*J. Mar. biol. Ass. India*, 1964, 7 (1): 150-168

# HYDROGRAPHY OF THE WEST COAST OF INDIA DURING THE PRE-MONSOON PERIOD OF THE YEAR 1962—PART 2: IN AND OFFSHORE WATERS OF THE KONKAN AND MALABAR COASTS*

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## INTRODUCTION

THE hydrographic conditions prevailing along the Maharashtra and southwest Saurashtra coasts during the pre-monsoon season of the year 1962, have already been published (Patil *et al.*, 1964). The present paper is a continuation of the same and describes the conditions off the central and southern parts of the west coast *viz.* the Konkan and Malabar coasts, and presents a pioneer survey of the region north of 13°N latitude along the west coast.

Ramamirtham and Jayaraman (1960) have shown that during December-February period there is present a northerly drift along the coast and associated with this drift is sinking of the offshore waters. This generally starts by late November, which is the transitional period between the post-monsoon and the actual sinking period. The main features observed during this period of sinking and the following summer months are discussed in detail in this paper with particular reference to latitudinal and meridional variations. During the latter half of the period of investigation, changes in the hydrographic conditions occur and the northerly drift mostly subsides. The latitudinal variation in salinity is quite conspicuous, but temperature variation is not so marked. In view of the fact that the data were collected within a long period (January-May), the horizontal sections are not satisfactorily synoptic and hence such discussions are not included in this paper.

The method of collection and analysis of data are essentially the same as those described in Part I of the series. The geographical locations of the hydrographic stations are given in Fig. 1.

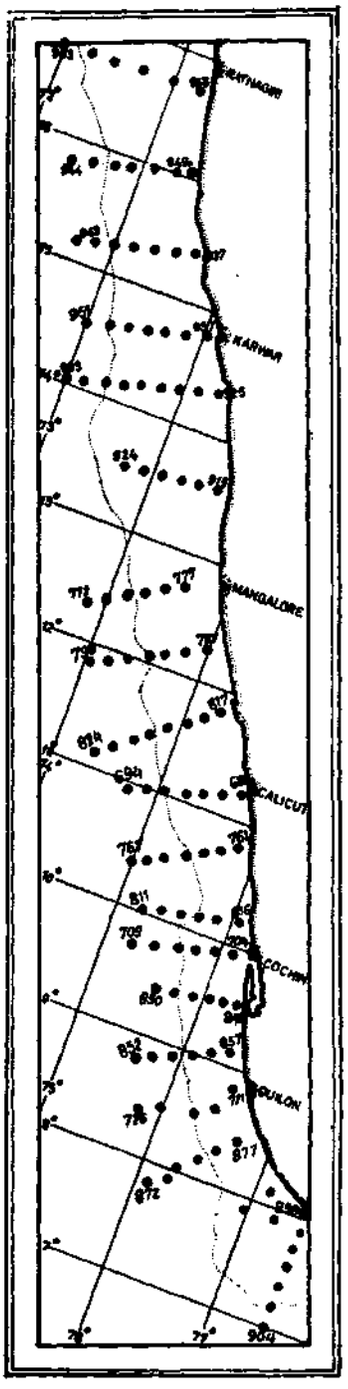


FIG. 1. Geographical positions of the hydrographic stations covered during the period of investigation.

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## Distribution of properties in the Vertical Plane

A. *Temperature :* In the section off Cape Comorin (Fig. 2A) temperature is found to increase off the coast. Near the edge of the shelf the distribution in the

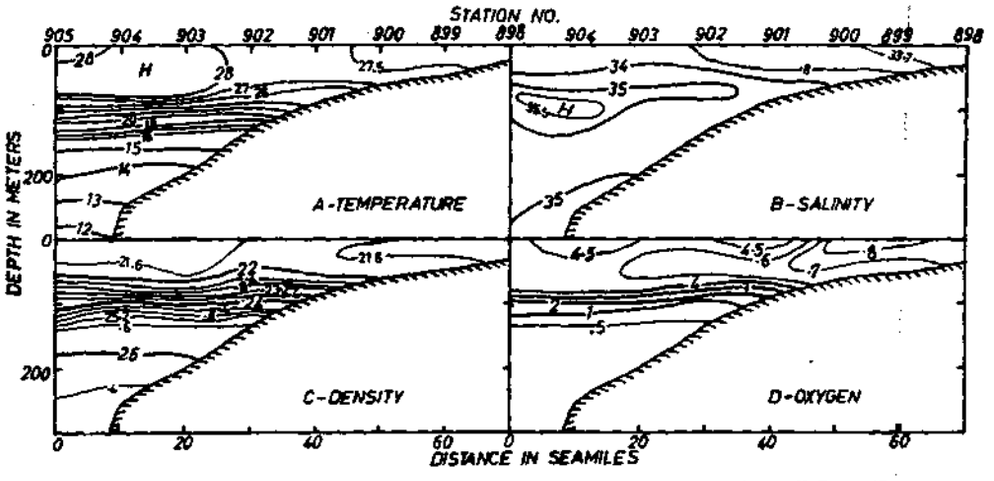


Fig. 2. Vertical distribution of oceanographic parameters in the section off Cape Comorin. Vertical exaggeration is 161 and is constant for all the sections.
H-higher values within the cell ; L-Lower values within the cell.

mixed layer is uniform as can be seen from the figure. The thermocline starts at a depth of 75 meters. The thermal gradient appears to be quite sharp. The trend of the isotherms indicate a more or less stable environment with weak easterly drift near the coast. Further northwest, off Trivandrum (Fig. 3A) the waters in the mixed layer are found to be warmer than the southern section and the coastal temperature is greater by nearly 1.5°C. Within the discontinuity layer the movement is restricted again, but the isotherms in the convection layer show slight shoreward upslope. Below the thermocline the vertical stratification as far as temperature is concerned is quite strong, as can be seen from the figure.

With a high temperature cell confined to the mixed layer, the waters in the section off Quilon (Fig. 4A) are warmer and the thermocline is quite strong. Two layered nature in the thermocline is noticed and the isotherms in these layers are nearly level showing a more or less uniform distribution in the horizontal. Similar features prevail off Kayamkulam (Fig. 5A), where the depth is shallow and the deep water observations are not available. Quite uniform conditions exist in the mixed layer and the waters are quite stagnant. Still the two layered nature of the discontinuity layer is perceptible. Off Alleppey (Fig. 6A) cell formations in the temperature structure are again evident. More or less similar features prevail just like the southern section. The month being February (mostly late sinking or transition period) sinking of the offshore waters is not so conspicuous.

During the month of January, off Cochin slight indications of sinking are seen but sloping of the isotherms are not at all sharp. A shoreward decrease in temperature is noticed and over the shelf, it can be inferred that isothermal features prevail. Within the discontinuity layer minimum lateral transport is observed and sinking is not at all perceptible. A strong anticyclonic eddy at about 250 meters

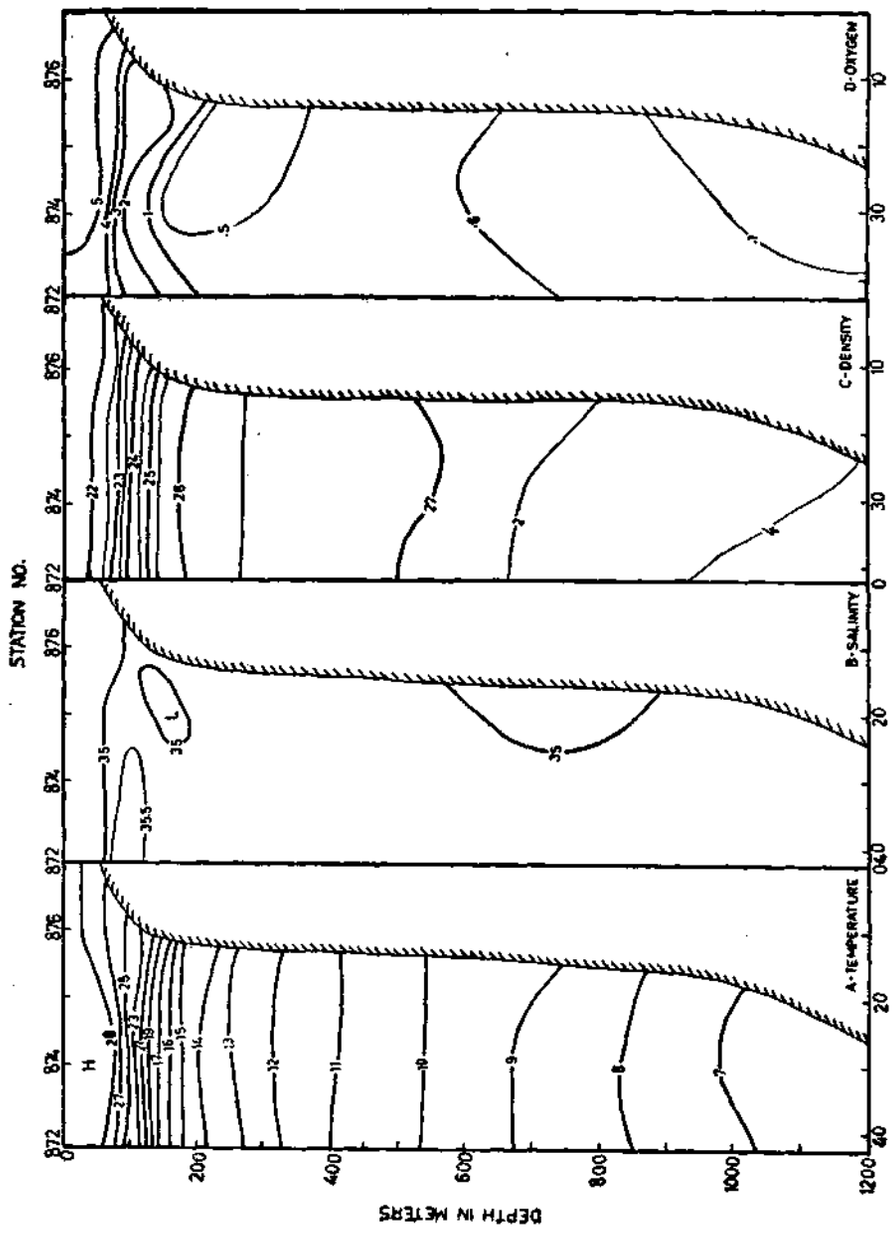


FIG. 3. Vertical distribution of oceanographic parameters in the section off Trivandrum.

is found off Cranganore (Fig. 8A), during middle February. A tongue of high temperature is found to extend eastwards in the mixed layer, and the discontinuity layer is not so well defined as the southern sections. In the upper regions of the eddy

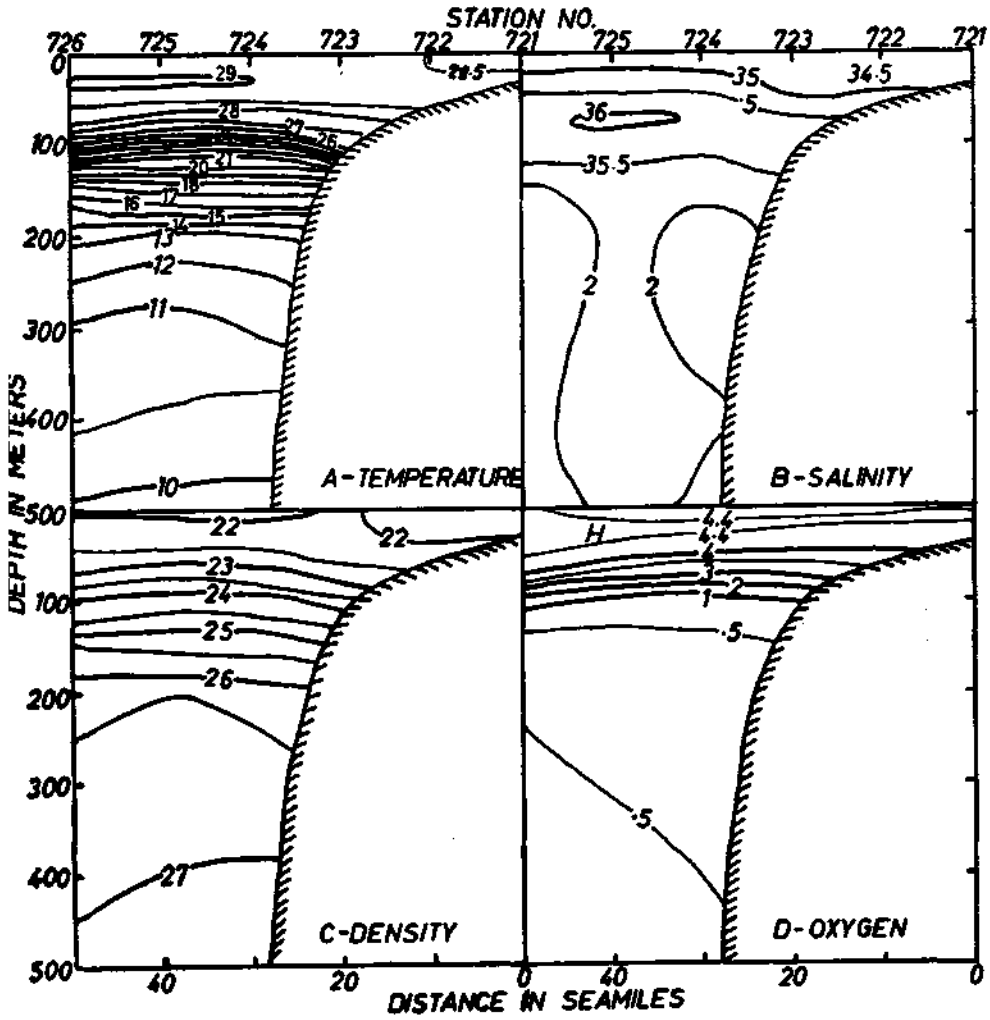


FIG. 4. Vertical distribution of oceanographic parameters in the section off Quilon.

this dissipation of the thermocline is more, and the vertical thermal gradient is much weaker than the lower regions. Such sloping of the isotherms is seen in the deeper layers also, and in this section too, mostly isothermal features exist over the shelf.

Proceeding north, in the section off Ponnani (Fig. 9A), such an eddy is absent and upto about 100 m. from the surface downwards, mostly isothermal features prevail again. The section was investigated during the transition period from winter to summer (early February) and the associated stagnant conditions are again visible in the section. Over the shelf indications of sinking are found in the section off

Calicut during early January (Fig. 10A), but in the offshore region a high temperature cell is formed. The thermocline is quite strong and stagnant, and between 200-300 m. the two layered nature of the thermocline is quite evident.

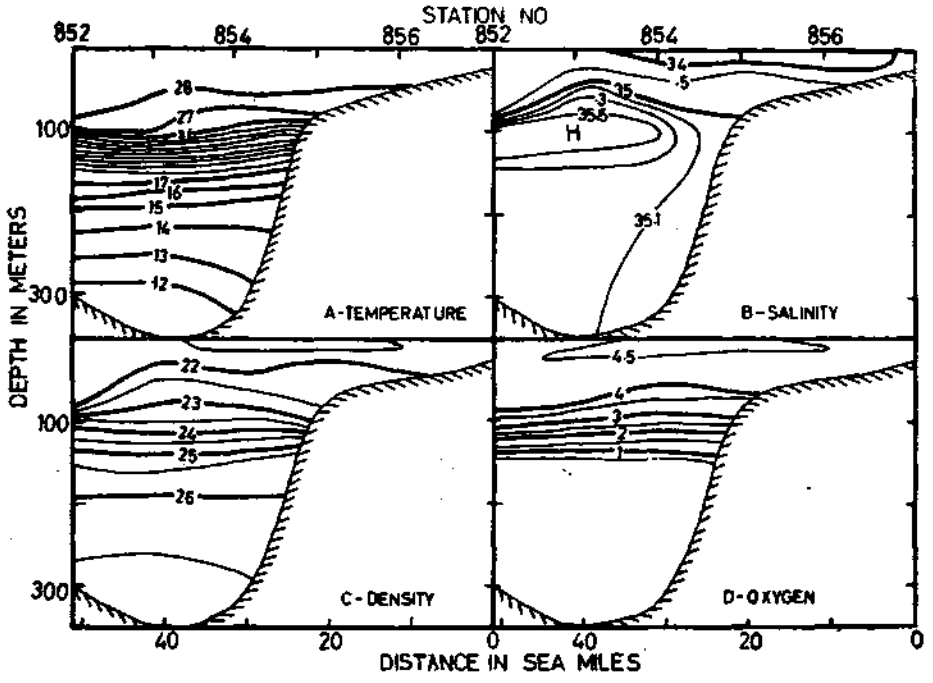


FIG. 5. Vertical distribution of oceanographic parameters in the section off Kayamkulam.

But quite dissimilar features are noticed in the region off Cannanore (Fig. 11A) during middle of February. Being late transition period sinking is absent and the upper 100 m. column is mostly isothermal. Two layered nature of the thermocline is evident and strong influence of internal waves is found within the thermocline. Reference may be made here to the Cranganore section where a strong anticyclonic eddy is encountered. During earlier investigations also such influence of internal waves has been noticed in the regions off Cranganore, Calicut and Cannanore. But the observations were not so synoptic as to draw any definite conclusions. Hourly B.T. observations in these regions have revealed existence of internal waves of amplitude of nearly 30-40 m. Such thermal features are totally absent further north off Bekal (Fig. 12A). Although the period of investigation is not much different (again early February) the thermocline off Bekal is without any sort of marked vertical or horizontal movement. Hence the feature found off Cannanore can be concluded as a regional one, influenced by some sort of underwater disturbance. But in the mixed layer, although higher temperatures exist conditions follow the same trend as those off Cannanore. The thermocline dissipates below 200 mm.

During early February mostly, uniform temperature conditions exist over the whole of the mixed layer off Mangalore (Fig. 13A). A high temperature cell is formed in the offshore region and the thermal discontinuity starts at about 100 m. depth. The vertical extent of the thermocline is quite considerable, in which the thermal dissipation starts at about 200 m. and the two layered nature of the thermo-

cline is observed. The region off Coondapur (Fig. 14A) was investigated during late March (summer season) and only shelf observations were available. High temperatures occur uniformly over the whole of the shelf, highest being observed near the coast.

A peculiarity in thermal structure is observed off Honavar (Fig. 15A). In this section although high temperatures occur very near the coast, outside the shelf the thermal discontinuity starts even at shallow depths such as 50 m. This section also was investigated during summer and conditions are comparable to those off Mangalore. The thermocline has further migrated upwards off Karwar (Fig. 16A) and the mixed layer is mostly obliterated in the offshore region, during early April. Over the shelf even, the vertical thermal gradient is perceptible and the isotherms exhibit slight sinking. This constitutes again a horizontal thermal gradient over the bottom of the shelf. Sinking over the shelf is again observed with weak intensity off Marmagoa, (Fig. 17A) and similar to Karwar the vertical temperature gradient starts even from the surface. But in both these sections (Off Karwar and Marmagoa) it is to be noted that the intense thermal gradients are confined to the region 100-200 m. This further divides the whole discontinuity layer into three layers, the uppermost being more stratified vertically than the lowermost one. Again it is to be remembered that this topmost discontinuity in temperature is not generally found in all the sections. Again, over the bottom of the shelf, horizontal temperature gradients develop. In both of these sections where the three layered nature of the thermocline is seen, the middle one is quite stratified within which the isotherms are mostly level.

Such thermal features have disappeared off Malvan (Fig. 18A) to a great extent, but even then the thermocline is found at comparatively shallower depths (at 50 m. or so) compared to the regions off Cannanore and south. In the lower region of the thermocline a weak northward drift is noticed and over the bottom of the shelf the horizontal temperature gradients have disappeared.

B. *Salinity :* During the period of investigation, throughout the area covered, there is found a salinity maximum mostly within the thermocline with a core of maximum salinity. Towards top and bottom of this maximum layer a gradient in salinity develops, the one towards top being much more intense than that towards the bottom. Within the mixed layer, in general, the salinities are low. A salinity transition zone at about 12-13°N. is noticed towards north of which the salinities increase rapidly.

Thus off Cape Comorin (Fig. 2B) the salinity maximum is found at about 100 m. depth, *i.e.* at the top of the temperature discontinuity layer. This maximum appears in the form of a tongue extending towards the coast. The surface salinities are lower than 34% and below 200 m. the salinity gradient is very weak. More or less similar features prevail off Trivandrum (Fig. 3B), but the salinities are a bit higher. In the deeper layers quite uniform distribution is evident from the figure. Off Quilon (Fig. 4B) salinity maximum is more well defined at the top of the thermocline. The low salinities are confined to the near coastal region. Below 200 m. marked uniformity in salinity distribution is noticed.

The tongue-like distribution of salinity is again noticed off Kayamkulam (Fig. 5B) and the core of maximum salinity coincides with the region where intense thermal gradients develop. The weak but regular ascendant is seen from surface downwards, and in the immediate surface layers the salinities are much low. In the

lower region of the thermocline uniformity in salinity distribution is again found. Comparable features are found off Alleppey (Fig. 6B) and in the deeper layers the

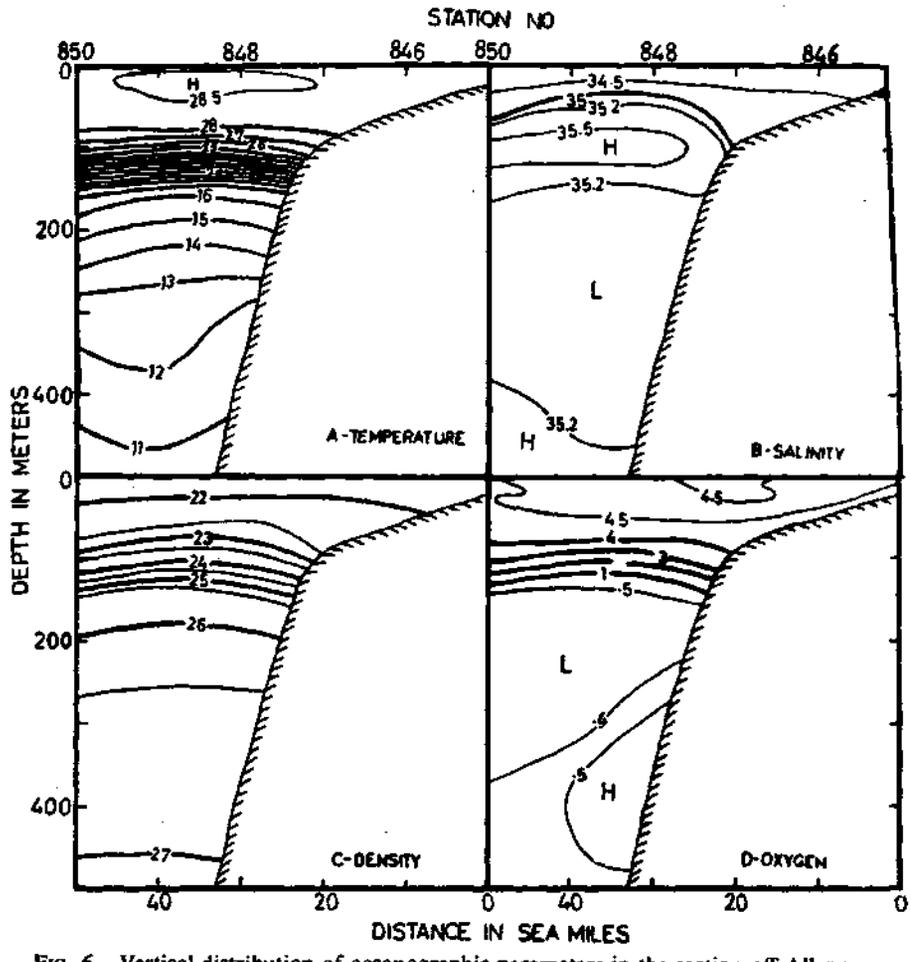


FIG. 6. Vertical distribution of oceanographic parameters in the section off Alleppey.

salinities are a bit higher than the preceding sections. With an indication of sinking of isohalines over the shelf the coastal salinities are again low in the region off Cochin (Fig. 7B). No major changes are noted in the distribution pattern from the sections further south of this. In the region off Cranganore where an anticyclonic eddy is developed within the thermocline, the salinity maximum zone is also well developed. In the mixed layer again a uniformity in the distribution is found (Fig. 8B), from the nature of the two 34.5‰ isohalines. Between 200 and 1200 m. mostly isohaline conditions are encountered with.

Such a pattern is not evident off Ponnani (Fig. 9B) where again a tongue of high salinity is found to extend towards the coast. Being early February sinking of the isohalines over the shelf is also not perceptible. Off Calicut (Fig. 10B) the maximum zone is not so conspicuous, but off Cannanore (Fig. 11B) during middle

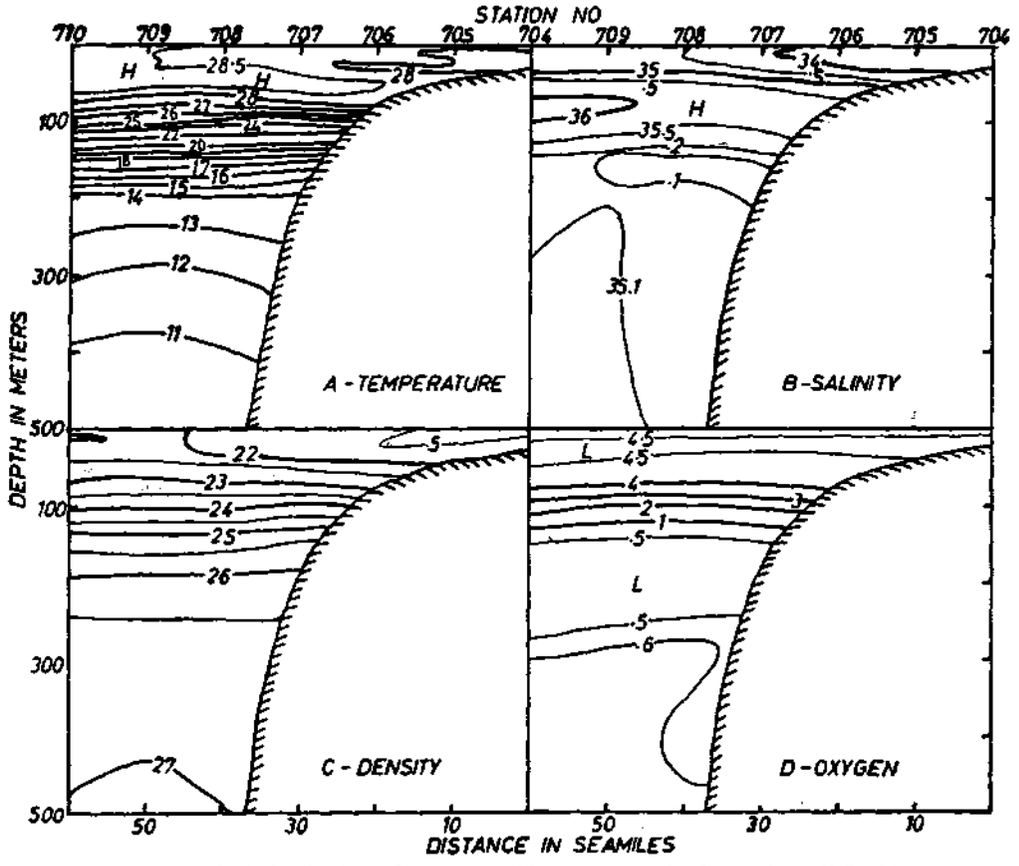


FIG. 7. Vertical distribution of oceanographic parameters in the section off Cochin.

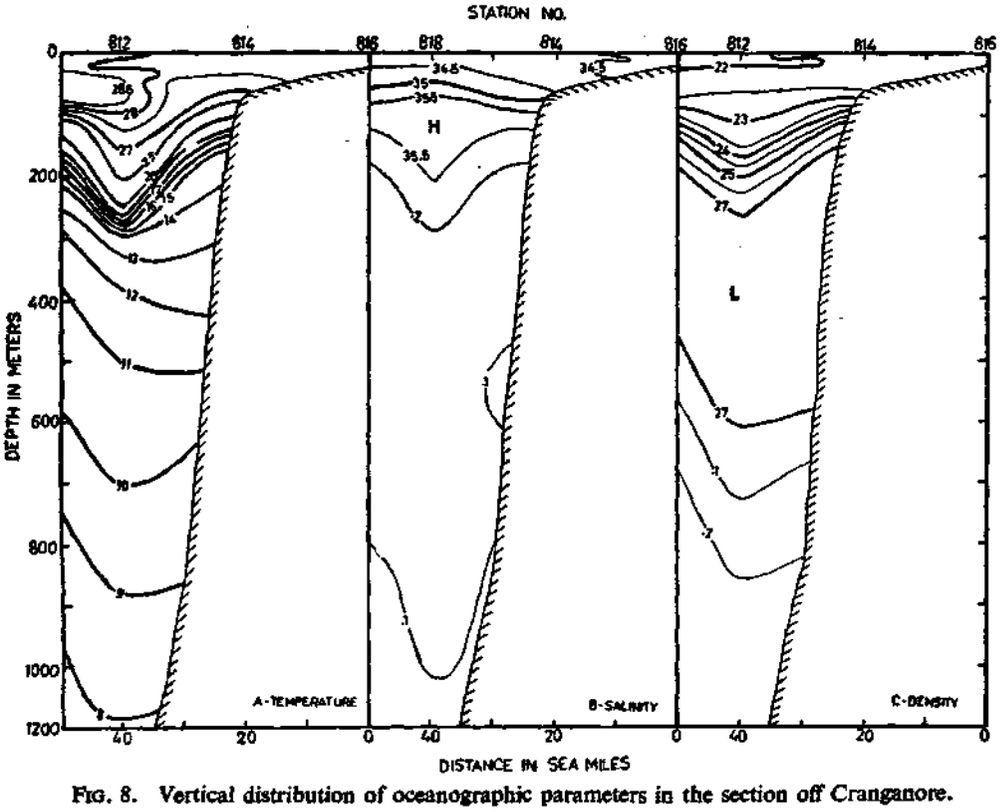


FIG. 8. Vertical distribution of oceanographic parameters in the section off Cranganore.

of February an intense salinity maximum has developed within the temperature discontinuity layer. The salinity gradient in the lower region of the thermocline,

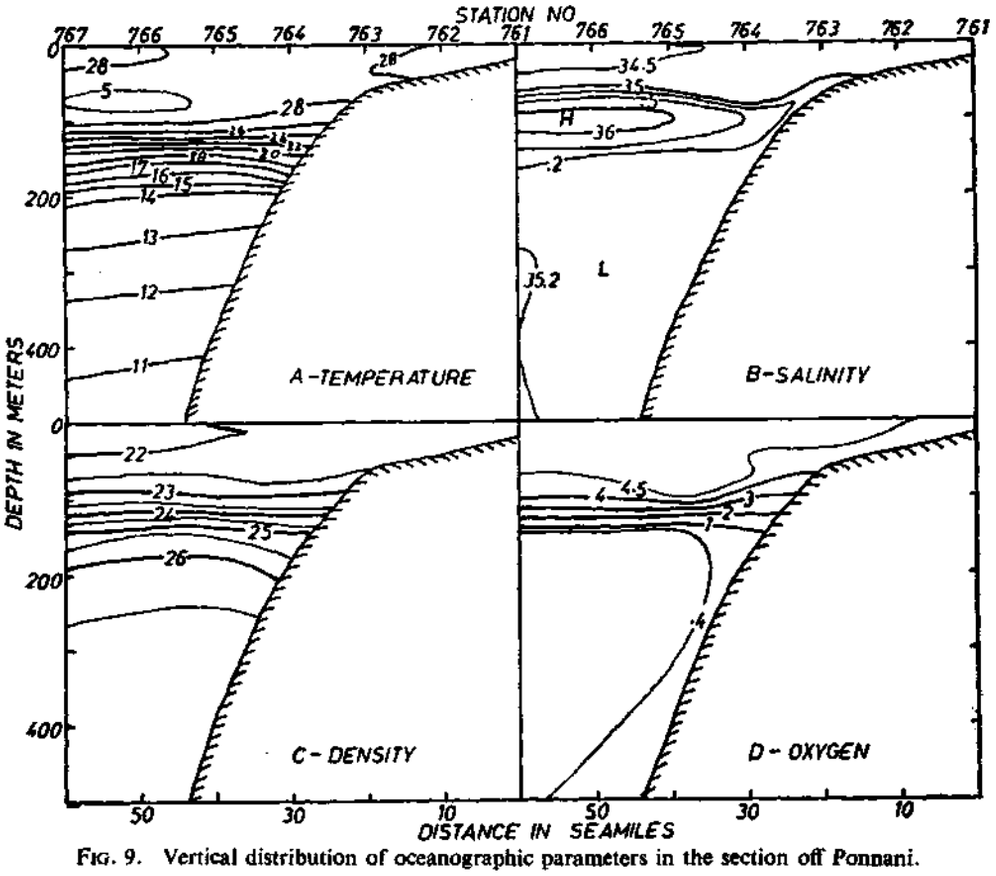


FIG. 9. Vertical distribution of oceanographic parameters in the section off Ponnani.

and the ascendant in the mixed layer are again noticed, but the two low saline cells indicate more or less uniform distribution pattern in the immediate surface layers, upto 10-20 m. depth. As a whole the top low saline layer coincides with the isothermal layer found above the thermocline. With a more pronounced salinity maximum, conditions in the section off Bekal (Fig. 12B) are comparable to that off Cannanore, during early February. But there is a trend for the salinities to increase in the deeper layers. This probably is a zonal characteristic.

An increase is found in the salinity values in the section off Mangalore (Fig. 13B). Even at surface, values as high as 35.2‰ occur at some of the stations. The vertical extent of the high salinity zone is found between 50 and 200 m. depths. This marked increase in the salinity values occur at about 13°N. which can primarily be taken as a transition region in salinity. This further divides the whole of the west coast into two regions from Cape Comorin to Ratnagiri, a third zone probably being north of Ratnagiri in the northern Arabian Sea. With still higher salinities within the shelf the distribution in the section off Coondapur (Fig. 14B) is more or less uniform during summer, but off Honavar (Fig. 15B) slight indication

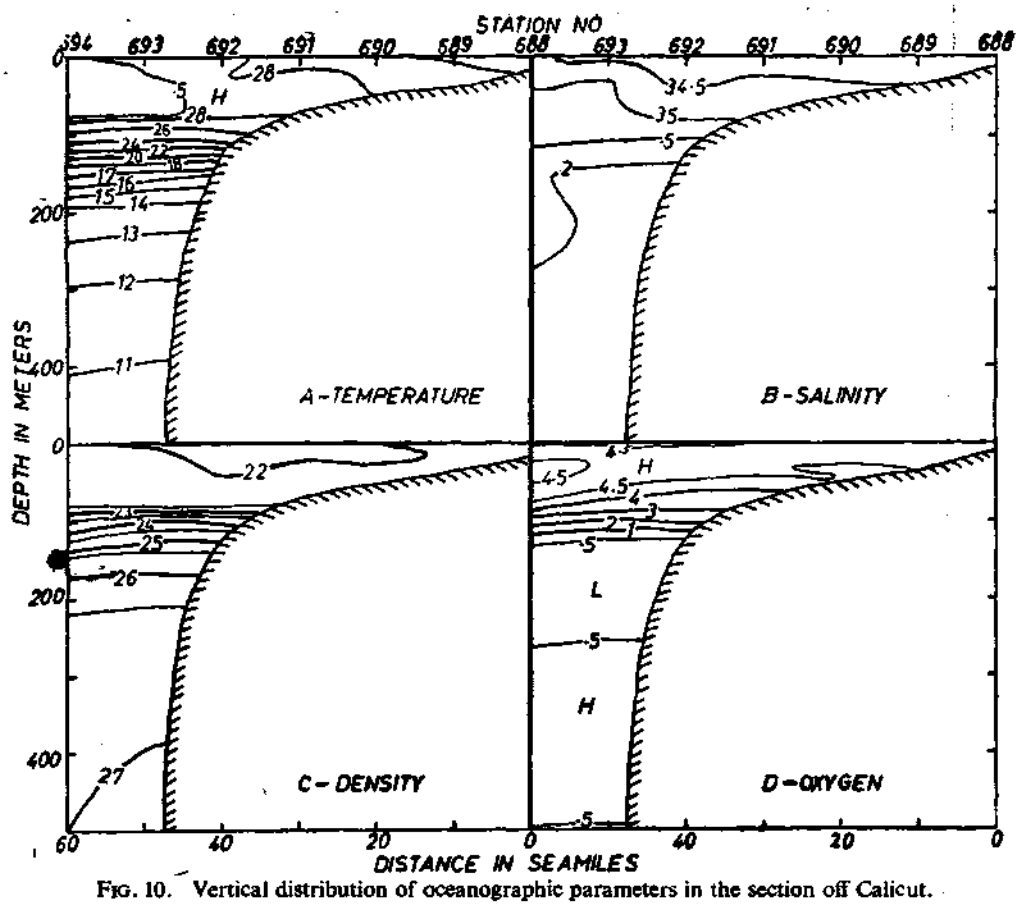


FIG. 10. Vertical distribution of oceanographic parameters in the section off Calicut.

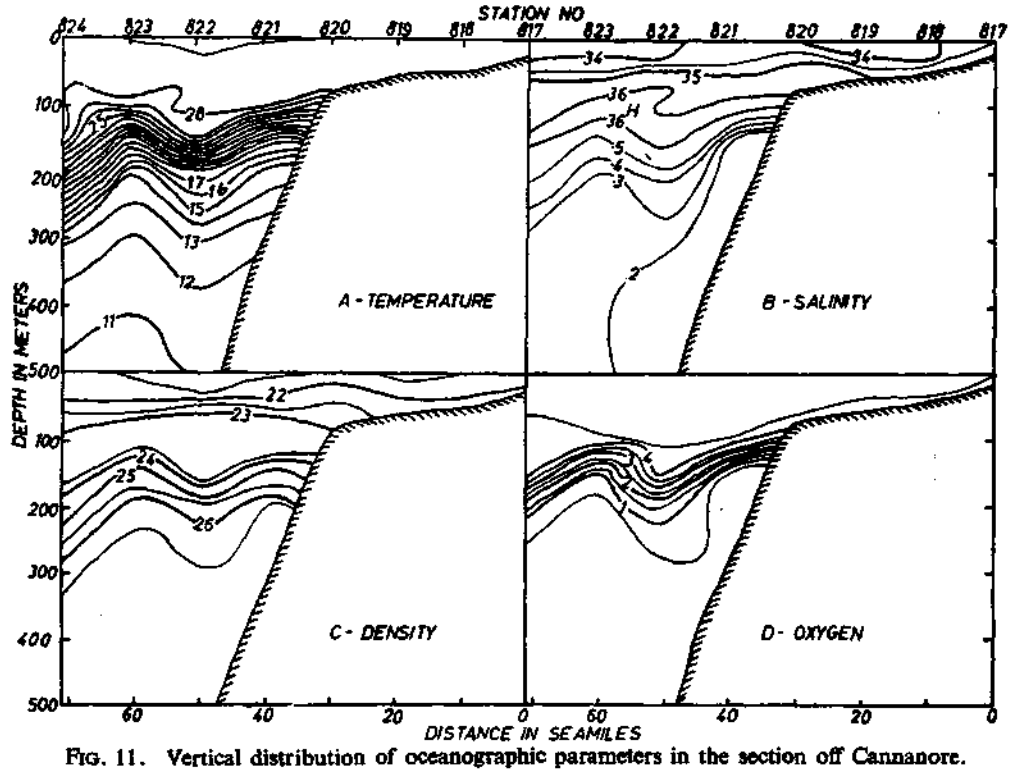


FIG. 11. Vertical distribution of oceanographic parameters in the section off Cannanore.

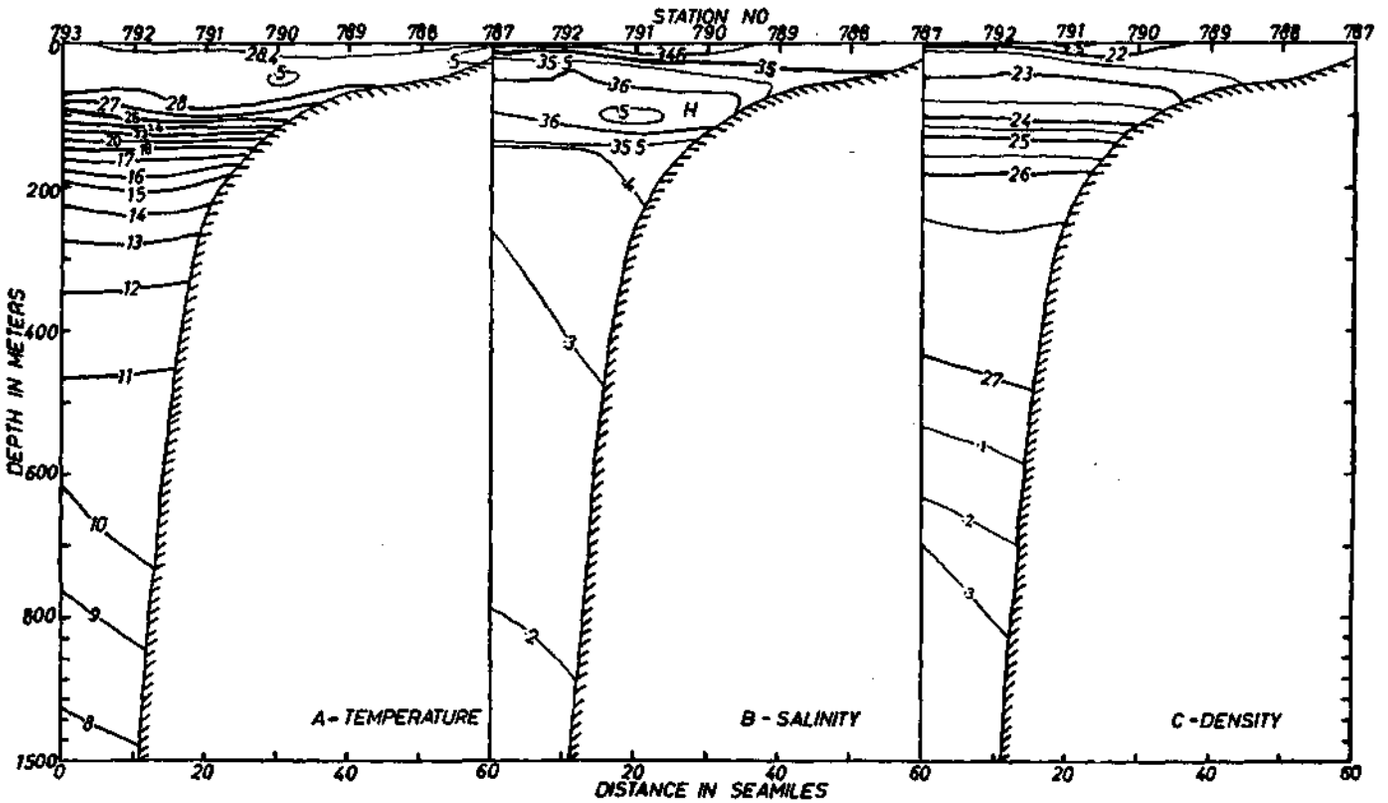


FIG. 12. Vertical distribution of oceanographic parameters in the section off Bekal.

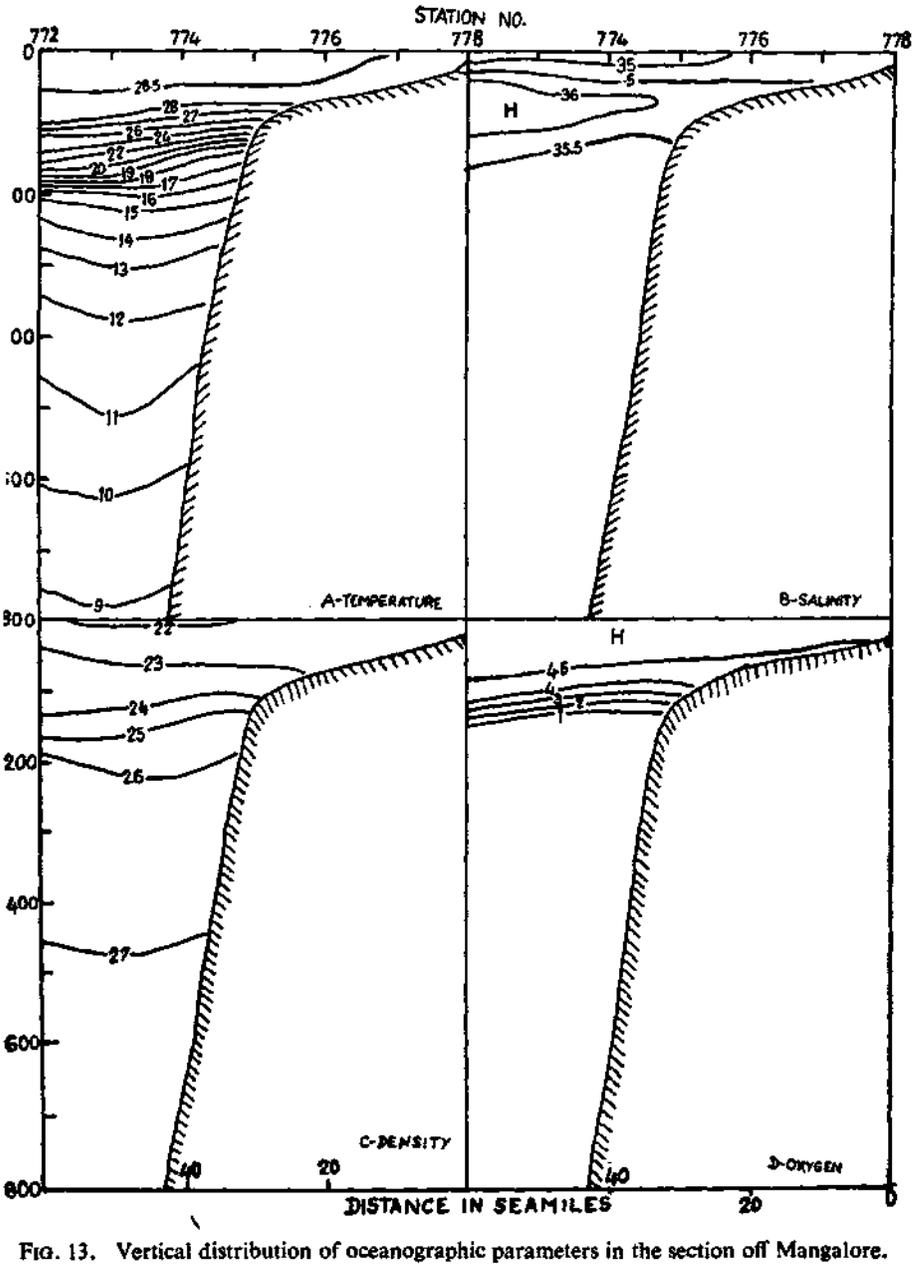


FIG. 13. Vertical distribution of oceanographic parameters in the section off Mangalore.

of sinking is noticed. The salinity maximum zone is well pronounced and corresponds to the upper region of the thermocline which is found at shallower depths compared to the sections further south. In the deeper layers too, values well above

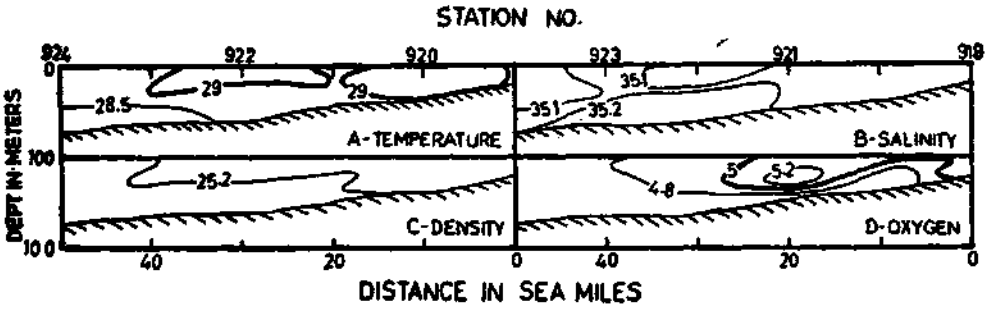


FIG. 14. Vertical distribution of oceanographic parameters in the section off Coondapur.

35.2‰ were encountered. Comparable features are found off Karwar (Fig. 16B) where the thermocline is found at shallower depths. Off Marmagoa (Fig. 17B) with indications of sinking of offshore waters over the shelf, the salinity maximum zone has migrated even upto the surface in the offshore regions, similar to the temperature discontinuity layer. The salinity maximum is much more intense than the sections farther south. The section according to the regional definition lies in the high saline zone. In this section, a marked gradient in salinity is found in the region where the temperature gradient is maximum, unlike the southern sections (sections south of 13°N.) where a maximum is found within the thermocline, and not a gradient. Off Malvan also (Fig. 18B) more or less the same features exist and as is the case when proceeding north, the salinities are gradually increasing. Even at deeper depths of 500-600 m. salinities as high as 35.4‰ occur as seen from the figure.

*C. Density (Sigma-T) :* As is to be expected, the distribution of density in the vertical plane is closely resembling that of temperature. Movements in a direction perpendicular to the vertical sections are not considerable especially in the region south of Calicut. In the regions where internal waves develop eddy formations can be inferred, which feature as explained, is well pronounced off Cranganore. In the northern regions, (north of Mangalore) where sinking is perceptible to a certain extent, a northerly drift is encountered over the shelf.

Thus off Cape Comorin (Fig. 2C) within the thermocline the isopycnals are mostly horizontal and the resultant drifts are very weak. The vertical stratification is quite pronounced within the pycnocline and over the mixed layer uniform distribution prevails. Comparable conditions exist off Trivandrum (Fig. 3C), but the two layered nature of the thermocline is not evident in the pycnocline. The vertical stratification extends only upto 200 m. below which the ascendant in density is very weak. Movements as a rule are highly restricted. Similar features prevail off Quilon, Kayankulam and Alleppey (Figs. 4C, 5C, 6C). Off Cochin (Fig. 7C) slight sinking of the isopycnals is noticed over the shelf, which can constitute a weak northerly drift. In conformity with the intense horizontal temperature gradient found at about 250 m., in the section off Cranganore the distribution of density further confirms the presence of the anticyclonic eddy. Except for this, lateral transports are minimum. But off Ponnani (Fig. 9C) such features

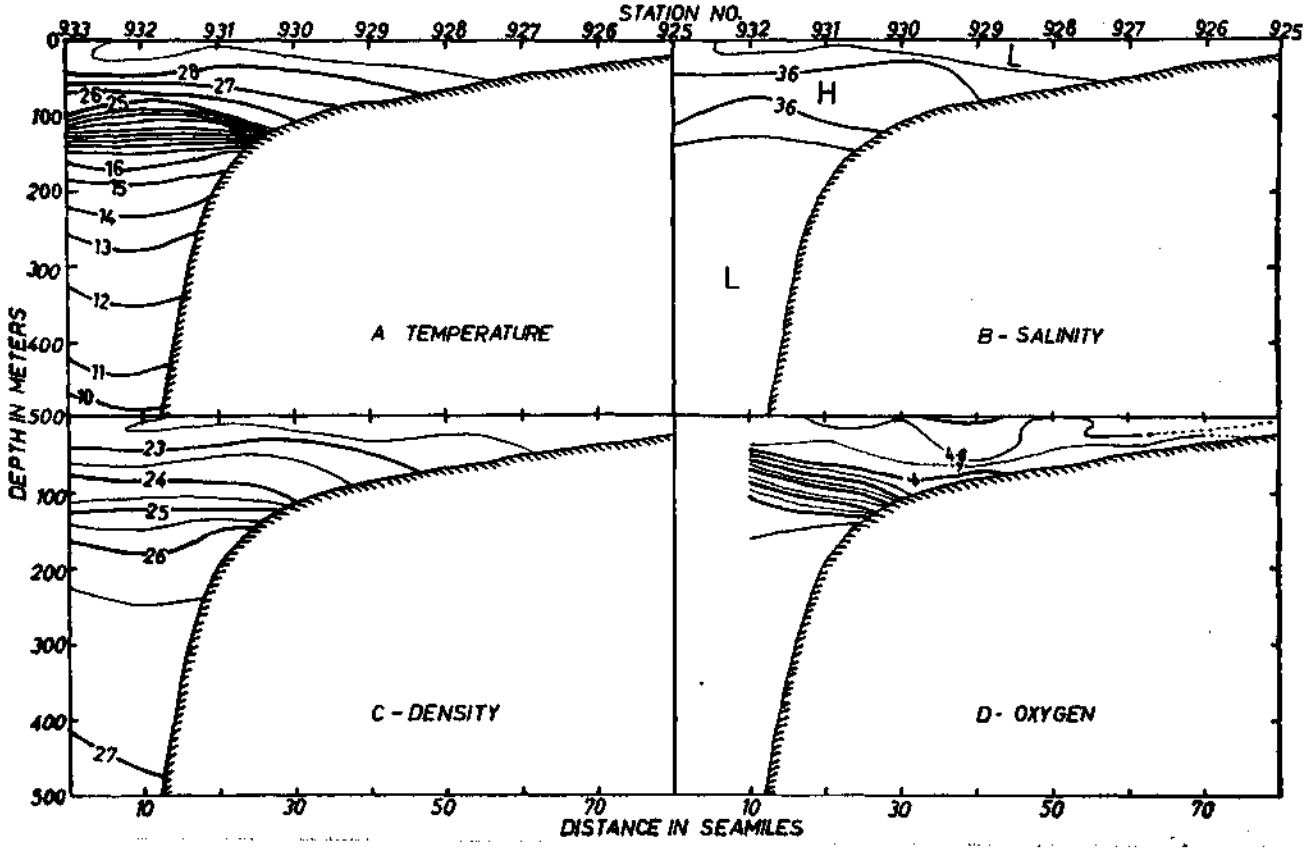


FIG. 15. Vertical distribution of oceanographic parameters in the section off Honavar.

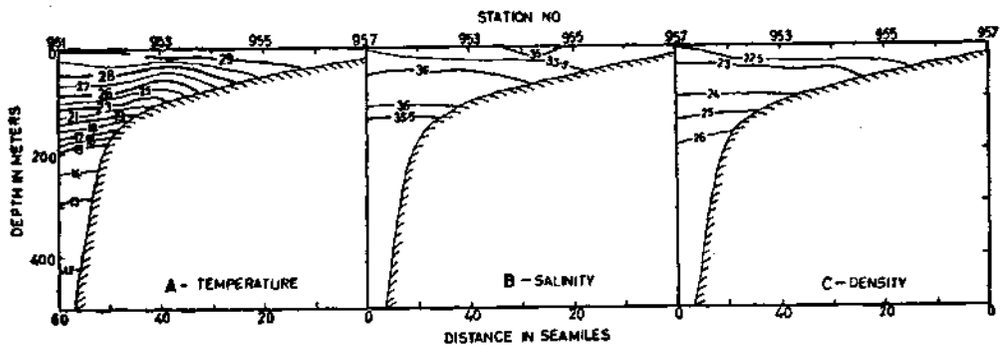


FIG. 16. Vertical distribution of oceanographic parameters in the section off Karwar.

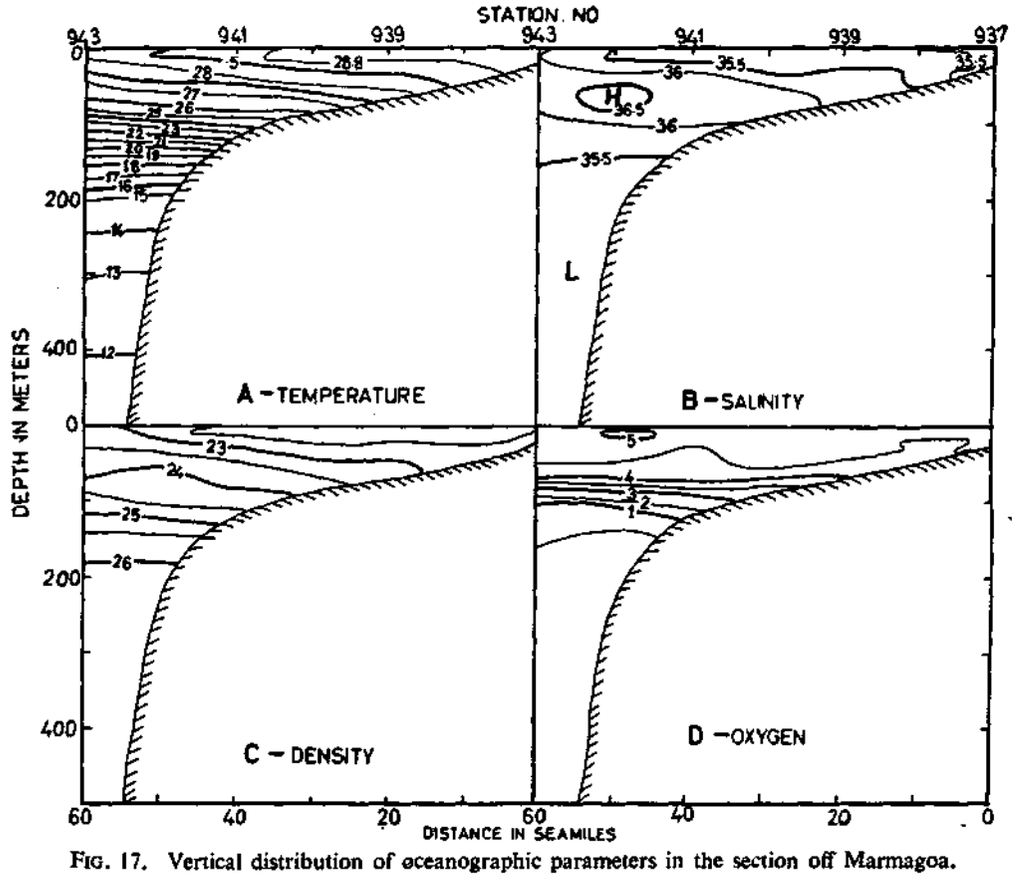


FIG. 17. Vertical distribution of oceanographic parameters in the section off Marmagoa.

are completely obliterated during early February, and stratified conditions are again perceptible. Off Calicut (Fig. 10C) similar conditions prevail, but in the region off Cannanore (Fig. 11C) although in the surface layer lateral drifts are restricted, in the region of the pycnocline wavy nature of the isopycnals are noticed suggesting formation of eddies. Again the reason probably is the influence of the internal waves which appear in the distribution patterns. Such features are not prevalent off Bekal during early February (Fig. 12C) wherein the region upto about 200 m. lateral drifts are highly restricted. Comparable features prevail off Mangalore (Fig. 13C) and a weak northerly drift is found within the pycnocline.

Uniform conditions exist in the region off Coondapur (Fig. 14C) but in the region off Honavar (Fig. 15C) sinking of the isopycnals over the continental shelf is observed during summer. Weak northerly drift are noted over the bottom of the shelf. Off Karwar the downward density ascendant starts even from the surface during early April (Fig. 16C) and, sinking and consequent northerly drift are noted over the shelf. Quite stratified conditions are noticed in the region where strong thermal gradients develop. Sinking is more pronounced off Marmagoa (Fig. 17C) and over the whole of shelf the northward drift is conspicuous. It is to be noted that this northward drift in the preceding three sections is confined mostly to the upper region of the thermocline and it has already been indicated that in these sections a three layered structure of the thermocline is observed. Within the middle region where the temperature gradient is maximum, the drifts are not so pronounced, and it is to be inferred that the surface convergence produces this northward drift. Similar to the isotherms the isopycnals also slope below 200 m.

D. *Dissolved oxygen :* In general, in the mixed layer, the waters are nearly 80% saturated with respect to dissolved oxygen, and near the coast values as high as 4.8 m.l./L. have been noted. A rapid decrease occurs within the temperature discontinuity layer and below 150 m. depth the values are never greater than 1.0 ml/L.

Thus in the sections off Cape Comorin, Quilon and Trivandrum (Figs. 2D, 3D and 4D) high values of oxygen are found in the mixed layer with the expected strong gradient within the thermocline. Off Quilon a large column of nearly 200 m. thickness contains very little oxygen which feature is usual in the particular season. Similar features are observed in the region off Kayamkulam, Alleppey and Cochin (Figs. 5D, 6D, and 7D). Off Alleppey below the oxygen deficit layer, over the continental slope a high oxygen cell is developed and off Cochin in the lower region of the thermocline the oxygen minimum layer is quite conspicuous. Off Ponnani (Fig. 9D) the vertical extent of oxygen minimum layer has widened upto even 500 m. depth.

Similar to the section off Alleppey, there is found, a high oxygen zone below the oxygen minimum layer in the region off Calicut too (Fig. 10D). With high values in the mixed layer the pattern of the distribution upto 200 m. is quite comparable to the previous sections. Off Cannanore during middle of February the effect of internal waves as indicated earlier, is found in the oxygen distribution also (Fig. 11D), the oxygen isolines showing wavy nature.

In the region off Mangalore, features are again comparable and proceeding further north, off Coondapur (Fig. 14D) the oxygen values over the continental shelf have increased much, as is evident from the figure. Such high values are found in the sections off Honavar and Marmagoa also. This increase in the oyxgen

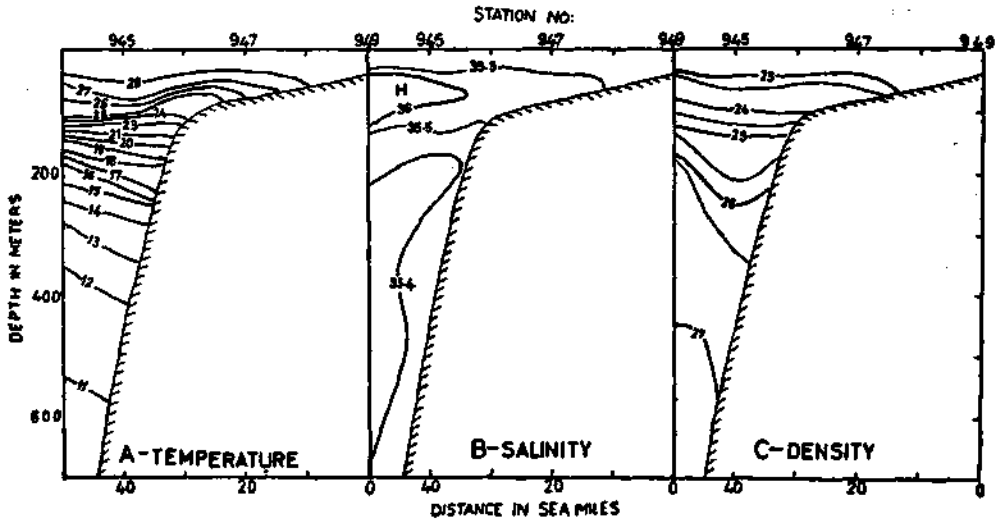


FIG. 18. Vertical distribution of oceanographic parameters in the section off Malvan.

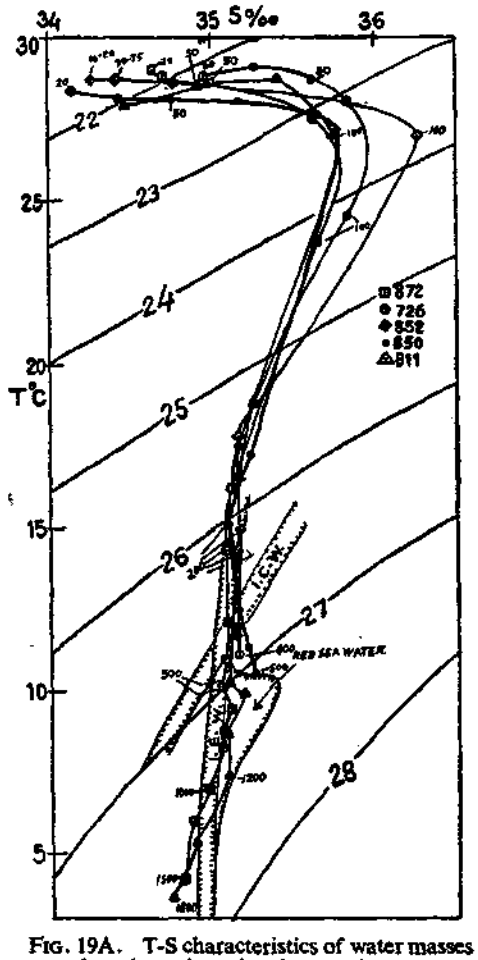


FIG. 19A. T-S characteristics of water masses at selected stations in the southern zone.

values correspond to the increased salinity values in these regions, mentioned earlier in the text.

E. *Water mass characteristics along the west coast during the premonsoon season :* In discussing the water mass characteristics, as mentioned earlier the whole region has been divided into three zones arbitrarily viz. southern zone (south of 10°N), middle zone (between 10 and 13°N) and northern zone (north of 13°N). This has been done taking into consideration the salinity transitions occurring at

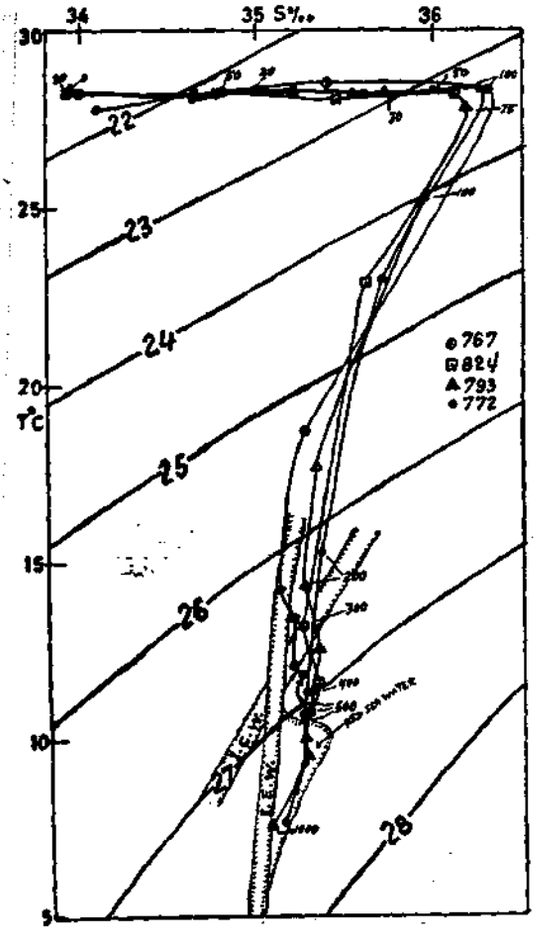


FIG. 19B. T-S characteristics of water masses in the middle zone. Inserted characteristics of the Indian Equatorial water, Indian Central water, and mixed Red Sea water are taken from Sverdrup's (1961) definitions.

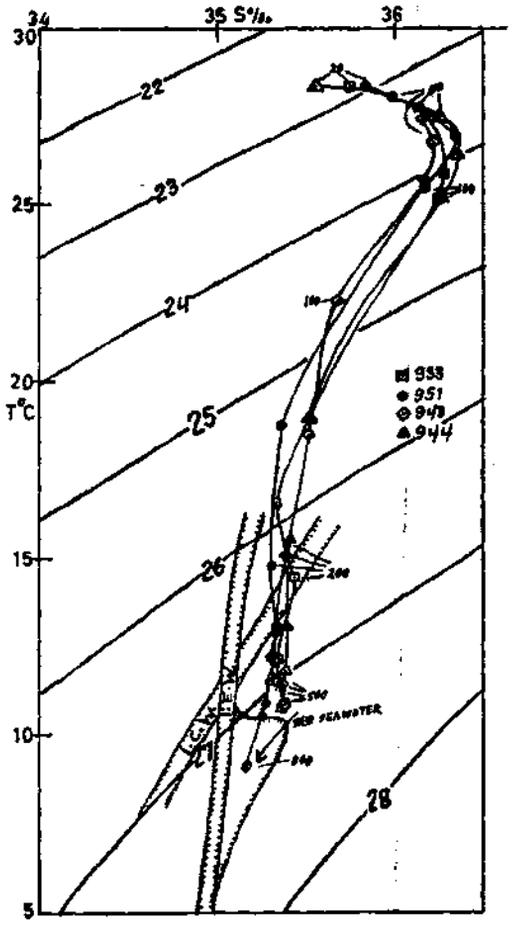


FIG. 19C. T-S characteristics of water masses in the northern zone.

10°N and 13°N latitudes. But these characteristics are mostly applicable to the upper layers, the change in salinity values in the deeper layers with latitude being much less than the upper layers above 200 m.

Thus in the southern zone three distinct water masses can be seen as suggested earlier by Ramasastry (1959) viz. Arabian Sea upper subsurface water,

with a wide salinity range (34-36‰) and a comparatively small temperature range (27-29°C), Arabian Sea lower subsurface water, with a wide temperature range (17-27°C) and a small salinity range (35.6-36. 2‰) and the deeper water mass with a very small salinity range and a very wide temperature range (Fig. 19A). The salinity maximum found during the premonsoon period along the west coast is attributed as a probable cause for the distinction between the upper water masses. In the diagram the density ranges (in terms of sigma-T) are also given and the depths of observations are also indicated. The influence of the mixed Red Sea water on the deeper Indian Equatorial Water, is also marked in the diagram.

Proceeding north, in the middle zone the temperature range of the upper subsurface water is still further reduced and as a whole the salinity ranges of the two deeper water masses have increased. This probably is due to the salinity transition occurring just north of 10°N. But thermal features of the water masses are comparable to those in the southern zone. Although there is good comparison between the two deep water masses in the middle and northern zones, the characteristics of the upper subsurface water have changed much in the northern zone. Due to the marked salinity transition at 13°N. the salinity range of the upper subsurface water has decreased much, the salinities being much higher (Fig. 19C). The density range is also narrowed down to 23-24 Sigma-T and as indicated in the earlier text the salinity in the deeper layers also has increased.

## Summary

The hydrographic features prevailing along the west coast from Cape Comorin to Ratnagiri during the premonsoon period are discussed. Due to the time lag occurred during the period of investigation no lateral distribution studies have been made. During the period early March-early April weak sinking phenomenon was noticed in the northernmost region (14-17°N.) and northerly movement is perceptible. The latitudinal variation in salinity is marked and the influence of this on the water mass characteristics has been discussed. Two layered nature of the thermocline is noted in general, and wherever sinking is noticed a three layered nature is also evident. In general, the continental shelf waters are highly oxygenated and north of 13°N. even 90% saturation is noted. The oxygen minimum layer started at the top of the thermocline and the oxygen deficit layer is uniformly found along the entire west coast.

## Acknowledgements

The authors wish to express their thanks to Dr. S. Jones for his keen interest in these investigations, and to Dr. R. Raghu Prasad for encouragement during the course of the work. The help rendered by the colleagues of the Central Marine Fisheries Research Institute during the cruises is gratefully acknowledged.

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