Upwelling Off the Southwest Coast of India

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Various factors responsible in inducing upwelling are discussed. A distinction is made between the process of upwelling and its effects on the environmental conditions. Upwelling off the southwest coast of India is discussed in relation to the time variation of density structure (σ_t), horizontal divergence of surface current vectors, wind stress components — parallel and perpendicular to the coast, thermal structure and sea level. Upwelling in this region commences in the deeper layers of about 90 m in March and the upwelled water reaches the surface by May. The process continues to occur vigorously till June. From then, with the increase in strength of southwest winds, intensity of upwelling reduces and finally ceases to be present by July/August when the onshore winds of the southwest monsoon have maximum strength. The reverse process, sinking, sets in by September. Vertical velocity, i.e. upwelling, calculated (i) from the vertical shift of the isopycnal with time and (ii) from the average horizontal divergence, is $1{\cdot}5\times10^{-3}$ and $1{\cdot}8\times10^{-3}$ cm sec^{-1} respectively.

VERTICAL motions are an integral part of the oceanic circulation. Of these, ascending motion known as upwelling is one of the several oceanic processes which are considered to have a significant effect on the distribution of pelagic fishes. Upwelling not only affects the environmental condition in which the fishes live, but also increases the nutrient content in the euphotic zone, thereby increasing the productivity of the region. Upwelling off the west coast of India and its influence on the fishery is evident from various earlier reports[1-6]. However, some controversy exists regarding the actual period of upwelling and its duration. This is mainly because, the term upwelling is commonly used to describe a wide variety of conditions involving upward transport of water in the sea and often is misused in describing the effect of the process rather than the process itself.

Various explicit and implicit definitions have been published. Smith[7,8] surveyed the literature on upwelling and suggested the following definition the most acceptable, "An ascending motion, of some minimum duration and extent, by which water from subsurface layers is brought into the surface layer and is removed from the area of upwelling by horizontal flow". This use of the term upwelling follows Sverdrup[9] and Wyrtki[10]. In this paper, apart from hydrographic conditions that show the sequence of water movements in a time series, various factors responsible for such a vertical circulation and also the effects of other processes that may lead to misinterpretation of the observations, are discussed.

Upwelling

Upwelling occurs along some of the coasts where surface water under the influence of the prevailing winds is directed away from the coast. According to Hidaka[11], the most intense upwelling occurs when the wind makes an angle of 21·5° with the coast line in an offshore direction. Upwelling also occurs in the regions of diverging currents[12].

In all cases, upwelling takes place under unstable conditions, being dependent on the strength, direction and consistency of the wind or current which ever is the causative factor. A current induced upwelling exists till the geostrophic balance is established. In practice, however, true geostrophic balance is never realized, because molecular and eddy viscosity lead to cross-isobar flow with an upwelling component. Ingham[13] distinguished between the 2 processes of the wind driven and current induced upwellings, and concludes: "In fact a cross-isobar flow exists in geostrophic balance, but that flow would be considerably weaker than the one involved in wind-driven upwelling".

Upwelling, and the accompanying horizontal advection, will markedly alter the distribution of physical and chemical properties of waters involved. The index of coastal upwelling is the presence of cooler, more saline and denser water containing less dissolved oxygen and more phosphates than usually found at a given depth. The vertical sections of temperature in an upwelling region show the upward tilt of thermocline and isotherms towards the coast. The salinity criterion, specified above, becomes ambiguous if the water is transported from a depth greater than that of the salinity maximum. According to Smith[8] the usual effect of vertical circulation is to reduce the surface salinity. Thus, the increase of salinity as an indicator of upwelling is subject to the presence of salinity maximum within the upwelled depth. Concentrations of oxygen and phosphate cannot be reliable indices of upwelling because their concentrations are liable to rapid modifications by biochemical processes. Tempera-

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ture can be used to help to resolve such cases because its vertical distribution is essentially monotonic. Even in this case, it is to be noted that the temperature in the surface layers is largely controlled by other localized factors such as insolation, presence of clouds and evaporation. The stratification of the water is governed by the density and so the isolines in the vertical section indicate the movement of water along the isopycnals. Hence, the vertical distribution of σ_t can be a better indicator of upwelling than the rest of the variables.

Upwelling can be expected to have an effect on sea level through steric variation; i.e. the change in the height of sea surface arising from isostatic adjustments due to changes in specific volume of the water column[14]. Upwelling, by replacing warm and less dense water, increases the mean density of the water column, and in adjusting isostatically the mean sea surface is lowered.

In addition to such indications of upwelling as more or less localized surface features as described above, increase in density at a constant depth within the layer of upwelling from month to month can be a better index of upwelling. One can make a crude estimate of the vertical speed from the upward shift of a particular isopycnal, representing the density of the upwelled water, with time.

Description of Study Area

The west coast of peninsular India forms a narrow belt of low land lying between the sea and the Western Ghats which extend throughout the whole length of the peninsula varying in width from 30 to 169 km inland and running in a direction north-northwest and south-southeast. There are a number of short rivers, many of which drain into the back-waters of varying breadth parallel to the coast.

The outstanding feature of the wind system in the Indian seas is a seasonal reversal of the direction associated with the 2 monsoons. During winter (December to February) the northeast winds of the land origin prevail. The spring transition begins by about March and lasts through April. By the middle of May the southwest monsoon winds of the oceanic origin are established. The winds continue to increase gradually until June when there is a 'burst' or sudden strengthening of the southwest winds. During July and August, the winds blow at their greatest strength and in September, the wind force decreases in preparation for the fall transition which lasts through October and November. In the Arabian Sea, of the 2 monsoons, the southwest monsoon endures over a longer period of the year and is stronger and steadier than the northeast one. The onset of the southwest monsoon is associated with overcast skies, showers and strong winds, as a result of which the solar insolation is cut off to a large extent. The total incident solar radiation off the southwest coast of India increases from 425 ly day^{-1} in January to 550 ly day^{-1} in April and reduces to a minimum of $<$ 400 ly day^{-1} in July[15]. In this region, the orographic precipitation on the Western Ghats is more pronounced. Despite the humid conditions, evaporation in the Arabian Sea is the maximum during the southwest monsoon unlike the usual intense evaporation in winter[16,17].

During the southwest monsoon, the coastal, current in the Arabian Sea sets in clockwise direction owing to the coastal configuration, and in a counter clockwise direction from November to January during the height of northeast monsoon. From February to April, when the northeast monsoon is weakening, the circulation off the west coast of India has a special character differing from the other transition period. The peculiarity of the current, during the spring transition, is that the current reversal precedes the wind reversal. The counter-clockwise circulation of the fall transition is in phase with the wind reversal, and is less well defined and weaker than the clockwise circulation of the spring transition.

Methods

To illustrate the vertical distribution of density off the west coast of India, profiles of σ_t have been drawn for 7 months, beginning with March using the hydrographic data collected on board *RV Varuna* in 1964. In order to emphasize the principal features of time variation, zonal sections along 10° 40'N have been presented for all the months other than for March and August for which months the sections are along 8°50'N and 10°00'N respectively due to non-availability of data along 10°40'N.

Current data from Dutch Atlas[18] have been used to evaluate the horizontal divergence. Horizontal divergence is given by

$$\nabla_H \cdot \boldsymbol{V} = \frac{\delta u}{\delta x} + \frac{\delta v}{\delta y} - \frac{v \tan \phi}{R} \quad \ldots(1)$$

using finite differences in the place of partial differentials

$$\nabla_H \cdot \boldsymbol{V} \approx \frac{\Delta u}{\Delta x} + \frac{\Delta v}{\Delta y} - \frac{v \tan \phi}{R} \quad \ldots(2)$$

where x and y are directed towards the east and north respectively, and u and v are the components of the current vector along east and north respectively, ϕ is the latitude of the place and R, the radius of the earth[19]. The term $v \tan \phi/R$ in equation (2) represents a contribution to divergence due to convergence of meridians, and this term will be of importance only at higher latitudes and greater meridional components. For the area under investigation, this term can be neglected. Hence, using the formula

$$\nabla_H \cdot \boldsymbol{V} \approx \frac{\Delta u}{\Delta x} + \frac{\Delta v}{\Delta y} \quad \ldots(3)$$

the horizontal divergence of the surface current vectors has been computed for alternate months from March to September.

Seasonal distribution of the windstress components, normal and parallel to the average trend of the coastline, covering the area 8°N-12°N and 72°E-76°E, is shown in Fig. 9. The wind data are from Dutch Atlas[18]. The method of converting these winds to stresses though differs somewhat from that used by Hidaka[20] is the same as that followed by Swallow[21].

Air temperature is an average of the mean temperature of air at 0830 and 1730 hrs for the period 1931-1960 at Calicut. These data are from the climatological tables of observatories in India (1931-1960) published by the India Meteorological Department.

Results

Vertical Distribution of Density

Vertical distribution of density (σ_t), for different months, is presented in Figs. 1 to 7. The density structure in March (Fig. 1) shows that the isopycnals near the coast in the upper 100 m tilt upwards while they are inclined down in the lower layers. Such a density distribution suggests, the water in the upper layers flows south, below which the flow is northerly. Although, this feature is not conspicuous along 10° 40'N in April (Fig. 2), probably because upwelling sets in earlier in the south and gradually extends to the north[5,6], it is prominent in May and June (Figs. 3 and 4). According to Yoshida and Tsuchiya[22], this is a condition associated with upwelling along any coast.

The isopycnal 22·5 g/litre in March runs at a greater depth away from the shelf and tilts upward approaching the shelf indicating an upward motion of subsurface water (Fig. 1). Upwelling along the bottom continues and the upwelled water gradually comes towards the coast reaching the surface by May. The ascending motion continues to be vigorous till June and also the zone of upwelling extends offshore. Upwelled water reaching the surface in May is apparent from the isopycnal 22 g/litre (Fig. 3), and its offshore extension. Still deeper waters appear in the surface in June as revealed by the isopycnal 23 g/litre in the surface layers (Fig. 4). The depth of this isopycnal, in March, is about 90 m. If we assume that upwelling starts at this depth in March, it can be inferred that the waters from a depth of only 90 m rise to the surface, although, there may be overturning of deeper waters into the upper layers.

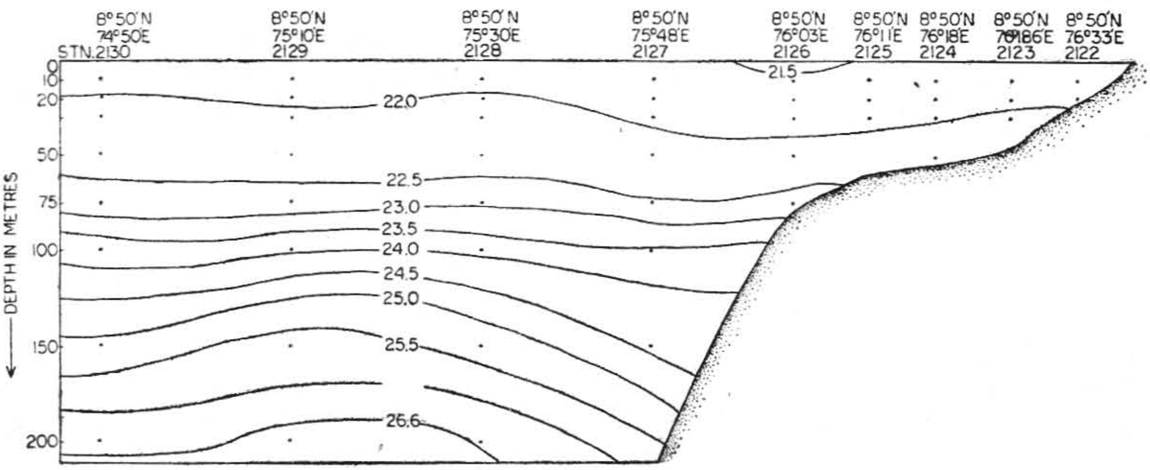

Fig. 1 — Vertical distribution of density (σ_t) along 8°50'N, March 7, 1964

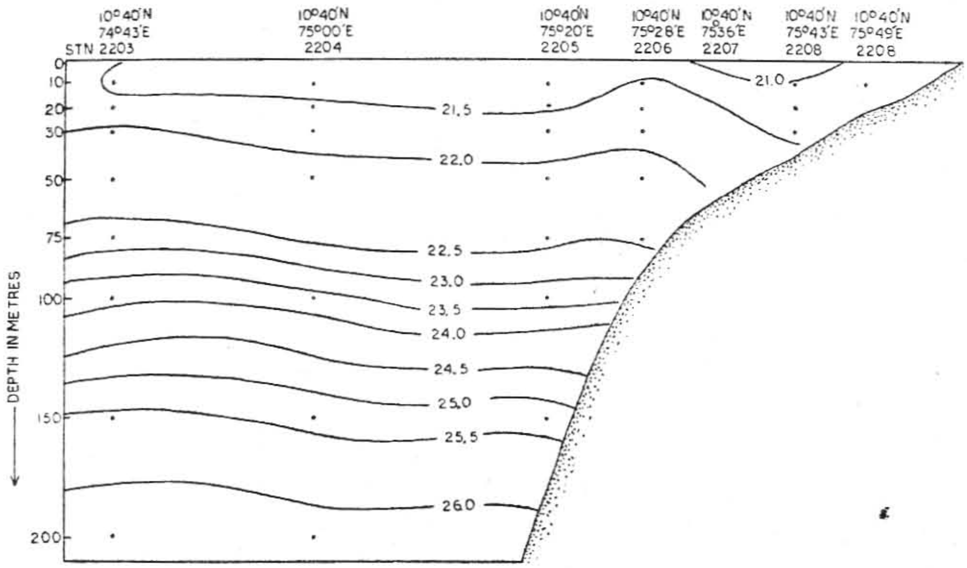

Fig. 2 — Vertical distribution of density (σ_t) along 10°40'N, April 9, 1964

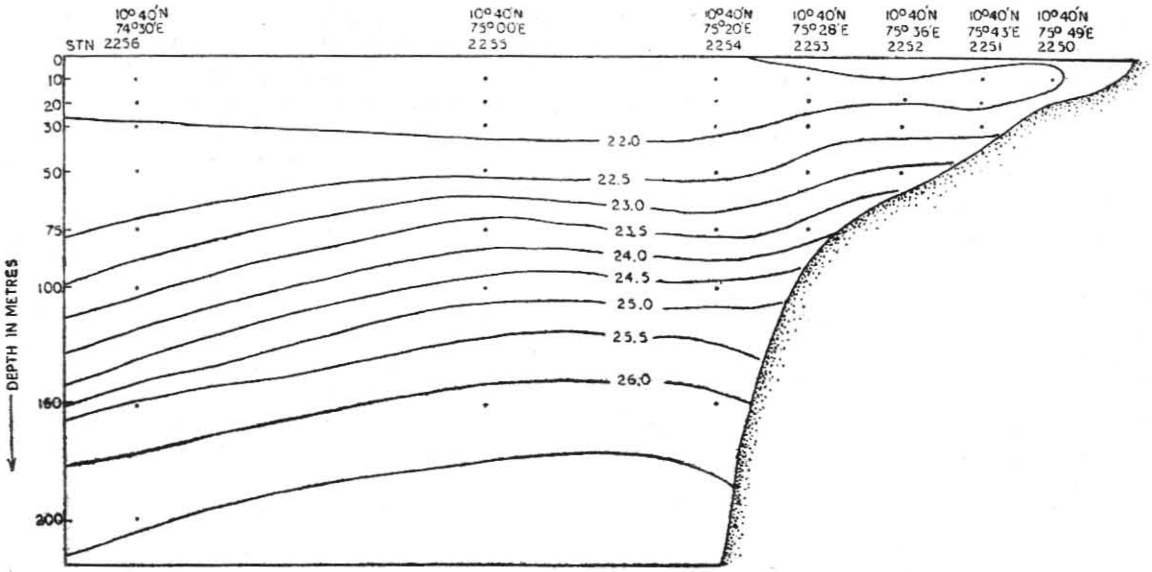

Fig. 3 — Vertical distribution of density (σ_t) along 10°40'N, May 3-4, 1964

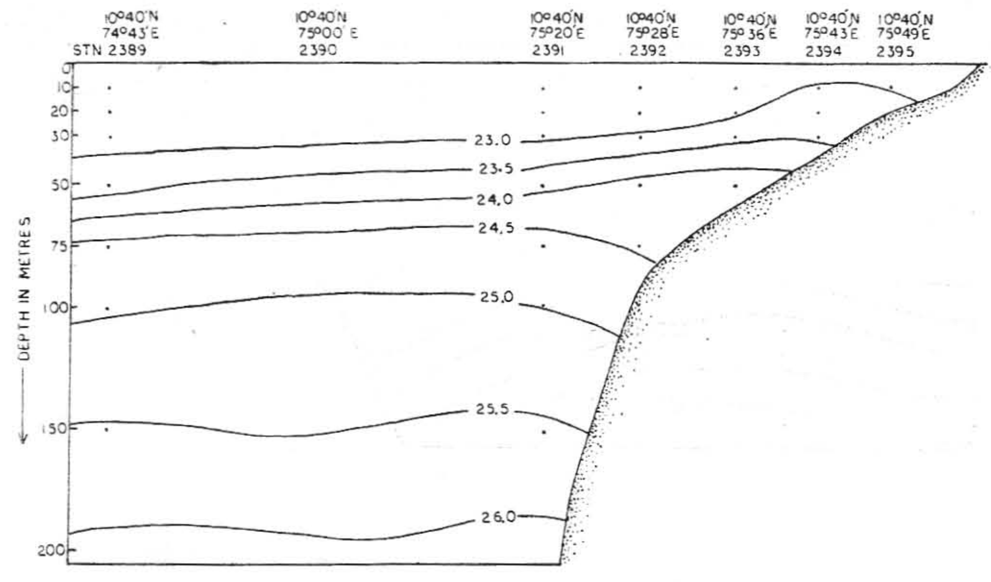

Fig. 4 — Vertical distribution of density (σ_t) along 10°40'N, June 11, 1964

By July, the isopycnal 23 g/litre is pushed down to a lower depth by incursion of rain and land drainage, resulting in steep vertical and horizontal gradients of density close to the coast. The isopycnals are maintained almost in the same position during July and August revealing a condition of mass readjustment and cessation of upwelling. Such a condition may, perhaps, be partly due to the pilling up of water transported by the strong onshore monsoon winds, apart from the land runoff.

The instability, shown in May (Fig. 3), in the upper 10 m may not be a permanent feature but only a transitory phase developed, giving rise to a favourable condition for upwelling to take place vigorously. This is a clear evidence of the incursion of upwelled water into the surface layers and also the offshore transport of coastal water. In fact, the effect of upwelling in the upper layers might have been masked to a certain extent in May because these layers are subjected to heating by the intense insolation in April and early May by which the cold upwelled water can not be well delineated. In contrast, after the onset of the southwest monsoon the effect of upwelling is virtually exaggerated due to the overcast skies and evaporation.

Among the other effects of upwelling, associated with the density structure, the inclination of the pycnocline towards the coast, the decrease in its depth with time, the onshore-offshore gradient of density at a constant depth and the weak vertical gradients of density in the pycnocline may be mentioned. The depth of pycnocline is 80 m in

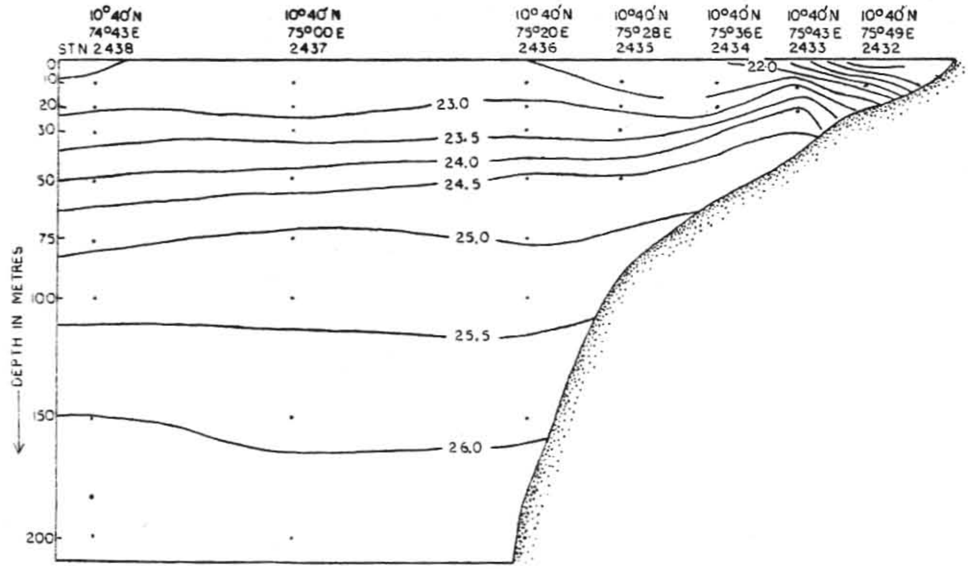

Fig. 5 — Vertical distribution of density (σ_t) along 10°40'N, July 13-14, 1964

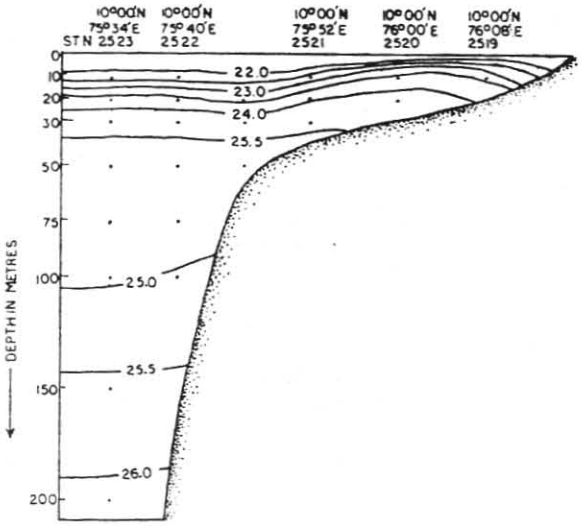

Fig. 6 — Vertical distribution of density (σ_t) along 10°N, August 13, 1964

March while it is <10 m in June. As the pycnocline tilts up towards the coast from March to June, the vertical density gradient decreases (Figs. 1 to 4). In July, there is no decrease in the vertical density gradient, and on the other hand, because of the influx of run off from land, a slight increase is noticed. The conditions in August and September reveal absolutely the absence of upward motion. In Figs. 1 to 7, depicting the distribution of density, the onshore-offshore gradient is observed at any depth, although, it is weak in the initial stages of upwelling. But its sign is changed in July, particularly, in the surface layers, indicating the stratification of waters to act as a barrier for further incursion of upwelled water into the surface layers.

The density, at a given depth, increases when upwelling starts at that depth and the increase in density either stops or changes sign when upwelling ceases to continue at that depth. The increase in density begins from March at a depth of about 100 m (see Fig. 8 of Sharma[6]). As the upwelling gradually ceases by August, a sharp decrease in density is noticed at all depths.

Summing up the results on vertical density structure, it can be inferred that the process of upwelling off the west coast of India in the deeper layer of about 90 m sets in by March and the upwelled water reaches the surface by May. The cessation of upwelling takes place in August and the reverse process of sinking begins by September.

An approximate value of the speed of upwelling current can be deduced from the movement of the isopycnal 23 g/litre from April to June. This isopycnal moves from a depth of 90 m on April 9, 1964 to about 10 m depth on June 11, 1964. In 2 months, the vertical movement is 80 m, giving rise to an average intensity of upwelling of 40 m/month (1.5×10^{-3} cm sec^{-1}). This value is of the same order of magnitude of upwelling in the Northwest Guinea[13]. But it is almost half of the value found off California[23].

Divergence of the Surface Current Vectors

One of the causative factors to induce upwelling is the horizontal divergence. While interpreting the divergence, calculated from the surface current charts giving the mean current vector as roses for each 2 degree latitude-longitude quadrangle, for upwelling, it is to be borne in mind that this distribution does not represent a synoptic picture, but an average over a few hundred square kilometres and the values cannot be quite representative very near the coast. Hence, no comprehensive estimate of the importance of the seasonal restrictions will be made here; however, a few qualitative remarks are in order.

The general character of the horizontal divergence distribution at the surface in the area off the west coast of India is presented for the months of March,

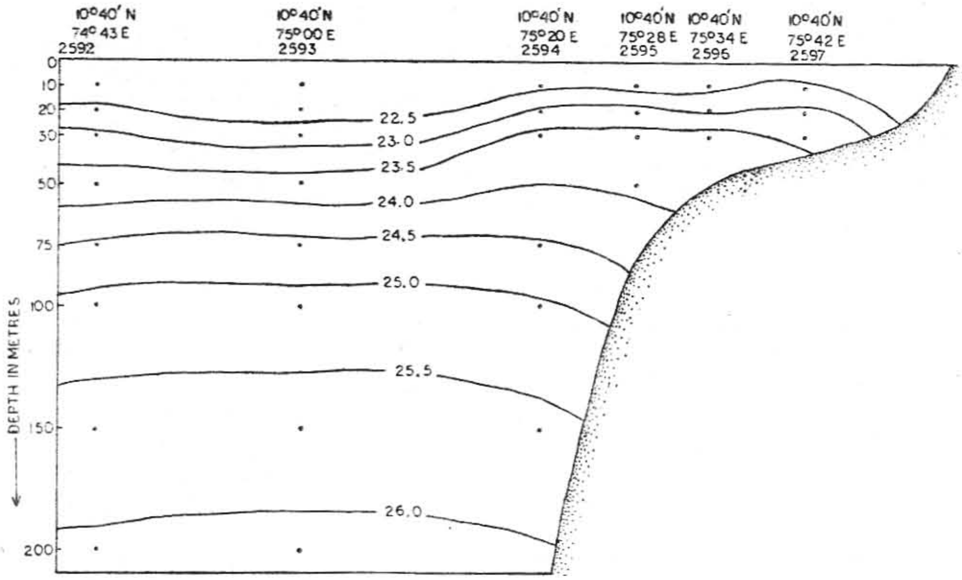

Fig. 7 — Vertical distribution of density (σ_t) along 10°40′N, September 13, 1964

May, July and September in Fig. 8, using the current data from KNMI Atlas[18]. In March, the divergence prevails in the southern region and convergence in the north. By May, the whole area is under the influence of divergence and its intensity also increased. The divergence in the southern region is replaced by convergence in July and the convergence zone spreads gradually to the north. By September, convergence predominates the whole area under investigation. It is apparent from the divergence distribution that upwelling sets earlier in the south by March and gradually extends to the north. The cessation of upwelling also takes place earlier in the south. The predominance of convergence in September confirms the presence of sinking off the west coast of India.

The magnitude of divergence in this region varies from 5×10^{-8} to 10^{-6} sec^{-1}. Considering a homogeneous layer of 90 m thickness from which depth the water upwelled reaches the surface, we can take the mean magnitude of the horizontal divergence to be 2×10^{-7} sec^{-1}. The vertical component of the current vector can be obtained by integrating the equation of continuity for a homogeneous water with respect to z from the surface to the depth, $z = h$.

$$w = -\int_o^h \left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}\right) dz = -\int_o^h \text{div } V_o \, dz \qquad \ldots(4)$$

where z is taken positive vertically downward and V_o denotes the current vector at the surface. When we know the average value of divergence, within a top layer of thickness h, div V, we can obtain the mean vertical velocity w_h between the levels $z = h$ and $z = o$, putting $w_o = o$ as the vertical velocity at the surface, from

$$w_h = -h \text{ div } V \qquad \ldots(5)$$

For the mean divergence of 2×10^{-7} sec^{-1} and thickness of 90 m, $w_h = 2\times10^{-7}\times9\times10^{3} = 1{\cdot}8\times10^{-3}$ cm sec^{-1}.

This value of vertical velocity agrees well with the intensity of upwelling evaluated from the uplift of isopycnals.

Windstress

The resolved windstress components normal and parallel to the average direction of the coastline are presented in Fig. 9. Note that strong components of windstress of the order of 1 dyne cm^{-2} and above prevail off the west coast of India only during the southwest monsoon and their strength is obviously very weak in the northeast monsoon indicating that the windstress components during the northeast monsoon may not play any major role in inducing the vertical circulation except to supplement when the current vector is favourable. Contrary to such a condition, during the southwest monsoon the windstress components, being very strong, control the vertical motions in this region.

As discussed earlier while the equatorward and offshore components of the windstress are favourable to induce upwelling, the poleward and onshore components act against upwelling. The equatorward component parallel to the coast is almost nonexistent except in November and December when the magnitude of the windstress component in this direction is so insignificant to produce any effect on the vertical circulation. The offshore component is present from October to May. It is, thus, obvious that the winds are favourable for upwelling only during the northeast monsoon period. But their strength is trivial to have any consequence on the vertical motion except when the current also supports the motion in the same direction. During the latter part of the northeast monsoon, the windstress off the southwest coast of India is weak. The coastal region also gets heated up during February-May due to intensive insolation. These factors, probably, are responsible for producing a gradient current that flows in a southerly direction

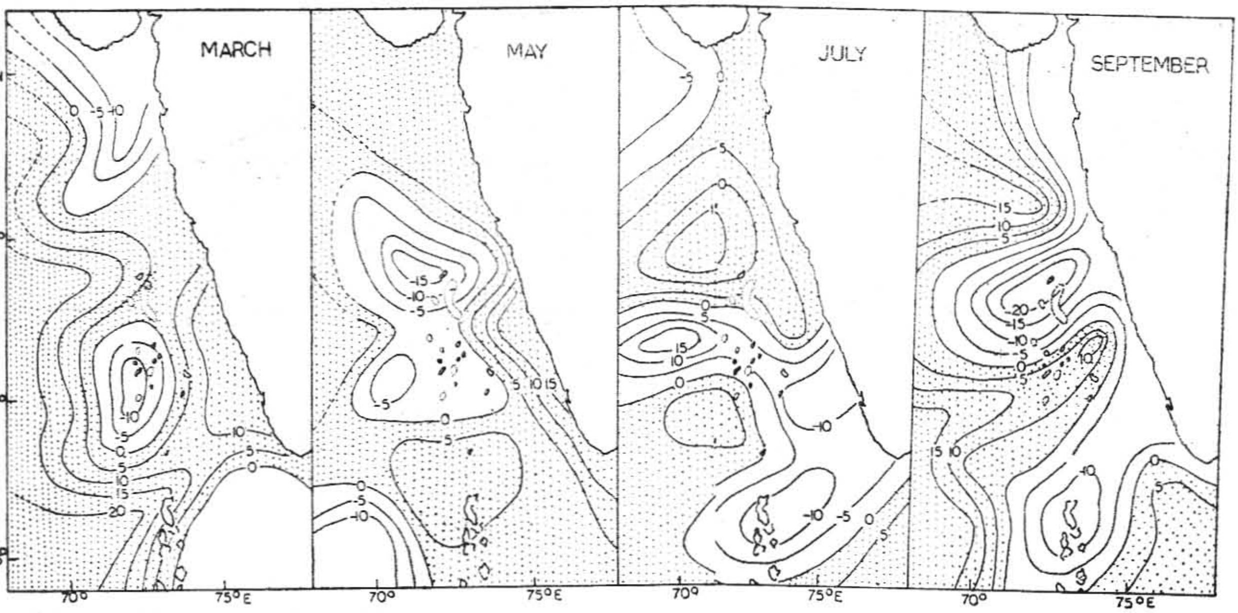

Fig. 8 — Horizontal divergence of surface current vectors [1 unit = 5×10^{-8} sec^{-1}). Shaded areas show divergence zones and unshaded areas convergence zones]

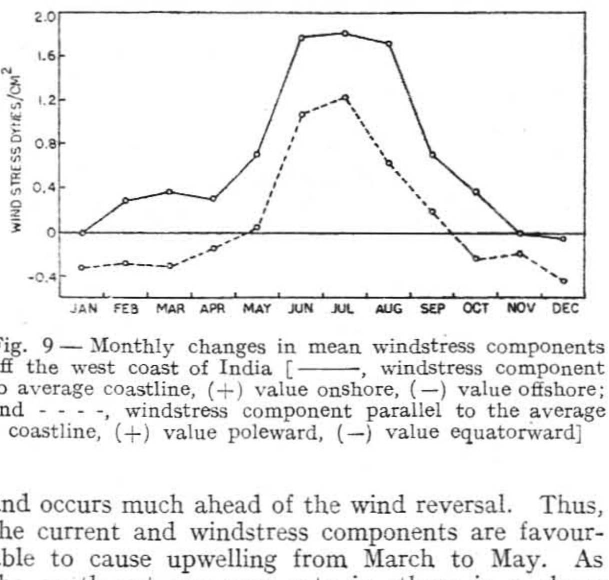

Fig. 9 — Monthly changes in mean windstress components off the west coast of India [———, windstress component to average coastline, (+) value onshore, (—) value offshore; and - - - -, windstress component parallel to the average coastline, (+) value poleward, (—) value equatorward]

and occurs much ahead of the wind reversal. Thus, the current and windstress components are favourable to cause upwelling from March to May. As the southwest monsoon sets in, there is a sharp increase in the magnitude of both the components of windstress; neither of them being favourable for upwelling. On the other hand, they check any further upward movement, existing earlier, from subsurface layers. Nevertheless, upwelling continues to take place till the geostrophic balance of the current is established, as the current is favourable for upwelling. From the density structure, it could be inferred that the geostrophic balance is installed by August.

Thermal Structure

Some of the evidences of upwelling can be had from the thermal structure. The 20°C isotherm is usually situated in the middle of the strong upper thermocline in the tropical and most subtropical regions except in its southern parts where it reaches the sea surface. Since, this upper thermocline separates the warm surface water from the cooler water of the main oceanic thermocline, the structure approaches a 2-layer system, and consequently the topography of the 20°C isotherm has a strong relation to circulation[24]. Hence, the topography of the 20°C isotherm can in turn be related to the vertical circulation of the waters. Another feature in the thermal structure that is related to the vertical circulation is the depth of the mixed layer. Its depth, in the absence of intense heating and cooling, and wind stirring, is reduced with upwelling and increased with sinking.

Bimonthly maps of the depth of the mixed layer and the 20°C isotherm have been presented in the Oceanographic Atlas of the International Indian Ocean Expedition[24]. Since the maps are only bimonthly the general time variation of the vertical circulation can only be studied using these maps.

The depth of the mixed layer in the area of the present study changes from >60 m in January-February to <60 m by March-April. By May-June the mixed layer still moves to upper layers and the least depth of <20 m is observed in July-August. From then, it starts deepening to a depth of about 40 m by September-October. The depth of 20°C isotherm off the west coast of India lies around 140 m during January to April. Its depth reduces to 120 m in May-June and to <80 m by July-August. In September-October the topography of the 20°C isotherm tilts down to deeper layers. From the variation in the depth of mixed layer and 20°C isotherm with time, it is apparent that the upward movement of the waters off the west coast of India must have commenced by March-April as evidenced from the decrease in depth of the mixed layer from January-February to March-April, and sinking should have started by September.

Sea Level Variation off Cochin

Seasonal change in the sea level off Cochin is given in Fig. 10 (ref. 2). The effect of upwelling on the sea level is that it is lowered with upwelling. In order to infer upwelling from the sea level variation, one should consider the increase or decrease in sea level instead of the maximum or minimum values. The sea level off Cochin starts decreasing by about January-February till May. But the rate of decrease up to March is not so significant and a sharp decrease is noticed from March to May when upwelling starts at deeper level and reaches the surface. In fact, during this period, but for upwelling there should have been an increase in sea level because of solar heating. From May, no significant change in sea level is visualized till September other than a slight increase followed by a decrease, owing to rain, land drainage and overcast skies. One of the minima occurring in May coincides with the time of upwelled water reaching the surface. The steep increase in sea level in September corresponds to the onset of sinking.

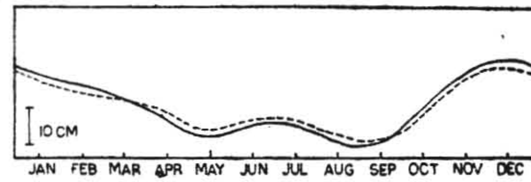

Fig. 10 — Mean sea level at Cochin [- - - -, actual observations and ———, former corrected for the effect of air pressure. From Banse, 1968]

Table 1 — Average Air Temperature at Calicut for the Period 1931-1960

	Temperature (°C)		Temperature (°C)
Jan.	27·4	July	25·9
Feb.	28·1	Aug.	26·2
March	29·5	Sept.	26·8
April	30·2	Oct.	27·4
May	29·6	Nov.	27·8
June	26·8	Dec.	27·4

Discussion

Many authors have dealt with upwelling along the west coast of India[1-6]. Among them Banse[2] and Sharma[5,6] considered the time variation of the properties and the latter stressed its importance in order to gain a complete understanding of this process. Furthermore, none of the earlier studies discussed qualitatively the various factors responsible for producing upwelling.

The surface temperature off the west coast of India is the lowest during July-August mainly due to the prevailing weather conditions, but not merely due to the after effect of upwelling. This is well demonstrated in the mean monthly air temperature at Calicut (Table 1), where the temperature recorded in July is much less than that of any of the winter months. It is evident that the lowest temperature in July is the result of decrease in solar insolation because of the overcast skies during the active southwest monsoon[15]. Besides, the intense evaporation, taking place during this period[16,17], lowers the sea surface temperature. Therefore, it would be improper to infer upwelling based on the sea surface temperature alone. However, Banse[2] observed the water colder than 27°C below 5 m in Cochin Harbour in May 1962 and inferred that the upwelling of 1962 must have already begun at that time. Based on similar observations of decrease in temperature in the surface layers from 30-31°C in April-May to 25-26°C towards the end of June 1958 and the first week of July 1959 in the harbour of Karwar, Banse[2] pointed out that in some years upwelling begins much earlier to May-June, unlike the earlier concept that it starts only in June-July.

Ramamirtham and Jayaraman[4] discussed the hydrographical features of the continental shelf waters off Cochin during 1958 and 1959 and concluded that upwelling occurs in this region during August-October. For this study, they used the temperature, salinity and oxygen data at 27 stations occupied in August, September, November, December and April. Of these, 2 stations occupied in August and 5 stations in September were confined to 20 and 50 m respectively. It is thus, evident that this conclusion is based on inadequate data for the period of upwelling referred to. On the contrary, Fig. 4 of the same authors, showing the distribution of temperature off Cochin on 1-2 April 1959, exhibits the upward slope of the isotherms towards the coast, prominently in the depth range of 20-100 m, indicating the movement of the subsurface water along the shelf.

Patil *et al.*[25] and Ramamirtham and Patil[26] studied the hydrography off the west coast of India during the premonsoon period of 1962. Distributions presented by these authors for the month of May[25] (Figs. 2 to 6 and 8) and for the months of February to May[26] (Figs. 2, 3, 5, 16 and 17) clearly demonstrate the upslope of the isotherms and isopycnals along the continental shelf towards the surface. Though this has not been associated with upwelling by these authors, the data given by them clearly indicate the presence of upwelling at different depths.

The maximum effect of upwelling, in the surface layers, can be observed only when the deepest possible water enters the surface layers and also after a prolonged period of its presence. The vertical velocity of the current off the west coast of India, being about 40 m/month, it takes about 2-3 months for the deepest water to reach the surface in order to produce the effect of vertical circulation in the surface layers. It is obvious from the present observation that the effects of upwelling are noticed in the surface water in May. Hence, it is reasonable to infer that upwelling should have commenced at about 100 m in March, particularly in the southernmost region and gradually extended to the north. But some of the earlier authors[1,3,4] attributed the upwelling to be present only when the lowest surface temperature and oxygen content are recorded.

Banse[1,2], Ramamirtham and Jayaraman[4] gave undue importance to the oxygen content as an indicator of upwelling. But it cannot be taken as an index of the vertical circulation because the oxygen content is controlled to some extent by the stagnation of water. The stratification of the coastal waters during July and August in the depth range of 10 to 30 m results in the depletion of oxygen content below the depth of stratification. Biochemical activities, such as photosynthesis and organic production also influence the oxity of the waters. But during the active southwest monsoon period overcast sky, turbidity of the surface layers caused by the phytoplankton production, wave stirring and the land drainage due to orographic precipitation, reduce the availability of light essential for photosynthesis. The increase in oxygen content due to photosynthesis is confined only to the upper layers of the compensation depth at which the oxygen production due to photosynthesis and the utilization due to respiration balance[20]. This depth varies with the season of the year, the time of the day, the cloudiness and the character of water. It lies between 27 and 44 m for a day observation[12]. During the southwest monsoon this depth is expected to be only 10 to 20 m. In addition to this, the increased utilization of oxygen by the decaying organic matter and the formation of mud banks which frequently occur in this region during this period bring in the oxygen depletion of water. Generally, the oxygen is too low in the central and the eastern Arabian Sea[27]. These points lend support to the view that the low oxygen content below the depth of stratification is not due to vertical circulation, but possibly caused by the factors mentioned above.

Absence of wind induced upwelling during the southwest monsoon when the winds are onshore has been indicated[6,28,29]. Some of the earlier workers fail to recognise the effect of such winds on the vertical circulation. They are misled by the northerly winds which prevail on the land between the Western Ghats and the coast because of the location of the Western Ghats. The circulation off the coast is not controlled by these northerly winds but by the southerly winds of the oceanic origin. Besides, the land and sea breezes affect the wind observations on the land, particularly, post monsoon period. Any interpretation on vertical circulation based on such data should be given with caution. Perhaps, the above confusion prompted Subrahmanyam[30] to conclude that during the dry hot months, there is double diurnal upwelling of water from some depth below towards or actually on to the surface. It may be noted that such an interpretation is not in accordance with the definition of upwelling.

As the process of upwelling is closely related with the biological factors, it would be appropriate to examine this aspect from the biological point of view. Upwelling acts as a first link of the food chain and enriches the euphotic zone leading to a bloom of phytoplankters. This will not happen all of a sudden, as the algae in the water have to grow and multiply, and usually the bloom occurs after lapse of some time. Off the west coast of India the phytoplankton bloom occurs in July/August[30]. This would indicate the commencement of upwelling much earlier than the onset of the southwest monsoon. From September onwards the phytoplankton bloom wanes and this would indicate the cessation of upwelling by that time. Based on a similar argument Subrahmanyam[31] concluded that upwelling must have been taking place off the west coast of India during February to July/August and sinking from September to January.

From the foregoing discussion, it can be concluded that upwelling commences at deeper layers off the west coast of India in March and the upwelled water reaches the surface by May. The intensity of upwelling reduces with strengthening of the southwest monsoon. Upwelling in this area ceases to be present after August. The process of sinking sets in by September. The magnitude of the vertical velocity of the current is of the order $1{\cdot}5 \times 10^{-3}$ cm sec^{-1}. The ascending motion of the subsurface water starts earlier in the south, and gradually extends to the north. Similarly, sinking also begins earlier in the south. The low oxity during the southwest monsoon is not due to vertical circulation but due to some other factors, such as decomposition of organic matter, increased respiration by phytoplankton blooms and lack of sufficient photosynthesis because of the poor transparency. Furthermore, the stratification in the upper layers due to the river run-off and rainfall is also partly responsible for the low oxity.

References

1. Banse, K., *J. mar. Biol. Ass. India*, **1** (1959), 33.
2. Banse, K., *Deep-Sea Res.*, **15** (1968), 45.
3. Rama Sastry, A. A. & Myrland, P., *Indian J. Fish.*, **6** (1960), 223.
4. Ramamirtham, C. P. & Jayaraman, R., *J. mar. Biol. Ass. India*, **2** (1960), 199.
5. Sharma, G. S., *J. mar. Biol. Ass. India*, **8** (1966), 8.
6. Sharma, G. S., *Proc. Symp. Indian Ocean Bull. NISI*, **38** (Pt. 1) (1968), 263.
7. Smith, R. L., *An investigation of upwelling along the Oregon Coast*, Ph.D. thesis, Oregon State University, Corvallis, 1964.
8. Smith, R. L., *Oceanogr. mar. Biol. Ann. Rev.*, **4** (1968), 33.
9. Sverdrup, H. U., *J. mar. Res.*, **1** (1938), 155.
10. Wyrtki, K., *Bull. Scripps Instn Oceanogr.*, **8** (1963), 313.
11. Hidaka, K., *Trans. Am. geophys. Un.*, **35** (1954), 431.
12. Sverdrup, H. U., Johnson, M. W. & Fleming, R. H., *The oceans: Their physics, chemistry and general biology* (Prentice-Hall Inc., New Jersey), 1942, 1087.
13. Ingham, M. C., *Bull. mar. Sci.*, **20** (1970), 1.
14. Pattullo, J. G., Munk, W., Revelle, R. & Strong, E., *J. mar. Res.*, **14** (1955), 88.
15. Portman, D. J. & Ryznar, E., *An investigation of heat exchange* (Eastwest Center Press, Honolulu), 1971, 78.
16. Venkiteswaran, S. V., *Indian J. Met. Geophys.*, **7** (1956), 265.
17. Jagannathan, P. & Ramasastry, A. A., *J. Geophys. Res.*, **69** (1964), 215.
18. Koninklijk Nederlands Meteorologisch Instituut, *Indische Oceaan: Oceanographische en Meteorologische Gegevens*, 1952, 2nd ed., Publ. No. 135, Vol. 1, text 31 pp., Vol. 2, 24 Charts.
19. Sherman, L., *Q. J. roy. Soc.*, **78** (1952), 633.
20. Hidaka, K., *Rec. Oceanogr. Wks. Japan, New Ser.*, **4** (1958), 77.
21. Swallow, J. C., *Stud. trop. Oceanogr. Miami*, **5** (1967), 15.

22. YOSHIDA, K. & TSUCHIYA, M., *Rec. Oceanogr. Wks. Japan*, **4** (1957), 14.
23. YOSHIDA, K., *Rec. Oceanogr. Wks. Japan*, **2** (1955), 8.
24. WYRTKI, K., *Oceanographic Atlas of the International Indian Ocean Expedition* (Nat. Sci. Found. Washington DC), 1971, 531.
25. PATIL, M. R., RAMAMIRTHAM, C. P., UDAYA VARMA, P. & ARAVINDAKSHAN NAIR, C. P., *J. mar. Biol. Ass. India*, **6** (1964), 151.
26. RAMAMIRTHAM, C. P. & PATIL, N. R., *J. mar. Biol. Ass. India*, **7** (1965), 150.
27. SHARMA, G. S., *J. mar. Res.*, **30** (1972), 102.
28. DARBYSHIRE, M., *Deep-Sea Res.*, **14** (1967), 295.
29. WOOSTER, W. S., SCHAEFER, M. S. & ROBINSON, M. K., *Atlas of the Arabian Sea for Fishery Oceanography*, (Inst. Marine Resources, Univ. Calif.), **67-12**, 1967, 1-35 plates.
30. SUBRAHMANYAM, R., *Proc. Indian Acad. Sci.*, **50B** (1959), 189.
31. SUBRAHMANYAM, R., *Proc. symp. living resources of the seas around India*, Spl Publ., CMFRI, Cochin, 1973, 199.