

CIRCULATION AND DISTRIBUTION OF SOME HYDROGRAPHICAL PROPERTIES DURING THE LATE WINTER IN THE BAY OF BENGAL

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ABSTRACT

Charts showing dynamic topography, mass distribution, temperature, salinity, dissolved oxygen and inorganic phosphate in the upper layers of the Bay of Bengal for the late winter period were analysed and presented. The nearsurface circulation has been discussed in relation to thermal structure and water mass characteristics. The analysis revealed that the field of motion in the nearsurface layers of the Bay of Bengal during the late winter is the result of various factors, such as the winter cooling near the head of the Bay, the influence of northeast monsoon winds, the influence of north equatorial current in the southern regions and the influence of fresh water discharges, especially in the northern Bay, Andaman Sea and along the east coast of India.

The integral mean concentration of nutrients in the surface mixed layer is in consonance with the nearsurface circulation in such a way that its higher (lower) value along with the lower (high) value of dissolved oxygen is associated with less (more) thickness of the surface layer projecting very clearly the effect of divergence of cyclonic gyre present in the nearsurface circulation. The salinity structure presented shows that the Bay of Bengal exhibits an estuarine type of circulation due to heavy discharge of fresh water all along its land peripheries.

INTRODUCTION

The importance of oceanic circulation on the redistribution of nutrients has been well recognised. Reid (1962) showed that the distribution of inorganic phosphates and the nature of the oceanic circulation are consonant with the observed distribution of zooplankton population and that the productivity of any region is closely linked to the oceanic circulation and the consequent redistribution of physico-chemical parameters. The transfer of nutrients across the mass discontinuity layer from the nutrient rich subsurface layer is governed by the processes of upwelling and vertical mixing. Upwelling envisages the vertical upward transfer of nutrients associated with the movement of water. On the other hand, vertical mixing envisages transfer of nutrients without any net vertical movement of water.

During the past three decades, quite a few studies on the physical, chemical and biological oceanographic aspects of the Bay of Bengal have been carried out. However, a synthesis of various studies bringing in the interrelationships between circulation and the other property distributions have not been attempted. The purpose of the present study is to show that the circulation, distributions of

temperature, salinity, dissolved oxygen and inorganic phosphates in the upper 500 m are consonant with each other.

In the present investigation the authors utilised the data collected in the Bay of Bengal, during the 33rd Cruise of R. V. *Vityaz* during 1961. Fig. 1 shows the station locations.

Circulation

The dynamic topographic charts at sea surface, 100 and 200 db surface relative to 1000 db surface are shown in Figs. 2, 3 and 4 respectively. An examination of the range of values of dynamic topography at various levels shows a gradual decrease of dynamic heights with the depth (0.4 dyn. m at the sea surface and 0.08 dyn. m at 500 db), suggesting that the currents are much stronger at the sea surface than at the layers below.

At the sea surface, an offshore current off Sumatra is observed in the equatorial regions. This current moves northwestwards to about 5°N , 72°E , where it branches into two—one entering the Andaman Sea and the other turning westward. A cyclonic gyre is located near the equator centered around 2°N , 70°E . All along the peripheries of the Bay of Bengal, the dynamic topography chart shows alternate bands of cyclonic and anticyclonic flows. At the head of the Bay, two gyres—one anti-

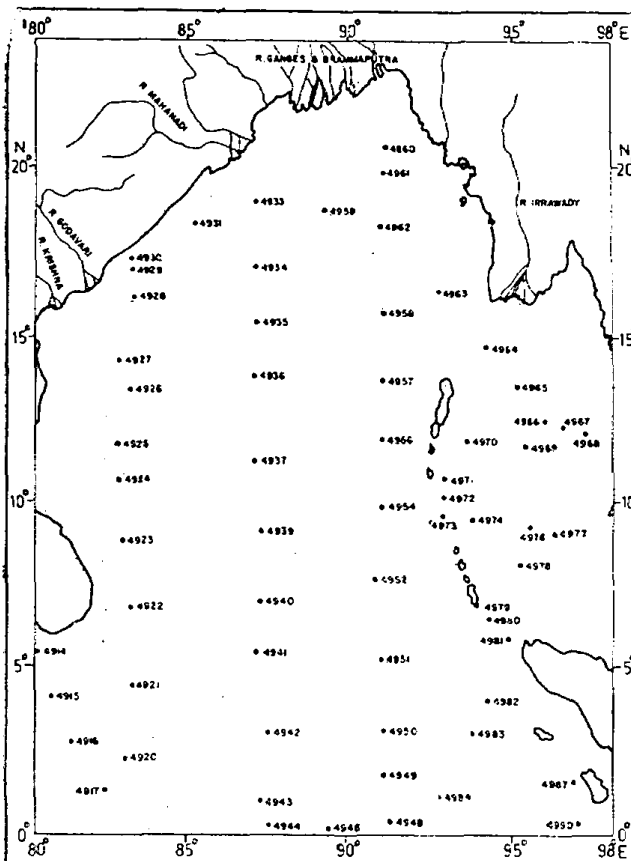


Fig. 1. Station locations.

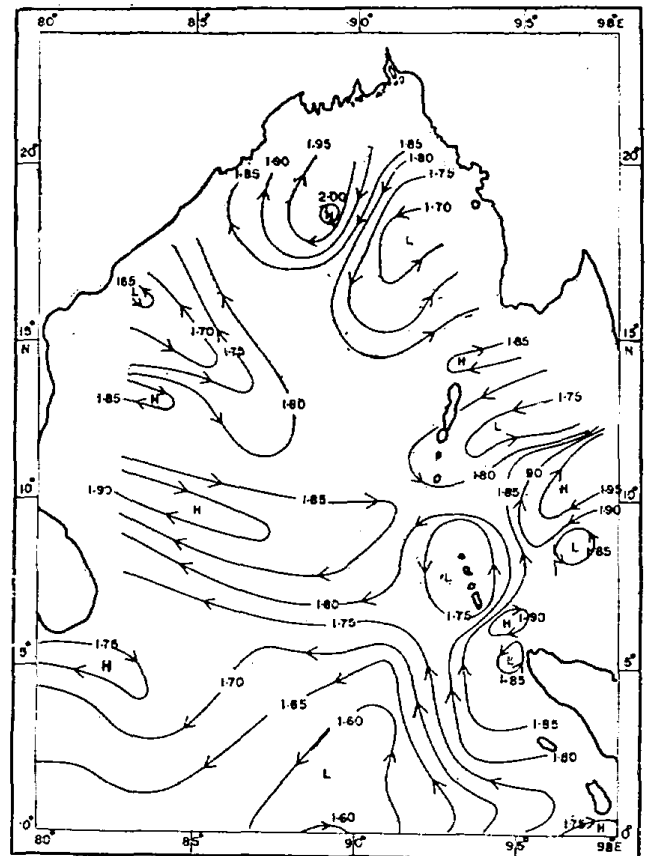


Fig. 2. Dynamic topography (dyn. m) at sea surface relative to 100 db.

cyclonic at the north-western Bay and the other cyclonic at the northeastern Bay are observed. Off the east coast of India, a cyclonic cell off the central part and anticyclonic gyre further south are also located. Similar cells are observed in the Andaman Sea also. The circulation pattern at 100 db surface is similar to that of the surface circulation. However, at 200 db surface, there is a noticeable change in the circulation pattern. At the head of Bay, eventhough two cells are still seen at this level, the anticyclonic cell appears to be fairly strong. From the northern Bay, a weak current flows towards equator and finally merging with the equatorial current. Along the east coast of India, two gyres as seen in the upper layers are observed. In the Andaman Sea, an anticyclonic gyre replaces the alternating bands of eastwest flow, observed at the higher levels. The flow at 500 db surface (not shown here) tends to be very weak.

Thermal Structure

Distribution of temperature: The sea surface temperature increases from about 25.5°C in the northern Bay to about 29.0°C in the equatorial regions (Fig. 5). In contrast, at 100 m (Fig. 6), strong temperature gradients prevail with the lowest temperature in the central equatorial regions (18.0°C), in the northern Bay and in some pockets of Andaman Sea (20.0°C). A tongue of warm water with the temperature

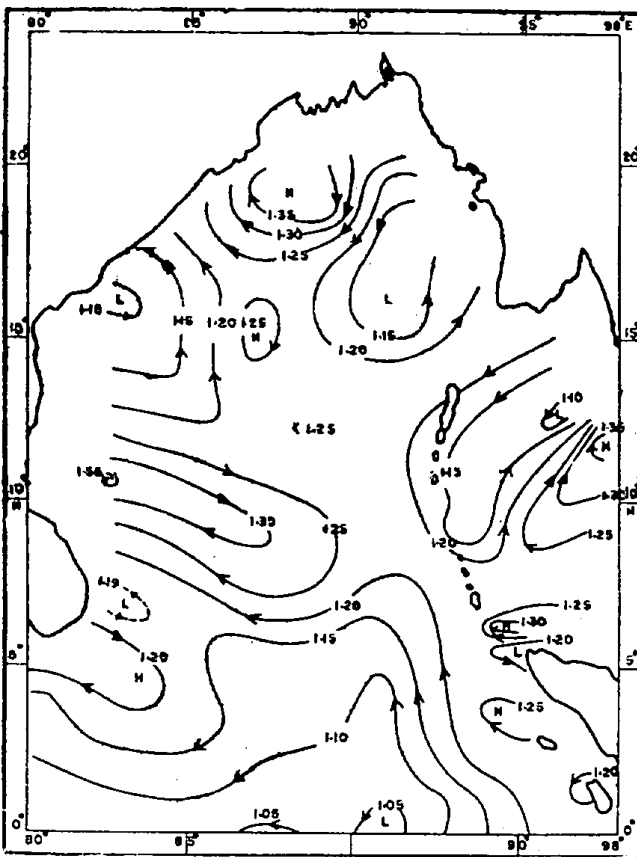


Fig. 3. Dynamic topography (dyn. m) at 100 db relative to 1000 db.

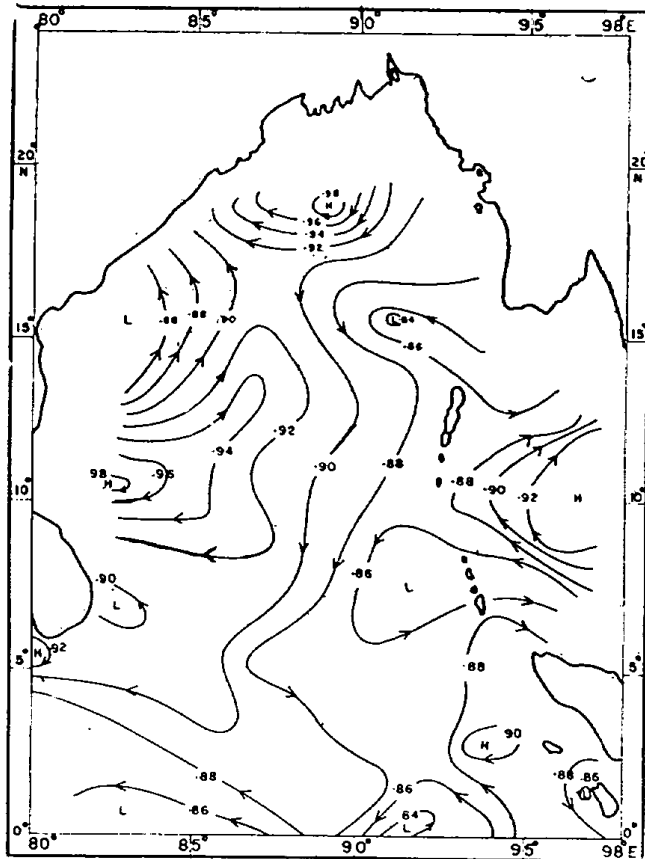


Fig. 4. Dynamic topography (dyn. m) at 200 db relative to 1000 db.

exceeding 27.0°C penetrates into the central Bay from regions northwest of Sumatra. Elsewhere, pockets of warm and cold waters could be seen on this surface. At 200 m, the temperature ranges from about 13.0 to 16.0°C , the central Bay being warmer.

The low sea surface temperatures at the head of the Bay during this season are partly due to winter cooling and partly due to cold fresh water discharge in this region. This feature had been reported earlier by Admiralty (1953), Balarama Murty (1958) and Wyrki (1971). The depth-temperature curves show temperature inversions at several stations in the upper 100 m. A typical example of such inversion is shown in Fig. 7b. In the northern Bay, these inversions are as high as 1.5°C at some of the stations. Such features have been reported earlier (Balarama Murty, 1958 and Anonymous, 1967a and 1967b). An analysis of the depth-salinity curves indicate that these inversions are associated with a strong halocline and the water column is strongly stratified. These features suggest that the inversions develop due to strong winter cooling and cold fresh water discharges into the northern Bay.

Surface layer: The surface layer extends from the sea surface to the depth where surface influences and vertical mixing are limited and within this layer, the properties are more or less homogeneous. Based on the above conceptual definition, several investigators had used different criteria such as temperature, salinity, density and other properties for evaluating the thickness of this layer (Sastry and D'Souza, 1970;

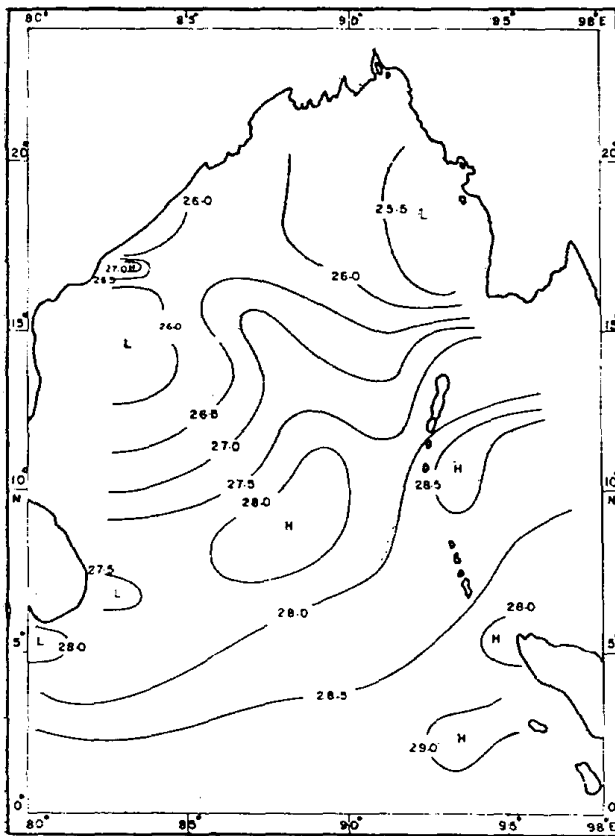


Fig. 5. Temperature ($^{\circ}\text{C}$) at sea surface.

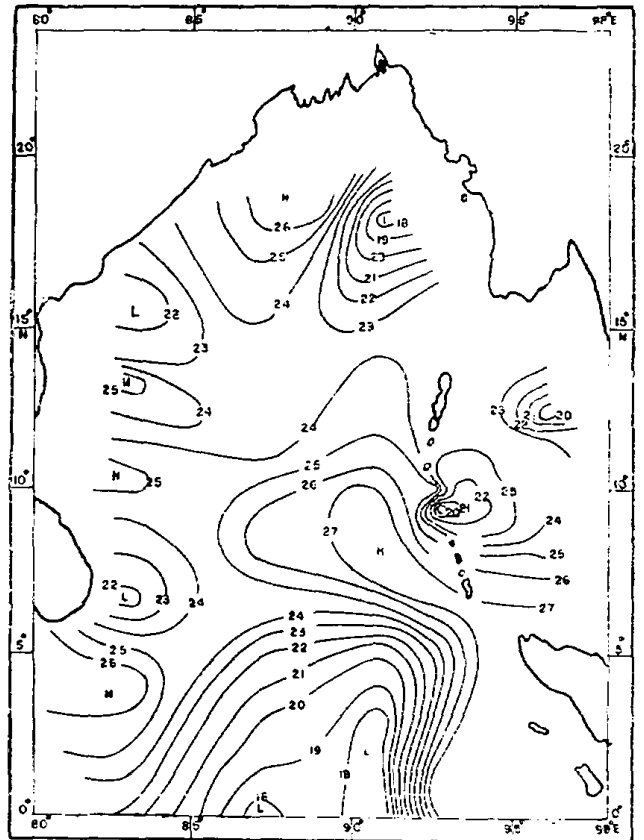


Fig. 6. Temperature ($^{\circ}\text{C}$) at 100 m.

Colborn 1971 and 1975, Wyrki, 1961 and 1971 and Panakala Rao, 1977). In this study, keeping in mind, the conceptual definition of the mixed layer, the thickness of the layer has been obtained according to the following criteria-

(i) In general, the surface layer thickness is defined as that layer extending from the sea surface to the surface where the water temperature is 1°C less than that at the sea surface;

(ii) When temperature inversions are present, the depth at which maximum temperature occurs; and

(iii) In the equatorial regions where the temperature falls rapidly in the first few metres and thereafter remains uniform, the surface at which the temperature gradients tend to increase rapidly.

Fig. 7 shows the three typical cases corresponding to the above criterion.

The thickness of the surface layer (Fig. 8) varies considerably from less than 30 m to more than 100 m. In the northern Bay, the thickness is more than 100 m at station 4959 and decreases to 60 m at the northeastern Bay. Off the east coast of India, it varies from 60 to 80 m. South of Sri Lanka, the thickness increases to more than 100 m. In the south central Bay, the thickness of the surface layer is less than 50 m. In the northern and central Andaman Sea, the thickness is about 50-60 m and increases in the southern regions. West of Andaman Islands and off west coast of Sumatra, the thickness exceeds more than 100 m while in the central and equatorial areas, it is less than 60 m.

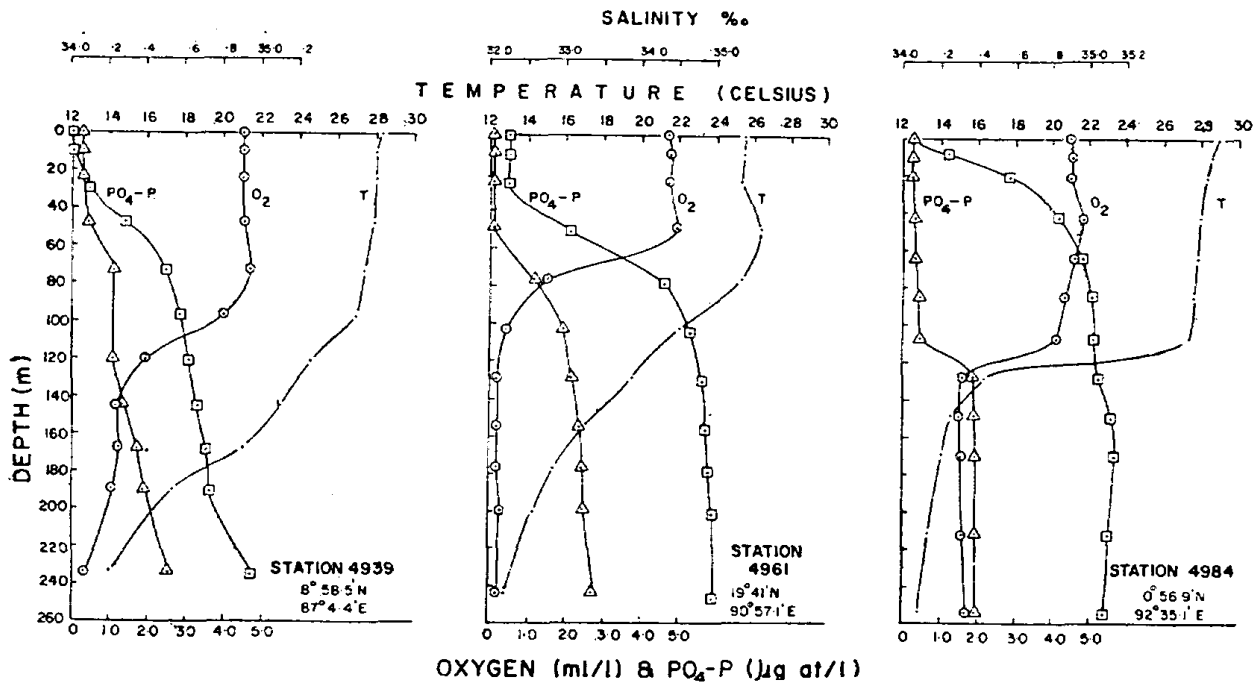


Fig. 7. Typical vertical distribution of temperature ($^{\circ}\text{C}$), salinity (per mil), oxygen (ml/l) and $\text{PO}_4\text{-P}$ ($\mu\text{g-at/l}$).

It has not been possible to secure reliable wind data over the Bay of Bengal during this period to correlate the wind data with the development of the thickness of the surface layer. The seasonal winds in this region as seen from the climatological atlas (K.N.M.I. Atlas, 1952), are weak and uniformly distributed, while the surface layer thickness shows considerable variation. Thus, it is clear that apart from the wind distribution, other physical processes are also responsible for the development of the surface layer. Further, the thickness of the surface layer is consonant with the topography of the 20 and 15°C isothermal surfaces (Figs. 9 and 10 respectively). The topography of 20°C isothermal surface as well as the dynamic topographic charts presented earlier suggest a clockwise gyre centered around station 4959 and it is at this place, the thickness of the surface layer is found to be maximum. Just east of this gyre, an anticyclonic gyre centered around station 4962 is seen where the thickness of the surface layer is reduced to less than 60 m. Similar features are seen along the east coast of India, central and southern Bays, some parts of Andaman Sea and central parts of the equatorial Bay where the northequatorial current appears to produce large scale cyclone gyre. At this place, the thickness of the surface layer is less than 60 m. It is, therefore, clear that the convergences and divergences associated with the near surface circulation give rise to the observed variation in the thickness of the surface layer.

Salinity: The surface salinity (Fig. 11) shows wider variations from about 30.10 to 35.10 per mil. In general, the salinity increases from the head of the Bay

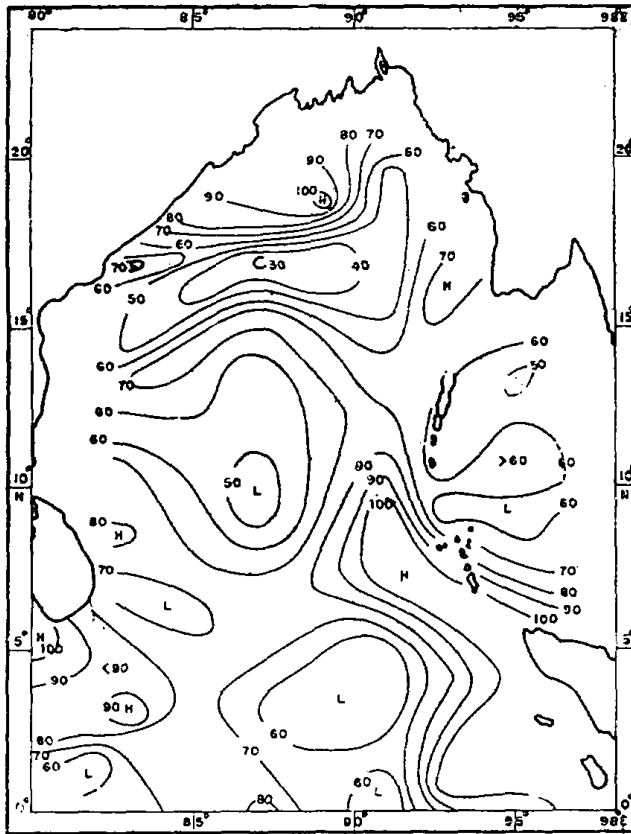


Fig. 8. Thickness of surface layer (m).



Fig. 9. Topography of 20°C isotherm (m).

to the equatorial regions. The salinities are also low all along the land boundaries due to the runoff from the several rivers emptying into the Bay of Bengal. Due to the fresh water discharges steep salinity gradients develop in the upper layers and in those regions far remote from the fresh water sources, there is not much vertical variation in the salinities as seen from the vertical sections. Fig. 7 shows typical salinity variations in the upper layers. Most of the rivers are in spate following the southwest monsoon rains over the subcontinent and much lower salinities could be expected during that period. However, by winter, the runoff is considerably reduced and the salinities tend to increase gradually all over the Bay. During this season, the surface salinity increases towards west and south. Salinity at 100 m (Fig. 12) shows a narrow range of variation and reduction in horizontal gradients. Below this layer, the salinity increases to maximum of 35.20 per mil at about 150 m and thereafter decreases.

This distribution of salinity in the upper 100 m shows the development of a strong halocline and further suggests estuarine characteristics. Fig. 13 shows the topography of the 33.60 per mil isohaline surface which has been selected to study the estuarine nature that prevails in the Bay consequent to the heavy fresh water discharge all along the peripheries. This surface occurs at deeper layers all along the coastal regions. Further offshore this surface shallows and cuts the sea surface in the

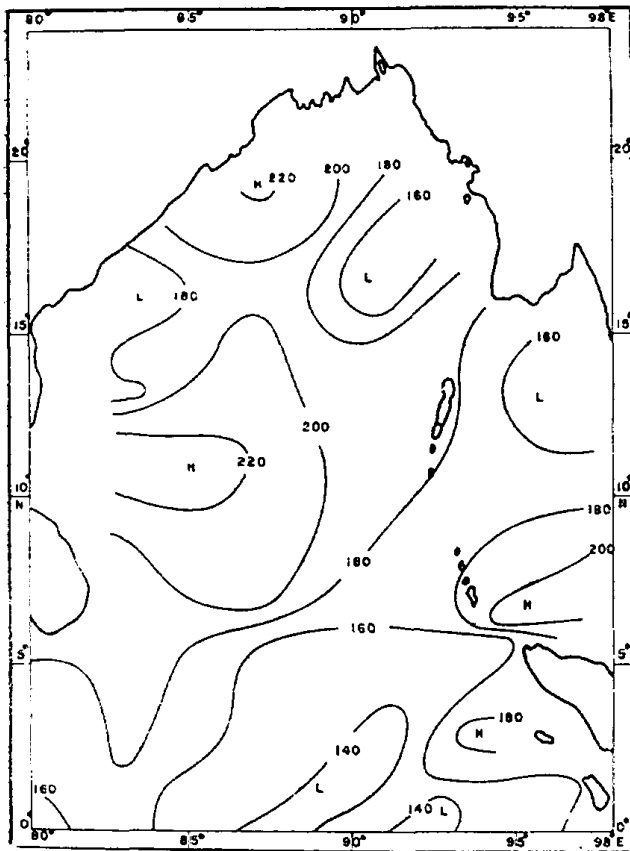


Fig. 10. Topography of 15°C isotherm (m).

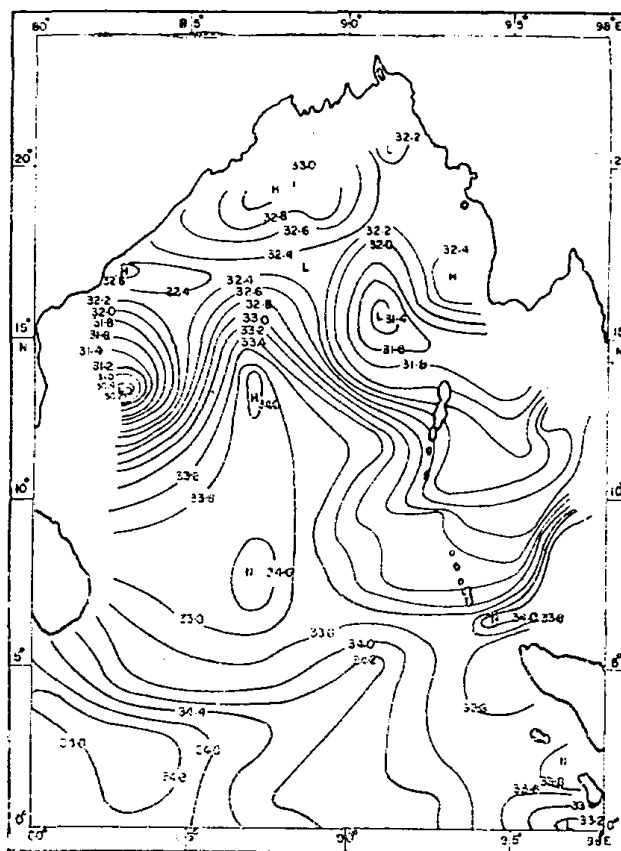


Fig. 11. Salinity (per mil) at sea surface.

southern and the central Bays. The topography of this surface shows that in the regions of convergences, the depth increases and in the regions of divergences it shallows. Thus, this surface plays a prominent role in the dynamics of the sea surface circulation as will be seen in the next section dealing with the mass distribution.

Mass distribution: At the sea surface the thermosteric anomaly (Fig. 14) varies from more than 780 cl/ton to less than 540 cl/ton. Higher values are generally found along the peripheries of the Bay. Off the southern coast of India and in the northern regions of the Andaman Sea the thermosteric anomaly values are the highest. Similarly higher values (about 700 cl/ton) are observed in the eastern regions of the equatorial Bay while south of Sri Lanka the thermosteric anomaly values are lower (less than 500 cl/ton). In the central Bay, these values range from about 580 to 640 cl/ton. In the Andaman Sea there is a southward decrease of thermosteric anomaly. A comparison of distribution of thermosteric anomaly at the sea surface with that of surface salinity (Fig. 11) indicates that the distribution of thermosteric anomaly follows salinity pattern to a larger extent. In the vertical, the mass discontinuity layer starts at about the same depth as that of the temperature discontinuity. The isanosteres follow the top and bottom of the thermocline similar to the other property distribution, viz., salinity, oxygen and phosphates as will be seen later. An examination of the mass discontinuity layer along with distribution of temperature and salinity suggests that within the

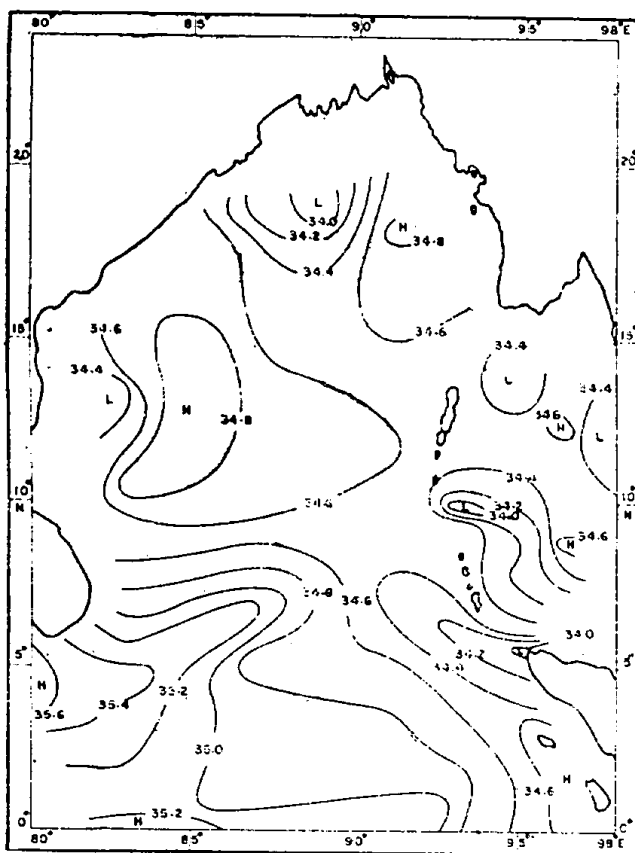


Fig. 12. Salinity (per mil) at 100 m.

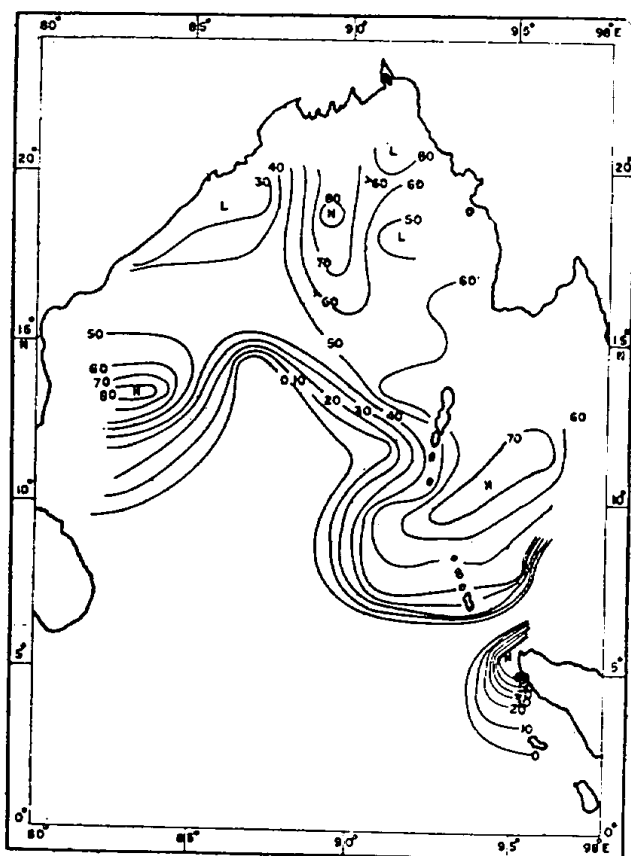


Fig. 13. Topography of 33.6 per mil isohaline surface (m).

surface layer, the isanosteres tend to follow the salinity pattern while in the thermocline they follow the temperature pattern. In the entire Bay, the thermosteric anomaly distribution indicates stable stratification even at locations where the temperature inversions occur within the surface layer suggesting that the salinity plays a compensating role in developing the stable stratification. In the equatorial regions, however, the isanosteres coincide with those of the isotherms. Below the mass discontinuity layer, the thermosteric anomaly decreases monotonically to less than 60 cl/ton at 1,250m.

At 100 m (Fig. 15), the thermosteric anomaly shows considerable variation. It varies from more than 580 cl/ton to less than 260 cl/ton. Comparatively higher values exceeding 500 cl/ton are found in the northern Bay, off the southern parts of the east coast of India, off the Sumatra coast and in the central Bay. While discussing the thermal structure at 100 m it was mentioned that the 100 m horizontal surface lies in the surface layer at some places and in the thermocline at other places. At places where this surface lies within the surface layer, the isanosteres follow the salinity structure and at places where this surface lies below the surface layer, the isanosteres follow the isotherms. The strong gradients on this surface indicate considerable flow.

At 200 m (Fig. 16), the thermosteric anomaly varies between more than 240 cl/ton and less than 160 cl/ton. Higher values are seen at the northwestern and the

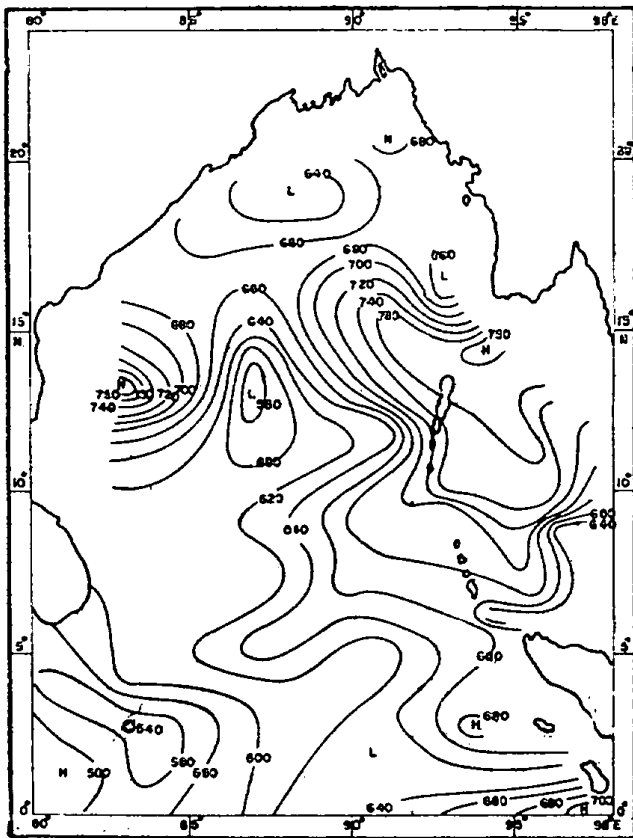


Fig. 14. Thermosteric anomaly (cl/t) at sea surface.

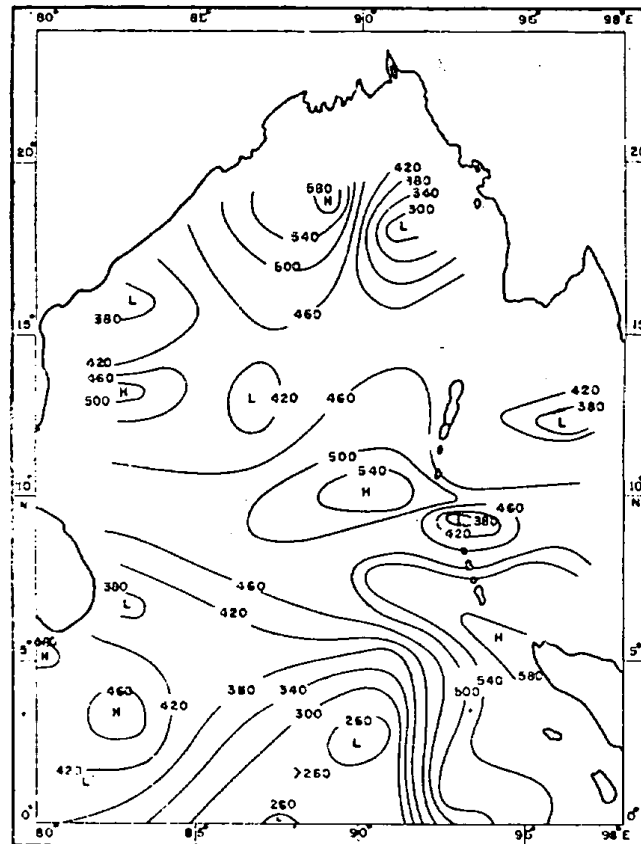


Fig. 15. Thermosteric anomaly (cl/t) at 100 m.

central Bay where the values exceed 240 cl/ton. The isanosteres on the surface follow the isotherms. The 180 and 200 cl/ton isanosteres running north-south along the central Bay are similar to the 14 and 15°C isotherms at 200 m. In the Andaman Sea, the variation in the thermosteric anomaly is not appreciable. At 500 m, the distribution of thermosteric anomaly follows the thermal structure and varies between 100 and 110 cl/ton.

The isanosteres in the vertical form a trough like structure in the central regions of the Bay. This is more prominent below the surface layer. Further, they show a tendency to deepen to north. Similar features are observed both in temperature and salinity distributions also.

As mentioned earlier, at several points along the Bay of Bengal, fresh water discharges are considerable. The mass distribution appears to reflect an estuarine type of circulation. The distributions presented earlier indicate in some respects the characteristics of a partially mixed estuary. In a partially mixed estuary, while there is well defined salt wedge, the sequence of salinity depth profiles at the interface between salt and fresh water appears as a broad band and the interface slopes upwards to the sea (Pritchard, 1965). Close to the river mouth, the net seaward flow in the upper layers is considerably larger than the river discharges. In order to compensate for higher volumes of flow in the upper fresh water layers, a flow towards the fresh water discharges must take place beneath the interface. Longitudinal and

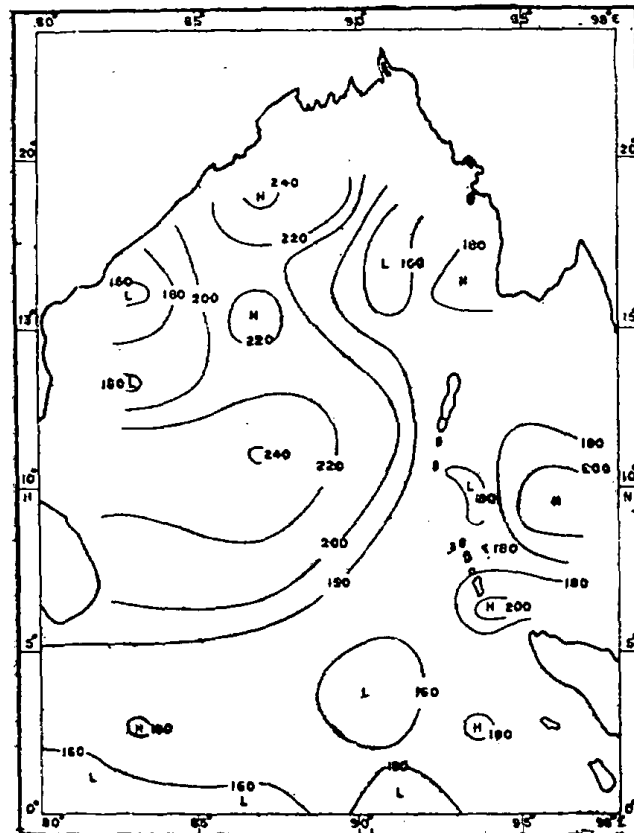


Fig. 16. Thermosteric anomaly (cl/t) at 200 m.

vertical advection and vertical diffusion across the interface seem to play an important role in the transportation of mass and salt. The topography of 33-60 per mil isothermal surface (Fig. 13) can be considered as the representative of the halocline in general, similar to that of the 20°C isothermal surface representing the thermocline. The 33-60 per mil isohaline surface is found at much greater depths near the regions of fresh water discharge and from there this surface shallows and cuts the surface in the central and southern Bays.

The salinity at deeper layers (exceeding 150 m) is about 35.00 per mil and this water forms an infinite source of supply for mixing with fresh water to increase its salinity. Thus, in the Bay of Bengal, where there are several rivers

discharging fresh water at various points along the peripheries, the mass distribution is generally altered and consequently the circulation. An elaborate estuarine pattern in the Bay of Bengal can thus be visualised in the upper layers. In the depth ranges of 50-100 m, water from the subsurface layers is drawn towards the regions of fresh water discharges. This mixes with the overlying fresh water and the mixture moves towards the central Bay. This process appears to be primarily responsible for the trough-like structure in the distribution of parameters in the central Bay. The relatively higher values of thermosteric anomaly exceeding 500 cl/ton in the central Bay at 100 m level (Fig. 15) appears to be the result of this phenomenon. This feature could be traced even on the 200 m surfaces (Fig. 16) where a broad region with relatively higher values of thermosteric anomaly are found in the same regions. Further, the alternating bands of cyclonic and anticyclonic flows seen along the peripheries, all along the coastal regions, are probably the result of intense dilution due to river discharges.

These features suggest that near the sea surface, the field of motion in the Bay of Bengal during this season is complicated and seems to be the result of various factors such as:

- (i) the winter cooling near the head of the Bay,
- (ii) the influence of the northeast monsoon winds,
- (iii) the influence of northequatorial current in the southern region, and
- (iv) the influence of fresh water discharges, especially in the northern Bay, Andaman Sea and along the east coast of India (from about June to October, the river discharges into the Bay of Bengal are generally heavy. From November onwards, these discharges are reduced and by about January, nearly stationary conditions would probably be attained).

Dissolved Oxygen

The dissolved oxygen at sea surface over most of the region is greater than 4.5 ml/l and fairly uniform within the surface layer. Coinciding with the steep gradients in the thermocline, a strong oxycline is present. Below the oxycline, an oxygen minimum layer is seen. The oxyty in the minimum layer is about 0.5 ml/l in the northern Bay and it increases to 1.5 ml/l in southern region. In general, the 15°C isotherm coincides with the oxygen minimum layer. At 100 m (Fig. 17), the oxyty distribution shows wide variations in contrast to more or less uniform values at the sea surface. A comparison of the oxyty distribution with that of the thickness of the surface layer reveals that at places where the thickness exceeds 100 m, fairly high values of oxyty are found and at places where the thickness of the surface layer is shallow, the oxyty is low.

At 200 m, the oxyty in the northern Bay is less than 0.5 ml/l and shows a gradual increase southwards. In the Andaman Sea, the oxyty is comparatively high (greater than 0.5 ml/l). At 500 m, the oxyty varies between 0.5 and 1.25 ml/l.

Inorganic Phosphates

At the sea surface, the concentration of inorganic phosphates is very low (about $0.25 \mu\text{g. at/l}$). It is nearly uniform within the surface layer and increases below this layer. Coinciding with the thermocline and oxycline, fairly strong gradients of phosphates are found. The isolines of phosphates in the mass discontinuity layer are parallel to the isotherms. Below the thermocline, the phosphate concentration increase to about $2.9 \mu\text{g. at/l}$ at depths of 1,000–1,250 m. In the depth range of 200–500 m, the phosphate values are higher in the northern regions than in the southern Bay.

At 100 m (Fig. 18), the distribution of inorganic phosphates show larger variations with pockets of low and high concentration further shows close association with the distribution of temperature on the same surface. At the northwestern Bay, the values are considerably low ($<0.5 \mu\text{g. at/l}$) and in the northeastern Bay, they increase to more than $2.00 \mu\text{g. at/l}$. Off the east coast of India, these values vary from about $1.00 \mu\text{g. at/l}$ to more than $1.75 \mu\text{g. at/l}$. In the central Bay, the phosphates range from about $0.5 \mu\text{g. at/l}$ to $1.25 \mu\text{g. at/l}$. At 200 m, the concentration of phosphates is relatively uniform over the entire Bay ($2.0\text{--}2.25 \mu\text{g. at/l}$). Below this layer, the inorganic phosphates increase gradually to more than $2.75 \mu\text{g. at/l}$.

The distribution suggests that similar to oxyty, the inorganic phosphate concentration is also governed by the circulation. This is evidenced from the fact that the

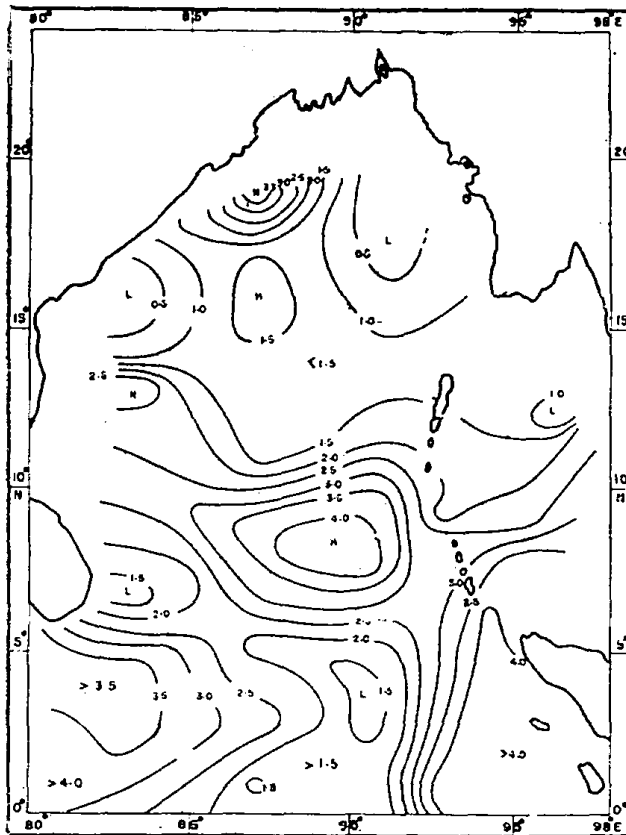


Fig. 17. Dissolved oxygen (ml/l) at 100 m.

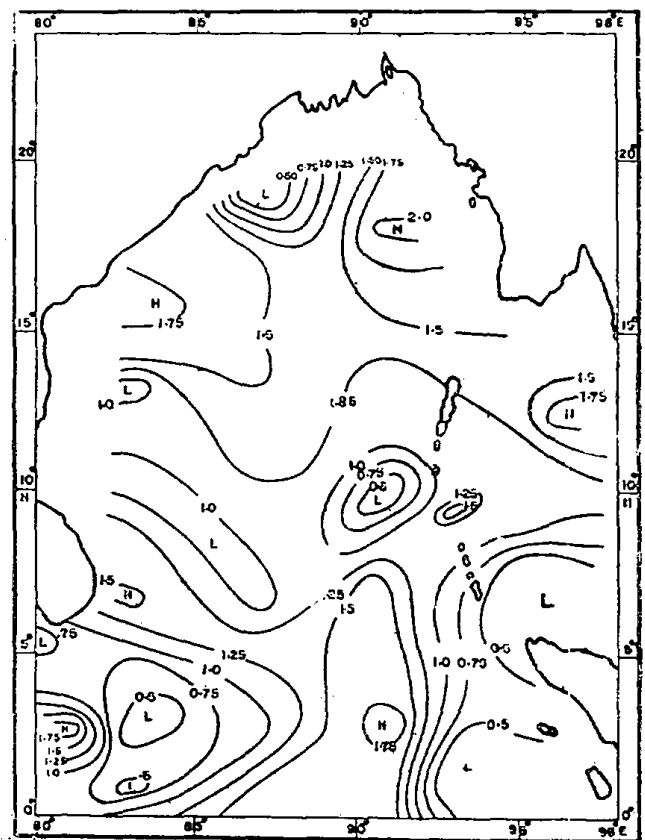


Fig. 18. Inorganic phosphates ($\mu\text{g. at/l}$) at 100 m.

concentration of phosphates is high in the places where divergence takes place and is less in the regions where convergence takes place in the nearsurface regions.

Integral Mean Concentration of Inorganic Phosphates

Our primary interest is to investigate the coherence between the nutrient concentrations in the euphotic zone and the physical parameters. The sub-surface layer is rich in nutrients, while the surface layer is generally poor. The processes of upwelling (wind driven) and the vertical mixing are primarily responsible for the upward transfer of nutrients into the surface layer.

In the present study, the distribution of the phosphates has been selected as the representative of the nutrient distribution in general. The distributions presented earlier revealed that the isotherms and the isolines of phosphates and oxygen closely followed each other in the mass discontinuity layer. Fig. 19 presents the distribution of Integral Mean Concentration of inorganic phosphates in the upper 100 m, to represent the euphotic zone.

The IMC values vary over a wide range from about $0.80 \mu\text{g.at/l}$ to less than $0.17 \mu\text{g.at/l}$ in the Bay of Bengal. Such a range is surprisingly high, especially when the variation in the surface values is from $0.10 \mu\text{g.at/l}$ to $0.25 \mu\text{g.at/l}$ over most of

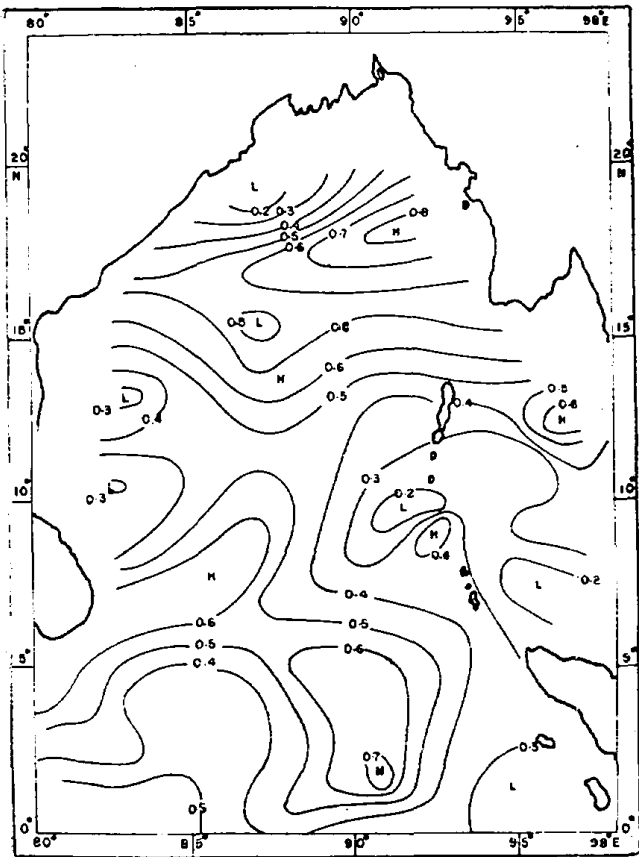


Fig. 19. Integral mean concentration of inorganic phosphates in the upper 100 m.

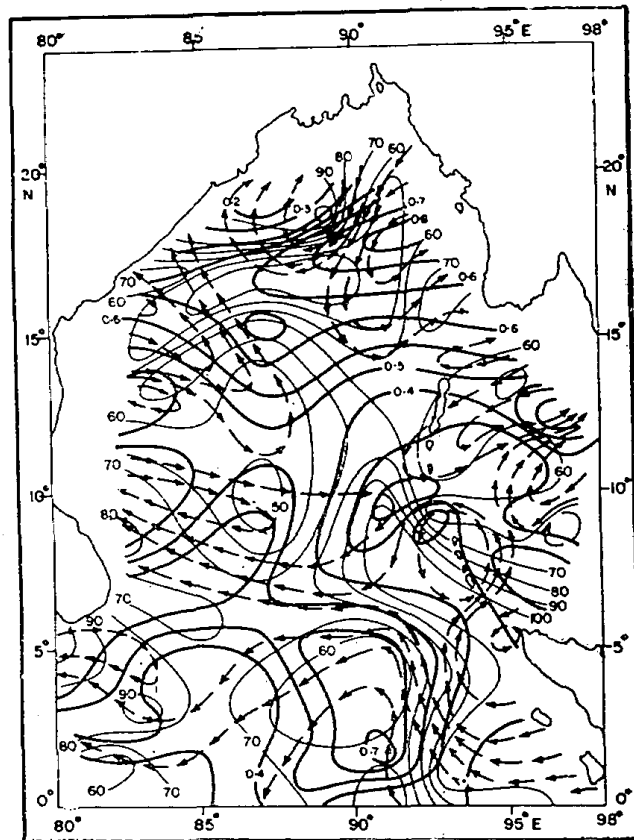


Fig. 20. Schematic representation of nearsurface circulation (broken lines), thickness of surface layer (thick lines) and IMC of phosphates (thin lines).

the Bay except in the southern regions of Sri Lanka. This large variation in the IMC is related to the nearsurface circulation. Fig. 20 presents the schematic surface circulation based on the dynamic topography of the seafloor, the thickness of the surface layer and the integral mean concentration of inorganic phosphates in the upper 100 m column. In Fig. 20, broken lines with arrows represent the surface circulation, thick lines show the thickness of the surface layer and the thin lines give the values of IMC. An examination of this figure reveals that the integral mean concentrations of phosphate are low within the anticyclonic gyres and are associated with the larger thickness of the surface layer. In the cyclonic gyres, the IMCs are higher and the thickness of the surface layer is relatively low. In an anticyclonic (cyclonic) gyre, convergence (divergence) at surface gives rise to downward (upward) shift of isolines.

At the Head of the Bay, there are two cells—one cyclonic and the other anticyclonic gyres existing side by side centred around stations 4962 and 4959 respectively. Within the cyclonic gyre, the thickness of the surface layer is low (60 m) and the IMC about $0.82 \mu\text{g}\cdot\text{at}/1$ while inside the anticyclonic vortex, the surface layer thickness exceed 100 m and the IMC is $0.17 \mu\text{g}\cdot\text{at}/1$ which is comparatively low. Another anticyclonic cell is centered around station 4926 where the thickness of the surface layer is 70 m while the IMC value is $0.29 \mu\text{g}\cdot\text{at}/1$, a low value. Similarly, a cyclonic cell is centered off the east coast of India, centered at station 4928 where the thickness of the surface layer is about 50 m and the IMC is $0.69 \mu\text{g}\cdot\text{at}/1$ which is also good agreement with the above conclusions. This feature is also seen in the equatorial regions. Thus, it is clear that the concentration of nutrients in the euphotic zone largely depends upon the near surface circulation which is consonant with the other property distributions.

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