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Seasonal variations in the physico-chemical and biological characteristics of the eastern Arabian Sea

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Abstract

The entire area along the west coast of India, between Cape Comorin and Kandla within the EEZ was covered in six research cruises of FORV *Sagar Sampada,* 2 each in pre-monsoon, monsoon and post-monsoon periods during 1991-93. Data on the physical, chemical and biological parameters were collected at every station (one degree square) from surface to maximum depth of 500 m by using Rosette samplers along with CTD Unit. The results of the investigations indicated definite fluctuations in the physico-chemical and biological features in different seasons. The influence of physico-chemical features on primary production in terms of chlorophyll *a* and other relevant observations made by earlier workers were compared and briefly discussed in order to get a comprehensive picture of the characterestics of the waters in different seasons in the eastern Arabian Sea.

Introduction

It is well known that the seasonal climatic changes in the marine environment play a significant role in the ecological cycle of the Indian seas, especially the Arabian sea. Observations made over the years point to the fact that the seasonal changes brought in through the pre-monsoon, monsoon and post-monsoon phenomena along with the resultant oceanographic changes influence the overall productivity of the region significantly. The biological productivity of the seas in this region is dependent on the complex physical, chemical and biological processes active in the medium and subsequently transferred to different trophic levels.

Observations made by Banse (1959, 1968), Ramamirtham and Jayaraman (1960), Edelman (1960), Ramasastry and Myrland (1960), Murthy (1965), Sharma (1966, 1968), the various reports published by the erstwhile FAO/UNDP Pelagic Fishery Project, relevant papers brought out by NIO based on IIOE, R. V. *Gaveshini* and ORV *Sagar Kanya* data, Darbyshire (1967), Wyrtki (1973), Pillai (1983, 1989, 1991, 1993) Pillai *et al.* (1980), Longhurst and Wooster (1990) etc. are worth mentioning in this context. Most of the observations made in the past had limited coverage both in terms of area as well as the number of parameters observed.

The data presented here were collected on board FORV *Sagar Sampada* during 1991-93. The authors sincerely acknow-led-ge the help and co-operation extended by the participants of the above cruises. The participants are K. G. Girijavallabhan, N. Kaliaperumal, M. Rajagopalan, G. S. D. Selvaraj, S. Muthusamy, R. N. Misra,

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Material and methods

The entire area along the west coast of India, between Cape Comorin and Kandla within the EEZ was covered in six research cruises of FORV *Sagar Sampada,* 2 each in pre-monsoon (March-April-May), monsoon (June-July-August-September) and postmonsoon (October-November-December-January-February) during the period 1991-93 (Fig. 1).

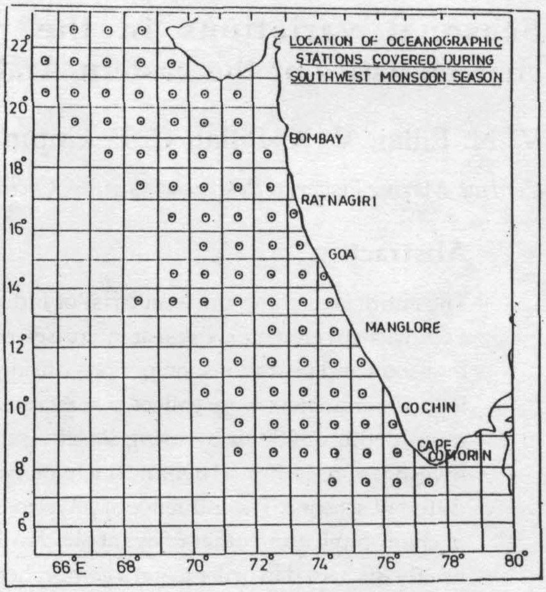

Fig. 1. *Location of stations covered*

Data on the physical and chemical aspects of the waters were collected at every station (representing one degree square) from surface to maximum depth of 500 m by using the Rosette samplers along with CTD Unit.

Surface water temperature was recorded using a bucket thermometer. Salinity was recorded from the CTD probe, and dissolved oxygen estimated by standard Winkler method. Nutrients were estimated by standard methods using a UV/VIS Spectrophotometer on board the vessel.

Results

Premonsoon

Sea Surface Temperature:

The sea surface temperature showed a variation of about 2°C between southeastern and northeastern regions, the lower temperature being observed towards northern latitudes. The water temperature over the shelf and beyond remained at around 30.5°C in the southern latitudes (05°30'N). The thermocline was detectable beyond the shelf at about 75m. The isotherms showed an upward tilt from the deeper layers (75-100m) of the outer continental shelf towards shallow depths (Fig. 2) showing the commencement of upwelling in the region.

Surface waters remained warmer (temperature >30°) in the coastal and oceanic region at 12°30'N latitude sector. In general, the sea surface temperature showed an increasing trend towards oceanic region. The depth of discountinuity layer was observed below 100m. The upward tilting of isotherms from depths below

100m indicated that the process of upwelling has already commenced in the deeper areas. However, over the shelf the water temperature remained above 28°C.

Towards north, at lat. 15°30' the surface waters were comparatively cooler compared to the south, with surface temperature ranging between 28.0° and 28.8°C. The thermocline was observed below 100 m but unlike in the southern region the presence of a strong thermal gradient was not noticed in this region. The sea surface temperature in the region at 18°30' latitude sector and further north ranged between 27.5°C and 28°C and comparatively low temperature prevailed over the entire shelf area. Isotherms at depths did not indicate any upward tilting and they existed almost parallel to the coast.

Salinity

Salinity showed a progressive increase towards northern latitudes within the coastal as well as oceanic region. The same trend was reported by the earlier workers during the pre-monsoon season for the west coast of India. A well defined salinity maximum was observed within a tongue of high saline water at deeper levels beyond the shelf in the southern sections (09°30' and 12°30'N lat.). Higher salinity pockets above 36‰ were observed between depth zones 30-100 m in the middle latitudes (12°30' - 15°30'N) (Fig. 3). Salinity above 36‰ were observed throughout the water column upto a depth of 100m in the northernmost section. In this region the water column within the shelf was more or less homohaline but not homothermal.

Dissolved oxygen

In the north-eastern region dissolved oxygen values were generally high and more or less uniform upto a depth of 50-75 m and below that there was considerable reduction in the dissolved oxygen levels at deeper levels. The oxygen levels in the surface layer were invariably high

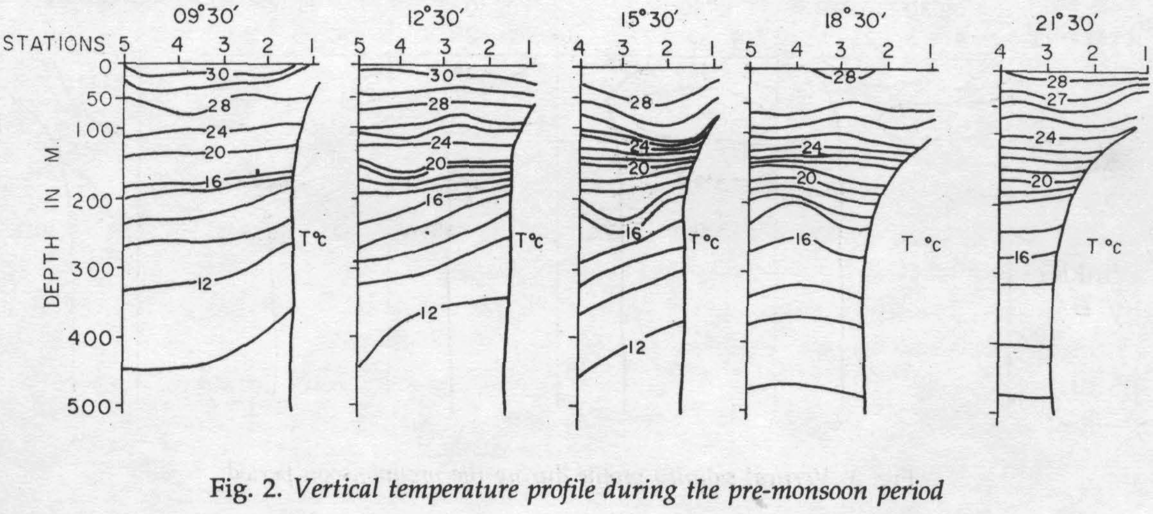

Fig. 2. *Vertical temperature profile during the pre-monsoon period*

(4.12 to 4.67 ml/l) and upto 70m depth the trend was almost similar. However, below 75m depth a rapid decrease was noted and below 100m the dissolved oxygen concentrations were less than 1.5 ml/l.

Nutrients

The distribution of nutrients showed that while phosphate showed a gradual increase towards bottom, nitrate and nitrite showed higher levels in the midwater layers.

Phosphate levels were mostly below 5µg at/m² (integrated value for column of 75m) in the stations south of lat.15°30'N both in the coastal and oceanic region, except for an isolated high value (49.5 µg at/m²) in the nearshore station at lat.8°30'N. While comparatively higher levels were observed in the region north of lat. 15°30'N lowest values observed were 13-23µg at/m² in the shallow coastal regions between 15°30-16°30'N and the coastal and oceanic region at lat. 17°30'N. Similar values were recorded in the coastal as well as oceanic waters in the 21°30'N lat sector. However, the highest values of phosphate were observed in the mid shelf stations at lat. 19°30'N where the level ranged from 109-133 µg at/m², while in the coastal region between latitude 18°30' to 21°30' the phosphate concentrations recorded were 50µg at/m². The nitrite levels were generally very low in the southern latitude stations (below 09°30'N) where the values recorded were less than 1 µg at/m². In the shallow coastal stations values were below 10µg at/m² in the southern latitude sector at 09°30'N. The nitrite concentration showed an increasing trend towards dee-per stations in the area between 10°30-13°'N and values ranging from 18-43 µg at/m² were recorded in the mid shelf and oceanic regions. In the northern latitude sector north of 15°30'N pockets of high concentration (20-29 µg at/m²) were recorded mostly in the outer

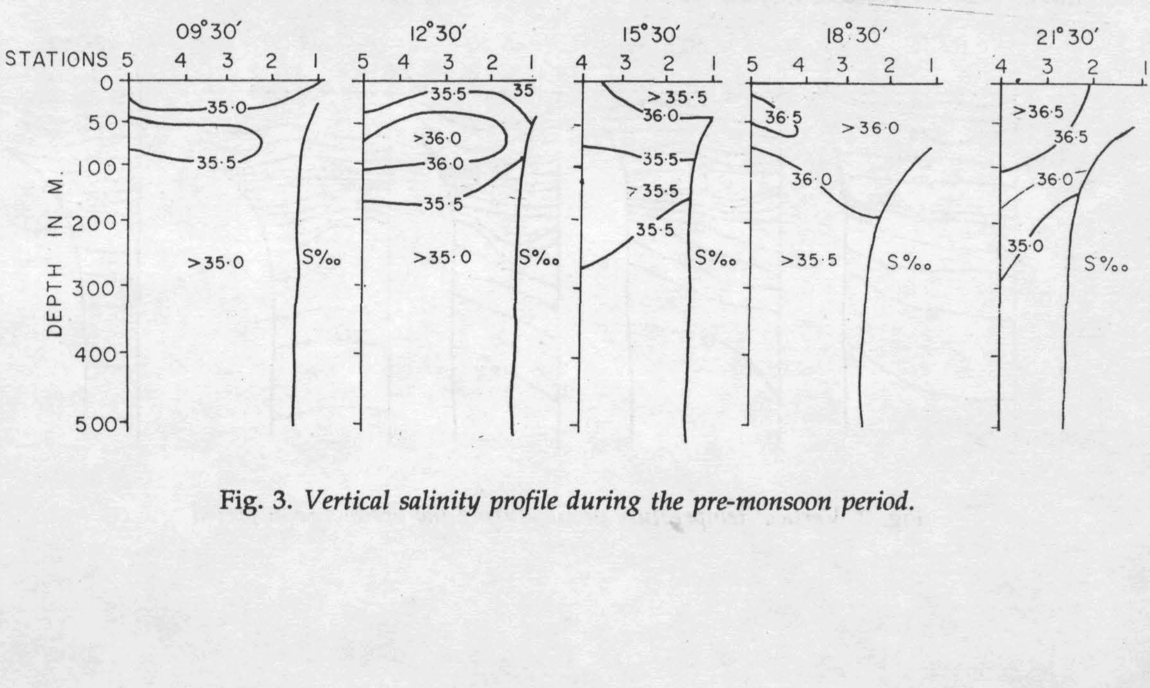

Fig. 3. *Vertical salinity profile during the pre-monsoon period.*

shelf stations between latitudes 15°30'-18°30'N and at 21°30'N. Rather low levels (less than 10µg at/m²) were observed in the coastal stations at 18°30'-19°30'N and at 21°30'N latitude sector. In general, the nitrite levels were mostly between 10-20 µg at/m² in the region north of lat. 15°30'N.

Chlorophyll-a concentration

The chlorophyll *-a* distribution in the euphotic zone indicated that the coastal waters of s.w. region and n.w. region have high rate of production. Along the south west coast, the Wadge Bank area recorded high rate of production (32.53 mg/m²) of chlorophyll-*a* in the water column. Similarly low to moderate levels of chlorophyll-*a* production (2.18 µg/m²) was recorded in the oceanic regions of the south west coast. The north-eastern Arabian sea near Bombay and Veraval showed high rate of production (50-70 mg/m²) (Fig. 4). However, low to moderate levels of chlorophyll-*a* were recorded in the oceanic region off Ratnagiri and Kandla.

Monsoon

Wind : Wind direction was predominantly westerly, sometimes deviating to south westerly. Wind speed varied between a maximum of 40 knots to a minimum of 7 knots.

Clouds : Clouds were predominantly Cumulonimbus and Nimbostratus, the amount varying between 2/10 and 9/10.

Sea state : Heavy swells with white horses prevailed in the major part of the area under observation.

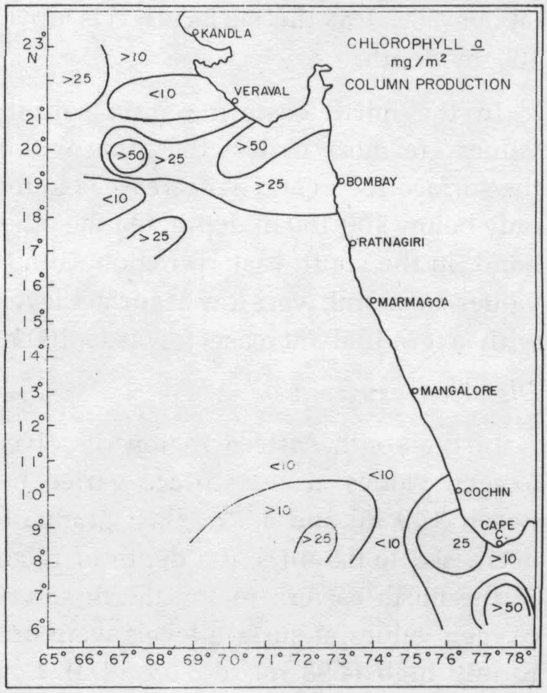

Fig. 4. *Column production of chlorophyll* a *(mg/m²) from surface to 50m depth during the premonsoon period.*

Sea surface temperature : SST varied between a minimum of 25°C and a maximum of 29.8°C in the south eastern region and the same varied between 26.08°C and 28.6°C in the north eastern region.

The main thermocline was observed between a minimum depth of 20m (top of the thermocline) and a maximum of 100 m (bottom of the thermocline).

Salinity:

In the southeastern region, sea surface salinity varied between 30.45‰ and 37.53‰. In the northeastern region, generally, high salinity was observed (above 36‰) at the surface levels up to 100 m depth.

In the north eastern region salinity values are more or less the same within the surface 100 m and a decrease is found only below 100-150 m depth. On the other hand, in the south eastern region salinity values, in gneral, were low at surface levels with a gradual increase towards 100m.

Dissolved oxygen :

In the south eastern region dissolved oxygen values at sea surface varied between 3.19 ml and 4.5 ml/l. It gradually decreased to 0.5 ml/l at a depth of 100m. In the north eastern region the dissolved oxygen values at surface levels were uniformly high (4.98 ml to 5.03 ml/l). Low values were found only at depths of 50m and below. The horizontal variations in dissolved oxygen content of waters at a depth of 50m clearly indicated a decrease towards south near the coast between Ratnagiri and Goa where values as low as 0.5 ml/l were observed.

Nutrients: Both in the south eastern as well as north eastern regions phosphate concentrations at surface levels varied between 0.1 and 1.83 µg at/1 and gradually increased towards deeper waters. Range values for the nutrients were as follows:

Phosphate	:	0-3.7 µg at/l
Nitrate	:	0-7.12 µg at/l
Nitrite	:	0-5.28 µg at/l
Silicate	:	0-28.4 µg at/l

Chlorophll-a concentrations:

In the southeastern region, at surface levels (the maximum depth of observation was 200m) chlorophyll-a varied between zero and 4.07 mg/m³. Horizontal variations of chlorophyll-*a* at surface levels in the south eastern region is plotted and presented in Fig. 5 A which clearly indicate comparatively higher concentrations in the coastal waters between Cochin and Quilon.

In the northeastern region, chlorophyll-a concentrations varied from traces to a maximum of 4.03 mg/m³ in the coastal waters near Bombay. Horizontal variations are presented in Fig. 5B.

Post-monsoon

Sea surface temperature

The surface water temperature during October-November '91 from Cape to Goa varied from 26.47 to 29.46°C and from Goa to Kandla, it ranged from 27.0 to 29.5°C. Surface temperature values were higher (>29°C) in the region between

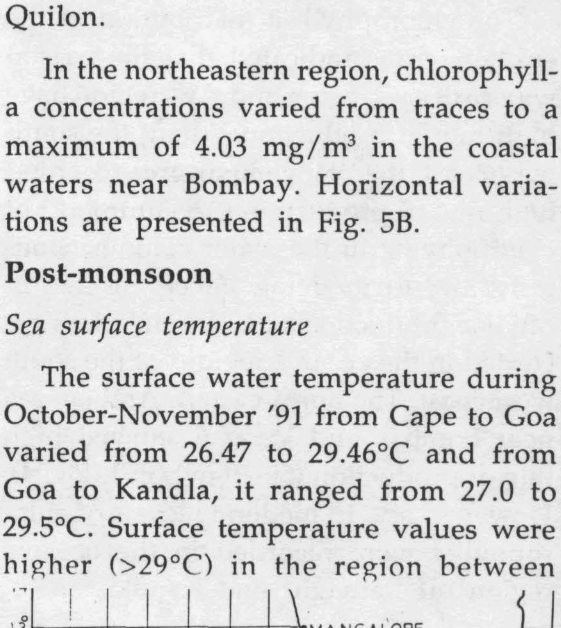

Fig. 5. A. *Horizontal variations of chlorophyll* a *(mg/m³) at sea surface level between Cochin and Quilon.*

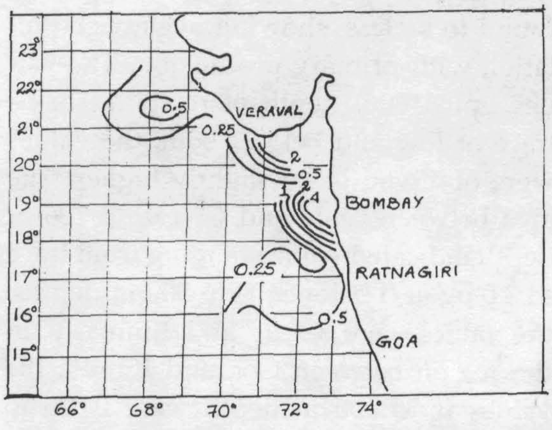

Fig. 5. B. *Horizontal variations of chlorophyll* a *(mg/m³) at sea surface in and around the area of possible upwelling activity.*

12°30′ to 18°30′N, compared to the area south and north of it. Temperature values above 50m water column varied between 24.59 to 29.12°C in the northern latitude areas, between 15°30' to 21°30′N with comparatively lower values in the southern part, while in the region below 12°30′N, the temperature values in the corresponding depth zone (0-30m) varied between 25.72 to 29.32°C. The depth of mixed layer is found deeper in the northern region (lat. 18°30' to 21°30′N) than the southern region. The bottom temperature values were below 17°C in the shelf region at 12°30′N section while the corresponding values for the same depth zone at 09°30′N were above 24°C. The isotherms showed an upward tilt towards shallower areas of the shelf in the section at 18°30′N. The vertical temperature profile indicated the presence of compartively lower temperature water in the southern section than the northern section. (Fig. 6).

Salinity

The salinity of the column waters upto 500m depth ranged from 34.53 to 36.91 ppt in the region between Cape to Goa during October-November '91 while the salinity values from Goa to Kandla during October '92 was in the range of 31.41 to 37.07 ppt. There was not much difference between the values at the surface and bottom levels in most of the stations covered (Fig. 7).

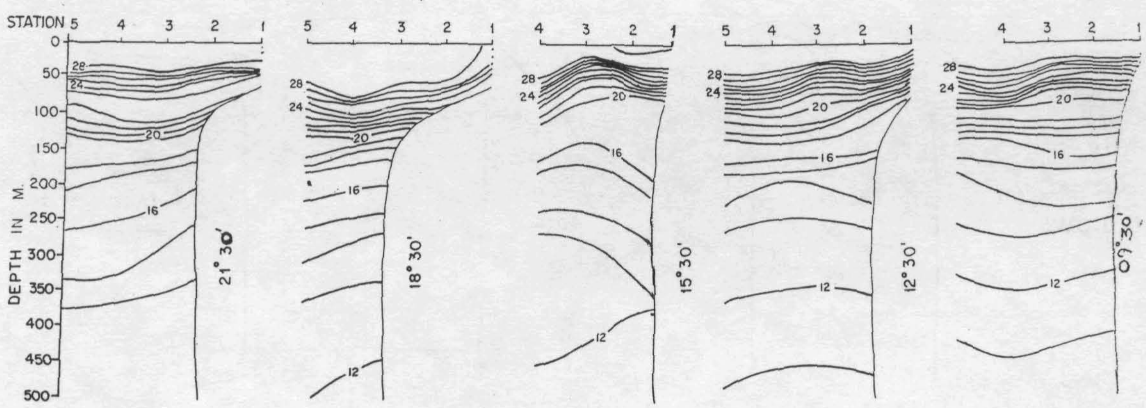

Fig. 6. *Vertical temperature profile during the post-monsoon period.*

Dissolved oxygen

The dissolved oxygen content at the surface between Cape and Goa during October-November '91 ranged from 2.84 to 4.95 ml/l and upto 50m depth, the values ranged from 1.80 to 2.40 ml/l; 50-100m depth, values ranged from 0.27 to 1.91 ml/l. The oxygen values within 100m to 500m depths were very low (0.01 to 0.21 ml/l) and sometimes negative values were also obtained below 250m depth.

The dissolved oxygen values between Goa and Kandla at the surface ranged from 3.04 to 5.76 ml/l, showing slightly higher values compared to the southern half. The values upto 50m depth indicated a range of 1.27 to 3.05 ml/l and 50-100m depth indicated a range of 0.32 to 2.62 ml/l. Within 100m to 500m depths, the values were found to be low to negligible levels (0.02 to 1.77 ml/l).

Nutrients

Similar to the nitrogenous compounds, the inorganic phosphate values were also found to be less, showing negative correlation with primary production. The values upto 100m depth were found to be trace or low and below 100m, the values were observed to be slightly higher. The area between Cape and Goa upto 100 m depth indicated values ranging from trace to 3.0 µg at/l below 100 to 500 m depths, the values were 3-7 µg at/l. Similarly, in the region between Goa and Kandla the values upto 100 m depth were 0.025 to 0.295 µg at/l and below 100-500 m depths, the values being 0.140 to 0.375 µg at/l. This revealed that the inorganic phosphate was slightly higher between Cape and Goa compared to the northern region.

The column production of the phosphate indicated high values (220-250 µg at/l) in the shallow nearshore stations off Trivandrum, off Calicut and at the oceanic regions off Mangalore all in the south-eastern region. Moderately high values (100-150 µg at/l) were observed in the

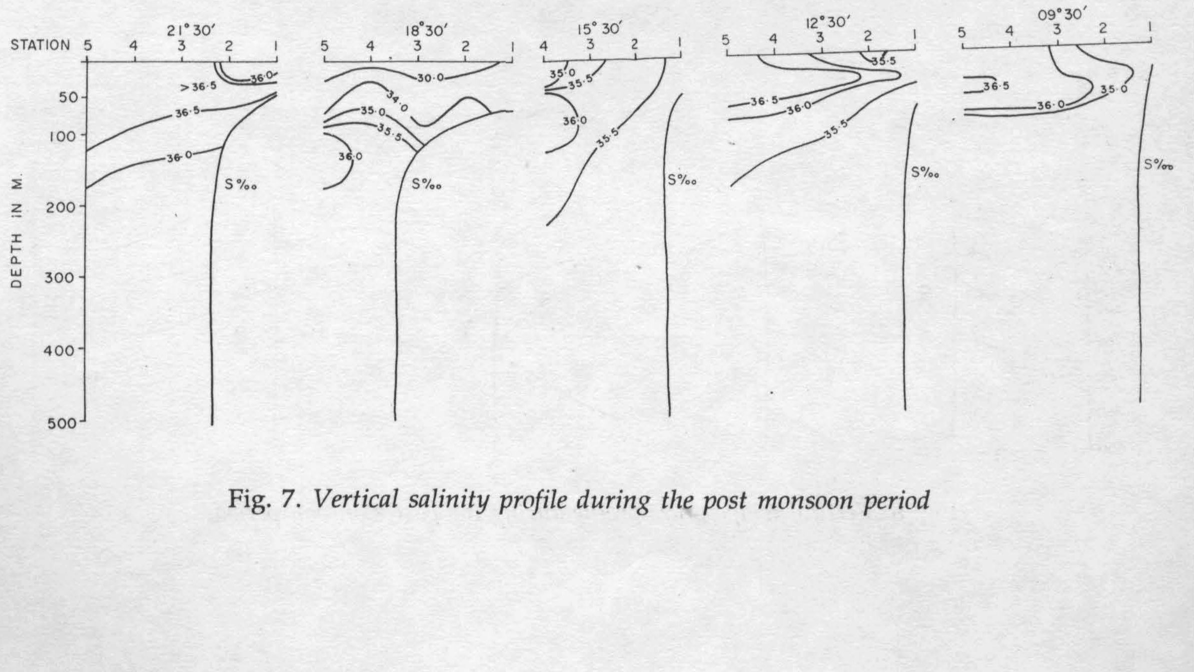

Fig. 7. *Vertical salinity profile during the post monsoon period*

oceanic regions between lat. 09°30'-12°00'N, in the Quilon-Kasargod area. Higher values were also observed in the deeper stations, lat. 10-11°N and 13-14°N (110-190 µg at/l). Comparatively low values were recorded (30-90 µg at/l) in the north eastern area with certain pockets of high values (150 µg at/l), off Veraval and in the area between Marmagoa and Ratnagiri (100-180 µg at/l).

The column production of phosphates revealed a close negative correlation with values of chlorophyll-*a* in the post-monsoon season along the west coast of India.

The nitrite content of the water column upto 100m depth in the area between Cape and Goa indicated trace values to a maximum of 3.91 µg at/l and from 100-500m depths, the values ranged from 0.006 to 0.428 µg at/l. Similarly, the area between Goa and Kandla showed values ranging from 0.002 to 0.315 µg at/l upto 100m depth and from 100-500m depths, the values were in the order of 0.008 to 0.484 µg at/l revealing that the nitrogenous materials are slightly at higher level between Cape and Goa during October-November period.

In contrast to the nitrite values, the values of nitrates were found to be slightly higher throughout the west coast during the study period. The area between Cape and Goa upto 50m depth indicated nil to trace values and 50-100 m depths, the values were ranging from 0.39 to 14.80 µg at/l. However, the values of nitrate from 100-500 m depths, showed 1.87 to 23.85 µg at/l. Similarly, the area between Goa and Kandla upto 50m depth showed traces or very low values (0.1 to 1.0 µg at/l) and from 50-100 m depth indicated low to moderate levels (1-10. 3 µg at/l) and below 100-500 m depths, very high values (3 to 23 µg at/l).

In contrast to the values of nitrate and phosphate, the silicate values were found to be very high in the water column of the eastern Arabian sea; especially the area below 100m depth. The region between Cape and Goa upto 100m showed values ranging from nil to 40µg at/l and high values were noted below 100m to 500 m depths (50-200 µg at/l). However, the region between Goa and Kandla upto 50m depth showed low values (1-45 µg at/l) with an increasing trend upto 100m. Very high values were observed below 100-500m depths (50-212 µg at/l).

Primary production

The data related to the primary production estimated by ^{14}C technique indicated that generally the rate of production was low to moderate levels (0.02 to 0.93 $gC/m^2/day$) throughout the area from Cape to Goa during the period of observations. Moderate to slightly high values were observed off Cochin (0.82 $gC/m^2/day$) and in the lat. 08°30'N and long 75°30'E off Wadge Bank area (0.93 $gC/m^2/day$). However, the rate of primary production estimated by oxygen technique, from Marmagoa to Kandla, especially off Bombay, Veraval and Kandla regions have low to moderate levels of production (0.1 to 0.19 $gC/m^2/day$).

Chlorophyll-a concentration

Fig. 8 indicate the chlorophyll-*a* distribution from surface to 50 m depths of the euphotic zone along the west coast during the post-monsoon period.

In the surface waters, pockets of high values exceeding 2 mg/m³ of chlorophyll-*a* were observed at lat. 11°30'N and long. 72°30' and 74°30'E; off Calicut and at 09°30' and 07°30' south of Cochin. High values were also observed in the Wadge Bank area, (06°30' to 07°30'N and long. 70°30'E). In the north, surface chlorophyll-*a* values ranged between 0-1.335 mg/m³ in the entire area. The highest chlorophyll *a* value observed in the south eastern Arabian Sea was 3.730 mg/m³ in the oceanic waters off Calicut. Southern part of the south eastern Arabian sea is found to be more productive during the post monsoon period.

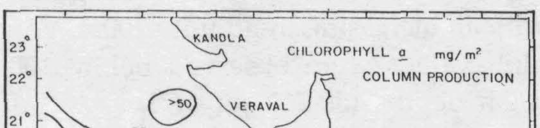

Fig. 8. *Column production of chlorophyll* a *(mg/m²) from the surfac to 50m depth.*

The distribution of chlorophyll-*a* at 10m depth indicated pockets of high values exceeding 2-4 mg/m³ in the coastal areas between Mangalore and Marmagoa and also on the southern side of the Wadge Bank area, while chlorophyll-*a* distribution in the north showed comparatively low values (<1.6 mg/m³), especially between Marmagoa and Ratnagiri (<0.267 mg/m³).

The concentration of chlorophyll-*a* at 20 m depth indicated pockets of high values (>5 mg/m³) in the oceanic regions south of Cochin and high concentrations of chlorophyll-*a* on the southern side of Wadge Bank (>4 mg/m³). Moderately high values of chlorophyll-*a* (>2 mg/m³) were observed in the coastal stations between Mangalore and Marmagoa. Low values as in the case of 10 m depth have been noticed (<0.3 mg/m³) between Marmagoa and Ratnagiri.

The distribution of chlorophyll-*a* at 30m depth indicated high values in the stations between Mangalore and Marmagoa (2-4 mg/m³). Pockets of high values were also observed in the oceanic regions at lat. 08°30'N and long. 73°30'E (>3 mg/m³). Very low values were observed between Marmagoa and Ratnagiri (<0.3 mg/m³). In the north, chlorophyll-*a* values ranged between 0.3 and 0.5 mg/m³ with certain pockets of high values (1-1.6 mg/m3)

High concentration of chlorophyll-*a* ranging from 2-4 mg/m^3 were observed at lat. 08°30′N in the 50m depth. Other areas along the south-west coast revealed 0.3-1.4 mg/m^3. The north-west coast showed 0.3 to 1 mg/m^3 with pockets of high values in the coastal waters off Ratnagiri (2.14 mg/m^3) and in the oceanic regions off Bombay (3.8 mg/m^3).

Column production of chlorophyll-*a* indicated that high values were noticed in the southern part lat. 08°30′N (>150 mg/m^2) in the oceanic region, 100-123 mg/m^2 at lat. 09°30′N, south of Cochin and lat. 11°20′N off Calicut. In the area between Mangalore and Marmagoa, in the coastal waters, the column chlorophyll-*a* was 50-80 mg/m^2. In the north eastern Arabian sea more than 10 mg/m^2 were observed in the oceanic regions off Bombay (lat. 19°30′N). Low values (<25 mg/m^2) were recorded in the area between Marmagoa and Ratnagiri.

Phaeo-pigments

Moderately low fractions of phaeo-pigme-nts were observed in the column waters of the oceanic regions between Cape and Goa (0-96 mg/m^2). The maximum phaeo-pigment content was observed at lat. 11°30′N and long. 71°30′E. Comparatively very low phaeo-pigments were observed in the north the maximum off Veraval (61 mg/m^2).

Discussion

Premonsoon

In the northernmost sector at 21°30′N latitude the water temperature showed reduction at the surface and in the entire water column within the shelf and beyond compared to southern region. However, the sea surface temperature varied between 27.8°C and 28.6°C in the region. The temperature discontinuity layer was not pronounced in this section and the isotherms showed stable summer conditions. Banse (1968) observed the presence of a weak thermocline in the northern latitudes (18°30' - 21°30′N) during the same season. He has also observed a thermal stratification in the waters during this period.

In general, the sea surface temperatures were comparatively higher in the southern latitudes (09°30' to 12°30') when compared to the temperature distribution in the northern region. The upward tilting of isotherms at depths observed in the southern latitudes were not seen in the northern sector. The 25°C isotherm was observed within 100-125m depth zone throughout the area while it was present at 30m depth in the shallow coastal station off Kandla. A low temperature pocket (below 28°C) was observed in the shallow regions off Veraval.

Ramamirtham and Patil (1966) while describing the hydrography of the west coast for the period January to May stated that a salinity transition zone is evident at about lat. 12-18°N in which the salinity increased rapidly. They also observed that an increase was found in the salinity values in the section off Mangalore. Even at surface values as high as 35.2 ‰ occurred at some of the stations and the vertical extent of the high salinity zone is found between 50 and 200m depths. They observed that this marked increase in the salinity occurred at about 13° N which can primarily be taken as a transition region for salinity. They stated that this further divides the whole of the west coast into two regions from Cape Comorin to Ratnagiri, a third zone probably being north of Ratnagiri in the northern Arabian Sea.

For the pre-monsoon season Ramamirtham and Patil (1966) observed that in general, in the mixed layer the waters are nearly 80% saturated in respect of dissolved oxygen concentrations and near the coast values as high as 4.8 ml/l have been noted. They also observed a rapid decrease within the temperature discontinuity layer and below 150m depth the values are never greater than 1.0 ml/l. For the north-eastern region (Ratnagiri to Veraval) Patil *et al* (1964) reported that along these sections surface values of dissolved oxygen varied between 3.95 and 4.8 ml/l. Down below the surface oxygen values were greater than 4.0 ml/l upto a depth of 75 m, maximum values being observed at varying depths from 10 to 50 m depth at individual stations. They also observed that below 75 m depth a sharp gradient in oxygen content occurred and this extended down to 150 m depth.

Monsoon

The period of coverage (July and August) in the eastern Arabian Sea represented the peak of southwest monsoon season in this region characterised by comparatively higher wind velocities, rough sea conditions and relatively high rainfall. The clockwise circulation which develops in the Arabian Sea during this season would have contributed to the higher salinity values observed in the northern stations. The southerly current which develops in May is known to continue till October. The effect of the spreading of the high-saline Arabian Sea water towards south is neutralised by the south west monsoon rains and river runoff. Hence the horizontal variation of salinity at surface levels is dependent on the onset of the south west monsoon and also the direction, velocity and duration of the southerly current mentioned above.

The seawater temperature within the area under study shows spatial fluctations. When the northern stations exhibit comparatively high temperatures, the situation prevailing in the central and southern stations is entirely different with comparatively lower temperatures.

In general, the shelf waters were poorly aerated during the south west monsoon, especialy towards south.

Detailed analysis of sea water temperature, salinity and dissolved oxygen data collected along 6 sections in the south eastern region between Cape Comorin and Goa revealed the presence of upwelling in this area between lat. 08°30'N (off Trivandrum) and 11°30'N (off Calicut) near the coast. In this area the 23°C isothern was found at comparatively shallower depths (18 to 25 m), the movement of which on the vertical plane could be taken as an indicator for the presence of upwelling or sinking, as the case may be.

The present study also confirmed that the vertical oscillation of 23°C isothern on a vertical time section can be taken as an indicator for the commencement, intensification and cessation of the process of upwelling along the southwest coast of India which was first revealed from a detailed analysis of similar data collected onboard Research vessels attached to the erstwhile FAO/UNDP Pelagic Fishery Project, Cochin between 1971 and 1978 (Pillai *et al* 1980).

In the present study upwelling activity was observed in the area between lat 08°30'N and 11°30'N lat. Fig. 9 shows the vertical movement of 23°C isotherm between long. 69°30'E and the south west coast of India during July, 1991 at different latitudes viz. 07°30'N, 08°30'N, 09°30'N, 10°30'N, 11°30'N, 13°30'N and 14°30'N. The vertical extent of oscillation of 23°C isotherm at the different latitudes is clearly brought out in Fig. 9.

Occurrence of 23°C isotherm at different stations along the above mentioned 6 sections located south off Goa, Karwar, Calicut, south off Ponnani, Alleppey and Trivandrum are presented in Fig. 10 which can be used as a possible indicator for the presence of upwelling, especially the horizontal spread in space. In the north eastern region the 23°C isotherm occured between depths of 50m and 131 m whereas in the south eastern region, especially in areas of possible upwelling activity the isotherm moved to shallower depths of 18 to 25 m.

Horizontal variations observed in the Chlorophyll-*a* concentrations at surface

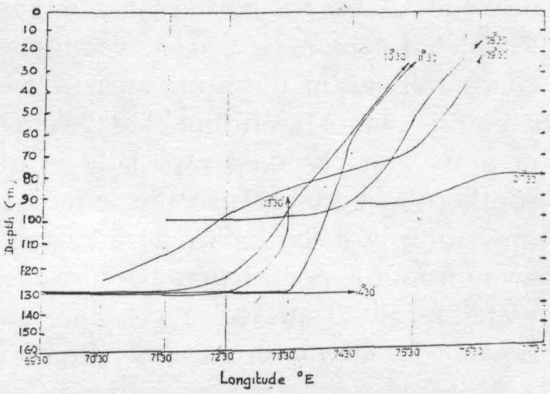

Fig. 9. *Vertical movement of 23°C isotherm between 69°30'E and south west coast of India during July, 1991 at different latitudes.*

levels clearly revealed higher concentrations in the coastal waters between 9° and 10°N latitudes in the south eastern region and also between 18° and 21°N latitudes

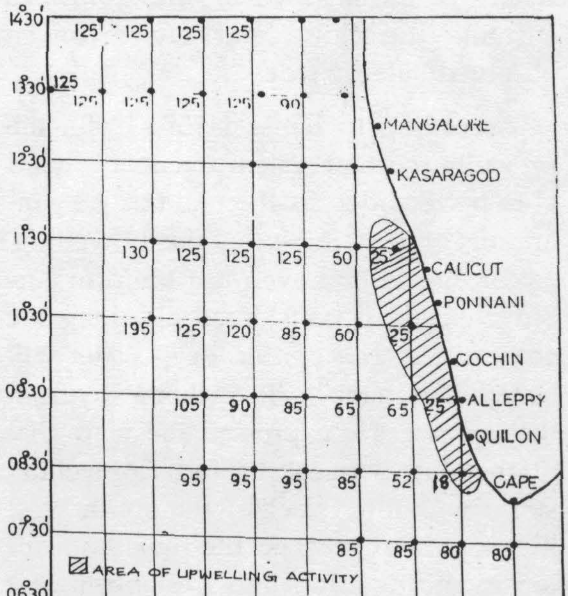

Fig. 10. *Depth of occurrence (m) of 23°C isotherm at different stations in the south eastern Arabian Sea during July 1991 as a possible indicator of the process of upwelling*

near the coast in the north eastern region. Zooplankton biomass also showed higher concentrations in the same areas. However, this cannot be attributed to the effect of upwelling observed especially in the southern region because the 'effect' of upwelling is to be looked at a distance away from the point where the upwelled water reached surface levels since the upwelled water is carried away from the area of surfacing by the prevailing surface currents which are southerly during July - August. Hence higher concentrations of nutrients, phytoplankton and zooplankton observed in the coastal areas during the south west monsoon season should be interpreted with care especially with regard to it's origin. There are few occasions where in the absence of strong surface currents, the 'cause' and 'effect' can be observed side by side.

According to Banse (1959, 1968), the prevailing current system and not the wind is to be regarded as the main cause generating and maintaining the upwelling. According to him even if a uniform current velocity is considered all along the coast, the rise of denser, deep water will be stronger in the north farther away from the equator. He expressed the view that off the south west coast of India, upwelling starts with the onset of the south west monsoon and reached the maximum intensity during July-August, established by late September and ends by mid October. Varadachari (1961) found that a northerly wind driven current on the east coast and a southerly wind driven current on the west coast in the northern hemisphere induce upward motion near the coast.

Sharma (1966) while reviewing the opinion given by earlier workers (Bense, 1959; Ramasastry and Myrland, 1960; Ramamirtham and Jayaraman, 1960) based on the work carried out during the late fifties and early sixties expressed the view that owing to limitations of facilities, none of the reports are based on continuous studies for at least one year. According to him unless the continuous variation of any one of the relevant parameters is considered, it is not possible to get a clear picture of the commencement and cessation of upwelling and sinking. Sharma (1966) after analysing hydrographic data (in the absence of adequate Bathythermograph data) for the period March, 1964 to August, 1965 and constructing topographic maps for the top of the thermocline and vertical time sections for sea water temperature for a coastal station near Cochin noticed that in the month of February the prevailing winds being northerly to north easterly and with offshore transport of the surface water, the conditions are favourable for upwelling. In the month of August the winds are south westerly to westerly and the surface flow few miles away from the coast being easterly to south easterly, turns parallel to the coast owing to boundary conditions giving rise to a southerly component. Further, the precipitation and river discharge near the coast stratify the surface layers opposing any tendency for upwelling. Except for a slight southerly component in the current, in general, all other conditions are unfavourable for upwelling in August and September along the south west coast of India.

Darbyshire (1967) concluded that there is no system of wind generated upwelling during the south west monsoon period along the west coast of India and the dense bottom waters approached the surface because of the immediate interplay of the current with the tilting of the sea surface and the thermocline. Wyrtki (1973) concluded that upwelling is nothing more than the shoaling of nearshore isopleths, a consequence of baroclinic adjustment to the anticyclonic monsoon circulation and hence is remotely forced.

Sharma (1968) after conducting a study of the seasonal variations of some hydrographic parameters of the shelf waters off the west coast of India concluded that upwelling along the west coast of India starts earlier in the south and slowly extends towards north. The process commenced at deeper depths earlier in February and reached the surface by May. Upwelling comes to an end by July-August when the top of the thermocline reaches the surface layers. The influence of the river run off and rain stratify the surface layers from July onwards thereby opposing the process.

Studies made by one of the authors (Pillai, 1983) revealed that none of the above mentioned theories is directly applicable to the south west coast of India as a whole. The causative factors which bring up the subsurface waters to surface levels vary in space and time. The studies revealed that the process of upwelling started as early as February at the bottom levels. It started at the different sections at different times each year. The commencement of the process in February was possibly initiated by the northerly winds which would transport the surface water away from the coast there by initiating a vertical ascending motion from below. Perhaps the depth at which the motion gets started, would to a great extent, depends upon the velocity, direction and duration of the prevailing wind system in a specific area, the bottom topograpy, the prevailing current system at the surface levels and also the vertical stability of the water column. The speed of the ascending motion would also depend on the continuance of the above mentioned favourable factors with more or less the same intensity. A closer examination of the prevailing wind system during the south west monsoon season revealed the presence of favourable northerly and north westerly components in certain localities where upwelling intensity also showed correspondingly higher values.

According to Longhurst and Wooster (1990) sea level can be an indicator of upwelling. The authors compared variations in oil sardine abundance with sea level as an indicator of recruitment success. One has to consider the invasion of the shelf with oxygen poor waters which occurs during Malabar coast upwelling, would tend to exclude oil sardine from the coastal region where diatom blooms are most intense. In such an event it is oil sardine rather than mackerel whose spawning strategy will place at risk that year's recruitment. According to them, this is the most likely explanation of statistical relationship between sardine recruitment failure and unusally early remotely forced upwelling. They also opined that the abundance of oil sardine on the Malabar coast is highly variable in the decadal scale. O- group recruitment to the fishery begins towards the end of summer monsoon. At this time sea level indicates remote forcing of upwelling (caused by the geostrophic upsloping of the isopleths towards the coastal) rather than the wind driven upwelling that occurs during the monsoon. Unusually early remote forcing appears to inhibit subsequent recruitment perhaps through the exclusion of spawning fish from the neritic zone by oxygen deficient upwelled water.

Very often a higher zooplankton biomass is observed away from the point where the upwelled water reached surface levels. It also varied from year to year. The upwelled water is carried away from the point of surfacing by wind generated or density currents which change its direction from place to place and from time to time. Hence the 'effect' of upwelling is to be looked at a distance from the point where the upwelled water reached surface levels. Higher concentration of nutrients, phytoplankton and zooplankton observed in the coastal areas during the upwelling season should be interpreted with care especially with regard to it's origin. There are rare occasions where in the sbsence of strong surface currents the 'cause' and 'effect' can be observed side by side. The results of the 1991 monsoon survey in the same area revealed very interesting features in support of the above claims.

Post-monsoon

It is well known that three factors such as light, nutrients and primary production are of importance for determining the biological productivity of an area. Light penetration of the waters determine the depth of the euphotic zone while the nutrients, especially nitrates and phosphates indicate the fertility of the waters to promote productivity and the availability of phytoplankton reveal the production at the primary level. Light penetration in the sea largely depends on surface irradiance and the type of water mass in a region.

From the present investigation, it was found that the average depth of the euphotic zone in the west coast is 60 m. According to Radhakrishna *et al* (1978) and Qasim (1982) the depth of the euphotic zone in the northern Arabian Sea was 40 m and that of the southern part 60m. However, in the present investigation during the post monsoon period indicated 75 m depth of photic zone along the north west coast in the oceanic waters. The photic zone in the Wadge bank area along the south west coast indicated 45-50 m depth only.

The source of the supply of nutrients in the topmost 100m layer in the west coast is largely due to upwelling and river run off and also drainage from the land. Very often the nutrients brought to the surface are not fully utilized and significant concentrations are detected in the surface and column waters, even during the period when there is no upwelling. The nitrogenous products upto 100m depth did not show any significant value but indicated a negative correlation with the primary production.However, the inorganic phosphate measured in the present investigation also indicated a close negative correlation with the chlorophyll-*a* values revealing that most of the nutrients have been utilized by the phytoplankton during the post-monsoon period. The values of silicates in the column waters of the west coast during the postmonsoon period showed a higher level with increase in depth. Upto 100 m depth, the values generally showed a lower level and below 100 m, the values were slightly higher, revealing that the silicates upto 100 m depth have been utilized by the diatoms for their cell wall formation.

According to Qasim (1977) and Radhakrishna *et al* (1978) the west coast of India is an area of wide temporal and spatial fluctuations from the point of productivity. Recently Nair and Pillai (1983) have reviewed the productivity of the Indian seas. Bhargava *et al* (1978) while studying the productivity of the Arabian Sea mentioned average values ranging from 76-806 $mgC/m^2/day$ in different months. Silas (1977) reported the productivity on the shelf waters between 50-200 m along the west coast of India as 470 $mgC/m^2/day$ and for the off-shore as 180 $mgC/m^2/day$. However, Radhakrishna *et al* (1978) reported high values of 875 $mgC/m^2/day$ in the shelf and 607 $mgC/m^2/day$ in the offshore waters of the Arabian Sea. Further, Qasim *et al* (1978) have reported a maximum production value of 0.75 $gC/m^2/day$ in the coastal waters off Karwar and Calicut. Radhakrishna (1989) has reported that during October '67, the production from Cochin to Quilon varied from 0.38 to 1.11 $gC/m^2/day$. Further, Radhakrishna (1989) has stated that high phytoplankton production during post monsoon months extending upto March-April and low in the south-west monsoon from the coast off Maharashtra. In the present investigation, conducted during the post-monsoon season, the shelf waters of the south-west coast of India indicated 0.19 $gC/m^2/day$ and the offshore waters an average value of 0.14 $gC/m^2/day$.

Based on the present investigation, it was observed that the regions of high concentrations of chlorophyll-*a* are the coastal waters of Gujarat and Bombay along the north-west coast and Wadge Bank area along the south-west coast. Integrated values of chlorophyll-*a* between 0-75 m depth of the west coast showed that much of the chlorophyll-*a* occurs below the surface. The concentration of photosynthetic pigment was found to exist between 20-30 m. Column production of chlorophyll-*a* along the west coast indicated that the southern region has higher values than northern regions. However, according to Radhakrishna *et al* (1978) and Qasim (1982) the average production in the northern Arabian sea is higher than the average for the entire west coast implying that the northern region is by and large more fertile than the southern region. Recent studies by Balachandran *et al* (1989) in the inshore surface waters of Cochin have pointed out the role of photosynthetic pigments as indices of biological productivity along the south west coast of India.

It is a general belief that upwelling along the south west coast during the south west monsoon has considerable influence on the coastal production. According to Subrahmanyan (1959), along the west coast maximum production of phytoplankton takes place during the south-west monsoon months of May-September after which there is a decline in the productivity. Comparatively low to moderate values of primary production along the north west coast observed during the post-monsoon season in the present study may be due to the cessation of upwelling phenomenon along the entire west coast. Earlier workers (Banse, 1959; Ramasastry and Myrland, 1960; Ramamirtham and Jayaraman, 1960 and Pillai 1982) have reported that upwelling may continue upto September or October. However, according to Sharma (1966) upwelling along the west coast start even as early as February-March and upwelled water gradually reaches the surface by May and upwelling ceases by July-August and sinking will start from September or October. The present investigations conducted during October-November periods support the views of above mentioned workers.

In conclusion, it could be stated that (i) the level of primary production and chlorophyll-*a* content of the waters during the post-monsoon along the south-west coast is generally high; that the waters off Cochin and Wadge Bank area off Cape are highly fertile with column production of >100 mg/m^2 of chlorophyll-*a* and primary production of 0.8 gC/m^2/day (ii) the maximum productivity occurs at subsurface layers (10-30 m) implying photoinhibition at the surface levels (iii) there is no direct relationship between chlorophyll production and availability of inorganic nutrients and (iv) the eastern Arabian sea is a region of great contrast constituting both very rich and very infertile pockets of photosynthetic materials.

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