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Oceanography of the Arabian Sea during southwest monsoon season
Part I : Thermal structure

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ABSTRACT. The thermal structure of the Arabian Sea (between 5° and 20°N) during the southwest monsoon season, 1963 is presented through a series of vertical sections and horizontal charts showing the temperature distribution at surface and subsurface levels. Charts showing the thickness of the surface layer, the extent of the thermocline and its variation with latitude and the topography of certain isothermal surfaces are also included. The studies revealed that the large spatial variations in surface temperature exceeding 11°C are due to processes such as radiation imbalances over the region, intense upwelling off the coasts of Somali and Arabia and a complex intermingling of various water masses. The thickness of surface layer has been found to vary from about 10 m to more than 120 m. It has been found that the near surface circulation affects the development of the surface layer considerably. The nature and the variation of the thermocline is investigated. The thermal characteristics of the intermediate and bottom waters are also presented.

1. Introduction

Much of our knowledge on the distribution of the variables—temperature, salinity, dissolved oxygen and nutrients—in the Arabian Sea as well as in the entire Indian Ocean was derived on the basis of data collected during several expeditions, *i.e.*, Valdivia (1898-99), Dana (1920-30), Snellius (1929), John Murray (1933-34), Swedish Deep-Sea Expedition (1947-48) etc. However, the information available from these expeditions is rather limited in space and time and is inadequate to describe in detail, the distribution of these variable in the Arabian Sea. The first systematic exploration of the Indian Ocean was the result of the International Indian Ocean Expedition (1960-65) when several ships of different nationalities participated. During this expedition, an enormous amount of data has been collected and it would take quite some time to analyse and synthesise the data.

As the surface circulation is mostly wind driven, any changes in the wind systems bring about corresponding changes in the surface circulation. The atmospheric circulation over the Arabian Sea, and in fact over the entire north Indian Ocean, undergoes a complete reversal in direction during a year. The southwest monsoon, a continuation of the southeast trade winds over the south Indian Ocean, blows over the Arabian Sea with wind speeds of about 20 kt over large areas, occasionally exceeding 30 kt in regions off the coasts of Somali and Arabia. Associated with the south west monsoon, transport of water into the Arabian Sea across the equator takes place. On the other hand, the northeast monsoon is weakly developed with wind speeds rarely exceeding 15 kt. The winds undergo a transition both in direction and magnitude during the intervening periods of the southwest and northeast monsoons.

The heat budget estimates in certain regions of the Arabian Sea are known to give enormous radiation balance with a corresponding excess of evaporation. Intense upwelling is known to take place off the coasts of Somali and Arabia. Recent studies indicate the existence of very high productivity regions in the Arabian Sea. In addition, the seasonal character of the Somali current, the inflow and further spreading of the Red Sea and Persian Gulf waters into the Arabian Sea make the oceanography in this region interesting.

Quite a few studies, some utilising IIOE data are made on the observed and derived distributions in coastal and near shore regions along the west coast of India by several workers. Rochford (1964) has studied the salinity distribution and discussed the probable flow patterns. Warren, Stommel and Swallow (1966) have discussed the chracteristics of the water masses and patterns of flow in the Somali Basin. More recently, Wooster, Schaefer and Robinson (1967) have prepared an atlas showing the climatological distributions of these properties. However, detailed seasonal distributions for the entire northwest Indian Ocean are lacking.

In this paper, a study of the temperature distribution in the Arabian Sea during the southwest season (Aug-Sep 1963) is presented in detail using the data collected on board the U.S. Research Vessel *Atlantis*. The distributions of salinity, density and other parameters will form the subject matter of later reports.

2. Data* and Treatment

Atlantis occupied stations along five sections in the Arabian Sea during Aug-Sep 1963. Section I is located across the Gulf of Aden (stations 52-56) and Sections II through V are situated approximately along 5°N (stations 112—131), 10°N (stations 89—197), 15°N (stations 56—72) and 20°N (stations 73—79) respectively. Fig. 1 is the station location map. Fig. 1 also includes the locations 80—88, which were used in presenting the spatial distribution.

Station curves are drawn for each of the stations. Temperature is plotted against depth, salinity and dissolved oxygen on sheets showing the thermosteric anomaly (δ_T) as a function of temperature and salinity. All these curves are smoothed and necessary adjustments are made for the missing and doubtful observations. From these curves, the values of temperature, salinity, thermosteric anomaly and dissolved oxygen are read for surface and subsurface levels (100, 200, 500, 1000 and 1500 m). For the preparation of the vertical sections, depths are read for the chosen isolines of temperature, salinity, thermosteric anomaly and dissolved oxygen. For describing the various properties on the δ_T surfaces, the values of these variables corresponding to the chosen δ_T surfaces (400, 300, 200, 100, 80 and 60 cl/T) are noted.

Figs. 2 through 6 show the vertical temperature distribution along the five sections. In these figures the dotted line near the surface represents the bottom of the surface (homogeneous or mixed layer. Here the surface layer is defined as the layer extending from the surface to the depth where the temperature is less by 1°C to that at the surface. As the temperatures are measured at discrete points using reversing thermometers, it is not always possible to fix the bottom limit of the surface layer with sufficient accuracy. Even the bathy-thermograms do not always show any well defined edge. The surface layer as defined above includes any temperature inversions which may be present close to the surface. It may be mentioned that Wyrtki (1961) allows a tolerance of 1°C and 0·20 ‰ for temperature and salinity respectively to define the thickness of the surface layer.

Further, the layer extending upward from the 15°C isothermal surface to the bottom of the surface layer will be referred as the thickness of the

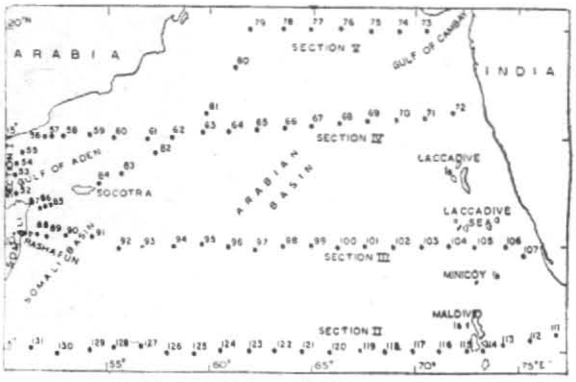

Fig. 1. Station location map

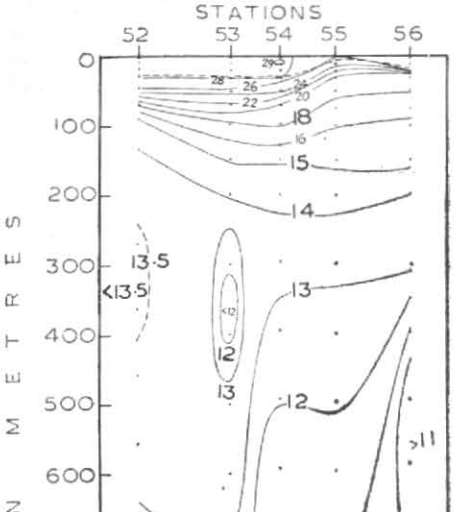

Fig. 2. Temperature (Celsius) along approximately 50°E (Section I)

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*The station data presented in this report has been kindly supplied by the National Oceanographic Data Center, Washington, D.C.

thermocline. The 15°C isotherm has been generally regarded to be at the bottom of the thermocline even though the entire oceanic troposphere should have been considered as thermocline. After examining several vertical temperature sections the 15°C isotherm is chosen to represent the bottom of the thermocline. It may be pointed out that the 14°C isotherm may as well be considered for this purpose as was done by Warren, Stommel and Swallow (1966) for their studies in the Somali Basin.

3. Analysis of results

Before presenting the spatial distributions, some characteristics of the thermal structure which are not evident in the spatial distributions are described below.

3·1 *Vertical Sections*—Fig. 2 shows the vertical temperature distribution across the Gulf of Aden (Section 1, Fig. 1). In general, the surface water is warmer in the southern regions of the Gulf. The surface temperature varies from 29·82°C at station 53 to 25·94°C at station 55. This large variation in surface temperature does not seem to be entirely due to diurnal variations but appears to be a consequence of the presence of different water masses.

In spite of moderate winds of 10 to 20 kt (Wooster, Schaefer and Robinson 1967) in this region, the surface layer is not well developed and it rarely exceeds 30 m in depth. In the northern regions of the Gulf, the surface layer appears only as a thin layer. The thickness of the thermocline increases northward along the section.

The thermal structure in the intermediate water below the thermocline to a depth of about 1000 m, is very complex. The salinity and oxygen distributions are equally complex. Temperature inversions appear to be a common feature. Isolated pockets of cold less saline water and warm saline water exist side by side. In Fig 7, the T-S and $T\text{-}O_2$ relationships for the five stations are shown. Comparing Figs. 2 and 7, it is evident that the finer details in the temperature structure are lost in Fig. 2 as the isotherms are drawn at an interval of 1°C. While a detailed discussion of the characteristics of the different water masses will be presented elsewhere, we shall briefly mention the gross features of these warm saline and cold less saline waters. At station 53, a layer of cold less saline water embedded in warm saline water occurs at depths of 250-450 m. The salinity minimum (35·22 ‰) coincides with the oxygen maximum (1·75 ml/1) and is located approximately on 130 cl/t δ_T surface ($\sigma_T = 26{\cdot}75$). Below this layer, a warm saline layer occurs with a salinity maximum of 36·27 ‰ and with low oxygen (less than 0·5 ml/1). However, at station 56, the salinity minimum (35·23 ‰) of the cold less saline water occurs at a depth of 400 m where δ_T is approximately 110 cl/T ($\sigma T = 26{\cdot}96$) and this coincides with the oxygen maximum (2·3 ml/1). Except at station 55, a layer of minimum salinity associated with an oxygen maximum occurs at depths varying between 200 to 500 m. Warren, Stommel and Swallow (1966) while discussing the possible sources of the water masses in the Somali Basin suggest that if a water mass, overlying a highly saline layer, has salinity decreasing with depth and has a relative maximum in oxygen concentration, then this water mass has the properties of the sub-tropical subsurface water in the south Indian Ocean. The decreasing salinity layer has all the characteristics mentioned above except that it is embedded in a relatively warm saline water giving rise to temperature inversions. The warm saline water below the cold less saline water is clearly the Red Sea water.

Below 1000 m, the temperature decreases gradually to less than 3°C at depths exceeding 2000 m.

Fig. 3 shows the temperature distribution along 5°N approximately. The surface temperature in general increases from west to east and varies from 25·33°C (station 131) to 28·98°C (station 115). The surface temperature gradually increases from the African coast (station 131) to about 60°E and further eastward remains relatively homogeneous with temperatures exceeding 28°C.

The thickness of the surface layer sharply decreases from over 130 m at station 131 to less than 40 m at station 129. Eastward of station 129, it gradually increases attaining a maximum thickness exceeding 100 m at station 126. In the central regions, the surface layer extends to about 75 m. East of 70° E, the thickness of the surface layer gradually decreases to about 50 m.

Off the African coast, the isotherms in the thermocline rise upward to station 129 and later slope downwards rapidly to station 127. Further eastward, the isotherms remain nearly horizontal with a slight upward inclination along the section.

Below the thermocline, the temperature decreases gradually, the isotherms showing a wavy structure. At great depths, the temperatures decrease to abyssal values.

The variations in the thickness of the surface layer in the Somali Basin west of station 124, appear to be the result of strong currents flowing in opposite directions as indicated by the bell shaped thermocline in that region. A further

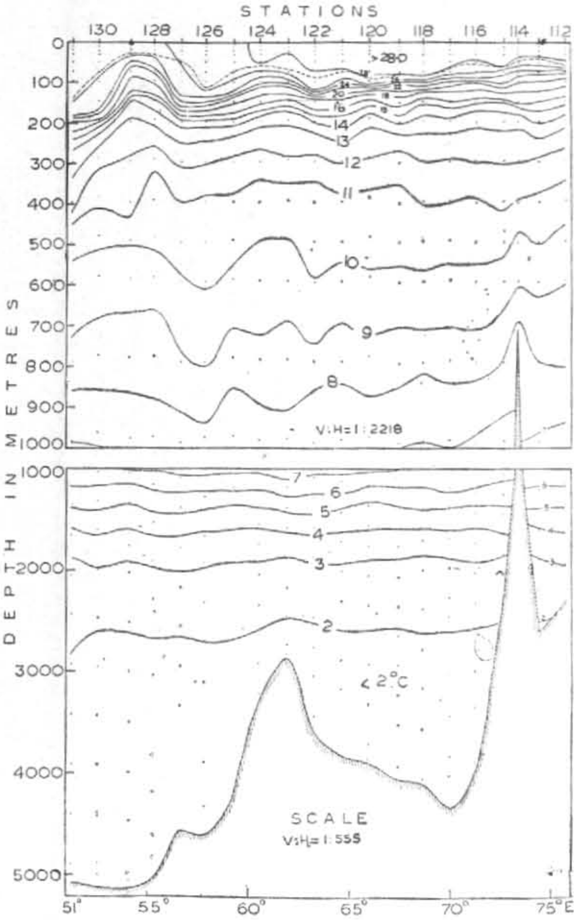


Fig. 3. Temperature (Celsius) along approximately 50°N (Section II)

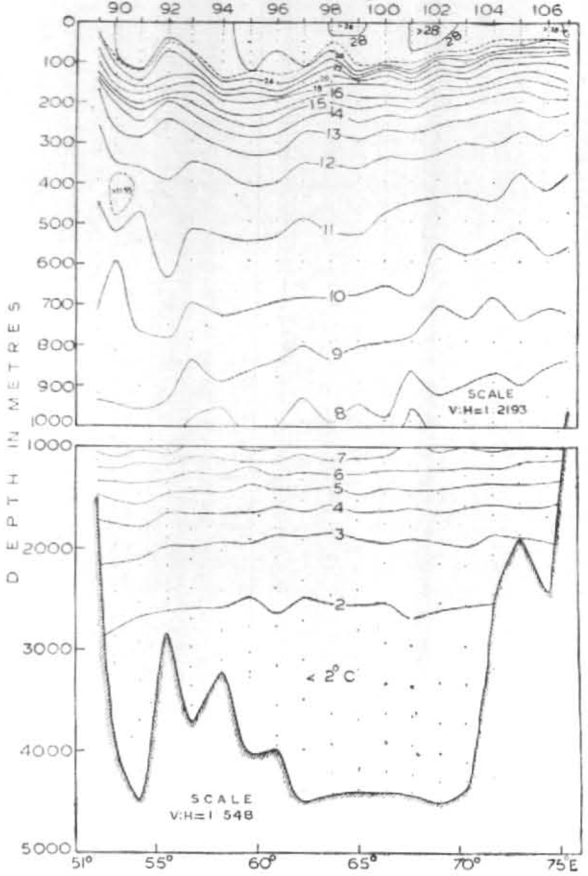


Fig. 4. Temperature (Celsius) along approximately 10°N (Section III)

discussion on these aspects will be presented later.

The surface temperature along 10°N (Fig. 4) shows a similar west-east increase as at 5°N. However, at 10°N the variation in surface temperature is quite large. In fact, at station 88 (not shown in Fig. 4) coldest water (17·62°C) occurs. In the central and eastern portions of the Arabian Sea the surface temperature varies from 26°C to 28°C except in isolated pockets where it exceeds 28°C.

The bottom surface of the mixed layer (or the top surface of the thermocline) appears corrugated of the coast of Somali and west of 65°E. The thermocline rises close to the surface west of station 89. East of station 89 the thickness of the surface layer varies from about 50 m (stations 91 and 98) to more than 120 m (stations 91, 94, 95 and 96). In the eastern regions of the Arabian Sea, the thickness of the surface layer gradually decreases eastward from over 100 m at 65°E to less than 50 m near the Indian coast.

In the eastern regions along this section, the thermocline is located slightly deeper than at 5°N. The isotherms are nearly horizontal with a slight upward inclination towards the Indian coast. Off the Somali coast, the structure of the thermocline is complex, the isotherms showing a wavy pattern.

In the intermediate water, the temperatures decrease gradually and the isotherms show an upward slope to the east. A pocket of relatively warm saline water (indicated by the additional contour) is found at station 90 causing a temperature inversion at 450 m. It is probable that this warm saline water pocket results by mixing of Red Sea water.

At great depths, the temperatures decrease monotonically to abyssal values.

The temperature distribution along Section-IV (Fig. 5) shows that relatively cold surface

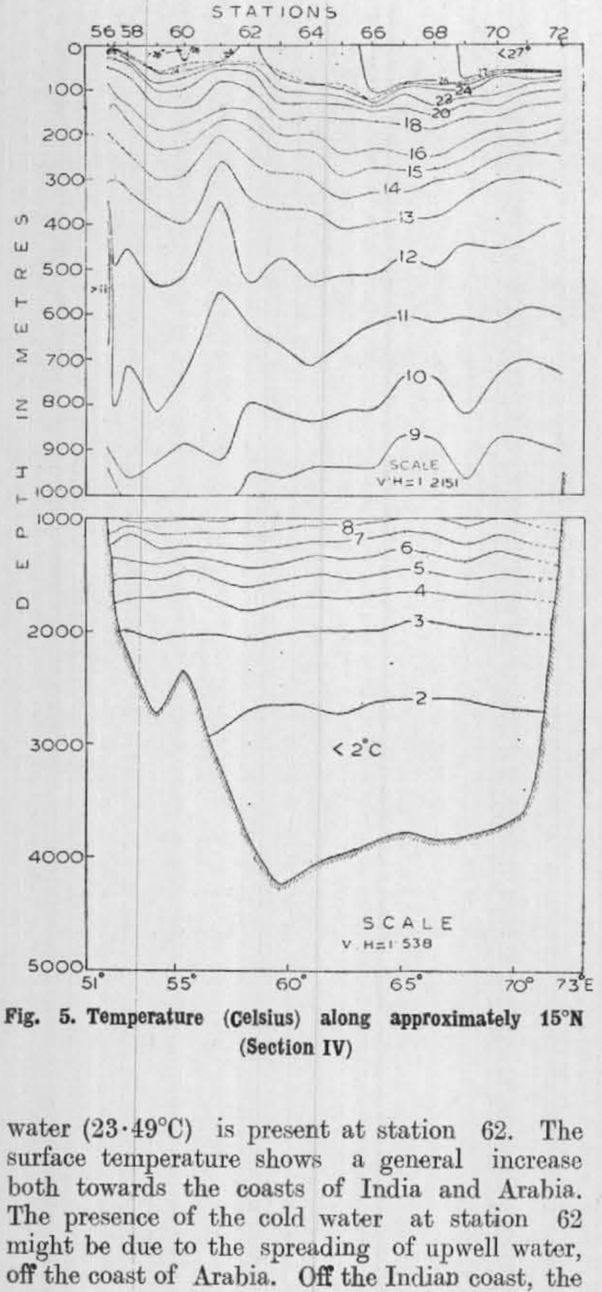


Fig. 5. Temperature (Celsius) along approximately 15°N (Section IV)

water (23·49°C) is present at station 62. The surface temperature shows a general increase both towards the coasts of India and Arabia. The presence of the cold water at station 62 might be due to the spreading of upwell water, off the coast of Arabia. Off the Indian coast, the surface temperature is less than 28°C, indicating that in the eastern Arabian Sea, the surface water is warmer near the equator.

The surface layer has its maximum development in the central portions of this section and its thickness exceeds 120 m (station 66). Near the Indian coast, its thickness is about 60 m while off the coast of Arabia, it is only a few metres thick.

Compared with the two earlier sections (Figs. 3 and 4), the thermocline is spread over a large thickness.

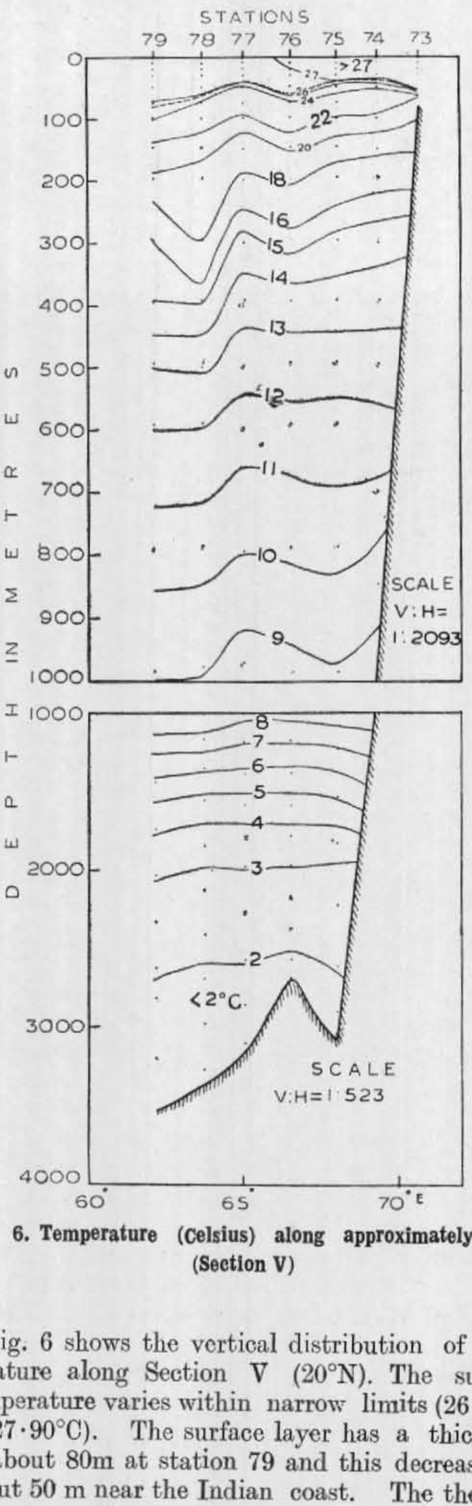


Fig. 6. Temperature (Celsius) along approximately 20°N (Section V)

Fig. 6 shows the vertical distribution of temperature along Section V (20°N). The surface temperature varies within narrow limits (26·37°C to 27·90°C). The surface layer has a thickness of about 80m at station 79 and this decreases to about 50 m near the Indian coast. The thermocline is weakly developed.

3.2. *Spatial distributions* — So far we have briefly described some characteristics of temperature distributions. To get a deeper insight into the various problems we now present the spatial distributions of temperature at different

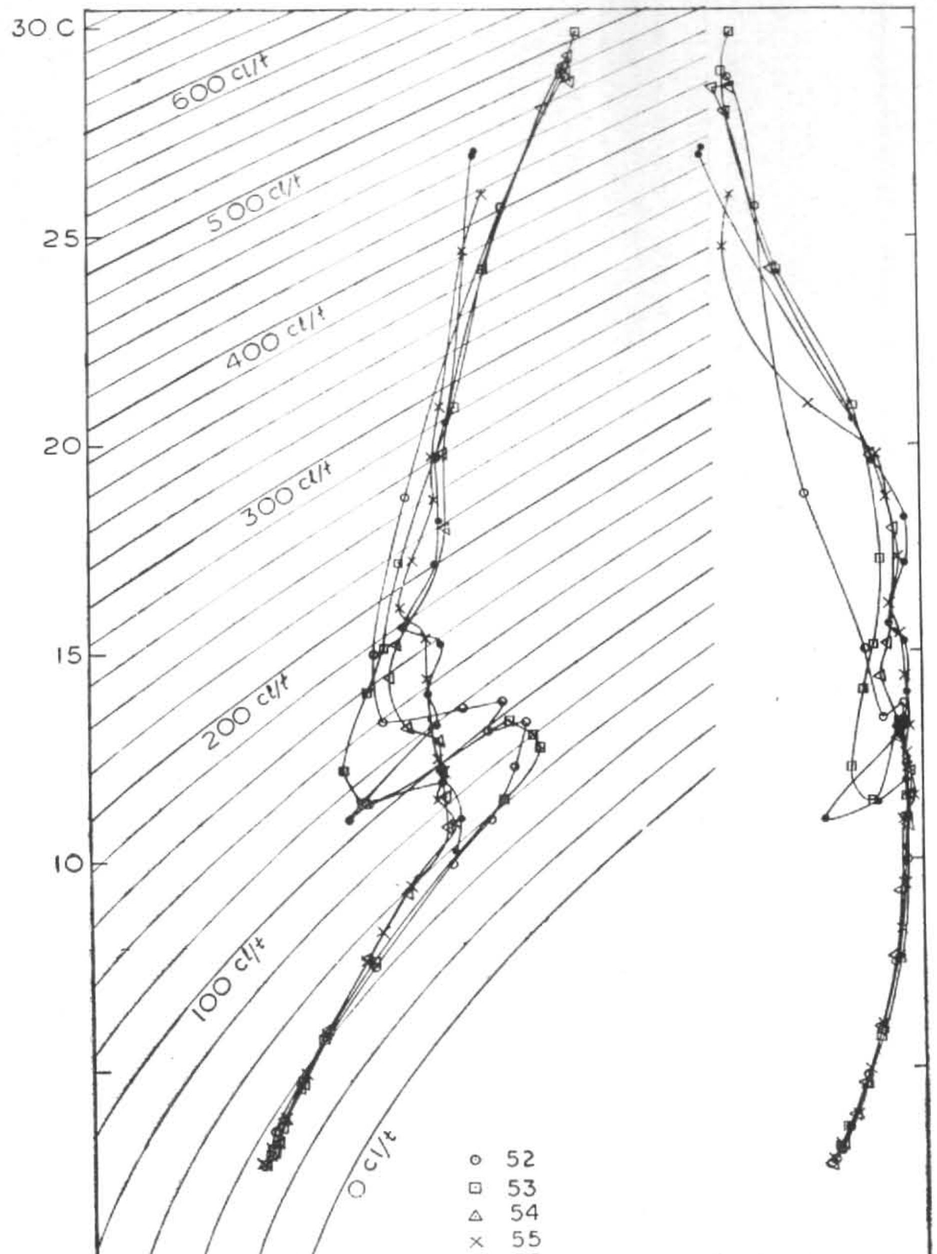


Fig. 7. T-S and T-O_2 diagram across Gulf of Aden

levels and some other characteristics describing the thermal structure. For convenience, we divide the oceanic column arbitrarily into three layers : (1) upper water, upto depths of 200 m or deeper to include the thermocline, (2) intermediate water extending upto 1500 m and (3) bottom water, depths exceeding 2000 m.

3.2.1. *Upper water* — The distribution of surface temperature (Fig. 8) shows that the spatial variation in temperature exceeds 11°C. In general, warm water occurs in the southern regions of the Gulf of Aden and in the southeastern Arabian Sea. Off the Somali coast the surface temperature is generally low.

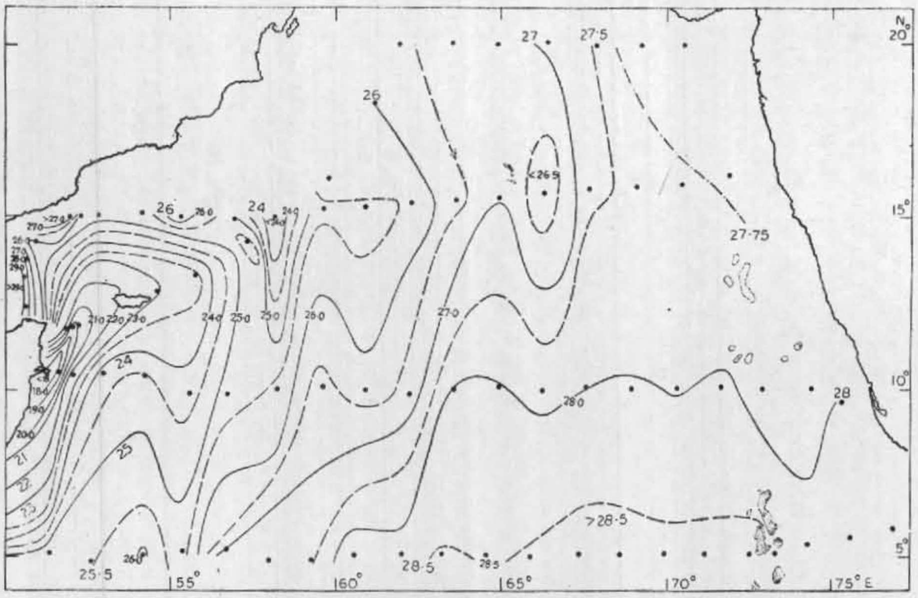


Fig. 8. Temperature (°C) at surface

At stations 52 and 53, across the Gulf of Aden, the surface temperature exceeds 29°C. Eastward of this region, it decreases rapidly to a minimum to the west coast of Socotra Island. The region of minimum temperature is located in the core of the cold water which spreads in a tongue like distribution extending in a general northeasterly direction from station 88 where the surface temperature is only 17·62°C. This tongue like distribution covers an extensive area in which the surface temperature increases away from the core. The 25°C isotherm may be considered to envelop the spread of the cold water.

Near the Somali coast, south of 10°N, the surface temperature increases both to east and south. Between 5°N and 10°N, the surface temperatures increase to a maximum along 54°E (approximately) and thereafter decrease to a minimum along 55°E. Further east of 55°E, the surface temperature shows a gradual increase towards the Indian coast.

At station 62, situated fairly away from the coast, the surface water is relatively cold (23·49°C) and appears as a pocket of cold water spreading south. Further east of this region, the temperatures in general increase.

In the southeastern regions of the Arabian Sea, warm water (>28·5°C) occurs. Off the west coast of India, the temperature decreases to the north. Fig. 8 shows that in general weak temperature gradients prevail in the southeastern and eastern Arabian Sea compared to those in the western and central Arabian Sea.

Thus, the temperature distribution at the surface presents a complicated picture. One might attribute the high surface temperature exceeding 26°C in the central and eastern Arabian Sea to the exceessive heat gain over the region. However, the surface salinity distribution indicates that the warm surface water is associated with high salinity exceeding $36\cdot2‰$ across the Gulf of Aden and exceeding $36\cdot5‰$ in the northeastern regions of the Arabian Sea. On the other hand, the warm water (>28·5°C) in the southeastern Arabian Sea, west of Laccadive and Maldive Islands is associated with relatively less saline water (salinity $35\cdot6‰$). These features suggest that the high temperature in the northeast Arabian Sea are due to enormous heat gain while the relatively warmer water in the southeastern regions appears to be due to the presence of warm and relatively less saline equatorial water.

It has been mentioned earlier that very cold water (17·62°C) occurs at station 88. Intense upwelling takes place off the coast of Somali during this season and this cold subsurface water rises to the surface and later spreads over an extensive area resulting in a tongue like distribution of temperature. It may be pointed out that some observers noted still lower temperatures in the region.

Off the coast of Arabia, the surface temperature charts prepared by Wooster, Schaefer and Robinson (1967) show considerable cooling near the coast as a result of upwelling during the south-

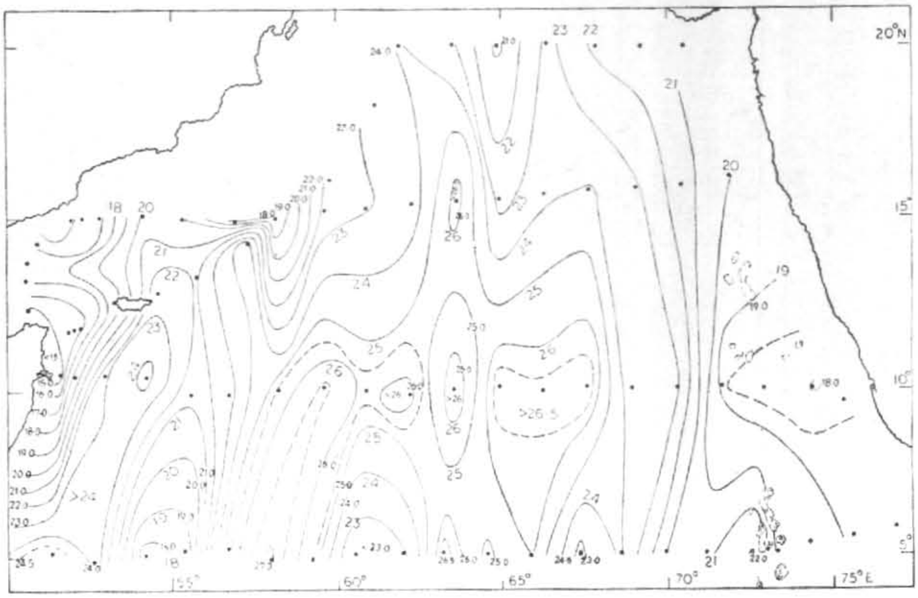


Fig. 9. Temperature (°C) at 100 m

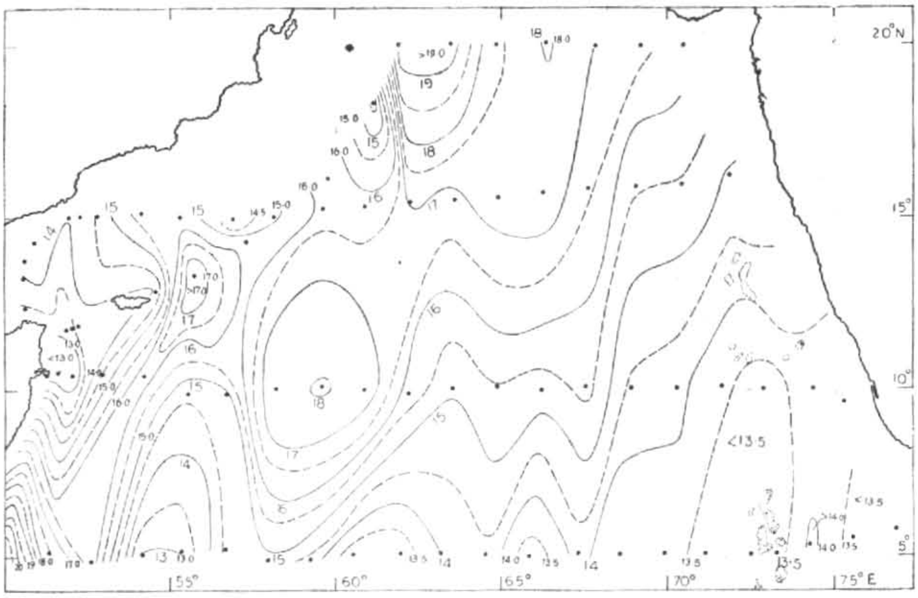


Fig. 10. Temperature (°C) at 200 m

west monsoon season. Unfortunately, we have no data close to the coast of Arabia. It is probable that this upwelled water spreads southward resulting in low temperature at station 62.

Thus, the surface temperature distribution during Aug-Sep 1963 appears to be the net result of the various processes—(*i*) radiation balance, (*ii*) upwelling off the coasts of Somali and Arabia and (*iii*) presence of equatorial and Red Sea water.

The temperature distribution at 100 m (Fig. 9) shows several pockets of warm water separated by relatively cold water resulting in strong thermal gradients laterally. The isopleth interval is not uniform and intermediate isopleths are drawn wherever they are found necessary and possible. The temperature pattern on this surface is very complex and one might draw several alternative patterns. It is believed that the pattern in Fig. 9 is more realistic. The location of this surface in the surface layer of relatively high temperature

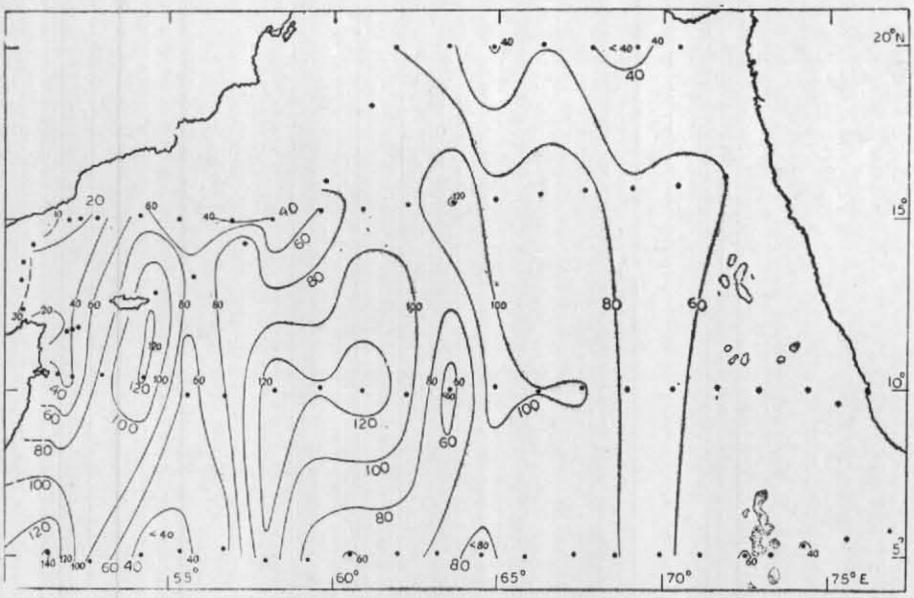


Fig. 11. Thickness of surface layer (m)

at some places and in the thermocline of strong vertical temperature gradients at other places causes these complications.

The temperature on this surface is found to vary from more than 27°C to less than 15°C. The core of cold water extending from station 88 to the region west of Socotra that was evident at the surface (Fig. 8) is hardly traceable at 100 m. The cold water core (15°C—16°C) extends in a near northerly direction from station 88 and turns into the southern portions of the Gulf of Aden. In the central Arabian Sea several warm water pockets exceeding 26°C are separated by relatively cold water. Off the west coast of India, the temperature increases away from the coast and the isotherms are oriented in a north-south direction.

The intense temperature gradients over this surface suggest that the circulation pattern is equally complex with several warm and cold water eddies existing side by side.

The temperature distribution at 200 m is presented in Fig. 10. East of 62°E the temperature increases with increasing latitude. In the northwestern regions (stations 78 and 79) the temperature exceeds 19°C while it is generally less than 13·5°C in the southern and southeastern Arabian Sea.

However, west of 62°E, the temperature distribution at this depth shows a complex pattern similar to that at 100 m (Fig. 9). An isolated pocket of warm water (>18°C) is centred around station 95. This is separated by another warm water cell (>17°C) at station 83 by relatively cold water. At station 128, the temperature is less than 13°C and the iostherms form a tongue like distribution. The axis of this cold water core runs in a northerly direction connecting the cold water at station 61. Off Ras Hafun, the temperature (12·6°C at station 88) increases away from the coast. In the southwestern regions (station 132, not shown in Fig. 10), the temperature exceeds 21°C.

Fig. 11 shows the spatial distribution of the thickness of the surface layer. The vertical extent of this layer varies from about 140 m to about 10 m. Across the Gulf of Aden and in the coastal regions off Somali, the surface layer is hardly developed and its thickness varies between 10 m to 40 m. Off the west coast of India, its thickness varies between 40 to 50 m and gradually increases to more than 100 m in the central Arabian Sea. In the central and western regions, the surface layer is well developed in some isolated regions where its thickness exceeds 120 m. These regions are separated by regions of relatively thin surface layer.

A study of the development and variation of this layer is of dynamical importance since the exchange of properties between this layer and the subsurface water is minimized because of strong density gradients in the thermocline. Any material introduced into this layer is well mixed within a short time and is subjected to

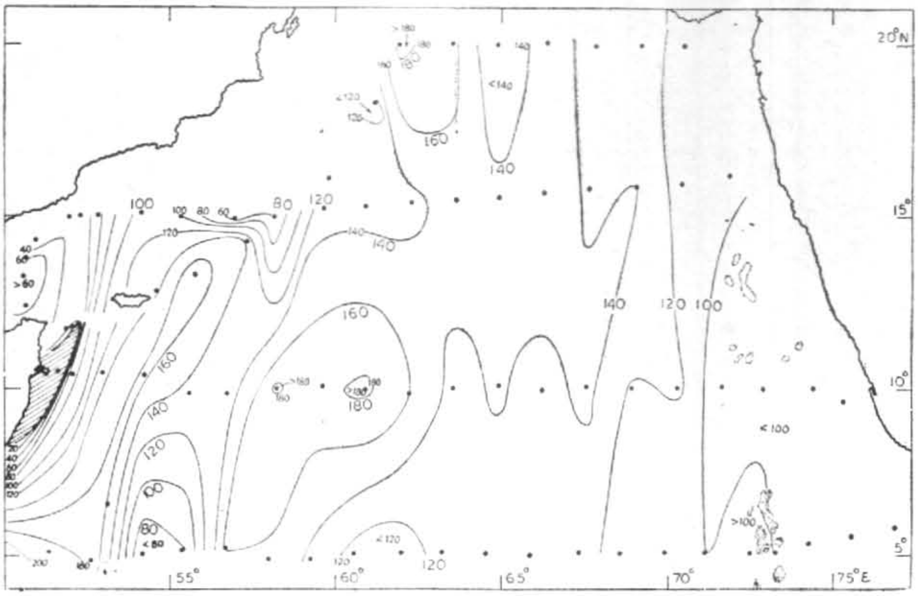


Fig. 12. Depth of 20°C isothermal surface (m)

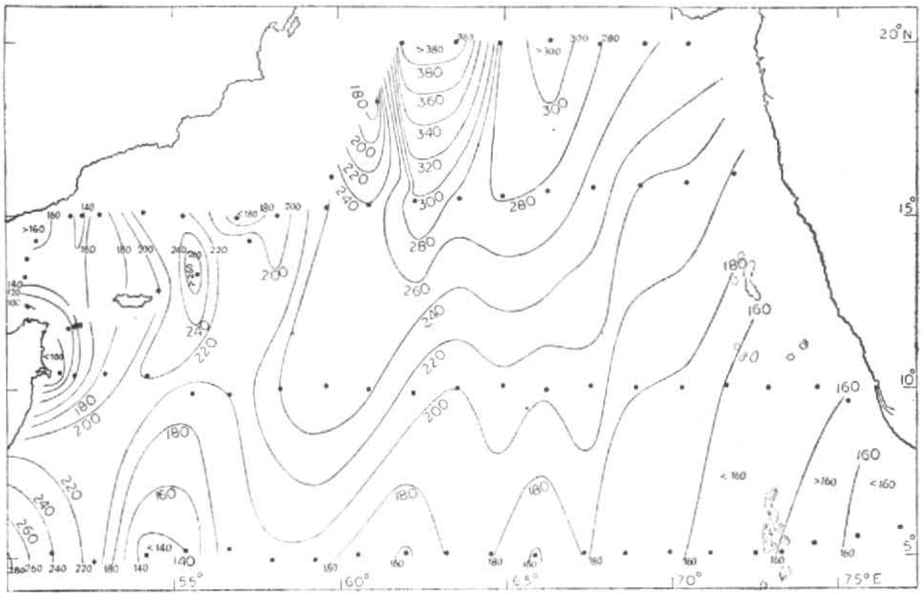


Fig. 13. Depth of 15°C isothermal surface (m)

a great horizontal dispersion since the horizontal coefficients of diffusion are large compared to the vertical coefficients.

The surface layer develops as a result of mixing by wind, currents, excessive evaporation and possibly by the processes of upwelling and sinking. Thus at any locality the vertical extent of this layer varies in time. Of the various processes mentioned above, wind action is believed to be of great importance. In such a case, the wind speed and its duration over an area determines the thickness of the surface layer. The monthly charts showing the resultant surface winds over the Arabian Sea by Wooster, Schaefer and Robinson (1967) indicate that steady southwest winds (22 to 33 kt) blow over large areas off the cost of Somali during July and August. In September, the wind force is considerably reduced (17 to 21 kt) while the orientation of the

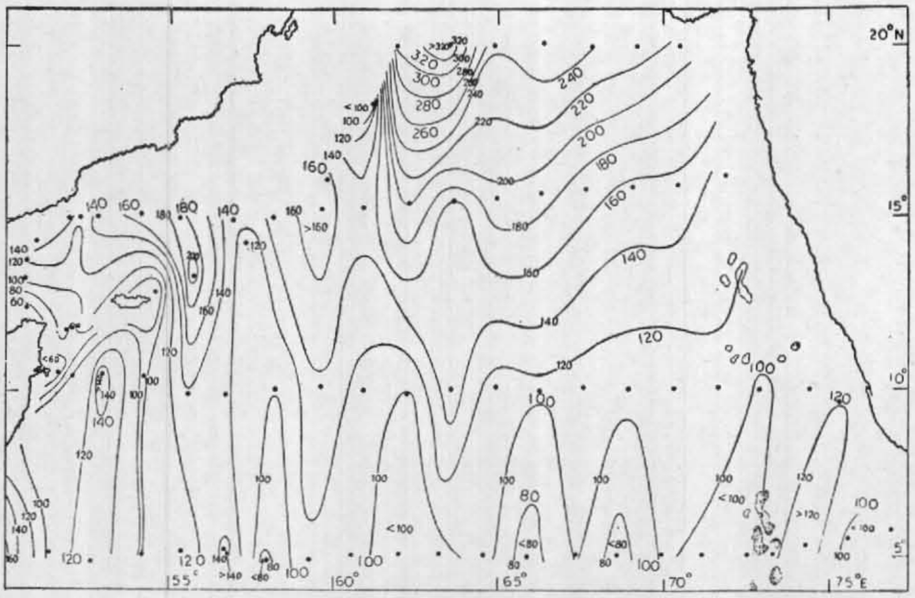
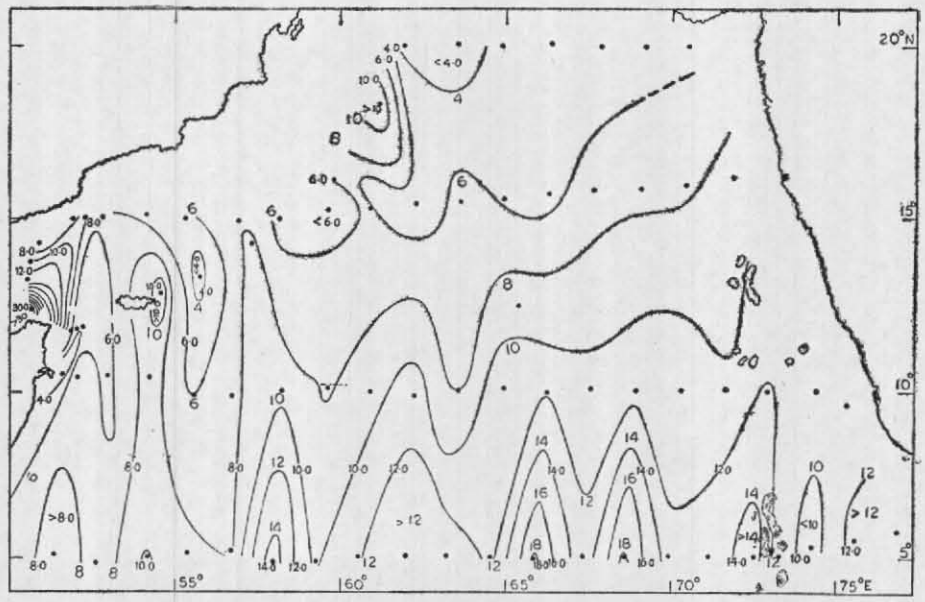


Fig. 14. Thickness of the thermocline (m)



Fi.g. 15. Mean vertical temperature gradient in the thermocline (—10² × °C/m)

fetch remains stationary. On approaching the Indian coasts, the wind force decreases (11 to 16 kt in August and 4 to 10 kt in September). These features suggest that the surface layer should extend far deeper off the Somali coast than off the Indian coast. While the relatively thin surface layer off the Indian coast fits into this scheme, the isolated regions of well developed surface layer separated by regions of thin surface layer in the central and western Arabian Sea and the very thin surface layer off the coast of Somali and across the Gulf of Aden require an explanation. The steady southwest winds blowing parallel to the Somali coast cause intense upwelling bringing cold subsurface water to the surface. In the process, the thermocline reaches the surface, and the surface layer is very much reduced. Across the Gulf of Aden, the mean wind patterns show that the winds are relatively weak and it is probable that the wind mixing does not penetrate the highly stratified subsurface layer as is evident from Fig. 15.

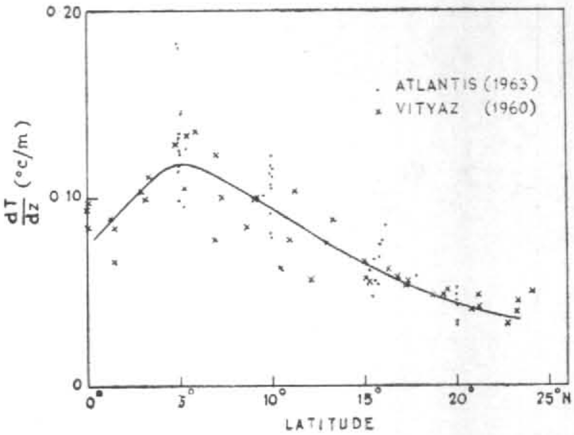


Fig. 16. Variation of vertical temperature gradient with latitude

A comparison of Figs. 9 and 11 suggests that the warm water pockets observed on the 100 m surface generally coincide with the regions where the surface layer is well developed. It was pointed out earlier that the strong lateral temperature gradients at 100 m in the western Arabian Sea give rise to complicated flow pattern. It is probable that the flow pattern at these levels modifies the development of the surface layer. Fig. 12 shows the topography of the 20°C isothermal surface. Except in the region of strong upwelling (shaded area in Fig. 12) where it cuts the sea surface, this surface always lies in the thermocline. We have plotted this chart to infer the near surface flow pattern in the western Arabian Sea. West of 62°E, the topography of this surface is very irregular. Off the Somali coast, along 10°N, this surface slopes down to more than 160 m, rises to more than 130m and slopes down again to more than 180m. At station 132 (not shown in Fig. 12) this surface is located at about 200 m. It rises to less than 80 m at stations 128 and 129 and slopes down to 160 m at station 127.

Off the Somali coast, north of 6°N, the isobaths suggest a strong flow to northeast and north. North of about 12°N this current splits into two branches, one flowing north and the other forming a clockwise eddy around station 83. Another clockwise eddy is located around station 95. These two warm water eddies are separated by two anti-clockwise cells located around stations 128 and 129 along 5°N and around stations 61 and 62 along 15°N. Thus comparing Figs, 9, 10 and 11 we find that wherever a warm water pocket exists, it is associated with clockwise circulation and the surface layer extends much deeper. In the atmosphere it is known that, in the vicinity of cyclones and anticyclones, vertical currents are developed (Haltiner and Martin 1957). Wyrtki (1964) associates upwelling with cyclonic circulation in the Costa Rica Dome. It is probable that large scale sinking associated with clockwise circulation might be responsible for the large thickness of the surface layer.*

As defined earlier, the charts showing the thickness of the surface layer (Fig. 11) represents the top surface of the thermocline while the topography of 15°C isothermal surface (Fig. 13) forms the bottom surface of the thermocline.

East of 62°E, in the northwestern regions, the 15°C isothermal surface is located at about 380 m and gradually rises to about 160 m in the southern and southeastern regions. West of 62°E, the topography of this surface is irregular and is located at depths varying from less than 100 m to more than 280 m.

The thickness of the thermocline (difference chart of Figs. 13 and 11) is shown in Fig. 14. East of 62°E, the thickness of the thermocline gradually increases from less than 80 m in the southern regions to more than 320 m in the northwestern regions. Thus, the thickness of thermocline increases with increasing latitude. However, west of 62°E, no regular pattern is observed and this

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*A reviewer comments as follows: "The probable reason for sinking is not due to eddy motion. It is known that sinking takes place below a level at which convergence occurs. From the surface isotherms the required convergence may be inferred at least in some regions where sinking is taking place. Further due to the velocity convergence in the low level wind structure (as also given by the authors); the wind driven circulation in the surface layers of the sea is expected to have sufficient convergence resulting in sinking. However, it may be stated that with the data on hand it is rather difficult to indicate the exact regions of velocity convergence in the surface layers of the sea, although the seasonal circulation would suggest velocity convergence in the central regions of the Arabian Sea".

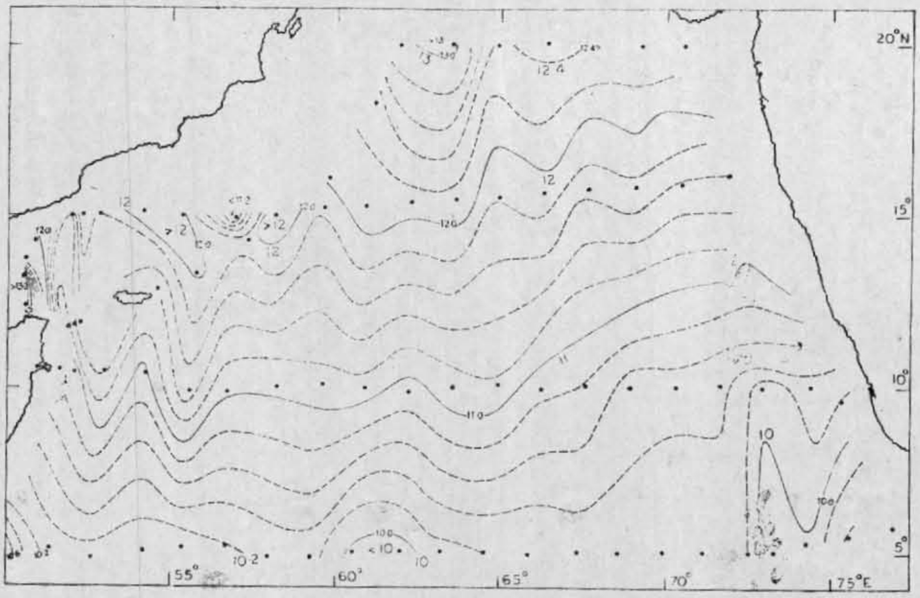

Fig. 17. Temperature (°C) at 500 m

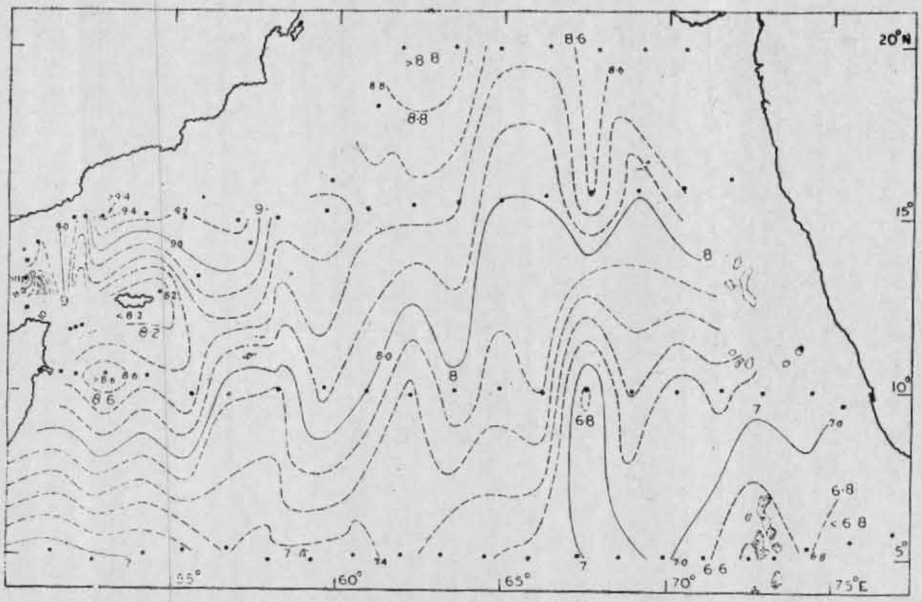

Fig. 18. Temperature (°C) at 1000 m

is partly due to the complex topography of the 15°C isothermal surface and partly due to the variations in the thickness of the surface layer (Fig. 11).

Fig. 15 shows the mean vertical temperature gradient in the thermocline. The isolines are drawn for values of 100. dT/dZ where T is temperature and Z is depth in metres. As is to be expected, the isolines in Figs. 14 and 15 suggest a reciprocal relation between the thickness of the thermocline and the temperature gradient. In the region east of 60°E, the temperature gradient varies with latitude and is brought out in Fig. 16. The dots in the figure refer to *Atlantis* data and the crosses to *Vitiaz* data (October-December 1960)*. A smooth curve is fitted to the data. Even though the two sets of data were collected at different times,

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*A paper on the distribution of properties in the Arabian Sea during the postmonsoon season utilizing the data collected by *Vitiaz* during October-December, 1960 is under preparation

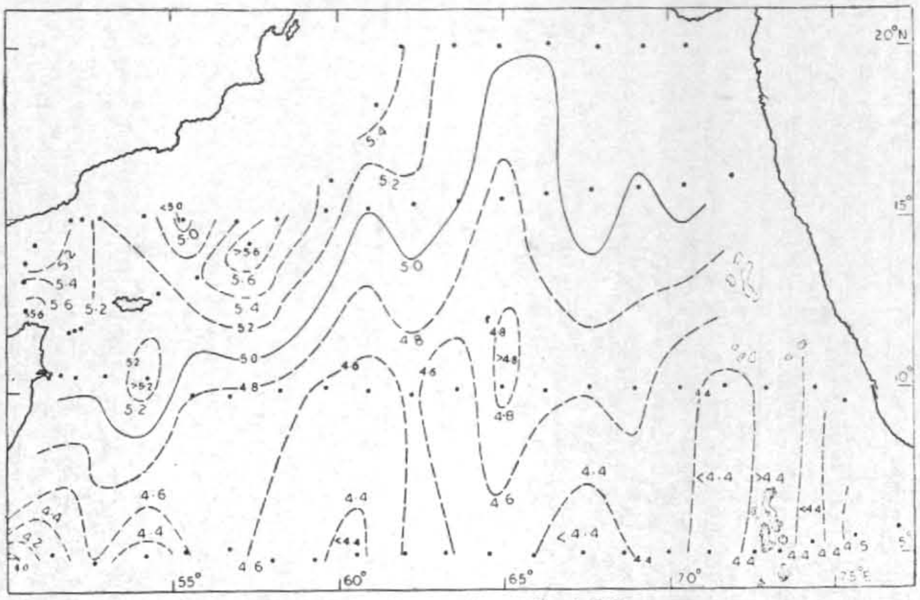

Fig. 19. Temperature (°C) at 1500 m

the scatter is uniform about the curve. The figure shows that maximum temperature gradients in the thermocline occur around 5°N. North of 5°N, the temperature gradients decrease linearly with latitude. Fig. 16 further shows that the scatter of the points increases from north to south with maximum scatter around 5°N. The large scatter around 5°N is probably due to the presence in varying amounts of equatorial water across 5°N at different places.

Across the Gulf of Aden, the mean vertical temperature gradients are highest. At station 52, the temperature gradient is 0·3°C/m.

As stability is dependent upon the temperature and salinity gradients, these studies show that the water (in the thermocline) across the Gulf of Aden and in the southern regions of the Arabian Sea is more stable. Since the coefficients of vertical diffusion are, to some extent, dependent upon stability, the vertical exchange of properties by diffusion processes is very much reduced in these regions.

3.2.2. *Intermediate water* — Figs. 17, 18 and 19 show the temperature distributions at 500, 1000 and 1500 m respectively. The patterns are relatively simple at these levels in contrast to the complex patterns in the upper 200 m. The basic feature is a northward increase of temperature. The spatial variations in temperature are small in comparison to those in upper water.

The temperature distribution at 500 m (Fig. 17) shows that the temperature exceeds 13°C in the northwestern regions of the Gulf of Aden. The temperature decreases gradually southwards to about 10·2°C along 5°N. The lowest temperature (9·6°C) occurs in the extreme southeastern Arabian Sea. The isotherms are more or less parallel and are oriented in a general east-west direction. In the Gulf of Aden, the east-west gradients of temperature are considerable.

The temperature distribution at 1000 m (Fig. 18) is basically similar to that at 500 m. In the southern region of the Gulf of Aden the temperature exceeds 11·2°C. In the northwestern Arabian Sea, the temperatures are less than 9°C. The temperature decreases to south to less than 7°C at some places and the lowest temperature (<6·6°C) occurs on the western side of Maldive Islands. The isotherms are oriented in a general east-west direction and show a wavy pattern.

The temperature distribution at 1500 m is presented in Fig. 19. The temperature exceeds 5·6°C in isolated pockets centred around stations 52 and 82. The lowest temperature (<4°C) is observed in the extreme southwest at station 132.

3.2.3. *Bottom water* — It has been pointed out earlier that the spatial temperature variations below 2000 m are small. At great depths, the temperatures reach abyssal values. Instead of presenting the charts of temperature distribution

TABLE 1

Potential temperature of bottom water at different regions

Station No.	Depth to bottom (m)	Depth of observation (m)	Potential temp. (°C)
	SOMALI BASIN		
129	5141	5069	0·89
130	5112	4994	0·92
131	5066	4984	0·92
91	4492	4189	0·97
	ARABIAN BASIN		
117	4345	4311	1.31
118	4098	4057	1·31
96	3985	3945	1·25
97	4512	4481	1.20
99	4413	4380	1.21
101	4451	4415	1.28
102	4532	4491	1.28
63	4245	4151	1·32
65	3974	3935	1·39
69	3811	3751	1·39
70	3740	3698	1·39
75	3091	3049	1·52
78	3360	3276	1·43
79	3541	3203	1·51
	LACCADIVE SEA		
106	2452	2422	1·98
112	2300	2266	2·01
113	2595	2566	1·79

at these depths, we have evaluated the potential temperature at several stations and these are presented in Table 1. As can be seen from the table, most of the observations are at depths within 100 m from the bottom and the potential temperatures given in column 5 may be considered as characteristic of the bottom water.

On a region wise basis, the potential temperatures are lowest (0·89°C to 0·92°C) in the Somali Basin and highest (1·79°C to 2·01°C) in the Laccadive Sea. In the Arabian Basin, the potential temperatures range from 1·20°C to 1·52°C.

At depths of 4000 m, the *in situ* temperatures in the Somali Basin are somewhat lower than in the Arabian Sea and this is also true in the case of potential temperatures. Comparing stations 91 and 63, the potential temperature in the Arabian Basin is 0·35°C higher than in the Somali Basin at almost identical depths. The regional differences in the *in situ* temperature have also been reported by Wooster, Schaefer and Robinson (19 7).

While a detailed study of the water masses in the Arabian Sea will be presented later, it may be mentioned that the bottom water in the Somali and Arabian Basins is circumpolar water (Warren, Stommel and Swallow 1966) and is different from that of Laccadive Sea.

4. Acknowledgement

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