DISTRIBUTION OF TEMPERATURE, SALINITY AND DENSITY IN THE ARABIAN SEA ALONG THE SOUTH MALABAR COAST (SOUTH INDIA) DURING THE POST-MONSOON SEASON

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1. INTRODUCTION

PHYSICAL oceanographic investigations form an important part of an integrated marine fisheries research programme. The Central Marine Fisheries Research Station in co-operation with the Indo-Norwegian Project has initiated a detailed oceanographic programme during the year 1957–58 in the waters off the Kerala Coast in order to obtain a detailed knowledge of the various Physical Oceanographic parameters in the Arabian Sea and their possible variations- both in time and space.

The purpose of this paper is to present in a detailed way, the distributions of temperature, salinity, density and the resultant circulation in the Arabian Sea off the coast of India between Cochin and Cape Comorin, immediately after the South-West Monsoon. Studies on the formation and identification of the water masses in the Arabian Sea together with the dynamical computations for gradient currents, mass, salt and energy transports are under progress and will be presented in subsequent publications.

2. COLLECTION AND TREATMENT OF DATA

The general observational programme is to collect the subsurface samples of water using Nansen and Ekman type of reversing bottles carrying deep sea reversing thermometers to obtain the temperature of each sample *in situ*, at all international depths up to 500 m., *viz.*, 10 m., 20 m., 30 m., 50 m., 75 m., 100 m., 150 m., 200 m., 300 m., 400 m. and 500 m. The surface

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samples were collected with a bucket and the temperature was immediately measured with a sensitive thermometer in shade.

The station closest to the shore will be on 10 fm. line; and the line of stations was arranged to be on parallels. Over the continental shelf, which in general along the west coast of India is marked by the 100 fm. line, the stations were spaced 5 miles apart and beyond the continental shelf the stations were spaced 10 miles apart and such deep sea stations were at least two in number in each section. The distance between sections varies from 10-15 miles. In all 82 stations spread over 8 latitudinal sections and one oblique section off Cape Comorin were used in this present investigation. The positions of stations are given in the chart showing surface currents (Fig. 28 B) and thus the area represented is between 7°-10° N. and 75°-77° 30' E.

The corrections to be applied for temperature recorded by reversing thermometers, to obtain the temperature *in situ*, were read from the special nomograms constructed for each thermometer for the purpose. However, unprotected thermometers were not used to calculate the thermometric depths; but the ship, "R. V. M. O. Kristensen" which was used for collecting these data, was manœuvred in such a way that the hydrographic wire carrying the reversing bottles was always vertical. Thus the depths of reversal were read from the metre wheel and were occasionally checked with the echo-sounder. Two protected thermometers were always used with each reversing bottle and the mean calculated temperature was taken. Then vertical profiles of temperature for all stations were drawn separately for subsequent analysis using the corrected temperature.

Water samples were analysed in the Laboratory for salinity following Knudsen's method and Knudsen's Tables (1901) have been used for obtaining salinity values from the corresponding chlorinities. As the field of density can be represented most conveniently by the σ_t field, values of σ_t are obtained from temperature and salinity data partly using Sund's oceanographic slide rule (1929) and partly from the nomograms of Kalle (1940).

Any scalar quantity can be represented either by means of isopleths of that particular entity in a vertical section along a line of stations or by a level chart showing the isopleths of the entity. Both these types of representation are employed in the present investigation, as the aim is to give as detailed a picture as possible, for further ready correlation with biological data. Thus nine vertical sections for each quantity running seawards,

ADDENDUM

Local and Scientific Names of the Fishes Discussed in the Text

Local Name	*Scientific Name*
Cat-fish ..	*Tachysurus thalassinus* Bleeker, *T. dussumieri* (C.V.), *Osteogeneiosus militaris* (Lin.), etc.
'Dara' ..	*Polydactylus indicus* (Shaw).
'Doma' ..	*Otolithes ruber* (Bl. Schn.), *O. argenteus* (C.V.), *Johnius belengeri* (C.V.), *Pseudosciæna sina* (C.V.), *Polydactylus heptadactylus* (C.), *Umbrina* sp., etc.
'Ghol' ..	*Pseudosciæna diacanthus* (Lac.).
'Karkara' ..	*Pomadasys hasta* (Bl.).
'Koth' ..	*Otolithoides brunneus* (Day) (?).
Pomfret ..	*Pampus argenteus* (Euphr.).
'Rawas' ..	*Eleutheronema tetradactylum* (Shaw).
Rays ..	*Dasyatis sephen* (Forsk.), *D. uarnak* (Forsk.), *Aetobatis narinari* (Euph.), *Rhinoptera* sp., etc.
Sharks (Including Skates) ..	*Chiloscyllium griseum* M.H., *Scoliodon sorrakowah* (C.), *S. walbeehmi* Blk., *Carcharhinus* spp., *Sphyrna blochii* (C.), *S. tudes* (V.), *Pristis* spp., *Rhynchobatus djiddensis* (Forsk.), *Rhinobatus* sp., etc.
'Tam' ..	*Lutjanus* sp. (*L. malabaricus* ?).
'Wam' ..	*Murænesox talabonoides* (Bleeker).

ERRATA

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from different points from the coast and eight sets of Level charts corresponding to depths 0, 10 m., 20 m., 30 m., 50 m., 75 m., 100 m. and 150 m., are presented together with discussions in the following sections. The level surfaces referred to here are in fact surfaces of equal geometric depth and for the purpose of this paper the distinction between the two is not very essential.

While constructing the vertical sections, in order to avoid an independent analysis of each variable so that the relationship among the several fields can be easily observable, the method of Montgomery (1954) has been kept in view in dealing with temperature and densities. But these fields are not superimposed on each other as such they are discussed independently. However, since the data consist of serial observations, and no Bathythermographs were employed Montgomery's method could not be completely followed especially with salinity data. It is because of the greater detail the salinity sections seem to be more complicated than the other two. Hence independent discussion of the vertical sections of different variables is given first, while the discussion on horizontal distributions is combined.

Along with the level charts, the oceanic circulation revealed by this study is also given. While drawing the conclusions about the circulation the various factors to be borne in mind are completely discussed by Sverdrup *et al.* (1942). Balarama Murty and Rama Sastry (1957) and Rama Sastry and Balarama Murty (1957) have summarised the factors to be considered for deriving the currents along the coasts especially from the distribution of temperature and density (σ_t).

3. Temperature Distribution—Vertical Sections

In this, as well as in the following sections, dealing with vertical distribution, the discussion is presented starting from the northern most section in the region.

During the South-West Monsoon the winds in the Arabian Sea along the coast-line of India are nearly westerlies and of average intensity of about 25 miles per hour. Hence the wind driven oceanic circulation will be south-east. As the current approaches the coast it is deflected further south and the main current in the surface layers is southerly. This feature is prominent probably with the reduced intensity even in the retreating monsoon as the observations were made immediately after the monsoon. But with decreased intensity of the varying winds the transport of water very near the coast is such that favourable conditions are produced for upwelling. Thus, in general, upwelling is to be noticed in Figs. 1-9. Intensity of

upwelling is more in the southern region which could not be completely attri-
buted to the wind action alone, relative to geometry of the coast-line, but
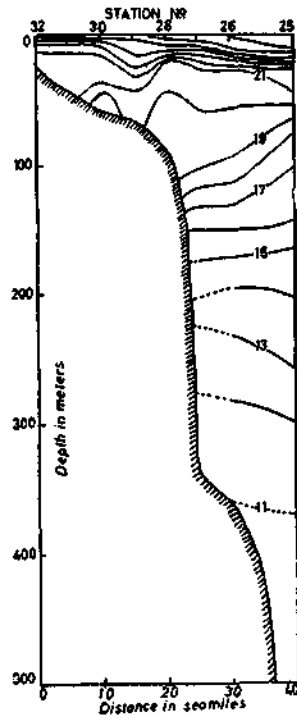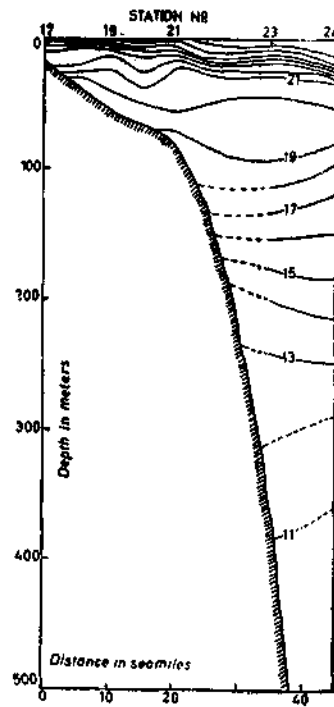it is to be understood partly from the change in the sea circulation.

Fig. 1   Fig. 2

Text-Figs. 1–2. Fig. 1. Vertical temperature structure in a section off Alleppey (Mean
latitude 9° 30′ N.), 19th September 1957. Vertical exaggeration is 463 and is constant for all
thermal sections. Fig. 2. Vertical temperature structure in a section at 10 miles south of Alleppey.
(Mean latitude 9° 20′ N.), 18th September 1957.

In a section off Alleppey (mean latitude 9° 30′ N.) (Fig. 1) sea surface
temperature is increasing with increasing distance from the coast with a
mean gradient of about 1° C. per 15 miles. Upwelling is prominent only
over the mid-continental shelf in the top 30 m. The thermocline is drawn
almost up to the surface in the entire section. Starting from about 20 miles
from the coast up to the continental slope, below a mean depth of 30 m.
the vertical gradients of temperature are very poorly defined and nearly
isothermal watermass is formed by mixing followed by reflection of the
bottom current with the upwelled waters. The downward bent of the iso-
therms corresponding to 17–19° C. towards the bottom is the result of the
slow drifting of the vertically isothermal waters along the continental slope.

Below a depth of 150 m. there is good stability, the upward bent of 12° and 13° C. isotherms being the effect of the bottom topography.
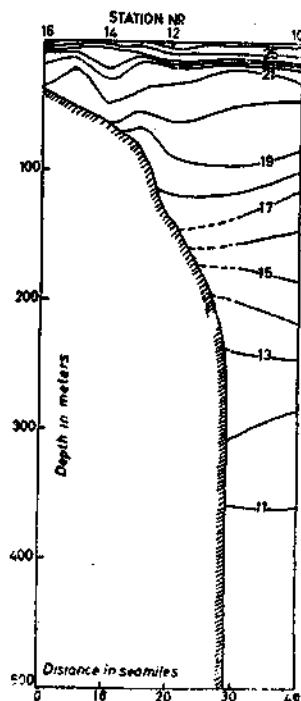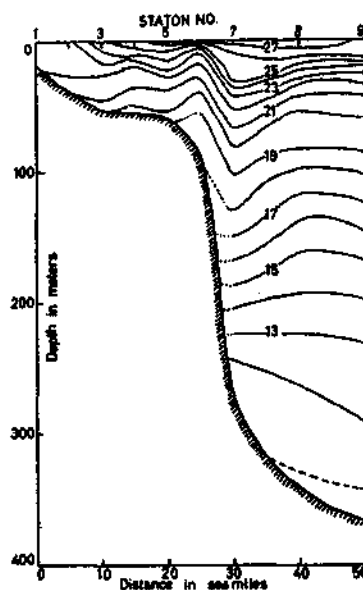

FIG. 3   FIG. 4

TEXT-FIGS. 3–4. Fig. 3. Vertical temperature structure in a section running due east, at 10 miles north of Quilon (Mean latitude 9° 10′ N.), 18th September 1957. Fig. 4. Vertical temperature structure off Quilon (Mean latitude 9° N.), 16th and 17th September 1957.

In two sections between Alleppey and Quilon (over latitudes 9° 20′ N. and 9° 10′ N.) (Figs. 2, 3) the thermal conditions are very nearly the same and they indicate upwelling in the upper 50 m. The vertically isothermal water mass is very poorly defined. The thermocline is alsmot drawn to the surface, thus the maximum thermal gradients in the vertical being in the top 25 m. below which the waters are either vertically stable or characterised by internal waves. The general current is towards the south in the upper 100 m. with a counter current in deeper depths. The intensity of the counter current is very small compared to the surface flow.

The northerly subsurface counter flow, when striking the bottom is reflected and vertical motion is induced as evidenced by the following section where upwelling has increased both in intensity and in space. Thus the subsurface tongue of low temperature, clearly seen in the horizontal charts

while rising upward produces very cold temperature near the coast off Quilon (Fig. 4). This region seems to be the northern limit of intense upwelling during the season. The characteristic crest of all the isotherms at Station 6 are the result of the effect of bottom topography and the vertical mixing referred. The minimum temperature found near the coast of Quilon is partly due to the exchange of the cold water of the Ashtamudi Lake which opens into the Arabian Sea at Quilon. A quantitative measure of this effect could not be studied for want of suitable data but it is felt that such a study would be of utmost importance in connection with the influence on productivity of the region. Off Quilon practically there is no formation of the type of continental shelf water, discussed above. Below a depth of 100 m. influence of internal waves is felt up to 225 m. below which the isotherms follow the bottom topography.
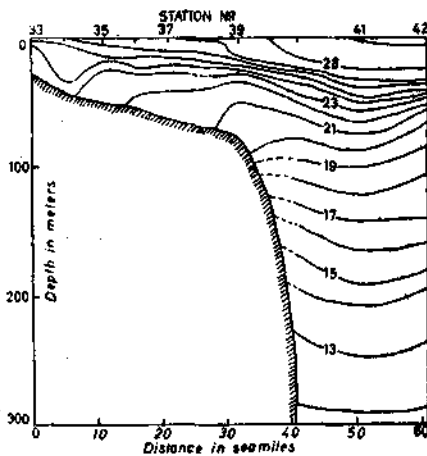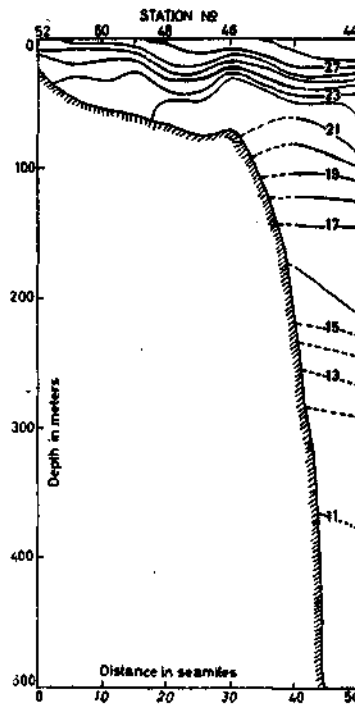

FIG. 5

FIG. 6

TEXT-FIGS. 5-6. Fig. 5. Vertical temperature structure in a section due east at 7 miles south of Quilon (Mean latitude 8° 45' N.), 5th October 1957. Fig. 6. Vertical temperature structure in a section entering coastwards at about 7 miles north of Trivandrum (Mean latitude 8° 30' N.), 5th and 6th October 1957.

The section about 7 miles south of Quilon, over a mean latitude of 8° 45' N. (Fig. 5) is similar to the one above in having very low temperature

near the coast. Even beyond 60 miles off the coast upwelling is prominent though the effective depth of upwelling decreases with increasing distance from the coast. Thus, thermocline forms beyond a distance of 45 miles from the coast at a mean depth of 20 m. As upwelling has extended to further distance, mixing at the bottom, resulting an overturning in the bottom water by the counter current flowing north, has been impeded. Thus we get the vertically isothermal waters over the continental shelf up to the Cape Comorin southwards. The break in the continuity of this shelf water occurs only at the northern limit of intense upwelling (Fig. 4).

The thermal conditions of the sea near Trivandrum (8° 30' N. and 8° 15' N.) (Figs. 6 and 7) show an apparent increase in the sea surface temperature

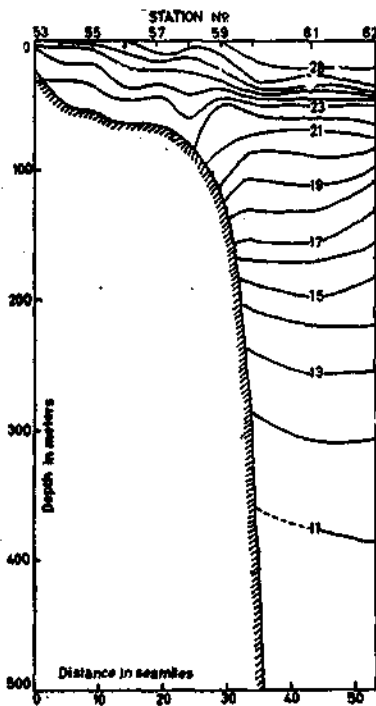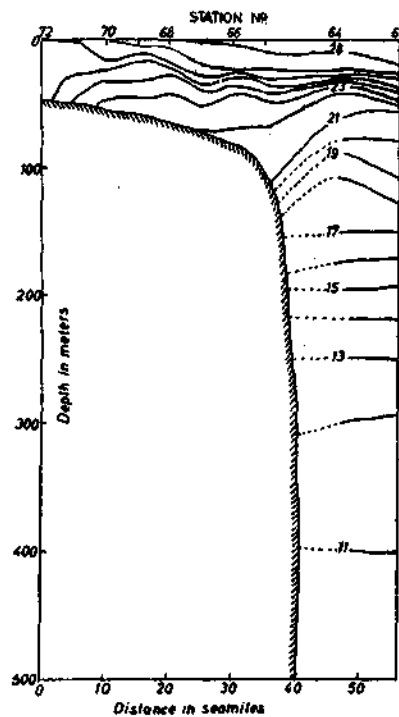
Fig. 7

Fig. 8

Text-Figs. 7–8. Fig. 7. Vertical temperature structure in a section at about 8 miles south of Trivandrum (Mean latitude 8° 15' N.), 6th and 7th October 1957. Fig. 8. Vertical temperature structure in an eastward section proceeding to the Cape Comorin (Mean latitude 8° N.), 7th October 1957.

along the coast southwards though upwelling seems to be more in the southern section. But a few metres below the sea surface the southern section registers

much lower temperature than the northern one. This is purely due to the diurnal variation of temperature as the Stations 52 and 53 were made respectively at 0810, 1237 hrs. on the same day. Thus, if the effects of the diurnal variation of temperature were to be removed from both the sections it would be seen that the intensity of upwelling is nearly the same in both sections. Thermocline forms below a depth of 20 m. in the region beyond the continental slope. As upwelling is confined to the upper 75 m. and observations were extended only up to 50 miles from the coast, it is not possible to establish the formation of thermocline at 20 m. in the open sea as a seasonal characteristic. The thickness of the continental shelf water is smaller in the southern section. Internal waves are present below a depth of 100 m.

Figures 8 and 9 represent two sections off the Cape Comorin one lying on the 8° N. and other running in a south-westerly direction. Though upwelling is common to both the sections they offer different characteristics at the very first sight. The latitudinal section (Fig. 8) is perpendicular to the mean current while the other (Fig. 9) is inclined at about 45° to the mean current. Thus in the latter section upwelling is prominent over the mid-continental shelf with a well formed mixed layer of 25 m., thickness from Station 75 onwards, while in the former upwelling is uniform over the entire continental shelf and the formation of the mixed layer is not as pronounced as in Fig. 9. Another dissimilarity is the formation of a tongue of low temperature from the continental slope up to mid-continental shelf in Fig. 9 indicating an intrusion of cold water near the bottom with indications of cyclonic circulation. Essentially by this reflection there will be vertical currents leading to the bent of the isotherms as at Station 75. These differences in the thermal structure, as far as upwelling is concerned, are mainly due to the orientation of the section with respect to the coast-line and the geometry and bottom topography of the continental shelf round Cape Comorin. Though the winds are mainly westerlies south of Trivandrum in the region under consideration, the continuous change in the shape of the land barrier relative to winds, produces upwelling of a different type mainly resulting from the change in the sea circulation. The effect of sea circulation in producing favourable conditions for increased upwelling gradually decreases northwards as is clear from the above.

4. SALINITY DISTRIBUTION—VERTICAL SECTIONS

The salinity variation both in space and time during the season is from 34–36‰ with a subsurface zone of maximum salinity, the depth of which varies from section to section. In the vertical sections to follow, the iso-

halines are reproduced at $0 \cdot 20\%_0$ intervals though they were constructed at $0 \cdot 10\%_0$ intervals.
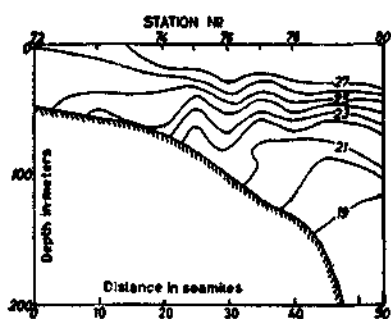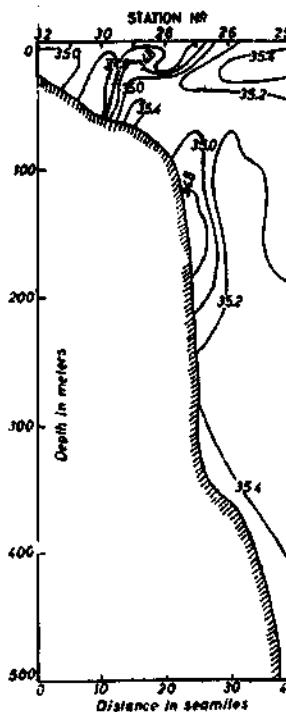

Fig. 9

Fig. 10

Text-Figs. 9–10. Fig. 9. Vertical temperature structure running towards south-west off the Cape Comorin, 7th and 8th October 1957. Fig. 10. Vertical section of salinity off Alleppey. Vertical exaggeration is 371 and is kept constant for all vertical sections of salinity and density.

In a section off Alleppey (Fig. 10) salinity varies from $34 \cdot 40$–$35 \cdot 50\%_0$ the low saline waters extending as distinct tongues upwards either from the bottom of the continental shelf or the slope. Those that occur over the continental shelf correspond to the water of zero vertical gradient of temperature and the one over the slope is in a region of steep downward bent of the isotherms. The two distinct tongues of high salinities approaching coastward, consequent probably on upwelled water, have broken into eddies and are seen as closed isohalines in the figure.

But due east of Alleppey (Fig. 11) high saline water, beyond the continental shelf extends as a tongue downwards up to about 200 m. which corresponds to the zone of maximum salinity. But very near the coast and at the surface the salinities are much lower and over the continental shelf, with the absence of the vertically isothermal water, the former tongues

of low salinity are now seen as small eddies. But even in this section low saline waters are along the bottom of the shelf and the slope. Thus the edge of the continental shelf seems to demarcate between the high saline oceanic waters and the low saline coastal waters.
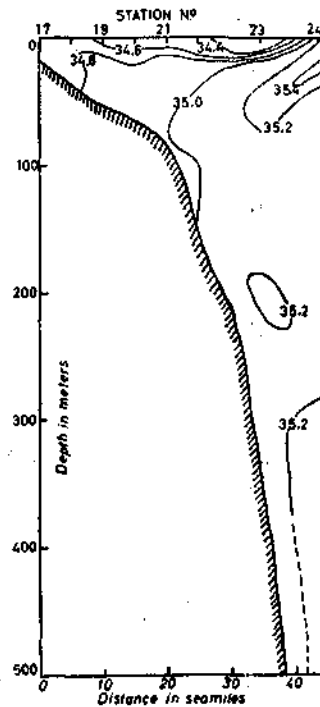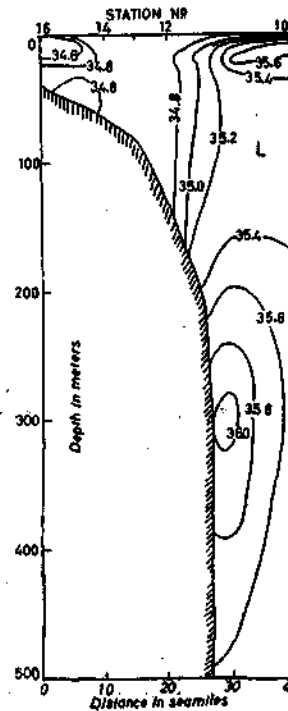

Fig. 11   Fig. 12

Text-Figs. 11-12. Fig. 11. Vertical section of salinity at 10 miles south of Alleppey. Fig. 12. Vertical section of salinity at 10 miles north of Quilon.

This feature is very prominently brought out in the next section Fig. 12 which is 10 miles further south, where the isohalines corresponding to 34·80–35·20‰ are nearly vertical lines between Stations 12 and 11. Over the shelf region the salinity is very uniform as a result of good mixing as is evident from the thermal section also. At 300 m. at Station 11 highest salinity is recorded probably as a result of vertical movements due to internal waves (vide Fig. 3).

Off Quilon, where upwelling is prominent only over the continental shelf (Fig. 4) the isohalines break up into a number of cells (Fig. 13) indicating that upwelling is not uniform and good mixing is taking place. Those high salinity tongues approaching coastwards, common to earlier sections, are not very prominent here. The salinity below 100 m. is more or less

uniform in the entire section, resulting in vertical stratification though lateral mixing should be of importance as southerly flow near the bottom up to 250 m. is indicated.
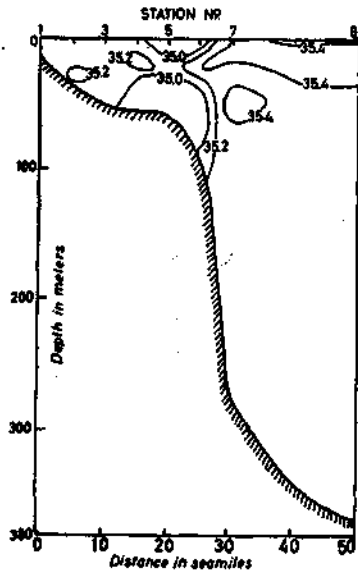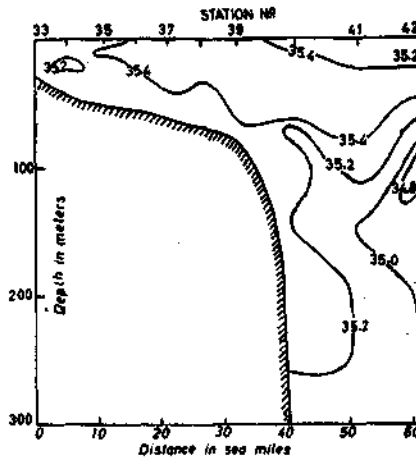

Fig. 13

Fig. 14

Text-Figs. 13–14. Fig. 13. Vertical section of salinity off Quilon. Fig. 14. Vertical section of salinity at 7 miles south of Quilon.

In a section south of Quilon, that is at the northern limit of intense upwelling (Fig. 14) as is to be expected the salinity of the surface layers is much higher than in the northern section. Also the subsurface zone of maximum salinity is at a mean depth of 40 m. extending as a tongue of high salinity coastwards from Station 42 to Station 38 with salinities higher than 35·50‰ (not shown in Fig. 14). The isohaline corresponding to a salinity of 35·40‰ runs almost the entire section serving a lower boundary of the upwelled top layer resting on the relatively undisturbed waters. Low saline waters along the bottom of the shelf during the course of mixing with the upwelled water form into a number of cells with salinities less than 35·30‰. The distinction between the low saline coastal waters and the high saline oceanic waters is apparently not to be seen, because the depth of bottom throughout the section is less than 400 m. with little effect of deep sea circulation.

Off Trivandrum (Northern Section: Fig. 15 and Southern Section Fig. 16) in addition to the subsurface zone of maximum salinity in the upper layers produced by upwelling, high saline waters are entering coastwards

at about 300 m. with an apparent thermohaline circulation in the vertical, but it might be due to the internal waves as the increase in salinity is only 0·30‰. The surface layers are characterised by a number of closed iso-halines consequent on mixing processes taking place. A study of turbulence in the region would be of interest in this connection and may reveal any possible interaction of the water masses.
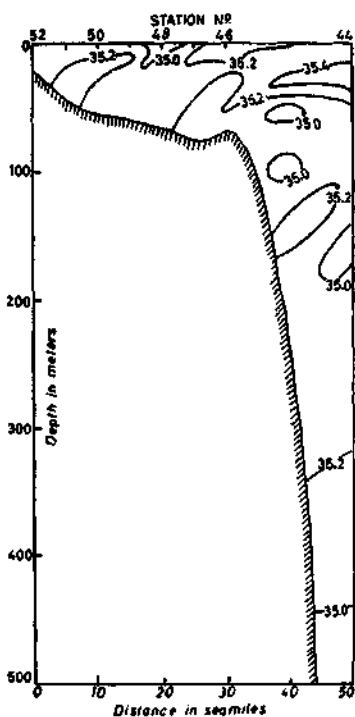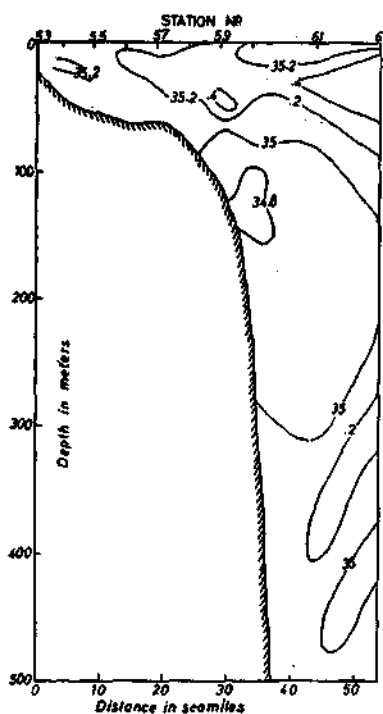

FIG. 15   FIG. 16

TEXT-FIGS. 15-16. Fig. 15. Vertical section of salinity at 7 miles north of Trivandrum. Fig. 16. Vertical section of salinity at 7 miles south of Trivandrum.

Off Cape Comorin (Figs. 17 and 18) near the shore the salinity is low and rapidly increases with increasing distance from the coast in the latitudinal section (Fig. 17) perpendicular to the mean current. This feature was not brought out in an oblique section off the Cape Comorin mainly due to the non-availability of salinity data at Stations 77-79, but when the details are not plotted it shows strong upwelling discussed in connection with Fig. 9. However it is felt that there will be good number of eddy formations as in Fig. 17 as a result of mixing. The low saline coastal waters extend up to 20 miles distance from the coast and to 50 m. depth. This corresponds to the region where there can be any exchange of waters between the Arabian

Sea and the Bay of Bengal through the Palk Straits.* Beyond this distance salinity is more or less uniform though increasing slightly in the surface layers. Between 300 and 500 m. a tongue of high salinity extending eastwards shows the general characteristic of the existence of low saline waters along the continental slope.
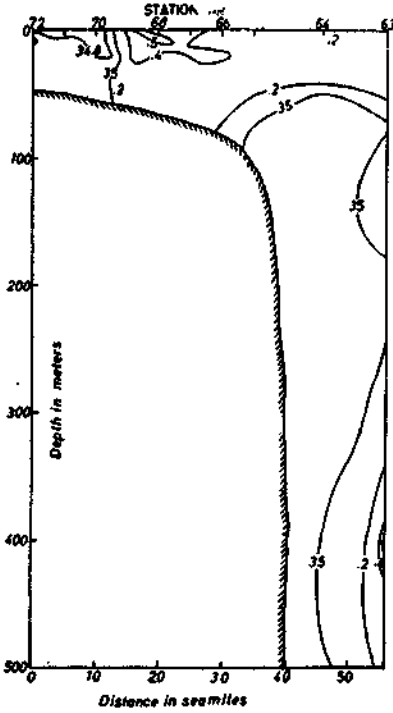

FIG. 17
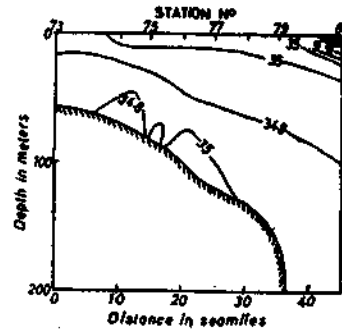
FIG. 18

TEXT-FIGS. 17–18. Fig. 17. Vertical section of salinity, south of the Cape Comorin. Fig. 18. Vertical section of salinity in a south-westerly direction at the Cape Comorin.

5. DENSITY DISTRIBUTION—VERTICAL SECTIONS

As very rapid depthwise increase of density occurs in the surface layers, the isopycnals (actually the isopleths of σ_t) are drawn at 0·50 gm./litre interval till a density of 25·00 gm./litre is reached and below this value the spacing is 0·20 gm./litre. In general the increase of density in the upper 75 m. is as much as that between 75–500 m. Such rapid rise of density in the topmost layers occurs because of the absence of the mixed layer consequent on upwelling. From the spacing of the isopycnals it is clear that the influence of upwelling is felt to the maximum depth of the isopycnal corresponding

* It should be remembered that the current deviates while passing over ridges.

to 24·5 gm./litre (hereafter to be designated by the numerals omitting the units).

At the surface the break in the isopycnals 22·5, 23·0 and 23·5 between Stations 30 and 28 (Fig. 19) show the maximum intensity of upwelling as the movement of water can only be along the σ_t-surfaces. The maximum density change takes place (from 22·5–24·5) only in the upper 40 m. in shallow depth and 20 m. in deep waters. Such a change is mainly because of the existence of the continental shelf water. Though the current at all depths up to 350 m. along the continental slope, is southerly the intensity decreases with depth and the flow is negligible below 300 m. A counterflow is indicated between Stations 26 and 25 at a mean depth of 175 m. As this feature is not found between Alleppey and Quilon (Figs. 20–22) it may be concluded that in the northernmost section the density structure represents eddy formations.

The distribution of density up to 100 m. off Alleppey (Fig. 20) is similar to the one discussed above but between 100 and 200 m. good stratification
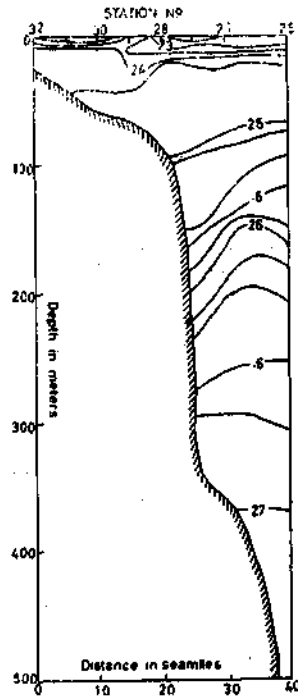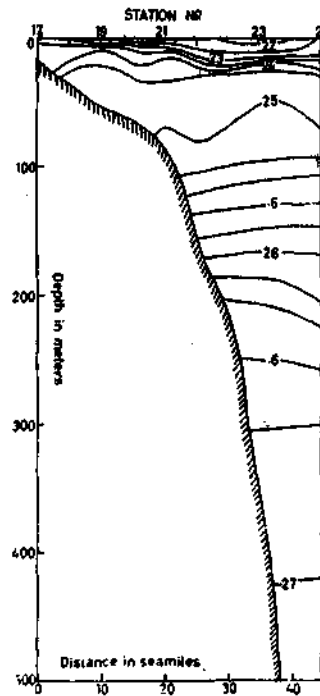

FIG. 19   FIG. 20

TEXT-FIGS. 19-20. Fig. 19. Vertical section of σ_t off Alleppey. Fig. 20. Vertical section of σ_t at 10 miles south of Alleppey.

is found. The eddies discussed above have very limited depth range round about 200 m. with a very sluggish flow, related to the distribution of mass up to 500 m.

But in a section between Quilon and Alleppy (Fig. 21) there is a definite counter flow towards north from 180-500 m. above which the flow is southerly. Thus the northerly flow initiated by the eddies in the northern sections develops fully into a subsurface counterflow in this region. In all possibility this flow might deviate to NW to NNW so that the flow is beyond the extent of observations in the northern sections and also this section must be almost at the turning point of the northerly flow. By a comparison of the other sections, it is felt that this counter current of the Arabian Sea should be in its initial stages during this part of the year to develop into a strong current to flow into the Red Sea (*vide* Sverdrup *et al.*, 1942). With the backing of the current, mixing takes place forming the eddies discussed above. Further this occurs at the northern boundary of maximum upwelling.

Even in two sections near Quilon (Figs. 22 and 23) where the depth of bottom is less than 400 m. these features are clearly indicated. The
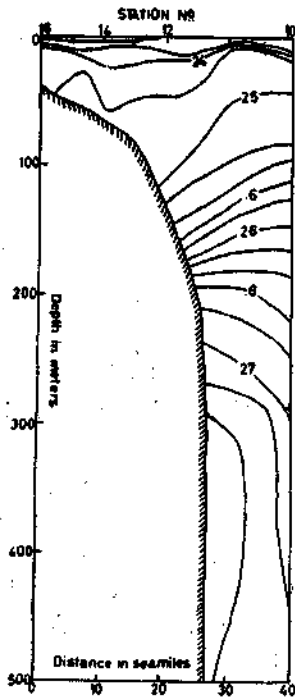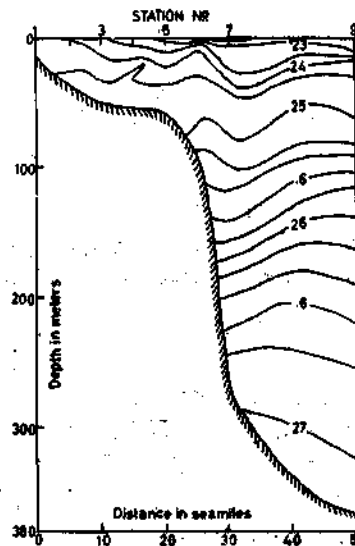

FIG. 21   FIG. 22

TEXT-FIGS. 21-22. Fig. 21. Vertical section of σ_t at 10 miles north of Quilon. Fig. 22. Vertical section of σ_t off Quilon.

density gradient in the surface layers is reduced consequent on increased upwelling resulting in mixing, followed by eddy formation in the vertical as in Fig. 22. Further, the stratification is very much disturbed slightly south of Quilon.

Near Trivandrum (Figs. 24 and 25) a further reduction in the vertical gradient of density is recorded. The steep bottomward bent of the isopycnal
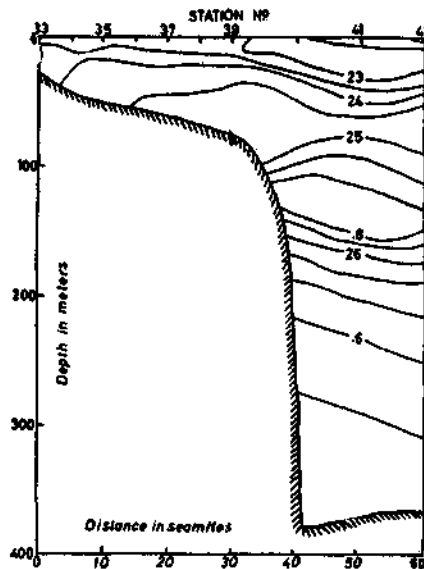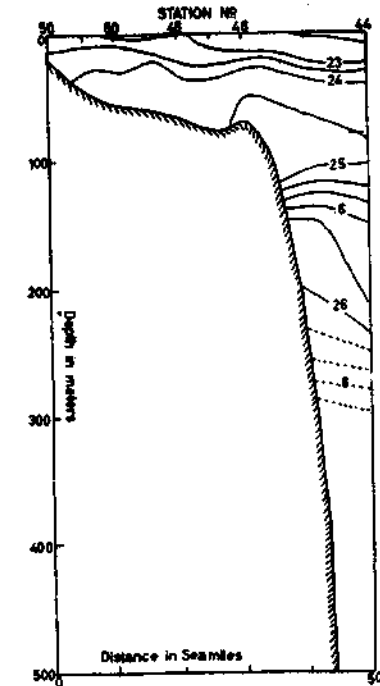
FIG. 23   FIG. 24

TEXT-FIGS. 23-24. Fig. 23. Vertical section of σ_t at 7 miles south of Quilon. Fig. 24. Vertical section of σ_t at 7 miles North of Trivandrum.

24·5 in both sections reflects the corresponding thermal structures as a result of the existence of the continental shelf water of zero gradients of temperature in the vertical. Here the effective northerly subsurface flow starts from a depth of 200 m. and it does not extend up to the continental slope in a section north of Trivandrum at depths greater than 350 m. indicating its early stages of formation with a continuous change in the direction towards north-north-west.

Off the Cape Comorin to the extent to which observations are extended (Figs. 26 and 27) the northerly flow at the depths under consideration could

FIG. 25

FIG. 26

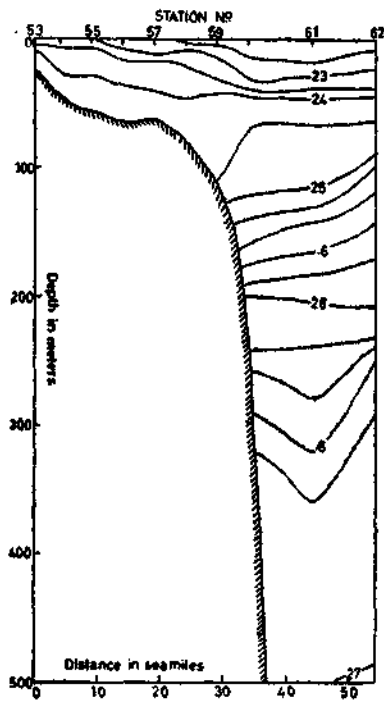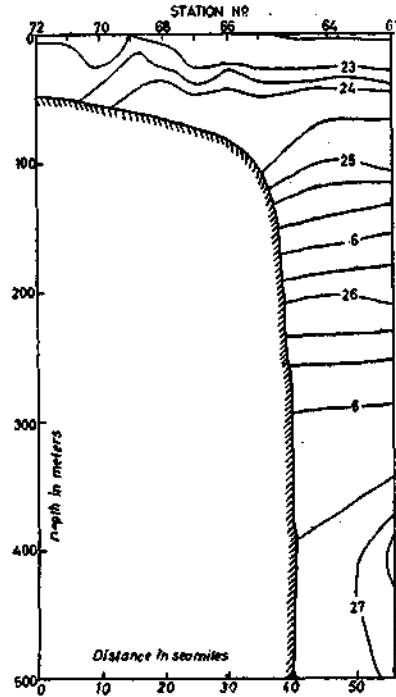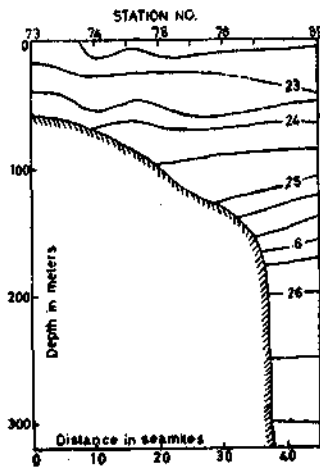TEXT-FIGS. 25-26. Fig. 25. Vertical section of σ_t at 7 miles south of Trivandrum. Fig. 26. Vertical section of σ_t south of the Cape Comorin.

not be traced. On the contrary after a stable stratification in the layer between 100 and 300 m. a weak southerly flow is indicated at a mean depth

TEXT-FIG. 27. Vertical section of σ_t in a south-westerly direction at the Cape Comorin.

2

of 400 m. But for want of further data still towards south and to greater distances from the coast it is not possible to assert whether this is in the transitory stage or a region of divergence. Therefore the tongue high density approaching coastwards could not be explained as it can be formed in either of the possibilities presented above with other suitable conditions superimposed.

The σ_t surface corresponding to 25·0 which was chosen to serve as a boundary between the higher top layer from the denser waters, in general, maintains its level at a mean depth of 80 m. up to Trivandrum but it dips rapidly to a depth of 120 m. at the Cape Comorin, thus producing an easterly flow.

6. THE KERALA COASTAL WATER OVER THE BOTTOM OF THE CONTINENTAL SHELF

The mixing of the Indian equatorial water with the Red Sea water is of importance for the formation of the intermediate to deep water masses in the Arabian Sea. Though it is not possible to go into the details of the formation of water masses in the Arabian Sea within the scope of this paper, it may be mentioned that good mixing takes place with the north equatorial water of the Indian Ocean along this coast and with the reversal of the circulation along the coast associated with the monsoons the coastal water is constantly displaced and overturned particularly by the processes of upwelling and the like.

As far as this present investigation is concerned it is proposed to present only the characteristics of the type of the continental shelf water discussed in the preceding pages, forming the bottom layers of the Kerala Coastal water. It is proposed to name this water type as 'The Kerala Coastal Deep Water'.

It is quite common to come across this type of water along the coast-lines where upwelling and sinking occur. Such a feature is recorded by one of the authors (Rama Sastry, 1955) along the east coast of India also, during the months of March and April, the period in which maximum up-welling occurs along that coast as a result of mixing of the upwelled water with the offshore drift and the north equatorial current in the early stages of formation. But in the case of the Kerala coastal water mixing takes place within the upwelled water and the northerly counterflow at the sub-surface levels which is actually turning north–north-west in the region under consideration. Because of these current systems, found during this part of the year, the isothermal nature of the Kerala coastal water is not continuous.

With increased mixing either at the edge of the continental shelf (Stations 28, 6, 39, 46, 58, 59, 65 and 79) or in shallow water near the coast (Stations 31, 32, 19, 16, 33, 49, 53, 71 and 72) the bottom water of the shelf is nearly isothermal as is clear from Table I.

TABLE I

Characteristics of the Kerala coastal deep water

Station No.	Maximum depth of formation m.	Thickness Actual m.	Thickness Sampled m.	Mean Temp. °C.	Mean sal. ‰	Mean σ_t gm.L^{-1}	Thermal gradients (fall of temperature °cm.$^{-1}$) Observed layer	Thermal gradients (fall of temperature °cm.$^{-1}$) Estimated up to bottom	Thermal gradients (fall of temperature °cm.$^{-1}$) Mean of the section
32	10	26	10	22·24	35·12	24·27	·078	·040	·178
15	30	22	20	20·16	34·82	24·63	·009	·010	·046
33	10	18	10	24·21	35·27	23·79	·005	..	·129
39	50	29	25	20·92	35·43	24·85	·017	..	·084
49	30	30	20	22·36	35·27	24·32	·031	·002	·111
53	10	14	10	23·15	35·15	24·11	·019	·001	·079
58	50	29	25	22·37	35·13	24·23	·018	·001	·077
65	75	25	18	21·49	35·00	24·37	·051	·003	·143
72	10	38	20	25·42	34·95	23·19	·022	·001	·099
74	30	40	20	24·97	34·83	23·17	·038	·030	·117
77	75	45	25	20·09	..	..	·019	·001	·090
78	75	56	25	20·51	..	..	·036	·003	·090

As no bathythermograph was used vertical temperature gradients down to the bottom could not be obtained in order to have a detailed picture of the isothermal nature of the Kerala coastal deep water. But from the vertical sections it is possible to estimate the gradients down to the bottom and they are listed in column 9 of Table I. Only such of the stations are included in Table I where the deep waters trend to be isothermal near the bottom. In column 10, the mean vertical gradients of temperature of the correspond-

ing depth layers in each of the sections are given for comparison. It is seen on an average that the observable gradient is one-fourth of the mean gradient which is eleven times the estimated gradient near bottom. On comparing the vertical thermal gradient of this water with that at a nearby station it is found the ratio is about one-tenth, thus showing the isothermal nature near bottom. The actual thickness of this bottom water increases towards south.

In 60% of the observations on this deep water (some of which are not included here) salinity shows a slight increase; in 5% salinity remains constant and in the remaining a slow depthwise decrease occurs. Since temperature is more or less uniform density also shows similar fluctuations. This shows the presence of vertical mixing and, therefore, it is not possible to establish whether this deep water is in the forming or in the dissipating stage. One would reach the same conclusion by noting the presence of this water type discontinuously. Repeated observations round the year are necessary for a complete study.

A simple mixing of two different waters is indicated by the T–S relationship in the case of the water near the edge of the continental shelf while for the formation near the coast-line there are at least three different water masses interacting. For an understanding of the actual formation and for the interaction among different waters, further study is necessary.

7. MEAN MERIDIONAL VARIATION OF THE PARAMETERS

Means of temperature, salinity and density at different levels on various parallels are given in Table II.

Up to 100 m. temperature decreases steadily from 8–9° N. or 9° 10′ N. with increasing rate of fall depthwise up to 50 m. From 9° at the sea surface and 9° 10′ N. at other levels up to 100 m. either the temperature shows a slight increase or remains nearly constant. In the same layer salinity is maximum at 8° 45′ N. and minimum at 8° 20′ N. Except in the top 10 m., the reduction in salinity has practically no effect in decreasing density values as the fall of temperature overcompensates the reduction in salinity. Therefore density up to 100 m. bears an inverse relation with temperature.

At 150 m. though there is a general decrease in temperature northwards at 9° N. temperature maximum is recorded. Similar characteristics occur at 200 m. the temperature maximum being shifted 30 miles southwards. At these levels salinity has a prominent maximum at 9° 10′ N. where the density also is correspondingly high. But for this high value, at these levels too, temperature and density are inversely related.

TABLE II

Meridional mean values of temperature, salinity and density at different depths

Depth (m.)	8° N. : Station 63 to 72			8° 15′ N. : Stations 53 to 62			8° 30′ N. : Stations 44 to 52			8° 45′ N. : Stations 33 to 42		
	Mean Temp. °C.	Mean Salinity °/oo	Mean σ_t gm. L⁻¹	Mean Temp. °C.	Mean Salinity °/oo	Mean σ_t gm. L⁻¹	Mean Temp. °C.	Mean Salinity °/oo	Mean σ_t gm. L⁻¹	Mean Temp. °C.	Mean Salinity °/oo	Mean σ_t gm. L⁻¹
0	27·51	35·21	22·71	27·44	35·14	22·67	27·34	35·29	22·84	27·39	35·31	22·83
10	27·19	35·24	22·84	26·39	35·18	23·06	26·27	35·17	23·03	26·50	35·38	23·11
20	26·60	35·21	23·00	25·66	35·27	23·37	25·35	35·29	23·51	25·33	35·42	23·55
30	25·34	35·22	23·40	25·53	35·29	23·46	23·76	35·29	23·94	23·57	35·44	24·12
50	22·80	35·18	24·13	22·65	35·22	24·22	21·95	35·20	24·38	22·10	35·41	24·51
75	21·27	35·05	24·48	21·19	35·03	24·49	21·31	35·10	24·63	20·29	35·25	24·89
100	·19·10	34·96	24·98	19·53	34·91	24·81	19·48	35·00	24·96	18·74	35·14	25·22
150	17·15	35·02	25·51	16·88	34·92	25·53	16·92	35·17	25·74	16·45	35·06	25·71
200	14·93	34·92	25·95	14·62	34·91	25·97	15·81	35·04	25·82	13·95	35·19	26·36
300	11·94	35·02	26·64	12·04	35·12	26·70	11·65	35·26	26·88	11·69	35·18	26·18
400	10·97	35·32	27·05	10·99	35·10	26·88	10·88	35·05	26·85	..	..	..
500	10·38	35·12	27·00	10·25	35·07	27·01	10·40	34·96	26·87	..	..	..

TABLE II (*Contd.*)

Depth (m.)	9° N. : Stations 1 to 9			9° 10′ N. : Stations 10 to 16			9° 20′ N. : Stations 17 to 24			9° 30′ N. : Stations 25 to 32		
	Mean Temp. °C.	Mean Salinity $^0/_{00}$	Mean σ_t gm. L^{-1}	Mean Temp. °C.	Mean Salinity $^0/_{00}$	Mean σ_t gm. L^{-1}	Mean Temp. °C.	Mean Salinity $^0/_{00}$	Mean σ_t gm. L^{-1}	Mean Temp. °C.	Mean Salinity $^0/_{00}$	Mean σ_t gm. L^{-1}
0	27·77	35·22	23·25	26·34	34·73	22·85	26·91	34·55	22·40	26·53	35·81	22·86
10	24·34	35·18	23·68	23·91	35·05	23·82	24·31	34·70	23·33	24·45	35·05	23·54
20	23·32	35·25	24·04	21·90	35·02	24·27	22·52	35·06	24·11	22·64	35·25	24·34
30	22·09	35·20	23·83	21·05	34·91	24·40	20·73	35·00	24·58	21·39	35·20	24·51
50	20·18	35·13	24·78	20·21	34·93	24·73	20·06	34·98	24·71	20·41	35·18	24·82
75	19·55	35·20	25·05	19·30	34·99	24·96	19·20	35·09	25·05	19·25	35·09	25·05
100	18·46	35·24	25·38	18·46	35·06	25·76	18·17	35·05	25·28	18·41	35·09	25·38
150	16·91	35·26	25·97	16·10	35·34	25·01	16·06	35·10	25·83	16·04	35·98	25·74
200	13·98	35·32	26·46	14·23	35·57	26·60	14·25	35·17	26·29	14·06	35·13	26·29
300	11·55	35·33	26·95	11·96	35·80	27·25	12·00	35·21	26·77	11·78	35·31	26·82
400	..	..	..	10·89	35·61	27·30	10·93	35·22	26·98	10·94	35·34	27·07
500	..	..	..	10·64	35·53	27·31	10·43	35·22	27·07	10·44	35·37	27·19

As the temperature at deeper levels up to 500 m. remains more or less constant, the density is influenced by the corresponding salinity variation latitudinally, thus both salinity and density maxima occur at 9° 10' N. From the foregoing it is clear that the temperature is a more representative factor for drawing conclusion regarding the oceanic circulation up to 200 m. from the distributions alone. But for deep water circulation, dynamical computations are necessary as the field of density, or salinity would be weak. Thus for a rapid survey of circulation a bathythermograph is of very great use in this region. But in the very surface layers, during the monsoon period, salinity also might be of importance.

In dealing with the latitudinal variation, only the factual account is given above without going into the actual mechanism operating. By a study of the mass, energy and salt transports together with the meridional circulation it is possible to explain the various facts presented above.

8. DISTRIBUTION OF VARIABLES AT DIFFERENT LEVELS WITH THE RESULTANT CIRCULATION

From the level charts oceanic circulation at each level is independently derived from the respective fields of temperature, salinity and density and the most representative circulation has been given in the charts. The construction of these charts justify the conclusion arrived towards the end of the last section. In the following level to level changes are discussed.

Except for a low temperature tongue off Quilon (the northern boundary of intense upwelling) the sea surface isotherms (Fig. 28) are parallel to the coast-line over the continental shelf where the temperature increases away from the coast. The isotherms are no longer parallel to the coast in the northern boundary of intense upwelling. It is in this region isolated cells of low salinity have formed whereas, in general, salinity increases southwards. As a result, the density field shows large eddies north-west off Quilon and these are further intensified at 10 m. Thus the current along the coast is south-easterly with two oppositely rotating gyrales in a region between Alleppey and Quilon. Along the Quilon Coast the current systems seems to be one of convergence and divergence alternately. In a period of upwelling, which should always be followed by divergence, convergence is only possible against either a barrier or its appearance should be the result of local eddies.

At 10 m., the isotherms though tend to be parallel to the coast-line, show two distinct tongues extending northwards (Fig. 29) between Trivandrum and Quilon where the salinity is nearly uniform. With the disappearance of cold waters off Quilon and increase in salinity, the anticlockwise
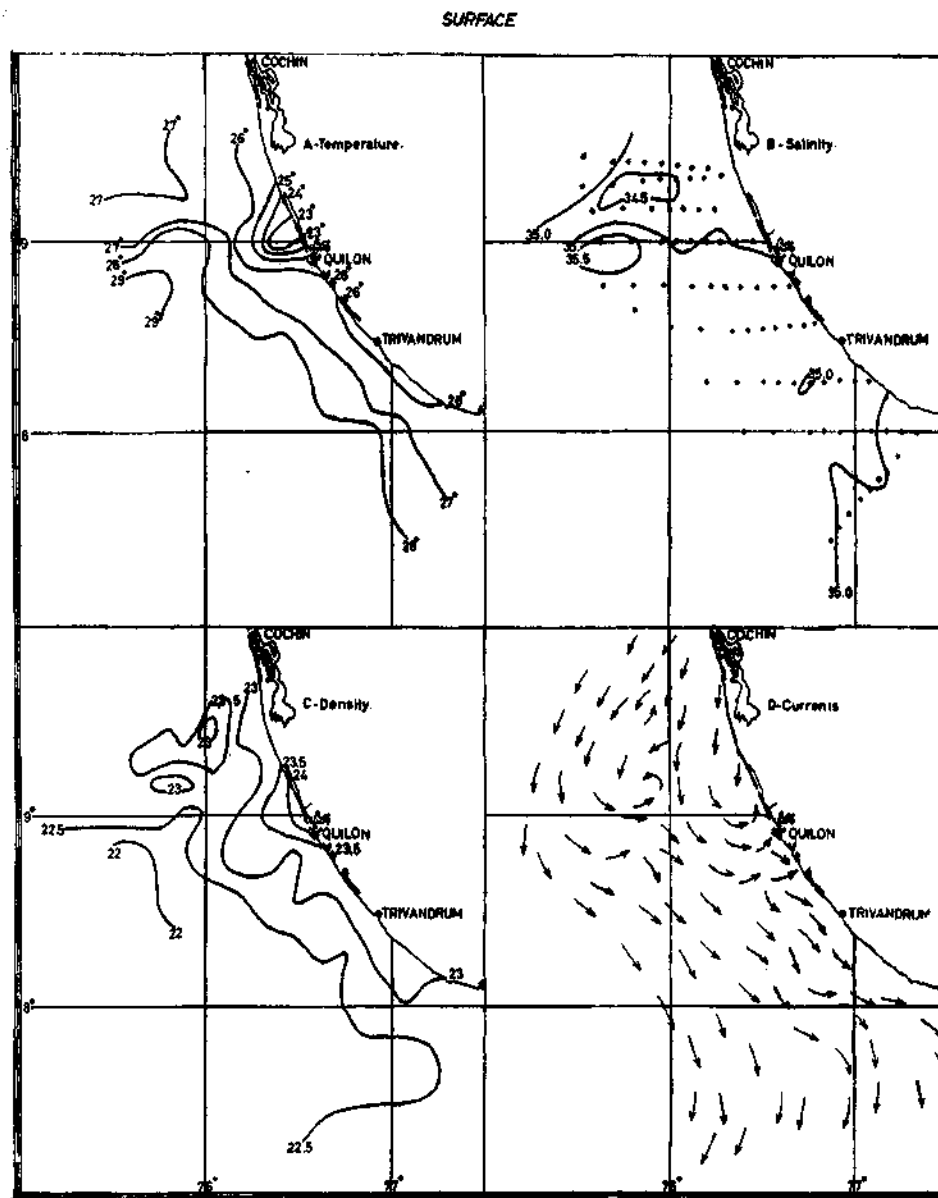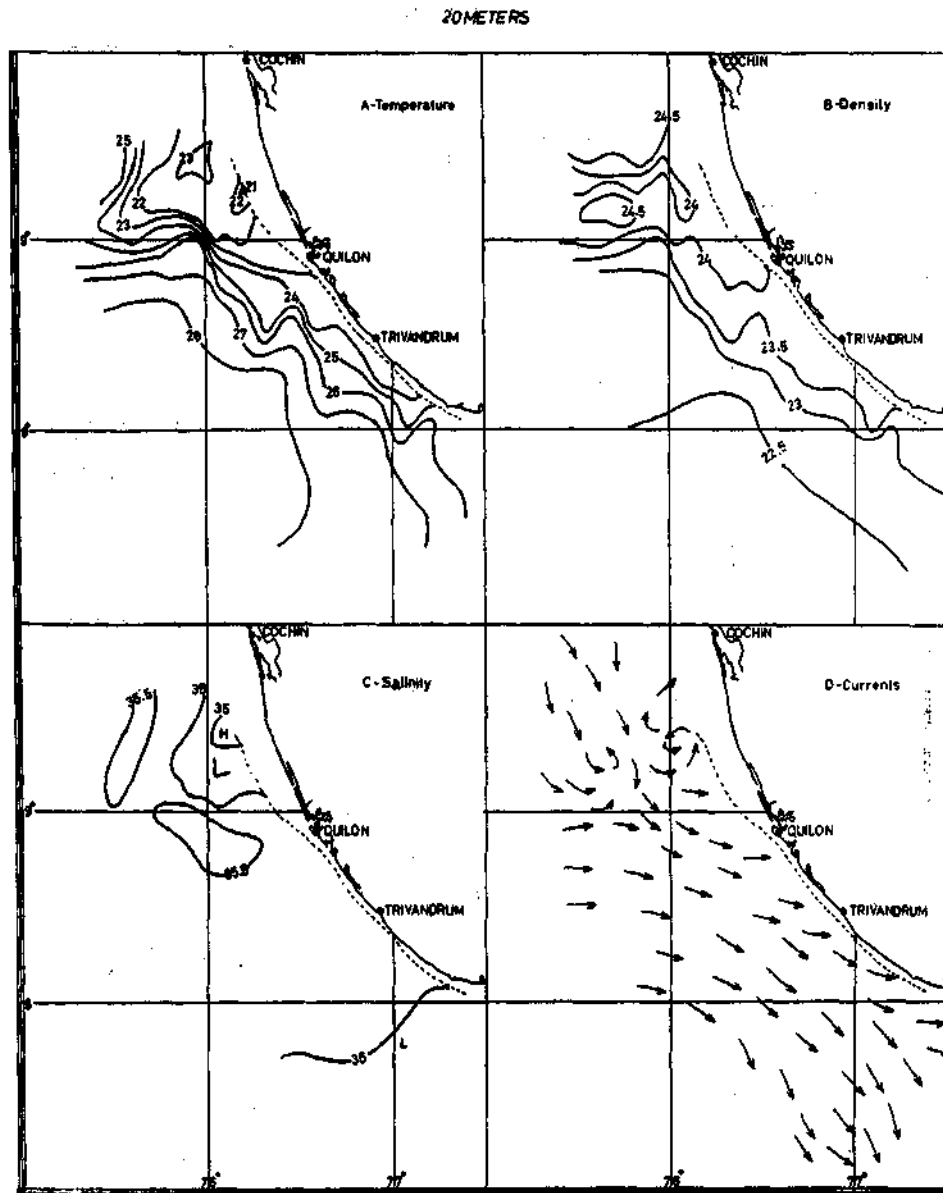
SURFACE

Text-Fig. 28. Chart showing the distribution of temperature, salinity, density and the resultant circulation at the sea surface during the post-monsoon season. The station positions are indicated in this figure.

circulation very near the coast is replaced by a coastal flow with alternate convergences and divergences. But the eddy formation clearly seen in the
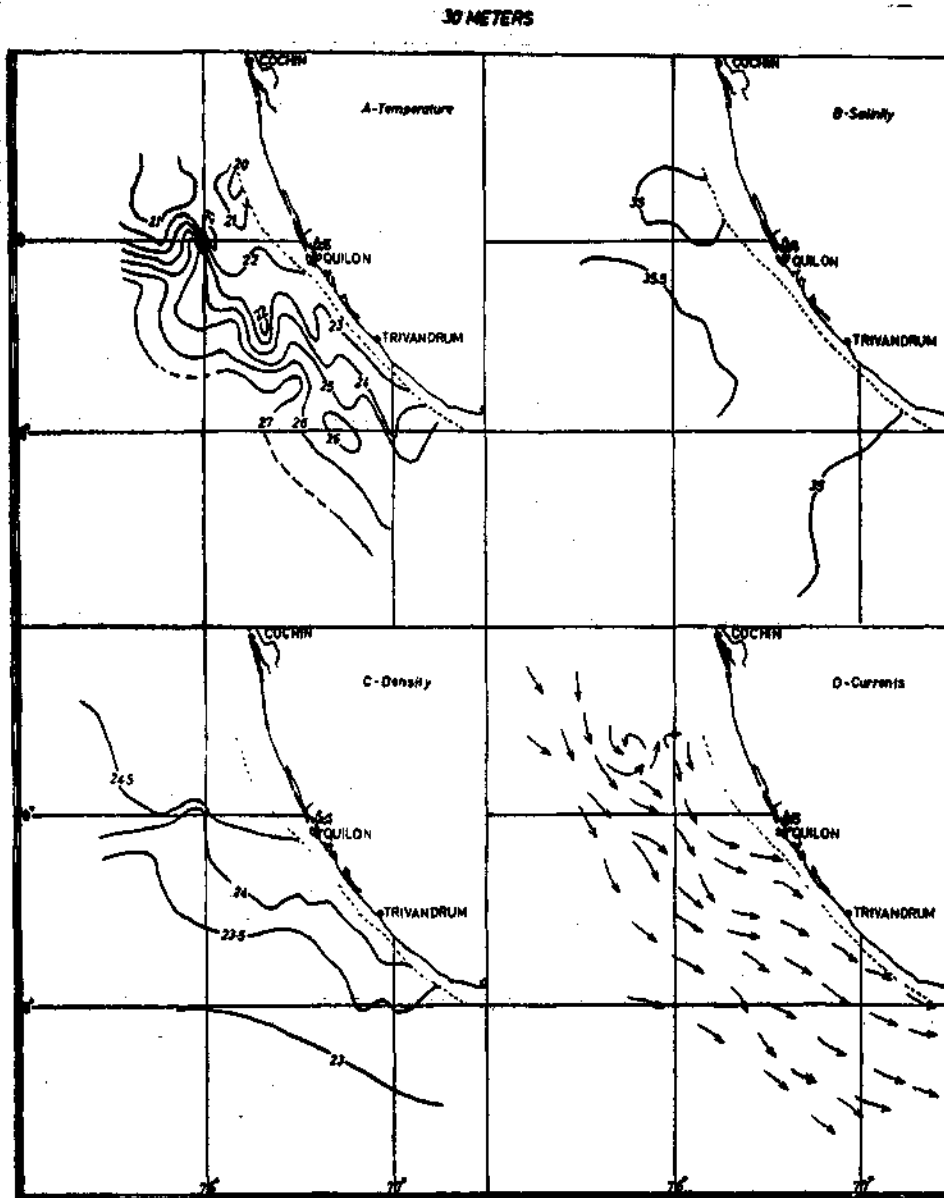
10METERS
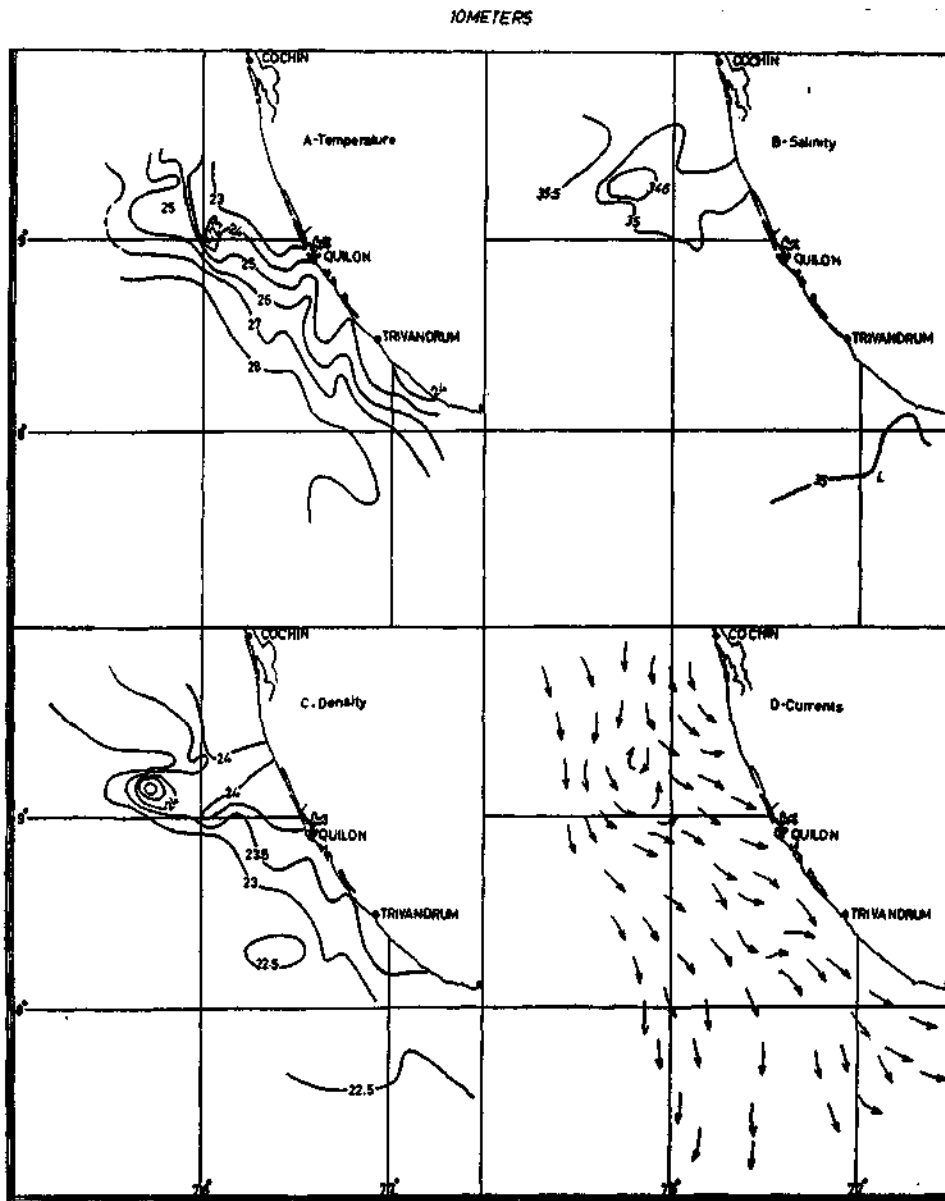
TEXT-FIG. 29. Chart showing the distribution of temperature, salinity, density and the resultant circulation at 10 m. level during the post-monsoon season.

density chart produces much turbulence. Only the offshore current, south of 8° N., has become southerly and the main coastal current is south-easterly.

20 METERS

TEXT-FIG. 30. Chart showing the distribution of temperature, salinity, density and the resultant circulation at 20 m. level during the post-monsoon season.

But at 20 m. (Fig. 30) with the packed isotherms centred at 9° N. and 76° E. and with increasing salinity eastwards from this point, a cell of maximum density centred approximately at 9° 10′ N. and 75° 40′ E. has

30 METERS

TEXT-FIG. 31. Chart showing the distribution of temperature, salinity, density and the resultant circulation at 30 m. level during the post-monsoon season.

formed. Above this cell, east to southerly tongue of l ow density has formed. Thus the circulation north of 9° N. is similar to that at the surface in forming two anticlockwise rotations though the extent of each is much smaller than at the surface. With these circulations only divergence near the coast

50 METERS
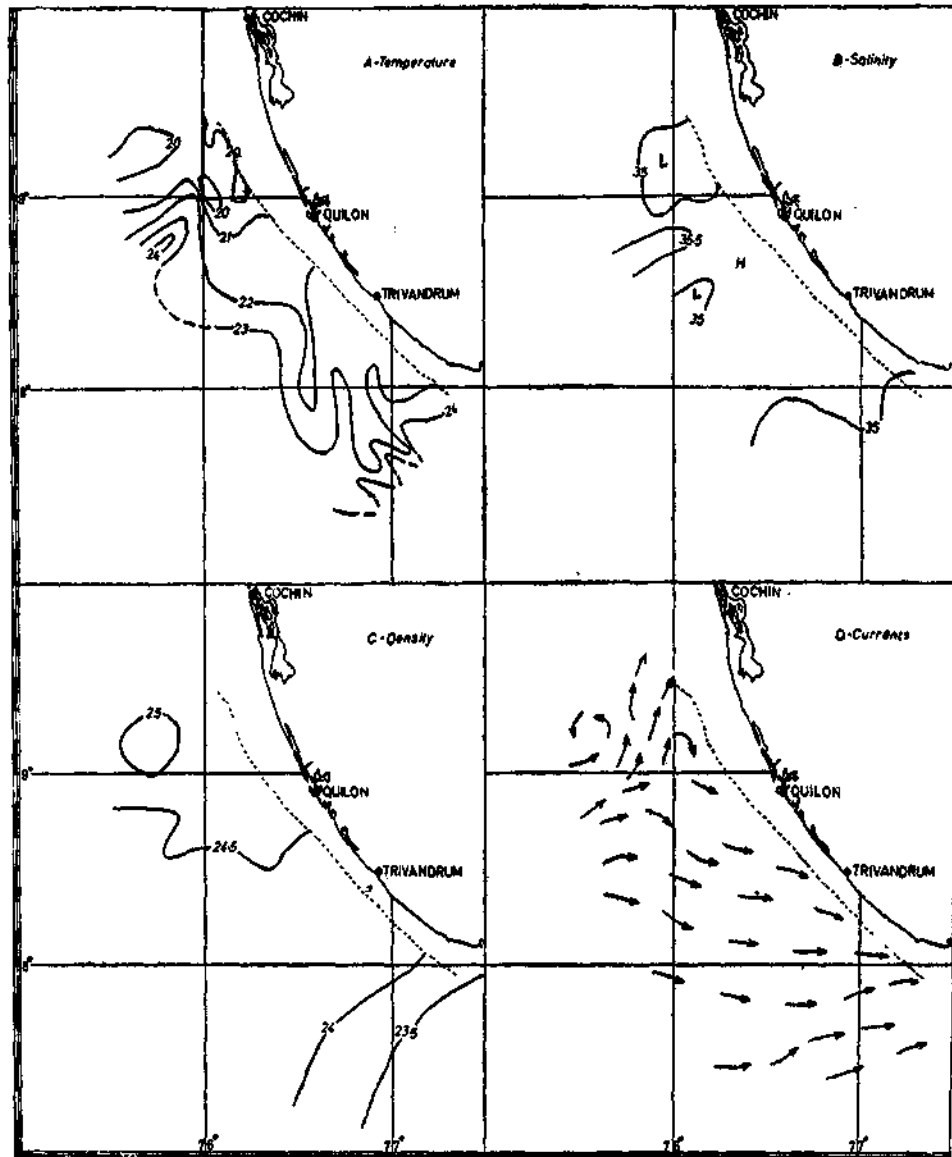
TEXT-FIG. 32. Chart showing the distribution of temperature, salinity, density and the resultant circulation at 50 m. level during the post-monsoon season.

slightly north of Quilon, is associated. The southern tongue of high temperature extending northwards at 10 m. is partially absent, with the result south of 8° N. the isopycnal of 22·5 follows the coast-line. Thus the easterly flow between 8° N. and 9° N. now tends to be mainly southerly up to Cape
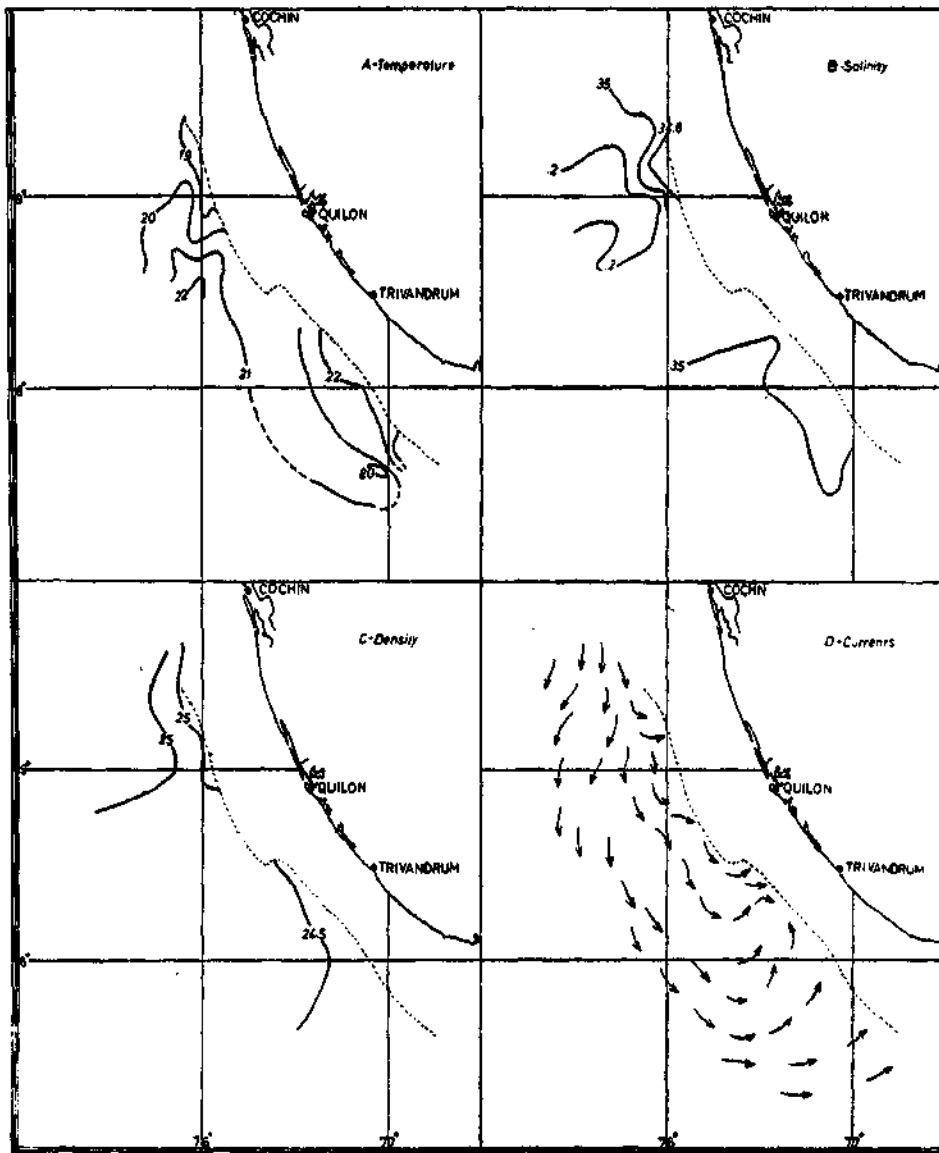
75 METERS

TEXT-FIG. 33. Chart showing the distribution of temperature, salinity, density and the resultant circulation at 75 m. level during the post-monsoon season.

Comorin where it has two branches one towards south probably to flow along the west coast of Ceylon and the other eastwards which at lower depths passes through the Palk Straights. This assumption about the exchange through the Palk Straights needs further investigation especially in that region.

100 METERS

TEXT-FIG. 34. Chart showing the distribution of temperature, salinity, density and the resultant circulation at 100 m. level during the post-monsoon season.

Off Quilon, the thermal structure at 30 m. (Fig. 31) is similar to the one at 20 m. But the isotherms between 8° N. and 9° N. do not follow the coast-line. Eddy formations on 8° N. with north-easterly to northerly tongue

of high temperature above the eddies are smoothed out in the density distribution because of the increase of salinity in the region. Thus the isopycnals run from north-west to south-east with decreasing density away from the coast. Thus the main current is south-easterly with an eastward branch off the Cape Comorin. Though the anticlockwise circulation still persists north of 9° N. the coastal convergence or divergence is eliminated at this level.

Upwelling and divergence near the bottom between 20 and 30 m. along the coast-line (north of Quilon) produce vertical accelerations with resultant lifting of the bottom waters. As the bottom is composed of fine silt, the mud is also consequently lifted up which comes almost to the surface. This mud being kept in position in the regions of convergence along the coast we get the formation of mud banks. Thus, as discussed above, the convergence is taking place against a barrier, *viz.*, the mud bank. With the data on hand it is not possible to study the dynamics of the formation, maintenance and dissipation of the mud banks along the coast-line. But though the circulatory patterns discussed present a relatively simple mechanism the system would be one of a complicated nature because of various forces coming into play simultaneously.

The transition between the southerly flow in the upper layers and the northerly subsurface counterflow in deep layers takes place between 50 m. and 75 m. Thus irregular tongues of higher temperature extend towards north, from the southernmost regions at 50 m. (Fig. 32) ultimately to develop higher temperature along the coast from 75 m. (Fig. 33) downwards. Likewise the salinity has also increased between 8° and 9° N. at 50 m. with a number of breaks in the isohalines whereas at 75 m. high salinities are found only south off Trivandrum. With these changes the density decreases southwards the isopycnals being nearly perpendicular to the coast at 50 m. and parallel to the coast at 75 m. The resultant circulation at 50 m. is eastwards in the region between Quilon and Cape Comorin, whereas in the same region at 75 m. it tends to be cyclonic which finally becomes northwards at 100 m. But in the region north of Quilon associated with low temperature and high salinities the current north of 9° N. is either north-easterly or cyclonic. But with a further decrease in salinity and temperature at 75 m. the density distribution is uniform giving a southerly flow in the region north of 9° N. and this flow forms the major arm of the cyclonic circulation in the south.

The general fall in salinity near bottom at 100 and 150 m. is overcompensated by the corresponding decrease in temperature as such high density

150 METERS
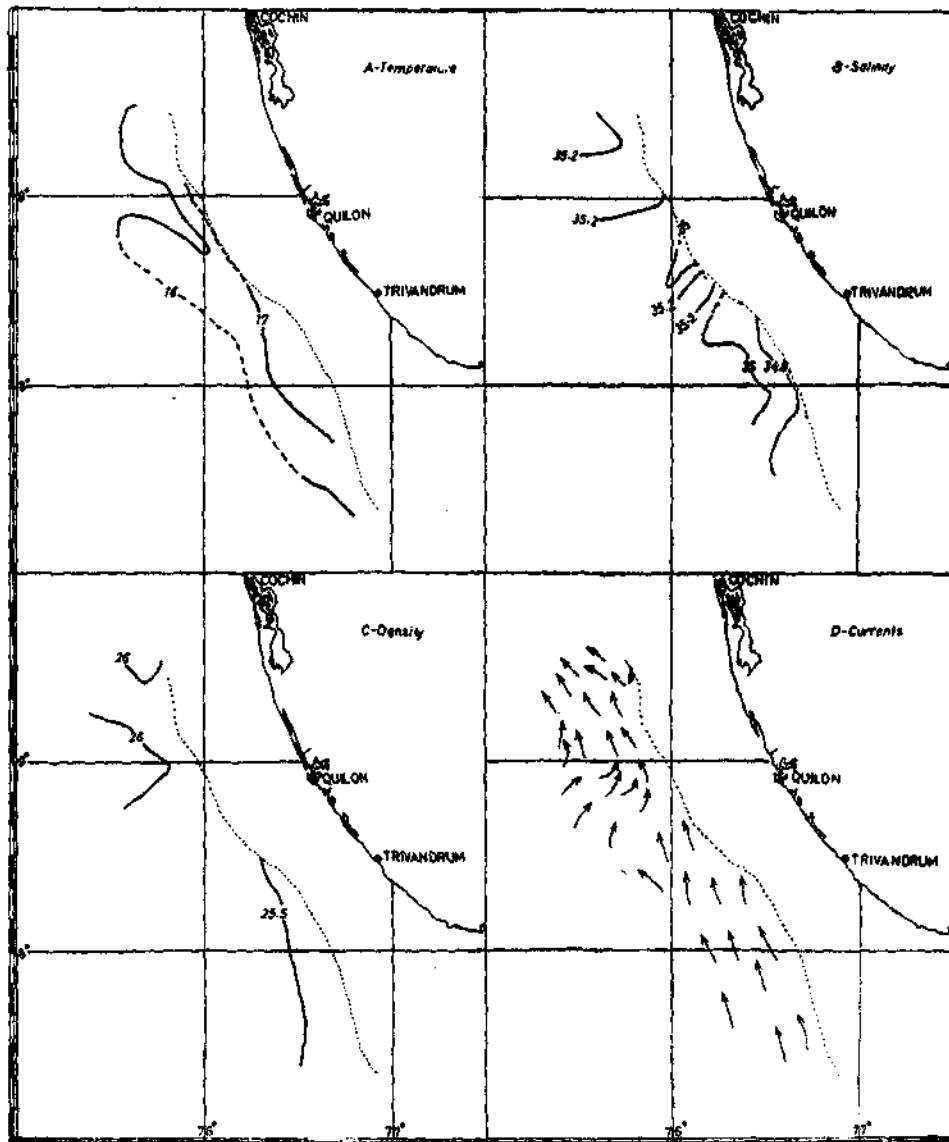
TEXT-FIG. 35. Chart showing the distribution of temperature, salinity, density and the resultant circulation at 150 m. level during the post-monsoon season.

appears towards the coast at these levels (Figs. 34 and 35). Consequently the main flow is northerly at 100 m. But at 150 m. in the northernmost regions current tends to be north-westerly and this branch, as has been con-

cluded from the vertical sections may be flowing into the Red Sea at still deeper levels.

It is assumed that this deep water circulation has its source from the north equatorial current of the Indian Ocean as revealed from the T.S. characteristics. This feature would be discussed more completely in the coming publications.

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