Phytoplankton production and chlorophyll distribution in the eastern and central Arabian Sea in 1994–1995

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Measurements of primary production, chlorophyll *a*, particulate organic carbon (POC) and nitrogen (PON) were carried out during the inter-monsoon, winter monsoon and summer monsoon seasons of 1994–95 in the central and eastern Arabian Sea. The integrated production rate varied between 193–199, 337–643 and 770 $mgCm^{-2} d^{-1}$ respectively in the open ocean (along 64°E) for the three seasons. The corresponding values in near coastal stations were 281–306, 200–807 and 440–1760 $mgCm^{-2} d^{-1}$. Column chlorophyll *a* values for these seasons were between 8–17, 13–27 and 34–44 mgm^{-2} in the open ocean and 11–12, 10–34 and 16 to 88 mgm^{-2} for near coastal waters. A subsurface chl maximum (SCM) at ~40–60 m was conspicuous during the intermonsoon period. The seasonal variation in productivity was consistent with the circulation patterns and associated nutrient levels. Phytoplankton and zooplankton (as carbon) contributed 10–22% of POC. Estimated division rate of phytoplankton varied from 0.7 to 3 for different seasons and locations.

INFORMATION on the primary production and chlorophyll is available to a reasonable extent from the northern regions of the Arabian Sea[1-7]. In recent years renewed interest in the region has been generated as part of the Joint Ocean Global Flux Study to assess the role of the oceanic regions as a source or sink of atmospheric CO_2 on a global context. The aim of this work was to obtain the rate of phytoplankton production and biomass in different seasons and examine the spatial variations. Data obtained during three cruises are presented in this article.

Materials and methods

Sampling was carried out onboard ORV *Sagar Kanya* during April–May 1994 (inter-monsoon), February–March 1995 (winter monsoon) and July–August 1995 (summer monsoon) (Figure 1). Water samples were collected from eight depths (0, 10, 20 m and then every 20 m up to 120 m) using 12 litre Go FLo samplers attached to the plastic coated winch wire. Water samples from each depth were transferred to 5 Nalgene PC bottles[8] of 300 ml capacity. 185 kbq of radioactive carbon (^{14}C) in 1 ml of aqueous solution was added to each of the PC bottles (^{14}C was obtained from BRIT, Department of Atomic Energy). To determine the initial activity in the bottles, 0.2 ml from one of the bottles was transferred to a scintillation vial and 0.2 ml of ethanolamine was added to it. 100 ml from one of the bottles was filtered on to 25 mm GF/F (nominal pore size 0.7 μm) filter paper for determining the initial adsorption of the ^{14}C by the particles in the bottle. From the remaining four bottles from each depth, one was covered with aluminium foil and transferred to a black bag to determine the dark production. Thus, one dark and 3 light bottles were used from each depth for *in situ* in-

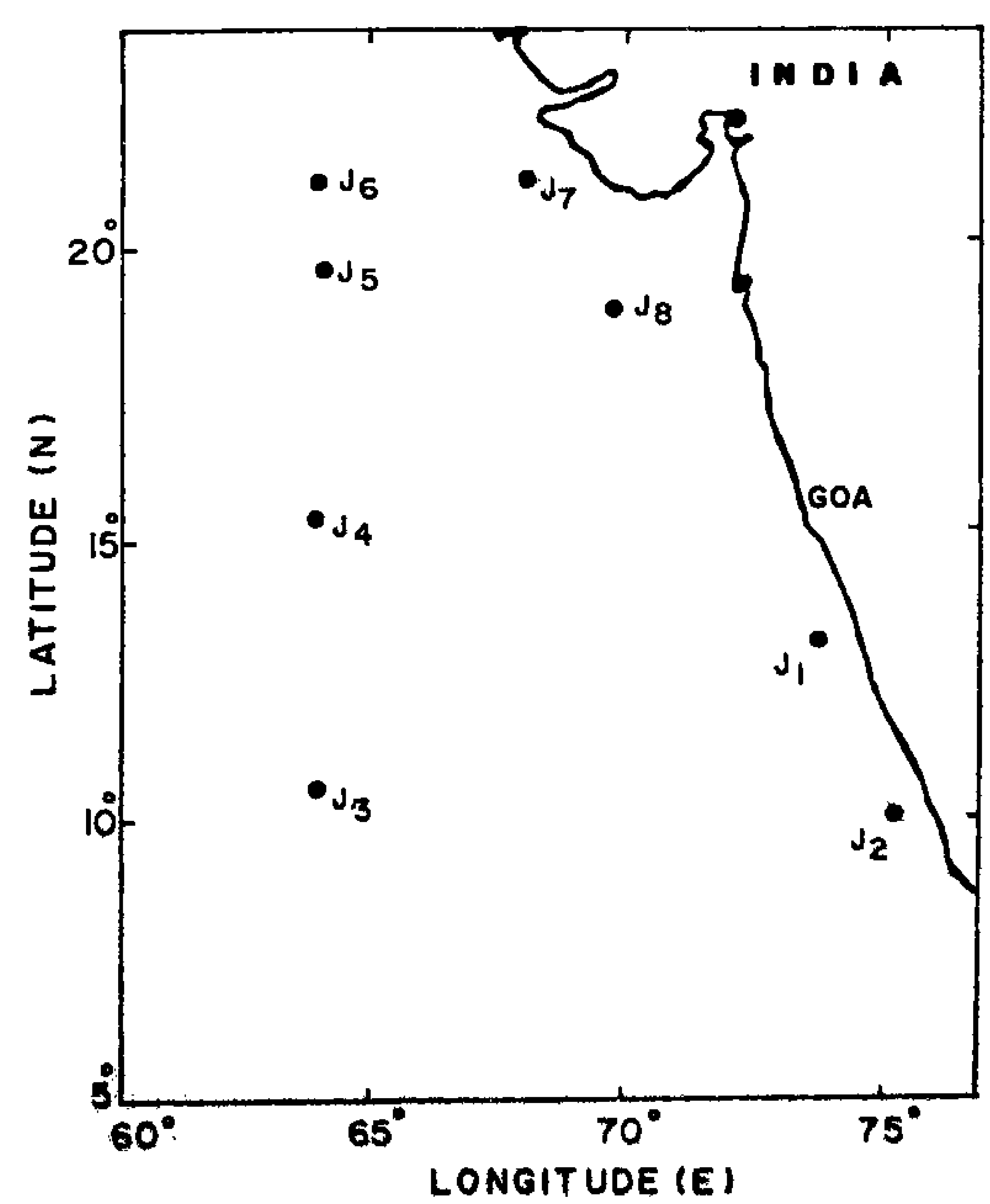

Figure 1. Location of sampling stations.

Table 1. Primary production and chlorophyll *a* in the eastern and central Arabian Sea (1994–95)

	Primary production ($mgCm^{-2}d^{-1}$)						Chlorophyll *a* (mgm^{-3})					
	Surface			Column			Surface			Column		
Station	I	II	III	I	II	III	I	II	III	I	II	III
Open ocean stations												
J3	0.7	3.8	12.8	199	337	770	0.04	0.06	0.42	9	13	44
J4	0.8	12	–	193	606	–	0.05	0.41	0.45	17	27	34
J5	–	6.7	–	–	477	–	0.03	0.27	–	9	21	–
J6	11.9	35.8	–	–	643	–	0.04	0.17	–	8	19	–
Near coastal stations												
J2	–	1.1	49.9	–	200	660	–	0.03	1.34	–	10	16
J1	3.3	–	9.4	281	–	1760	0.05	–	0.09	11	–	88
J8	–	–	12	–	–	440	–	0.22	0.29	–	17	21
J7	8.8	21.4	–	306	807	–	0.05	0.31	–	12	34	–

Inter-monsoon, winter monsoon and summer monsoon observations are indicated by I, II and III. First 4 stations (J3–J6) are from open ocean (along 64°E) and the rest are from coastal areas.

cubation. The bottles were later suspended at appropriate water depths using polypropylene line attached to a buoy. The system was deployed approximately one hour before sunrise, and was retrieved half an hour after sunset. Upon retrieval, the samples were filtered on to GF/F filters and the filters were transferred to scintillation vials to which 0.25 ml of 0.5 N HCl was added and held at room temperature until later analysis. In the shore laboratory sample vials were left uncapped overnight to dry. Liquid scintillation cocktail was added to the vials and after about a day, during which time the scintillation were stabilized, they were counted in a Packard 2500 TR liquid scintillation system. The counted rates were converted to daily production rates ($mgCm^{-3}d^{-1}$). The production rates obtained from the triplicates generally agreed within ± 10% and averaged to obtain mean values for a given depth (Table 1). Dark bottle production rate was subtracted from the mean rate of light bottle to correct for non-photoautotrophic carbon fixation or adsorption. The daily production rate of various depths was used to calculate the water column integrated production ($mgCm^{-2}d^{-1}$).

Chlorophyll *a* was determined by filtering one litre of water samples from each depth using 47 mm GF/F filters (nominal pore size 0.7 μm) under low vacuum (less than 100 mm Hg). The chlorophyll was extracted using 10 ml of 90% acetone (AR) in the dark for 24 hours in a refrigerator. Samples are brought to room temperature and the fluoroscence was measured in a Turner Designs Fluorometer before and after acidification with two drops of (1.2N HCl) acid[8]. The chlorophyll *a* was calculated from the fluoroscence using the appropriate calibration factor. The value from each depth was integrated to obtain the column concentration. The instrument was calibrated with pure Chl *a* (Sigma) before the cruise.

For the measurements of suspended particulate organic carbon (POC) and nitrogen (PON), 3 litres of water samples from each depth was filtered on to precombusted 47 mm GF/F filters (nominal pore size 0.7 μm). The filter is removed, wrapped in precombusted aluminium foil and stored frozen in a deep freezer (–20°C) before analysis[8]. Later filters were dried overnight at 60°C. The dried filters were exposed to fuming HCl to remove inorganic carbonate. The filters dried again at 60°C were divided equally into four sections and analysed for POC and PON samples on a Perkin Elmer 2400 CHN analyser. Standards and blanks were run before analysis of samples.

Results

During the inter-monsoon period the surface primary production varied from 0.7 to 11.9 $mgCm^{-3}d^{-1}$ in the three open ocean station samples and from 3.3 to 8.8 $mgCm^{-3}d^{-1}$ in the two coastal stations (Table 1, Figure 2). The surface production at the northernmost station J6 was higher by an order of magnitude than those of the other two stations. Most of the stations sampled had higher production in subsurface layers compared to that at the surface (Figure 2). Column production for two

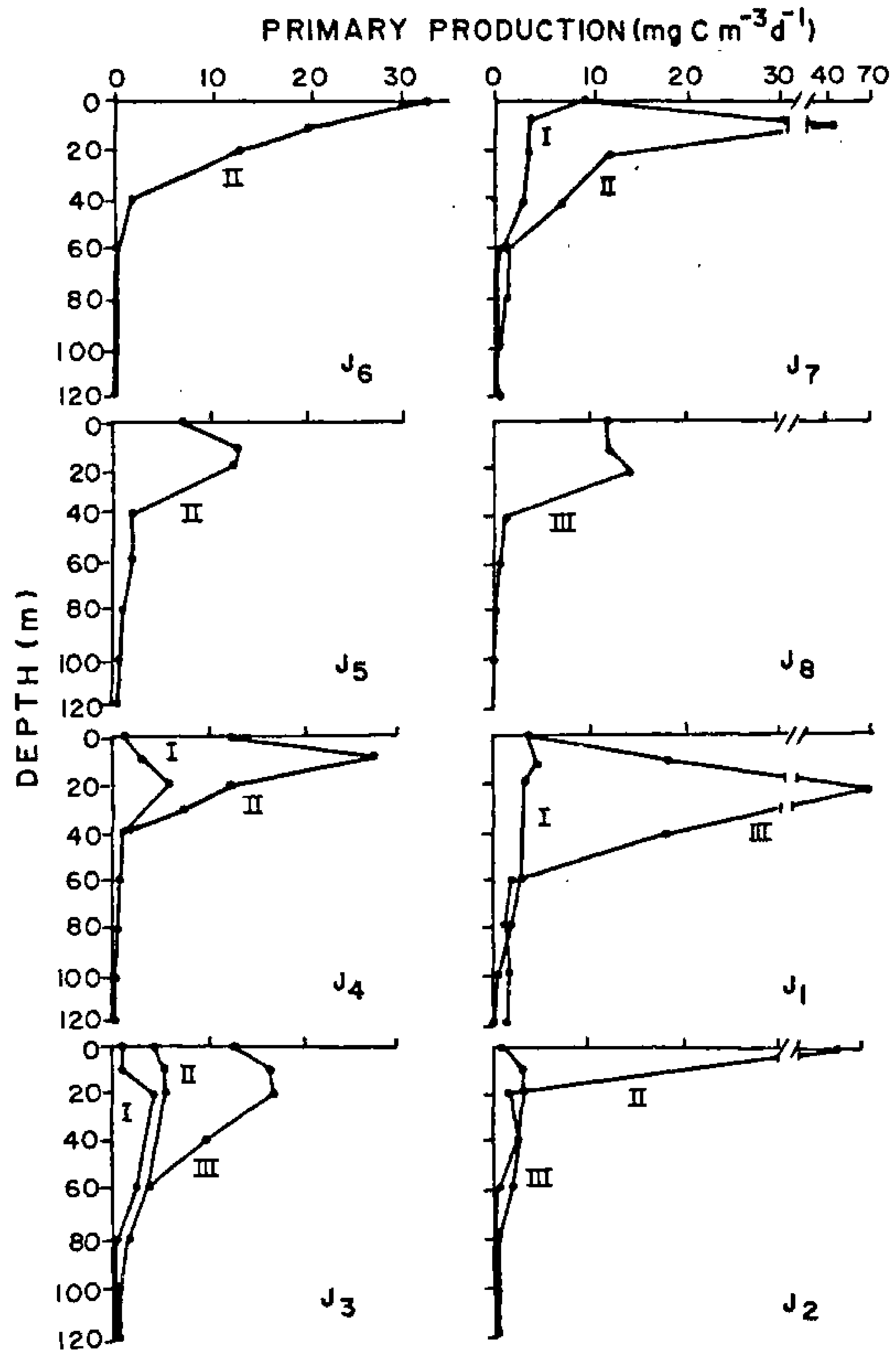

Figure 2. Primary production during the inter-monsoon (I), winter monsoon (II) and summer monsoon (III) periods.

open ocean stations varied from 193 to 199 mgCm^{-2} d^{-1} and for the coastal stations from 281 to 306 mgCm^{-2} d^{-1} (Table 1). During the winter months the offshore and inshore surface production varied from 3.8 to 35.8 and 1.1 to 21.4 mgCm^{-3} d^{-1}. The column production was between 337 and 643 mgCm^{-3} d^{-1} in the offshore region and between 200 and 807 mgCm^{-2} d^{-1} in the coastal region. Comparison of production between inter-monsoon and winter monsoon seasons shows higher values during the latter. During the summer monsoon the surface production in the single offshore station was 12.8 while that at the coastal stations varied from 9.4 to 49.9 mgCm^{-3} d^{-1}. The corresponding column production was 770 at the offshore station while that in coastal stations varied from 440 to 1760 mgCm^{-2} d^{-1}. Thus during the three seasons sampled, higher production rates were generally observed at the coastal stations with highest being during summer monsoon.

Chlorophyll distribution

The surface chlorophyll concentration was generally lowest during inter-monsoon seasons, with values in the range of 0.03 to 0.05 mgm^{-3} in both coastal and open ocean stations (Table 1, Figure 3). The column values were also similar (~ 11 mgm^{-2}) in these two regions during the season. The chlorophyll distribution exhibited pronounced subsurface maximum (SCM) at 60 m (Figure 3) in all stations sampled. During winter monsoon the surface Chl *a* exhibited a larger range and was between 0.06 and 0.41 and 0.03 to 0.31 mgm^{-3} respectively in the open and coastal water stations respectively. The corresponding column values were between 13 and 27 and 10 and 34 mgm^{-2}. SCM was present only at few stations and was between 40 and 60 m. At two open ocean stations occupied during summer monsoon, surface and column Chl *a* were between 0.41 and 0.45 mgm^{-3} and 34 and 44 mg m^{-2} respectively. Concentrations at the coastal stations varied from 0.09 to 1.34 mgm^{-3} while column values ranged from 16 to 88 mg m^{-2}. At the coastal station J1 where there were evidences of strong upwelling, column Chl *a* and primary production were the highest among all samples measured.

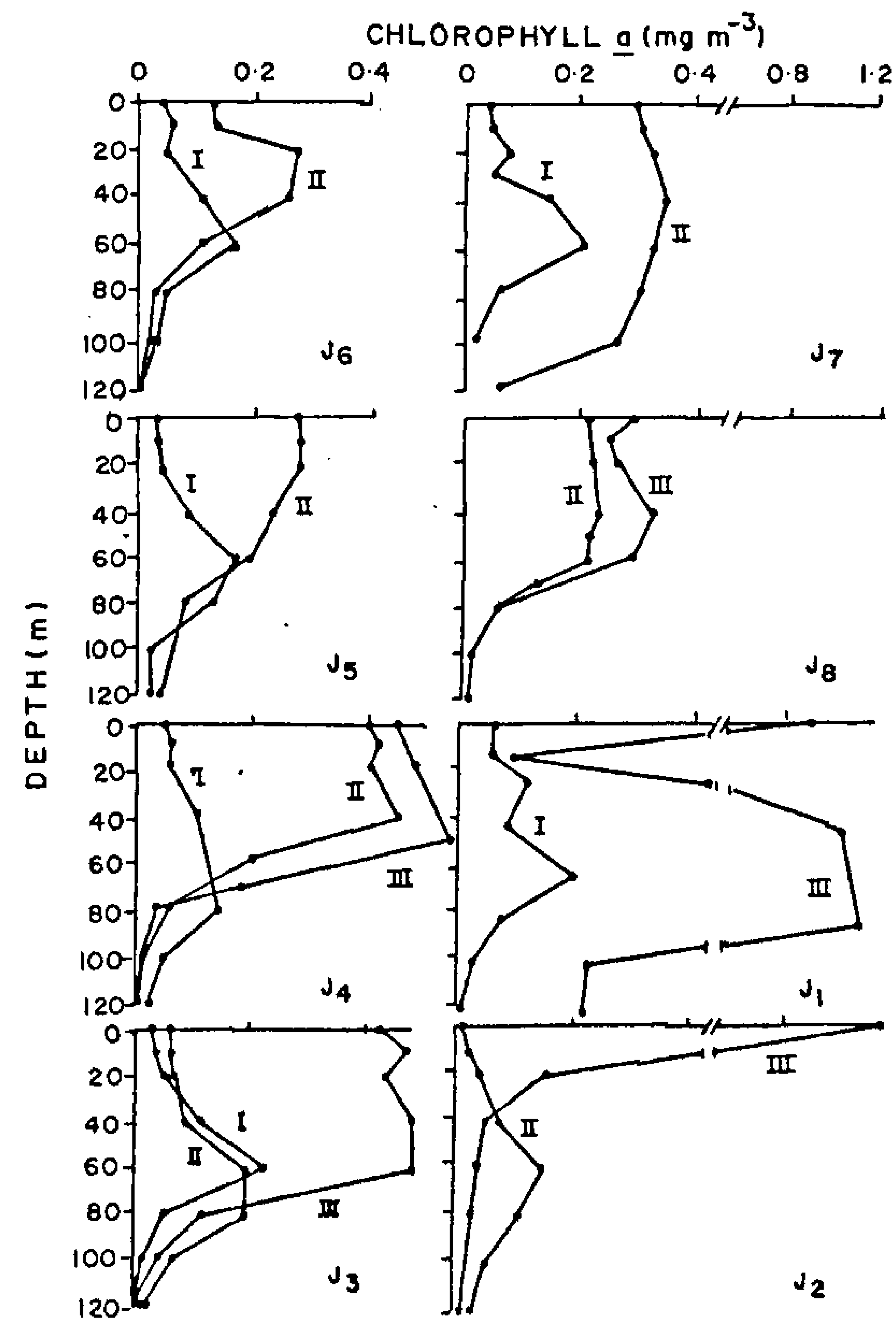

Figure 3. Chlorophyll *a* during the inter-monsoon (I), winter monsoon (II) and summer monsoon (III) periods.

Estimates of the turnover time scales of phytoplankton carbon in the eastern and central Arabian Sea can be derived from the column primary production rate and the standing stock of phytoplankton carbon. The latter was estimated from the measured Chl *a* using appropriate conversion factors (for regimes where nitrate was depleted a factor of 30 was used and where nitrate was repleted and light was limited a factor of 50 was used)[9]. The turnover time scales in the open and coastal stations during the three seasons sampled centered around (1 ± 0.5) days. This would correspond to a division rate of about 0.6–2 per day. These estimates indicate that there is no significant difference in the division rates spatially and temporally in the eastern Arabian Sea.

Particulate organic carbon and nitrogen

Depthwise values of Chl *a*, POC, PON and C/N (atomic ratios) from station J3 are shown in Figure 4 for three seasons. For other stations, measurements were not made for all seasons and therefore not presented here. During inter-monsoon, winter and summer monsoons the POC in the top 120 m had a range from 73 to 150, 140 to 290, 80 to 195 mgm^{-3}, and PON from 7 to 27, 12 to 24 and 5 to 15 mgm^{-3}. C/N ratios were between 7 and 12 up to a depth of 100 m. The ratio was 16 at 120 m. During winter monsoon C/N ratio was found to be higher with minimum and maximum being 9 and 23. A value of 23 for C/N was found during summer monsoon.

An estimate of the contribution of phytoplankton and zooplankton to the POC could be made by converting the Chl *a* concentration and zooplankton biomass to carbon by appropriate conversion factors. The phytoplankton carbon was estimated by multiplying Chl *a* by a factor of 30 and 50 depending on whether nutrient depleted or repleted and light limited. Zooplankton biomass was converted to carbon[10] by multiplying wet weight by a factor of 0.0235. Contribution by these two was in the range of 5–12 and 5–10%. During monsoon the combined contribution by phytoplankton and zooplankton to POC was 22%.

Productivity in relation to mixed layer settings

During inter-monsoon period, mixed layer along the western shelf was 25 m in the south and 10 m in the north[11–12]. Along 64°E mixed layer depth (MLD) remained thin with shallowing towards north. During winter monsoon mixed layer varied from 80 m to 120 m, the lower value being at 10°N. Along 64°E MLD deepened from 65 to 125 m between 11 and 17°N and thereafter shoaled to 80 m at 20°N. During summer monsoon MLD in the coastal waters was shallower (15 m) in the

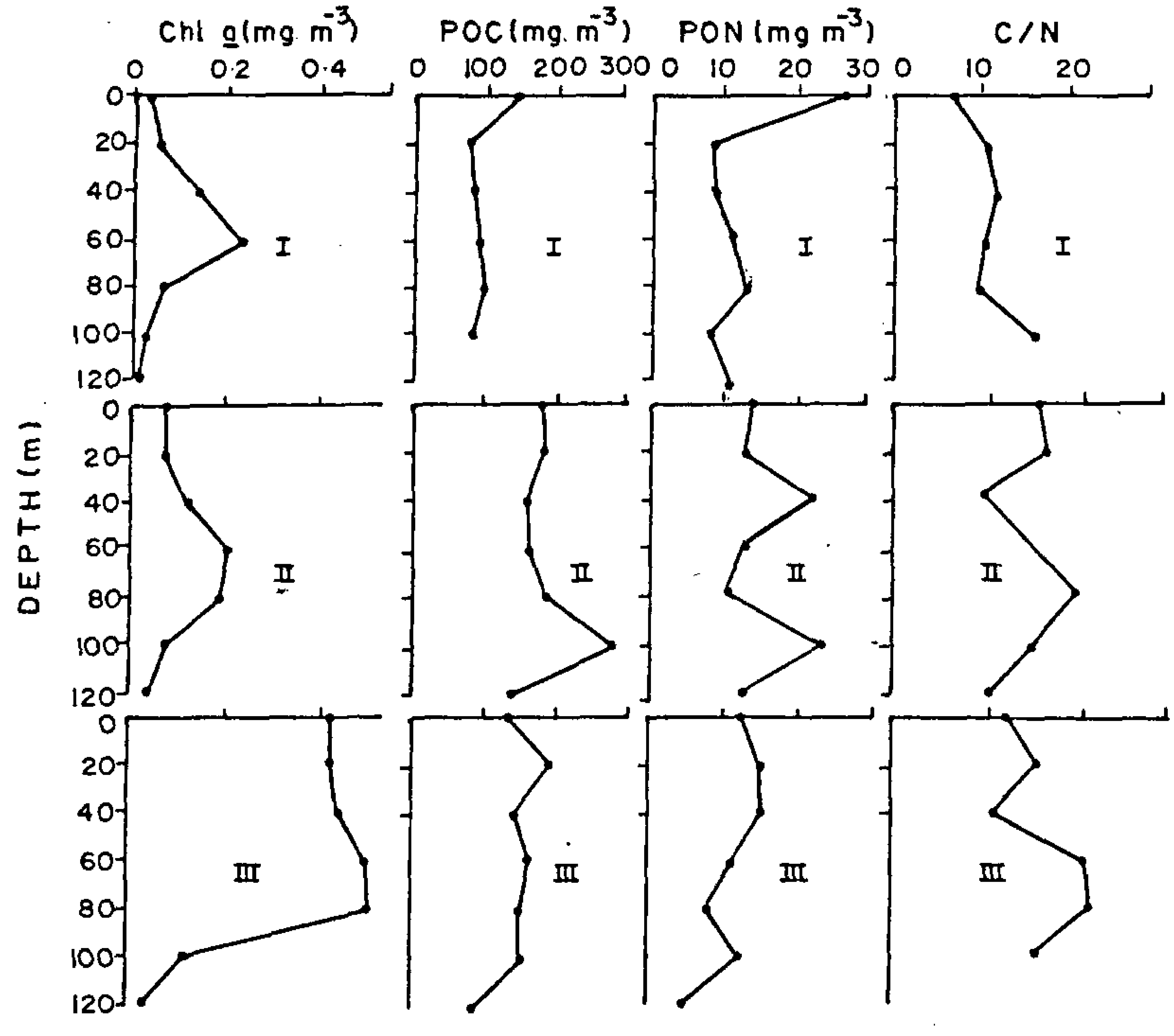

Figure 4. Chlorophyll *a*, particulate organic carbon (POC), particulate organic nitrogen (PON) and C/N ratio (atomic) during inter-monsoon (I), winter monsoon (II) and summer monsoon (III) periods at station J3.

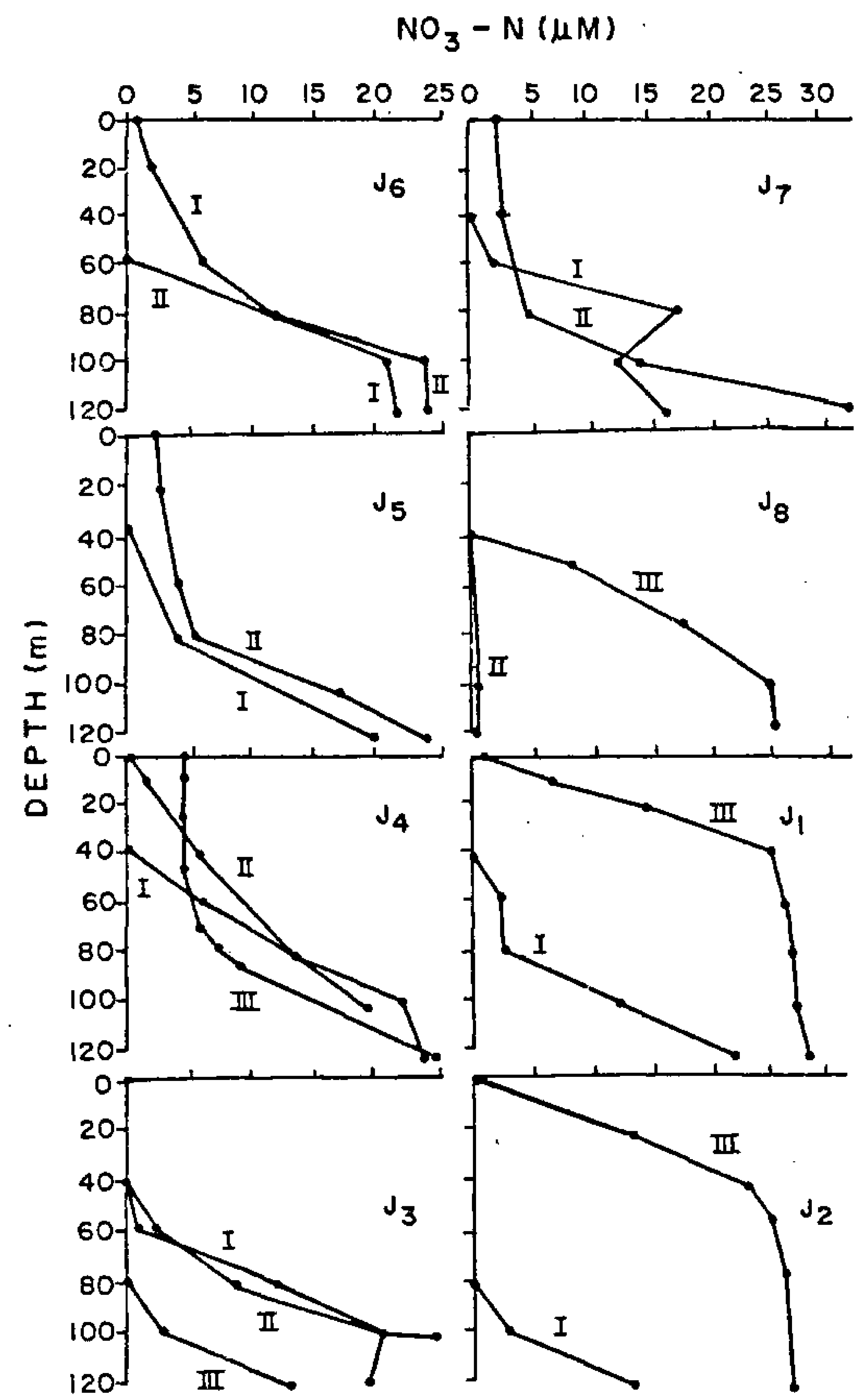

Figure 5. Vertical distribution of nitrate during the inter-monsoon (I), winter monsoon (II) and summer monsoon (III) periods.

south while it deepened northward (45 m). Along 64°E MLD was 90–80 between 11–14°N and about 45 m at 16–18°N.

During inter-monsoon the concentration of nitrate in the shelf and along 64°E was near zero in the upper 40–60 m (Figure 5). 1 µM of nitrate concentration was generally found around 60 m or deeper in most areas. During winter monsoon, the nitrate distribution in the surface waters showed distinct difference between north and south. Shelf waters had near-zero nitrate up to 40 m in the southern region whereas in the northern (off Gujarat) they had 2 µM nitrate at the surface. A similar trend was observed along 64°E. The upper 40 m had near zero nitrate in the southernmost station and further northward 2 µM nitrate was measured at 20 m. During summer monsoon, surface nitrate in the shelf region was high from south of Goa. Thus, off Goa 1 µM nitrate was measured at 24 m, off Mangalore 2.8 µM at 10 m and off Cochin 13.2 µM at 22 m. Along 64°E nitrate was near zero to a depth 100 m in the latitudinal range of 11–18°N except for a patch of 4.6 µM at surface at 16°N.

Discussion

The inter-monsoon period showed lowest primary production and chlorophyll concentration (Table 1, Figure 1). Primary production in the eastern Arabian Sea during April–May was reported to be in the range of 161–1590 (av. 607 $mgCm^{-2} d^{-1}$) in the offshore areas and 109–2665 (av. 876 $mgCm^{-2} d^{-1}$) in the shelf region[13]. Earlier studies during IIOE have shown that during March–October the shelf waters of Arabian Sea have primary production above 500 and along 64°E between 150 and 500 $mgCm^{-2} d^{-1}$. During November–April the same region had more variable production both in the shelf and offshore[1], however the overall values were less with larger areas between 10 and 15°N having low values, i.e. < 100 $mgCm^{-2} d^{-1}$. Column primary production has been observed to be more than 1000 $mgCm^{-2} d^{-1}$ during southwest monsoon and 500 $mgCm^{-2} d^{-1}$ during northeast monsoon over most of the northern Arabian Sea[7]. During August 1987 primary production and chlorophyll *a* between 8 and 20°N was reported to be between 365 and 1130 $mgCm^{-2} d^{-1}$ and 13.1 to 32.5 mgm^{-2} in the central Arabian Sea[14]. Although the methods adopted for the measurement of primary production earlier were different from those used in the present study, the values during different seasons are generally similar, with the inter-monsoon period having the lowest primary production and phytoplankton abundances. This could be attributed to the low or near-zero nitrate level in the upper layers. During winter monsoon, low surface water temperature caused by cool, dry wind leads to vertical convection and mixing. This enhances the nutrient supply to the mixed layer and results in higher phytoplankton production and chlorophyll *a* has been observed[15,16]. During this study, the highest primary production was observed during the summer monsoon near the coast. This was due to the upwelling contributing to high nitrate levels in the top layers which in turn supported high phytoplankton production and chlorophyll. Thus at station J1 off Mangalore, where strong upwelling signature was evident, the highest column production and chlorophyll were measured. At this station the nitrate level at 10 m was 2.8 µM, indicating a direct influence of nutrients on the production and chlorophyll. The increase or decrease in both biomass and productivity was in part due to the shoaling or deepening of the mixed layer. For inter-monsoon period, Jochem *et al.*[17] reported primary production in the range of 680 to 790 $mgCm^{-2} d^{-1}$ and chlorophyll from 28.7 to 35.8 mgm^{-2} at 18°N, 65°E. During September the primary production and chlorophyll in the coastal Arabian Sea was reported to vary from 235 to 511 $mgCm^{-2} d^{-1}$ and from 12 to 46 mgm^{-2}

(euphotic zone was considered as 70 m for computing the column chlorophyll from the mean chlorophyll value given in Table 1)[18].

POC and PON values reported in this work at station J3 (up to a depth of 120 m) had maximum values of 150 and 27 mgm^{-3}. Jochem *et al.*[17] observed highest values of both POC and PON from one station from the central Arabian Sea higher than the values reported here. These authors found that subsurface maxima of POC coincided with that of Chl *a*, a result which is not observed in this work. C/N (atomic ratio) measured in this study at J3 was more than that reported by Jochem *et al.*[17]. The probable reason for a higher C/N ratio could be due to the higher level of detritus (we have not made any estimate of detritus concentration).

Division rates of phytoplankton as estimated from turnover rate did not show significant seasonal variation with values centering around 2 in the open ocean. Banse[9] estimated division rates of phytoplankton (from the measurements made during March 1963 and mid-May, 1964) for January–May to be between 0.5 and 1.5 d^{-1}, while for October–November, to be 1.5 d^{-1}. Although there are differences in the type of filters used and techniques adopted for measurements of chlorophyll over the years with corrections applied to earlier data, the estimates of division rates do not seem to differ significantly.

Observations made for the three seasons point towards the seasonal fluctuations in the productivity regimes of the eastern and central Arabian Sea. The entire area becomes more or less oligotrophic during the intermonsoon period. During winter monsoon the northern latitudes (north of 15°N) became more productive due to winter cooling and convective mixing[15]. During the summer monsoon primary production increases along the eastern Arabian Sea as a result of upwelling[18].

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