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Studies of Upwelling along the West Coast of India using Geopotential Anomaly

P. N. LATHIPHA & A. V. S. MURTY
Central Marine Fisheries Research Institute, Cochin 682018

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As summer is the season of mixing and winter the season of stratification in the Arabian Sea along the west coast of India, summer minus winter dynamic depth which takes into account the integrated effects of temperature, salinity and pressure is considered to reveal regional differences of the intensity of upwelling relative to winter situation. The areas of intensive upwelling are thus identified. Stabilities of water layers during summer are examined with respect to those during winter. Deeper waters are relatively less stable during summer. Stability increases during summer in the middle range of thermocline depth (core of thermocline). More mixing is found in the subsurface in the case of the regions of intense upwelling. Following model is suggested for explaining upwelling in the waters: Upwelling during summer should occur in the deep waters and the upward currents should cease to exist through the core of thermocline which becomes more stratified disallowing upward movement of water. Heat and salt are, therefore, to be transferred from the depth where upwelling ceases to the subsurface and surface by means of eddy diffusion. A mixing at the top layers reduces the core of thermocline and thereby intensifies the process of vertical transfer of properties. Thus, the cumulative manifestation of the entire mechanism of the total process is to make the characteristic properties such as coldness and denseness of the deeper waters appear at the subsurface and surface layers. Effects of physical processes such as those of horizontal advection, precipitation and river discharge are neglected in the analysis in order to make the model less cumbersome.

UPWELLING involves upward currents[1-4] which give rise to the presence of colder, denser and deeper water at the surface. As the surface waters are enriched with nutrients by this process, the areas having intense upwelling are also the areas of high plankton, productivity and fisheries[5-9].

Details of regions of upwelling, its effects and general models of the phenomenon have been described[4]. Upwelling[10-12] on the east coast of India is attributed to the persistent southwest monsoon.

Upwelling is reported by several authors[13-19] in the Arabian Sea in general and off the west coast of India in particular. The southwest monsoon striking against the coast, does not directly favour upwelling on the west coast of India. Nevertheless, the process is more intensified on the southwest coast[20], perhaps, as a result of the combined effect of strong southerly currents of the southwest monsoon season and the southeasterly orientation of the coastline. Sastry and D'souza[21,22] have observed divergence in the field of geostrophic motion at surface and subsurface levels off the southwest coast of India.

As summer is the season of upwelling and winter is the season of stratification in the waters of the Arabian Sea along the west coast of India, the condition of summer minus winter dynamic depth is considered here to indicate the regional relative difference of the intensity of upwelling. Also, the overall mechanism of the process is studied from the relative stabilities of the waters. In the light of the above, the time scale of the effect of upwelling may be assumed to be of the order of a season's period.

Materials and Methods

One degree squares (Fig. 1) were considered for these studies. Temperature and salinity data from 875 stations were collected for each grid during summer (433 stations; June-July) and winter (442 stations; December-January) and the data sources being CMFRI, Cochin and National Oceanographic Data Centre, Washington.

Mean values at standard depths of each parameter (T and S) were obtained for each grid for each season. From these mean values, corresponding density (σ_t) values were computed from a nomogram[23]. Values of σ_0 for the corresponding mean values of salinity were obtained from Sund's slide rule[24]. The specific volume anomaly at the corresponding decibaric surfaces was obtained from values of σ_0, σ_t and the corresponding mean temperatures using the same slide rule. The mean value of specific volume anomaly for each pair of adjacent depths was obtained. This mean value of specific volume anomaly multiplied by the corresponding pressure interval gives the dynamic depth anomaly corresponding to that pressure interval. Dynamic depth anomaly of the corresponding pressure intervals are cumulated to get the dynamic depth anomaly corresponding to the total depth at the

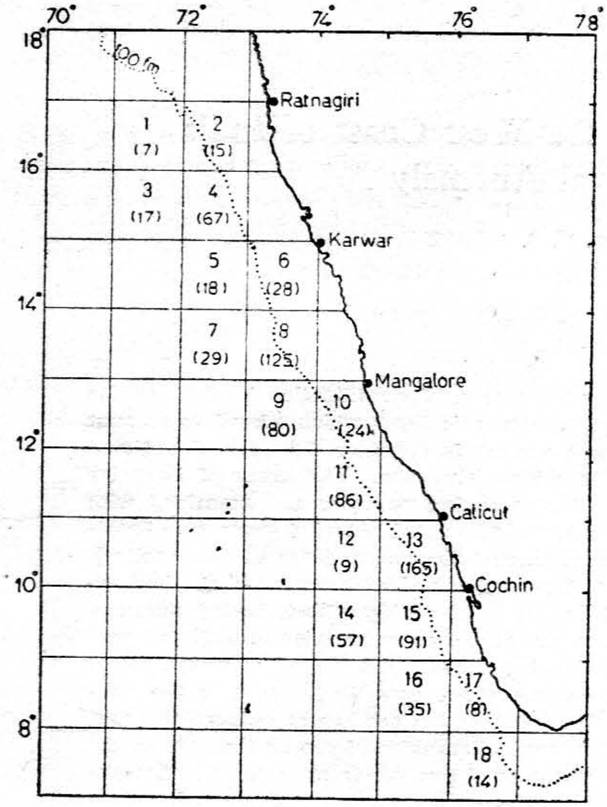

Fig. 1 — Area of investigation [One degree squares are numbered and number of observations indicated in parentheses]

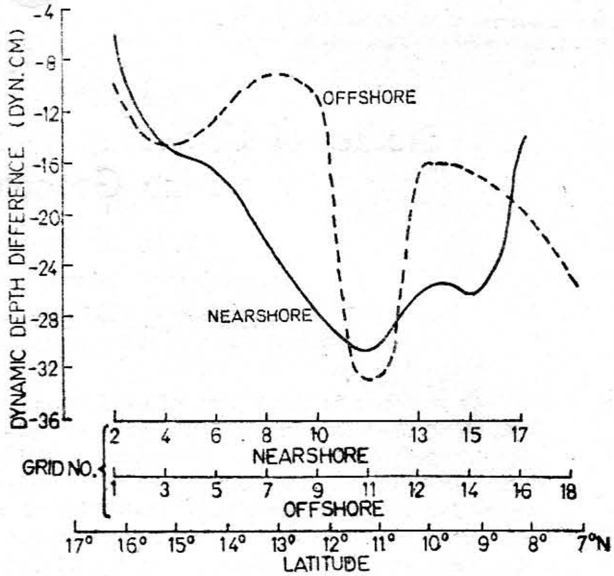

Fig. 2 — Summer minus winter dynamic depth variations along the coastline

point. The above cumulative dynamic depth anomaly values were then expressed relative to the values at 500 m depth (i.e. 500 m decibaric surface is chosen as reference level). The surface geopotential thus obtained for each season is considered in the analysis.

Mean *T-S* diagrams of the northern zone (Ratnagiri-Karwar), central zone (Mangalore-Calicut) and southern zone (Cochin-Trivandrum) were also constructed to explain the process from stability point of view.

Results and Discussion

Results of the summer minus winter dynamic depth along the coast are presented in Fig. 2. The conditions for the nearshore and offshore waters are separately shown. The nature of analysis is such that it provided a means to study the changes of characteristics of sea water from a state of stratified condition (winter) to the situation of perturbation (summer) at different places along the coastline. Therefore, one expects lower dynamic depths in the region where upwelling is prevalent. Accordingly, the phenomenon seems to be more pronounced in the middle and southern regions, especially in the middle region of the coastline (Calicut-Mangalore region) where the dynamic depth is the lowest. Nevertheless, the process exists with lesser degree in the remaining areas. The results are in general agreement with the earlier findings based on vertical sections of various parameters[25].

Results of net radiation and evaporation published in IIOE Meteorological Atlas[26] indicate that they are of the same order in the area during summer and winter, as their absolute average values ranged only from 260 to 270 cal/cm^2/day. Hence, their effect to produce relative cooling at the surface is neglected. The effects of physical processes such as those of horizontal advection, precipitation and river discharge are also neglected in the foregoing analysis in order to make the model less cumbersome.

It is possible, with the help of *T-S* diagrams, to further understand the nature of the process taking place in the waters. Mean *T-S* diagrams of the three zones are presented in Fig. 3a for winter and in Fig. 3b for summer. The nearly isothermal mixed layer which existed to a depth of about 50 m during winter is practically absent by summer except in the middle region where it is limited only to a very shallow depth of about 20 m or even less. A depth of about 150 m may be recorded as the lower limit of thermocline.

The change in stability of the waters from winter to summer can be studied from the above two sets of *T-S* diagrams. A pair of σ_t lines of values 24·9 and 25 are drawn and transferred to a piece of tracing paper and a normal is drawn passing through their middle (inset, Fig. 3b). The separating thickness of the pair of lines is assumed to be practically same at all σ_t surfaces for an increment of 0·1 from their original values. The piece of tracing paper is overlaid on the *T-S* grid. The lower line of the pair of σ_t surfaces is made to coincide with a particular σ_t surface and is slided along the latter until its point of intersection with its normal coincides with the point of intersection of the *T-S* curve with its corresponding σ_t surface. The point where the upper line of the pair crosses the underlaid *T-S* curve is easily noticeable. Its distance from the normal is measured by means of a pair of dividers. This distance, L, divided by the distance of separation, h, of the pair of lines is a

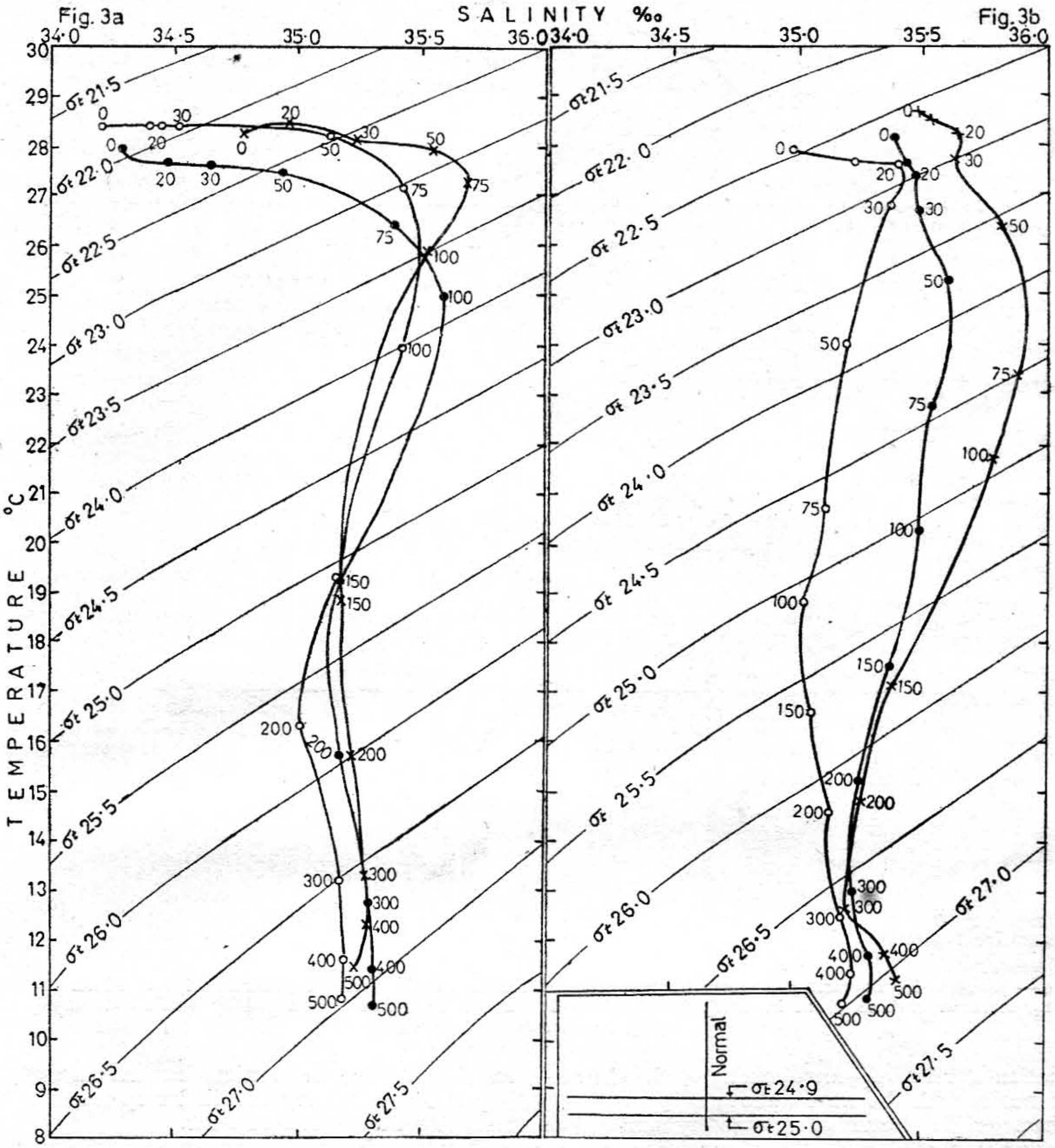

Fig. 3 — Mean T-S diagrams for winter (a) and summer (b) [×—× northern zone; ○—○ central zone; ●—● southern zone. Depth indicated in metres]

measure of inclination of the *T-S* curve with the corresponding σ_t surface. The more the inclination, the less would be the stability of the water at the corresponding σ_t surface. Using the above notation, relative stabilities of the waters during summer compared with winter are presented in Fig. 4a.

Zonal mean stability variation of the waters for individual seasons have been computed from the vertical gradients of density variations ($E = 10^{-3} \Delta\sigma_t/\Delta z$) based on the mean temperature and salinity variations with depth in the zone. The stability excess of summer over winter obtained from this analysis is presented in Fig. 4b.

Following observations may be made from the curves of stabilities presented in Fig. 4a and b. The general trend of the 2 sets of curves is the same, i.e. lesser stability in the lower layers and higher stability in the upper layers during summer as compared to winter. Stability increases within the thermocline (within the σ_t surfaces of values about 23 and 24) from winter to summer in the entire area.

Vertical thermal gradient of the summer in the thermocline region off the west coast of India is stronger than that of the winter[27]. It may be noted from Fig. 3a that the winter *T-S* curve of either the middle zone or the southern zone is more rounded off at the upper side of the thermocline than that of the northern zone. This feature of the middle and southern zones is an

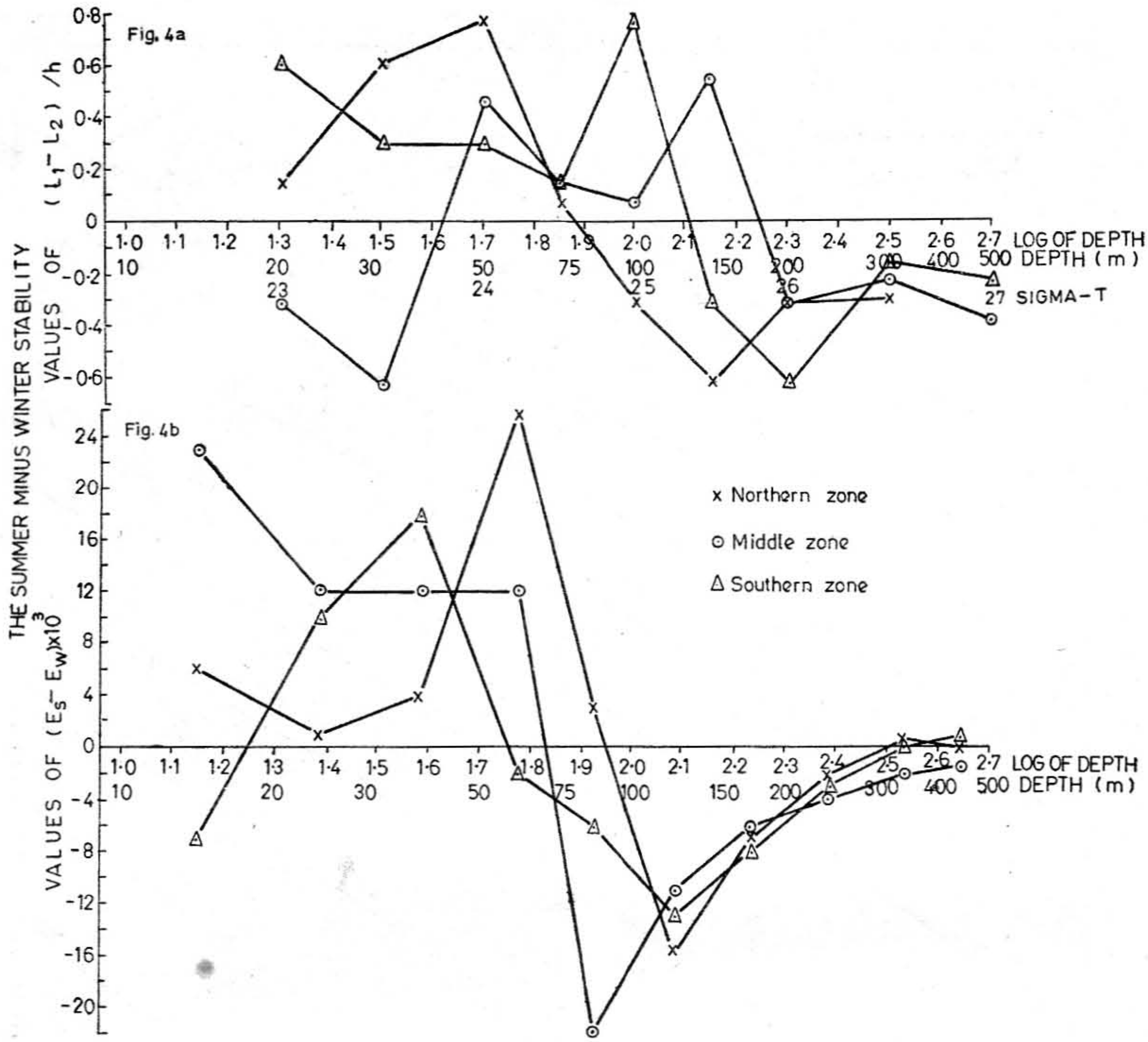

Fig. 4 — (a) Stability at various isopycnal layers at three different zones during summer relative to winter [L_1, winter and L_2, summer. L/h as given in text]. (b) Stability at various depths as determined by vertical density gradients during summer relative to winter

indication of relatively more mixing of the thermocline waters with the waters above.

Characteristic features of stability/mixing are remarkably related with the phenomenon of upwelling. As the relatively weak stability in the deeper waters is common to all zones, so also is upwelling. The upwelling is intensified in the region where mixing from the waters above the thermocline is more.

Suggested model for upwelling — The coastal upwelling is explained by a simple model[28,29] implying that the vertically upward currents are set in (the region where upwelling existed) as a result of the surface water (under favourable conditions of horizontal current system or wind) being driven off the coast by Ekman effect and thereby making deeper water to rush towards surface to compensate for the loss of hydrostatic pressure in the region in order to restore equilibrium in the waters. The model essentially retains the central idea of Hidaka[2] that the vertical upward currents generated at depths reduce to zero at (or near) the surface. In the absence of vertical current meter[30], the importance of theory lies in its speculative value regarding the vertical currents.

However, the analysis presented in the preceding section partially subscribes for the above idea, but suggests the following modified scheme:

Upwelling perhaps starts and prevails in deeper waters during the appropriate season of least stability (summer). The process would not extend far into the thermocline and the upward velocities should cease in the core of the thermocline which becomes more intensified (more stable) during the season of upwelling. Alternatively, the stability through the core of the thermocline would have been easily weakened in the presence of upward movements of water, if any. Chemical concentrations of the waters from the depths where upwelling ceases is exchanged with that of the top (or surface) layers by eddy diffusion[22]. The process of diffusion is rapid if mixing is more in the sub-surface waters (as in the middle or southern region of investigation) as the latter reduces the core of thermocline. The scheme explains qualitatively the manifestation at the surface waters of coldness and denseness, etc. of the deeper waters and hence paves the path for numerical[31] model of upwelling in the waters.

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