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HYDROGRAPHY OF THE LACCADIVES OFFSHORE WATERS— A STUDY OF THE WINTER CONDITIONS*

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A DETAILED study of the hydrography of the waters of the Laccadive region was first carried out during the summer of 1959 and the results have been presented and discussed by Jayaraman *et ah* (1959 & 1960). To investigate further about the winter conditions of this region, a cruise on board the Research Vessel *VARUNA* was undertaken during the second half of December, 1961 and the data collected form the subject matter of the present report.

COLLECTION OF DATA AND MODE OF TREATMENT

Thirteen hydrographic stations (Fig. 1) were occupied during the cruise, the locations of which are given in Fig. 1. Temperature and salinity observations were made serially at all stations, while oxygen and pH measurements were carried out

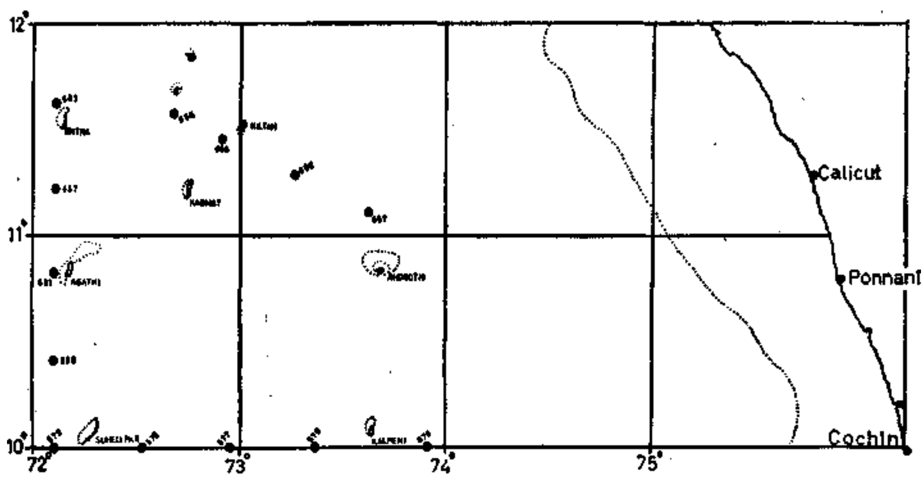

Fig. I. Geographical location of the hydrographic stations in the Laccadives region.

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at alternate stations, and at two stations, respectively. All the international depths from surface to a maximum of 2000 m. were sampled wherever possible. Due to the limited range of the Echo-sounder on board R. V. *VARUNA* viz. 1500 m. at that time, the Admirality charts had to be consulted for greater depths, and hence the bottom profiles given in the vertical sections are only approximate.

In order to bring about a good comparison and the influence of watermasses of one area on that of another allthe stations of the three different sections are plotted along a single straight line with adequate spacing in between, and the change from one section to another is indicated by broken lines. Furthermore, the depth scale below 200 m. in the vertical sections has been reduced to l/5th of the scale used in upper 200 m. Computations of geopotential anomalies were made and a vertical profile of the isobaric surfaces with reference to the 500 db. surface was drawn to get a general idea of the relative currents.

VERTICAL DISTRIBUTION OF PARAMETERS

A. *Temperature :* Vertical distribution of temperature is shown in Fig. 2.

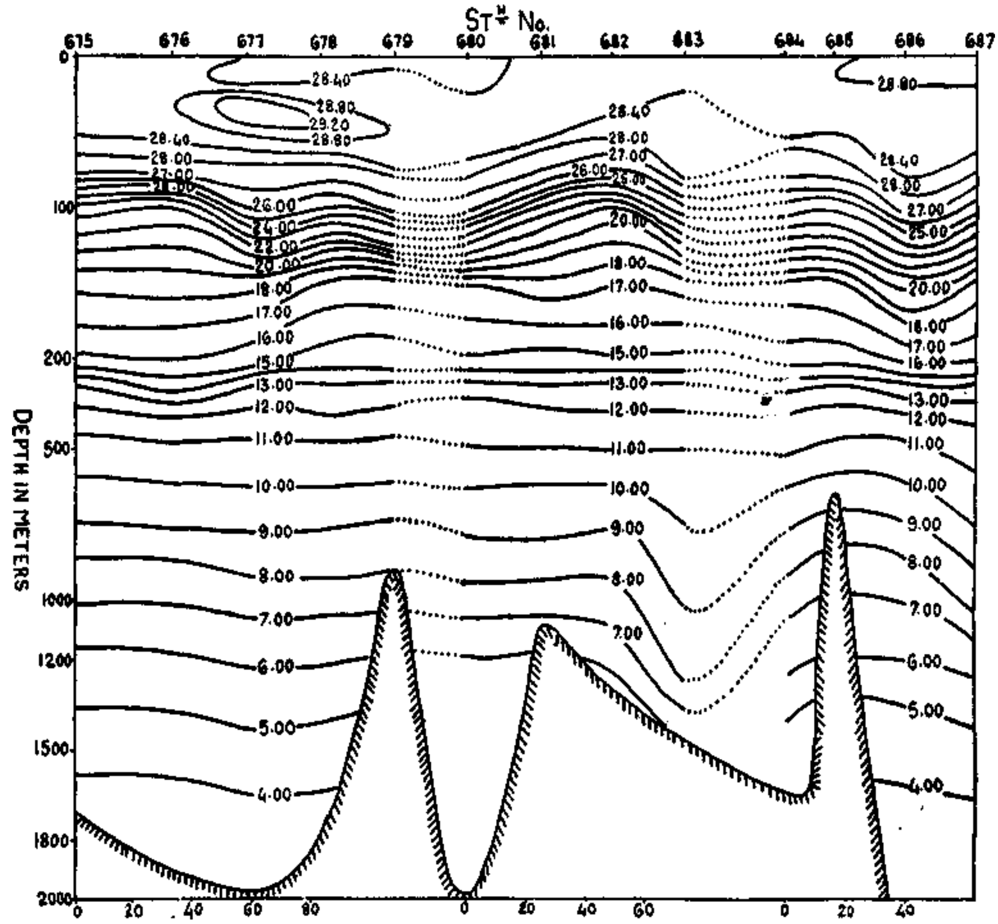

Fig. 2. Vertical distribution of temperature in the Laccadives region.

Continuous record of surface temperature was obtained from the sea surface thermograph, in addition to the surface readings obtained from the bucket thermometer. These records indicate that surface temperature is quite high during the period under consideration and it varied between 28.00 and 29.00°C, along the entire course of the cruise. In general, warmer water was found towards the north-north-western region while slightly colder water was found in the south-western region. It may be observed that a sudden change of temperature (about 0.5°C) occurs in the vicinity of the islands, the exact significance of which will be discussed later in this paper.

The distribution of temperature at subsurface depths shows that large temperature differences exist at equal depths throughout the Laccadive area in and above the thermocline region, while below the thermocline these differences arc reduced considerably with increase in depth. At 300 m. and below the differences are very little. The mixed layer which extends to an average depth of 65-80 m. shows temperature inversion at most of the stations except those which occur in the north-north-western region of the Laccadives. Within the surface layer temperature varies between 28 and 29°C. [In the southern region along Section A, comparatively colder water in the upper 20 m. layer occurs in the middle of the section (Stn. 677)] while below this depth to a maximum of 50 m. an elongated thermal cell of warmer water exists. In the western region of the Laccadives more or less uniform temperature occurs in the mixed layer near Agathi and Bitra islands, but tlve general slope of the isotherms indicates warmer water towards south. The thermocline which begins below the mixed layer extends further to a depth of 150 m. Characteristic ' domings ' and ' depressions ' of isotherms, are noted, within the thermocline, which in some cases modifies the lower limit of the thermocline. Below the thermocline isotherms are nearly horizontal and parallel to the bottom except in the western section, B, and north-north-eastern section C, where they form a depression below 700 m. at Stn. 683, and a doming below 300 m. at Stn. 685.

B. *Salinity :* The vertical distribution of salinity is represented in Fig. 3.

Surface s?"inity varied within a wide range from region to region in between 34.2, and 36.z /)0 the lowest value being observed in the middle of the southern region (Stn. 677) while, highest value was observed in the north-western region (Stn. 681-684). The surface salinity is found to increase northwards, steep horizontal gradients being observed in the north-western region and near Agathi Island.

The distribution of salinity in the mixed and thermocline layers is very much akin to that of temperature, in the sense that considerable differences occur at equal depths at the various stations. From the surface there is found an increase in the salinity depthwise, and at about 75 m. maximum salinity is noted, except for the stations 682 and 686 where the salinity maximum is found at 50 and 30 m. respectively. Within the thermocline the salinity decreases rapidly towards the lower limit of the thermocline and below this, and especially below 200 m. to a maximum of 800 m., the distribution in the vertical plane is nearly uniform. Distribution of salinity in and above the discontinuity layer is quite characteristic in the different sections, the southern section indicating low saline water in the midsection, a steep gradient of 1.4°/00 between 20 and 50 m. depth, while nearly uniform but very high values are observed between 50 and 100 m. depths. The thickness of this layer is more towards the western part where a tongue of high saline water seems to extend slightly towards west, up to about 20 miles west of Stn. 677. Wavelike nature of the isohalines is found within the discontinuity layer. In the western section B, uniform values of salinity are noted in the upper 20 m. layer towards Agathi Island while towards its north a steep upslope is observed. A characteristic feature of this section is the occurrence of a saline eddy of very high value of 37.3°/$_{00}$ with its core at Stn. 682, which extends both towards south and north, most probably limited by the islands of Agathi and Bitra. In this section slightly higher values than the corresponding

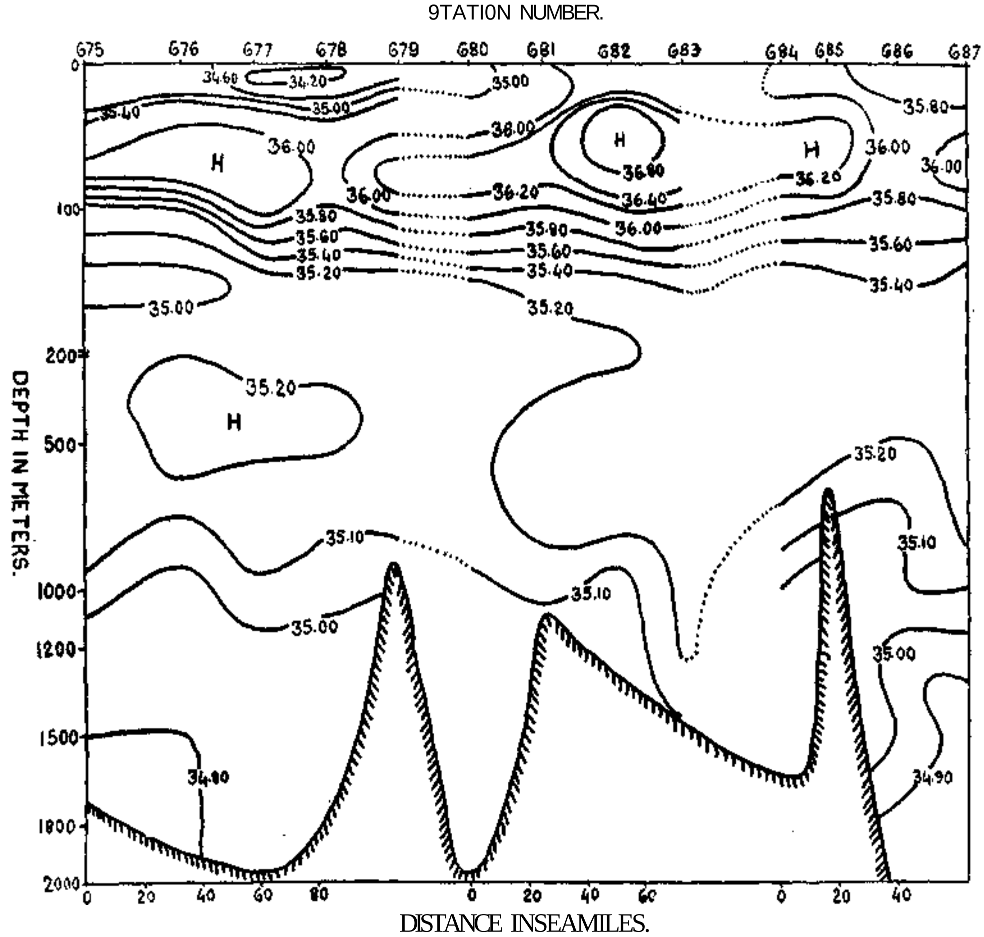

Fig. 3. Vertical distribution of salinity in the Laccadives region.

Section A, occur nearly at all depths. In the north-north-eastern section C, akinto temperature distribution, nearly uniform values of salinity occur in the mixed layer. The region of high saline water as was observed in Section A is in this case at slightly higher depths and is found between 30 and 90 m. The thickness of this layer is found to be reduced to 50-80 m. depth towards the south-eastern part. Below the thermocline region the distribution of salinity is found to be uniform except for an isolated cell of high salinity found at about 200-500 m. in section A.

C. *Oxygen :* Vertical distribution of oxygen is shown in Fig. 4.

The surface values of dissolved oxygen content varied from 4.3 to 4.6 ml/L, slightly higher values occurring between Stns. 680 and 682. The mixed layer contained high amounts of oxygen, a gradual decrease being noted depthwise. Comparatively higher values are found to occur towards western part of section A. In the section extending from Suhelipar to Bitra island a cell of high oxygen having a value of 4.55 ml/L at the core is observed between 30 and 60 m. depth. In the

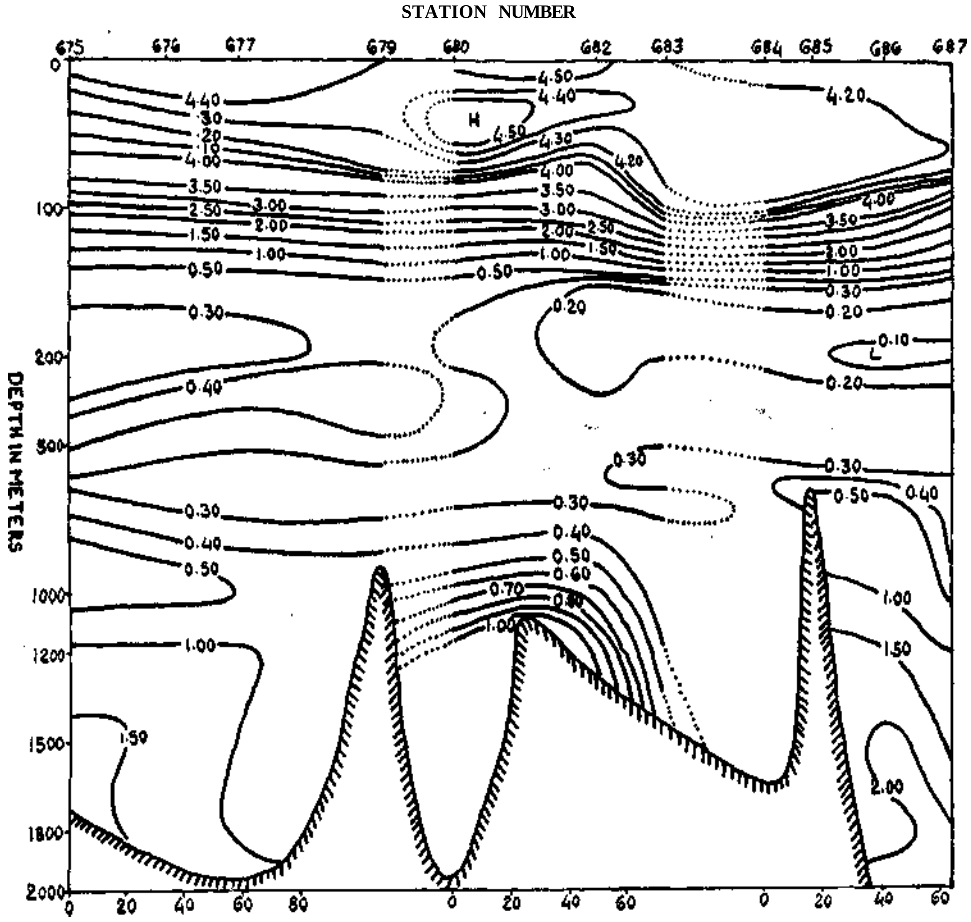

Fig. 4. Vertical distribution of dissolved oxygen content in the Laccadives region.

north-north-eastern section C, however, nearly uniform values occur from surface to maximum depth of 100 m., especially towards the northern region while the thickness of this uniform layer decreases towards south-east direction and at Stn. 686 it is found between 30 and 75 m. depth. Within the thermocline, however, oxygen values are found to decrease rapidly and around 150 m. depth the values range between 0.2 and 0.5 ml/L. Further decrease in dissolved oxygen contents is found to occur to a depth of 200 m., where minimum values are observed (0.05-0.35 ml/L) while below this depth to a maximum of 700 m. the values are mostly uniform, with very little variation. At 800 m. and below, a tendency towards increase in oxygen values depthwise is found, and values as high as 2.45 ml/L are noted at 2000 m. depth.

The oxygen poor intermediate layer mentioned above is the most prominent feature of the oxygen distribution of the ocean in middle and low latitudes. Below this minimum layer the oxygen rich water encountered within the Laccadives region, is nearly 60 % saturated. This oxygen content of the deep sea circulation of the oceans originates from the major convection areas of the subpolar and polar regions of the ocean, where the watermasses in the surface layers can sink to great depths and from there also fill the depths at middle and lower latitudes. In spite of the long path travelled by these watermasses there is little depletion because of the low temperature and the small amount of organic material present, and the oxygen content shows only slight decrease. (Defant, 1961). Later observations made on board R. V. *VARUNA* in deeper waters of the Arabian Sea have indicated values as high as 3.7 ml./L at 3500 m. depth.

In section B, below the oxygen minimum layer the amounts of dissolved oxygen are found to be lesser than the other two sections. It is well known that enclosed stagnating watermasses will always have low oxygen content and have minima extending almost to the bottom. Compared to the other two sections A and C, section B lies between two submarine ridges and this may limit thermohaline circulations and mixing. In Section C a tongue of high oxygen rising from a depth of 1800 m. from the south-east is formed andean be traced slightly even above 1500 m. at Stn. 686, striking it at 1200-1400 m. depth therby slightly deflecting in the north-easternly direction. Thus, this oxygen rich water rising along the submarine ridge and modifying the waters in the upper layers between 700 m. and 1500 m. seems to be an important feature.

D. *pH:* The vertical profiles of pH are given in Fig. 5.

pH determinations were made at two stations only, one being in section A, where oxygen sampling was done and the other in section B, where no oxygen sampling was carried out. pH measurements were carried out on board R. V. *VARUNA* by a Radiometer, Copenhagen pH meter 22. A general idea about the pH variation could only be given due to scarcity of data.

pH varied between 8.30 and 8.35 at the surface. Uniform values were noted in the mixed layer (variation being 0.10 pH), with slight increasing trend towards a depth of 20 to 30 m. A rapid decrease is found to occur within the thermocline, and around 150 m. depth it was mostly between 7.90 and 7.98. A further decrease is found to occur up to 300 m. and between 300 and 1000 m. the values are fluctuating very little. Below 1000 m. a slight increase is indicated.

E. *Specific Volume Anomaly :*

Computations of sigma-T and specific volume anomaly were carried out from serial temperature and salinity observations. As isosters and isopycnals obtained from the vertical profiles of specific volume anomaly and sigma-T respectively, lead to the same interpretations, vertical distribution chart of only the former is given here and is represented in Fig. 6.

The distribution of specific volume anomaly is very much akin to that of temperature especially in and below the thermocline region, while in the mixed layer, during the observational period considerable influence of salinity is indicated. As is shown by both temperature and salinity, considerable differences at equal depths occur in the mixed and discontinuity layers. In the mixed layer lighter water is observed slightly towards east of Suheli par island within the upper 20 m. where a general upslope of isosters is observed towards west the gradient being very small. In section B, water of same specific volume anomaly as was observed in the middle of section A, is found to extend towards north up to Agathi island. Considerable slope of the isosters occurs between Suhelipar and Bitra. Characteristic 'domings'

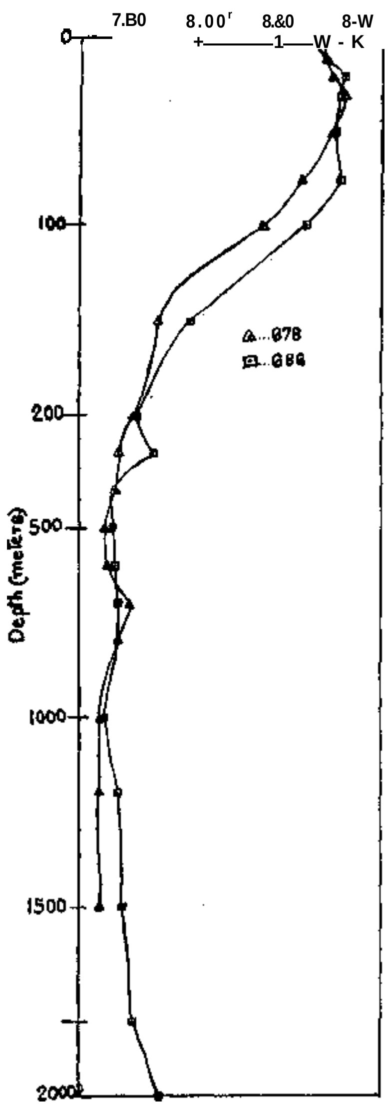

Fig. 5. Vertical' pH ' structure.

and ' depressions' are observed below 30 m. depth in all the sections up to the lower limit of the discontinuity layer, below which the isosters are mostly horizontal. Since the bottom topography can modify the temperature structure, slight' domings' and ' depressions ' in the specific volume anomaly distribution are noted at deeper depths.

CHARACTERISTICS OF WATERMASSES

T-S diagrams of nine representative stations are given in Fig. 7. In constructing these the upper 30 m. layer has been omitted as this is subjected to local influences

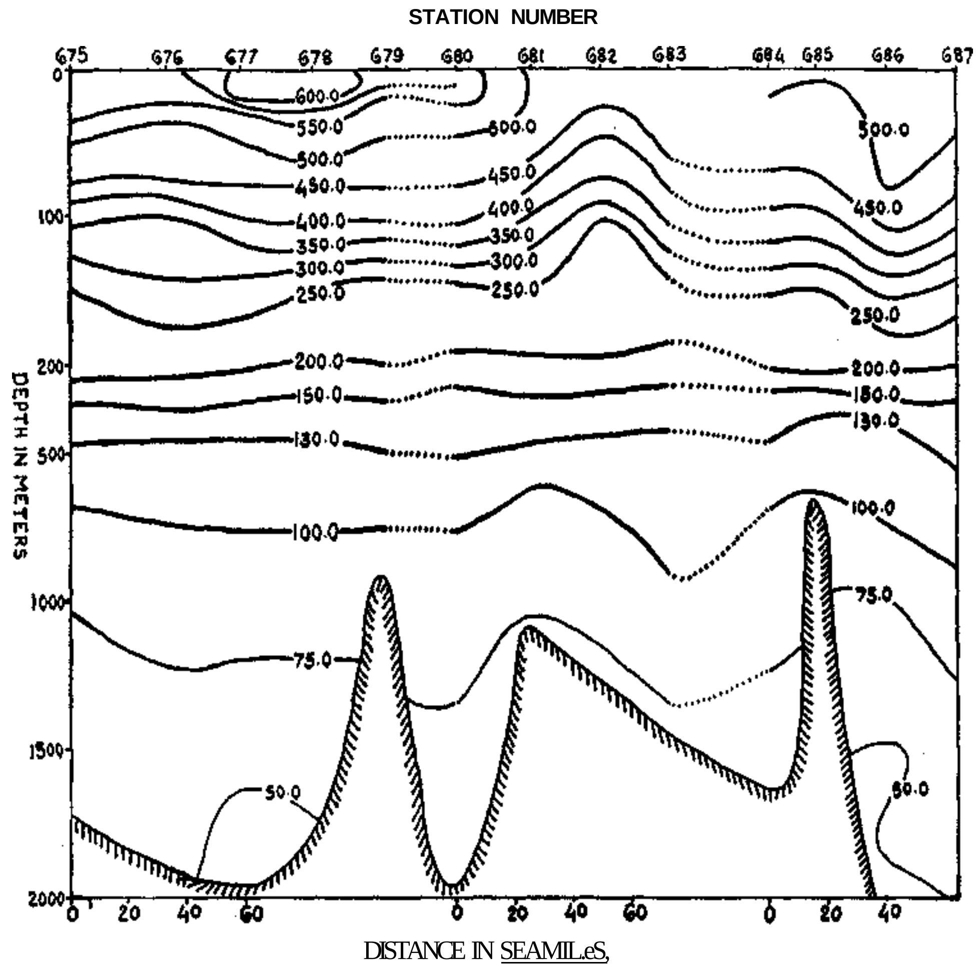

Fig. 6. Vertical distribution of specific volume anomaly in the Laccadive region.

(Jayaraman, *et al.* 1960). The curves of the three different sections are plotted differently in order to depict their salient features.

The upper 200 m. layer which constitute Arabian Sea water has different T-S characteristics from the one below this level, i.e. the Indian Ocean Equatorial, water (Defant, 1961; T; 4-16°C, S.; 34.8-35.2°/$_{00}$). In the present investigations the lower and upper salinity ranges are found to be slightly lowered and increased respectively, which is supposed to be a feature of the season. A probable explanation for the lower salinities below 1200 m. at certain stations can be that Antarctic Intermediate water, a tongue of which proceeds crossing the equator to the south of Ceylon, and (Sewell, 1925-29) bifurcating towards Arabian sea and Bay of Bengal can be traced in the eastern part of the Laccadive region. The occurrence of high oxygen values at these levels observed towards the eastern part of the Laccadives, lend support to the above explanation.

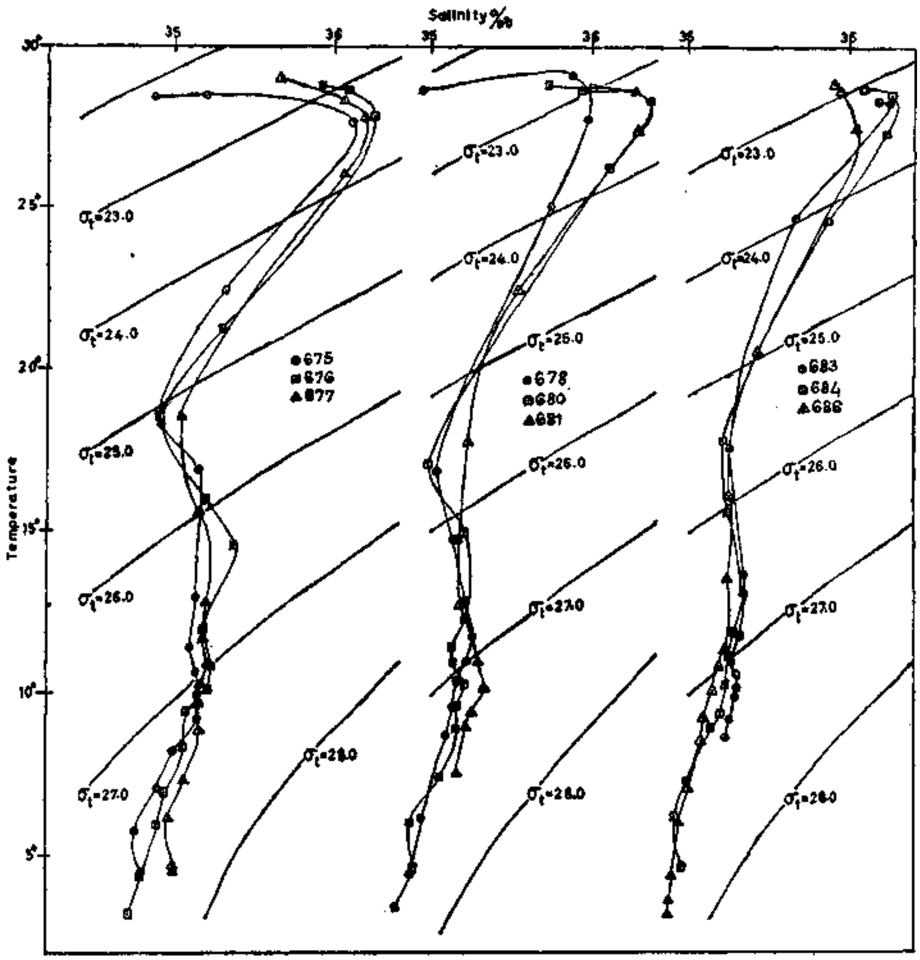

Fig. 7. Temperature-Salinity relationships in the Laccadives region.

The Arabian sea water can further be classified into three classes as suggested by Jayaraman, *et al.* (1960) when discussing the water masses of this region observed during the summer of 1959. The water masses are :—

1. The surface layer, which is transitory and does not show any definite characteristics and which is undergoing transformation continuously due to mixing caused by local conditions. This layer extends up to 30 m. from the surface.

2. The upper subsurface water, characterised by small temperature range with a sharp salinity gradient; this layer extends up to 80 m. depth and in a few cases to somewhat greater depths. It is interesting to note that this layer shows quite

a wide variation in salinity especially in the upper layers with regard to the geographical position of the stations, the southern region showing greater variation than the northern region. This is due to the latitudinal difference of the northern region, which shows higher surface salinity. Sinking and turbulence minimises the salinity difference. Owing to these reasons it is found that the upper subsurface water as described by Sastry (1960) and which is found between the 21.00 and 23.00 sigma-T surfaces in this region (Jayaraman, *et ah,* 1960) shows higher values of salinity and gives rise to more or less uniform density layer (23.00-23.50). It is evident that a good deal of mixing is taking place in this layer.

3. The lower subsurface layer. Below the above layer and up to 150 m. the watermass is characterised by a steep temperature and comparatively low salinity gradient. The sigma-T values lie between 23.50 and 25.50, again showing an increased range than that observed during summer. Though mixing is indicated in this layer it is comparatively less than what is observed in the upper layer.

WATER MOVEMENTS

Water movements are primarily envisaged from the distribution of properties from surface to bottom, special mention being made to density and specific volume anomaly. In addition to above, to have a more clear idea of these movements a vertical profile of the isobaric surfaces relative to the 500 db. surface was plotted.

It can be seen from these vertical charts that circulatory movements are present during this period as was observed during summer, the intensity of these however, being considerably reduced and particularly limited to a shallow depth of about 200 m. Significant circulatory movements are found in the northern region especially near Bitra island where it is cyclonic while near Agathi and south-east of Kiltan island (Stn. 686) it is anticyclonic. Superimposed upon this general circulatory movements around the islands north-westerly drift produced by the prevailing winds is noted in the upper 30 m. towards west of Suhelipar in Section A, and further towards east due south of Agathi island as indicated from observations of temperature, salinity, and density. North of Agathi and Androth islands an easterly drift in the upper layers is indicated. Probably due to these opposite currents, and to a lesser degree due to the prevailing winds which cause turbulence, quite uniform values of the hydrographic parameters are found near Agathi, Bitra, Kadmat and Chetlat islands as discussed previously. There does not seem to be any appreciable degree of water movements at the subsurface levels. The influence of bottom topography on the distribution of various parameters in the subsurface waters could already be seen in this region as elsewhere is described by Lukyaanov and Moiseyev (1960). It is obvious that nearly all the parameters follow the bottom contour especially over a ridge that occurs at Station 681. In the noithern Section C, considerable slope of isopycnals and isolines for Dyn. Ht. Anomalies between the depths of 700 and 1800 m. are noted and observations of other parameters as temperature, salinity and oxygen indicate considerable movements. An important characteristic of the season is the sinking which is seen along the 23.00 sigma-T surface especially in the western section B. The surface salinity of the north-north-western region is very high and is supposed to be due to the excess of evaporation over precipitation which is a characteristic of the winter season.

COMPARATIVE FEATURES OF THE SUMMER AND WINTER CONDITIONS

A comparison of the observations during this period with those of during summer reveals the following salient features. General circulatory movements observed around the islands during summer, are not very significant in this season, the intensity and the lower limit up to which the movements occur being comparatively much less and superimposed upon these movements, north-westerly drift in the southern region and easterly drift in the northern region are noted during winter, while absence of these are observed during summer. Sinking, observations of very high values of salinity from surface downwards, and turbulence near the islands probably due to the prevailing winds or due to the reversed current system or both, is noted in the upper layers.

SUMMARY

The paper deals with the winter conditions observed in the Laccadive region and is a continuation of the work done during summer by Jayaraman et al. (1959, 1960). The vertical distributions of the various parameters are discussed, water masses traced and discussed, and water movements are shown. A comparison of the winter and summer conditions is also made. During winter high surface salinites and sinking are noted. Lateral movements at surface and at very great depths were observed. However, these movements are not appreciable. Also circulatory movements, on a considerably reduced scale than those observed during summer, were noted during the period of investigation. The watermasses viz., Arabian Sea lower subsurface water and Indian ocean equatorial water mainly contribute up to 2000 m. depths and presence of Antarctic Intermediate water especially in the eastern part of the Laccadives region above 2000 m. was traced.

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