

VERTICAL DISTRIBUTION OF TEMPERATURE, SALINITY AND DENSITY IN THE UPPER 500 METRES OF THE NORTH EQUATORIAL INDIAN OCEAN DURING THE NORTH-EAST MONSOON PERIOD

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In the 4th and 5th scientific cruises of INS KISTNA under the Indian Programme of IIOE, five sections were worked out in the North Equatorial Indian Ocean during Jan.-Feb. 1963. Using the physical oceanographic data collected in these cruises, the vertical profiles of temperature, salinity and density (σ_t) for the upper 500 metres are prepared in the case of each section and the vertical distribution of each parameter is discussed. Two water masses—the low salinity water of Bay of Bengal ($S < 34.0\text{‰}$; $\sigma_t < 22.0$) and the high salinity water associated with the typical subsurface salinity maximum of the Equatorial Indian Ocean and the Salinity Maximum E ($S > 35.4\text{‰}$) reported by Rochford, are identified in the upper 150 metres. The former water is found at the surface between 5° N and 8° N in the middle part and north of 5° N in the eastern part of the region under study, while the latter water mass is observed in most of the regions, north as well as south of the equator. The deepening of this high salinity water up to 150-190 m depth under the Bay of Bengal Water in the northern region of the middle part is noteworthy. At the subsurface levels below 150 m, the Indian Ocean Equatorial Water ($T=4-16^\circ$ C; $S=34.8-35.2\text{‰}$) is encountered as a major water mass, while the Persian Gulf High Salinity Water ($S > 35.2\text{‰}$) at an average depth of about 200 m and the Red Sea High Salinity Water ($S > 35.3\text{‰}$) at depths greater than 450 m are traced only in a few specific regions with limited extents. Two regions of divergence—one between 50 m level and 150 m level within 2° south of the equator at $61-63^\circ$ E and the other in the upper 150 m off the East Coast of Ceylon (along 83° E), are observed. The former is attributed to the presence of Equatorial Undercurrent, probably flowing in an ENEly direction across this region, while the latter is connected to the divergence between the southern boundary of anticyclonic circulation of Bay of Bengal and the northern boundary of North Equatorial Current off the East Coast of Ceylon.

INTRODUCTION

The Indian Ocean, which is the only major ocean land-locked on the north and connected to only one of the polar regions, has several features of great scientific interest. The northern part of the Indian Ocean is considered to be one of the oceanographically important regions of the world. This is particularly because of the fact that some of the general features—such as circulation patterns and the presence of permanent boundary currents, which are common to both Pacific and Atlantic oceans are either modified considerably or absent in the Indian Ocean. Another interesting feature is its association with the monsoon systems, which have a great impact on the climate of the bordering countries. In spite of its great importance, it remained as the least explored among the world oceans until 1960.

Valdivia (1898-99), Dana (1920-30), Snellius (1929), John Murray (1933-34) and Swedish Deep-Sea (1947-48) expeditions have done the earlier work in this region. But the information available from these early works is very limited and incomplete.

During the International Indian Ocean Expedition (IIOE), which was launched in 1960 for a systematic exploration of the Indian Ocean, a number of scientific cruises were carried out by the Indian and foreign research ships in this region. Among the foreign research ships, which had participated in IIOE, special mention must be made about R/V VITYAZ (U.S.S.R.), R/V ANTON BRUUN (U.S.A.), R/V ARGO (U.S.A.), R/V ATLANTIS (U.S.A.), RRS DISCOVERY (U.K.) and R/V METEOR (Federal Republic of Germany) as they had carried out extensive observations in the North Indian Ocean. Under the Indian Programme of IIOE, INS KISTNA of the Indian Navy and R/V VARUNA of the Indo-Norwegian Fisheries Project carried out a few special cruises in the North Equatorial Indian Ocean and collected considerable data for the study of its hydrography. The data collected by INS KISTNA under two such cruises form the basis of the present investigation.

SCIENTIFIC CRUISES CARRIED OUT BY I.N.S. KISTNA DURING
JAN.-FEB. 1963 UNDER THE INDIAN PROGRAMME OF
INTERNATIONAL INDIAN OCEAN EXPEDITION

CRUISE	PERIOD	TRACK	STATIONS COVERED
IV	17/1/1963—29/1/1963	COCHIN—COCHIN	102—123
V	5/2/1963—15/2/1963	COCHIN—MADRAS	124—146.

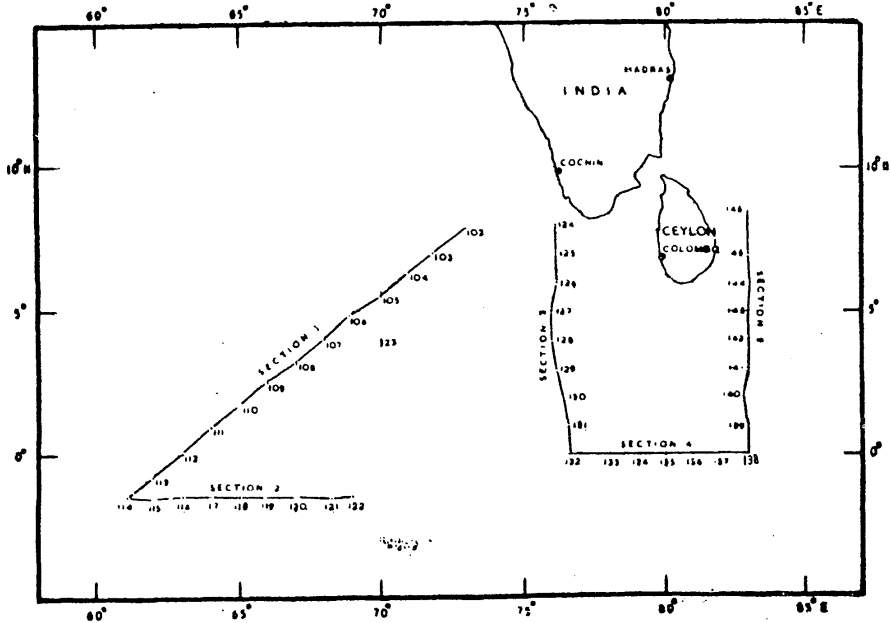


FIG. 1.

Chart showing the positions of stations and sections chosen for study.

TREATMENT OF DATA

INS KISTNA has carried out its 4th and 5th scientific cruises in the North Equatorial Indian Ocean from the 17th January to the 15th February, 1963. Altogether 45 hydrographic stations were occupied covering two latitudinal sections, two meridional sections and one diagonal section i.e., altogether 5 sections in the North Equatorial Indian Ocean. The positions of stations and sections considered for this study are shown in Fig. 1. The physical oceanographic data of these two cruises (in the form of observed data given for actual depths) are used by the authors in the present study after checking them for quality. As the hydrographic casts were lowered to ≤ 500 m depth at most of the stations, the present study is limited to the upper 500 metres. Vertical profiles of temperature, salinity and density (σ_t) are prepared for each of the five sections using the actual values of temperature, salinity and density in terms of σ_t corresponding to the accepted depths. In all sections, the vertical scale is exaggerated by 1839 times the horizontal scale (i.e., in all sections there is vertical distortion by a factor 1: 1839). While analysing the temperature sections, the isotherms are drawn at the interval of 1°C . In the top layer of weak thermal gradients, an additional isotherm at 0.5°C interval is drawn and shown as dash-dotted line. In the case of salinity sections, the isohalines are generally drawn at the interval of 0.1‰ . But in a few cases associated with sharp salinity gradients in the surface layers, 0.2‰ is chosen as contour interval. While analysing the vertical sections of density in terms of σ_t , the isopycnals are drawn at the interval of 0.2 gm/litre. The observed values of temperature, salinity and σ_t at the actual depth considered for the analysis are represented by dots on the vertical sections.

DISCUSSION

From the earlier studies (Ramasastry 1961) it is known that in the tropical regions of the Indian Ocean, a warm top layer of nearly constant temperature—often called the mixed layer is present. Its formation depends on the intensity of solar radiation and of mixing resulting from wind action. Below this mixed layer, there is a layer within which the temperature decreases rapidly with depth. This transition layer generally has the characteristics of a discontinuity and is known as thermocline. In the subsurface water below thermocline, the temperature gradually decreases with depth. Salinity, in general, increases with depth to give a salinity maximum within the equatorial waters at the top of thermocline. Actually this salinity maximum appears at the depth where the first drop in temperature occurs beneath the nearly isothermal surface water. Along with the temperature transition in thermocline, there may be localised strong vertical gradients of salinity generally referred to as halocline. According to Pollak (1958), the salinity in the surface waters of the Equatorial and Subtropical Indian Ocean ranges from 34.00‰ to 36.00‰ , surface water being defined as that above the 200 m level. Below the subsurface salinity maximum, the salinity gradually decreases down to the bottom. In the lower and middle latitudes, the temperature of the surface water of the open

ocean is so high that the density of the water remains low even in the regions where excess evaporation causes high salinities. Consequently, the convection currents are limited to a relatively thin layer near the surface. Just beneath this top layer of lighter water, a transition layer begins raising the density gradient to maximum and then slowly decreasing it towards the deeper layers. The sharp boundary surface which develops between the lighter top water and the denser water at some greater depths is known as density discontinuity layer. Because it is associated with steep vertical gradients of density it is often referred to as pycnocline. With this general background, the vertical distribution of temperature, salinity and density (in terms of σ_t) are discussed separately in the following paragraphs for each of the five sections.

Section 1:

This is a diagonal section across the North Equatorial Indian Ocean extending from $01^{\circ}32'S-61^{\circ}04.5'E$ to $07^{\circ}52'N-72^{\circ}58'E$.

Temperature (Fig. 2a): The surface temperature varies between $29.2^{\circ}C$ (at Stn. 107; 1540 hrs. IST) and $28.2^{\circ}C$ (at Stn. 114; 0423 hrs. IST). This surface temperature variation of $1.0^{\circ}C$ may be chiefly associated with the diurnal variation of sea surface temperature. The mixed layer* is developed well with weak thermal gradients in the northern half of the section compared to the southern half. Its thickness gradually decreases from about 100 m at Stns. 102-104 to about 35 m at Stns. 113-114, indicating that the thickness of mixed layer decreases towards the equator. The

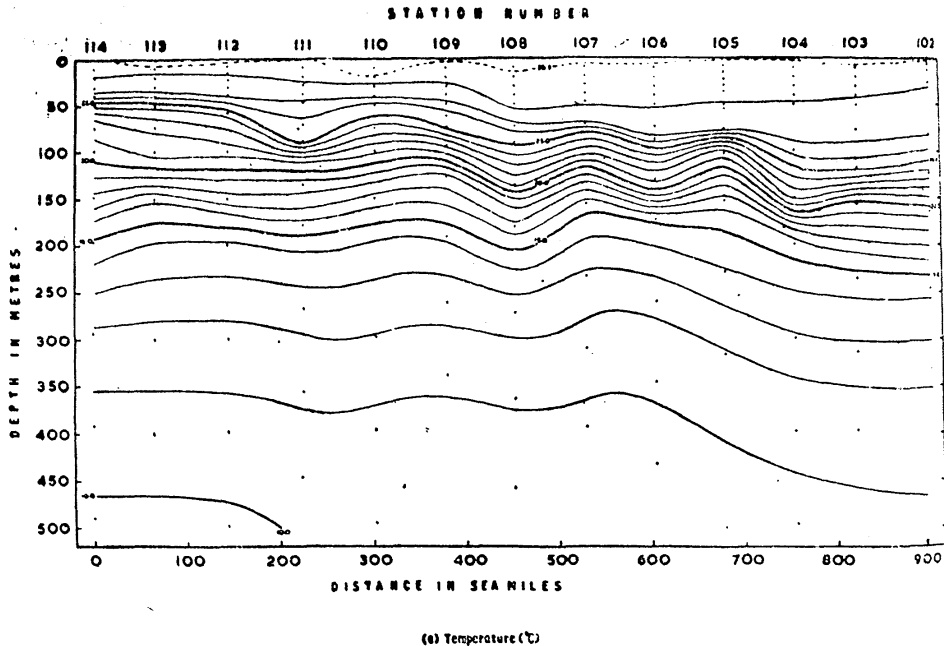
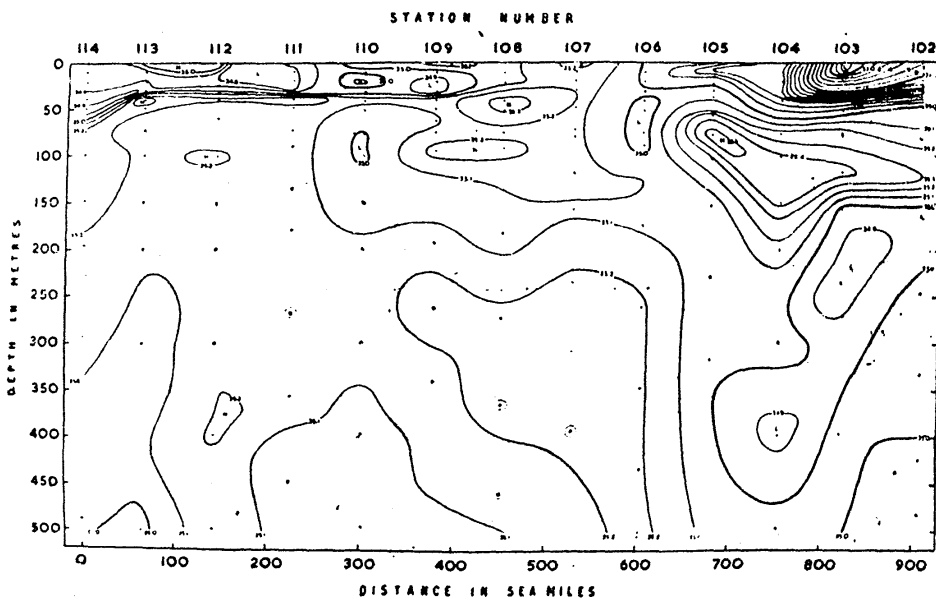


FIG. 2a.

FIG. 2a-c. Vertical Distribution of Temperature, Salinity and Density along Section 1.

thermocline* is seen to start at about 120 m depth under Stns. 102-104. It is drawn up to 76 m depth under Stn. 105 and 70 m depth under Stn. 107 in a wavy pattern. South-west of Stn. 107, the thermocline is gradually drawn up towards the surface except at Stn. 111 where it is pushed down to 90 m depth. The thermocline is seen at 40 m depth under Stn. 112 and 35 m depth under Stns. 113-114. Thus the depth of thermocline is seen generally to decrease gradually towards the equator. This feature is in agreement with the meridional depth variation of thermocline in the Atlantic (Defant 1961). The thickness of thermocline increases from about 55 m under Stns. 102-103 to about 100 m under Stns. 106-107. The maximum thermal gradients in the thermocline are of the order of $0.25^{\circ}\text{C}/\text{m}$. The regular wavy nature of the isotherms of thermocline under Stns. 103-108 may be the result of internal waves. South-West of Stn. 107, the thermocline is seen to spread and this spreading is more marked at a mean depth of 100 m under Stns. 112-114. This feature may be associated with the presence of an undercurrent in the equatorial region. Below the thermocline, there is a gradual decrease of temperature gradient towards greater depths and the thermal structure is normal.

Salinity (Fig. 2b): The surface salinity varies between 35.25‰ and 32.56‰ . The high value of surface salinity viz., 35.25‰ found at Stn. 107 may be due to the presence of locally upwelled water resulting from the divergence above the thermo-



(b) Salinity (‰)

FIG. 2b.

* In the present discussion, a vertical temperature gradient of $0.1^{\circ}\text{C}/\text{m}$ is taken as the lowest limit to define thermocline (Defant 1961) and the warm top layer of relatively low gradients of temperature lying above thermocline is termed as mixed layer.

cline ahead of the crest of internal wave (LaFond and Lee 1962). The low values of surface salinity ($<34.00\%$ found in the northern part of the section at Stns. 103 and 102 may be due to the presence of Bay of Bengal water brought in by the North Equatorial Current. The salinity structure in the top 30 metres between Stns. 114-108 (in particular, the presence of the cells of high salinity and low salinity under Stns. 110 and 109) may indicate lack of mixing in the surface waters of the southern half of the section. In the northern part of the section, westward intrusion of low salinity water is clearly seen in the top 60 metres up to Stn. 106. A well developed local halocline is seen in the northern part of the section at about 30 m depth under Stns. 102-103. Moderately developed halocline is present under Stns. 109-113 at 30-40 m depth. The absence of halocline and the presence of almost uniform salinity under Stns. 107 and 106 may be the result of local convergence above the thermocline behind the crest of internal wave (LaFond and Lee 1962). The salinity is more or less uniform below 50 m level in the southern part of the section under Stns. 114-111 indicating a vertical stratification probably resulting from lateral mixing. A huge volume of high salinity water with a well developed core seen in the northern part of the section under Stns. 102-105 at a mean depth of 100 m may represent the high salinity water associated with the Salinity Maximum E reported by Rochford (1964). This feature can also be related to the typical subsurface salinity maximum. A tongue of relatively high salinity water found under Stns. 109-106 at depths greater than 200 m and a tongue of relatively low salinity water found

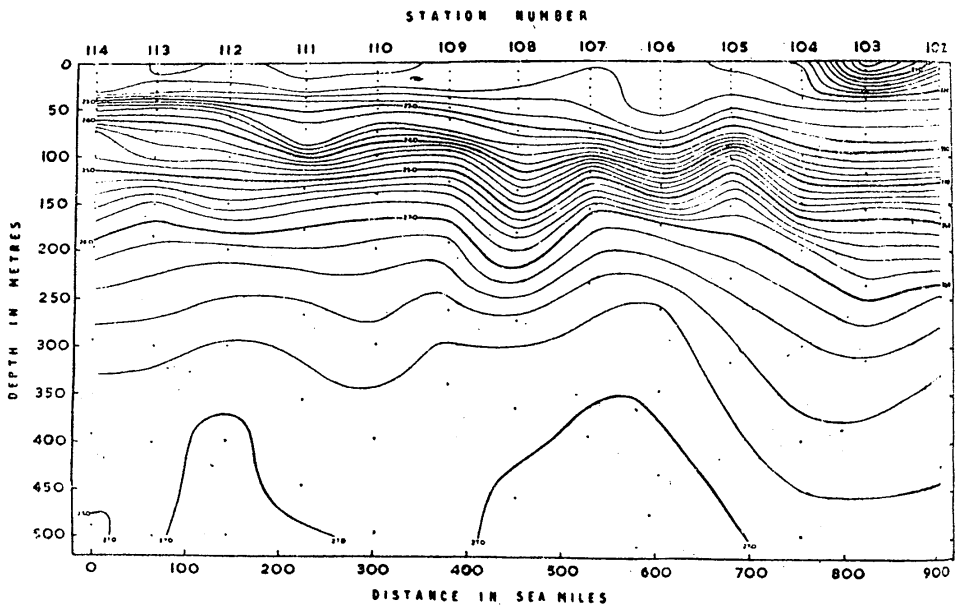
(c) Density (σ_t)

FIG. 2c.

under Stns. 105-102 at depths greater than 150 m may indicate movement of water in the deeper layers.

Density in terms of σ_t (Fig. 2c): In the northern part of the section, a parcel of relatively lighter water ($\sigma_t < 22.00$) is present in the top 40 m at Stns. 102-104. This low density water, which appears to flow westward in the surface across the section with its core at Stn. 103, can be inferred as the Bay of Bengal water as indicated earlier. Throughout the remaining part of the section, a light top layer, typical to the tropics, is present. Below this light top layer, the density discontinuity layer (pycnocline) is seen. It is developed well in the middle part of the section under Stns. 104-111 compared to the extreme parts. The regular wavy pattern exhibited by the isopycnals of pycnocline under Stns. 104-108 clearly indicates the presence of internal waves. Under Stns. 112-114, there is weakening of the density discontinuity layer associated with a reversal in the slope of isopycnals between 50 m level and 150 m level. This feature may indicate the presence of a subsurface current flowing in a direction opposite to that of surface current. Because the surface current is known to be westward, this sub-surface current may be flowing eastward and hence it can be related to the Equatorial Undercurrent. The 'domings' and 'depressions' exhibited by the isopycnals at greater depths indicate deep water movements.

Section 2:

This section lies almost along the latitude $01^{\circ}30'S$ from $61^{\circ}04.5'E$ to $69^{\circ}00'E$.

Temperature (Fig. 3a): The sea surface temperature varies between $29.7^{\circ}C$ (at Stn. 115; 1427 IST) and $28.2^{\circ}C$ (at Stn. 114; 0423 hrs. IST). This surface temperature variation of $1.5^{\circ}C$ appears to be the combined effect of the diurnal variation of sea surface temperature and the water movements in the upper layers. The mixed layer is not well developed in the western part of the section between Stns. 114 and 117, its thickness being only about 30 metres. East of Stn. 117, there is a gradual development of mixed layer and at Stns. 120-122 its thickness is seen to increase from 70 m to 100 m. The thermocline is seen to start at a mean depth of 33 m in the western part of the section under Stns. 114-117 and to come down to 46 m depth under Stn. 119. East of Stn. 119, the thermocline is pushed down gradually and it is present at a depth of 100 m under Stn. 122. The thermocline is well marked under Stns. 121-122, where its thickness is about 60 m and the maximum thermal gradients are of the order of $0.2^{\circ}C/m$. West of Stn. 121, the thermocline has started to spread gradually and this spreading of thermocline especially in its lower part is more marked in the western part of the section under Stns. 114-116 at a mean depth of 90 m. Thus the shallowing of thermocline accompanied by its spreading in the western part of the section clearly indicates the presence of divergence at these levels. This feature being found along $01^{\circ}30'S$ may possibly be associated with the Equatorial Undercurrent. Under Stns. 114-117, beneath 100 m level, the isotherms which have gradually assumed a trough-like feature centred under Stn. 116. This feature, is more marked at depths greater than 200 m between Stns. 114 and 118, may indicate sinking of water in the subsurface layers below 150 m level.

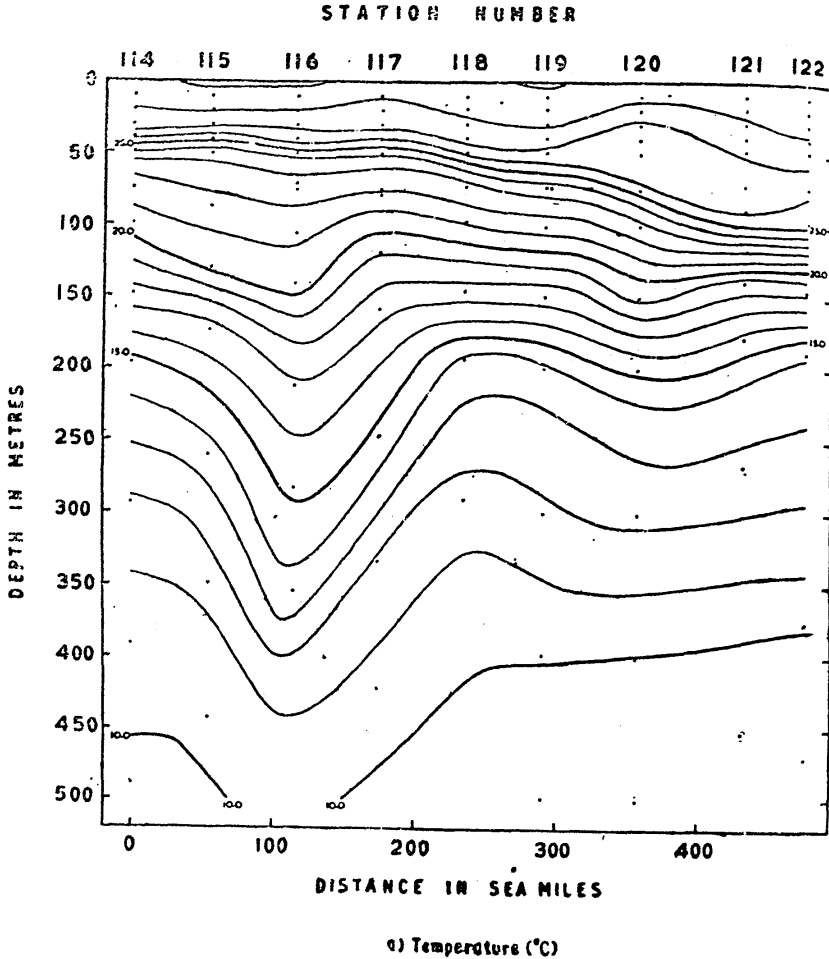
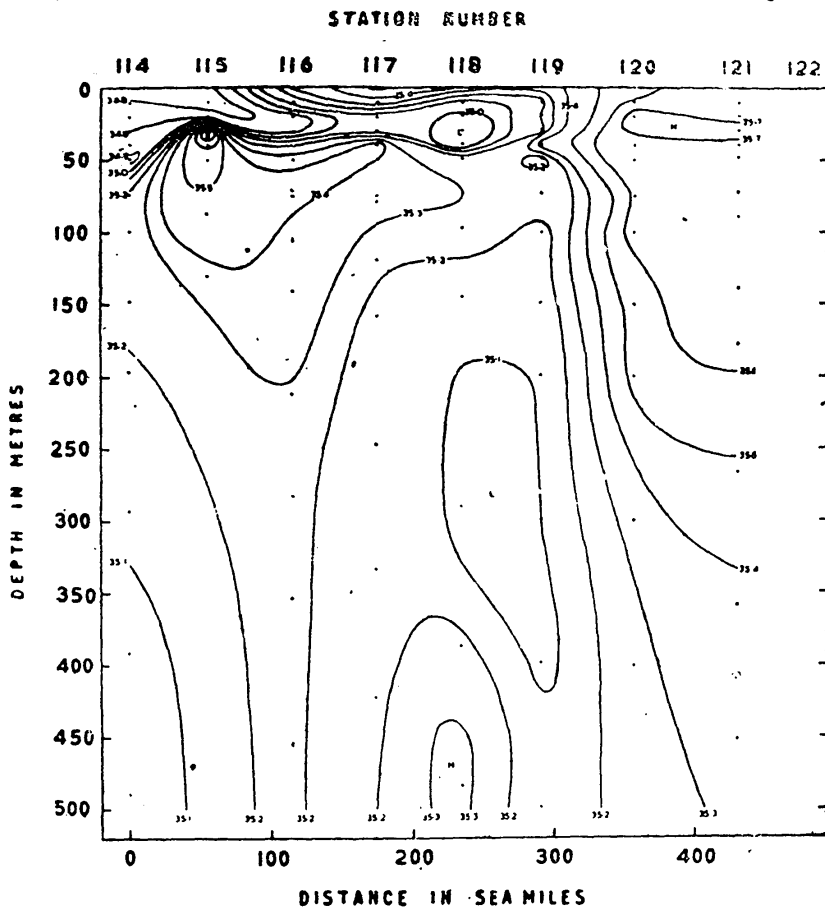


FIG. 3a.

FIG. 3a-c. Vertical Distribution of Temperature, Salinity and Density along Section 2.

Salinity (Fig. 3b): The surface salinity varies between 35.75‰ and 34.72‰. The high values of salinity (<35.50‰) in the surface layers at Stns. 120 and 121 examined in conjunction with the temperature and density structures where the isopleths show an upward tilt, indicate the possibility of small scale divergence, the intensity of which is probably not sufficient to cause any high degree of upwelling. In the surface layers of the western and middle parts of the section an eastward intrusion of a tongue of low salinity water is clearly seen between Stns. 114 and 119. This feature may be due to the advection of relatively low salinity waters of North Equatorial Current into the Equatorial Countercurrent. The halocline is seen at 20-30 m depth under Stn. 115, 30-40 m depth under Stns. 116-117 and 40-50 m depth under Stn. 118. It is well developed under Stn. 115 and moderately developed under Stns. 116-118. The high salinity values that are found just below the halo-

cline under Stns. 115-118 appear to be in accordance with the Salinity Maximum E reported by Rochford (1964) in the upper 110 metres of the Equatorial Indian Ocean. The distribution of high salinity water along 01°30'S (i.e., just south of the equator) in the region of thermocline and the eastward extension of the high salinity cells associated with this high salinity water can be related to the Equatorial Undercurrent (Knauss and Taft 1964). The downward extension of these high salinity



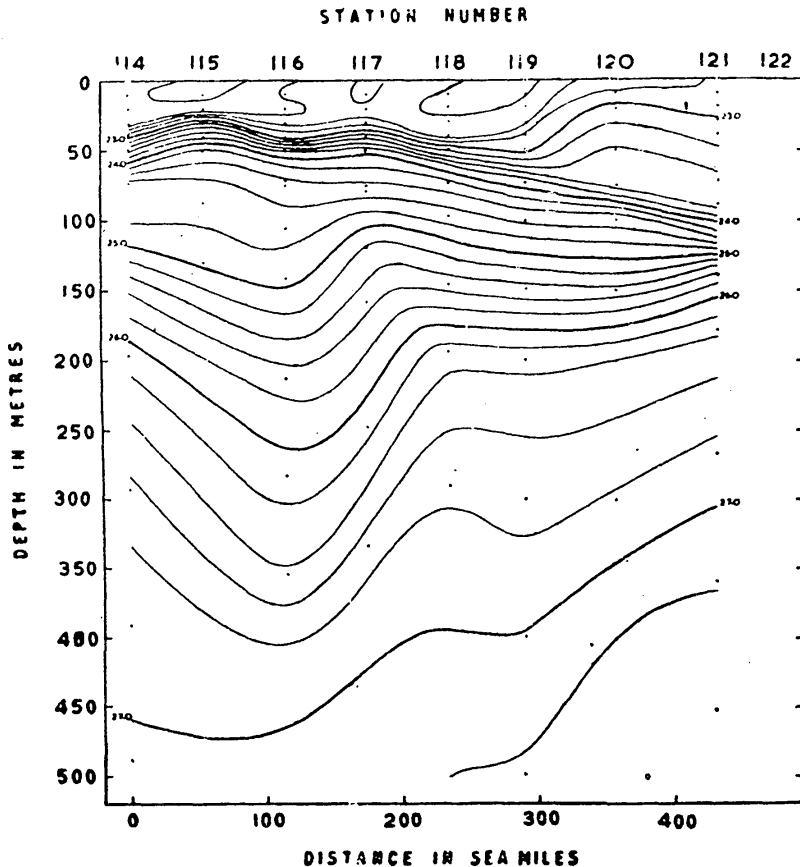
(b) Salinity (‰)

FIG. 3b.

cells between Stns. 114 and 117 indicates the sinking of high salinity water to greater depths. A tongue of higher salinity water extending upwards from the deeper levels under Stn. 118 may indicate the vertical extension of Red Sea water, whose presence is well established in these levels. Thus besides the temperature structure, the salinity structure also shows considerable vertical movement of the subsurface

waters below 150 m level between Stns. 114-120. The abnormal high salinity found at all subsurface depths under Stns. 120 and 121 is an interesting feature in the distribution but this feature cannot be explained at this stage.

Density in terms of σ_t (Fig. 3c): A top layer of relatively low density water is present in the surface at Stns. 114-119. The density structure in this top layer



(c) Density (σ_t)

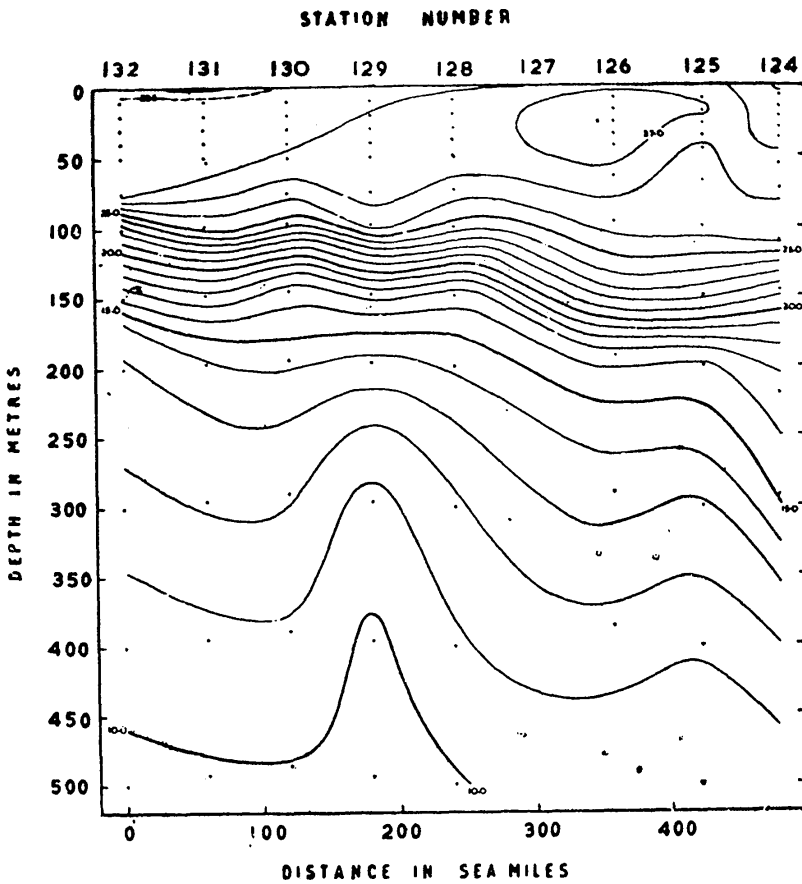
FIG. 3c.

clearly indicates the advection of lighter water possibly from the North Equatorial Current. Just below this light top layer, the density discontinuity layer (pycnocline) is seen. The depth of its occurrence increases from about 20 m under Stn. 115 to about 40 m under Stn. 118. The upward tilt of isopycnals in the upper 60 metres between Stns. 119-121 indicates some amount of divergence as already discussed under salinity distribution. West of Stn. 121, the pycnocline is seen to spread and this spreading of pycnocline especially in its lower part is more marked in the western

part of the section under Stns. 114-116 with an appreciable drop in the density gradient between 50 m level and 150 m level. These features clearly establish the presence of a subsurface divergence between 50 m level and 150 m level in the western part of the section under Stns. 114-116. It is quite possible that this subsurface divergence is associated with the presence of an undercurrent in this region. The huge depression exhibited by the isopycnals in the western part of the section between Stns. 114-117 at depths greater than 120 m indicates a downward movement of water. The rather high slopes of isopycnals under Stns. 118-121 at depths greater than 200 m also indicate movements of water in the deeper layers.

Section 3:

This section is situated across the North Equatorial Indian Ocean between the



(a) Temperature (°C)

FIG. 4a.

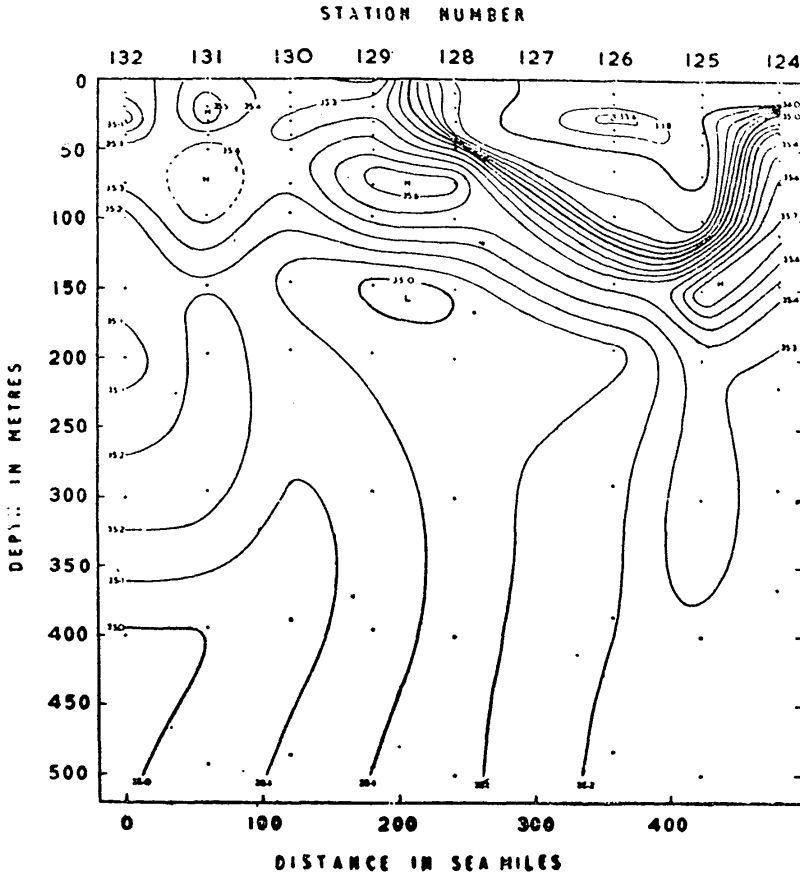
FIG. 4a-c. Vertical Distribution of Temperature, Salinity and Density along Section 3.

longitudes $76^{\circ}00'E$ and $76^{\circ}40'E$ (i.e., roughly along the mean longitude $76^{\circ}20'E$) and extends from the equator to $8^{\circ}N$.

Temperature (Fig. 4a): The sea surface temperature varies between $29.2^{\circ}C$ (at Stn. 131; 1410 hrs, IST) and $27.3^{\circ}C$ (at Stn. 126, 2250 hrs. IST). The low surface temperature found at Stn. 126 may be the combined effect of the cooling of surface water during night time and the influx of relatively colder water from the Gulf of Mannar at this time of the year. Though the mixed layer is developed well with weak thermal gradients in the southern part of the section compared to the northern part, its thickness (about 75 m) is less in the southern part compared to its thickness (more than 100 m) in the northern part. This feature has resulted from the presence of a parcel of comparatively colder water, probably from the Gulf of Mannar, with temperature less than $27.0^{\circ}C$ in the northern part of the section between Stns. 128 and 124. The thermocline is noticed at a depth of 110 m under Stn. 124. It is gradually drawn up southwards in a wavy pattern and under Stn. 132 situated on the equator, it is present at 75 m depth. This feature, in general, agrees with the meridional depth variation of thermocline in the Atlantic (Defant 1961). Throughout the section, the thermocline has a mean thickness of about 90 m. But it is developed well in the southern part of the section, the maximum thermal gradients being of the order of $0.25^{\circ}C/m$, compared to the northern part. The regular wavy pattern exhibited by the isotherms of thermocline (especially under Stns. 132-127) is probably the result of internal waves. In the subsurface levels beneath thermocline, there is a gradual decrease in temperature gradient with increasing depth. The isotherms are still exhibiting wavy pattern with greater wave length. There is a gradual increase in the amplitude of this wavy pattern with increasing depth and two wave crests—one under Stn. 129 and another under Stn. 125, are more clearly marked. This feature may indicate the development of internal waves as standing waves in these levels.

Salinity (Fig. 4b): The surface salinity varies between 35.43‰ and 33.78‰. The low surface salinity (<34.00 ‰) in the northern part of the section in association with considerable amount of low salinity water in the surface layers between Stns. 124 and 128 may be related to the Bay of Bengal water, which has intruded into the North Equatorial Current and has been carried westward across the section. The thickness of this low salinity water has shown a sudden increase from 15 m at Stn. 124 to more than 100 m at Stns. 125-126 and a gradual decrease southwards to 40 m at Stn. 128. The lowest salinity in its core, situated at 25-30 m depth under Stn. 126, is 33.57‰. In the northern part of the section, a well developed halocline is present just below the parcel of low salinity water. Halocline is not seen in the southern part of the section. A tongue of high salinity water, which is seen to intrude southwards just below the halocline in the northern part of the section and the cells of relatively high salinity water found at a mean depth of 75 m in the southern and middle parts of the section may represent the Salinity Maximum E reported by Rochford (1964) in the upper 110 metres of the Equatorial Indian Ocean as well as the typical subsurface salinity maximum within the equatorial waters of the Indian Ocean. Below the salinity maxima in the middle and southern parts of the section,

there are vertically rising huge tongues of low salinity water clearly indicating an upward movement of low salinity water from the deeper layers. Because the



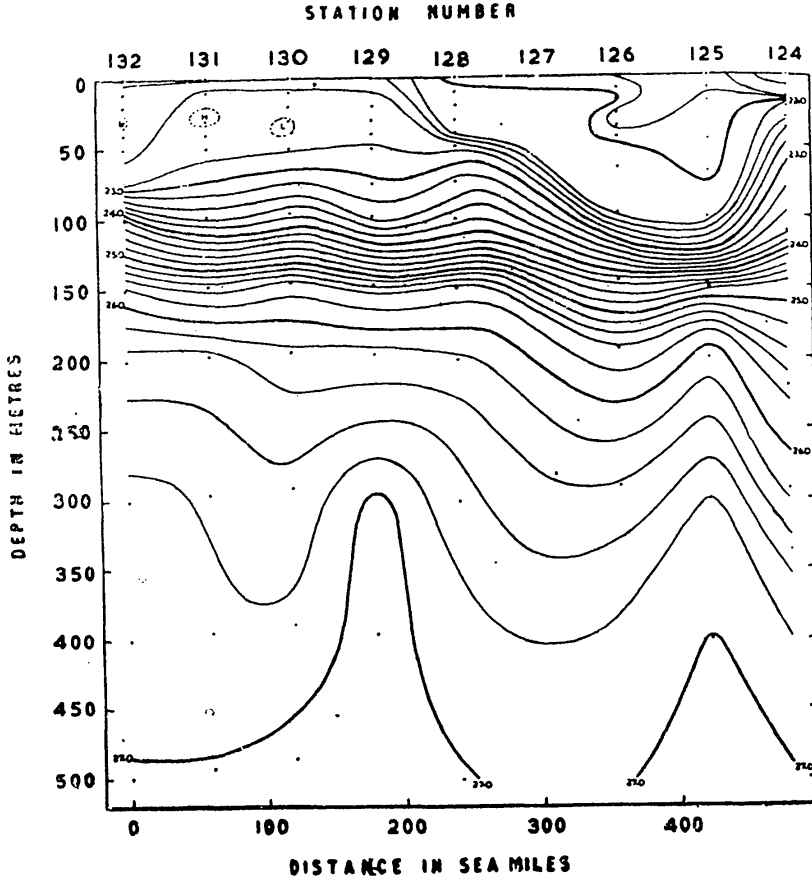
(b) Salinity (‰)

FIG. 4b.

temperature structure also supports this feature, these vertical movements of water at the subsurface depths below thermocline are considered to be associated with the internal waves that might have developed as standing waves in these levels. The downward extension of isohalines below the high salinity tongue in the northern part of the section indicates subsurface sinking of high salinity water to greater depths.

Density in terms of σ_t (Fig. 4c): In the surface layers of the northern part of the section, a huge volume of relatively lighter water ($\sigma_t < 22.20$) is distinctly seen at Stns. 124-128. This low density water, which has a maximum thickness of about 100 m at Stns. 125-126, is the Bay of Bengal water flowing westward across the

section as already indicated under salinity. Its thickness is reduced to about 20 m at Stn. 124 and to about 40 m at Stn. 128. In the surface levels of the southern



(c) Density (g)

FIG. 4c.

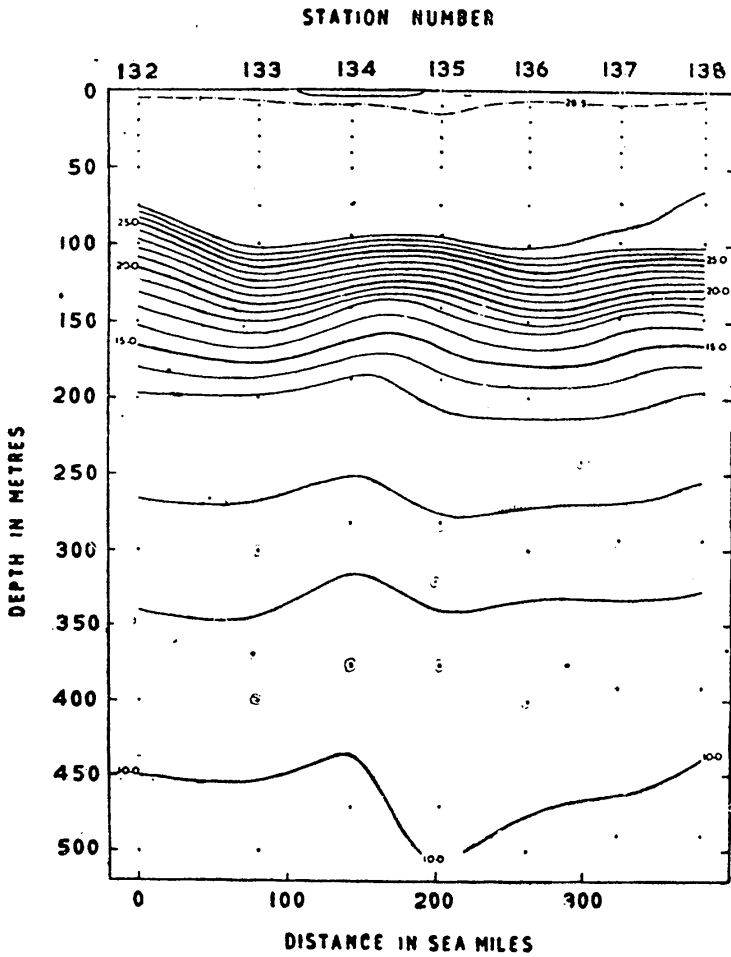
part of the section at Stns. 129-132, a top layer with low density gradients is present. Below this top layer of low density gradients, the density discontinuity layer (pycnocline) is well marked. The pycnocline is strongly developed with more thickness just below the huge volume of lighter water in the northern part of the section. The regular wavy pattern exhibited by the isopycnals of pycnocline, particularly between Stns. 127-132 clearly indicates the presence of internal waves. Below the pycnocline, the isopycnals are exhibiting 'domings' and 'depressions' with an increasing amplitude towards deeper layers. This feature appears to confirm vertical

movement of deeper waters probably associated with the development of internal waves as standing waves.

Section 4:

This section is along the equator from 76° 40'E to 83° 00'E.

Temperature (Fig. 5a): The surface temperature varies between 29.5°C and 28.7°C. The high value of surface temperature (29.5°C) at Stn. 134 (1508 hrs. IST) appears to be purely the effect of the heating of surface water during day time. The low range of surface temperature variation (viz., 0.8°C) indicates the presence of

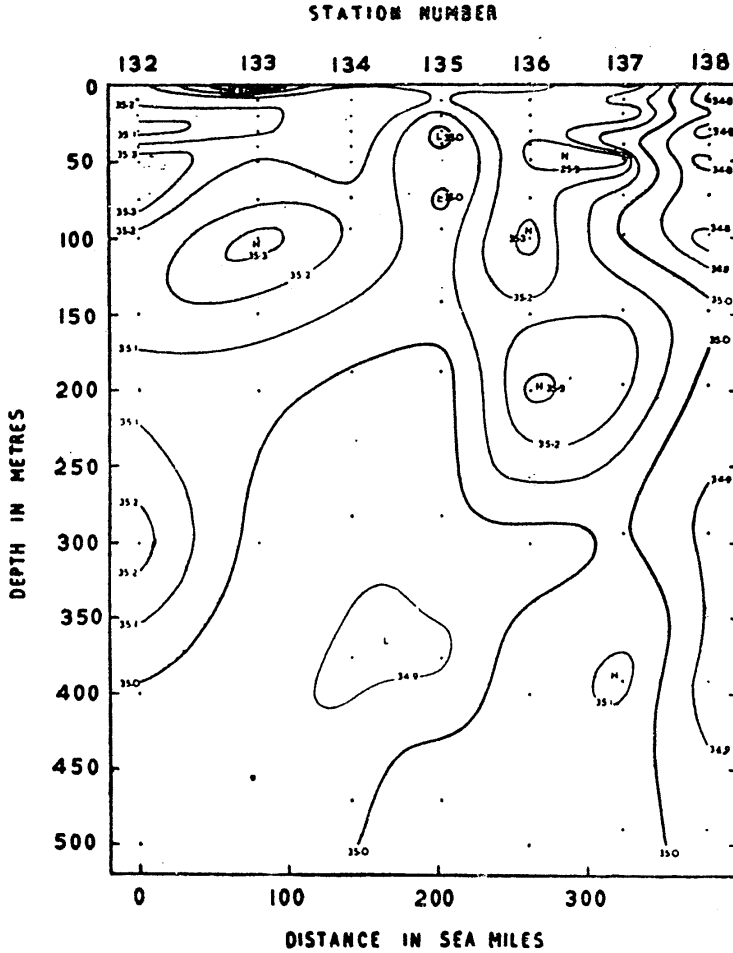


(a) Temperature (°C)

FIG. 5a.

FIG. 5a-c. Vertical Distribution of Temperature, Salinity and Density along Section 4.

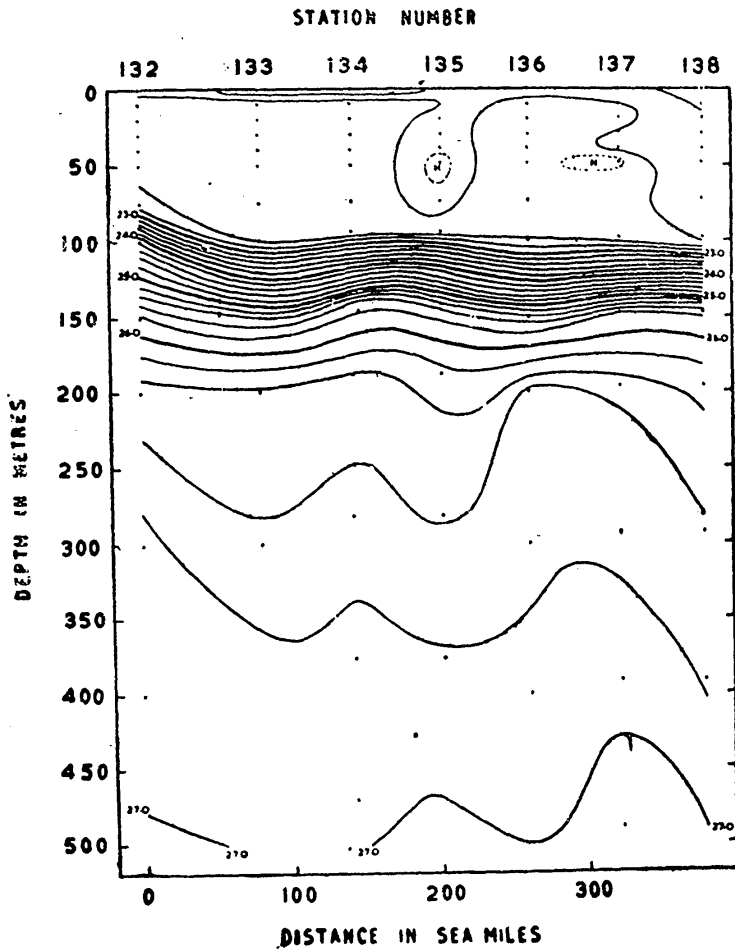
nearly homogeneous water in the surface. The mixed layer is developed well throughout the section with considerable thickness. The temperature gradients are so low that the entire mixed layer can be treated as a nearly isothermal water mass. It has a mean thickness of about 100 m between Stns. 133 and 138. Its thickness decreased to 75 m at Stn. 132. The thermocline is well developed just below the mixed layer, the maximum temperature gradients being of the order of $0.33^{\circ}\text{C}/\text{m}$. This typical formation of thermocline in association with a well developed mixed layer indicates a stable stratification in the upper layers. The depth of occurrence of thermocline increases from 75 m under Stn. 132 to 100 m under



(b) Salinity (‰)

FIG. 5b.

Stn. 133. The thermocline is drawn up to 94 m depth under Stn. 134, 135 and again pushed down to 100 m depth under Stns. 136-38 in a wavy pattern. This wavy pattern is maintained by all the isotherms of thermocline throughout the section indicating the presence of internal waves. The thickness of thermocline is 75-85 m under Stns. 132-133 and 60-55 m under Stns. 134-138. The internal waves appear to extend downwards below the thermocline as the isotherms below the thermocline are also showing the wavy pattern, which is less regular with increasing depth. The ridge and trough pattern of isotherms of the subsurface levels below thermocline



(c) Density (σ_t)

FIG. 5c.

under Stns. 133-138 indicates the vertical movements of water probably associated with the internal waves.

Salinity (Fig. 5b): The surface salinity varies between 35.32‰ and 34.87‰. Thus the range of surface salinity variation is only 0.45‰ confirming the existence of nearly homogeneous water in the surface indicated by the temperature structure. The tongue of relatively low salinity water extending eastwards just below the surface under Stns. 132-134 may be associated with the advection of relatively low salinity waters of North Equatorial Current into the Equatorial Countercurrent. The cells of high salinity water found under Stns. 133 and 136 at a mean depth of about 100 m may be associated with the typical subsurface salinity maximum generally found at the top of thermocline within the equatorial waters of the Indian Ocean. The high salinity water enclosed by a cell of 35.20‰ isohaline at a mean depth of 200 m under Stns. 136-137 may represent the Persian Gulf High Salinity Water (Salinity Maximum B) reported by Rochford (1964). At the subsurface levels there is an upward extension of the isohalines between Stns. 133-136 and also a downward extension of the isohalines between Stns. 135-138. This feature indicates vertical displacements of water as inferred from the temperature structure.

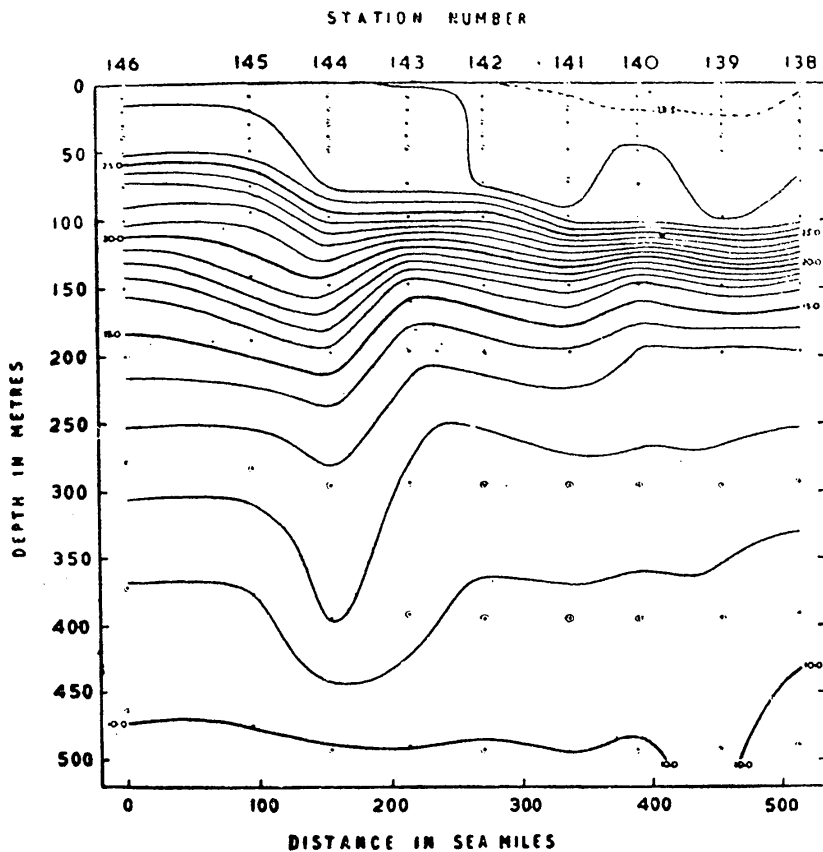
Density in terms of σ_t (Fig. 5c): A light top layer, typical to the tropics, is well developed throughout the section with considerable thickness. Its thickness is about 100 m at all the stations except at Stn. 132, where it is reduced to about 75 m. Just below the top layer of light water, a well defined density discontinuity layer (pycnocline) is present. The regular wavy pattern exhibited by the isopycnals of pycnocline confirms the presence of internal waves indicated by the temperature structure. Below the pycnocline, the density gradient is seen to decrease gradually with increasing depth and the isopycnals are exhibiting 'domings' and 'depressions' with an increasing amplitude towards deeper layers. These are interpreted in terms of vertical displacements as brought out in the foregoing paragraphs.

Section 5:

This section is situated across the North Equatorial Indian Ocean along the 83°E meridian and extends from 08°33'N to the equator.

Temperature (Fig. 6a): The surface temperature varies between 29.0°C and 27.4°C. It is comparatively lower (<28.0°C) in the northern part of the section at Stns. 144-146 possibly due to the advection of relatively colder water of Bay of Bengal into the North Equatorial Current in the surface. The mixed layer is developed well in the southern and middle parts of the section compared to the northern part. Its thickness is about 100 m in the southern part (at Stns. 138-141), about 80 m in the middle part (at Stns. 141-144) and about 50 m in the northern part (at Stns. 145-146). Thus there is a gradual decrease in the thickness of mixed layer from the equator towards north. The presence of a thick volume of relatively colder water at Stns. 143-144 is considered to be associated with the divergence above the thermocline ahead of the crest of internal wave. The thermocline is seen to start at a depth of about 100 m in the southern part of the section under Stns. 138-141. It is drawn up

towards north in two steps—at Stn. 142 to a depth of about 80 m and at Stn. 145 to a depth of about 50 m. Thus gradual shallowing of thermocline is noticed



(a) Temperature (°C)

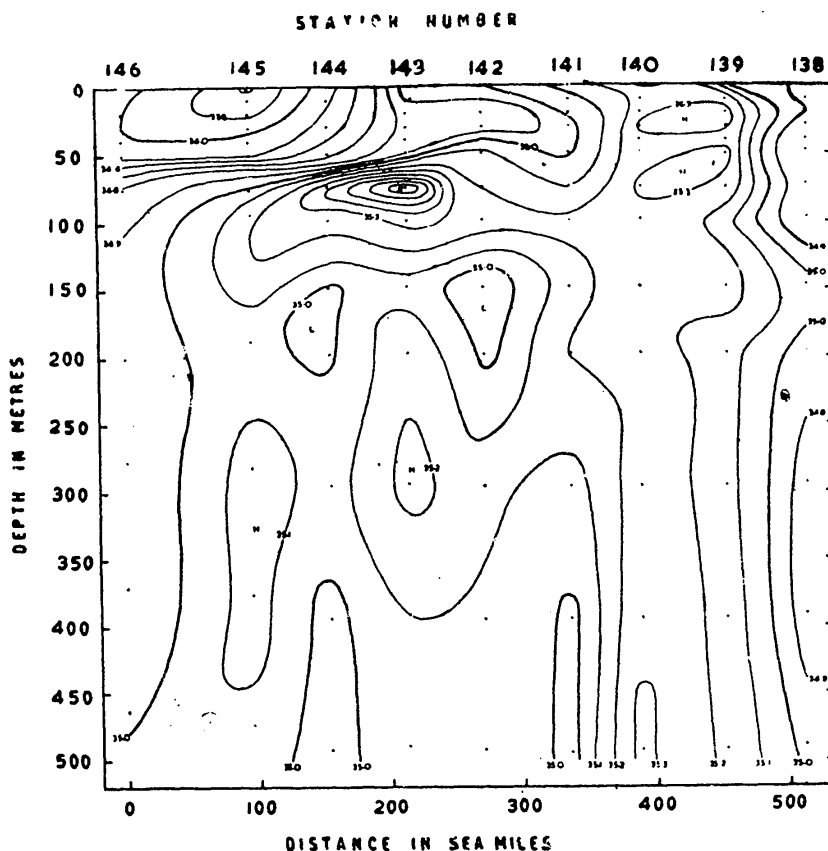
FIG. 6a.

FIG. 6a-c. Vertical Distribution of Temperature, Salinity and Density along Section 5.

towards north. In this connection it may be recalled that this feature is quite opposite to the meridional depth variation of thermocline in the Atlantic (Defant 1961). The thermocline is well defined in the southern part of the section under Stns. 138-140 with a mean thickness of about 50 m and maximum thermal gradients of the order of 0.33°C/m. The presence of a well defined thermocline in association with a well developed and relatively thick mixed layer in the southern part of the section may indicate a stable stratification in the upper layers. The isotherms of thermocline are exhibiting slight, but regular, wavy pattern under Stns. 138-144 indicating the presence of internal waves. North of Stn. 140, the thermocline starts to spread and under Stns. 141-143, its thickness is about 75 m. The spreading of

thermocline is more prominent under Stns. 144-146 in association with an upward tilt of the upper part of thermocline. This feature may be related to the presence of the zone of divergence between the southern boundary of anticyclonic circulation of Bay of Bengal and the northern boundary of North Equatorial Current off the East Coast of Ceylon. The downward trend of isotherms under Stn. 144 gradually assumed a trough pattern at 250-450 m depth probably indicating subsurface sinking.

Salinity (Fig. 6b): The surface salinity varies between 35.34‰ and 33.57‰. The low values of surface salinity in the northern part of the section around Stn. 145 may indicate the advection of relatively less saline Bay of Bengal waters. This low salinity water is limited to the upper 40 metres at Stns. 146-145. The upward tilting

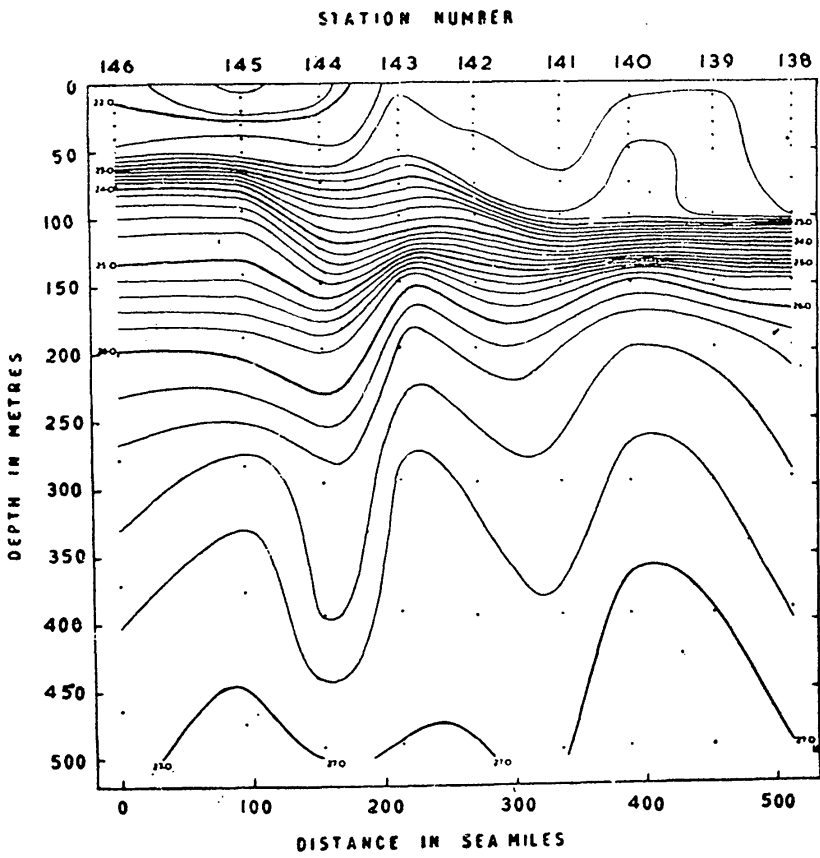


(b) Salinity (‰)

FIG. 6b.

of isohalines in the surface layers at Stns. 143-144 and their termination at the surface clearly indicates divergence and consequent upwelling of relatively high salinity waters towards the surface. The tongue-like southward extension of the isohalines seen in the surface layers of middle part of the section between Stns. 143-140 indi-

cates that the upwelled water of relatively higher salinity at Stn. 143 spreads southwards and accumulates between Stns. 142-140 and tends to sink around Stn. 141. But its sinking seems to be limited at 100 m depth by the well defined discontinuity layer (indicated by the density structure). The high salinity cell found at the top of thermocline in the southern part of the section at Stns. 139-140 may be associated with the subsurface salinity maximum of the Equatorial Indian Ocean. Halocline is developed just below the low salinity water in the northern part of the section and it extends from 50 m depth to about 70 m depth under Stns. 146-143. A parcel of high salinity water found just below the halocline between Stns. 145-142 represents probably the high salinity water associated with the Salinity Maximum E reported by Rochford (1964) as mentioned in the case of a few earlier sections. The core of this high salinity water is situated at a depth of 74 m under Stn. 143 with a maximum salinity of 35.79‰. The vertical trend of isohalines and the presence of a few



(c) Density (σ_t)

FIG. 6c

vertically elongated cells of high and low salinities in the deeper levels under Stns. 146-141 may indicate eddy mixing associated with the subsurface divergence and convergence phenomena. The high salinity water present at all depths below the thermocline under Stns. 139-140 and bounded by almost vertical isohalines on either side may indicate strong movement of subsurface waters.

Density in terms of σ_t (Fig. 6c): A layer of lighter water ($\sigma_t < 22.20$) is seen in the surface with a thickness of about 40 m at Stns. 144-146 confirming the intrusion of waters from the Bay of Bengal. The upward tilting of the isopycnals in the surface levels at Stns. 143-144 and their termination at the surface clearly indicates divergence and consequent upwelling of relatively higher density waters towards the surface. In the southern part of the section, a top layer of low density gradients is developed well with a thickness of about 100 m at Stns. 138-141. North of Stn. 141, its thickness gradually reduced to about 50 m at Stn. 143. The density discontinuity layer (pycnocline) is well developed with steep density gradients in the southern part of the section under Stns. 138-140. The slight, but regular, wavy pattern exhibited by the isopycnals of pycnocline confirms the presence of internal waves. North of Stn. 140, the pycnocline is seen to spread gradually in a wavy pattern exhibiting a crest under Stn. 143 and a trough under Stn. 144. North of Stn. 144, the isopycnals of the pycnocline which has spread, have accumulated to form a steep, but relatively thin, discontinuity layer just below the top layer of lighter water at Stns. 145-146. The crest exhibited by this pycnocline under Stn. 143 indicates that the divergence seen in the surface layers of this region is moderately strong. The pinching of this pycnocline under Stn. 144 indicates subsurface sinking. The shallowing of pycnocline under Stns. 144-146 may be associated with the presence of the zone of divergence between the southern boundary of the anticyclonic circulation of Bay of Bengal and the northern boundary of North Equatorial Current off the East Coast of Ceylon. The isopycnals continued their wavy pattern even below the pycnocline to steepen the troughs and crests at greater depths. This feature clearly indicates considerable movement of deeper waters.

GENERAL REMARKS

The following salient features are evident from the preceding discussion :

1. *Surface Temperature:*

In general, the surface temperature increases towards the equator. Its value generally varies between 28.0°C and 29.0°C, the extreme cases being 27.3°C at 6°N (Stn. 126; 2250 hrs. IST) and 29.7° C at 01°30'S (Stn. 115; 1427 hrs. IST).

2. *Mixed Layer:*

The mixed layer is well developed in the region east of 68°E meridian (with thickness of 75-100 m) compared to the region west of it. Along the equator, its thickness appears to decrease from about 100 m in the eastern part to less than 50 m

in the western part of the region under study. In the western and middle parts, the thickness of mixed layer gradually increases towards north, but in the eastern part (along 83°E meridian) the increase is towards the equator.

3. *Thermocline:*

The depth of occurrence of thermocline, in general, decreases towards the equator in accordance with the meridional depth variation of thermocline in the Atlantic as reported by Defant (1961). This feature is prominent in the western part of this region (the decrease being from about 100 m depth north of 6°N to less than 50 m depth at the equator). But in the eastern part (along 83°E) the depth of thermocline appears to increase towards the equator (the increase being from about 50 m off the East Coast of Ceylon to about 100 m at the equator). This feature may be a special case associated with the shallowing of thermocline resulting from the divergence off the East Coast of Ceylon. Along the equator itself, the thermocline shallows towards west (from about 100 m depth in the eastern part to less than 50 m depth in the western part). The thermocline is sharply developed (with maximum thermal gradients of the order of 0.25-0.33°C/m and thickness ranging from 50 m to 90 m) in the eastern and middle parts of this region (especially at 0°-5°N) than in the western part.

4. *Density Discontinuity Layer (Pycnocline):*

Along the equator, east of 76°40'E, and from the equator to 3°N in the eastern part (along 83°E), the density discontinuity layer is sharply developed with steep density gradients and starts (along with thermocline) at 95-100 m depth. In the eastern part, north of 3°N, the pycnocline gradually rises towards the surface and off the East Coast of Ceylon along 83°E, it is seen at 50 m depth. In the middle part (along 76°20'E), north of the equator, its depth of occurrence appears to vary between 50-100 m. In the western part a gradual shallowing of pycnocline is noticed towards south and west (from about 90 m depth at 8°-7°N, east of 71°E to 20-30 m depth at 01°30'S, west of 65°E). Along the equator, there is shallowing of pycnocline towards west (from about 95-100 m depth in the eastern part to about 30 m depth in the western part).

5. *Internal Waves:*

Internal waves are encountered south of 6°N in the eastern and middle parts of the region under study. They are seen in the western part also between 4°N and 7°N. These features in association with well developed thermocline and thick mixed layer indicate stable stratification in the upper layers of the respective regions. In the middle part of the region (along 76°20'E), north of the equator, the internal waves appear to develop as standing waves at the subsurface levels below thermocline.

6. *Surface Salinity:*

In the regions south of 5°N in the western portion and south of 4°N in the middle and eastern portions, the surface salinity generally varies between 35.0‰.

and 35.6 ‰. It is less than 35.0 ‰ (the lowest values being less than 34.0 ‰ between 6°N and 8°N) in the area which is under the influence of the Bay of Bengal Water brought by the North Equatorial Current.

7. *Subsurface Salinity Maximum:*

The subsurface salinity maximum, whose presence at the top of thermocline within the equatorial waters of the Indian Ocean is reported by the earlier workers, is generally found throughout the region under study except in a few limited areas (examples: Stns. 106, 134 and 135). Special mention must be made about the characteristic deepening of this salinity maximum into the thermocline region in the areas where the Bay of Bengal Water overlies.

8. *Water masses:*

Two water masses are encountered in the upper 150 metres. The first one is the low salinity water of Bay of Bengal ($S < 34.0$ ‰ and $\sigma_t < 22.0$). This water is found between 5°N and 8°N in the middle part and north of 5°N in the eastern part. It is limited to the upper 40 metres in the eastern part (along 83°E). But in the middle part (along 76°10'E) its maximum thickness is more than 70 metres. West of 70°E, its vertical as well as horizontal extent appears to decrease gradually. The second water mass is the high salinity water associated with the Salinity Maximum E ($S > 35.4$ ‰) reported by Rochford (1964) in the upper 110 metres of the North Indian Ocean between 10°N and 10°S. This water mass is distinctly seen north of the equator in the middle part (along 76°20'E). But in the eastern and western parts, north of the equator, it appears to be limited between 4°N and 7°N. It could not be traced along the equator in the middle and the eastern sectors. In the western part, it is noticed south of the equator (along 01°30'S) between 61°E and 65°E. Wherever it is present, it is found to be always associated with the typical subsurface salinity maximum of the Equatorial Indian Ocean. It is interesting to note the deepening of this water up to 150-190 m depth in the areas where the Bay of Bengal Water overlies.

At the subsurface levels below 150 m, two high salinity water masses are traced in few specific regions with limited extent. The first one is the Persian Gulf High Salinity Water associated with the Salinity Maximum B ($S > 35.2$ ‰) reported by Rochford (1964). This water is found beneath the equator between 80°E and 83°E (i.e., under Stns. 136-137) at an average depth of about 200 m. The second water mass is the Red Sea High Salinity Water associated with the Salinity Maximum A ($S > 35.3$ ‰) reported by Rochford (1964). This water is traced under Stn. 118 (01°31'S, 65°00'E) and Stn. 140 (02°05'N, 82°50'E) at depths greater than 450 m. It is possible that this water has been drawn slightly upwards from its usual depth to more than 500 m under the influence of considerable vertical movements in the deeper layers of these regions.

The major subsurface water mass of the region under study is the Indian Ocean Equatorial Water with the temperature range 4°-16°C and the salinity range 34.8-35.2 ‰. This water is encountered in all parts of the region below 150-200 m depth.

9. *Regions of Divergence:*

Abnormal subsurface divergence is encountered between 50 m level and 150 m level within 2° south of the equator at 61°-63°E (i.e. under Stns. 112-116). Considerable spreading of thermocline, distribution of high salinity water in it, appreciable weakening of density discontinuity layer in association with reversal in the slope of isopycnals—all these features associated with the above mentioned divergence establish the presence of Equatorial Undercurrent in this region. It appears to be flowing in an ENEly direction across this region.

Another zone of divergence is found off the East Coast of Ceylon (along 83°E) in the upper 150 metres. It appears to be associated with the divergence between the southern boundary of anticyclonic circulation of Bay of Bengal and the northern boundary of North Equatorial Current off the East Coast of Ceylon.

10. *Water Movements at Subsurface Levels:*

In the subsurface layers below thermocline, the isopycnals generally exhibit characteristic 'doming' and 'depression' more prominently than isotherms. It is possible to infer from these features, the presence of subsurface water movements of appreciable magnitude in some areas of the middle and eastern parts north of the equator and in the western part south of the equator.

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