Seasonality and composition of phytoplankton in the Arabian Sea

Surekha Sawant and M. Madhupratap

National Institute of Oceanography, Dona Paula, Goa 403 004, India

Phytoplankton abundance and composition were studied from the central and eastern Arabian Sea during three seasons namely inter-monsoon, winter and summer. Overall, phytoplankton population density was high during winter and summer periods and low during the inter-monsoon. Integrated cell numbers in the upper 120 m was from 0.4 to 1.2, 1.7 to 170 and 0.3 to 10 ($\times 10^8$) cells m^{-2} during inter-monsoon, winter and summer monsoon periods respectively. Diatoms comprised 86% of the total population when three seasons were combined, followed by cyanobacteria (7%) and dinoflagellate (6%). The common diatoms were *Nitzschia* sp., *N. seriata*, *N. longissima*, *Thalassiothrix* spp., *Rhizosolenia* spp. and *Chaetoceros* spp. Some diatoms like *Fragilaria* sp., *Thalassiothrix longissima*, *N. longissima*, *Rhizosolenia* sp. and *Chaetoceros pendulus* were more abundant during the summer monsoon. The genera *Fragilaria*, *Guinardia*, *Hemiaulus*, *Leptocylindrus* and *Lauderia* appeared only during this season. A large number of diatoms were observed in sediment traps during winter.

THE Arabian Sea is an ocean basin where the strength of the physical forcing and biological response vary seasonally. Reversal of surface circulation during monsoon, seasonality in nutrient distribution and high light intensities drive phytoplankton growth processes in the Arabian Sea. Although there is considerable information on the primary production in the Arabian Sea[1-7], not much is known about phytoplankton abundance and composition except from inshore waters of the west coast of India[8-10]. In this article we compare the phytoplankton communities in the Arabian Sea during inter-monsoon, winter and summer monsoon periods. The research forms part of the Joint Ocean Global Flux Studies. As the main goal of these process studies is to quantify biogeochemical cycling in the Arabian Sea, here we present information on phytoplankton biomass and analyse their seasonal variations from coastal as well as open waters of this region.

Materials and methods

The study was conducted as part of the Joint Global Ocean Flux Studies (JGOFS-India) in the central and eastern Arabian Sea. Collections were made onboard *ORV Sagar Kanya* in the three cruises conducted from 12 April to 12 May 1994 (inter-monsoon), 3 February to 4 March 1995 (winter monsoon) and 20 July to 12 August 1995 (summer monsoon).

Forty-eight samples were collected from 6 stations during April–May while 56 and 40 samples from 7 and 5 stations, respectively were processed from winter and summer cruises (Figure 1). 250 ml seawater samples were drawn at 0, 10, 20, 40, 60, 80, 100 and 120 m depth from Go-Flo samplers fitted on a CTD rosette. Samples was fixed in 1% Lugol's iodine and preserved in 3% formaldehyde solution. The samples were stored in the dark at low temperature until enumeration within a period of one month after collections.

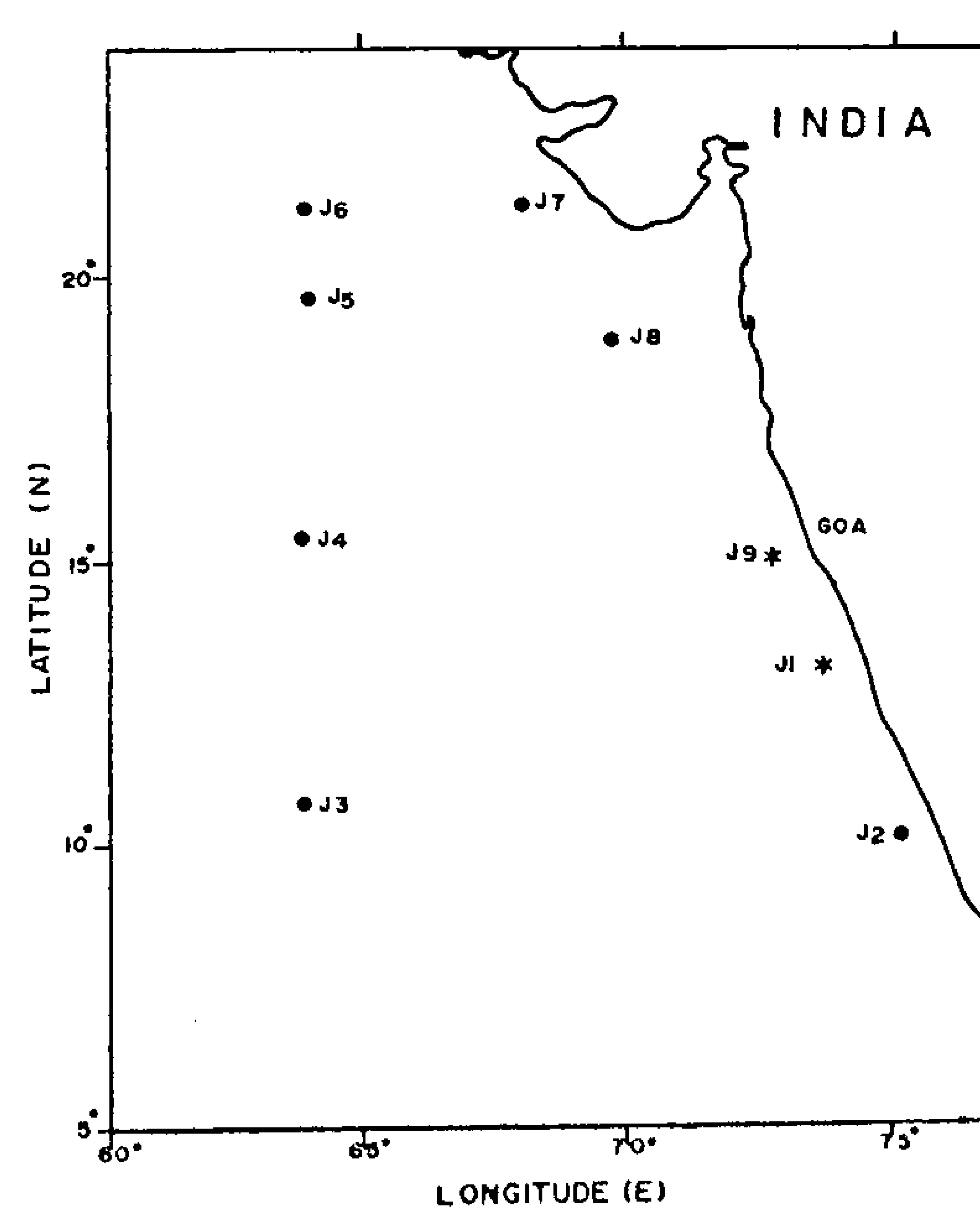

Figure 1. Station location of *ORV Sagar Kanya* cruises: 12 April–12 May (inter-monsoon), 3 February–4 March (winter monsoon), 20 July–12 August (summer monsoon) '●' denotes the stations occupied, '*' denotes additional stations during July–August, 1995, J4-J7 were not occupied during April–May, 1994, J9 and J1 were not occupied during February–March, 1995.

A settling and siphoning procedure was followed to obtain 20–25 ml concentrate. 1 ml of this concentrated sample was examined microscopically in triplicate under a stereoscopic binocular microscope (magnification 100 ×) in a Sedgewick–Rafter Plankton Counting Chamber for phytoplankton of size >5 µm. Species identification was done according to Subrahmanyan[11] and Wimpenny[12]. Chain-forming cells were counted on a per cell basis and empty cells were excluded. Phytoplankton not identified to species was collectively placed under generic listings.

Results

Abundances

The integrated phytoplankton cell counts for upper 120 m for different seasons are presented in Table 1. The abundances were generally higher during the winter monsoon, in northern areas both in coastal and open ocean stations compared to inter and summer monsoon periods. The highest cell count (133 × 10^3 cells l^{-1}) was observed during winter at 15°N 64°E, at 20 m depth (Figure 2 *a*). Phytoplankton population was dominated by *Nitzschia* sp. (47%) at this depth. Diatoms formed the major group in this season making an overall contribution of 87%, whereas, dinoflagellates contributed 7% followed by cyanobacteria comprising *Trichodesmium* sp. (6%).

The abundance of phytoplankton was quite low during the inter-monsoon period. Integrated cell counts ranged from 0.4 to 1.4 (10^8 cells m^{-2}). The offshore stations at 15°N 64°E had the maximum cell count (9.4 × 10^3 cells l^{-1}) at 20 m (Figure 2 *a*), where *Nitzschia seriata* and *Chaetoceros* sp. were the dominant phytoplanktons contributing 50% and 15% respectively. Diatoms formed 90% of the phytoplankton during this season followed by cyanobacteria (6%) and dinoflagellates (4%).

The only open ocean station (11°N 64°E) sampled

Table 1. Integrated phytoplankton abundance (10^8 cells m^{-2} ; 0–120 m depth) at different stations and seasons

Stations	April–May	February–March	July–August
Open stations			
J3 11°N 64°E	0.5	1.7	10
J4 15°N 64°E	1.2	47.0	–
J5 19°N 64°E	0.8	6.1	–
J6 21°N 64°E	0.7	55.4	–
Coastal stations			
J7 21°N 67°E	0.4	170.0	–
J8 19°N 70°E	–	91.0	0.4
J9 15°N 70°E	–	–	0.3
J1 12°N 74°E	–	–	2.3
J2 10°N 75°E	1.4	3.4	0.7

– indicates no observation was made.

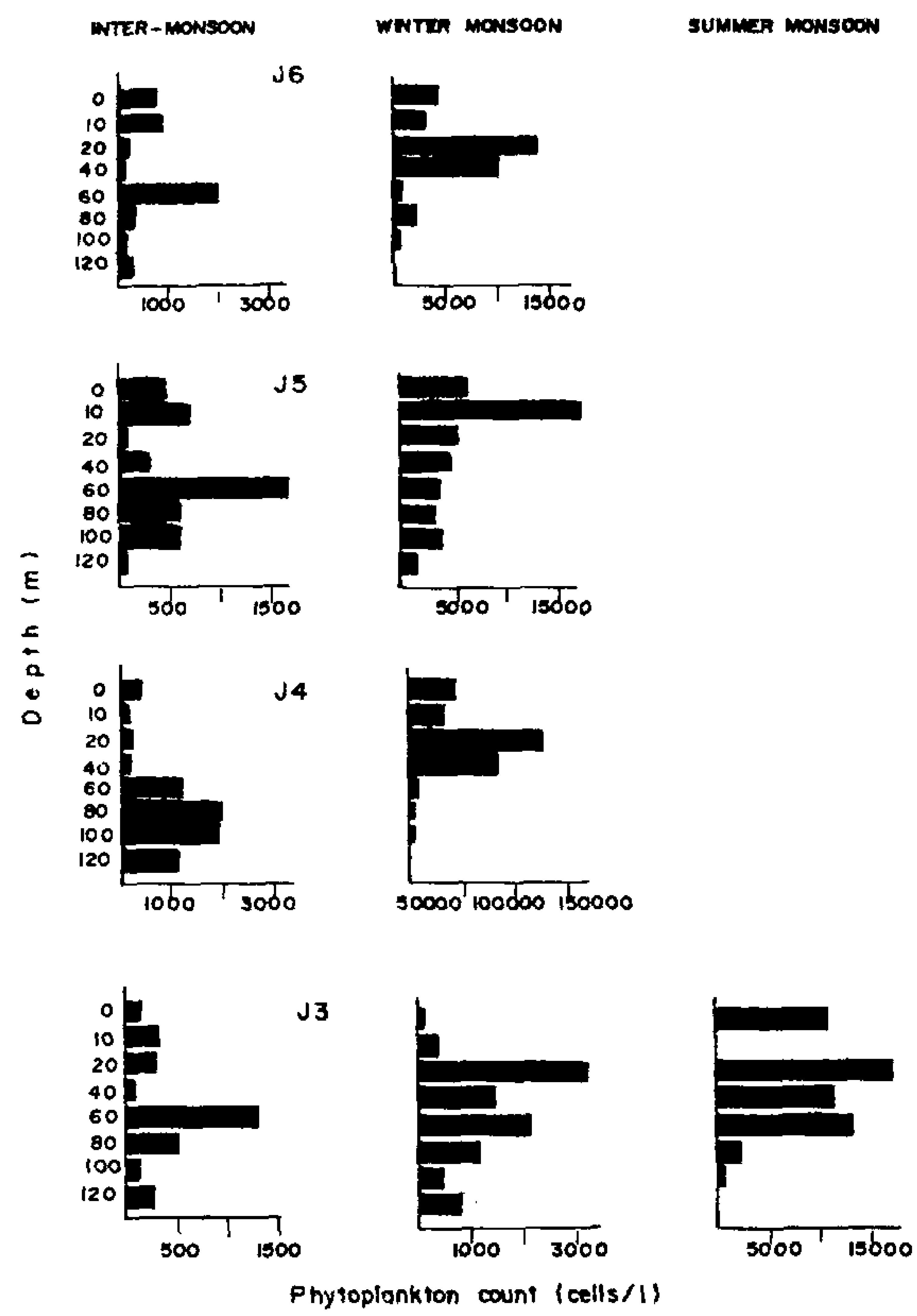

Figure 2 *a*. Cell concentrations (l^{-1}) at various depths at offshore stations during different seasons.

during summer monsoon had the highest cell count of the season (Table 1). This was also relatively high comparing the three seasons at this southernmost station. The highest cell count (15.5 × 10^3 cells l^{-1}) was recorded at 20 m depth (Figure 2 *a*), where diatoms *Thalassiothrix longissima* (29%) and *Chaetoceros pendulus* (26%) formed bulk of the population. Comparable density (13.9 × 10^3 cells l^{-1}) was recorded at 0 m depth at the coastal station J1 where active upwelling was observed[13], but numbers rapidly decreased with depth. Unlike at the open waters, the common diatoms recorded were *Rhizosolenia stolterfothii* (18%) and *Guinardia flaccida* (13%). The distribution of phytoplankton at coastal stations during the summer monsoon was restricted to a depth of about 80 m (Figure 2 *b*). However at coastal station J2, comparatively higher phytoplankton count (2000 cell l^{-1}) was seen at the depth of 100 m (Figure 2 *b*). The population at this depth was entirely dominated by *Fragilaria oceanica* comprising 96% of the cell count. Overall, diatoms contributed 89% followed by dinoflagellates (6%) and cyanobacteria population decreased to 1% during this season.

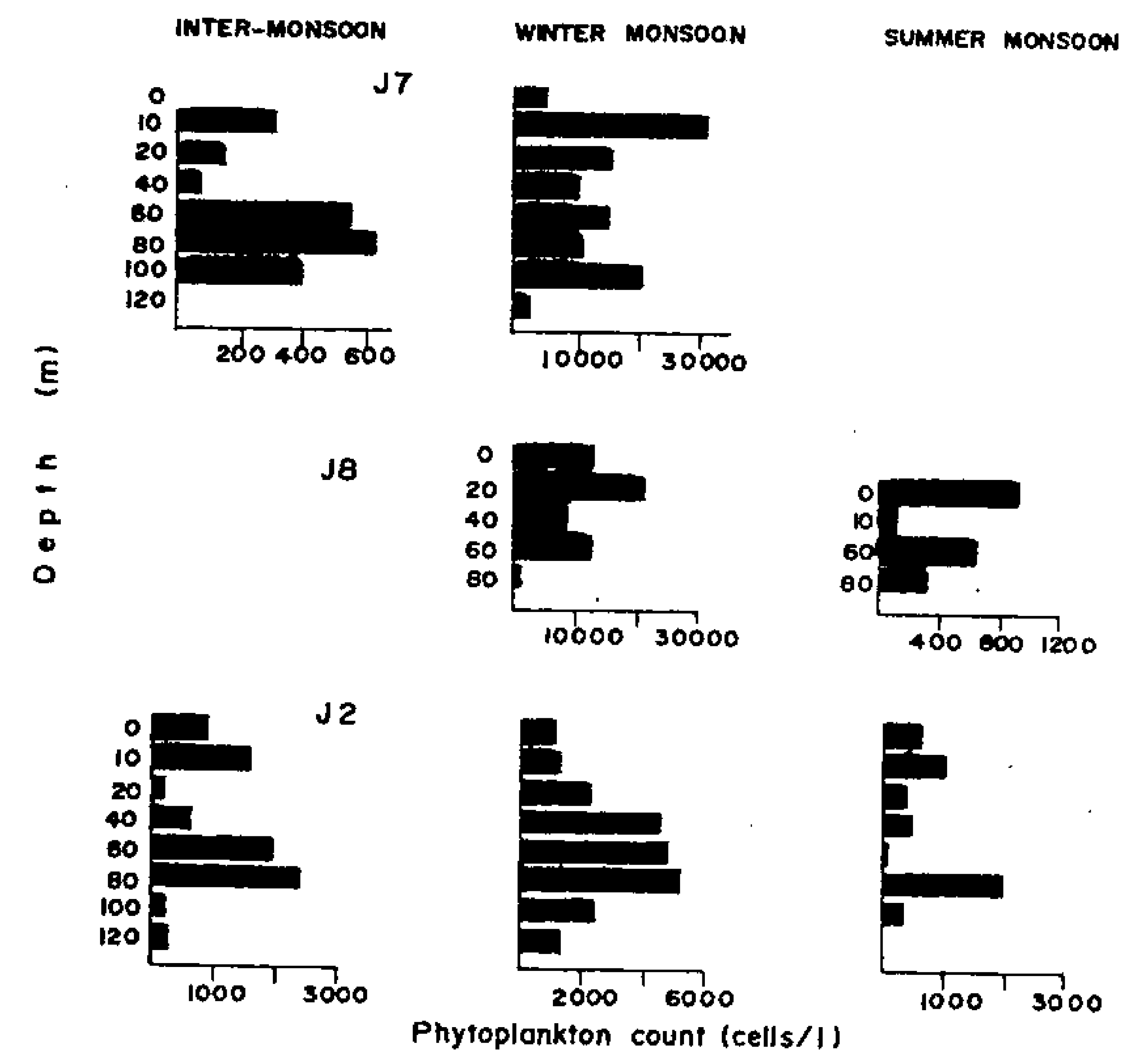

Figure 2 *b*. Cell concentrations (l^{-1}) at various depths at coastal stations during different seasons.

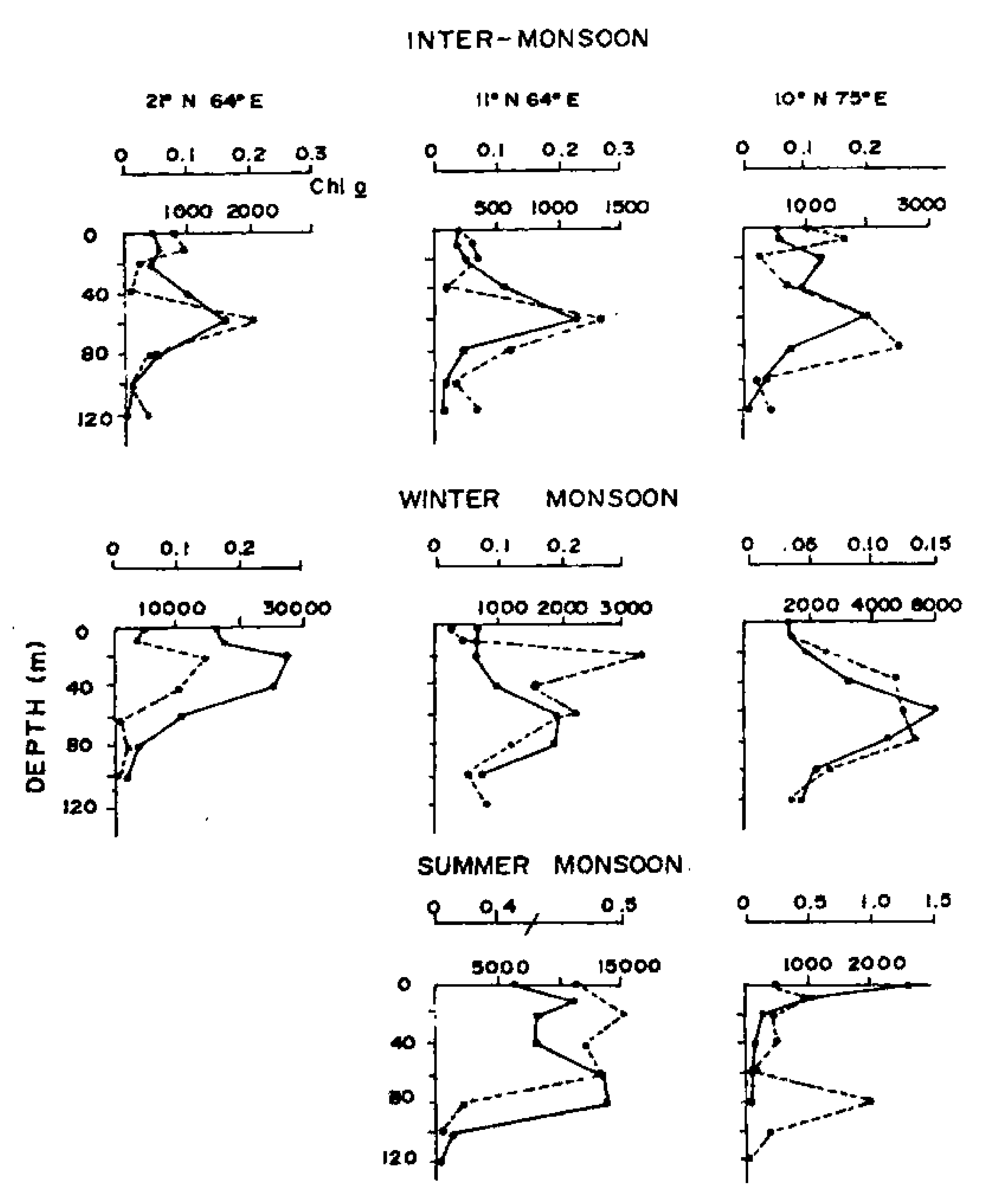

Figure 3. Phytoplankton distribution (cells l^{-1}, solid lines) and chlorophyll *a* (mg m^{-3}, broken lines) at 3 stations during the inter-monsoon and winter monsoon seasons and 2 stations during the summer monsoon.

Higher phytoplankton population was observed at subsurface depths (10–80 m) at the different stations during the three seasons (Figure 2 *a*, *b*). Generally, the peak in phytoplankton abundance showed a direct relation to the subsurface chlorophyll maximum (SCM) layer which varied from 20 to 60 m (Figure 3).

Assemblages

A variety of phytoplankton taxa (36) were identified. The more abundant genera and species are listed in Table 2. Diatoms were the dominant group followed by dinoflagellates and cyanobacteria. During inter-monsoon, population was dominated by species like *Nitzschia seriata*, *N. closterium* and *N. pungens* at all the stations (ca. 25% of total population), except at 15°N 64°E, where *Navicula* was common (22%) followed by *Rhizosolenia* spp. (10%) and *Chaetoceros* sp. (9%). Dinoflagellates were represented by *Ceratium* sp. and *Peridinium* sp. constituting 4%.

During winter monsoon, the dominant phytoplankton taxa were *Nitzschia* sp. (37%), *N. seriata* (21%), *Chaetoceros* sp. (8%), *Rhizosolenia* spp. (7%) and *N. longissima* (5%). Dinoflagellates were represented by *Ceratium* spp., *Peridinium* sp., *Dinophysis* sp., *Prorocentrum* sp. and *Gymnodium lunula*. *Rhizosolenia* spp. however, were generally dominant at coastal stations, constituting 20%. Some diatoms like *Bellarochea* sp., *Schroderella* sp., *Cyclotella* sp., *Strepotheca* sp., *Climacodium* sp., and *Hyalodiscus* occurred in few numbers.

Maximum variety of diatom species occurred during summer monsoon. Important species in terms of abundance were *Thalassiothrix longissima* (22%), *Nitzschia longissima* (8%), *Chaetoceros* sp. (5%), *Rhizosolenia* sp. (5%), *R. stolterfothii* (4%), *N. seriata* (4%) and *Thalassiosira* sp. (2%). Species of diatoms belonging to the genera *Ditylum, Eucampia, Fragilaria, Guinardia, Gyrosigma, Hemiaulus, Hyalodiscus, Leptocylindrus, Lauderia, Lycmophora* and *G. flaccida* occurred only during summer monsoon, and at the coastal stations in particular.

The other species which were recorded in low densities in the present study and not listed under Table 2 or elsewhere, were *Actinoptychus* sp. *Asteromphalus* sp., *Biddulphia aurita*, *B. mobiliensis*, *Ceratualina* sp., *Climacosphaenia* sp., *Chaetoceros affinis*, *C. contortum*, *C. schuttii*, *C. holsaticus*, *C. teres*, *C. decipiens*, *C. curvisetus*, *C. constrictus*, *C. didymis*, *Melosira* sp., *Nitzschia bilobata*, *N. directa*, *Pleurosigma* sp., *Planktoniella* sp., *Rhizosolenia delicatula*, *R. hebatata*, *Stephanopyxis* sp, *Thalassiosira* sp, *Thalassiothrix nitzschoides*, *T. frauenfeldii*, *Tropedoneis* sp., *Ceratium furca*, *C. fusus*, and *C. bucephalum*.

Discussion

In this paper we present the floristic documentation of the seasonal composition and abundance of the phytoplankton of the eastern and central Arabian Sea.

Species encountered in this study have been reported in the checklist for diatoms of the Indian Ocean[14], and previously recorded from the west coast of India[8,9].

The population was dominated by diatoms at both coastal and open waters in all seasons. The abundance of this group (all seasons combined) was 86%. Subrahmanyan and Sarma[10] reported the dominance of diatoms during summer monsoon but list Dinophyceae as more abundant during post-monsoon (September–October) period. However, dominance of diatoms during both post and premonsoon has also been noted in earlier studies from the coastal waters of west coast of India[15]. The most common diatoms encountered in the present study were *Nitzschia* spp., *Navicula* sp., *Chaetoceros* spp. and *Rhizosolenia* spp.

Among the seasons sampled, the winter and summer monsoon were more conducive for phytoplankton population. About 25% of the total photosynthetic production of the Arabian Sea occurs in the northern regions in winter[1] as corroborated in our cell counts (Table 1). During winter monsoon, deepening of the surface layer and vertical mixing due to convection[13] enhanced nutrient availability, leading to increase in phytoplankton

Table 2. Mean seasonal concentrations (cells l^{-1}) of common phytoplankton species at coastal and open ocean stations (I = intermonsoon, W = winter monsoon and S = summer monsoon)

Phytoplankton species	Open ocean			Coastal		
	I	W	S	I	W	S
Diatoms						
Biddulphia sp.	20	–	–	80	33	–
Cerataulina sp.	–	–	166	–	533	20
Chaetoceros sp.	980	2500	533	200	9900	460
Coscinodiscus sp.	240	75	17	400	350	120
Navicula sp.	1820	3100	–	760	3000	200
Nitzschia sp.	660	49575	166	–	9700	160
N. seriata	2100	27950	650	–	6066	120
N. closterium	400	100	16	640	2666	100
N. longissima	–	8650	800	–	–	640
N. pungens	–	–	–	80	6400	–
Rhizosolenia sp.	620	3850	450	320	7366	440
R. alata	–	2375	–	–	3233	60
R. cylindrus	60	225	–	–	333	–
R. fragillisima	–	75	–	–	1366	140
R. stolterfothii	–	100	50	–	1066	740
R. setigera	–	25	–	–	266	220
R. styliformis	–	150	–	–	266	80
Thalassiosira sp.	140	975	–	40	1066	440
T. nitzchiodes	–	–	–	400	900	220
Dinoflagellates						
Ceratium sp.	220	200	–	40	33	20
Peridinium sp.	20	150	–	–	133	–
Cyanobacterium						
Trichodesmium sp.	–	100	–	480	–	60

population (Table 1, Figure 2 *a*, *b*). The northern coastal and offshore areas above 15°N latitude, were found to be more productive during winter[16]. Kuz'menko[17] also reported high abundance of phytoplankton in terms of numbers as well as biomass during this season from the central region of the Arabian Sea.

Along the south west coast of India, upwelling which bring nutrients to the euphotic zone, starts with the onset of the summer monsoon in May–June, and intensifies in July–August[18–21]. This leads to marked increase in phytoplankton growth (e.g. at 12°N 74°E) where active upwelling was observed[22]. The corresponding column Chl *a* and column primary production values at this station were also high (80 mg m^{-2} and 1.7 $gCm^{-2}d^{-1}$ respectively)[22]. This is also reflected in the surface cell counts we obtained. The only offshore station, at 11°N 64°E, which was sampled during this season also showed higher cell count (Table 1) and high column Chl *a* (44 mgm^{-2}) and primary production (770 $mgCm^{-2}d^{-1}$), despite the absence of upwelling signature[22, 23]. An interesting feature observed during the summer monsoon was the decrease in cyanobacteria population from 6% to 1%. This is probably because *Trichodesmium* requires stable, warm conditions for their growth[24]. The occurrence of *Fragilaria oceanica* has been noted to be common during the summer monsoon in the coastal waters of the west coast of India[24]. The phytoplankton production and cell counts during the inter-monsoon remained low. The nutrient supply and chlorophyll values also showed declination during this season[16,25].

We observed that maximum concentrations of phytoplankton usually occurred at intermediate depths (10–80 m). Thus the phytoplankton abundances showed a direct relation with the subsurface chlorophyll maximum layer, at the nutricline[24], especially, during the inter-monsoon period (Figure 3). The restriction of their distribution at coastal stations during summer monsoon to a depth of ca. 80 m seems to result from high turbidity.

A large number of diatoms were seen in floating sediment trap samples (deployed during winter) at 300 m depth at 15°N 64°E station (Dr V. Ramaswamy, pers. comm.). The diatoms *Rhizosolenia* sp., *Nitzschia* sp., *Thalassiosira* sp., *Navicula* sp., *Coscinodiscus* sp. common in the water column were found in significant numbers (ca. 3 × 10^3 cells l^{-1}). Presence of intact diatoms in traps at shallow depth (80 m) has been reported from the western Arabian Sea during inter-monsoon season[26]. The floral composition also was somewhat similar. The dominant forms were *Rhizosolenia*, *Chaetoceros* and *Guinardia* spp. Although phytoplankton may be consumed or mineralized in the surface waters (or form aggregates and sink out), their presence as recognizable forms at this aphotic depth (300 m) points to role of phytoplankton in rapid carbon export. This may also indicate that during productive periods (summer and winter), mesozooplankton grazing does not effectively control the phytoplankton production in the Arabian Sea[27].

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