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Distribution of density and the associated currents at the sea surface in the Bay of Bengal

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ABSTRACT. Charts showing isopycnics, density having been expressed as σ_t, at the sea surface in the region between 13° to 18°N and 80° to 84°E in the Bay of Bengal, are prepared for three seasons. In addition, a similar chart showing the conditions at the head of the Bay, the *swatch of no ground*, during the winter season only, is also prepared. From the above, surface current directions are deduced and entered on the charts. These conclusions are found generally to agree with similar conclusions derived from the thermal field by the authors elsewhere. In some cases, the surface current directions obtained in the present investigation are found to agree with those at 40-ft level, derived from the thermal field.

1. Introduction

In an earlier paper (communicated for publication elsewhere), the authors have discussed the distribution of temperature along the east coast of India from the observational data collected by the Andhra University during 1952-53. From the thermal field inferences are made regarding the circulation along the east coast of India at different depths. Since the distribution of salinity also influences the mass distribution in the sea, the currents derived either from thermal or saline considerations alone, would be only near approximations. In the following, the distribution of density of the sea surface waters along the east coast of India has been presented as a field of σ_t and the oceanic circulation has been derived consid ring the various processes enumerated by the authors elsewhere.

At a good number of bathythermographic stations surface samples of sea water are collected and their temperatures and salinities obtained. From these observations the density, at each place, expressed as σ_t, is obtained by using partly Knudsen's Hydrographical tables and partly tables prepared by La Fond (Processing Oceangraphic Data, 1951). The values of σ_t are plotted and the isolines are drawn on different charts, each to represent a particular season or region, the classification of the seasons being the same as that in the previous paper.

2. Distribution of density and the associated currents

Post monsoon season (October and November):—The general tendency of the field of σ_t is to increase with distance from the shore, the range being from $\sigma_t = 14$ to $\sigma_t = 19$ in the region under consideration. This is the general seasonal characteristic which might be noticed even from the Admiralty charts (1944). Superimposed on this general distribution, the following deviations could be noticed mainly because in the present investigation the distribution chart (Fig. 1) has been prepared in greater detail and further, Fig. 1 represents conditions only in a single season. Along the coast line, density gradually increases towards the south. Thus off Visakhapatnam σ_t values, as low as $\sigma_t = 12 \cdot 00$ (not included in Fig. 1), are sometimes noticed during this season; off the Godavari and off Madras the σ_t is $14 \cdot 00$, even though slightly away from the coast, at the latter two places, σ_t is reduced to $13 \cdot 00$. An inspection of the number of rainy days and the rainfall during this season has shown that the southwest monsoon retreats from northern India and from the northern part of the Bay of Bengal towards the end of

Fig. 1

the month of September and by about the middle of October along the Andhra coast. Under these conditions, because of greater dilution towards south, one should expect lower densities in the south along the coast. But the apparent discrepancy could be solved by considering the enormous quantities of fresh water delivered by the Ganges, the Brahmaputra and the Mahanadi in the north. Even though the southwest monsoon sets in a northeasterly or northnortheasterly current in the open Bay, the coastal current flows from the head of the Bay southwards bending almost following the coast line. This water can be traced to the extreme south of the Peninsular India. This current brings in low saline water and further due to the retreat of the monsoon, currents in the Bay will be variable resulting in lateral mixing. By these processes density along the coast line increases towards south.

Between Waltair and the Godavari the isopycnics run almost perpendicular to the coast while further south they follow the coast line. Off Visakhapatnam the isopycnics are very irregular resulting in the formation of a good number of eddies, rotating in opposite directions. In the estuarine region of the Godavari upto about 60 miles off the coast the distribution of density is uniform. From here within a distance of about 20 miles the density increases from $\sigma_t = 14 \cdot 00$ to $\sigma_t = 18 \cdot 00$. Thus a tongue of low density projects into the Bay from the mouths of the Ganges and this tongue surrounds the region of low density water, thus producing a clockwise circulation off the Godavari. In a region north of theKrishna and south of the Godavari there is not much horizontal gradient in the σ_t – field but two counterclockwise rotations are noticed in this region. Near Madras a tongue of low density extends from south towards the coast carrying a small clockwise circulation. In this region, on the thermal field chart two eddies rotating in opposite directions are found. But on Fig. 1 both have merged. Hence a turbulent circulation is a feature in this region.

A current which presumably starts from the head of the Bay breaks into a number of eddies along the coast, turns southwest along the coast as down as the river Krishna and then takes southsouthwesterly to southerly turn becoming a southward current off Madras. A comparison of the currents derived from the distribution of density and that of temperature would reveal that both the results are almost identical as far as the general trend of the current during this season is concerned. The general pattern of eddies off Visakhapatnam in both these charts are nearly the same. But off the Godavari the currents associated with the σ_t field resemble those at the 40-ft level of the thermal field. The close resemblance of the currents derived by these two different methods shows that the distribution of temperature and salinity are such that any one of these two parameters may be considered for the field of mass. At 40-ft depth (Fig. 2 of thermal fields) lower values of surface temperature in the region under consideration are

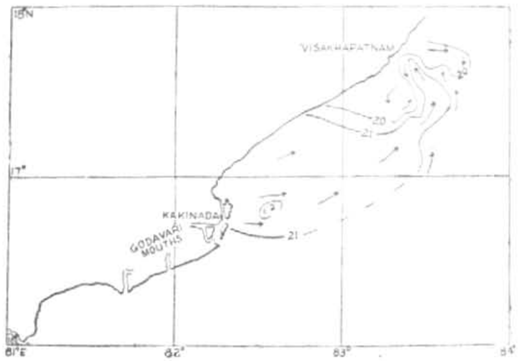

Fig. 2

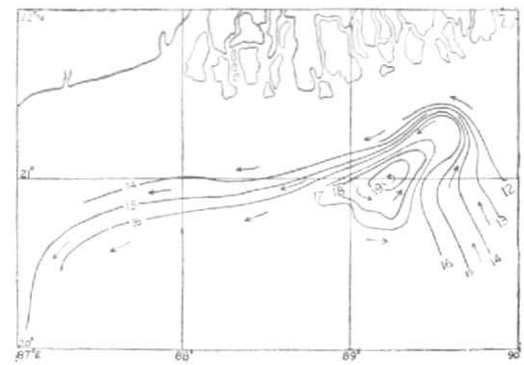

Fig. 3

not recorded, because of the existing subsurface zone of maximum temperature and these are compensated by dilution. This is the reason why the surface currents associated with the field of density coincided with those associated with the thermal field at 40-ft level.

Northeast monsoon season (*December to February*)—(*a*) Visakhapatnam region: In this region the density of the surface has become almost uniform. Only two isopycnics run throughout the entire region. As in the previous season the density increases with increasing distance from the shore. The isopycnics are more irregular off Visakhapatnam which should be mainly attributed to the greater number of the observations available at that place. The isopycnic corresponding to $\sigma_t = 20\cdot00$ shows a wavy pattern (Fig. 2) off Visakhapatnam where a tongue of high density water is flowing towards the coast in a northwesterly direction. A part of this water is deflected towards north and another towards south to form two small eddies rotating in opposite directions.

The general trend of the current in a region off Kakinada and off Visakhapatnam is to run in a northeasterly direction. This current takes a turn towards north and then northwest at about 17°20′N and 83°40′E. It is this that divides itself into two eddies as described above. Even though the isopycnics (Fig. 2) do not resemble with the isotherms of the corresponding chart of the thermal field, the general trend of the currents is identical including the formation of two eddies referred to above. This region actually formed a dividing place of currents during this season (*vide* Admiralty chart).

(*b*) At the head of the Bay—Over the *swatch of no ground* at the head of the Bay of Bengal there is an intense horizontal gradient in the distribution of density (Fig. 3). High density water ($\sigma_t = 20\cdot00$ to $\sigma_t = 24\cdot00$) accumulated over the *swatch of no ground* north of which isopycnics corresponding to $\sigma_t = 16\cdot00$ to $\sigma_t = 11\cdot00$ form a northeasterly tongue. This formation is because of dilution of sea water very near the mouths of the two rivers of the region. Up to the Mahanadi the isopycnics are parallel to the coast and these are not so densely packed near to one another as they do at the head of the Bay. The range is $\sigma_t = 14\cdot00$ to $\sigma_t = 16\cdot00$, the latter being away from the coast. Hence a current from the Burma coast goes to the head of the Bay in a northwesterly direction and almost mixes with the river waters and gets diluted. Then it enters into a counter clockwise circulation over the *swatch of no ground*. From here it flows along the Orissa coast as a westerly to westsouthwesterly current. The general pattern of the currents (Fig. 3) of this study agrees with that of the thermal field corresponding to 40-ft depth. The isopycnics in Fig. 3 which lie just over the submarine canyon (where maximum depths are found) are elliptical in shape whereas the isotherms of the corresponding figure form a tongue of low temperature over the *swatch*

Fig. 4

of no ground entering from a southerly direction to northnortheasterly and another tongue of high temperature proceeds from the mouths of the Ganges towards the southern extremity in a southeasterly direction. Once again the similarity of the isotherms at 40 ft level (Fig. 12 of the author's paper on thermal field) and the isopycnics of the surface (Fig. 3) resulted because of the subsurface zone of maximum temperature at the *swatch of no ground.*

From both considerations (temperature and density) the currents at the head of the Bay very near the estuarine regions show considerable differences from the pattern obtained by Sewell (1929), in that an anticlockwise gyrale of the present investigation replaces a clockwise gyrale of Sewell which, of course, is found slightly towards south. This difference is partly due to the detailed observations made in the present investigation over that particular area and partly due to the fact that Sewell's data extend over a number of years thus providing a mean feature. Some such differences are also noticed in the southwest monsoon months of 1955 This shows the individual pattern of the currents at the head of the Bay are predominantly influenced by the turbulent mixing of the river waters with the sea water.

If a subsurface zone of maximum temperature occurs, currents at the surface as derived from the distribution of density are showing similarities with those derived from the field of temperature corresponding roughly to the subsurface level of maximum temperatures. Hence it is worth confirming whether one should consider (in case of temperature inversion existing in the surface layer of the sea) the maximum temperature of topmost layer of the sea as the representative temperature of the sea surface for drawing conclusion about the sea surface currents from the thermal field. Unfortunately this could not be done for want of more data.

Hot weather season (March and April)—The distribution of density along this coast (off Visakhapatnam to off Madras) has become uniform and is round about $\sigma_t = 21 \cdot 50$. Hence no isopycnics could be drawn for this season (Fig. 4) but the following observations could be made. The density of water along the coast is greater than when measured slightly into the Bay. Towards north off the Godavari delta the density distribution is such that it results in a weak clockwise circulation. Off the Krishna the circulation is a counter-clockwise gyrale. The greater density of the water near and along the coast are due to the upwelling which is more or less restricted to the coastal region and extends only up to the middle of the continental shelf during the greater part of this season.

A north to northeasterly current starts from south of Madras and continues to flow with slight deviations in direction in the open waters of the Bay in the entire region under consideration. As the horizontal distribution of density is uniform the currents during this part of the year are extremely weak as compared to the previous two seasons. This season forms the transition period for the south to southwesterly currents of the northeast monsoon and north to northeasterly currents of the southwest monsoon along this coast. With the reduction in density and the changed direction of the winds the surface currents are variable during this transition period.

3. Seasonal variation in the density of coastal waters

As the density of sea water depends upon both the temperature and salinity, all the factors that affect temperature and salinity will also affect density. The distribution of density will be further affected by the existing current, even though a majority of current patterns have their origin in the distribution of mass. The Bay of Bengal is subjected to two systems of oceanic currents in a year depending upon the prevailing monsoon winds. At least at the surface, the oceanic circulation is mainly due to this alternating seasonal wind systems. The change in sea surface current results in a change and a re-adjustment of the distribution of density at the surface layers. These remarks will apply to the entire Bay of Bengal as far as the structure of the sea surface isopycnics and the associated currents are concerned. There are two distinct periods along the east coast of India when intense mixing takes place as a consequence of upwelling and sinking. This mixing will result in a changed distribution of density along this coast from season to season. In the following paragraph the seasonal variation in density of the surface waters of this coast has been discussed.

During the southwest monsoon season, rainfall will be heavy and widespread throughout India and the Bay of Bengal. This results in large quantities of run-off and drainage water being mixed with the water of the Bay which will reduce the salinity of the coastal waters to a greater extent. Hence in the distribution of surface density, by the time the monsoon retreats, the denser water is found off the coast resulting in a southerly flow in general during the retreating monsoon period. As sinking in-shore has been found in this season, mixing of water takes place much over the continental shelf giving irregular patterns of the surface isopycnics.

Late in the post monsoon period and early in the northeast monsoon period the surface temperature begins to fall rapidly and due to the absence of rain and any appreciable quantity of run-off from rivers (as compared with southwest monsoon period) the salinity rises resulting in a high density surface water. Due to the proximity of land, the fall of temperature is greater along the coast than in the open Bay. Hence the changing density of the surface waters near the coast (from $\sigma_t = 14{\cdot}00$ in the post-monsoon season to $\sigma_t = 20{\cdot}00$ in the northeast monsoon season) is greater than in the off-shore regions (from $\sigma_t = 19{\cdot}00$ to $\sigma_t = 21{\cdot}00$). Sinking followed by mixing is also partly responsible for a greater rise in density of the coastal waters. Thus in this season the horizontal gradient in density are reduced very much.

The change in the wind system towards the end of this season and the consequent upwelling resulted in a redistribution of density of the surface waters. Thus in the hot weather season the density of the coastal water has become very uniform having slightly higher density water towards the coast.

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