

Northward undercurrent along west coast of India during upwelling—Some inferences

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Received 3 October 1989; revised 9 January 1990

Utilizing hydrographic data covering several months from a section along 15°N in the eastern Arabian Sea, a northward flowing undercurrent at the time of upwelling along the west coast of India has been identified from the downward tilt of the isotherms below the upwelling layer. This northward flow which appears to be weak occurs in the slope region between 100 and 150 m below the surface. Temperature ranging between 18° and 20°C and a salinity minimum ranging between 35.14 and 35.4×10^{-3} are found to be associated with this flow. The T-S relationship for selected stations vertically across the undercurrent shows two distinct water characteristics—a warm and high saline surface water and a low temperature, low saline subsurface water. This northward subsurface flow appears to be either absent or reversed during the downwelling season (Dec.-May) along this part of the coast.

Poleward undercurrent has been identified as one of the components of the coastal circulation system along the eastern boundaries of the world oceans. Theoretical models¹⁻³ have shown that an equatorward wind along the eastern boundary drives an offshore Ekman drift at the ocean surface and a return flow underneath. This is accompanied by a surface equatorward jet and a poleward undercurrent that decays offshore. The isopycnals bend sharply upwards towards the coast above the core of the undercurrent (indicating upwelling) and they bend downward below that. Yoshida⁴ has described the northward flow in the lower layer as an indication of coastal upwelling by relating the north-south movement of water to the vertical motion. The author has also derived the northward flow from the downward tilt of the isotherms below the surface layer.

Poleward undercurrents have been detected through direct measurements off California^{5,6} and Peru^{7,8} coasts and have been shown on the dynamic charts of 200 db surface along the west coast of Africa⁹. Inferences on these currents can also be made from the downward tilt of the isotherms or isopycnals below the upwelling layer^{4,5,10}. In fact, observations carried out along major upwelling regions show that the isotherms tilt downward in the undercurrent region^{5,10}. Therefore, in the light of the suggestive evidences that undercurrents can be identified from the downward tilt of the isopycnals/isotherms in the hydrographic sections, an attempt is made in this study to investigate their possible occurrence along

the west coast of India. However, absence of continuity in the data set has introduced, at various stages, difficulties in this investigation. Nonetheless, it is hoped that the evidences presented here may create interest for further studies in this topic as not much information on the undercurrents seems to be available along the Indian coasts.

Materials and Methods

Data used in this study were from a hydrographic section (along 15°N lat.) that extends between the west coast of India and 69°E in the Arabian Sea (Fig. 1). This section was repeatedly covered by *RV Gaves-*

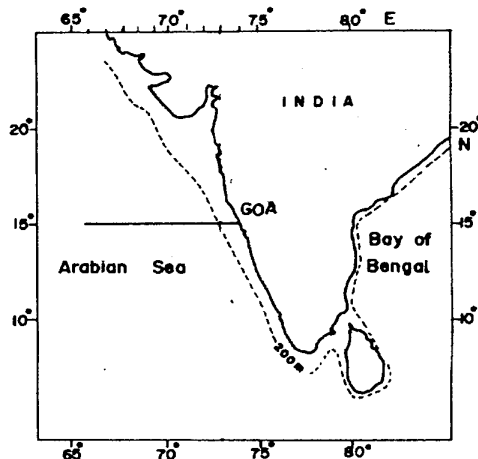


Fig. 1—Location of hydrographic stations along 15°N

hani in different months between 1979-1981 and data from 7 such cruises were utilized for the present investigation. Temperature and salinity data during these cruises were obtained through hydrocasts and CSTD (Guildline, Canada) and the raw data were subjected to routine corrections employing standard methods. Using the corrected data, vertical profiles and sections of temperature and salinity and T-S plots were prepared.

The bottom topography at this part of the Arabian Sea is such that the 15°N lat. line intersects the 73°E long. line at 200 m depth contour (shelf edge). The region beyond 73°E towards offshore, where the depth increases very rapidly, forms the slope region. The discussions on the undercurrent in this paper mainly pertain to this slope region.

Results

As mentioned earlier, the inferences on the northward undercurrent were made from the downward tilt of the isotherms below the upwelling layer. In the subsequent sections, the characteristics of the hydrographic sections that enabled the identification of the undercurrent were presented along with some of its derived features.

Vertical temperature sections—Fig. 2 shows vertical sections of temperature along 15°N for different months of the upwelling season, when the northward undercurrents are expected to be present. These figures exhibit two features prominently near the coast: (i) upward tilt of isotherms in the upper layer and (ii) downward tilt of isotherms in the layer below that. The first familiar feature shows the process of upwell-

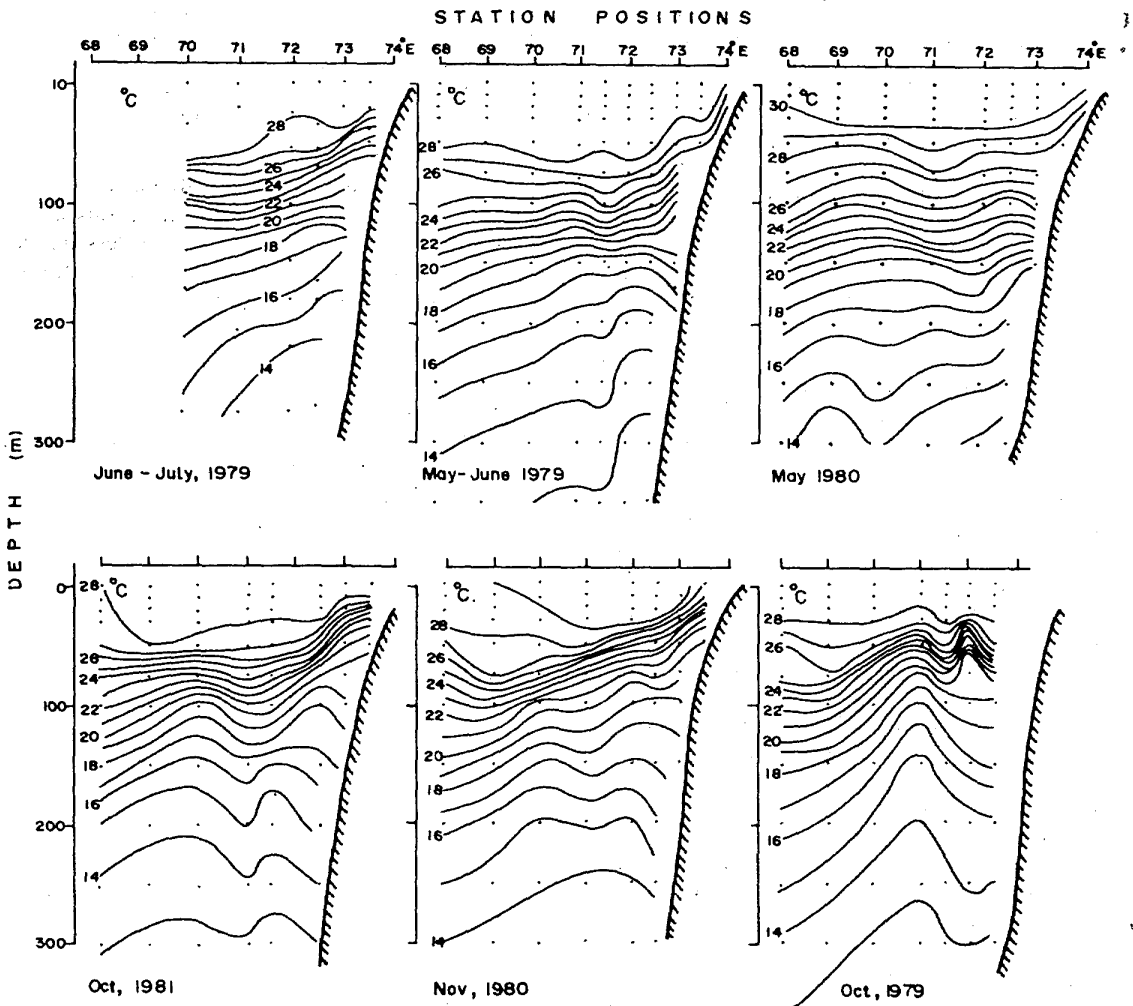


Fig. 2—Vertical sections of temperature along 15°N lat. during monsoon months

ing apparently due to an equatorward wind. The second feature, downward tilt of isotherms, is presumed to be induced by a northward flowing undercurrent that is being discussed here. This downward tilt, though very weak, is consistently seen in all temperature sections. The gradient of the downward tilt of the isotherms differs in different months.

The temperature sections show that the water temperature of the undercurrent varies between 18° and 20°C (upper limit) and is slightly higher than the temperature of the water at the same depth just offshore. This difference in temperature ranges between 0.5° and 1.5°C for a horizontal distance of about 50 km. The depth of the undercurrent varies between 100 and 150 m below the surface in the slope region off the coast. Interestingly, these depth values are very close to the values obtained from the theoretical models. With the available data it is difficult to derive the thickness of the undercurrent.

Difficulty arose, while evaluating the isotherm tilt, at least in some cases, because of the internal oscillations as may be noticed during October 1979 observations (Fig. 2), where an objective assessment of the isotherm tilt became complicated due to the isotherm oscillation. Therefore, caution must be exercised while interpreting the downward tilt of isotherms below the thermocline.

In the present case, the minimum horizontal distance between the hydrographic stations in the undercurrent region is about 50 km. Therefore, the width of the undercurrent can not be estimated to be < 50 km., which is an over estimate compared to the results of the theoretical models.

Salinity sections—Fig. 3 depicts salinity distribution across the section which is characterised by a high salinity upper layer and a low salinity layer below that. This less saline water tends to come up to the surface through upwelling. However, what is interes-

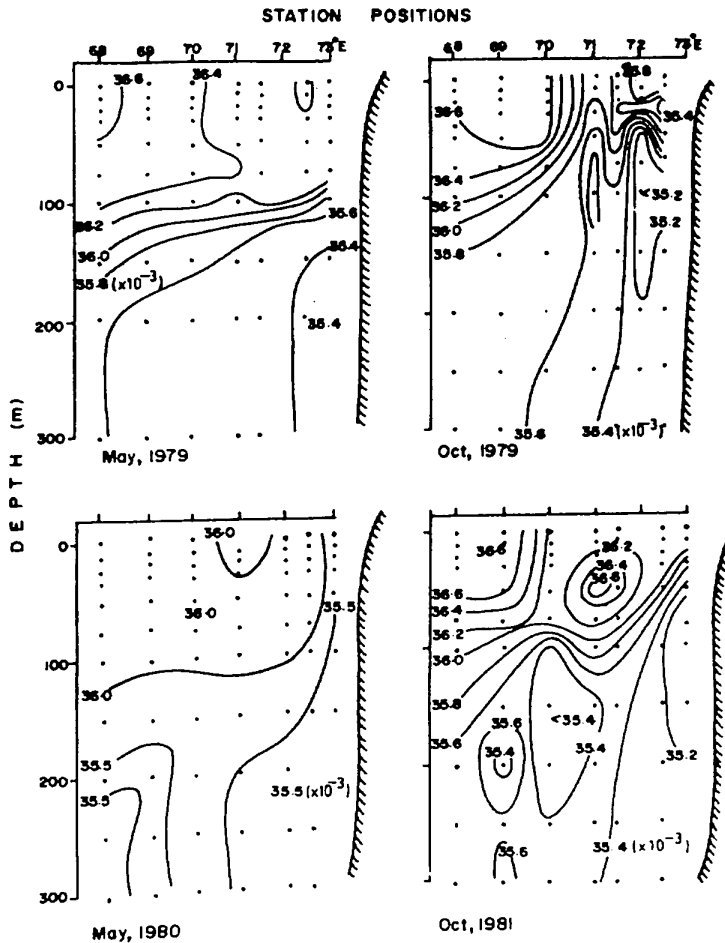


Fig. 3—Vertical sections of salinity along 15°N lat. during monsoon months

ting in Fig. 3 is the presence of a weak salinity minimum below the upwelling layer that almost coincides with the area where the downward tilt of the isotherms is observed, i.e. the undercurrent region. This salinity minimum which is noticeable in all the sections examined, has values ranging between 35.14 and 35.40×10^{-3} . Thus the undercurrent appears to be less saline and warmer than the water at the same depth just offshore.

Vertical profiles of temperature and salinity—Fig. 4 shows two sets each - one through the undercurrent and the other, through the adjacent water column offshore - of vertical temperature and salinity profiles for 3 different occasions. A very conspicuous feature observed in Fig. 4 is the temperature difference between the shoreward station (undercurrent region) and the offshore station at a depth between 100 and 150 m. This difference of temperature, which is of the order of 1° to 1.5°C (for the cases presented) for a horizontal

distance of 50-100 km, is responsible for the downward tilt of the isotherms in the vertical sections (Fig. 2). Above this depth, colder water is found as compared to the offshore station apparently due to upwelling.

The salinity profiles show a high salinity surface layer and more clearly, a salinity minimum below that. This salinity minimum almost coincides with the temperature increase in the nearshore profile.

The above mentioned temperature increase coupled with salinity minimum below a depth of 100 m at the shoreward station is expected to provide the required tilt to the density surface to drive a current opposite to that at the surface.

Temperature-salinity (T-S) relationship—T-S relationship for selected stations vertically through the undercurrent is presented in Fig. 5. It can be seen that the points in the Fig. 5 are concentrated at 2 regions, apparently representing 2 different water properties: a high saline, high temperature water near the surface

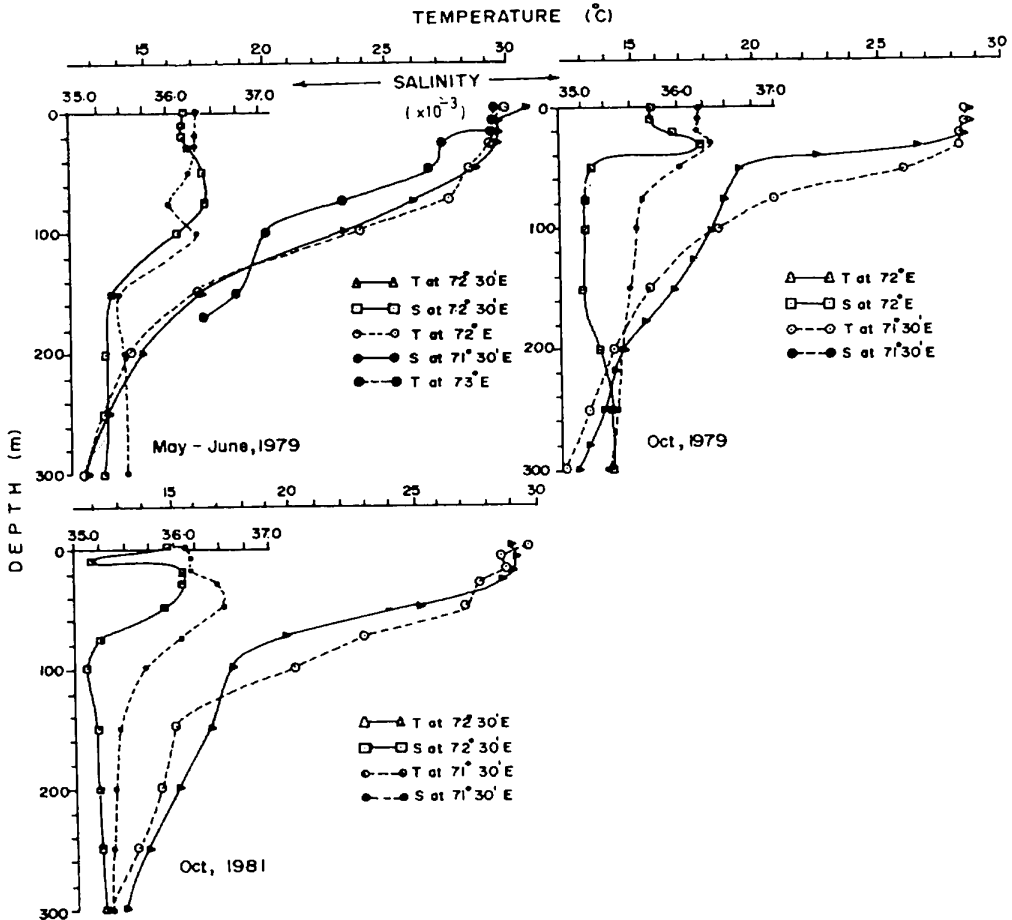


Fig. 4—Vertical profiles of temperature and salinity through (i) undercurrent and (ii) adjacent water column offshore

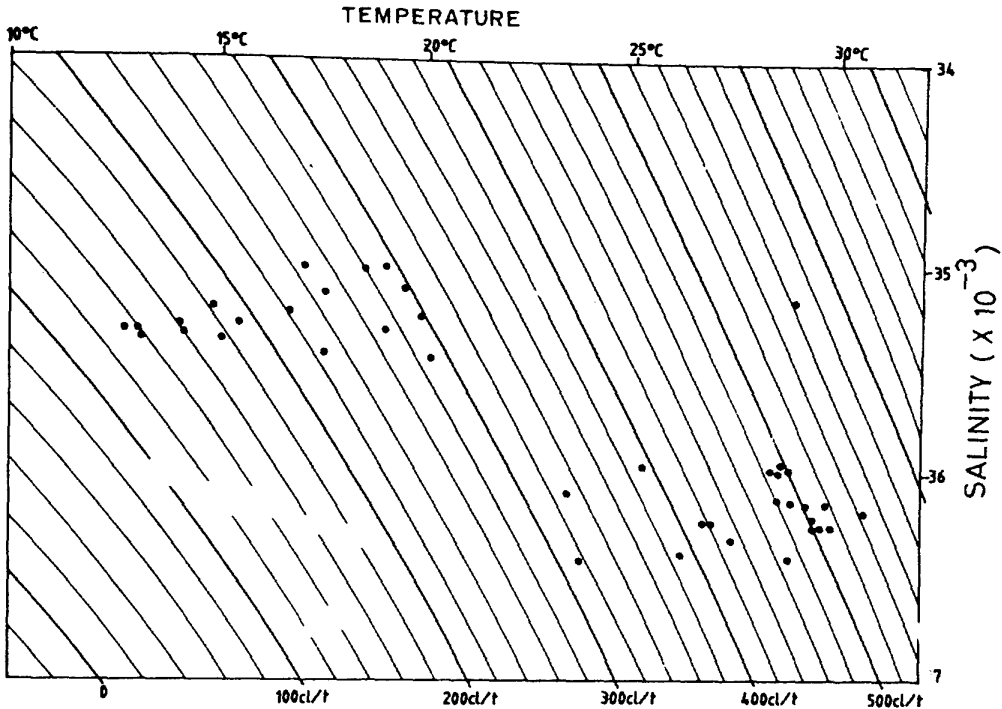


Fig. 5—T-S relationship for stations vertically across the undercurrent

and a low temperature, low saline water below that. The first one is presumed to be the Arabian Sea high salinity water and it extends to a depth of about 100 m. The surface water mass has a salinity minimum between 100 and 150 m where the temperature increases marginally compared to the offshore water at the same depth. The above mentioned salinity minimum can be noted in the T-S plot also.

Discussion

The inferences made in the present paper on the presence of undercurrent along the west coast of India are based on downward tilt of isotherms below the upwelling layer. In addition to the theoretical support for this, the field measurements carried out in other upwelling regions of the world oceans also show that the isotherms tilt downwards below the upwelling layer in the regions of undercurrents. Though the downward tilt observed in the present study in certain cases may not appear strong enough to drive a current, the persistence of this feature in almost all the sections examined is very convincing. Moreover, it is conspicuous by its absence during the downwelling season in the same area (Fig. 6). It is worth mentioning here that, the vertical sections presented by earlier workers¹¹ to illustrate coastal upwelling clearly show this downward tilt below the upwelling layer indicat-

ing undercurrent. It is possible that while trying to emphasise on the upwelling phenomenon, the less prominent features below that would have escaped their attention.

Some of the features of the northward flowing undercurrent derived from this study are: (i) undercurrent occurs at a depth between 100 and 150 m below the upwelling layer in the slope region; (ii) water temperature within the current varies between 18° and 20°C; (iii) it is associated with a salinity minimum that varies between 35.14 and 35.4×10^{-3} ; and (iv) it appears to be warmer than the water at the same depth just offshore.

The depth of the undercurrent and its location in the slope region are almost in accordance with the results of the theoretical models. The observations along other upwelling regions show that the undercurrent is associated with high salinity, whereas, in the present case it is associated with low salinity. One probable explanation for this could be that elsewhere (i.e. off California, Peru, West Africa, etc.) the source of undercurrent water is likely to be the equatorial region whereas in the present case, the source is presumed to be the Bay of Bengal, which is less saline compared to the Arabian Sea. Regarding the speed of the current it can only be stated that the flow appears to be weak as seen from the gradient of the isotherm tilt.

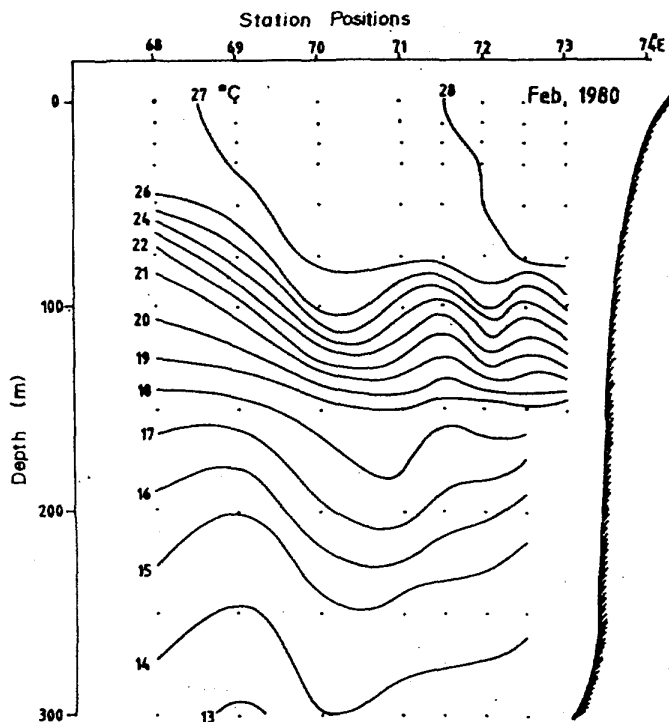


Fig. 6—Vertical section of temperature along 15°N lat. during non-monsoon month

The order of magnitude of the speed along the California and Peru coasts is about $5-10 \text{ cm. sec}^{-1}$. Along the Indian coast, as the process of upwelling itself is considered to be weaker than the above areas, the speed of the undercurrent is also likely to be weaker. In the present data set there is one instance where the temperature data from 15° and 13°N are available almost at the same time. It is observed in this case that the downward tilt of the isotherms at 13°N is stronger than the one at 15°N. Theoretical studies² have shown that the presence of shelf tends to slow down the undercurrent as the shelf induces a baroclinic component towards the equator. Along the west coast of India, the shelf width increases towards north and therefore, it is possible that the strength of the undercurrent may also decrease towards north as indicated by differential strength of the downward tilt of the isotherms at 13° and 15°N lat.

It will be interesting to examine the situation along this coast during the non-monsoon season. The temperature distribution during February shows that downwelling occurs in the surface layers in the same location (Fig. 6). It is possible that this downwelling is forced by a northward wind. However, an interesting thing noticed in Fig. 6 is the upward tilt of the isotherms below the surface layer suggesting a

reversal of the undercurrent. Though this is purely a speculation at the moment, this possibility can not be ruled out as there is a reversal in the surface flow in this season.

It is imperative at this stage to look into the process of upwelling along the west coast of India. Earlier studies¹² along this coast show that upwelling commences around February-March in the deeper layers and reaches the surface by May. Subsequent studies^{13,14} have indicated that off Goa coast cold, upwelled water is seen in the surface layers even during October, this however needs further confirmation. The temperature sections presented in this study show that the thermocline off the coast along 15°N is very shallow even in November (Fig. 2c) and the thermocline appears to come up only after May. However, we are unable to present any conclusive inferences regarding this aspect due to lack of systematic data. A comprehensive long term study is needed to understand the process of upwelling and undercurrent along this coast.

Acknowledgement

The author wishes to express his sincere thanks to the Director, and Head, Physical Oceanography Division for their interest. He is also indebted to the scien-

tists and officers and crew of *RV Gaveshani* for their involvement in the collection of data.

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