

# HYDROGRAPHICAL FEATURES OF THE SOUTHERN AND CENTRAL BAY OF BENGAL DURING THE TRANSITION PERIOD BETWEEN WINTER AND SUMMER

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During Feb.-Mar. 1963, INS KISTNA has carried out its 6th and 7th oceanographic cruises in the southern and central parts of Bay of Bengal under the Indian Programme of IIOE. With the physical oceanographic data collected in these cruises, the general hydrographical features in the upper 500 metres are studied by preparing the vertical profiles of temperature, salinity and density ( $\sigma_t$ ) along the 6 sections chosen for the purpose and discussing the vertical distribution of each parameter in the case of each section. In the upper 50 metres of the Eastern Bay and the Andaman Sea, a low salinity water mass ( $S < 33.0\text{‰}$ ,  $\sigma_t < 21.0$ ), which could be tentatively named as the "Eastern Dilute Water of Indo-Pacific Origin", is encountered. Another water mass, which resembles the "Southern Bay of Bengal Water" with the salinity range 33.0-34.0‰ and  $\sigma_t$  range 21.0-22.0, is identified in the upper 100 metres of the Southern Bay and the western and middle parts of the Central Bay. Throughout the region under study, the Indian Ocean Equatorial Water ( $T=4^\circ\text{-}16^\circ\text{C}$ ;  $S=34.8\text{-}35.2\text{‰}$ ) is encountered as the major sub-surface water mass below 100-150 m depth. Traces of the high salinity water, which can be related to that of Persian Gulf are found with limited extent in a specific region in the central part of the Bay below 300 m depth. Regions of divergence and convergence in the southern boundary of the Bay and a zone of strong convergence in the Central Bay are indicated. In the upper 75 metres, the southwestward spreading of fresh water discharged from the mouths of Irrawaddy River and also a possible northward flow of relatively warm, but more saline and denser water in the Western Bay are inferred.

## INTRODUCTION

The Bay of Bengal, which forms the north-eastern part of the Indian Ocean, has many interesting features. The off-shore regions lying between  $8^\circ\text{N}$  and  $22^\circ\text{N}$  resemble clear blue tropical water, while the near-shore waters undergo seasonal cycles of colour varying from deep blue to the greenish hue of plankton and the brown of coastal drainage (LaFond 1958). The physical and chemical properties and circulation of the surface waters of the Bay of Bengal are greatly influenced by the meteorological conditions associated with the monsoon system. Under the influence of monsoons, this part of the Indian Ocean exhibits a well defined seasonal cycle in the pattern of circulation. The drainage into the Bay of a number of river systems contribute to a considerable extent the dilution of the waters. The oceanographic features of the Bay of Bengal are thus very complex and present many fascinating problems for study.

The earliest investigations in the Bay of Bengal were carried out on board 'Investigator' by Col. Sewell and the results were discussed by him in a series of papers published in the *Memoirs of the Asiatic Society of Bengal* (1925-35). Subsequent to the work of Col. Sewell, there have not been much studies till the investigations were taken up by the Andhra University in 1952 under the guidance of Prof.

E. C. LaFond. These studies were continued up to 1956. But the work was limited to only 200 miles off the East Coast of India between Calcutta and Madras. Although the Danish Ship 'Galathea' did a traverse through the Bay of Bengal in 1951, the work was mostly confined to the biological and productivity studies only with a few hydrographic observations. Under the IGY Programme, the Russian Research Ship 'OB' occupied a number of oceanographic stations in the Bay of Bengal during 1956-57. But the information available from this work is very limited.

Recently, under the International Indian Ocean Expedition (IIOE), which was launched in 1960 for a systematic exploration of the various regions of the Indian Ocean, some of the foreign research vessels like VITYAZ (U.S.S.R.), ANTON BRUUN (U.S.A.) and PIONEER (U.S.A.) worked out a few oceanographic cruises in the Bay of Bengal and collected valuable data. Under the Indian Programme of IIOE, INS KISTNA of the Indian Navy carried out many oceanographic cruises in the Bay of Bengal during 1963-65 and gathered considerable data for a detailed

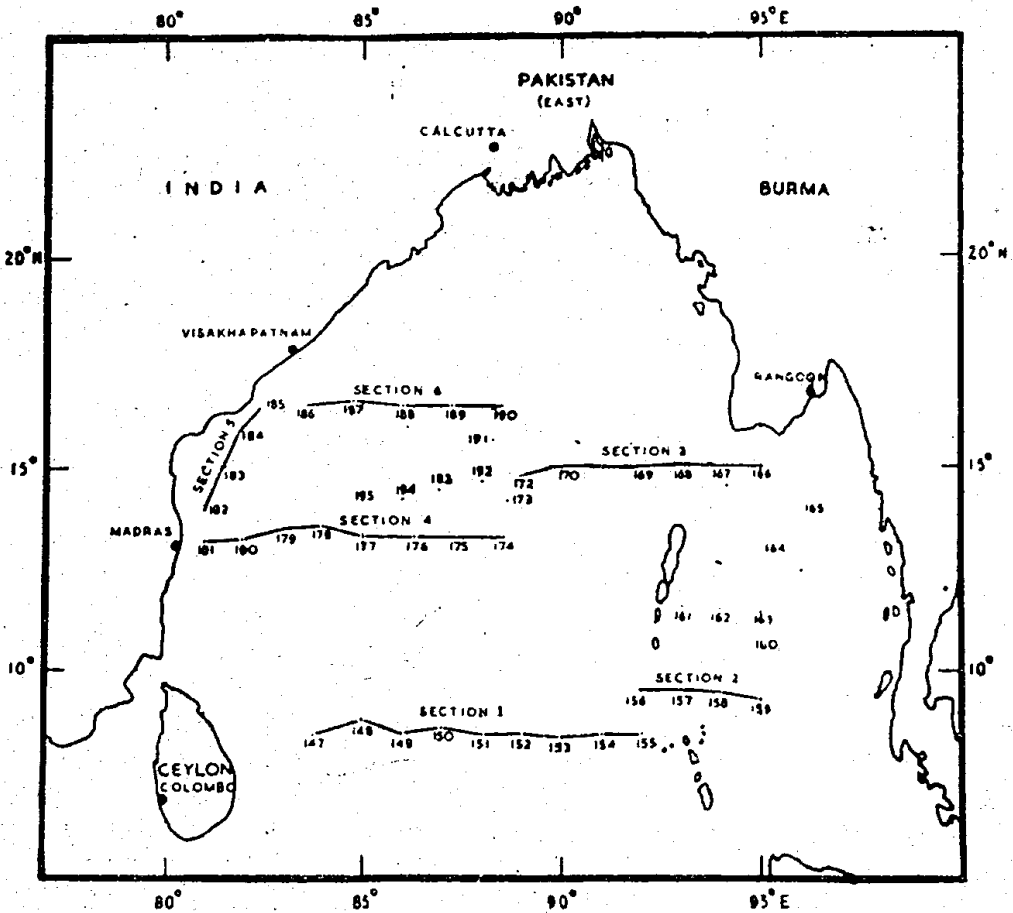


FIG. 1. Chart showing the positions of stations and sections chosen for study.

investigation of its hydrography. This paper is based on the data collected in two of these cruises.

## TREATMENT OF DATA

INS KISTNA has carried out its 6th and 7th scientific cruises in the southern and central parts of Bay of Bengal from the 21st February to the 20th March, 1963. Altogether 49 hydrographic stations were occupied covering 10 sections. The station positions along the various sections are shown in Fig. 1. For the present investigation, the authors have chosen 6 sections and used the physical oceanographic data (in the form of observed data given for actual depths) after checking them for quality. The present study is limited to the upper 500 metres and the treatment of data is on the same lines as indicated in an earlier paper by the authors (Gangadhara Rao and Jayaraman 1967).

## DISCUSSION

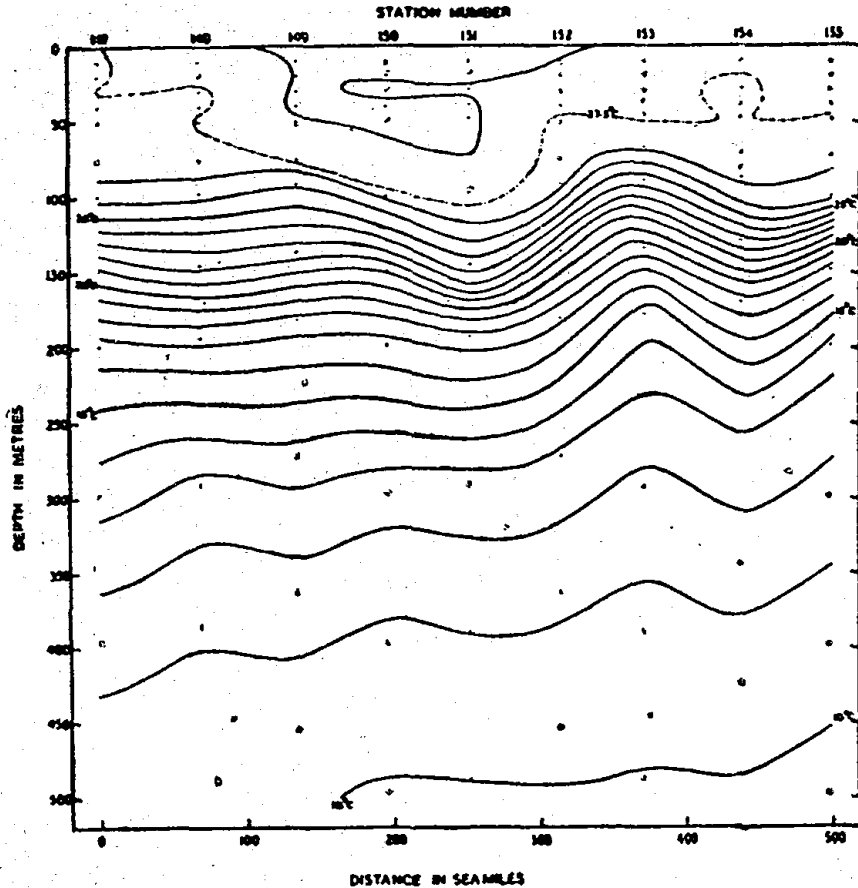
*Section 1:*

This section lies almost along the latitude  $08^{\circ}30'$  N from  $83^{\circ}46'$  E to  $92^{\circ}00'$  E.

*Temperature (Fig. 2a):* The surface temperature varies between  $28.6^{\circ}\text{C}$  (at Stn. 151; 1337 hrs. IST) and  $27.1^{\circ}\text{C}$  (at Stn. 147; 0549 hrs. IST). This surface temperature variation with a range  $1.5^{\circ}\text{C}$  may be attribute to the effect of water movements in the surface layers and of the diurnal variation of sea surface temperature. The mixed layer\* is moderately developed and has a thickness of about 90 m in the western part of the section at Stns. 147-148 and also in the eastern part of the section at Stns. 154-155. Its thickness has a maximum value of more than 100 m in the middle part of the section between Stns. 150-152 and a minimum value of about 70 m at Stn. 153. The thermocline\* is seen to start at a mean depth of about 100 m in the western part of the section at Stns. 147-148 and also in the eastern part at Stns. 154-155. It is pushed down between Stns. 149-152 and seen at a maximum depth of about 116 m under Stn. 151. It is drawn up between Stns. 152-154 and seen at a minimum depth of about 70 m under Stn. 153. The thermocline is well developed under Stns. 150-155 with a thickness of about 80 m and maximum thermal gradients of the order of  $0.20^{\circ}\text{C}/\text{m}$   $0.25^{\circ}\text{C}/\text{m}$ . West of Stn. 150, the thermocline started to spread and this spreading of thermocline especially in its upper portion is prominent under Stns. 147-149. This feature in association with relatively low temperatures in the surface layers at Stns. 147 and 148 indicates some amount of upwelling of subsurface water into the surface layers. This upwelling may probably 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. The trough exhibited by the thermocline between Stns. 149 and 152 in association

\*In the present discussion, a vertical temperature gradient of  $0^{\circ} 1^{\circ}\text{C}/\text{m}$  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.

with a thick mixed layer with relatively high temperatures in the surface layers may be related to the presence of a zone of convergence between the southern boundary of clockwise circulation of Bay of Bengal and the northern boundary of North Equatorial Current. The regular wavy pattern exhibited by the isotherms of thermocline between Stns. 150-155 may indicate the presence of internal waves. Under Stns. 152-155, the ridge and trough pattern exhibited by the isotherms of thermocline continues to greater depths indicating that the effect of internal waves extends to considerable depth.

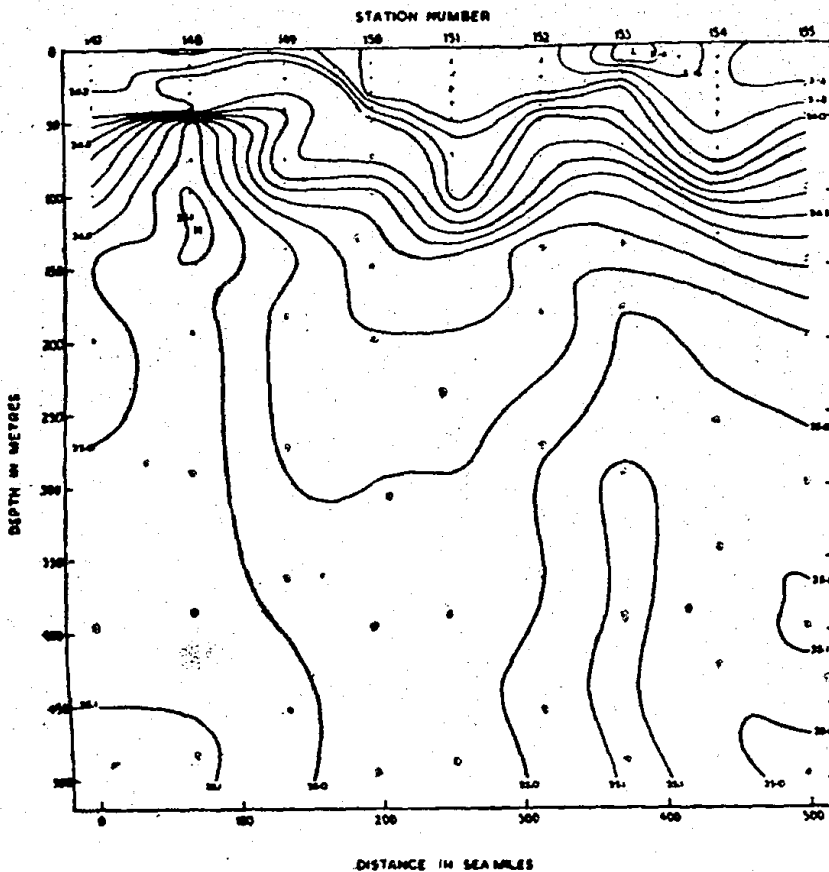


a. Temperature ( $^{\circ}\text{C}$ )

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

*Salinity (Fig. 2b):* The surface salinity varies between 34.23‰ and 33.37‰. The high values of surface salinity ( $>34.10\text{‰}$ ) found in the western part of the section at Stns. 147-149 may be due to the upwelling of relatively high salinity sub-surface water probably associated with divergence. The presence of a thin parcel of low salinity water in the surface around Stn. 153 may be the result of the advection

of Bay of Bengal water into the North Equatorial Current. The westward extension of low salinity water (with salinity less than 34.00‰) up to Stn. 150 may be related

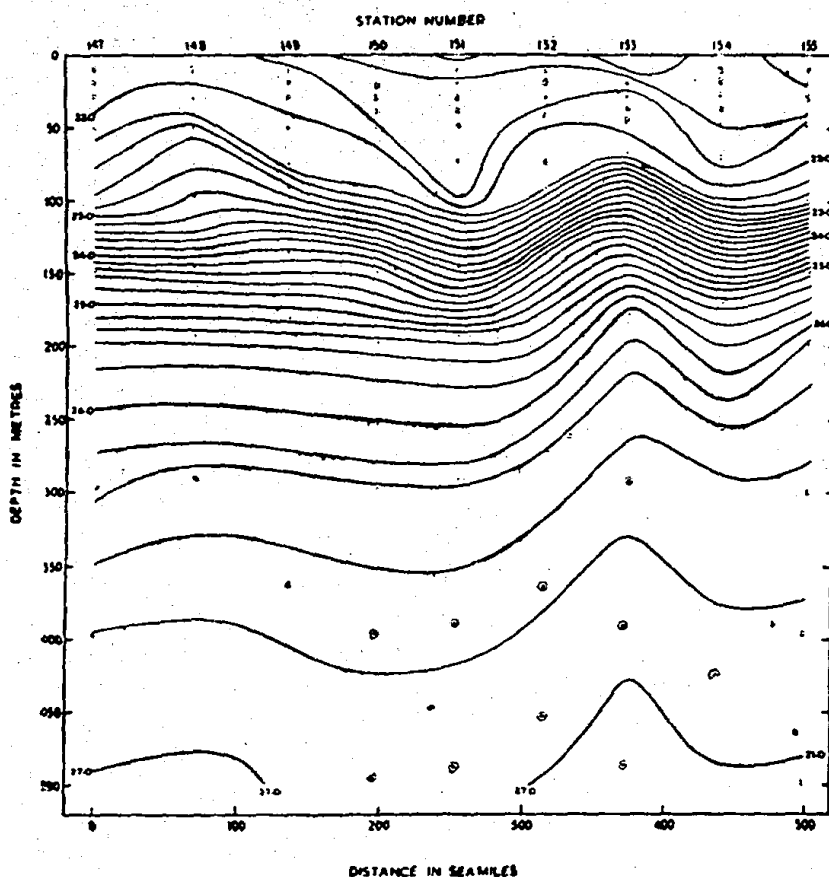


b. Salinity (‰)

to the westward drift of the southern Bay of Bengal water by the North Equatorial Current. In the western part of the section the presence of relatively high salinity waters in the surface layers in association with a distinct vertical tilt of isohalines at greater depths between Stns. 147-149 to form a steep local halocline at a shallow depth of 40-50 m under Stn. 148 clearly indicates the upwelling of high salinity subsurface waters towards the surface. This feature can be related to the presence of a zone of divergence as mentioned under "Temperature". The downward bending of isohalines just below the surface layer of low salinity water in association with a trough in the weakly developed halocline in the middle part of the section between Stns. 149-152 indicates the sinking of surface water to greater depths. This sinking seems to extend to deeper levels as the isohalines tend to assume vertical pattern at greater depths. The upward tilting of isohalines and also weakly developed halocline seen just below the thin surface layer of low salinity water between Stns. 152

and 154 indicates an upward movement of water, from the subsurface levels towards the surface, probably associated with the internal waves. The deeper waters also appear to be in vertical motion from the presence of vertically rising tongues of high salinity water at greater depths under Stns. 152-155.

*Density in terms of  $\sigma_t$  (Fig. 2c):* The relatively lighter water present in the surface at Stns. 151, 153 and 155 may be the result of the southward extension of



c. Density ( $\sigma_t$ )

Bay of Bengal water, while the presence of relatively denser water at Stns. 147-149 may be due to some upwelling there. In the surface levels a layer of weak density gradients is distinctly seen throughout the section. It has a maximum thickness of about 100 metres at Stn. 151 and minimum thickness of about 40 metres at Stn. 148. Below this top layer of weak density gradients, the density discontinuity layer (pycnocline) is present. The pycnocline is strongly developed in the eastern and middle parts of the section compared to the western part. In the western part of the section, the upward tilt of the isopycnals of the upper part of the pycnocline in association with the thin top layer of weak density gradients and the presence of

relatively high density water at the surface clearly indicates upwelling of subsurface water into the surface layers possibly associated with the divergence discussed under "Temperature". The presence of a thick top layer of weak density gradients between Stns. 149 and 152 and the downward bending of isopycnals within that layer in association with the trough in the pycnocline may indicate sinking of surface waters to subsurface depths at the zone of convergence (see "Temperature"). As the isopycnals are exhibiting the trough pattern even beneath the pycnocline, this sinking seems to extend to greater depths. The regular wavy pattern exhibited by the isopycnals of the pycnocline between Stns. 150-155 confirms the presence of internal waves indicated by the temperature structure. The upward tilt of the isopycnals in the surface layers in association with the 'doming' exhibited by the pycnocline between Stns. 152-154 indicates an upward movement, of subsurface water towards surface, probably associated with the internal waves. The 'doming' and 'depression' exhibited by the pycnocline under Stns. 152-155 is seen to extend to greater depths indicating that the vertical movements in the eastern part of the section, which appear to be mainly associated with the internal waves, extend to deeper layers.

It is interesting to note that in this long section extending through nearly 500 sea miles, the distribution of the various physical parameters indicate the three aspects namely, divergence, convergence and the stable stratification associated with the internal waves.

#### *Section 2:*

This section is in between Andaman and Nicobar Islands and lies almost along the latitude  $09^{\circ}30'$  N from  $91^{\circ}53'$  E to  $95^{\circ}00'$  E.

*Temperature (Fig. 3a):* The surface temperature varies between  $27.9^{\circ}\text{C}$  and  $27.3^{\circ}\text{C}$ . The mixed layer is developed well with a thickness of more than 50 m throughout the section. The thermocline is seen to start at about 75 m depth under Stns. 156-157. It is slightly drawn upwards to 50-60 m depth under Stns. 158-159. It is well developed under Stn. 156 with a thickness of about 75 m and maximum thermal gradients of the order of  $0.2^{\circ}\text{C}/\text{m}$ . East of Stn. 156, it started to spread and this spreading of thermocline especially in its upper half is more prominent under Stns. 158-159 probably indicating the presence of some subsurface divergence at 60-150 m depth. The trough exhibited by the isotherms under Stn. 157 at depths greater than 150 m may be the effect of bottom topography.

*Salinity (Fig. 3b):* The surface salinity varies between  $33.01\text{‰}$  and  $32.63\text{‰}$ . The presence of a layer of relatively low salinity water ( $S < 32.80\text{‰}$ ) in the upper 40 metres at Stns. 157-159 enclosing a cell of lower salinity water ( $S < 32.60\text{‰}$ ) at Stn. 157 may indicate considerable advection in the surface levels. The halocline starts at about 40-50 m depth. The spreading of halocline in its upper part under Stns. 156-157 and in its lower part under Stns. 157-159 in a wavy pattern may indicate the presence of subsurface divergence between 50 m and 150 m depth. The salinity distribution below 150 m depth clearly indicates the presence of a huge mass of near homohaline water at greater depths.

*Density in terms of  $\sigma_t$  (Fig. 3c):* A parcel of relatively lighter water seen in the surface levels at and around Stn. 157 may be the result of advection from the

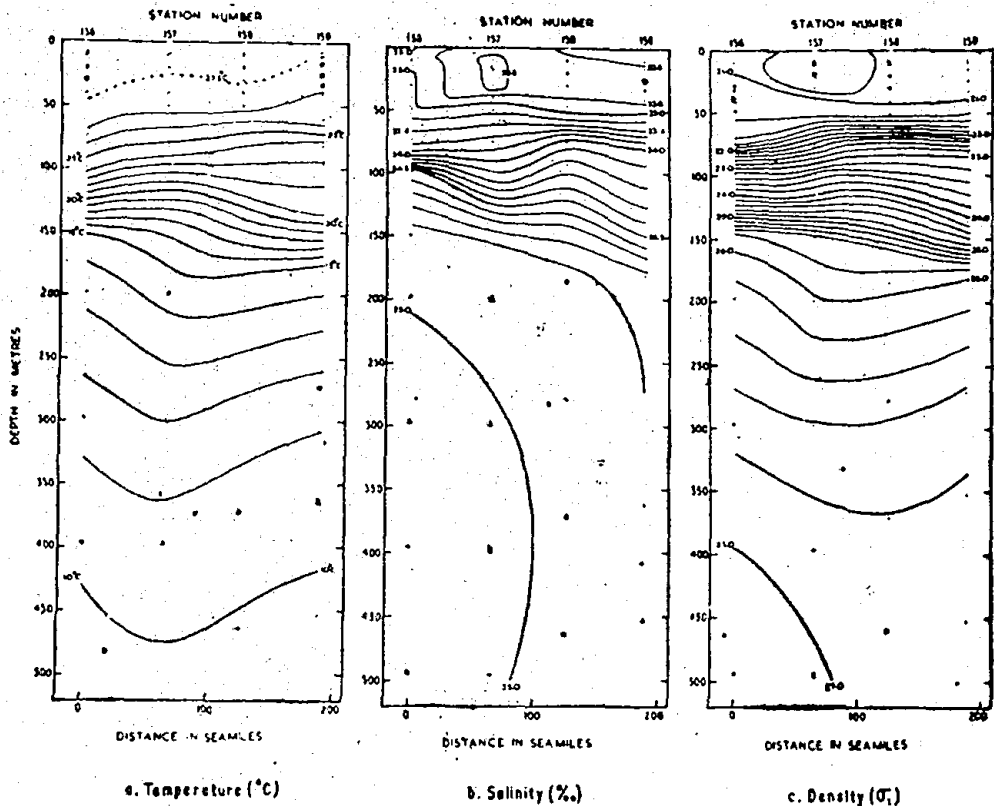


FIG. 3a-c. Vertical Distribution of Temperature, Salinity and Density along Section 2.

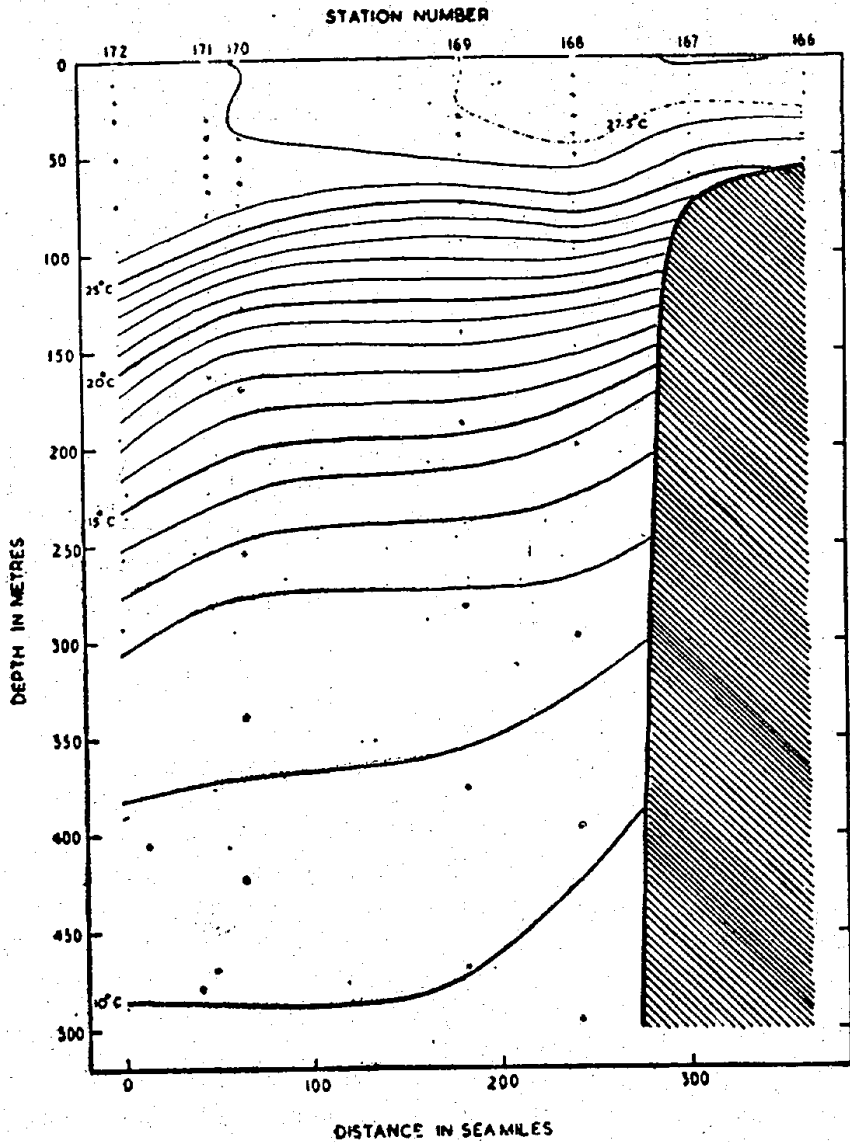
surrounding areas. Just below the top layer of low density gradients, which extends to about 70 m depth under Stn. 156 and to about 50 m depth under Stns. 157-159, the density discontinuity layer (pycnocline) is present. It is steeply developed with high density gradients under Stn. 156 with a thickness of about 75 m. East of Stn. 156, it started to spread and this spreading of pycnocline especially in its central part is gradually increased towards east and more distinctly seen under Stns. 158-159 at 75-150 m depth. This feature confirms the presence of subsurface divergence mentioned earlier. Just below the pycnocline, the density gradient suddenly decreased. While the isopycnals in the lower part of the pycnocline exhibit slight 'doming' under Stns. 157-158, the isopycnals in the subsurface levels below pycnocline are exhibiting trough pattern centred under Stns. 157-158. These features may indicate that the direction of flow in the region of density discontinuity layer is different from that at greater depths. The prominent upward trend of the isopycnals in the deeper layers under Stn. 156 may be attributed to the effect of bottom topography.



*Section 3:*

This section is almost along the latitude  $15^{\circ}00'$  N and extends from  $89^{\circ}00'$  E to  $95^{\circ}00'$  E.

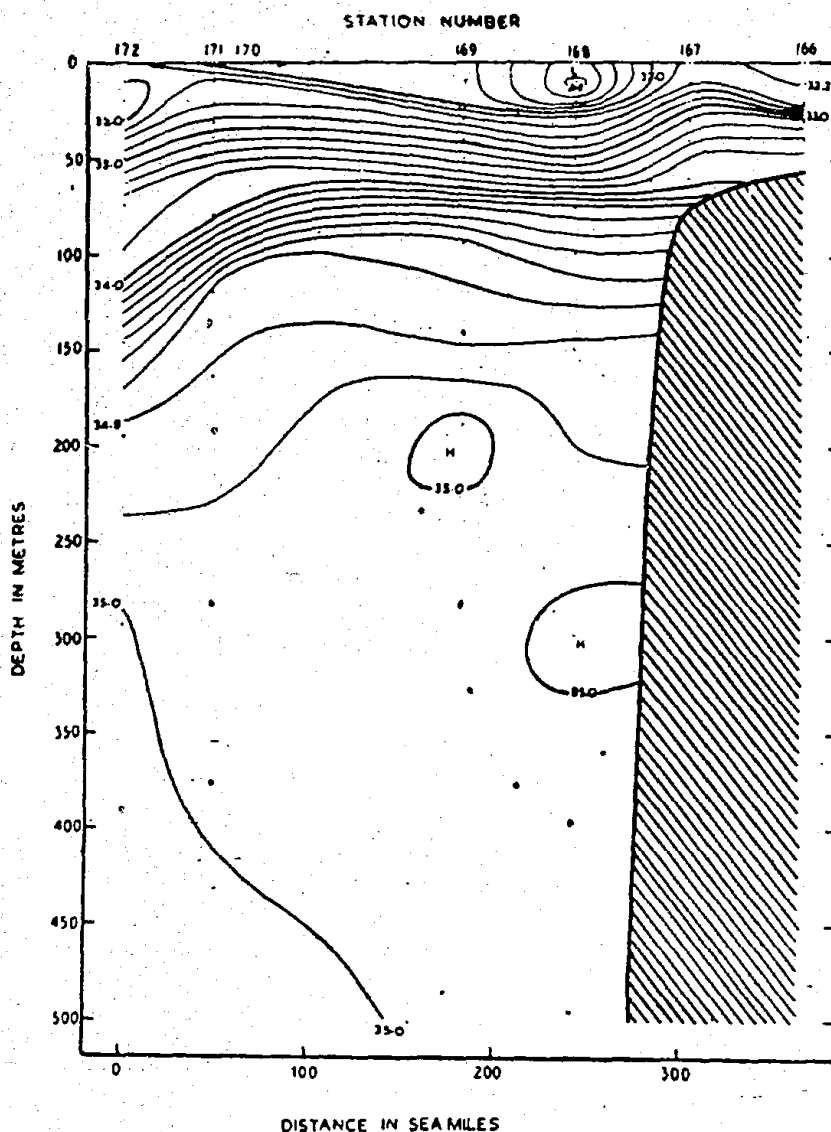
*Temperature (Fig. 4a):* The surface temperature varies between  $28.2^{\circ}\text{C}$  and  $26.8^{\circ}\text{C}$ . The highest value of surface temperature viz.,  $28.2^{\circ}\text{C}$  seen at Stn. 167 (1517 hrs. IST) may be associated with the diurnal sea surface temperature maximum in the early afternoon hours. The well defined layer of nearly isothermal water seen



a. Temperature ( $^{\circ}\text{C}$ )

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

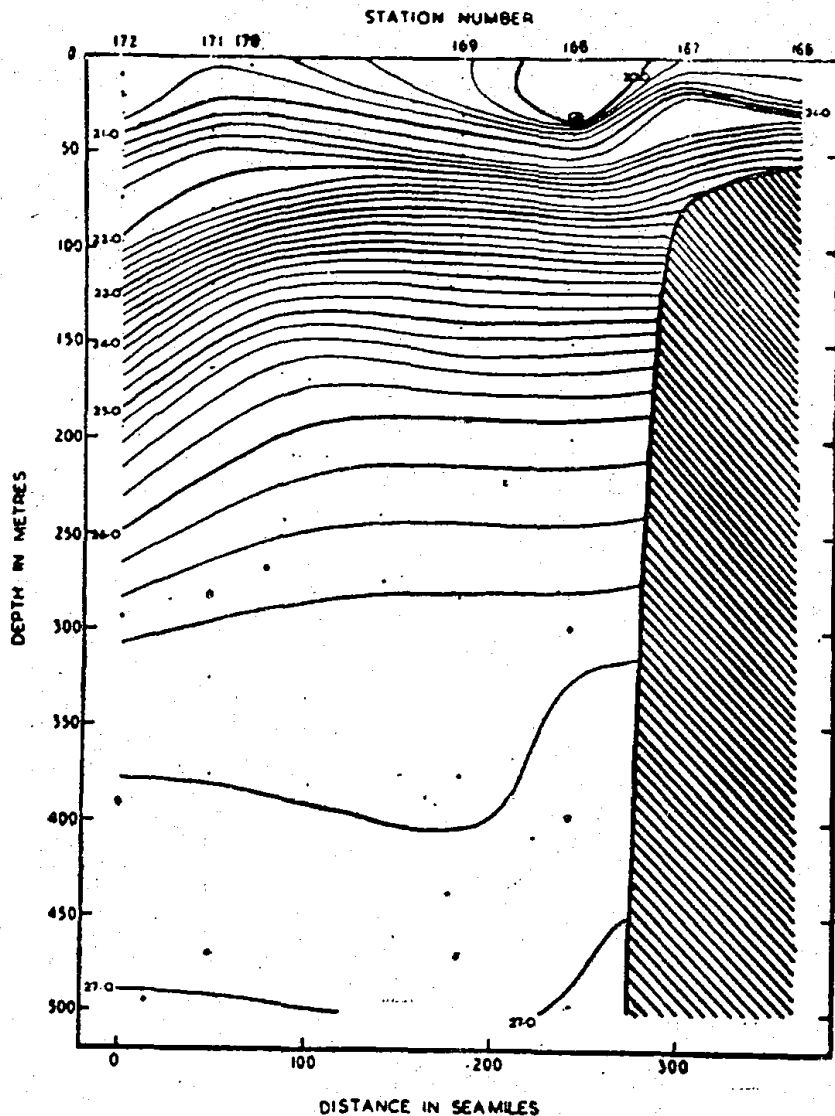
at the surface with considerable thickness at Stns. 166-170 can be related to the fresh water influx from the mouths of Irrawaddy River. The low temperature of the surface waters at Stns. 172-170 is probably the result of water movements in the surface layers. The mixed layer is developed well with considerable thickness in the western part of the section compared to the eastern part. It has a thickness of about 100 m at Stn. 172. East of Stn. 172, its thickness decreases gradually and



### b. Salinity (%)

at Stns. 169-167 it has an average thickness of about 65 m. The thermocline is seen to start at a depth of about 100 m under Stn. 172. East of Stn. 172, it rises gradually

and under Stns. 169-168, it is detectable at 65-70 m depth. It is drawn up further to 60 m depth under Stn. 167. Its thickness is about 70 m in the middle part of the section and about 75 m in the extreme parts. The downward bending of thermocline and other isotherms up to about 400 m depth in association with the presence of a thick mixed layer in the surface levels at Stns. 170-172 may be due to sinking associated with the convergence at the centre of the well-known clockwise circulation of Bay of Bengal in March. The upward tilt of thermocline and other isotherms under



Stns. 168-167 appears to be the effect of bottom topography. The effect of bottom topography is more prominently seen at greater depths under Stns. 169-167.

*Salinity (Fig. 4b):* The surface salinity varies between 32.25‰ and 31.29‰. The thin parcel of low salinity water ( $S < 32.00$ ‰) seen at the surface between Stns. 167-171 with its core at Stn. 168 is probably the result of influx of fresh water from the mouths of Irrawaddy River. The halocline is present just below this low salinity water. It is seen to spread westward and the resulting low salinity gradients in the top 80 metres at Stn. 171 and 110 metres at Stn. 172 may indicate good mixing in the surface levels at Stns. 170-172. The tilting up of the halocline between Stns. 168-166 may be the effect of bottom topography. The downward bending of the lower part of the halocline and the other isohalines up to 250 m depth under Stns. 170-172 may be associated with the sinking referred earlier. Beneath 200 m depth under Stns. 169-168, the salinity gradients are so negligible that the presence of a nearly homohaline water can be inferred along the continental slope at greater depths.

*Density in terms of  $\sigma_t$  (Fig. 4c):* The presence of water of lower density at the surface between Stns. 169-167 is clearly indicative of the influx of fresh water from the mouths of Irrawaddy River. This lighter water may be flowing across the section in a southwestward direction\*, the flow being intensified by the north to northeasterly surface winds. A locally developed thin pycnocline is seen just below this lighter water. The divergence as indicated by the tilting up of the isopycnals of this local pycnocline towards surface at Stn. 167 may be associated with the effect of surface current centred at Stn. 168 and flowing across the section. Beyond the continental shelf, the density discontinuity layer has a thickness of more than 80 metres. The upward tilt of the upper part of the pycnocline under Stns. 168-166 seems to be purely the effect of bottom topography. The downward bending of the pycnocline and the other isopycnals up to 350 m depth under Stns. 170-172 can be related to the sinking associated with the convergence at the centre of the clockwise circulation of Bay of Bengal in March. Isopycnals at depths greater than 300 m appear to be greatly influenced by the bottom topography under Stns. 169-167 as they have tilted up towards the continental slope probably indicating the rushing up of some water along the continental slope at greater depths.

#### Section 4:

This section is situated off Madras almost along the latitude 13°20' N and extends from 81°00' E to 88°35' E.

*Temperature (Fig. 5a):* The sea surface temperature varies between 28.4°C and 26.3°C. The relatively high surface temperature ( $> 28.0$ °C) at Stn. 180 (1517 hrs. IST) and Stn. 177 (1657 hrs. IST) appears to be mainly associated with the typical diurnal sea surface temperature maximum in the early afternoon hours. The mixed layer is developed well at Stns. 174-179 with its thickness varying between 75 m and 100 m. West of Stn. 179, a decrease is noticed in its thickness. The depth of occurrence of thermocline varies between 75 m and 100 m under Stns. 174-179. West of Stn. 179,

\*In the northern hemisphere, the higher density values are found to the left of the direction of flow (Defant 1961).

the thermocline rises gradually and it is observed at 75 m depth under Stn. 180 and at 60 m depth under Stn. 181. Its thickness varies between 40 metres and 70 metres. The regular wavy pattern exhibited by the thermocline between Stns. 174-178 may indicate the presence of internal waves in the eastern and middle parts of the section. It is also to be noted here that the influence of the internal waves might have extended down to greater depths as shown by the wavy nature of the isotherms beneath the thermocline also. The upward tilting of the thermocline at Stns. 179-181 may be associated with a sub-surface flow in the western part of the section below the upper 30 metres. This flow appears to extend to greater depths as the deeper isotherms also exhibit the upward tilt towards west under Stns. 180-181.

*Salinity (Fig. 5b):* The surface salinity varies between 34.47‰ and 33.08‰. In the surface levels, two parcels of relatively low salinity water, one in the eastern

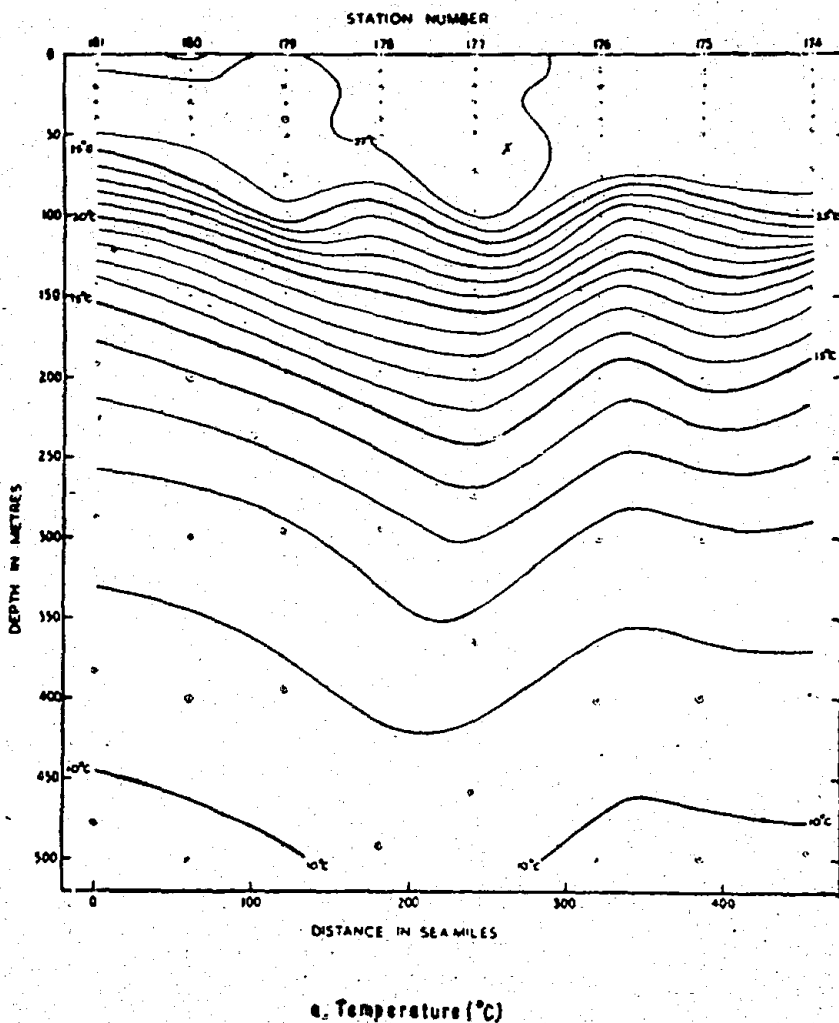
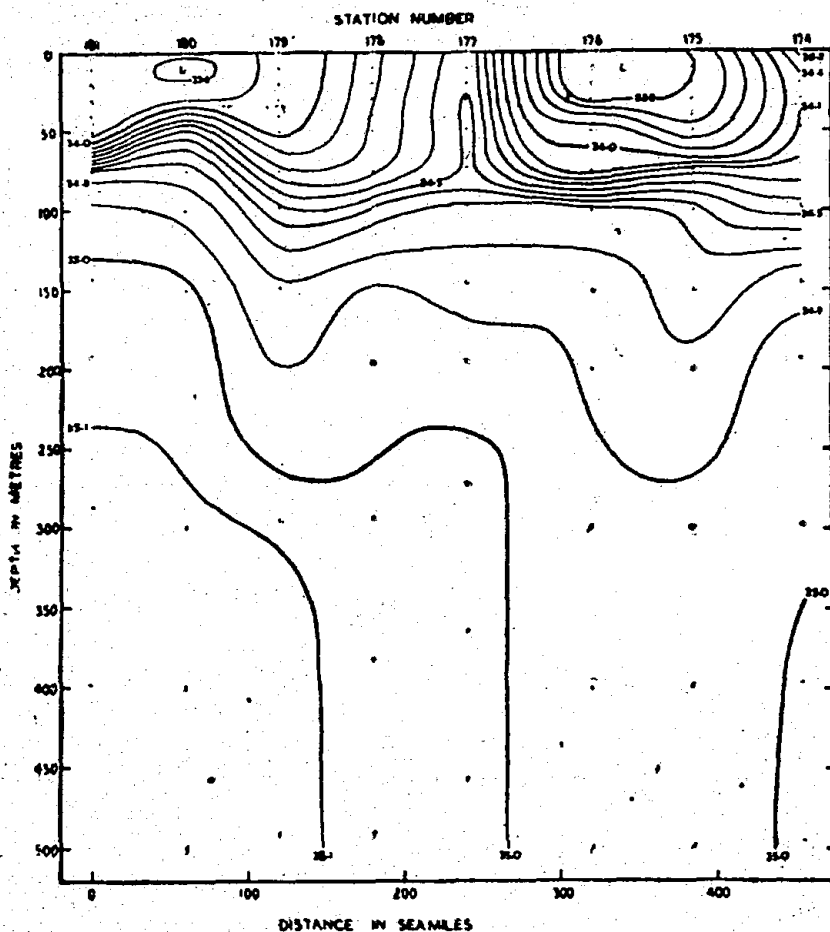


FIG. 5a-c. Vertical Distribution of Temperature, Salinity and Density along Section 4.

part of the section and the other in the western part are seen to be separated by relatively high salinity water in the middle part of the section. These features appear

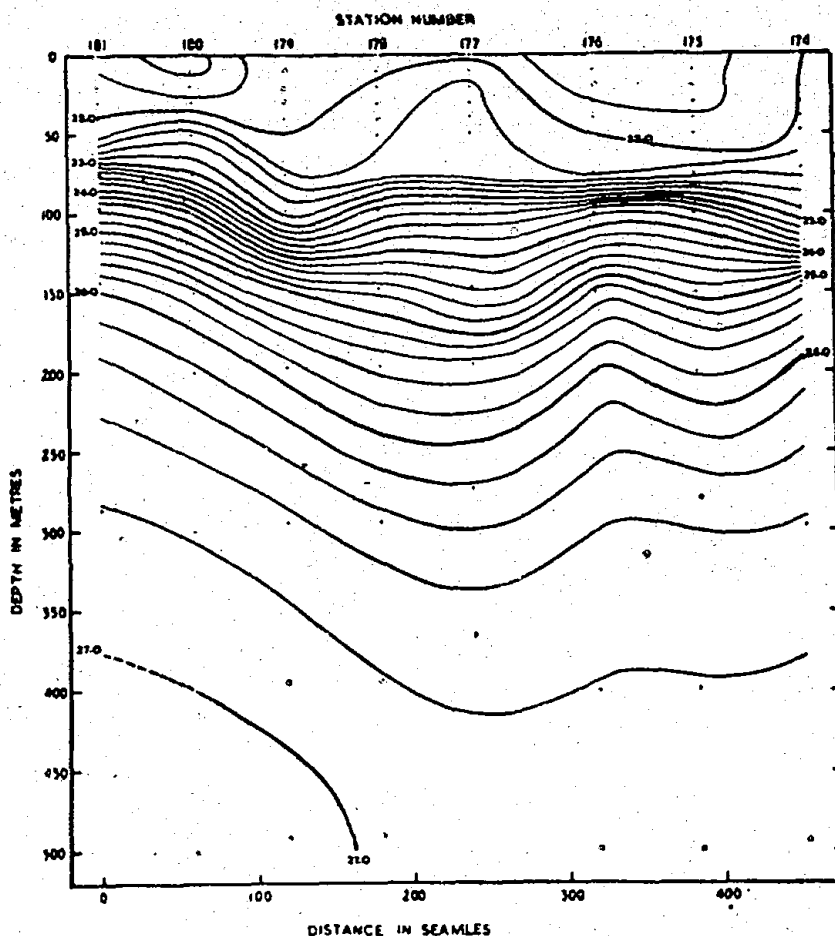
to be mainly associated with the advection in the surface levels. The data also indicate a possible meridional flow from the southern Bay bringing in relatively high salinity water. A volume transport down to approximately 75 metres is indicated between Stns. 179 and 176. The halocline is developed well below the two parcels of relatively low salinity water in the eastern and western parts of the section. The upward tilt of the halocline and other isohalines under Stns. 179-181 may be associated with a sub-surface flow at depths greater than 30 metres. At the subsurface depths below the halocline, the salinity pattern clearly indicates considerable movements throughout the section. These movements appear to be mainly associated with the internal waves under Stns. 174-179 and with the subsurface flow under Stns. 179-181.

*Density in terms of  $\sigma_t$  (Fig. 5c):* In the surface levels, two parcels of lighter water—one in the eastern part of the section at Stns. 175-176 and the other in the western part at Stns. 179-181 are seen to be divided by a volume of relatively denser



b. Salinity (‰)

water in the middle part of the section at Stns. 177-178. These features may be associated with considerable advection in the surface levels as indicated by the



c. Density ( $\sigma_t$ )

temperature and salinity structures. At the same time, the density gradients are low in the surface levels and a layer of weak density gradients can be seen throughout the section. Its thickness is about 75 metres at Stns. 174-179. East of Stn. 179, its thickness is seen to decrease considerably and at Stns. 180 and 181, the thickness is only about 40 metres. Below this top layer of low density gradients, the density discontinuity layer (pycnocline) is present. The regular wavy pattern exhibited by the lower part of the pycnocline under Stns. 174-178 indicates the presence of internal waves. Even below the pycnocline, the isopycnals continued to exhibit the regular wavy pattern indicating that the effects associated with the internal waves extend to greater depths. The spreading of the upper part of the pycnocline at Stns. 179 and

180 and the upward tilting of the pycnocline as a whole under Stns. 179-181 appears to be associated with a northerly subsurface flow in the western part of the section at depths greater than 30 m under Stns. 180-181. This flow appears to extend to greater depths as the isopycnals exhibit the upward tilting towards west even below the pycnocline. The steep gradient of the isopycnals at greater depths in the western half of the section probably associated with the subsurface flow under Stns. 180-181 and the regular wavy pattern of the isopycnals in the eastern half of the section probably associated with the internal waves, indicate notable movements at greater depths.

### Section 5:

This section is situated off the East Coast of India between Madras and Kakinada and extends from (14°01' N-81°00' E) to (16°30' N-82°30' E).

*Temperature (Fig. 6a):* The surface temperature varies between 28.1°C and 27.3°C. Throughout the section, the mixed layer is well developed with a thickness of more than 50 m indicating the presence of nearly homogeneous water in the

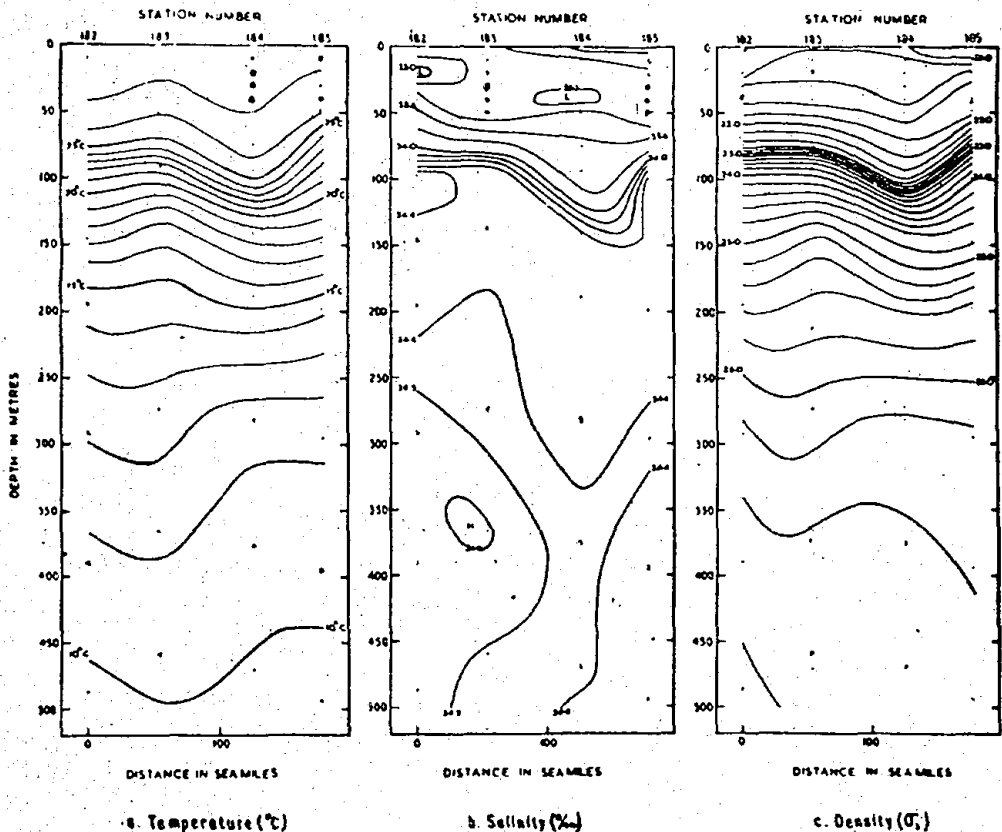


FIG. 6. Vertical Distribution of Temperature, Salinity and Density along Section 5.

surface levels. The thickness of mixed layer is remarkably high (about 100 m) at



Stn. 184. The thermocline is seen to start at about 75 m depth under Stn. 182, 70 m depth under Stn. 183, 100 m depth under Stn. 184 and 50 m depth under Stn. 185. The thickness of thermocline varies between 38 m and 50 m. The prominent depression exhibited by the thermocline and other isotherms up to about 200 m depth between Stns. 183 and 185 and the presence of thick mixed layer in the surface levels may probably be associated with the influx of fresh water from the mouths of Godavari and Krishna Rivers. At depths greater than 200 m, the isotherms tend to assume a huge 'depression' under Stns. 182-184 and a 'doming' under Stns. 184-185. This feature may be associated with the vertical movements of deeper waters.

*Salinity (Fig. 6b):* The surface salinity varies between 33.55‰ and 32.94‰. A thick layer of low salinity water is present in the surface at Stns. 183-185. Below this low salinity water, the halocline is present and it is well defined under Stns. 182-183 and 185. The depression exhibited by the halocline between Stns. 183-185 and the presence of a thick layer of low salinity water in the surface levels may be associated with the influx of fresh water from the mouths of Godavari and Krishna Rivers. The salinity pattern below 150 m depth under Stns. 182-185 may reveal good mixing at greater depths.

*Density in terms of  $\sigma_t$  (Fig. 6c):* A layer of lighter water is present in the surface with maximum thickness at Stn. 184. Below this top layer of low density gradients, the density discontinuity layer (pycnocline) is developed well throughout the section. The prominent depression exhibited by the pycnocline and other isopycnals up to about 200 m depth between Stns. 183 and 185, and the presence of a thick layer of lighter water in the surface appears to be mainly associated with the influx of fresh water from the mouths of Krishna and Godavari Rivers. At depths greater than 200 m the density pattern also indicates vertical movements.

#### *Section 6:*

This section lies along the latitude 16°30' N and extends from 83°30' E to 88°30' E.

*Temperature (Fig. 7a):* The surface temperature varies between 27.9°C and 27.2°C. The highest value of surface temperature viz., 27.9°C at Stn. 188 (1341 hrs. IST) may be associated with the diurnal sea surface temperature maximum in the early afternoon hours. The mixed layer is well developed throughout the section with a thickness of more than 75 m. This feature in association with relatively low range of surface temperature variation may indicate nearly homogeneous water in the surface levels. The thickness of mixed layer is remarkably high (>100 m) at Stn. 189. The depth of occurrence of thermocline gradually increases from about 83 m at Stn. 186 to about 100 m at Stn. 188. Under Stn. 189, the thermocline is pushed down to about 112 m depth and at Stn. 190, it is drawn up to about 75 m depth. The thermocline has an average thickness of about 50 m under Stns. 186-188. Its thickness increases eastwards to about 60 m under Stn. 189 and to about 80 m under Stn. 190. The prominent depression exhibited by the thermocline between Stns. 188 and 190 in association with the presence of well formed mixed layer of

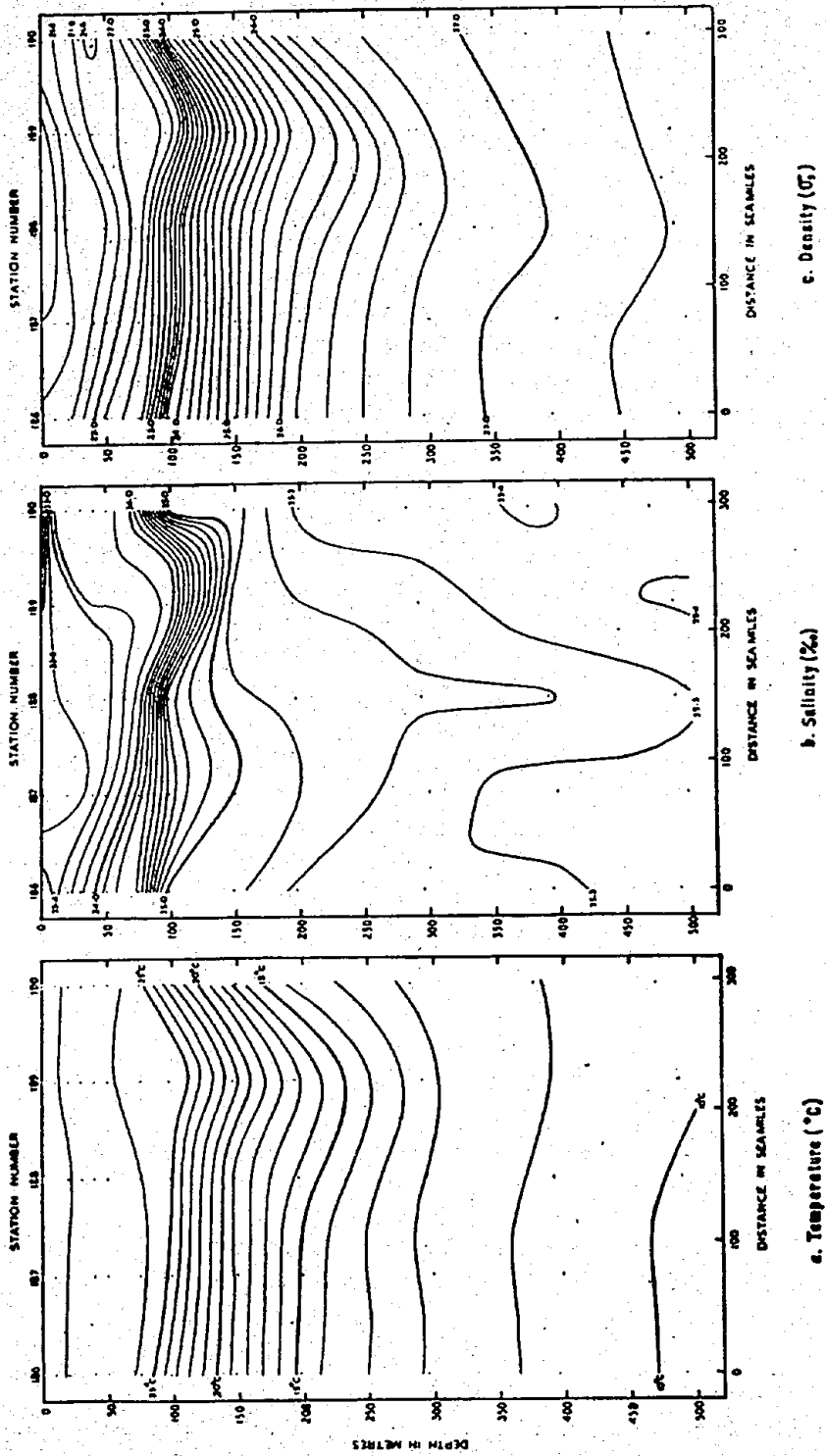


FIG. 7.a-c Vertical Distribution of Temperature, Salinity and Density along Section 6.

remarkably high thickness ( $>100$  m) at Stn. 189 indicates sinking between Stns. 188 and 190. The isotherms are exhibiting this depression even below the thermocline indicating that the sinking penetrates through fairly greater depths. This sinking may probably be associated with the convergence at the centre of the well-known clockwise circulation of Bay of Bengal in March.

*Salinity (Fig. 7b):* The surface salinity varies between 33.60‰ and 32.36‰. A layer of low and uniform salinity is developed well in the surface at Stns. 187-189. Another layer of slightly high but of nearly constant salinity is seen under Stn. 190 in the top 75 metres. These two waters appear to be converging at Stn. 189 and sinking there. The halocline is developed well below the surface waters of low salinity gradients. It exhibits a trough between Stns. 188-190 and this is in support of the above inference regarding sinking under Stn. 189. The salinity pattern at the subsurface depths below halocline seems to indicate sinking in the middle part of the section under Stns. 187-189. The values of high salinity found at depths greater than 300 m under Stns. 189-190 may indicate the presence of Persian Gulf Water probably overlying the Red Sea Water (Rochford 1964).

*Density in terms of  $\sigma_t$  (Fig. 7c):* A layer of low density gradients is seen in the surface throughout the section. Its thickness is maximum ( $>100$  m) at Stn. 189. Just below this layer of low density gradients, the pycnocline is present. The prominent depression exhibited by the pycnocline and other isopycnals up to about 200 m depth between Stns. 188-190 in association with the presence of a thick layer of low density gradients in the surface confirms the presence of sinking indicated by the temperature and salinity structures. As already mentioned, this sinking may probably be associated with the convergence at the centre of the well-known clockwise circulation of Bay of Bengal in March. At depths greater than 200 m, the pattern of isopycnals indicates gradual shifting of this depression towards the centre of the section. This feature leads to the inference that the sinking seen in the upper 200 metres penetrates through greater depths with a slight westward shift.

#### GENERAL REMARKS

Some of the interesting features in the hydrographical conditions of the Central and Southern Bay of Bengal, as revealed by the distribution of the parameters, are indicated below:

##### 1. *Surface Temperature:*

The surface temperature, in general, increases towards south. It generally varies between 27.0°C and 28.0°C except along the southern boundary of the Bay (8°-9°N), where it normally has a value between 27.5°C and 28.5°C.

##### 2. *Mixed Layer:*

The mixed layer is well developed (with thickness of 75-100 m) in the Western Bay (west of 90°E meridian) compared to the Eastern Bay. It has a maximum

thickness of more than 110 m in two specific regions—one in the Central Bay (at Stn. 189) and other in the middle part of the southern boundary of the Bay (at Stn. 151). In the Eastern Bay and the Andaman Sea, the thickness of mixed layer varies between 50 m and 100 m.

### 3. *Thermocline:*

The depth of occurrence of thermocline, in general, increases slightly towards south and varies between 75 m and 120 m in the Western Bay (west of 90°E meridian). In the Eastern Bay, it starts at a depth in between 50 m level and 100 m level. The thermocline is well developed in the middle part of the Central and Southern Bay and its thickness generally varies between 40 m and 80 m. A sharp and thick thermocline (with maximum thermal gradients of the order of 0.20°C/m-0.25°C/m and thickness 80 m) is present in the middle part of the southern boundary of the Bay (along 08°30' N between 87°E and 92°E).

### 4. *Density Discontinuity Layer (Pycnocline):*

In the Western Bay (west of 90°E), the depth of occurrence of density discontinuity layer, in general, slightly increases towards south and varies from 75 m to 100 m. In the Eastern Bay and the Andaman Sea, it normally starts at comparatively lower depth. The pycnocline is developed steeply and has more thickness in the Eastern Bay and along the middle part of the southern boundary of the Bay compared to the Western Bay.

### 5. *Internal Waves:*

Internal waves are encountered in the middle part of the Central and Southern Bay (along 13°20' N and 08°30' N). This feature in association with well developed thermocline and mixed layer indicates stable stratification in the surface layers of these regions. The effects associated with the internal waves appear to extend to considerable depth.

### 6. *Surface Salinity:*

In general, the surface salinity increases towards west and south. It generally varies between 32.0‰ and 34.5‰ except in the eastern part of the Central Bay and the Andaman Sea, where its value normally lies between 30.0‰ and 32.5‰.

### 7. *Subsurface Salinity Maximum:*

The subsurface salinity maximum, which is usually present at the top of thermocline within the equatorial waters of the Indian Ocean, is not, in general, found in the Bay of Bengal. Special mention must, however, be made about the salinity maximum present in the upper half of thermocline at 08°52.0'N-85°00.0'E (Stn. 148).

### 8. *Water Masses:*

Two water masses are encountered in the upper 100 metres. Because the surface layers are subjected to seasonal and local influences resulting in wide variation of the temperature and salinity values, the limits assigned to these water masses in the following statements would be tentative. The first water mass is found in the upper 50 metres in the Eastern Bay of Bengal and the Andaman Sea with salinity less than 33.0‰ and  $\sigma_t$  less than 21.0. This water appears to be formed by the admixture of the run off water from the Burmese Coast with the (less saline) waters of Pacific origin entering the south-eastern Bay through the Straits of Malacca. This water mass which has so far not been described could be named as the Eastern Dilute Water of Indo-Pacific origin. The second water mass is encountered in the upper 100 metres of the Southern Bay and the western and middle parts of the Central Bay with the salinity range 33.0-34.0‰ and  $\sigma_t$  range 21-22. This water may be related to the Southern Bay of Bengal Water reported by LaFond (1958).

A high salinity water mass is traced in a specific region in the central part of the Bay (under Stns. 189-190) below 300 m depth. This may be the Persian Gulf Water probably overlying the Red Sea Water.

The major subsurface water mass of the region under study viz., the Indian Ocean Equatorial Water with the temperature range 16°-4°C, salinity range 34.8-35.2‰ and  $\sigma_t$  greater than 24.0, is encountered in all parts of the Southern and Central Bay below 100-150 m depth.

### 9. *Regions of Divergence:*

A zone of divergence is found in the western part of the southern boundary of the Bay of Bengal (at Stns. 147-149) in the upper 150 metres. It may be related to the divergence between the southern boundary of anticyclonic circulation of Bay of Bengal and the northern boundary of North Equatorial Current in this region.

A zone of subsurface divergence is found in the region of discontinuity layer (in association with considerable spreading of thermocline, halocline and pycnocline) between 75 m level and 150 m level in the eastern part of the Southern Bay of Bengal along 09°30' N, east of 93°E (at Stns. 158-159). This feature indicates the possibility of a subsurface flow in the region of discontinuity layer with its direction different from that of deeper waters.

### 10. *Regions of Convergence:*

A zone of convergence is noticed in the middle part of the southern boundary of the Bay (at Stns. 150-152) in the upper 100 metres. It may be related to the zone of convergence between the southern boundary of clockwise circulation of Bay of Bengal and the northern boundary of North Equatorial Current in this region. The sinking associated with this convergence appears to extend to greater depths.

Another zone of convergence is encountered in the Central Bay between 86°E and 90°E, and 14°N and 17°N (along Stns. 189-191-172) in the upper 100 metres.

It is thought to be associated with the convergence at the centre of the well-known clockwise circulation of Bay of Bengal in March. The sinking associated with this convergence appears to penetrate through considerable depth.

#### 11. *Water Movements:*

Two surface flows are prominent in the upper 75 metres. The first one is the southwestward flow of relatively low salinity lighter surface water in the eastern part of the Central Bay across  $15^{\circ}\text{N}$  between  $91^{\circ}\text{E}$  and  $94^{\circ}\text{E}$  (at Stns. 169-168). This flow, which is limited to the upper 30 metres, appears to be associated with the southwestward spreading of the fresh water discharged from the mouths of Irrawaddy River probably intensified by the north to northeasterly surface winds. The second flow is that of relatively warm, but more saline and denser water in the Western Bay, across  $13^{\circ}20'\text{N}$  between  $83^{\circ}\text{E}$  and  $86^{\circ}\text{E}$  (at Stns. 178-177). This volume transport, which extends down to about 75 m depth, may be related to a possible meridional flow from the Southern Bay bringing in relatively high salinity water.

A northerly subsurface flow is encountered outside the continental slope off Madras, below 30 m depth. This subsurface flow appears to extend even beneath 500 m depth.

In the subsurface layers below thermocline, a region of prominent vertical movements, indicated by the ridge and trough pattern of isopycnals and vertically rising tongues of high salinity water, is noticed in the middle part of the southern boundary of the Bay (along  $08^{\circ}30'\text{N}$  between  $89^{\circ}\text{E}$  and  $92^{\circ}\text{E}$ ). In most of the other parts of the region under study, the salinity and density patterns indicate good mixing in the deeper layers.

#### 12. *Influence of River Discharge:*

In the region off the mouths of Krishna and Godavari Rivers (at Stns. 184), the effect of fresh water influx is indicated in a prominent deepening of thermocline, halocline and pycnocline in association with the presence of a thick layer of nearly homogeneous and relatively less saline lighter water in the surface levels.

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#### REFERENCES

- Anonymous. (1953). Bay of Bengal Pilot. Hydrographic Dept. Admiralty, London.  
 Defant, A. (1961). Physical Oceanography, Vol. 1. Pergamon Press.  
 Gangadhara Rao, L.V., and Jayaraman, R. (1967). Vertical Distribution of Temperature, Salinity and Density in the upper 500 metres of the North Equatorial Indian Ocean during the North-east Monsoon Period. (Mss. 'Symposium on Indian Ocean', 1967).  
 LaFond, E.C. (1958). Oceanographic Studies in the Bay of Bengal. *Proc. Indian Acad. Sci.*, 46B, 1-46.  
 Rochford, D.J. (1964). Salinity maxima in the upper 1,000 metres of the North Indian Ocean. *Aust. J. mar. Freshwat. Res.*, 15, 1-24.  
 Sverdrup, H.U., Johnson, M.W., and Fleming, R.H. (1942). The Oceans, Prentice-Hall Inc.