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ON UPWELLING AND BOTTOM-TRAWLING OFF THE SOUTHWEST COAST OF INDIA

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Introduction

While starting an investigation on basic production off Cochin at the southwest coast of India, a section across the shelf with serial observations on temperature, salinity, and oxygen content was run in the last week of August 1958. The bottom water was observed to be very badly aerated, and from the hydrographic data it was inferred that these conditions were connected with upwelling. Berner and Schemainda (1957) have shown for the basins of the Baltic that at low oxygen figures the cod either migrates away or turns to midwater life so that bottom trawling becomes unprofitable. Therefore, it was thought worthwhile to investigate closely the upwelling and its effect on the catch of demersal fishes off Cochin.

Extent of Upwelling

Upwelling off Cochin and farther south was found by Sastry and Myrland (unpublished) during their first series of cruises in October 1957. The phenomenon extended to a mean distance of 60 miles from the shore, and it was stated that the upwelling water reaching the surface came from depths between 50 and 75 m. The duration of upwelling and its extent towards north were not determined by the authors.

From previous investigations the following can be concluded : As shown by Sewell (1929) there is a double seasonal oscillation of the surface temperature of the water in the Laccadive Sea which is connected with the monsoons : Maxima of surface temperature are observed before and after the SW-monsoon whereas during the SW-monsoon season the temperatures are low. The effect of the summer monsoon on the surface temperature is distinctly shown by the investigations on the yearly variation of the temperature and evaporation from tanks near Trivandrum (Broune, 1906). But whereas Sewell estimated the yearly variation of monthly average temperatures in the Laccadive Sea to be 1.88°C (2.7° in the tanks of Broune), the variation in the surface data of the sea near Calicut is 4-5°C ; for the surface waters of this area, observations are published for a period of 16 years (Chidambaram, 1950 ; George, 1953 ; Seshappa and Jayaraman, 1956 ; Kasturirangan, 1957) which show that after the annual maximum of the inshore water temperature in April/May of about 30°C, there is a sudden decrease in June ; in some years the monthly average temperature begins to decrease in May. The lowest averages of about 25°C are found in July/August, and only in October/November is a remarkable increase of the monthly average temperature usually noticed (secondary annual maximum of about 29°C). So the annual minimum of surface temperature in the sea off Calicut is found during summer time.

The data collected by George (1953) from 1949 to 1952, given as weekly averages, show that the fall in surface temperature during May/June occurs suddenly. It is not related to the onset of the monsoon rain. Further, the observations made by Seshappa and Jayaraman (1956), at 19 m depth, as well as those of Sastry and Myrland (MS), demonstrate that at this depth, the temperature before SW-monsoon is nearly as high as that at the surface. So the sudden decrease of the surface temperature during the onset of the monsoon is not caused by turbulence due to the increased wave action either, but is due to upwelling. The larger variation of monthly average surface temperature off Calicut during 16 years of observation, compared with that of the open Laccadive Sea indicates that off Calicut upwelling is regularly

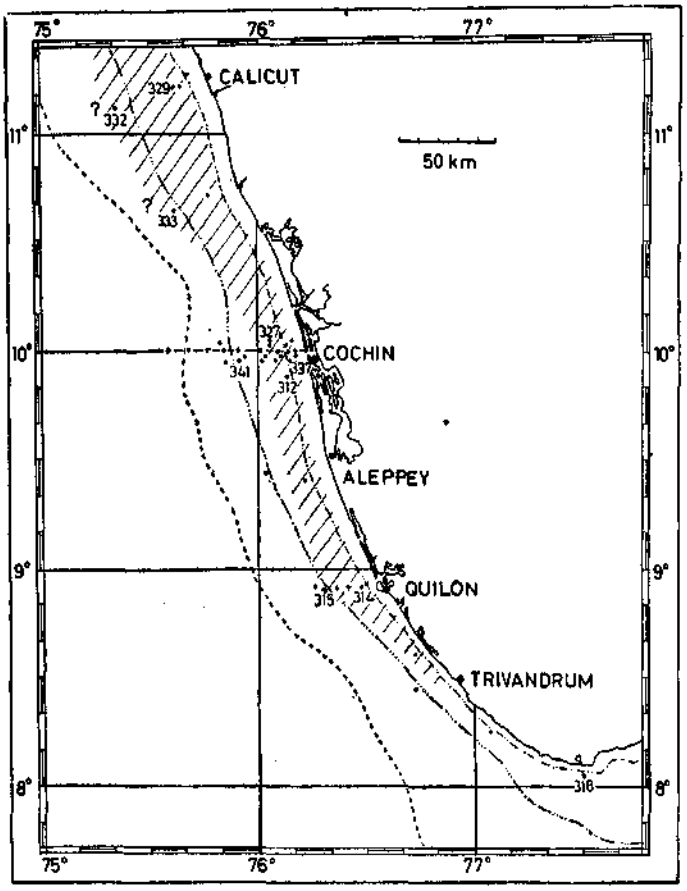

FIG. 1. Area of investigation. Of depth contours, the 20m, 50m and 180m (100 fs isobaths are given. '.': Station with serial observations, eventually with bathythermograph reading. '+': Station with bathythermograph reading only. Off Cochin, all stations were done on 9° 58′ N, except from nos. 312 and 327. The hatched area indicates the region where during the visits in September/October 1958, according to oxygen observations, bottom trawling would have been unprofitable.

found during the whole period of SW-monsoon ; its effect is felt strongest in July and August (refer also to the observations on phosphate content off that place, p. 35), and it lasts till October. The proof for the deduction that upwelling is the reason for the peculiar temperature conditions near Calicut, is the rise of temperature towards the open sea (Horizontal gradients in October 1957 of 1°C per 15 m, as stated by Sastry and Myrland), as well as the vertical distribution of temperature observed in 1957 and 1958 (Fig. 3).

According to the observations in 1957 and 1958, the upwelling extends southwards to Cape Comorin (*i.e.* to 8° N, Fig. 2). Towards north the upwelling certainly reaches 15°, and perhaps 18° N., as shown by the following discussion.

The observations compiled in 'Temperatuurmaandkaarten vor de Indische Oceaan' (Anon., 1952) show cold water off the southwest coast of India to occur from June to August and even October (extending to about 15° N, *i.e.* south of Goa). According to the 'World Atlas of Sea Surface Temperatures' (Anon., 1948), and the 'Monthly Meteorological Charts of the Indian Ocean' (Anon., 1944-45) cold water is found off the Indian southwest coast in August and September. The inconsistency of the temperature distribution, as given in these publications which are mainly based on the regular observations of merchant vessels, is understood by the fact that the bulk of the data is collected along the tracks of traffic ; due to the restricted harbour facilities along the west coast of India during SW-monsoon, observations from the area near the coast are to be expected only from a small number of places. Interestingly enough, the calculation of the range of sea surface temperature in the respective months which is based on the same material ('Monthly Meteorological Charts of the Indian Ocean'), seems to show the occurrence of upwelling more clearly than the charts of mean or minimum temperatures. It appears that off the south west coast, in varying extension, an area is found with a range of $>$6° F (*ca.* 3.3°C). It is smallest in June (*i.e.* the surface temperature is invariably low as shown by the chart of the mean temperature ; upwelling occurs most regularly), and extends to 16-17° N in September/October. Towards south, the Gulf of Mannar and the southern coasts of Ceylon generally are included in the area with a range $>$6° F ; also the mean temperatures south of Cape Comorin (Wadge Bank) are low so that the upwelling extends mostly or always to the area of the continental slope.

The observations of Jayaraman and Gogate (1957), on the shelf off Bombay, indicate a decrease in surface temperature during this season that mostly is stronger than to be expected from the temperature variation of the Laccadive Sea as computed by Sewell (1929) ; if it would be caused by the monsoon wind effect on the evaporation alone, it could hardly become so large. Apparently, off Bombay, the fall of temperature sets in during August only, and is not so marked as off the southwest coast, as far as it can be derived from the regional averages given by the authors.

The analyses of total phosphorus content of surface water by Jayaraman and Seshappa (1957) reveal that during SW-monsoon, as far north as the observations were extended (18° N), the surface figures in this season are consistently higher than during NE-monsoon. Also this fact indicates that upwelling in some form occurs so far to the north. For detailed discussion of phosphate distribution see p. 41.

In order to illustrate the actual temperature distribution during the upwelling period, a section parallel to the southwest coast run by R.V. KALAVA along the 25m contour line in September/October 1958 is given in Fig. 2*a* (Inner line of stations in Fig. 1). The salient features are the low surface temperature south of Alleppey (Station 313) and the very shallow thermocline north of that place; only south of Alleppey the upwelling water reached the surface so that the surface values of temperatures (and of oxygen, Fig. 2*b*) were considerably lowered.

The observations were made after the time, when usually the annual minimum surface temperature is to be found. The sections north and south of Cochin were not run simultaneously, as indicated in the top of Fig. 2*a*, but measurements off Cochin prove that—at least there, and leaving apart the influence of the back-waters above 10 m depth which depends on the state of the tide—the conditions did not change too much during the interval. During September, at about 50 m depth the thermocline sank down hardly 10 m which suggested some weakening of the forces causing the upwelling. The high surface values of temperature off Cochin (Station 312 and 327 in Fig. 2*a*, 27° C) were accompanied by low salinities; this place is very often influenced by the land-locked back-waters. The lowering of isotherms off Quilon (Station 314) was a local disturbance that was not related to the state of the tide. Off this station, a 9-mile section was run across the shelf which revealed the sinking of isotherms to be restricted to the area near the coast.

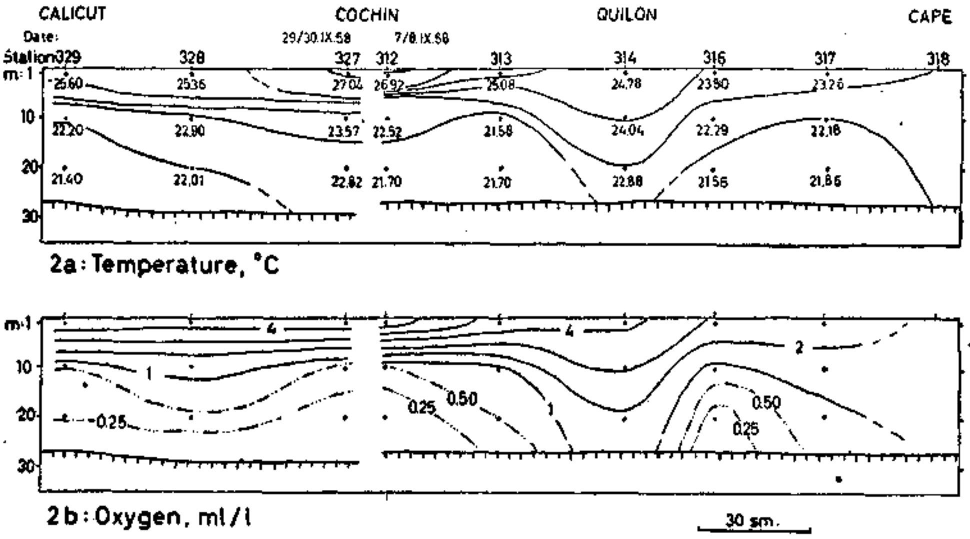

FIG. 2. Section of temperature and oxygen content along the southwest coast of India. The depths of isotherms are based on bathythermograph readings; the readings from reversing thermometers are entered for purpose of comparison.

The same conditions as shown in Fig. 2*a* hold good off Calicut also for previous years. Apparently, the upwelling water there reaches the very surface only occasionally as indicated by sudden drops of temperature (see the weekly averaged observations of George, 1953). Then, also off Calicut, the surface temperatures may register a fall to 23.2°C, as shown by the values of extreme temperatures for 1950 (Seshappa, 1953). This lowers the average surface temperature far enough to become visible in monthly charts as discussed earlier. A section along the 55 m contour line at about the same time as that of Fig. 2 (Outer line of stations in Fig. 1) fundamentally gave the same results as that for the near-shore waters. Generally, the thermocline was found between 10 and 20 m depths ; it tended to widen slightly.

The upwelling along the west coast of India may be caused by the following events : According to the ' West Coast of India Pilot ' (Anon., 1950) towards the end of the NE-monsoon season, the current off the west coast turns to SE (end of February to April). After the onset of the SW-monsoon the coastal current becomes considerably stronger, and, consequently, on its left side the more dense deep water must rise ; supposing a uniform current velocity all along the coast, the rise will be stronger in the north, farther away from the Equator. By this, cold water will enter the shallower parts of the shelf along the entire west coast, and it might depend on the wind when this water will reach the surface (' Upwelling ' in the strict meaning of the term). In the same way, Schott (1935) has explained the occurrence, during SW-monsoon, of cool water off the south coast of Ceylon. This upwelling area appears to be continuous with that off the south-west coast of India as can be seen from ' Temperatuurmaandkaarten vor de Indische Oceaan ' quoted earlier. According to the ' Monthly Meteorological Charts of the Indian Ocean ' (Anon., 1944-45) the predominant winds, as well as the resultant winds (vector means) exhibit under the first half of the SW-monsoon, off the southwest coast of India, a more marked western component than off Bombay. This difference continues also later when directions from W to NW are prevailing in the monsoon wind (August/September). In consequence, the water transport by the wind driven current always gets a stronger off shore component off the southwest coast than off Bombay ; and for the latter region it is seen that upwelling due to wind action normally will occur only from August onwards, as indicated by the observations published by Jayaraman and Gogate (1957).

During the SW-monsoon season, Trivandrum receives winds from W or NW much more regularly than Cochin (' Climatological Tables of Observatories in India ', Anon., 1953). Further, as already pointed out by Sastry and Myrland (unpublished) the coast line south of Quilon bends SE so that the offshore component of the wind driven current is increased. Finally, some divergence in the coastal current may be caused by the fact that the shallower parts of the shelf in that area become narrower so that the near-shore current bends away from the coast. Therefore, both in 1957 and 1958 in the second half of the SW-monsoon season (earlier observations are not at hand), continuous presence of cold water at the surface was found south of Alleppey and Quilon (See Fig. 2 *a*, stations 313 and 314).

Certainly, the prevailing current system, and not the wind, is to be regarded as the main reason for the upwelling off the southwest coast of India as indicated by the following consideration : Both by its geographical position and by its large north-south extent this upwelling area bears some resemblance to the ' classical ' upwelling regions off the west coasts of the continents in low latitudes, *i.e.* at the eastern sides of the trade wind regions. However, the upwelling in the area in question does not occur when the air circulation is similar to that of the trade wind system, *i.e.* during

NE-monsoon, but during SW-monsoon. This explains the climatological difference against other upwelling regions. Whereas elsewhere during upwelling fog frequently is met with, off the south west coast of India during this season heavy precipitation is observed which causes stabilisation of the coastal waters by lowering of salinity.

It should be noted that, according to Sastry and Myrland, in depths below 75 (50) m the current runs north. This feature is found in many other upwelling areas also (Yoshida and Mao, 1957 ; earlier literature is quoted there).—As another example of upwelling off the coasts of India, from the Bay of Bengal, the paper of La Fond (1957, with figures of oxygen and nutrient salts distribution) may be referred to ; upwelling there occurred in spring during SW winds.

Effect of Upwelling on the Distribution of Oxygen and Nutrient Salts

As in the case of the temperature, the distribution of oxygen, pH, and nutrient salts during SW-monsoon is decisively influenced by the upwelling. From the observations off Calicut by earlier workers it appears that near the coast the effect of upwelling is felt most from July to September.

Observations on the oxygen content of surface water near Calicut is available for a period of six years (*vide* Kasturirangan, 1957 ; and Subrahmanyan, 1958). In the six years' averages of Subrahmanyan, the minimum of about 3.5 ml/L O_2 (*ca.* 72% of the saturation value) is observed in September, the maximum of about 5.0 ml/L (*ca.* 108%) in November. During the peak of the phytoplankton standing crop in July (Subrahmanyan), the average value of about 4.35 ml/L (*ca.* 87%) is very small especially for stratified waters as they prevail during this season. Taking the conditions during individual years of that period into consideration (*vide* Kasturirangan, 1957), it is seen that the minimum always occurs is September (the lowest average is 3.01 ml/L O_2, *i.e.* 58.5% of the saturation value, based on 8 observations) whereas the trend during the preceding months varies considerably. The highest average saturation of 125% during four years of inshore observations was found in July 1950, not in November as in the six years' average of Subramanyan. Generally speaking, it is seen that the high stock of phytoplankton found during SW-monsoon is not producing enough oxygen to lift the content up to the saturation level.

For four years, from about the same place of observations as in the oxygen sampling, measurements of pH are at hand[1]: The surface water in 1949/50 and 1951-53, and in 1952/53 the bottom water from 4 and 19 m depths, exhibited rather low figures from June (May) to September. The minimum of 7.6 in the bottom water of September, at the inshore station of Seshappa and Jayaraman (1953), which is 0.3 units lower than the figure of the underlying mud at that time, indicates that the decrease of pH during monsoon time cannot be caused by the stirring up of the sediment and by the release of the interstitial water alone. But both the oxygen and pH

[1] 'Administr. Rep. Dept. Fish. Madras, for 1951/52 (Anon., 1952) ; observations published in older reports were not available to me. Seshappa (1953) ; Seshappa and Jayaraman (1956) ; 'Fisheries Stations Reports and Yearbook, Dept. Fish. Madras, for 1954/55' (Anon., 1956).

figures are heavily affected by the upwelling which brings badly aerated water to the surface.

An example of the oxygen distribution met with during the present investigation is given in Fig. 2 *b*. The picture resembles that of the temperature distribution (Fig. 2 *a*); stronger vertical mixing is observed at Quilon (Stations 314/315) and farther south by which the oxygen values at 1 m depth are lowered to nearly 50% of the saturation value, whereas the bottom figures are higher than in the north. North of Quilon, the oxygen content 5 m above sea-bed is very low (as long as the observations lasted, off Cochin $\leqslant$0.5 ml/L O_2, *i.e.* $\leqslant$10% of the saturation value was found; off Calicut, 30, IX. '58 to 2.X. '58$\leqslant$0.2 ml/L *i.e.*$\leqslant$4% saturation was observed). In the offshore section mentioned above, along the 55 m contour line, the trend was similar. The surface values varied between 4.1 and 6.9 ml/L O_2 (86 and 141% of the saturation value); near the sea-bed south of Quilon$>$1 ml/L O_2 was found, off Cochin 0.65 ml/L, and off Calicut O ml/L ($>$20, 12 and 0% of the saturation value resp.). Also at station 333, situated 33 miles south of station 332 (see Fig. 1) no oxygen was observed 5m above sea-bed. Off Cochin repeated observations are at hand which show that the seaward extension of the area with 0.5 ml/L O_2 (less than about 10% of the saturation value) varied considerably: On five occasions between the end of August and the beginning of October, 1958, in the sample above the sea-bed, this figure was found at depths varying between 38 and about 80 m *i.e.* between 15 and 30 miles from the shore. The figure of 0.25 ml/L (about 5% of the saturation values) was found on the same occasions at depths between 20 and 41 m.

Fig. 3 demonstrates these conditions during a section across the shallower parts of the shelf off Cochin on Oct. 7, 1958. It appears that the water highly depleted of oxygen is confined to the vicinity of the bottom, *i.e.* that the oxygen consumption near the sea-bed is very high. The oxygen content can become so small because the original concentration in the upwelling water is low. The temperature indicates that the water is coming from the layers just below the thermocline, *i.e.* from above the depth where the upper intermediate oxygen minimum of the tropical oceans is found (see Sastry and Myrland about the depth from where the rising water originated in 1957). The observations of the 'Dana'-Expedition (Thomson, 1937) and the Swedish Deep-Sea Expedition (Bruneau, Jerlov and Koczy, 1953), as well as investigations made by the present author off Cochin in November/December 1958, prove that in the south and southwest of India, north of the Equator, the oxygen content of water at about 20°C is often as low as 1 ml/L (roughly 20% of the saturation value) though somewhat higher figures do occur also. Because the oxygen content of the coldest water ($<$21.5° C) met with on the inner shelf off Cochin (upto 100 m depth) during the upwelling period of 1958, was 0.65—0.70 ml/L, the higher consumption does not start on the shallower parts of the shelf only, as it may be derived from Fig. 3 *b*; but only on the shallower parts of the shelf the oxygen depletion turns critical for the demersal fishes as discussed later.

According to the observations of the John Murray Expedition (Gilson, 1937), in the Arabian Sea off the coasts of India, the thermocline and the intermediate oxygen minimum layer are rising towards north to shallower depths; this is accompanied by the lowering of the oxygen concentration in the minimum layer. The observations were made in autumn and winter time; but if the results are true for the season of the summer monsoon also, upwelling even from shallower depths than observed off the southwest coast, off Bombay can cause as bad conditions as off Cochin. On p. 37 it was mentioned that due to the coastal current,

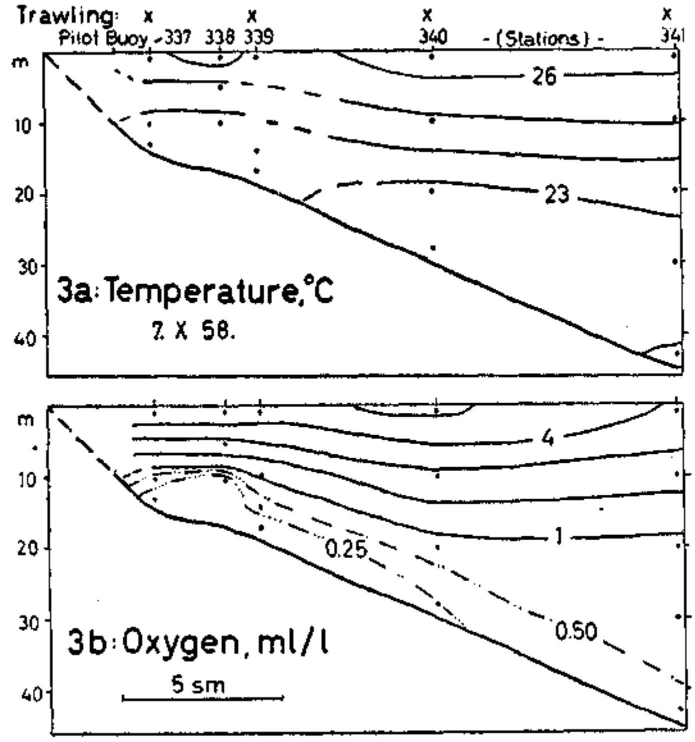

FIG. 3. Temperature and oxygen distribution off Cochin on Oct. 7, 1958. ' x ' marks stations where exploratory trawling was performed.

all along the west coast of India, the shallower parts of the shelf will be entered by the cool deep water during southwest monsoon. Even if off Bombay this water is not reaching the surface so that the average temperature is brought down, it may happen that at rather shallow depths (about 50 m) biological conditions prevail which are similar to those that are the rule off Cochin during this season.

The belt of heavy oxygen-depletion running along the Malabar Coast will not touch the very shore as shown in Fig. 3 *b* ; this is due to the vertical mixing caused by the wave action on small depths which effects a steady stream of oxygen from the surface down. The outer border of the aerated inshore zone at a certain place depends on the strength of the wave action, and should be found farther out during the first monsoon months. Off Cochin, at the time of the present investigation (August to October) usually it occurred within the 10 m contour, for, near the coast the oxygen values at 10 m depth were mostly very low.

Before concluding the discussion of the oxygen distribution, a remark on the phytoplankton cycle during the upwelling period may be given : Near the coast, the very shallow, stabilized surface layers under the strongly overcast sky should allow, during the season of upwelling, a heavy development of phytoplankton, if the stabilization is maintained for some time, *i.e.* if the upwelling to the surface is not going on continuously : in the inshore waters, the thermocline is strengthened by the lowering of the surface salinity due to the river discharge, so that even in the turbid surface waters near the shore, the time of south-west monsoon is the season with maximum standing stock of phytoplankton. Leaving apart the November peaks of oxygen saturation in the observations of Kasturirangan (1957), the connection between stability and phytoplankton can be seen even from these monthly average values (as far as low salinity can be taken as an indication of stability, and the oxygen values as the indication of phytoplankton production) : Largely, oxygen peaks are accompanied by lowered salinity.—All previous authors report from Calicut repeated blooming of phytoplankton during the SW-monsoon season which is to be expected by the irregular break-down of suitable conditions due to new upwelling water. The November maximum of oxygen saturation found off Calicut might represent the balance between production and consumption of oxygen under stable conditions ; the daily production of phytoplankton may still be fairly high due to the amount of phosphate and nitrate present (average values of nutrient content are given by Subrahmanyan, 1958).

Observations on the annual cycle of the phosphate content off Calicut are available for a period of 7 years (George, 1953 ; Seshappa and Jayaraman, 1956 ; Jayaraman and Seshappa, 1957 ; Suryanarayana Rao, 1957, with total phosphorus ; Subrahmanyan, 1958). They show the yearly maximum of surface phosphate values to fall into the months of June and July during 4 years ; in the remaining years it occurred in August or September (monthly means well above 1 μg-at. P/L upto 1.9). In 1954, the phosphate maximum in September (monthly average 1.9 μg-at. P/L at the surface, 3.1 near the sea-bed at 15 m) was preceded in August by the maxima of total phosphorus of 9.5 and 10.4 μg-at. P/L respectively. (Suryanarayana Rao, 1957).

Consideration of weekly averages as given by George (1953) shows that already in May the phosphate content of the surface water can go up to nearly 1 μg-at. P/L respectively 1.5 in the following year. From George's Figure 2 it becomes evident that the frequent peaks of phosphate concentration during SW-monsoon cannot be related to the occurrence of low salinities ; so the river discharge during this time is not the cause of the high phosphorus level of that region. This was already stated by Suryanarayana Rao on the basis of direct analysis. But from the observations of George during 1949 and 1950 it appears that high phosphate values during SW-monsoon are often accompanied by a decrease of surface temperatures. Thus the upwelling is a main source of the high surface values of phosphate. The high phosphorus content of the bottom water is brought to the surface intermittently (see Figs. 2—4, George, 1953), as it is usual with upwelling elsewhere.—As mentioned earlier, the inshore water, in the interval between two intrusions of cold upwelling water into the surface layers, is stabilized and allows a plankton bloom which off Calicut within some days does not consume the enormous amounts of phosphate available, so that there is no inverse relationship between the plankton and that nutrient salt. In the post-monsoon time, when the upwelling is over, the phosphate content also in this area seems to vary inversely with the amount of diatoms present as suggested by George (1953) though the phosphate figures never will reach zero.

The phosphate concentration in the upwelling water approaching the shelf in 1958 cannot be stated with great accuracy due to the small number of observations at hand; it varied in 1958 in the coldest water met with between 2.0 and 3.5 μg-at. P/L (corrected for salt error). The observations of Suryanarayana Rao (1957) suggest that on the shelf the break-down of total phosphorus into phosphate may have a bearing on the figures of the latter during this season.

Seshappa and Jayaraman (1956) found during one year of observations off Calicut a considerable variation of phosphate content in the bottom mud ; the figures of interstitial phosphate were lowest during SW-monsoon. It may be noted that the simultaneous observations on the phosphate content of the water close to the sea-bed show that the highest values were not reached in June or July when the stirring up of the mud should be most effective but only later (The pH-minimum in the mud was found in April to June, and minima of interstitial phosphate in June-July). The maximum figures of 2.4 to 3.5 μg-at. P/L stated by the authors for the water above the sea-bed are similar to the estimations in the off-shore deep water mentioned earlier. Also this observation is in favour of the above statement that the main source of the high phosphate content of that area during SW-monsoon is due to upwelling ; it can cause the initial rise of phosphate figures at the onset of the season, and it serves during many months as the source of replenishment, the existence of which has been postulated by Jayaraman and Seshappa (1957). It may be mentioned that even without being indicated by a marked decrease of surface temperatures, *i.e.* without proper upwelling, during SW-monsoon the cross-circulation in the coastal current off the west coast of India continuously will bring small amounts of deep water, rich in nutrients, to the surface.

In 1958, nitrite too has been estimated but the distribution is not easy to understand, as it often happens with this nutrient salt. The maxima of concentrations frequently met with at intermediate depths indicate that rather quick changes can take place. The cold water approaching the shelf is not supplying nitrogen in the form of nitrite, as observed in November/December 1958 in deep water beyond the shelf (see also Gilson, 1937).

Finally, it may be noted that the water enriched with nutrients by the strong upwelling south of about Quilon will be swept by the current beyond the continental slope south of Cape Comorin ; it is to be expected that in this season more plankton will be found south and southeast of India than farther west at the same latitude.

Upwelling and Demersal Fishes

In the introduction it was mentioned that the demersal fishes were supposed to be affected by the low oxygen figures of the bottom water. This view was supported by the experience of the trawling operations off Cochin, introduced in 1956, according to which, with the onset of the SW-monsoon, the demersal fishes used to disappear suddenly from the shallow areas. It happened also in 1958, in the middle of June, and when the trawling off Cochin was resumed in the beginning of September, fish (mainly *Synagris japonicus*) in appreciable quantities (>25 lbs per hour of trawling by 35′ vessels) was got in deep water only (about 35 m and deeper). Subsequently, the depth figure beyond which fish was found, varied ; during September and after

October 10, heavy catches (often > 1000 lbs per haul) usually were obtained beyond 25-35 m depth, whereas in the shallower waters, all efforts were in vain.

As an example of pronounced fluctuations of the depth limit within which fish (and prawn) were not caught, the fishing operations in the first ten days of October 1958 may be described in detail (result of the trawling of about 5 vessels with 2-3 hauls per day each if no heavy catches were made): On Sept. 30, the catches at 27-29 m and deeper often amounted to > 1000 lbs per trawling hour, as in the preceding weeks. On Oct. 1, all operations upto 38 m depth were in vain (figures from deeper water were not available). On Oct. 3, again heavy catches ($\geqslant$ 1000 lbs) were obtained at 28 m and deeper, and even at 20 m, 120 lbs were caught per trawling hour. On Oct. 6 and 7, all efforts between 13 and 46 m depth (from deeper water no results were available) practically did not produce any fish or prawn whereas on Oct. 10, beyond a very sharp limit at 29 m depth, again large quantities of fish were caught. After the 10th of October, the conditions remained, apart from minor fluctuations, the same as in September.

On Oct. 7, exploratory trawling was undertaken along a section given in Fig. 3, by a vessel kindly placed at my disposal by the Indo-Norwegian Project. In the top of the figure, those stations are marked by 'x' where 30 minutes trawling was done; simultaneously, hydrographic observations were run by R.V. *KALAVA*. The first haul at 14 m depth contained two serpents, the second one at 19 m one young Kalava (*Serranus* sp.), the third one at 30 m nothing, and only the fourth one at 45 m depth brought some pounds of Kilimeen (*Synagris japonicus*). The oxygen content 2 m above sea-bed was 0.20, 0.10, 0.25 and 0.40 ml/L resp. (accuracy $\pm$ 0.05 ml/L).

On Oct. 29 and 30, between 7 and 47 m no fish or prawn was found, whereas on resuming the operations on Nov. 3, and on subsequent days, hauls approaching 1000 lbs per hour were obtained at depths between 7 and 22 m. The first hydrographic observations after Oct. 7 (Fig. 3), on Nov. 3 (the section across the shelf upto 60 m depth not included in Fig. 1) revealed that at all stations near the bottom warm water rich in oxygen was present. The density distribution indicated current to the north and sinking of surface water. Thus, the definitely favourable conditions for trawling were established off Cochin within two days.

The reason for the quick disappearance of the demersal fishes at the beginning of the monsoon season, as well as for the shifting of the populated area, and for the observed sudden establishment of normal conditions are not to be looked for in the effect on the fish of the SW-monsoon itself. From the operations performed by two Ceylonese trawlers during many years on the Wadge Bank (*i.e.* the shelf south of Cape Comorin, *vide* Sivalingam and Metcof, 1957) it is seen that during SW-monsoon both the total catch and the catch per unit time of trawling are about twice that of the intermonsoon period and the NE-monsoon season; this is due to the appearance of migrant fishes mainly of the family Carangidae. The hydrographic conditions on the Wadge Bank during the summer monsoon would be similar to those met with south of Quilon (see Fig. 2). Neither the upwelling itself nor the low temperatures in the bottom water are influencing the distribution of the fishes which in 1958 were caught off Cochin, as seen from Fig. 3: The temperature decreased towards the region where fish occurred (the differences in the salinity of the bottom water were nil). Also the distribution of the bottom fauna cannot be responsible for the quick changes in the area where demersal fishes were caught during upwelling, and for the sudden recovering of the fishery in November. Also for the Soles, *Cynoglossus* spp., during the end of the SW-monsoon season, a sudden return to the shore is the rule along the Malabar Coast (George, 1958).

It appears that the upwelling only indirectly exerts a governing influence on the distribution of the demersal fishes. Its low original oxygen content is further depleted on the shelf so that the fish could no longer stand the bad aeration of the bottom water. By plotting the trawling results off Cochin for September and October, 1958, against dates and depths (the original drawing cannot be given here), and comparing it with the oxygen values observed close to the sea-bed, it is seen that fish was found only when the oxygen content was above 0.25-0.50 ml/L (about 5-10% of the saturation value); owing to the comparatively few oxygen estimations, a more accurate statement is not possible. The bulk of the catch concerned was made up by *Synagris japonicus* (about 93% of the total catch of the trawlers), followed by *Platycephalus* spp. (about 4.5% of the catch).

According to the daily reports of the trawlers of the Indo-Norwegian Project, principally, the same distribution of demersal fishes, as in 1958, was met with in 1956 and 1957. In June 1956, the disappearance of fish within a few days upto about 40m was rather well marked (in this year, the places of trawling were chosen nearly at random), whereas in 1957 in depths <20m, probably the fish disappeared one or two weeks earlier than from the deeper water. At the end of the season, in 1956 and 1957, the area of profitable trawling moved slowly from the deep water towards the coast, as well as from the region off Alleppey northward to Cochin. In all three years, the disappearance of fish from the shallower parts of the area coincided, within a very few days, with the onset of the SW-monsoon along the coast; in 1958, the sudden reappearance of demersal fishes followed the activity of a depression in the Bay of Bengal. During this time of the year, the summer monsoon circulation is finally broken down by such disturbances.

In 1957, in the region inside the desolated area, trawling was very profitable. Due to the origin of the aerated belt near the shore (see p. 40) its seaward extent varied considerably, sometimes reaching to 15 m depth. Because of the changed region of trawling the composition of the catches was of another type compared with 1958 when all efforts in the inshore waters failed. For 1956, no compilation of catch composition is available.

The hatched area in Fig. 1 (from the observations of 1958) shows, based on the oxygen determinations, the extent of the region where bottom trawling, probably, would have been unprofitable during the visits to the respective places, between the beginning of September and the beginning of October, 1958. Based on the experience of three years and on the discussion on the extent of upwelling in space and time, it seems justified to regard the rather sketchy indication of an area devoid of demersal fishes as the representation of a typical feature of the marine biology of the Malabar Coast. It may be emphasized again that the limiting oxygen values have been derived mainly from the distribution of *Synagris japonicus*; but because oxygen values of ≤ 0.25 ml/L have been frequently met with, the distribution of other species, very probably, is also affected which is indicated by some observations mentioned below. In Fig. 1, off Cochin, the average limit of that area during the period of observations could be given, whereas seaward of the stations 332 and 333, off Calicut, the position of the border is unknown. (At these stations, the oxygen had completely disappeared from near the sea-bed). The continuation of the desolated area towards north is also uncertain but according to the hydrographic evidence, nearly the same conditions as along the Malabar Coast will prevail upto Goa. Off Bombay, north of that area from where upwelling is definitely known, the rising of the deep water on the left side of the coastal current may cause similar biological conditions near the sea-bed as off Cochin, as pointed out on p. 40. This will not necessarily become reflected by changes in the very surface layers.

The relation between the oxygen figures and the depth distribution of successful hauls in the operations off Cochin during 1958 suggests that it should be possible, on the basis of occasional hydrographic sections across the shelf during SW-monsoon, to direct the working of the trawler fleet to some extent so that the number of unsuccessful hauls may be reduced. It was not possible to correlate for 1956-58 the daily observations on surface temperature and surface current done by the trawlers themselves, to their catches during SW-monsoon. For the temperature this result was to be expected because, during periods of stabilization of the upper water layers, the surface temperature varies practically independently of the conditions prevailing below the discontinuity layer.

It would be worth investigating as to what happens to the populations of demersal fishes when the badly aerated water in June suddenly covers the shelf and deteriorates there. Reports on regular large-scale mortality of fish during this season have not been published. Therefore, either the fishes (and prawns) are pressed against the shore, or are migrating to deep water. Mid-water life does not seem to be maintained for a long period even if it occurs.

The presence of an inshore trawling area in 1957 testifies to the first possibility, as well as the observation of Seshappa (1953) that in 1950 the mud-goby *Trypauchen vagina* appeared in the inshore area at Calicut with the onset of the monsoon conditions. This species has been found by Kurian (1953) to live at a depth between 8 and 25 m. Finally, Krishna Menon (1958) states that on the Malabar Coast, from June to August, fishermen frequently catch prawns with cast nets, *i.e.* in quite shallow water, because the shoals come near the shore at this time of the year. It is also true that the yield of fish caught by country crafts in the shallow inshore waters is affected during the season of SW-monsoon (see Bhimachar and Venkataraman, 1952). It seems to me worth while to investigate more closely, on the basis of the already available data, and taking into account the biology of the species (f. i. demersal *versus* pelagic fishes), the events happening within the area depleted of oxygen. Perhaps it is even possible to find out by this method how far to the north the same biological offshore conditions as along the Malabar Coast are to be expected.

The heavy catches of the trawlers of the Indo-Norwegian Project, during three years in offshore waters, indicate that the fish, after the commencement of the unsuitable conditions near the sea-bed in near shore waters, can also migrate to greater depths (here, a close investigation on the composition of the catches, as compared with that of the other seasons is desirable). Also among the crustacea this might happen : For the purely marine prawn, *Parapenaeopsis stylifera*, it was stated by Krishna Menon (1953) that the younger animals begin to leave the inshore area towards the end of May, after the commencement of the SW-monsoon, followed by the older individuals so that from July onwards only very few specimens are to be caught there. They return in October. Table I of Bhimachar and Venkataraman (1952) gives an example for the decline in the catch of prawns in June off Calicut. The reason for this migration is not known.

Regarding the possible resorting of fishes to mid-water life, George (1958) stated with reference to the soles (*Cynoglossus* spp.) that these demersal fishes disappear from the shore during the onset of the SW-monsoon, and return when its vigour has passed. They return by mid-water, not along the bottom. Usually, they reach the coast in August-September ; in 1958, they arrived at the shores near Mangalore during the last days of September, but they were not present at Calicut during the period of hydrographic observations, Sept. 30-Oct. 2. Resorting to mid-water life is usual with the Baltic cod when the bottom water becomes badly aerated. It is felt that this change in behaviour is not maintained for a long time by the fishes of this area because, in the cruises in 1958, we did not see mid-water traces of fish in the echo-sounder in the area in question.

It is obvious that only some members of the bottom fauna can stand the complete depletion of oxygen from the water near the sea-bed (stations 332 and 333), and also these species would tolerate it only for a limited time. Off Calicut in 1950, Seshappa (1953) did not observe complete disappearance of the bottom fauna at 15 and 18 m depth. This happened only in shallower water and was supposed to be due to the unstable sediment during the time of SW-monsoon. But the wet weight of bottom animals (including shells) of 2.5 and 2.8 g/m^2 at 15 and 18 m depth (October and September 1950, respectively) is rather low, compared with the maxima of 43.5 and 25.8 g respectively during May. Seshappa suggested that the lowering of wet weights at 15 and 18 m depth was not caused by the whirling up of the sediments. So it may be that there occurs mortality among the bottom fauna due to bad aeration of the bottom water. Observations from deeper water are wanting. It may be noted that Seshappa observed from the shore dying of crabs in June 1949 ; one of the species, *Neptunus sanguinolentus*, was stated by Krishna Menon (1952) to be practically absent from the inshore waters after the onset of the monsoon rain. Kurian (1953) found it to live at depths between 10 and 25 (30) m. So it would seem that, sometimes, this species is also pressed against the shore during SW-monsoon season. Seshappa concluded the discussion of his observation by suggesting that the death was not due to the release of deleterious substances from the agitated mud, because, some days later, following the final disappearance of the mud bank off West Hill, immediately fishing activities were resumed in that region.

Summary

It is shown that off the west coast of India, from 8° to at least 15° N, strong upwelling is regularly observed during the whole south-west monsoon season, *i.e.* for about five months. The oxygen content of the upwelling water which comes from near the upper intermediate oxygen minimum layer, is further reduced by the increased oxygen consumption on the shelf. As a result, off the south-west coast of India

demersal fishes have been found to disappear from a rather broad belt parallel to the coast. Therefore, during this season, bottom trawling is profitable only in deeper water, and occasionally in very shallow water too. Further, it is shown that the high phosphate content at the surface, regularly observed off the west coast of India during south-west monsoon, is mostly due to the upwelling.

Addendum :

After the manuscript was given to the press, I received the paper of Carruthers, J. N., Gogate, S. S., Naidu, J. R., and Laevastu, T. : 'Shorewards upslope of the layer of minimum oxygen off Bombay : Its influence on marine biology, especially fisheries', Nature **183**, 1959, 1084-1087. The authors observed upwelling off Bombay. During the entire period of observations, from Oct. 24 to Nov. 11, 1958, they found stable hydrographic conditions, the isolines of the investigated properties rising towards the coast. On October 24, near the bottom of a station with 42 m depth, they measured a current speed of one-third knot (direction towards 210° magnetic). It may be added here that at Bombay, according to the 'Indian Daily Weather Report' (Meteorological Office, Poona), during the period of observations the surface wind steadily exhibited, at 0830 IST, a direction from NE or E (N), and a speed of 2-7 knots, and at 1730 IST, a direction from about NW, and a speed of 4-10 knots.

On p. 37 it was indicated that off Bombay upwelling to the surface will occur only from August onwards. It appears that in 1958 the NE-monsoon which may regularly cause upwelling off Bombay also (Jayaraman and Gogate, 1957), started there before the SW-monsoon current patterns along the west coast of India was changed. That will facilitate the bringing up of the depth water to the surface. It may be recalled that the upwelling off Cochin, in 1958, ended in the very first days of November, probably in connection with the reversal of the coastal current pattern.

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References

Anonymous. 1944. *World Atlas of Sea Surface Temperatures*, 2nd Ed. Univ. Calif. Press (Reprinted 1948).

———. 1944-45. *Monthly Meteorological Charts of the Indian Ocean*. H.M. Stationery Office, London.

———. 1950. *West Coast of India Pilot*, 9th Ed. Hydrogr. Dept. Admiralty, London.

———. 1952. *Temperatuurmaandkaarten vor de Indische Oceaan*. Uitgave **135**. Staatdruckerij, Den Haag.

ANONYMOUS. 1955. *Climatological Tables of Observatories in India.* Manager of Publications, Delhi.

BERNER, M. AND SCHEMAINDA, R. 1957. Ueber den Einfluss der hydrographischen Situation—insbesondere des Durchlueftungszustandes—auf die vertikale Verteilung und den Fang der Laichdorschschwaerme im Bornholmbecken. *Z. Fisch.*, NF **6**.

BHIMACHAR, B. S. AND VENKATARAMAN, G. 1952. A preliminary study of the fish populations along the Malabar Coast. *Proc. nat. Inst. Sci. India*, **18** : 627-655.

BROUNE, J. A. 1906. Taeglicher und jaehrlicher Gang der Verdunstung in Suedindien. *Meteorol. Z.*, **41** : 428 (cited after Sewell, 1929).

BRUNEAU, L., JERLOV, N. G. AND KOCZY, F. F. 1953. Physical and chemical methods. Appendix : Physical and chemical data. *Rep. Swed. Deep-Sea Exped.* **3** (4) : I-LV.

CHIDAMBARAM, K. 1950. Studies on length frequency of the oil sardine, *Sardinella longiceps* Cuv. & Val., and on certain factors influencing their appearance on the Calicut coast of the Madras Presidency. *Proc. Indian Acad. Sci.*, **B 31** : 252-286.

GEORGE, P. C. 1953. The marine plankton of the coastal waters of Calicut with observations on the hydrological conditions. *J. zool. Soc. India*, **5** : 76-107.

———. 1958. Sole Fisheries In *Fisheries of the West Coast of India*, 51-54. Mandapam Camp. India.

GILSON, H. C. 1937. The nitrogen cycle. *Sci. Rep. Murray Exped.*, **2** : 21-81.

JAYARAMAN, R. AND GOGATE, S. S. 1957. Salinity and temperature variations in the surface waters of the Arabian Sea off the Bombay and Saurashtra coasts. *Proc. Indian Acad. Sci.*, **B 45** : 151-164.

—— AND SESHAPPA, G. 1957. Phosphorus cycle in the sea with particular reference to tropical inshore waters. *Ibid.*, **B 46** : 110-125.

KASTURIRANGAN, L. R. 1957. A study of the seasonal changes in dissolved oxygen of the surface water of the sea on the Malabar Coast. *Indian J. Fish.*, **4** : 139-149.

KRISHNA MENON, M. 1952. A note on the bionomics and fishery of the swimming crab, *Neptunus sanguinolentus* (Herbst), on the Malabar Coast. *J. zool. Soc. India*, **4** : 177-184.

———. 1953. Notes on the bionomics and fishery of the prawn, *Parapenaeopsis stylifera* (M.-Edw.)., on the Malabar Coast. *Ibid.*, **5** : 153-162.

———. 1958. Prawn Fisheries : In *Fisheries of the West Coast of India*, 45-50. Mandapam Camp. India.

KURIAN, C. V. 1953. A preliminary survey of the bottom fauna and bottom deposits of the Travancore Coast within the 15-fathom line. *Proc. nat. Inst. Sci. India*, **19** : 746-775.

LAFOND, E. C. 1957. Oceanographic studies in the Bay of Bengal. *Proc. Indian Acad. Sci.*, **B 46** : 1-46.

SASTRY, A. A. R. AND MYRLAND, P. Distribution of temperature, salinity and density in the Arabian Sea along the south Kerala coast (South India) during the post monsoon season. (MS.)

SCHOTT, G. 1935. *Geographie des Indischen und Stillen Ozeans*, 1-413, Boysen, Hamburg.

SESHAPPA, G. 1953. Observations on the physical and biological features of the inshore sea bottom along the Malabar Coast. *Proc. nat. Inst. Sci. India*, **19** : 257-279.

—— AND JAYARAMAN, R. 1956. Observations on the composition of bottom muds in relation to the phosphate cycle in the inshore waters of the Malabar Coast. *Proc. Indian Acad. Sci.*, **B 43** : 288-301.

SEWELL, R. B. S. 1929. Geographic and oceanographic research in Indian Waters, V. Temperature and salinity of the surface waters of the Bay of Bengal and Andaman Sea, with reference to the Laccadive Sea. *Mem. Asiat. Soc. Bengal*, **9** : 207-356.

SIVALINGAM, S. AND METCOF, J. C. 1957. General features and productivity of the Wadge Bank trawl fishery. *Bull. Fish. Res. Stn. Ceylon*, **6** : 1-23.

SUBRAHMANYAN, R. 1958. Ecological studies on the marine phytoplankton on the west coast of India. *Mem. Indian bot. Soc.*, **1** : 145-151.

SURYANARAYANA RAO, S. V. 1957. Preliminary observations on the total phosphorus content of the inshore waters of the Malabar Coast off Calicut. *Proc. Indian Acad. Sci.*, **B 45** : 77-85.

THOMSEN, H. 1937. Hydrographic observations made during the 'Dana'—Expedition 1928-30. *Dana-Report*, **12** : 1-46.

YOSHIDA, K. AND MAO, H. L. 1957. A theory of upwelling of large horizontal extent. *J. Mar. Res.*, **16** : 40.