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WATER MASSES AND THE FREQUENCY OF SEA WATER CHARACTERISTICS IN THE UPPER LAYERS OF THE SOUTH EASTERN ARABIAN SEA*

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INTRODUCTION

The *temperature-salinity* diagram, introduced by Helland-Hansen has become very important in Physical Oceanography for the study of water masses of the Oceans. But the seasonal and local variations of these parameters restrict the use of the T-S diagrams for the topmost layers of the Sea. Thus it has become necessary to describe the characteristics of the upper layers of the sea both in time and space. Though the seasonal variation below 20 m is not very prominent, localities influenced by processes like upwelling, local variations are very important. It is so because the surface layer will be completely replaced by the subsurface water. In such instances it is desirable to use a consistent nomenclature for the water masses identified to avoid confusion.

During the periods of intense vertical mixing the T-S relations are non-stationary in the upper layers as such the individual variations could not be clearly brought out in the mean vertical T-S diagrams. But a scatter diagram for any specified level in the temperature—salinity co-ordinates will give a two-dimensional picture of the frequency distribution as has been worked out by Cochrane (1956) and Montgomery (1955). Even for constructing these, simultaneous serial oceanographic observations are never available. Thus the effect of the individual seasonal and local variations could not be completely eliminated. But these could be minimised by reducing the period and increasing the number of observations in any given region when the frequency distributions are constructed from serial observations of temperature and salinity.

Hence in the following monthly frequency distributions are given for five months for the area between 7°20′N to 12°15′N and 74°E to 77°30′E. Unfortunately this entire area could not be covered in every month as such the monthly distributions represent the sub areas given in Table I.

TABLE I

Areas covered in different months together with the number of stations.

Month.	*Area*	*No. of stations.*
September 1957	9°N to 9°30′N. and 75°30′E. to 76°30′E.	32
October 1957	7°20′N to 8°45′N. and 75°30′E. to 77°30′E.	50
November 1957	9°45′N. to 11°30′N. and 74°20′E. to 76°10′E.	78
December 1957	10°15′N. to 12°15′N. and 74°E. to 76°E.	44
April 1958 (including a few observations on the 31st March 58)	8°N. to 12°15′N. and 74°E. to 77°20′E.	74

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But these monthly distributions could be considered as representative of the whole region, within the limits of accuracy that could be expected of a statistical method as this, in view of the fact that the water masses in this small region are not essentially different as was shown by the author elsewhere. Further, this method serves the purpose of studying the seasonal variations of the different water masses present.

Data and Methods

The data used in this investigation were collected between September 1957 and April 1958, mostly on board R.V. 'Kalava' and at the first 32 stations on board R.V. 'M.O. Kristensen'. A station was made every five miles, starting from 10 fm. line (about 15 m.) along the west coast of India, over the continental shelf and every 10 miles thereafter. Most of the sections are on the parallels with a latitudinal separation of 10 to 15 miles and they extend to about 65 miles off the coast. During February 1958 the area between the Laccadives, and the Indian Coast lying between 8° and 11°N was occupied by 16 stations. Only during April 1958 the lines of stations were oblique to the coast. Serial hydrographic observations were made at every station by standard methods thus obtaining temperature and salinity data at all the International depth levels normally up to 500 m. and occasionally up to 2000 m. Frequency distributions for February are not included in this study as they do not represent the area under consideration.

Following Montgomery and Cochrane a sea water characteristic is defined as point on the T-S diagram for any specified level and the characteristic class represents the area on the diagram between the class boundaries of the variates. The number of observations falling within the characteristic class for any specified period denotes its frequency. This last definition is different from that of Montgomery or Cochrane, in that the present definition does not include the duration of the characteristic class during the period in question. This has become necessary because, observations were not repeated at any fixed station during the specified periods and further the local fluctuations (with time) are not known adequately. This amounts to the assumption that characteristic classes are stationary in given localities in each of the periods. But this assumption for our purposes, seems to be justifiable, as has been pointed out by Cochrane. Though in general the local range of salinity during any period is less than its class interval (0.25‰) the corresponding temperature change is somewhat higher in certain periods. But this does not have very much influence in shifting the modes of the two dimensional distribution. Thus the central tendencies of the distributions are representative of the periods for purposes of studying the water masses and their transition through seasons.

Temperature and salinity ranges for the respective class intervals are 0.5°C and 0.25‰. The frequency of the characteristic class, expressed as percentage to total number of observations utilised at any specified level of a period, is entered at the mid value of the characteristic class. Smooth isopleths of percentage frequencies were entered in each diagram to understand the differences from level to level or from month to month. In the same diagrams frequency curves of the individual variates were drawn on the respective areas as abscissae. From the original data monthly mean vertical T-S diagrams were drawn and isopycnals expressed as constant to σ_t lines were entered in all diagrams.

Discussion of Results

The frequency distributions were drawn for each month at the sea surface, 10 m, 20 m, 30 m, 50 m, 75 m and 100 m levels. But the 100 m level charts are not presented here because the total frequency is too rapidly decreasing with depth below 50 m, though the important features are discussed here.

September :

This is the period of upwelling along this coast and the subsurface water mass between 75 and 100 m in undisturbed conditions is drawn up to the surface. Consequently very low temperature and high salinities would be encountered at all levels. Mixing of the upwelled water changes its characteristics as will be shown later in this section.

Except at 10 m (Fig. 1) the salinity is unimodal (between 34.75 and 35.25) at all levels where as temperature shows a number of modes with a prominent one corresponding to the unimodal salinity interval. Surface and 20 m distributions are vertically elongated and bear certain resemblance with the vertical T-S curves (Fig. 5) indicating the presence of the same water mass both horizontally and depth wise up to 30 m. As the upwelled water flows away from the coast in the upper levels one is to expect the characteristics mentioned. The characteristics at 10 m indicate two modes the prominent one corresponding to lower levels. Gradual increase in salinity and a steep decrease in temperature with depth highly concentrated unimodal distributions were found at 30 m and downwards. Thus in September as will be shown later a single water mass is found in the upper 100 m.

October :

A further rise of salinity during October (Fig. 2) compared to September, is a result of the absence of precipitation at surface levels. The presence of the same water mass as in September below 50 m. depth, though upwelling decreases almost in October, is the result of intense mixing and displacement of higher salinities at all depths. The presence of the same water mass as in September, with the modifications described above could be very well seen from the similarity of the isopleths in October 50 and 75 m levels and September surface and 20 m levels.

At all levels salinity is unimodal whereas the frequency curves of temperature are similar to those in September. With decrease and gradual absence of upwelling in the upper 30 m the continuity of the water mass is lost or modified. Thus the surface distribution appearing as the figure of eight breaks into a number of isolated concentrations of the characteristics in the upper 30 m.

November :

Near winter conditions are setting during this month and with the complete absence of upwelling, the water drawn up to the upper layers has settled in its normal depth levels. Further the surface layer with low salinities has formed and there is nearly 1.5°C rise in temperature in the surface water. This, as shown in the following, is the characteristic Arabian Sea surface water. The characteristic formation of the thermocline in the equatorial water has appeared between 50 and 75 m. Thus the frequency distribution of the characteristics are essentially different from the earlier months at least up to 50 m. Low salinity and high temperature characteristics reduce density of the surface layers.

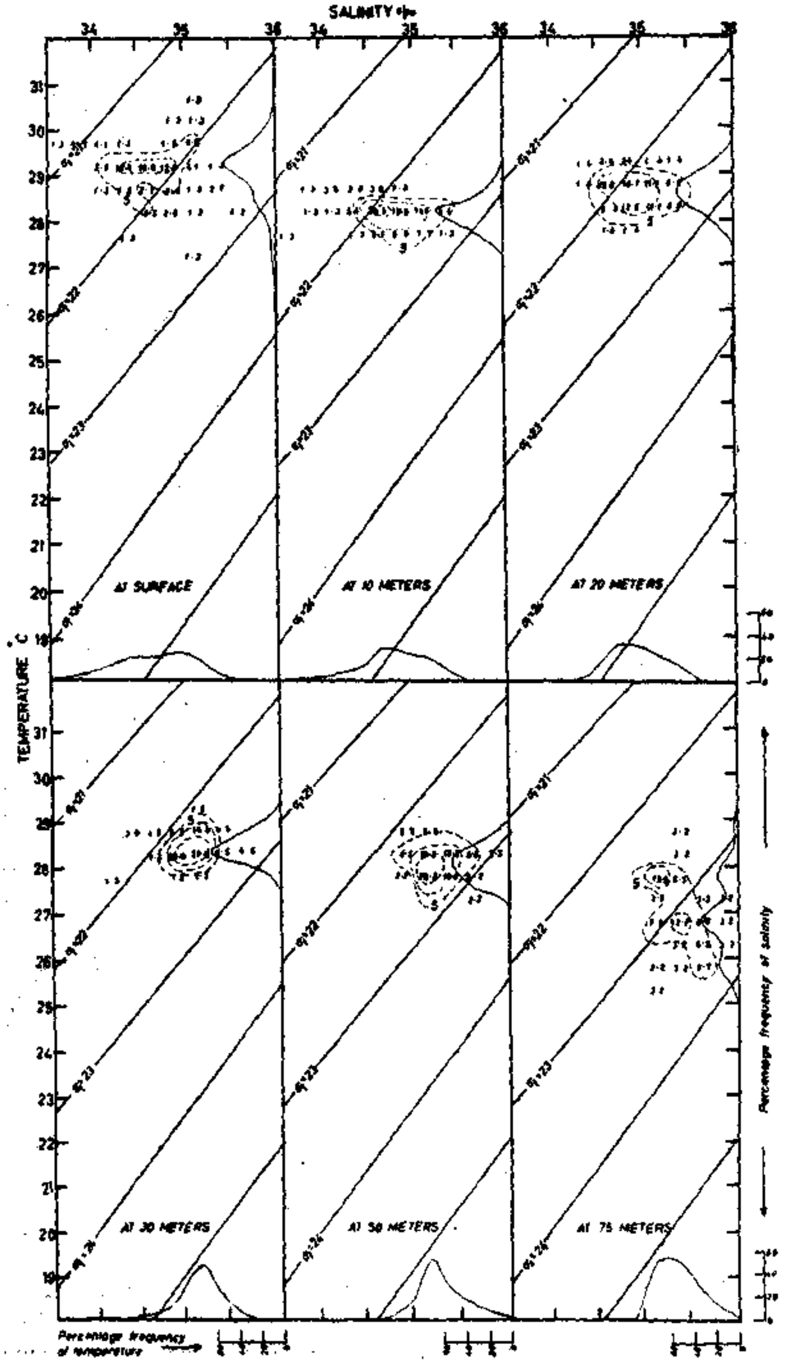

FIG. 1. Frequency distribution of the sea water characteristics at different depths during September (lower figures) and April (upper Figures). Frequency curves of temperature and salinity are shown on the respective axes. Dotted frequency curves represent April.

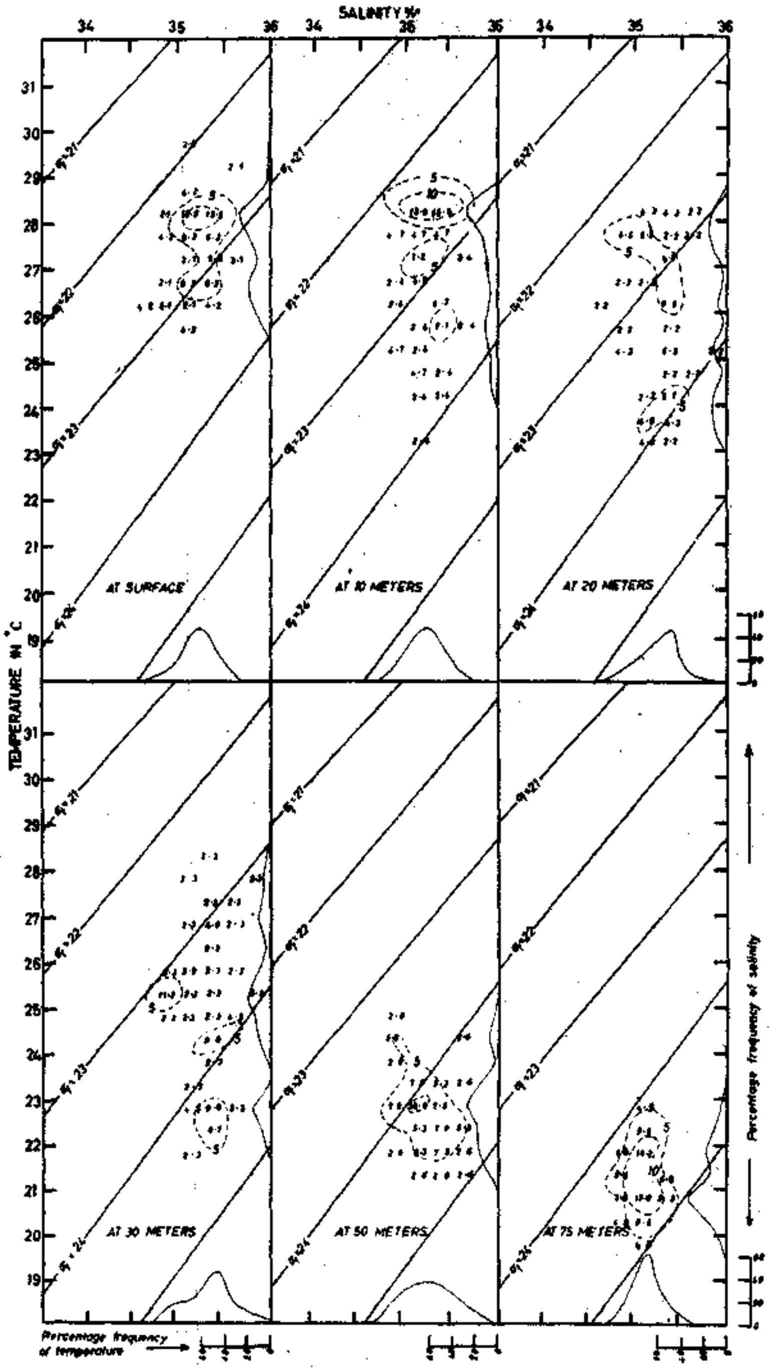

FIG. 2. Frequency distribution of the sea water characteristics at different depths during October. Frequency curves of temperature and salinity are shown on the respective axes.

The frequency curves of salinity (Fig. 3) are very flat peaked in the upper 20 m and show a marked peakedness in deep water up to 100 m. in constrast with the earlier periods. Further the temperature is unimodal in the upper 50 m, though it retains its earlier characteristics at 75 and 100 m. Nearly horizontal (same temperature) elongated frequency distributions in the upper 20 m bear a similarity to the vertical T-S relation (Fig. 5) indicating uniform mixed layer. At 80 m and 50 m the distributions appear as if the upper distributions were rotated clockwise through 90° and gradually shifted to a high σt surface. But November 75 m distribution appears to be a mixture of the water mass found in the surface layers in September and the one between 30 and 50 m in October. Thus at 75 m the water mass is still undergoing transition. The water at 100 m. level appears to have the characteristics intermediate to those found at depths of 75 m. in October and 20 m. in September. These changes indicate gradual retreat of the upwelled water to its normal level during November. On the contrary the water found at the sea surface during the period of upwelling has got the characteristics of that water which normally occurs between 75 m. and 100 m.

December :

Complete winter conditions in December reduce temperature up to 50 m by about 1 to 2°C (Fig. 4). With cooling at the sea surface thermal inversions are frequent in the topmost layers. With further deepening of the formation of the thermocline and vertical mixing followed by surface cooling, keeps the temperature range in the mixed layer very low. But in the same layer salinity variation has not decreased as much as in the previous months.

With greater uniformity of temperature in the layer depth, temperature frequency curves are very peaked and unimodal. Salinity distributions are also unimodal at all levels except at the surface and 50 m. General increase of salinity seawards and differential evaporations related to the geographical relation of land and sea, result in different modes of salinity at the surface. The increased vertical stability at the top of the thermocline whose depth of formation is varying could be attributed to the bimodal nature of salinity at 50 m. Hence the frequency distributions of the characteristics indicate good vertical stability up to 50 m and they bear a certain resemblance to the pre-winter conditions. Further, the mean horizontal characteristic resembles somewhat the vertical T-S relation suggesting the homogeneity and the mode of formation of this water. The observations at 75 m are not sufficient for purposes of comparison, but the characteristic distribution strongly suggests the possibility of the existence of partly the surface water up to 75 m and partly the subsurface water to which reference will be made later.

April :

This month represents hot weather season and consequently the sea surface temperature is maximum and in the topmost layers of the sea the temperature decreases by about 1°C in 25 vertical metres. Thermocline forms at 60 m with increasing depth towards north. The range of salinity is from 33.50‰ to 36.00‰.

Up to 30 m salinity shows two modes (Fig. 1) between 34.0 and 34.25‰ (the prominent) and 34.75 and 35.0‰ (the secondary one). The same characteristic with a displacement of 0.25‰ is found at 50 m. and 75 m levels. Temperature except at the surface shows only one mode at all levels and the modal value decreases depthwise. The presence of two modes at the surface is related to the high coastal values.

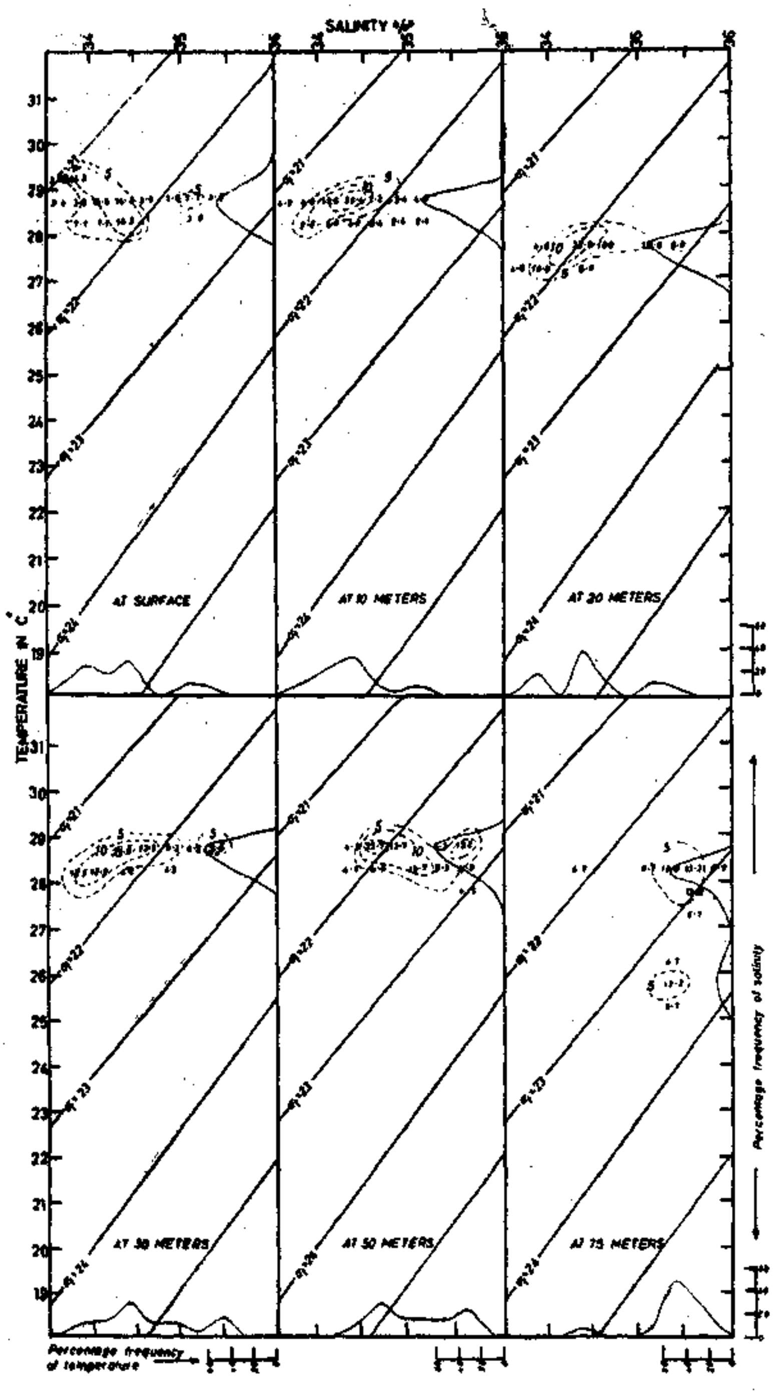

FIG. 3. Frequency distribution of the sea water characteristics at different depths during November. Frequency curves of temperature and salinity are shown on the respective axes.

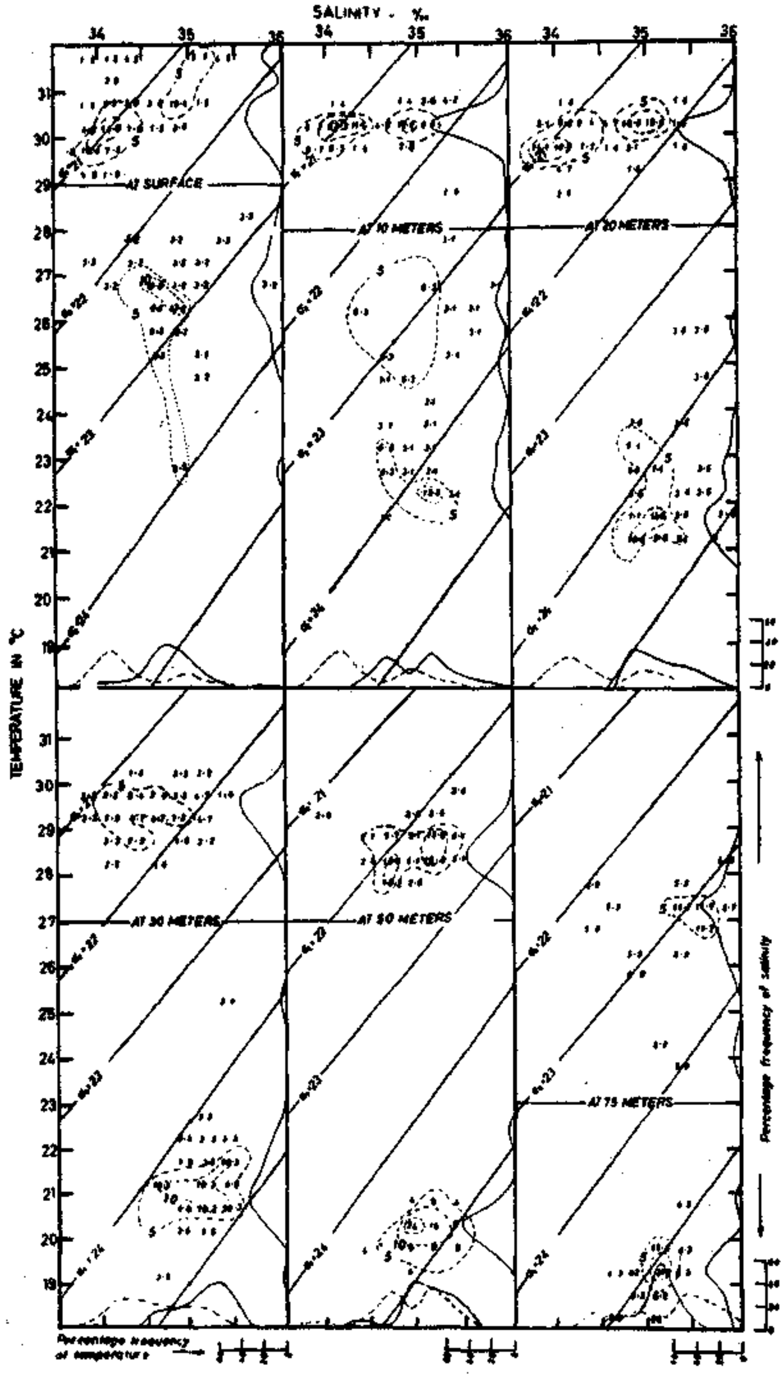

FIG. 4. Frequency distribution of the sea water characteristics at different depths during December. Frequency curves of temperature and salinity are shown on the respective axes.

Associated with these up to 20 m the frequency distributions are bimodal and thus the presence of two different water types one with low temperature and low salinity and the other less prominent one with high temperature and salinity could be traced. The latter one was found in the northern-most region. But at 30 m the water mass is nearly uniform (within σ_t's=21 and 22 ; S=34.55‰ and T=29.35). The bimodal distribution of 50 m depends greatly on the depth of formation of the thermocline. At 75 m a single mode centered at 27°C and 35.5‰ indicates the characteristic northern water which in fact is the prominent water mass of the region whereas the other type found in the upper levels results partly from the dilution by the rivers near Calicut and from the influence of the Cochin backwater system.

In general, the distributions are highly concentrated at all levels during winter and less in summer and the least during the period of upwelling in contrast with the sea surface distributions of the Pacific Ocean, according to Cochrane (1956) where the distributions are highly concentrated during summer and less in winter. Further, in our case the percentage of concentration within the same percentage-frequency isopleths is more than three times in winter and twice in other months compared to the Pacific conditions. Of course, this is easily understandable because of a very small region of the present study where many water masses could not be present compared to an ocean wide investigation.

The proportion of the total frequency enclosed within the 5 and 10 per centage-frequency isopleths increase depthwise in the topmost 50 m. during the entire period except towards the end of upwelling. The upwelled water while returning to its normal σ_t level it mixes both laterally and vertically resulting in a uniform distribution without marked peakedness. Thus, during this period the water mass is in transition between Arabian Sea surface water and the subsurface water.

Water masses of the upper layers

While discussing the frequency distributions the existence of two principal water masses in the upper 100 m was clearly brought out. These water masses may be named as the Arabian Sea surface water which extends up to about 75 m. and the Arabian Sea subsurface water lying just below the surface water probably extending to about 30 m and completely filling the continental shelf along the coast in question. The Arabian Sea subsurface water can be subdivided into two different masses depending whether or not it is interacting with the upper water mass during the periods of seasonal upwelling. The subdivided masses can be termed as the Arabian sea upper subsurface water and the Arabian sea lower subsurface water.

Mean monthly T-S relations in the upper layers from September to December (1957) and February and April (1958) are given in Figure 5. Also for comparison three Dana stations between Ceylon and the African Coasts were included in the same diagram. As conditions are stationary in winter without local secondary circulations and further as all stations during February were far removed from the coastal effects the February T-S relation can be considered as typical T-S characteristic of the Arabian Sea. The remarkable coincidence of the Dana station 3912 off the West coast of Ceylon clearly supports the view that the undisturbed condition in the South eastern Arabian Sea are found during winter. In this period the salinity rapidly increases in the upper 75 m. without much range in temperature

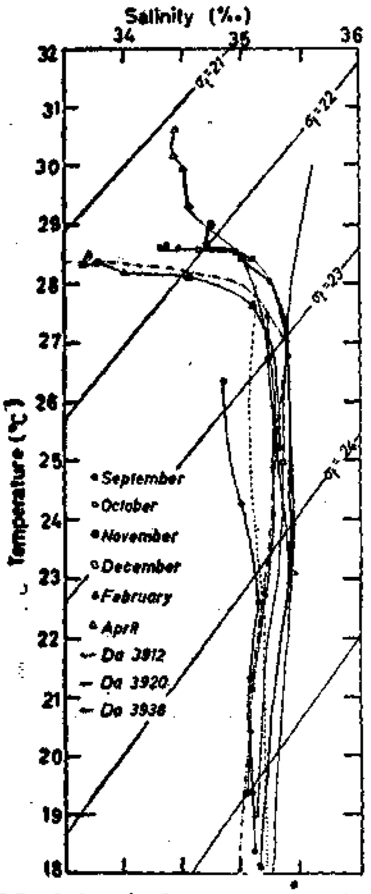

FIG. 5. Mean monthly T-S relations in the upper layers of the south eastern Arabian Sea together with three *Dana* stations in the Arabian Sea.

(mean value 28.2°C.). Between 75 and 100 m. salinity variation is very small while the temperature decreases rapidly. Thus the two straight parts of the T-S characteristics are representative of two distinct water-masses, they could be termed as the Arabian Sea surface water and the Arabian Sea subsurface water. These water masses are formed in the Arabian Sea itself in the regions where high salinity is found at the surface. In the same region the high salinity water sinks and mixes with low saline coastal water to form the subsurface water. Further sinking at the regions of formation leads to the I-water of Thomsen (1933) at 400 m. (T=11°C. and S=35.15‰). Thus the Arabian Sea subsurface water with higher salinity than 35.15‰ is in continuation upwards of the I-water of the Indian Ocean and it maintains its level because of higher temperature especially in the thermocline. This subsurface water extends to about 300 m. and fills the entire continental shelf along the Indian coast. The level of transition between the subsurface water and the one below seems to fluctuate and this aspect is dealt with separately by the author in connection with the deep water masses of the Arabian Sea.

It is interesting to note the entire subsurface water shows similar characteristics and falls within the Dana stations 3920 nearly at the equator on 62°E and 3938 north of Madagascar on the African coast at 45°E. The former station is in the high surface salinity zone while the latter is influenced by low salinities of the coastal water. Thus the marked similarity in the characteristics of the present T-S curves with observations made nearly 30 years ago at such wide distance suggests the homogeneity and constancy of the subsurface water. However, results of the investigations relating to the age of the water masses in the Arabian sea will fall beyond the scope of this paper and hence they will be published elsewhere.

During the period of upwelling the Arabian Sea surface water flows away from the coast and in its place the subsurface water is drawn up. Depending upon the intensity of upwelling which varies from year to year, the amount of the subsurface water drawn to the surface layers varies. But in general the upper 100 m. of the subsurface water interacts in this process though the still deeper water rises vertically upwards to some extent but never up to the depths of the surface water. Thus the subsurface water can be subdivided into (a) the upper subsurface water which comes to the surface layers in upwelling and (b) the lower subsurface water which does not vary much in its depth levels. Thus in all in the upper layers we get three water masses viz., (1) the Arabian Sea surface water, (2) the Arabian Sea upper subsurface water, and (3) the Arabian Sea lower subsurface water.

The above classification avoids the confusion which unfortunately exists in the classifications of the surface waters of the Bay of Bengal proposed by Poornachandra Rao (1956) and Balarama Murty (1957). These authors worked independently for two different seasons and the water mass having nearly the same T-S relationship was named differently by them. Thus the southern Bay of Bengal water and the upwelled water described by Poornachandra Rao are respectively named as the sinking and the subsurface waters by Balarama Murty. As sinking and upwelling are coastal phenomena confined only to the topmost layers of the sea, naming of water masses, depending on these phenomena has resulted in the above confusion. A broader basis for the classification should have been used so that the same water could not be called by different names. Thus the use of the T-S characteristics for identification and naming of the water masses would not only be consistent but also leads to a proper understanding to the extent to which different waters are present at a particular locality at any time. Since surface waters are influenced by the seasonal changes brought about by factors like upwelling and sinking, resulting in admixture of different water masses, these changes should be explained rather than utilising them as a basis of classification. Hence the mean seasonal changes in the Arabian Sea surface water are listed below.

Typical Arabian Sea surface water forms in winter with rapidly increasing salinity depthwise with nearly uniform temperature at 28°C. This mixes with the subsurface water of high salinity at its lower boundary. It is within $\sigma_t = 21.6$ and $\sigma_t = 23.0$ in December and $\sigma_t = 21.2$ and $\sigma_t = 23.0$ in February. With increased solar radiation and with continued long absence of any large scale precipitation, in summer salinity range decreases and temperature increases with the result the characteristic up to 30 m. appears more or less vertical. Also the level to level increase in salinity could be attributed to the surface circulation drawing high saline water into the region. Hence the surface water is within the σ_t levels of 21.0 and 22.8. More orderly wind-driven circulation sets in with the onset of S.W. monsoon. Temperature decreases gradually and salinity falls rapidly. But with steady increase of monsoon, upwelling starts along the Indian coast and the low saline surface water drifts away from the coast. With increased upwelling the upper subsurface water replaces the surface water. While doing so as it mixes with the existing surface water of low salinity and high temperature the subsurface water decreases considerably in salinity (from 35.20°/₀₀ to 34.85°/₀₀ in September). This decrease occurs only in the upper 20 m. below which the upper subsurface water does not show much variation. Hence during September (probably a month or so earlier also) the surface water is absent along the coast. This conclusion, as was shown earlier, is also evident from the comparison of the T-S relations with the two dimensional frequency distributions. But only at the surface (less than 10 m. thickness) the Arabian Sea surface water mixes with over 70% of the subsurface water. Upwelling declines during October and is almost absent in November. During this period the subsurface (upwelled) water gets back to its original σ_t level and the surface water makes its appearance gradually with increasing thickness during the postmonsoon and early winter thus beginning the new cycle of changes in the surface water.

Besides the thermal inversions in the topmost layers during early winter, one encounters a vertically isothermal water resting over the continental shelf towards the end of upwelling. On an average the vertical thermal gradients were estimated to be less than 0.01°C per metre. This water of mean temperature 22.3°C. and salinity 35.10‰, is discontinuous along the coast line during late September to October. Corresponding to these characteristics either the secondary or primary modes of temperature occur in the frequency distributions. Thus in certain levels in the bimodal frequency distributions of characteristics cellular structure occurs. The isothermal nature of this water, results from the intense mixing of the upper subsurface water (i.e. the upwelled water which is retreating to its normal level, towards the end of upwelling, with the northerly subsurface counterflow turning north-west along the Kerala coast. This transitory water has been named as the *Kerala coastal deep water* and its complete characteristics are discussed elsewhere (Ramasastry and Myrland, 1959). As the extent and duration of this water is purely transitory, the type of mixing requires further study which could not be included in this paper as we are dealing with the mean conditions only.

Thus the discussion presented here is highly simplified. But the individual T-S relations of the topmost layers vary considerably as is evident from the two dimensional frequency distributions which give the ranges of temperature and salinity at any depth. A schematic representation of the changes of water masses up to 300 m. is reproduced in Figure 6 showing the presence of different water masses both in extent and duration.

Conclusions

The frequency distributions of salinity are highly concentrated generally with a single mode, in most cases approximating to normal distributions.

Temperature distribution in most cases, except during winter, is bimodal or multimodal.

The bimodal distributions of the characteristics are highly concentrated, at all levels, during winter, less in summer and the least in the upwelling season.

Three different water masses viz., the Arabian Sea surface water, the Arabian Sea upper subsurface water and the Arabian Sea lower subsurface water, are found.

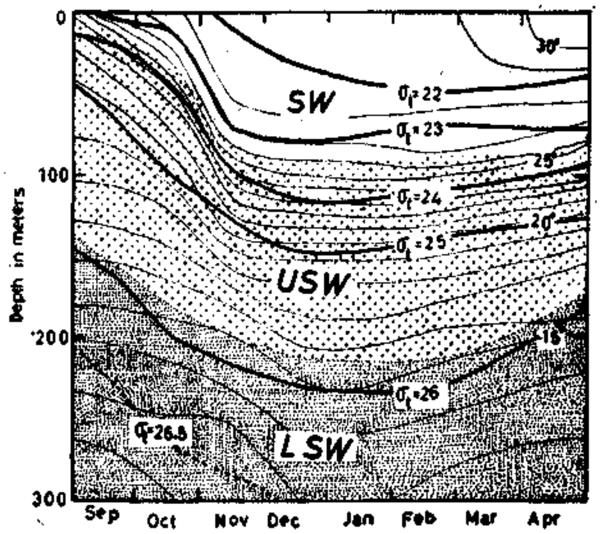

FIG. 6. Water masses in the upper 300 m. in the northeastern Arabian Sea.

During the southwest monsoon upwelling takes place along this coast, during which period the Arabian sea surface water is displaced by the upper subsurface water. Almost a complete overturning takes place during upwelling in the entire water over the continental shelf.

The non-continuous isothermal water over the continental shelf towards the end of upwelling the '*Kerala coastal deep water*' is mostly a mixture of the upper subsurface water, getting back to its original σ_t level, with the subsurface counter flow.

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REFERENCES

BALARAMA MURTY, C. 1957. Water masses of the western Central Bay of Bengal during November. *Curr. Sci.*, 26 : 80.

COCHRANE, J. D. 1956. The frequency distribution of surface water characteristics in the Pacific Ocean. *Deep Sea Res.*, 14 : 45-55.

MONTGOMERY, R. B. 1955. Characteristics of surface water at weather ship—*J. Ibid., Suppl.* 3 : 331-334.

POORNACHANDRA RAO, C. 1956. Water masses in the Bay of Bengal, *Curr. Sci.*, **25** : 51-53.

RAMASASTRY, A. A. AND MYRLAND, P. 1959. Distribution of temperature, salinity and density in the Arabian Sea along the south Malabar coast during the post monsoon season—*Indian J. Fish.*, **6** : 223-255.

SVERDRUP, H. U., JOHNSON, M. W. AND FLEMING R. H. 1942. *The Oceans, Their Physics, Chemistry and General Biology. New York.*

THOMSEN, H. 1933. The circulation in the depths of the Indian Ocean. *J. Cons. int. Explor. Mer*, **8** : 73-79.

———. 1937. Hydrographical observations made during the 'Dana' Expedition 1928-30. *Dana Rep., No.* 12.