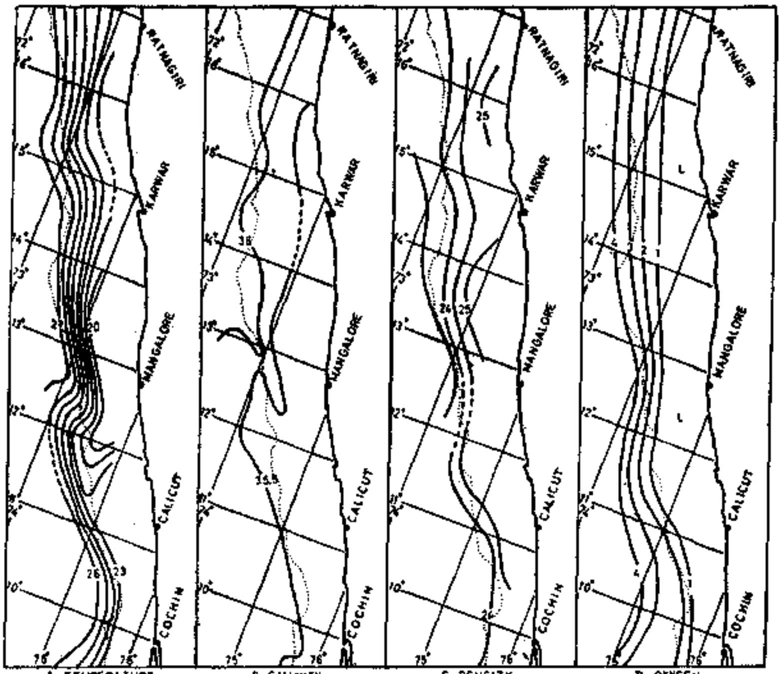

Fig. 11. Distribution of hydrographic parameters at 50 m level.

A significant feature of the season is the occurrence of upwelling along the west coast. Waters from the intermediate oxygen deficit layer which are normally found at 75- 100 m depths, seem to have been drawn to the upper levels, and low oxygenated waters have pervaded almost the whole of the continental shelf. Carruthers *et al.* (1958) have shown that the shoreward upslope of the oxygen minimum layer can be considered as an indication of upwelling along the west coast of India. Besides, some Japanese workers have opined that the counter current at the deeper layers can be taken as an indication of upwelling (Yoshida, 1955). As described earlier, comparatively colder, denser and very poorly oxygenated waters occur along the Karwar, Mangalore and Calicut coasts as pockets. Moreover, the southward coastal current is observed from the marked upslope of the isotherms and isopycnals. Hence, from such observations it may be inferred that upwelling along the west coast occurs during the active period of the monsoon. In fact, some authors have already reported this phenomenon (Sewell, 1937; Rama Sastry and Myrland, 1959). From the present investigations the northern limit of upwelling at 15°N as already inferred is extended further northward upto 17°N. The varied nature of the thermal field observed during the present investigations along the coast indicates that the intensity of upwelling differs from time to time and as Rama Sastry and Myrland (1959) has reported the intensity again varies along the different areas of the coast and from year to year. The upwelled water being rich in nutrients, can fertilize the waters in the upper layers after oxygenation by wind and wave action, thus subsequently making it a pasture ground for zooplankton, fish larvae and herbivorous fishes followed by a rich fishery. Hence, the intensity and duration of upwelling along the coast is of considerable importance in determining the subsequent fishery. As a direct effect of upwelling the demersal and pelagic fishes may migrate either towards the coastal waters or to offshore waters outside the upwelling zone and the pelagic species may also congregate in the surface waters.

An important factor to which the authors wish to draw attention is the probable cause of upwelling along the coast. The study of winds along the coast revealed that the maximum frequency was for the winds from the west. The frequency of the north, north-northwest, northwest and west-northwest components amount to slightly greater than that of the westerly winds. In the present case the coast is oriented northwest-southeast and the westerly wind can transport waters in a direction parallel to the coast and thus produce a current system. Other components of the winds which are mostly parallel to the coast can promote upwelling (Defant, 1961). Varadachari (1961) when discussing the process of upwelling and sinking along the east coast of India has stated that the currents that flow along the coast are more responsible for the above said phenomenon along that coast. An overall clockwise coastal circulation is also present in the Arabian Sea during the monsoon, which will be parallel to the west coast of India and could promote upwelling.

In this connection a reference to the work of Varadachari and Sharma (1964) on the vergence field in the north Indian Ocean is pertinent here. These authors from mathematical considerations and direct measurements of sea surface currents availed from ships, have demarcated the divergence and convergence zones in the north Indian Ocean. According to them, the monsoon months (June, July and August) are the months of intense divergence of surface currents in the north Indian Ocean, and in the region Cochin-Karwar they have indicated a large divergence zone during the monsoon. Divergence associated with surface waters can give rise to upwelling and further the diverging pattern of the isotherms over the continental slope around 200-300 m (as found in the present case) can also promote upwelling. As there is a southward flow during the season, to restore the balance, a sub-surface northward one also may develop. The intensity of the surface current depends upon the wind field, and the divergence field created by these oppositely moving currents can give rise to upwelling along this coast. Hence, it is inferred that these phenomena probably depend upon the intensity of the wind components, and these components act as a feeding mechanism for upwelling. Thus, the intensity of upwelling is found to be different along the different regions of the coast and the intensity in the same region may vary with time according to the changes in the wind field.

Reference may be made to Fig. 1 which represents the bathymetric chart of the depth of the convection layer (indicated roughly by the depth of the 2.0 ml/L of oxygen value). It may be noticed that the bottom of the convection layer has a remarkable upslope towards the coast. The maximum slope is in the region Karwar-Ratnagiri while in the region Cochin-Calicut also the slope is quite intense. This observation is an additional confirmation to the fact that upwelling prevails along this coast during monsoon. Due to upwelling the thermocline is as a whole lifted up especially in the shelf region, thus creating a slope in the isentropic surfaces which again facilitates the southward flow along this coast. This flow has the maximum intensity at the upper region of the thermocline as can be seen from the vertical sections.

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