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RESEARCH ARTICLE

VERTICAL DISTRIBUTION OF BIOLOGICAL CHARACTERISTICS AND PHYTOPLANKTON COMMUNITY STRUCTURE IN THE SHELF WATERS OFF SOUTHWEST COAST OF INDIA

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ABSTRACT

The diversity, abundance, biomass of phytoplankton and primary productivity in the shelf waters of four stations along the southwest coast of India were studied for the first time during May - June 2005. In order to study the vertical distribution, five sampling depths starting from (5 to 35 m) were elected within the euphotic zone. Nutrients (nitrate, nitrite, phosphate and silicate) showed an increasing trend from 5 m to deeper waters with a significant positive relationship with salinity ($r > 0.83$, $p < 0.01$). Result indicates that Primary Productivity (PP) and phytoplankton standing crop were direct tune with chlorophyll *a* and nutrient concentrations. Further, a significant positive correlation was observed between PP and phytoplankton standing crop ($r > 0.87$, $p < 0.01$) in most of the stations and also with chlorophyll *a* and phytoplankton standing crop ($p < 0.01$, $r > 0.96$). Among stations, 35 m depth at Kodungallur station recorded the least phytoplankton standing crop (0.87×10^3 cells L^{-1}) and 10 m depth at Mangalore recorded the maximum (31.53×10^3 cells L^{-1}**)**. Phytoplankton community composition revealed 67 species of phytoplankton belonging to different taxonomic groups, in which bacillariophyceae constituted 49, pyrrophyceae 17 and cyanophyceae 1. *Chaetoceros lorenzianus* invariably constituted maximum abundance throughout the water column in all stations except Mangalore 10 m depth. Depth integrated (5 to 35 m) primary productivity of Mangalore (1284.7 mg C m^{-2} d^{-1}) was nearly three times as high at Kodungallur (431.8 mg C m^{-2} d^{-1}). The maximum depth integrated chlorophyll *a* (49.70 mg m^{-2}) was recorded at Mangalore and minimum of 13.25 mg m^{-2} were recorded at Kodungallur. Vertical accretion of phytoplankton species was remarkable and the species diversity was predominant at 10 – 15 m water column depth, which is in concord with maximum biomass (chlorophyll *a*) and pycnocline layer. In general, increased phytoplankton diversity, Margalef richness *d’* (5.53 ± 0.23), Shannon-Wiener *H’* (2.56 ± 0.37), Pielou’s evenness *J’* (0.61 ± 0.44) in the northern shelf waters Karwar and Mangalore (12 - 14°N) relative to southern shelf waters Calicut and Kodungallur (10 - 11°N) with concomitant increase both in abundance and biomass. In this study an attempt was also made to distinguish the phytoplankton community in to its different assemblages according to their locations (e.g., depth and station-ways). Mangalore recorded the maximum species diversity (52) followed by Karwar (49), Calicut (42) and Kodungallur (19). Southwest coast of India, Phytoplankton abundance and biomass could be affected by its spatial variability in community structure with species specific association (e.g., depth ways) and largely with respect to differences in the hydrographical conditions. The study suggests that phytoplankton community structure was varied with depth and plays a crucial role on PP and quantity of phytoplankton biomass available to the marine food web.

INTRODUCTION

Continental shelf and adjacent slope waters represents only 10 - 20% of surface area of global oceans, but these ocean margins are highly productive, contribute 25 - 50% of total oceanic primary production (Walsh, 1988). Since phytoplankton composition plays an important role in the rate of primary production and various trophic interaction, quantification of phytoplankton biomass and community composition is important for understanding the structure and dynamics of marine ecosystems. The ability of phytoplankton cells to synthesize new biomass is critically depending on their ability to assimilate sufficient carbon, nitrogen and phosphorous, as well as minor nutrients, to ensure replication. As phytoplankton assemblage grows, they deplete the concentrations of nutrients in the surrounding waters, then future generations must adapt to decreasing nutrient concentrations. Therefore, the

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environment in which phytoplankton grow is significantly modified by their growth, and over time periods of only a few days, assemblages may move from a situation of nutrient excess to nutrient depletion.

Low nutrient concentration limit total biomass of phytoplankton assemblage but need not necessarily reduce the growth rate of those cells, which are adapted to the assimilation of nutrient at very low concentration (Rees *et al.,* 1999). The availability of nutrients in the euphotic zone and its subsequent biochemical response is the basis of biological productivity and plays an important role in regulating phytoplankton community structure (Malone, 1980; Platt *et al.,* 1983; Chavez, 1989). Besides nutrients, light, vertical mixing and depth influence the spatial distribution of biological characteristics in sea (Prestidge and Taylor, 1995; Keifer and Kremer, 1981; Hilmer and Bate, 1990; Smith, 2006).

The semi-annual reversal of coastal currents in the Arabian Sea introduces a high degree of seasonality in the physico-chemical environment (Banse, 1968; Naqvi *et al.,* 2000; 2006). The south west monsoon is the time of an equatoward current along the west coast and upwelling occurs (Shetye *et al.,* 1990). Along the shelf waters of southwest (SW) coast of India, phytoplankton has been found to be most abundant during the upwelling period that lasts from May-June to October-November (Sharma, 1968; Madhupratap *et al.,* 2001). During the period, by which denser nutrient rich water is brought to the surface, leading to marked increase in phytoplankton growth thereby increasing chlorophyll *a* and gross primary productivity ((Sankaranarayanan *et al.,* 1978; Prasanna Kumar *et al.,* 2002, Ryther and Menzel, 1965; Nair and Pillai, 1983; Qasim, 1977; Prasanna Kumar *et al.,* 2001; Habeebrehman *et al.,* 2008). The consequent strong biological response includes marked changes in the composition of phytoplankton, a subject of several previous studies (e.g., Dehadrai and Bhargava, 1972; Banse, 1987; Devassy and Goes, 1988; Bhattathiri *et al.,* 1996), all of which have been confined to seasonality of phytoplankton and pigment concentration. Most of the studies made in Arabian Sea are restricted to gross surface production, chlorophyll *a* and phytoplankton. (Rajagopalan *et al.,* 1992; Varshney *et al.,* 1983; Rany Mary and Vasantha Kumar,1984; Saraladevi *et al.,* 1997; Roy *et al.,* 2006) and deep sea by Radhakrishna *et al.,* 1978; Qasim, 1982; Prasanna Kumar *et al.,* 2000, 2001; Satya Prakash and Ramesh, 2007).

The holistic understanding of factors determining marine productivity requires detailed knowledge of the marine ecosystem and the physico-chemical characteristics, holding key to the primary production. Studies on the vertical distribution of sub surface shelf waters of southwest coast of India, in an integrated manner are rather limited. Hence, along the shelf waters of SW coast of India, an attempt was made for the first time in this regard. Multivariate analysis is used to **e**valuate the factors influencing phytoplankton dynamics especially species composition and community structure. Finding made during the investigation are considered important since much of our knowledge on phytoplankton community analysis is based on examples derived from temperate waters and there is a need to focus on tropical situations.

MATERIALS AND METHODS

Study area

Measurements were carried out at sub surface waters of four stations along ~ 560 Km between 10 °N and 14 °N long shelf waters of Southwest coast of India, in which two stations were selected from off state of Karnataka and two from off Kerala state (Fig.1). All the four stations were situated within the limit of shelf waters nearly at forty meter depth, Station 1 (Karwar 14°47'N, 73°52'E), Station 2, (Mangalore 12°56'N, 74°35'E), Station 3, (Calicut 11°12'N 75°30'E) and Station 4, (Kodungallur 10°11'N 75°53'E), during the *CRV Sagar Purvi* cruise from May to June 2005. The SW coast of India is a monsoon dominated coast. Coastal upwelling occurs along the coast during the southwest monsoon (June to September) season between 14 °N and 7 °N (Banse, 1959; Lathipha and Murthy, 1985). In this region, upwelling is a wind-driven process and the strength of alongshore winds stress modulates the coastal divergence and hence the input of cold upwelled water over the shelf. Southwest coast of India between 14 °N and 7 °N is a major fishing ground and plays a key role on India's exploitable fisheries potential. Station 1 (Karwar) is a charming port, situated at the mouth of the Kalindi River. Kalindi River flows through the town and joins into Arabian Sea at Karwar. Station 2 (Mangalore) is the administrative headquarters of the Dakshina Kannada, and developed as a port on the Arabian Sea to this day it remains one of the major ports of India, lying on the backwaters formed by the Netravati and Gurupura rivers. Both these rivers joint at Mangalore and ultimately flow into the Arabian Sea. Station 3. (Calicut) is the most important coastal city of Malabar the north region of state of Kerala. As the bank of Mangalore and Calicut coast, thickly populated and urbanized to great extent, the shelf waters are subjected to multifarious activities, such as fishing and port activities etc. Mangalore fishing harbor is situated at the companied estuary of Netravati and Gurupura rivers, the biggest fish landing centers, were more than thousand mechanized boats operates daily. Station 4 (Kodungallur) is famous fishing ground and a sea-port at the mouth of the Periyar River in the state of Kerala. It is located about 38 km from the present day city of Kochi. River *Periyar is* the longest *river* in Kerala, eventually joins with Arabian Sea on two permanent outlets at *Kodungallur* in the north, and at Kochi in the south. All these four stations playing a major role on the socio-economic status of coastal community along the south west coast of India.

Sampling Strategy and analysis

Water samples were collected from the five standard depths starting from 5, 10, 15, 25 and 35 m depths using a 5 L Niskin bottle, equipped with silicon seals and closures. For the collection of phytoplankton, 1 L seawater sample were drawn from the depths mentioned above fixed with Lugol's iodine and 4% formalin for further analysis.

Physico-chemical parameters

In-situ temperature was recorded using Brannan thermometer (1-51 °C range within ± 0.1°C). Light transparency of the water column was measured using the Secchi disc (Ds m) and light extinction coefficient (ke, m^{-1}) was calculated following the relationship $ke = 1.4/Ds$, where 1.4 is an empirical constant for turbid waters (Holmes, 1970). Dissolved oxygen (DO) was estimated according to Winkler's titration method. All carboys, filtering devices, glassware and tubings were acid-washed (10% HCl) and rinsed (thrice) with deionized water prior to use. It was then rinsed twice with their own volume of sample, capped and stored in the dark at 4 ^{o}C until analysis. Analyses for nutrients (NO^{-}_{2}, NO^{-}_{3}, PO^{3-}_{4} and SiO_4-Si) were carried out on filtered sea water, following standard procedures (Grasshoff *et al.,* 1999), within 2-3 h of collection. Chlorinity was determined by the Argentometric (Mohr-Kndusaen) method and salinity was computed from chlorinity using Knudsen table.

Pigment extraction (chlorophyll a)

For pigment extraction, 1 L water samples were filtered through Whatman GF/F glass fiber filters, which were then immersed in 10 ml 90% acetone and allowed to extract in darkness at 20 ^{o}C for approximately 12 h. After extraction, the samples were vortexed. The samples were then centrifuged and absorbance of supernatant was measured before and after acidification using a Perkin Elmer spectrometer (Parsons *et al.,* 1984).

Primary productivity (PP)

Primary production (PP) was measured by the radiocarbon (^{14}C) method (UNESCO, 1994; Bhattathiri *et al.,* 1996). Water samples were taken from 5 depths (5-35 m) using Niskin bottle samplers and were transferred to 300 ml polycarbonate bottles (Nalgene, Germany). Each bottle was spiked with 1 ml of $NaH^{14}CO_3$ (5 µCi ml^{-1}, Board of Radioisotope Technology, Department of Atomic Energy, India) and the bottles were incubated in situ with the help of a mooring system. Three light bottles and one dark bottle were used at each depth. The incubation lasted from 1 h before sunrise to 30 min after sunset, after which the samples were retrieved and filtered through GF/F filters under gentle suction. The filters were exposed to concentrate HCl fumes to remove excess inorganic carbon and transferred to scintillation vials for subsequent estimation. A day before analysis, 5 ml of liquid scintillation cocktail (Sisco Research Laboratory, Mumbai) was added to the vials and the activity counted in a scintillation counter (Wallace 1409 DSA, Perkin-Elmer, USA). The disintegration per minute (DPM) was converted into daily production rates (mg C m^{-2} d^{-1}) taking into account the initial activity in the bottles and the initial adsorption of ^{14}C by particles in the bottles (Strickland and Parsons, 1972). Column PP (mg C m^{-2} d^{-1}) and column Chl. *a* (mg m^{-2}) was calculated by integrating over 35 m depth.

Algal identification

For qualitative studies of phytoplankton (>5 µm), 1000 ml of seawater samples were drawn from the depths mentioned above, fixed in 1% Lugol's iodine and preserved in 3% formalin solution. The samples were stored in the dark at low temperature until the enumeration within a period of one month after collection. A settling and siphoning procedure was followed to obtain 20-25 ml concentrates. One ml of this concentrated sample was examined microscopically under a stereoscope binocular inverted microscope (magnification 100 ×) in a Sedgewick–Rafter counting chamber. Chain-forming cells were counted on per cell basis and empty cells were excluded. The phytoplankton groups were identified to species level. Taxonomic criteria and diagnosis for phytoplankton identification mainly relied on Subrahmanyan, 1959; UNESCO, 1978; Santhanam *et al.,* 1987.

Statistical analysis

Community indices: Diversity is a concise expression of how individuals of a community are distributed in subsets of groups. Diversity decreases when one or a few groups dominate in a community, when individuals of a more common group replace individuals of a rare group or when one or a few groups rapidly reproduce. To mathematically analyze and compare changes in aquatic communities due to environmental influence, species diversity can be used as one of the tools.

Shannon and Weaver species diversity index

$H' = -\sum [P_i (\log_2 P_i)]$

$Pi = n_i / n$ (proportion of the sample belonging to the *i*th species).

Margalef s species richness index

$d' = (S - 1)/\log_e^N$

Where *S* is the number of species and *N* is the total number of individuals of all the species in the sample.

Pielou's evenness

$J = H'/\log_e S$

Cluster analysis

Multivariate procedures included, Multilinkage cluster analysis using group linkage method for similarity between stations. Bray-Curtis similarity index (Clifford and Stephensen, 1975) is applied on the standardized $\log_{10}(X + 1)$. Species ordination through multidimensional scaling (MDS) implemented in PRIMER v6 (Clarke and Gorley, 2006; Clarke and Warwick, 1994). Diversity indices (*d, H', J'*) were estimated on species abundance data. Other PRIMER protocols included similarity percentage (e.g., SIMPER) to identify 'discriminating species'.

RESULTS

General Hydrography

Average water column temperature at shelf waters varied between 28.12 ^{o}C and 30.96 ^{o}C at stn.4 and stn.2. (mean 29.65 ± 0.98 ^{o}C). Vertical variation of temperature maxima (2.52 ^{o}C) at stn. 2 and the minima at stn. 1 (1.75 ^{o}C). Further statistical analysis revealed a strong negative correlation with nutrients. Further the statistical analysis revealed a significant positive correlation between temperature, primary production (r = 0.68 to 0.76, $p <$ 0.01 max at stn.1) and phytoplankton density (r = 0.56 to 0.84, $p < 0.01$ at Stn.4). Due to the less turbidity, minimum light attenuation coefficient (*k*e) was recorded along Karnataka shelf waters compared to Kerala shelf waters. (*k*e) was ranged from (0.9 – 1.2 m $^{-1}$) along shelf waters of Karnataka as compared to Kerala shelf waters (2.4 – 2.7 m^{-1})(Fig.2).

Salinity at 5 m depths was slightly lesser than the deeper water and was found increased with depths and reached normal values at 25 and 35 m depths in all stations. On sub surface shelf water, salinity ranged from 34.81 (Calicut10 m) to 35.68 (Karwar 35 m) with mean of (35.32 ± 0.29). Salinity having significant negative correlation with dissolved oxygen indicating the high photosynthetic activities in low salinities (5 - 15 m). This

Table 1. Vertical variation of biological characteristics along southwest coast shelf waters

Stations	Karwar					Mangalore					Calicut					Kodungallur				
Depth	5m	10m	15m	25m	35m	5m	10m	15m	25m	35m	5m	10m	15m	25m	35m	5m	10m	15m	25m	35m
Chlorophyll.*a* (mgm^{-3})	1.52	1.67	2.12	0.97	0.69	1.48	2.79	1.83	1.19	0.73	0.43	0.87	0.59	0.39	0.33	0.43	0.67	0.51	0.33	0.19
Net Primary productivity ($mgCm^{-3}d^{-1}$)	24.62	37.5	51.28	18.2	6.46	39.55	73.2	62.15	28.6	12.42	32.4	44.26	21.32	13.76	7.12	14.92	28.58	17.3	7.18	5.60

Table 2. Depth-integrated values for (5-35 m) Chl. *a* ($mg\ m^{-2}$), and Primary production ($mg\ C\ m^{-2}\ d^{-1}$)

Stations	Chl.*a* ($mg\ m^{-2}$)	Primary production ($mg\ C\ m^{-2}\ d^{-1}$)
Karwar	43.15	813.6
Mangalore	49.70	1284.7
Calicut	16.65	698.7
Kodungallur	13.25	431.8

Table 4. Species number encountered for each taxonomic groups of phytoplankton

Taxonomic groups	Station 1	Station 2	Station 3	Station 4
Bacillariophyceae	37	38	31	18
Pyrrophyceae	11	13	10	0
Cyanophyceae	1	1	1	1
Total	49	52	42	19

is supported by the negative correlation between salinity with primary productivity ($r = -0.79$, $p < 0.05$ at Stn.3) and chlorophyll *a* ($p < 0.05$, $r = -0.71$) at stn.3 and stn.4 respectively.

Dissolved oxygen and nutrients

Dissolved oxygen (DO) distribution showed a uniform pattern without much vertical variation, slightly decreasing with depth. The DO in water column ranged from 5.98 mg L^{-1} at Mangalore (5 m) to 5.73 mg L^{-1}Kodungallur (35 m) waters (5.84 ± 0.07). The concentration of the nutrients showed gradual increase with depth except station 4. At stations 1, 2 and 3, the nitrite nitrogen and nitrate nitrogen increased gradually up to 10 m, beyond which they increased steeply and reach maximum at 35 m. At stn. 4, nitrite and nitrate showed an irregular pattern. The nitrite concentrations are in the range of below detectable level (BDL) to 0.83 µmol L^{-1} at Karwar with mean of (0.21 ± 0.27). Nitrate concentrations changed with depth, deeper waters recorded higher concentration than surface values. The highest nitrate nitrogen concentration of 6.69 µmol L^{-1} was recorded at Mangalore (35 m) depth. At all other stations, concentration was < 5µmol L^{-1} except 5 m depth of station Karwar. Phosphate concentrations fluctuated in the range of < 0.25 to 0.86 µmol L^{-1} (0.45 ± 0.18). The highest phosphate value was found at Mangalore 35 m and the lowest at 5 depth of Karwar. Phosphate levels increased slightly in water column with depth. PO_4^{3-} concentration is having a strong negative correlation of ($r = -0.88$ (stn.2) to $r = -0.91$ (stn.4), $p = < 0.01$) with DO. Silicate concentrations ranged from (0.09 µmolL^{-1} to 3.7 µmolL^{-1}) with an average of (0.94 ± 0.79). The highest vertical silicate concentration was found at 35 m depth of station 2 and lowest was at 10 m depth of station 3. Silicate concentration showing strong negative correlation (- 0.49 to - 0.99) with phytoplankton density suggests silicate might be actively removed from water column diatom cells in upper pycnocline waters (5-15 m). Nutrient data showed an increasing trend from 5 m to deeper waters except at station Kodungallur. This is evidenced by the statistical analysis, which revealed a positive significant relationship between nutrients (nitrite, nitrate, phosphate) and salinity ($r > 0.83$, $p < 0.01$).

The interactions among the sampling depths at each station were obtained through cluster analysis using Primer software (linkage between groups), with euclidean distance as a similarity measure and were synthesized in to dendrogram plots. The hydrographical parameters like temperature, salinity DO, NO_2-N, NO_3-N, PO_4-P, SiO_4-Si and biological

Table 3. Phytoplankton species encountered at each station (+ + + highly abundant (> 10000 cells L^{-1}), + + moderately abundant (100-5000 cells L^{-1}), + presence (1-100 cells L^{-1})

Species	Station 1	Station 2	Station 3	Station 4
Bacillariophyceae				
Asterionella japonica	-	+	+++	+++
Asteromphalus flagellatus	-	+	-	-
Asteromphalus wyvillei	+	-	-	-
Bacillaria paradoxa	-	+	+	-
Bacteriastrum comosum	+	-	-	-
Bacteriastrum delicatulum	+	+	+	+
Bacteriastrum hyalinum	+	+	++	+
Bacteriastrum varians	+	++	-	-
Biddulphia mobiliensis	+	+	+	-
Biddulphia sinensis	+	+++	+	+
Chaetoceros compressus	+	+	-	-
Chaetoceros coarctatus	+	+	+	+
Chaetoceros curvisetus	++	+++	+	-
Chaetoceros diversus	+	+	+	-
Chaetoceros lorenzianus	+++	+++	++	++
Chaetoceros meassanensis	+	+	-	-
Chaetoceros peruvianus	+++	+++	+	+
Climacodium frauenfeldianum	+	+	-	-
Corethron hystrix	-	+	+	-
Coscinodiscus eccentricus	+	+	+	-
Cyclotella striata	-	-	+	-
Ditylum brightwelli	+	+	-	+
Eucapmia cornuta	-	+	+	-
Eucapmia zoodiacus	+	+	-	+
Gossleriella tropica	-	+	-	-
Guinardia flaccida	-	+	-	-
Hemiaulus sinensis	+	+	-	-
Leptocylindrus danicus	-	+	+	+
Lithodesmium undulatum	+	+	-	-
Nitzschia seriata	-	-	+	-
Planktoniella sol	+	+	+	-
Pleurosigma angulatum	+	-	+	-
Pleurosigma elongatum	+	+	+	+
Pleurosigma normanii	+	-	-	+
Rhizosolenia alata	+	+	+	+
Rhizosolenia crassispina	+	+	-	-
Rhizosolenia cylindrus	+	+	+	+
Rhizosolenia robusta	+	-	+	-
Rhizosolenia setigera	+	+	-	-
Rhizosolenia stolterfothii	+	+	+	-
Rhizosolenia styliformis	+	+	+	+
Skeletonema costatum	++	+++	+	-
Stephanopyxis palmeriana	-	-	+	-
Streptotheca indica	+	+	-	-
Talassionema nitzschioides	+	-	-	+
Thalassiosira subtilis	-	-	+	-
Thalassiothrix frauenfeldii	+	+	+	+
Thalassiothrix longissima	+++	++	+	-
Triceratium favus	+	-	+	+
Pyrrophyceae				
Ceratium breve	+	+	+	-
Ceratium furca	+	+	+	-
Ceratium fusus	-	+	+	-
Ceratium inflatum	+	+	-	-
Ceratium pulchellum	-	+	+	-
Ceratium trichoceros	+	-	+	-
Ceratium tripos	-	+	-	-
Ceratium macroceros	+	-	+	-
Dinophysis miles	+	-	+	-
Ornithocercus steinii	-	+	-	-
Oxytoxum scolopax	+	-	+	-
Protoperidinium depressum	-	+	-	-
Protoperidinium pedunculatum	+	+	-	-
Protoperidinium oceanicum	+	+	+	-
Protoperidinium steinii	+	+	+	-
Prorocentrum micans	+	+	-	-
Pyrophacus horologicum	-	+	-	-
Cyanophyceae				
Trichdesmium erythraeum	++	++	+	+

parameters like Chlorophyll a, Primary production and Phytoplankton standing crop were used as variables. Group average clustering from euclidean distances and 2-dimensional MDS based on the hydrobiology with respect to depth at each station shown in (Fig.3). From the dendrogram it is quite clear that stns.1 and 2 showing depth ways similar pattern. These consisted of lower dendrogram (5, 10 and15 m depths) and upper dendrogram (35 and 25 m). At stns.3 and 4, upper dendrograms (5 and 10 m) forming one cluster and (25 and 35 m forming one cluster) were as 35 m depth forming entirely different pattern compared to other depths. The dentrogram provided a sequence of group of vertical profile (depth ways) confirmed by MDS plot for the same location. MDS plot based on the hydrographical condition for the same stations provide a fairly convincing two group of stations (stns.1 and 2 forming one group correspond to Karnataka shelf waters and stns.3 and 4 represent to Kerala shelf waters) with respect to hydrobiological condition prevailing that region (Fig.4).

Pigment concentration

The chlorophyll *a* (chl.*a*) data showed variation with depth in all stations and concentrations were more in the northern stations (Stn.1&2). The maximum concentration of 2.79 mg m^{-3} was recorded at 10 m depth of stn.2 and the minimum 0.19 mg m^{-3} at 35 m depth of stn. 4 (Table 1). The maximum depth integrated (5-35 m) chl. *a* of 49.70 mg m^{-2} was recorded at Stn. 2 and minimum of 13.25 mg m^{-2} were recorded at Stn. 4 (Table 2). Further chl.*a* having strong positive correlation with Phytoplankton density ($p = < 0.05$, $r = > 0.81$) and Primary production ($p = < 0.01$, $r = > 0.96$). Except at stn. 4, maxim chl. *a* concentration was at 10 to 15 m water column depths; were as stn. 4 recorded maximum chl. *a* at 5 m depth.

Primary Production

Among all stations, 10 m depth of stn.2 recorded the maximum primary productivity (73.2 mg C m^{-3} d^{-1}) whereas; station 4 (35 m) recorded the minimum (5.60 mg C m^{-3} d^{-1}) (Table 1). Depth integrated (5-35 m) primary productivity of Stn. 2 (1284.7 mg C m^{-2} d^{-1}) was nearly four time as high at Stn. 4 (431.8 mg C m^{-2} d^{-1}) (Table 2). The depth-integrated productivity obtained in this study showed a positive relationship with depth integrated chl. *a* concentration throughout the water column. The average column productivity in the shelf waters of state of Karnataka was 1049.15 mg C m^{-2} d^{-1} and that for the Kerala shelf waters were 565.25 mg C m^{-2} d^{-1} respectively. At Stn.2. (12 °N and 74 °E) an enhanced rate of column primary productivity of 1284.7 mg C m^{-2} d^{-1} and chl. *a* of 49.70 mg m^{-2} were observed. Primary productivity was maximum at 10 to 15 m water except at stn. 3, where the maximum at 5 m depth. This is in correlation with phytoplankton and nutrient distribution.

Algal composition

Phytoplankton distribution revealed 67 species of phytoplankton belonging to 3 taxonomic groups, were distinguished. Of these taxa, 1 species of cyanophyceae (1genus and 1species), 49 belonged to cl ass bacillariophyceae (28 genara, 49 species), 17 to Pyrrophyceae (dinophyceae), (7genara, 17 species) were eminent in the neritic waters of sowth west coast of

India Table 3). Among class bacillariophyceae, centrales were the predominant (40 centrales to 9 pennales). The species number at each station was in the order stn.4 < stn.3 < stn.1 < stn.2 (Table 4). The dominant species represented by bacillariophyceae (18 to 38) followed by dinophyceae (10 to 13) and cynophycae (1). Representatives of bacillariophyceae were found gradually decreasing in the order of stn.4 < stn.3 < stn.1 < Stn.2. Results show 100% relative numerical abundance of bacillariophyceae at stn. 4 except 5m depth, whereas 25m depths at station 2 recorded the maximum numerical abundance (24.21%) of pyrrophyceae. Among class pyrophyceae, peridiniales (14) were dominant, the number is in the order of prorocentrales (1) < dinophysiales (2) < Peridiniales (14) respectively. Mangalore 10 m recorded maximum relative abundance of class cyanophyceae (52.44%). Among the genera, richest in terms of species was *Rhizosolenia* sp. (7 species out of total 67 species), *Chaetoceros* sp. (7 species out of 67 species), *Bacteriastrum* sp. (4 species out of 67 species); *Ceratium* sp. (8 species out of 67 species) and *Protoperidinium* sp. (4 species out of 67 species). The species composition of phytoplankton may be used as a measure of the community's stage of development, history and nature of fertility of coastal waters.

abundance was in the range of 35.36 % at station 2 (10 m) to 99.27 % at station 4 (5 m). Among stations, relative numerical abundance of class cyanophyceae were high compared to all other stations at 10 m depth of (stn. 2) and 5 & 15 m depths at stn. 1. At 10 m depth of stn. 2, cyanophyceae representatives were reaching up to (47.44%). Among bacillariophyceae, *Chaetoceros lorenzianus* invariably constituted maximum numerical abundance throughout the water column in all stations except station Mangalore 10 m. No Pyrrophyceal representatives were observed at stn. 4. Relative abundance of bacillariophyceae, dinophyceae, cyanophyceae at each station was illustrated in Table 5.

Vertical variations of phytoplankton density at different station are given in Table 6. In all the four stations, maximum standing crop was found at depth range of 10 to 15 m water column with a maximum density of 31.53 × 10^3 cells L^{-1} at 10 m depth of stn. 2. and minimum of 0.87 × 10^3 cells L^{-1} at 35 m depth of stn.4. Diatom cell number increased vertically with depths (5 - 10 m depth) at all stations (Table 7). This was commonly observed at inner shelf waters although abundance and dominant species were variable among stations. *C. lorenzianus* was the most dominant throughout the water column at all stations, and the biomass increased towards the mid column water

Table 5. Relative numerical abundance of bacillariophyceae, pyrrophyceae, cyanophyceae at each station. (In %)

Algal class	Karwar-5 m	Karwar-10 m	Karwar-15 m	Karwar-25 m	Karwar-35 m
Bacillariphyceae	66.05	94.4	54.43	95.58	75.2
Pyrrophyceae	8.95	2.4	6.83	3.64	19.2
Cyanophyceae	25.00	3.20	38.74	0.78	5.6
	Mangalore-5 m	Mangalore-10 m	Mangalore-15 m	Mangalore-25 m	Mangalore-35 m
Bacillariphyceae	78.50	35.36	71.12	61.05	85.58
Pyrrophyceae	14.06	12.2	14.24	24.21	10.57
Cyanophyceae	7.44	47.44	14.64	14.74	3.85
	Calicut-5 m	Calicut-10 m	Calicut-15 m	Calicut-25 m	Calicut-35 m
Bacillariphyceae	97.19	93.12	93.34	93.81	97.2
Pyrrophyceae	1.12	3.06	6.66	6.19	2.11
Cyanophyceae	1.69	3.82	ND	ND	0.69
	Kodungallur-5 m	Kodungallur-10 m	Kodungallur-15 m	Kodungallur-25 m	Kodungallur-35 m
Bacillariphyceae	99.27	100	100	100	100
Pyrrophyceae	ND	ND	ND	ND	ND
Cyanophyceae	0.73	ND	ND	ND	ND

Table 6. Phytoplankton density (no. x 10^3 cells L^{-1})

Depth	Karwar	Mangalore	Calicut	Kodungallur
5 m	15.41	18.56	6.63	4.34
10 m	19.55	31.53	8.74	6.52
15 m	26.17	22.38	3.64	3.20
25 m	8.74	12.72	2.87	1.60
35 m	3.65	6.53	1.24	0.87

Table 7.Total diatom (bacillariophyceae) (no. x 10^3 cells L^{-1})

Depth	Karwar	Mangalore	Calicut	Kodungalore
5 m	13.86	17.69	5.76	3.98
10 m	16.91	29.92	7.81	5.11
15 m	24.56	20.69	2.61	2.89
25 m	7.210	10.49	1.59	1.37
35 m	2.835	5.21	1.03	0.72

Column profile of all stations except 5 m depth of stn. 2, bacillariophyceae members were the predominant constituents at all depth, and their relative numerical

(10-15 m) depth. Its relative abundance ranged from 3.66 % at 10 m depth of stn. 2 to 76.81 % at station 4 (5 m).

The pyrrophyceae representative was present throughout the water column in all stations except stn. 4.

Table 8. Information (range and mean) on the diversity indices of phytoplankton in the shelf waters Karnataka and Kerala.

Diversity indices	Shelf waters of Karnataka (Karwar & Mangalore)	Shelf waters of Kerala (Calicut & Kodungallur)
Number of Species (*S*)	52 - 49 (50.5 ± 2.12)	42 - 19 (30.5 ± 16.26)
cells L^{-1} (*N*)	73520 – 91720* (82620 ± 12869)	23120 – 4659* (19825 ± 4659)
Species Richness (*d'*)	5.36 - 5.69 (5.53 ± 0.23)	4.88 - 2.31 (3.60 ± 1.82)
Evenness Index (*J'*)	0.61 - 0.74 (0.68 ± 0.91)	0.45 - 0.36 (0.41 ± 0.06)
Shannon-Wiener (*H'*)	2.3 - 2.82 (2.56 ± 0.37)	1.65 - 1.03 (1.34 ± 0.44)

Table 9. Diversity indices of phytoplankton at each station

Stations	Diversity indices				
	S	*N*	*d'*	*J'*	*H'*(loge)
Karwar	52	$*73.52 \times 10^3$	5.36	0.61	2.30
Mangalore	49	$*91.72 \times 10^3$	5.69	0.74	2.82
Calicut	42	$*23.12 \times 10^3$	4.88	0.45	1.65
Kodungallur	19	$*46.59 \times 10^3$	2.31	0.36	1.03

S - Total species; *N* - cells L^{-1}(* depth integrated cell count) ; *d* - Margalef diversity; *H'*-Shannon-Wiener; *J'*-evenness index

(four stations companied together). Bray-Curtis similarities were calculated on root-transformed data and, from the resulting dendrogram, it is possible to define the locations of phytoplankton species with respect to depth (Fig. 5). The dendrogram provide a sequence of fairly convincing group of species segregation is evidently due to differences among the samples-phytoplankton species composition and their abundance in relation to hydrographical conditions at each depth. Hierarchical clustering, using group average linking on phytoplankton species abundance data for the 4 stations representing shelf waters of Karnataka and Kerala (Fig. 6). Phytoplankton community structure showing spatial changes with respect to stations**.** Bray-Curtis similarities were calculated on root-tranformed data and, from the resulting dendrogram, it is possible to define the locations into two groups. These consisted of Group I [stations 1 & 2 (lower dendrogram)] representing Karnataka shelf waters (12-14 ^{o}N), and Group II stations [3 & 4 (upper dendrogram] belongs to Kerala shelf waters (10-11 ^{o}N). The dendrogram provide a sequence of fairly convincing group of stations.

Diversity and similarity indices

In general, increased phytoplankton diversity (Margalef richness *d'* (5.53 ± 0.23), Shannon-Wiener *H'* (2.56 ± 0.37), Pielou's evenness *J'* (0.68 ± 0.91) in the northern shelf waters (Karwar and Mangalore) relative to southern shelf waters (Calicut and Kodungallur) with concomitant increase both in abundance and biomass (Table 8). On the basis of these findings, it is concluded that the southern shelf waters is least diverse both in species richness (Margalef richness *d',* Shannon-Wiener *H' and* evenness

Table 10. SIMPER for 67 species of phytoplankton

Species	Shelf waters of Karnataka (Karwar & Mangalore) Group I	Shelf waters of Kerala (Calicut & Kodungallur) Group II			
	Av.Abund	Av.Abund	Av.Diss	Diss/SD	Contrib%
Asterionella japonica	4.97	313.24	7.57	79.13	10.04
Chaetoceros peruvianus	309.37	11.67	7.31	81.24	9.7
Chaetoceros curvisetus	299.42	9.43	7.12	57.45	9.45
Skeletonema costatum	296.56	12.62	6.97	247.43	9.25
Thalassiothrix longissima	275.82	12	6.48	74.96	8.59
Bacteriastrum varians	267.63	11.39	6.29	42.27	8.35
Rhizosolenia alata	260.08	8.04	6.19	23.71	8.21
Biddulphia sinensis	143.19	20.06	3.02	16.66	4.01
Trichdesmium erythraeum	124.23	12.46	2.74	26.67	3.64
Ceratium macroceros	115.14	5.59	2.69	41.17	3.57
Leptocylindrus danicus	107.3	5.24	2.51	12.38	3.33
Coscinodiscus eccentricus	99.12	3.16	2.36	12.44	3.13

Group I and II: Average dissimilarity = 75.36, Av.: average; Diss.: dissimilarity

Trichdesmium erythraeum was the only one representative of class cyanophyceae and it was more predominant at 15 and 10 m depth of stations Karwar and Mangalore respectively. Percentage compositions of major algal composition at (Station ways and depth ways) were illustrated in (Fig.8).

Phytoplankton community structure

Phytoplankton community structure was determined on Bray-Curtis similarity through hierarchical clustering and completes linking on phytoplankton species at each depth

J', while 6 -7 species contribute up to 80% of total phytoplankton population in northern shelf waters (Karwar and Mangalore), there were 2-3 made up to 80% of total phytoplankton population in southern shelf waters (Calicut and Kodungallur) suggesting overwhelming of certain species in population. The cumulative dominant plot (Fig. 7) is in concordance with above findings. Significant variation in similarity indices were noticed along the shelf waters of south west coast of India. Compared to Kerala shelf waters (Calicut and Kodungallur), the highest phytoplankton species richness *d'* (5.36-5.69; 5.53 ± 0.23) species diversity *H'* (2.3 - 2.82; 2.56 ± 0.37) and species evenness *J'* (0.61-0.74; 0.68 ± 0.91) were characteristics features of Karnataka shelf waters (Karwar and Mangalore). Among stations, maximum species richness, species diversity and evenness were noticed at stn. 2 (5.69, 2.82 and 0.74 respectively). Among stations, coefficients of variations of species richness, species diversity and species evenness were in order of stn.4 < stn.3 < stn.1< stn.2. (Table 9).

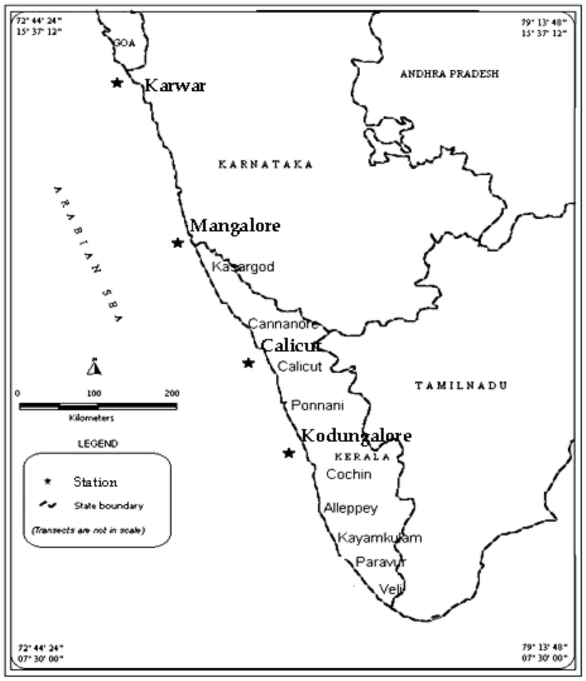


Fig.1. Study area map with sampling locations

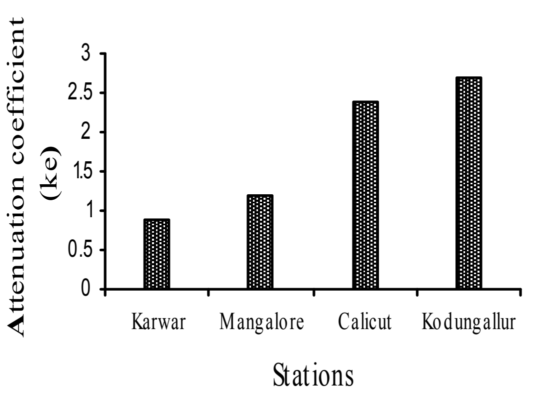


Fig.2. Light Attenuation coeffcient (*ke*) at different stations

Similarity percentage (SIMPER) analysis

To find out discriminating species (those which characterize a particular biotic assemblage or community), similarity percentage (SIMPER) analysis were carried out. (Table 10) shows result of breaking down the discrimination between samples/groups, I and II in to species contributions. Species are ordered by their average contribution *δi to the average dissimilarity* $\delta = \sum\delta i$ = 61.25. Species which are likely to be good discriminating of Group I and II (i.e. Shelf waters of Karnataka (Karwar and Mangalore) and shelf waters of Kerala (Calicut and Kodungallur) respectively). Nearly 90% of the contribution to the *δ* is accounted for the first twelve species listed, with over 80% accounted for by the first seven.

DISCUSSION

The Arabian Sea is a highly complex oceanic basin, strongly influenced by biannual monsoon winds that blow from the southwest (SW) during June to September (summer monsoon) and the northeast (NE) during December to February (winter monsoon). (Burkill *et al.,* 1993). During the summer (SW) monsoon, wind-driven upwelling occurs along a broad region parallel to the coast, which brings cooler but nutrient rich water into the euphotic zone, inducing a strong coupling between physical and biological processes (Banse, 1987). The present study brings out the vertical variation in biological characteristics with respect to prevailing hydrographical conditions. During the study period, the shelf waters of waters southwest coast of India were warm and stratified. The isotherms were found down to 10 m in station 1, 2 and 4 below which temperature declined and extended up to 35 m. However, in station 3, the isothermal effect was seen down up to 25 m. Weak thermocline was established in the all stations, attesting to the vertical mixing of water column. The present observations bring out the seasonality in the environmental behavior of SW coast controlled by the monsoon induced fresh water flow. Along the Kerala coast, with the onset of summer monsoon, substantial increase in river discharge following rains and intense cloud cover during this period reduces solar radiation and the massive input of suspended materials makes shelf waters fairly turbid as compared to shelf waters of Karnataka. The reduction in turbidity (due to low run off) might be subsequently reduces the water column light attenuation (*k*e; 0.9 – 1.2 m $^{-1}$) along the Karnataka shelf waters. Less salinity of upper water was probably due to monsoonal rain, but it reached normal values at 25 and 35 m depths in all stations. Significant negative correlation of salinity with dissolved oxygen indicating the high photosynthetic activities in low salinities (5-15 m).

The negative correlation of DO (r = - 0.67 to -0.90, p <0.01at stn.3) with NO_3 be a sign of conversion of NO_2 to NO_3 in presence of DO. In the present study a strong inverse relationship between DO and nutrients imply that the organic portion of nutrients might playing a major role in the depletion of DO in all station might be due to heterotrophic microorganisms. Further statistical analysis revealed a significant positive correlation between temperature primary production and light as observed in earlier studies (Goldman and Carpenter, 1974). In marine ecosystem, temperature is of prime importance in the physical environment of an organism to regulate the survival, growth, reproduction and distribution of organisms (Kinne, 1970; Langford, 1990). It is also noticed that vertical hydrographical properties, often limits the biological activity in the coastal waters. All the nutrients showed strong negative correlation in all stations with DO indicating consumption of nutrients by phytoplankton with release of oxygen through photosynthesis. In the coastal zone of western India experiencing upwelling during summer monsoon (May-June) makes the beginning of upwelling along the

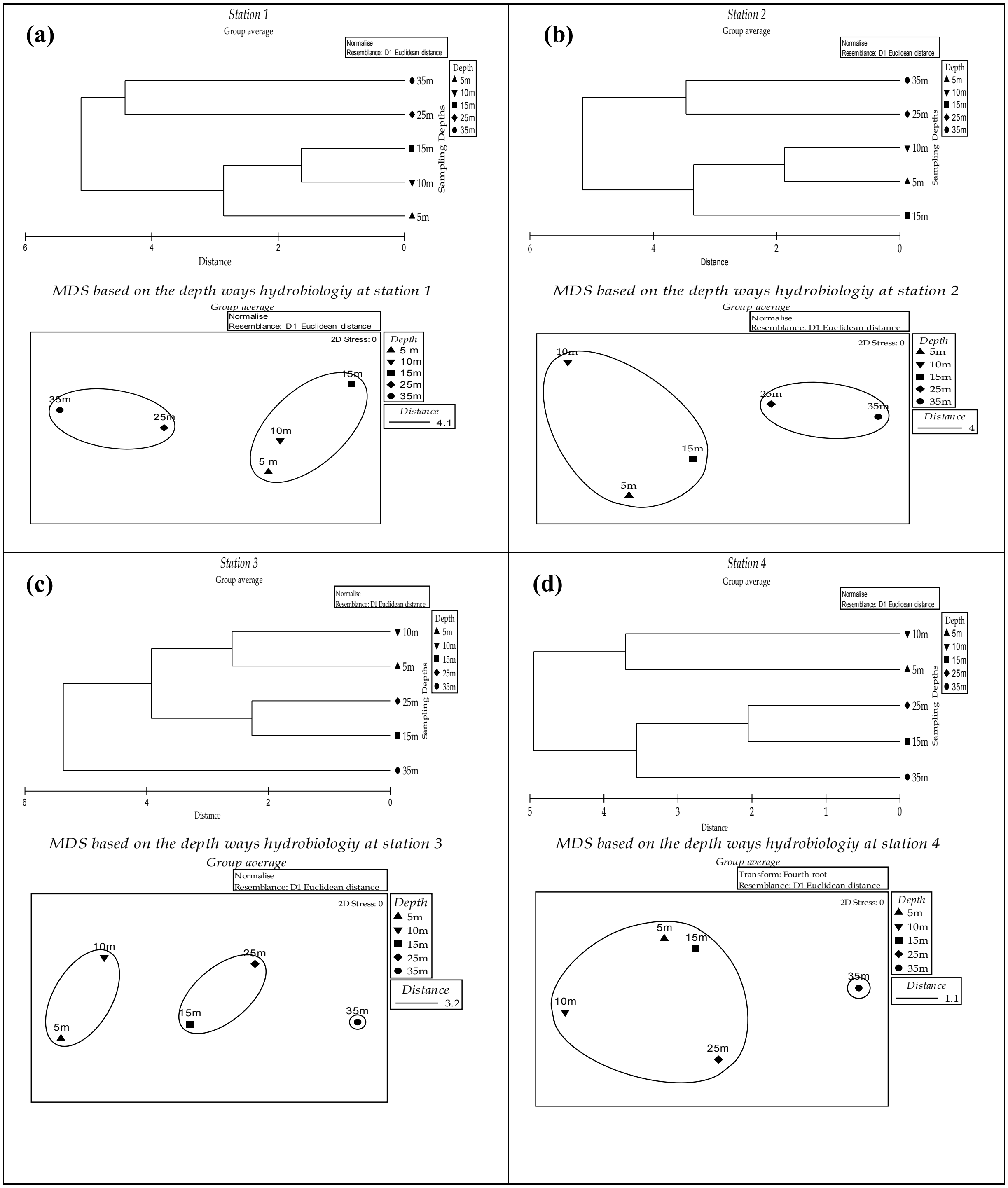


Fig.3. Group average clustering from Euclidean distances and 2-dimensional MDS based on the hydrobiology with respect to depth at each station along southwest coast of India. (a) Stn. 1; (b) Stn. 2; (c) Stn. 3; (d) Stn. 4.

SW coast of India (Sharma, 1968; Shetye et.al., 1990; Unnikrishnan and Antony, 1992). The cold saline up-welled water is usually forming a thick pycnocline layer at depth of 10 to15 m, causing stratification and poor ventilation of sub pycnocline waters and oxidation of organic matter below pycnocline layer might be the reason for depletion of DO concentrations at the deeper shelf waters. A steep change in salinity from 10 m on wards at all the station could be due to this pycnocline layer.

The stations1 and 2 recorded slightly elevated levels of NO_2^--N and NO_3^--N concentration which might be due to the nitrite laden fresh water inflow from River (*Kalindi, Netravati and Gurupur) input.* Results shows low values at upper water column might be due to higher biological uptake by phytoplankton (Sankaranarayanan and Qasim, 1969) has attributed low values of nitrite may be due to its conversion in to nitrate. Nitrogen is the limiting nutrient for primary and secondary production in most marine

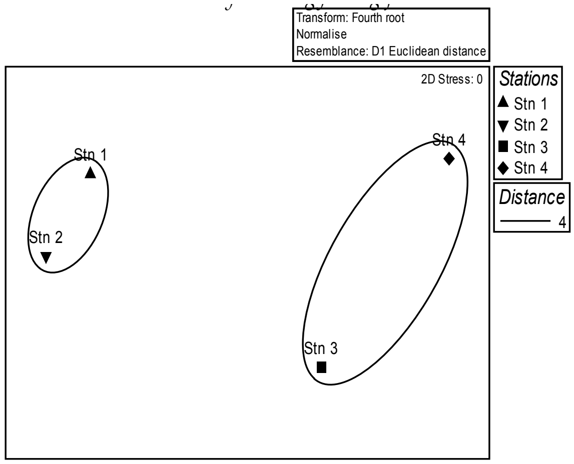
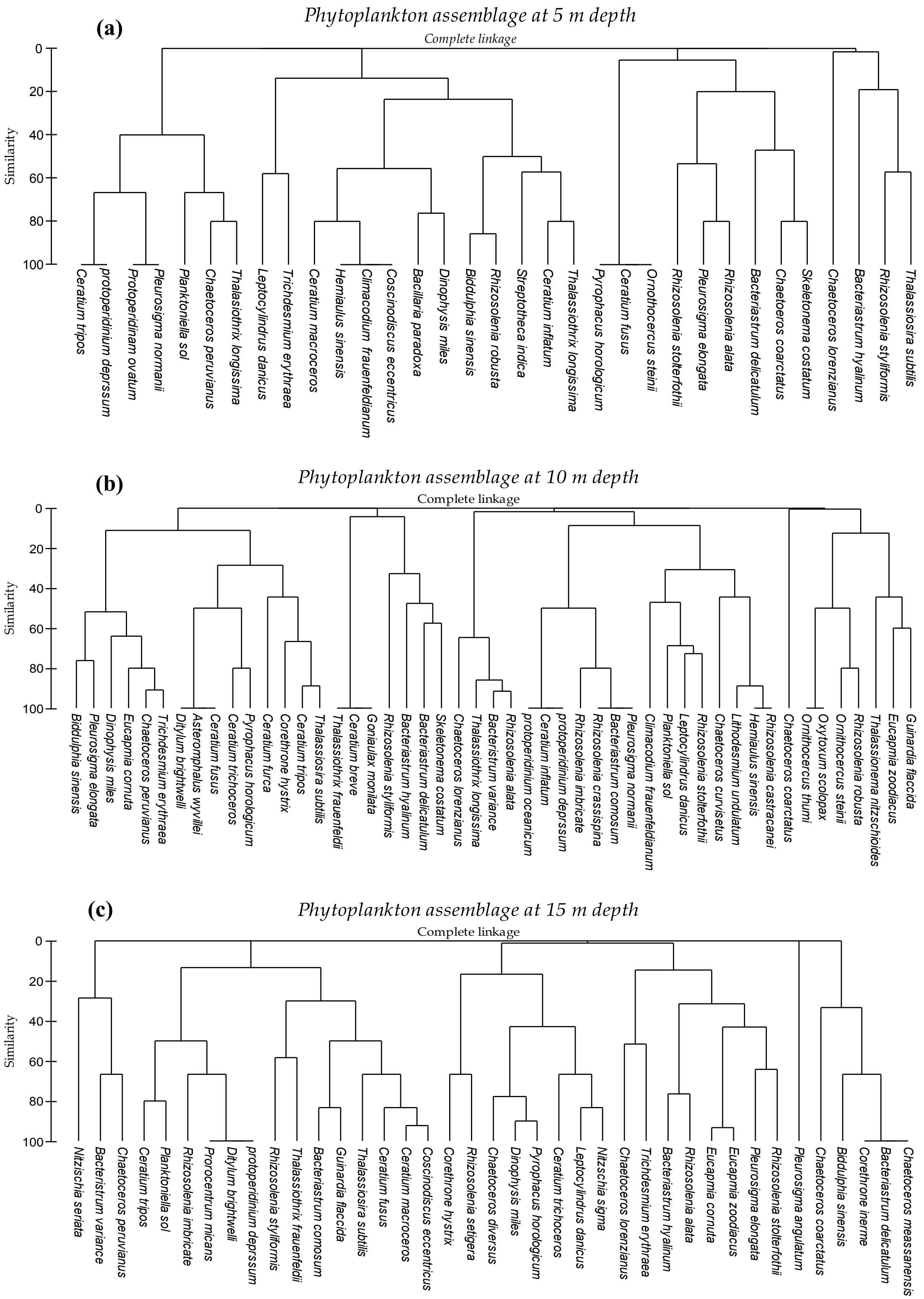


Fig.4. 2-dimensional MDS based on the hydrobiology along four stations

ecosystems (Rhyther and Dunstan, 1971). Increase of nitrite with maximum around 50 to 100 m depth, and is at the top of the thermocline. This maximum in association with wide range of oxygen (2 to 5 ml L^{-1}) levels is due to nitrification activity (Sankaranarayan *et al.,* 1983; Sen Gupta *et al.,* 1980). In present investigation, variation in nitrite concentration among stations might be due to varying amount of organic load and stages of their oxidation. The elevated levels of NO_3^- concentrations at deeper waters may be due to biological oxidation of organic nitrogen substances, which produced indigenously in the water. (Parson *et al.,* 1990) have reported nitrate is an important source for phytoplankton growth, however high amount of nitrate in the coastal water increase the growth of nuisance algae and trigger eutrophication. Rapid biological uptake of dissolved nitrogenous nutrients by phytoplankton at 5 - 15 m depth compared to deeper waters and negative correlation of dissolved oxygen with NO_3^- may be the cause for governing the NO_2^- and NO_3^- concentrations in the SW of India. This avowal is in concord with earlier observation done by Darmaraj and Nair, 1981).

A strong negative correlation of PO_4-P with DO demonstrating consumption of phosphate due to biological utilization by phytoplankton with the release of oxygen through photosynthesis. The elevated levels of PO_4-P at Mangalore might be allocated to the release of phosphate from sediments due to the turbulent action of seawater with low saline river water , it can also be attributed to release of phosphorus from mud occurs at low dissolved oxygen (Rochford, 1951) and at high pH (Carrit and Goodgal, 1954). Liss, (1976) has reported that, non conservative behavior of dissolved forms of phosphorus is not due to biological effects and considered that sediment must be capable of both removing PO_4^{3-} from phosphate rich water and adding it to water low in phosphate content. Phosphate load in water considerably increases through soil disturbances and disposal of sewage and other waste (Smith and Longmore, 1980). From the data it is quite obvious that the concentrations of PO_4^{3-} content in upper water column (5-15 m depth) is less compared to sub pycnocline waters, attributed to the removal of phosphate by biological utilization, high suspended sediment load coupled with low salinity and high oxygenated condition in agreement with earlier works (De Sousa *et al.,* 1981). Phosphorus recycled rapidly between the water and phytoplankton as a result, may often be a rate limit steps in primary productivity (Jeffrey, 1995; Parson *et al.,* 1990). In the present study a strong inverse relationship between DO and nutrients imply that the organic portion of nutrients play a major role in the depletion of DO in all station. The high silicate laden fresh water input from the *Netravati and Gurupur Rivers* might be the reason for elevated levels of silicate concentrations at Stn.2 compared to other stations. Silicate concentration showing strong negative correlation with phytoplankton density suggests silicate might be actively removed from water column diatom cells in upper pycnocline waters (5-15 m). Silicon is essential for the growth of those organisms such as diatom, which processes siliceous frustules or skeleton. Comparatively low SiO_4-Si concentrations were recorded at all stations might be the reason for less diatom density encountered during the study period. Depletion of silicon in coastal waters inhibits cell division and eventually suppresses the metabolic activity of the cells and limit diatom population. Dissolution of clay minerals of riverine origin and dead and decaying diatom frustules containing solidified silicates have been supposed to be the reason for elevated levels of silicate content at deeper waters of station 2 compared to all other stations. A strong positive correlation between salinity and the nutrients except silicate suggest that leaching of nutrients from fine sediment particles of riverine origin at higher salinities. High nutrients below 10 m suggest degradation activity either in the water column or in the bottom sediment. Severe cyclonic depressions during the summer monsoon and churning of bottom sediment might be reason for the irregular nutrient distribution observed at Stn. 4.

Further chl. *a* having strong positive correlation with Phytoplankton density and Primary production indicating the maximum chl.*a* concentration coincide with the peak value of phytoplankton standing crop and primary productivity at all stations as observed in studies under similar situations elsewhere (e.g., Devassy and Goes, 1991; Sarupriya and Bhargava, 1998; Tiwari and Vijayalakshmi, 1998). Except at stn. 4, maxim chl. *a* concentration was at 10 to 15 m water column depths whereas stn. 4 recorded maximum chl. *a* at 5 m depth. Result indicate that apart from few sampling depths, phytoplankton standing crop, coinciding with the high value of chl. *a* in all four stations, this observation is in agreement with (Devassy and Goes 1991; Qasim, 1978). In studies related to marine food chain or trophodynamics an estimate of the standing crop of phytoplankton become the necessary prerequisite. Chl. *a* indicate the total plant material available in the aquatic body at the primary stage of food chain. Close to southwest coast, up-welled nutrient-rich water often spreads at pycnocline depth 10 to 15 m, causing strong stratification and prevents sinking of phytoplankton cells below sub pycnocline waters and algal cells accumulate above pycnocline layer. This might be the reason for higher values of pigment concentration were recorded at 10-15 m depths except station 4. Devassy and Goes, 1991 reported that sub-surface chlorophyll maxima (SCM), is related to the optimum light availability (16% of surface irradiance). Further, chl. *a* is having moderate negative correlation with all nutrient


(a)
Phytoplankton assemblage at 5 m depth
Complete linkage
Similarity
0
20
40
60
80
100
Ceratium tripos
protoperidinium deprssum
Protoperidinam ovatum
Pleurosigma normanii
Planktoniella sol
Chaetoceros peruvianus
Thalasiothrix longissima
Leptocylindrus danicus
Trichodesmium erythraea
Ceratium macroceros
Hemiaulus sinensis
Climacodium frauenfeldianum
Coscinodiscus eccentricus
Bacillaria paradoxa
Dinophysis miles
Biddulphia sinensis
Rhizosolenia robusta
Streptotheca indica
Ceratium inflatum
Thalassiothrix longissima
Pyrophacus horologicum
Ceratium fusus
Ornothocercus steinii
Rhizosolenia stolterfothii
Pleurosigma elongata
Rhizosolenia alata
Bacteriastrum delicatulum
Chaetoceros coarctatus
Skeletonema costatum
Chaetoceros lorenzianus
Bacteriastrum hyalinum
Rhizosolenia styliformis
Thalassiosira subtilis
(b)
Phytoplankton assemblage at 10 m depth
Complete linkage
Similarity
0
20
40
60
80
100
Biddulphia sinensis
Pleurosigma elongata
Dinophysis miles
Eucapmia cornuta
Chaetoceros peruvianus
Trichodesmium erythraea
Ditylum brightwelli
Asteromphalus wyvillei
Ceratium fusus
Ceratium trichoceros
Pyrophacus horologicum
Ceratium furca
Corethrone hystrix
Ceratium tripos
Thalassiosira subtilis
Thalassiothrix frauenfeldii
Ceratium breve
Goniaulax monilata
Rhizosolenia styliformis
Bacteriastrum hyalinum
Bacteriastrum delicatulum
Skeletonema costatum
Chaetoceros lorenzianus
Thalassiothrix longissima
Bacteristrum variance
Rhizosolenia alata
protoperidinium oceanicum
Ceratium inflatum
protoperidinium deprssum
Rhizosolenia imbricate
Rhizosolenia crassispina
Bacteriastrum comosum
Pleurosigma normanii
Climacodium frauenfeldianum
Planktoniella sol
Leptocylindrus danicus
Rhizosolenia stolterfothii
Chaetoceros curvisetus
Lithodesmium undulatum
Hemiaulus sinensis
Rhizosolenia castracanei
Chaetoceros coarctatus
Ornithocercus thumi
Oxytoxum scolopax
Ornithocercus steinii
Rhizosolenia robusta
Thalassionema nitzschioides
Eucapmia zoodiacus
Guinardia flaccida
(c)
Phytoplankton assemblage at 15 m depth
Complete linkage
Similarity
0
20
40
60
80
100
Nitzschia seriata
Bacteristrum variance
Chaetoceros peruvianus
Ceratium tripos
Planktoniella sol
Rhizosolenia imbricate
Prorocentrum micans
Ditylum brightwelli
protoperidinium deprssum
Rhizosolenia styliformis
Thalassiothrix frauenfeldii
Bacteriastrum comosum
Guinardia flaccida
Thalassiosira subtilis
Ceratium fusus
Ceratium macroceros
Coscinodiscus eccentricus
Corethrone hystrix
Rhizosolenia setigera
Chaetoceros diversus
Dinophysis miles
Pyrophacus horologicum
Ceratium trichoceros
Leptocylindrus danicus
Nitzschia sigma
Chaetoceros lorenzianus
Trichodesmium erythraea
Bacteriastrum hyalinum
Rhizosolenia alata
Eucapmia cornuta
Eucapmia zoodiacus
Pleurosigma elongata
Rhizosolenia stolterfothii
Pleurosigma angulatum
Chaetoceros coarctatus
Biddulphia sinensis
Corethrone inerme
Bacteriastrum delicatulum
Chaetoceros meassanensis

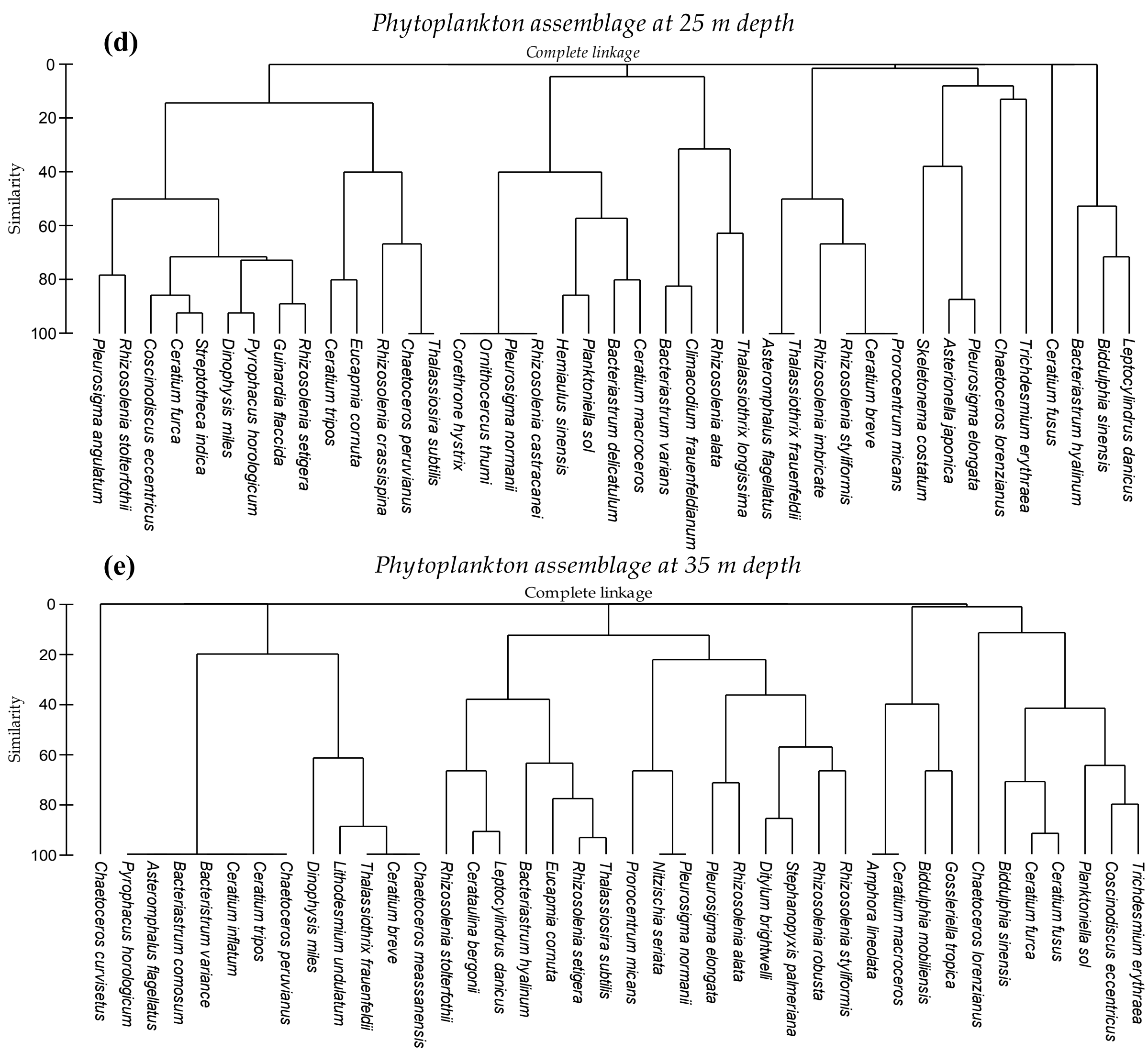


Fig. 5. Dendrogram showing depth ways Bray-Curtis similarities of phytoplankton assemblage at each depth (a) 5 m, (b)10 m (c) 15 m (d) 25 m and 35 m respectively

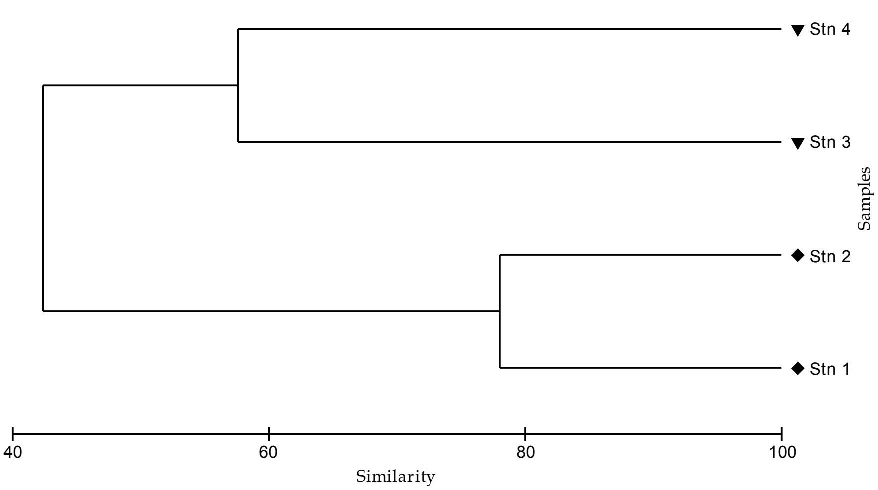


Fig.6. Group-averaged clustering from Bray - Curtis similarities among stations

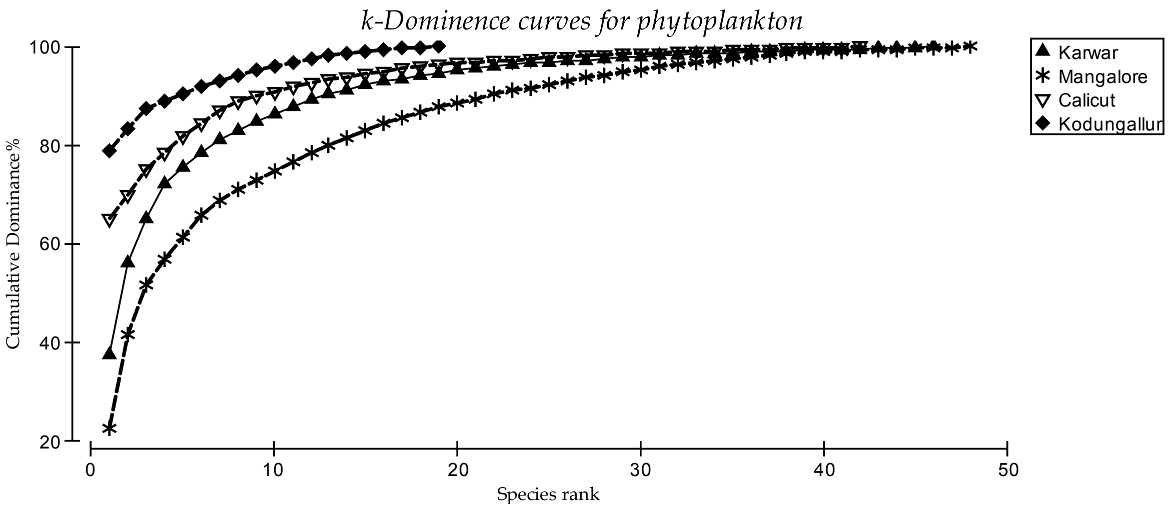


Fig.7. Cumulative dominance plot showing least diversity for the station Kodungallur

clearly indicated direct uptake of nutrients by algal cells and corresponding increase in pigment concentration. The enhanced nutrient supply to coastal waters might have resulted in high phytoplankton and chl. *a* production (Banse, 1984). The present study clearly indicated interrelationship between nutrients and chlorophyll *a* concentration. (Saraladevi, *et al.,* 1997) also made similar observation along the southwest coast of India. Various processes have been mentioned as responsible for the formation and maintenance of subsurface chlorophyll maximum (SCM) layers. (Steele, 1964) found that the SCM in the Gulf of Mexico did not correspond to a maximum in biomass, but reflected shade adaptation to lower light levels of the slowly sinking cells. (Anderson, 1969), on the other hand, describes an SCM made up of actively growing algal cells.

A trend in increased primary productivity was observed towards northern transects (Mangalore and Karwar) and also showed a moderate positive correlation with chl *a* and phytoplankton standing crop except stn. 4. This is in concordance with observations made under similar situations elsewhere (e.g., Bhargava *et al.,* 1978; Sumitra Vijayaraghavan and Krishnakumari, 1989; Bhargava, 1996; Prasanna Kumar *et al.,* 2002; Habeebrehman *et al.,* 2008). Latitudinal variations in primary productivity and chlorophyll distribution at south west coast of India (Arabian Sea) indicate that shelf waters of state of Karnataka (12-14 ^{o}N) is more productive than shelf waters of state of Kerala shelf waters (10-11 ^{o}N). Along the coastal belt of state of Kerala, experiences large cloud cover with rough sea weather conditions and turbid mixed layer might be responsible for low productivity along shelf waters of Kerala. Even though upwelling bring nutrient rich water subsurface water to euphotic zone, high turbid mixed layer and cloud cover over shelf waters hindrance the phytoplankton growth and their by the productivity. Low rate of primary production at shelf waters might be due to the low biomass of phytoplankton in the upwelled waters, although the elevated concentrations of nutrients prevailing provide a conducive environment for active growth of phytoplankton. This mismatch is due to the fact that there is normally a lag between strong upwelling and high phytoplankton biomass, because the population needs time to take up the nutrients and grow (Barber *et al.,* 1971, Duarthe, 1990). The lag period is due to the physical adjustments of phytoplankton to the changed environment and the external factors such as turbulence, grazing, etc (Duarthe 1990). Depression exerted agitation and resultant high-suspended load in the water column might have obstructed proper light penetration and influenced the process of photosynthesis at Station 4. With the onset of the summer monsoon, the conditions along shelf waters of state of Karnataka will change considerably, under the influence of the south westerly winds along the west coast the event of upwelling will intensified and often nutrient rich water might enhance the proliferation of phytoplankton cells and productivity.

At all stations, 10-15 m water column recorded maximum primary production except for station 3, is in association with pycnocline layer and the phytoplankton growth was irradiance limited underneath the pycnocline. It is also noted that increased algal growth cannot be an immediate result of enhanced nutrient supply. In some cases, the uplifted, nutrient rich water lies under a shallow, sharp thermocline as observed at 13 °N, during peak summer monsoon. The mixed layer acts to store much of the solar heat input, and the depth of the mixed layer relative to the light input strongly influences the rate of primary production. Therefore, the relationship between mixed layer depth and chl. *a* should be obscure at any station. Denman and Marra, 1986 demonstrated that large variations in the depth to which phytoplankton are mixed have a significant impact on their subsequent growth because of changes in the light field to which they are exposed. Very low productivity in highly turbid euphotic waters of Maharashtra coast is attributed to the effect of turbidity on primary productivity (Varshney et.al., 1983). Among the several factors, the most obvious factor influencing primary production is the amount of solar energy reaching the surface water (Jerlov, 1970). The spatial variation of primary productivity is of great

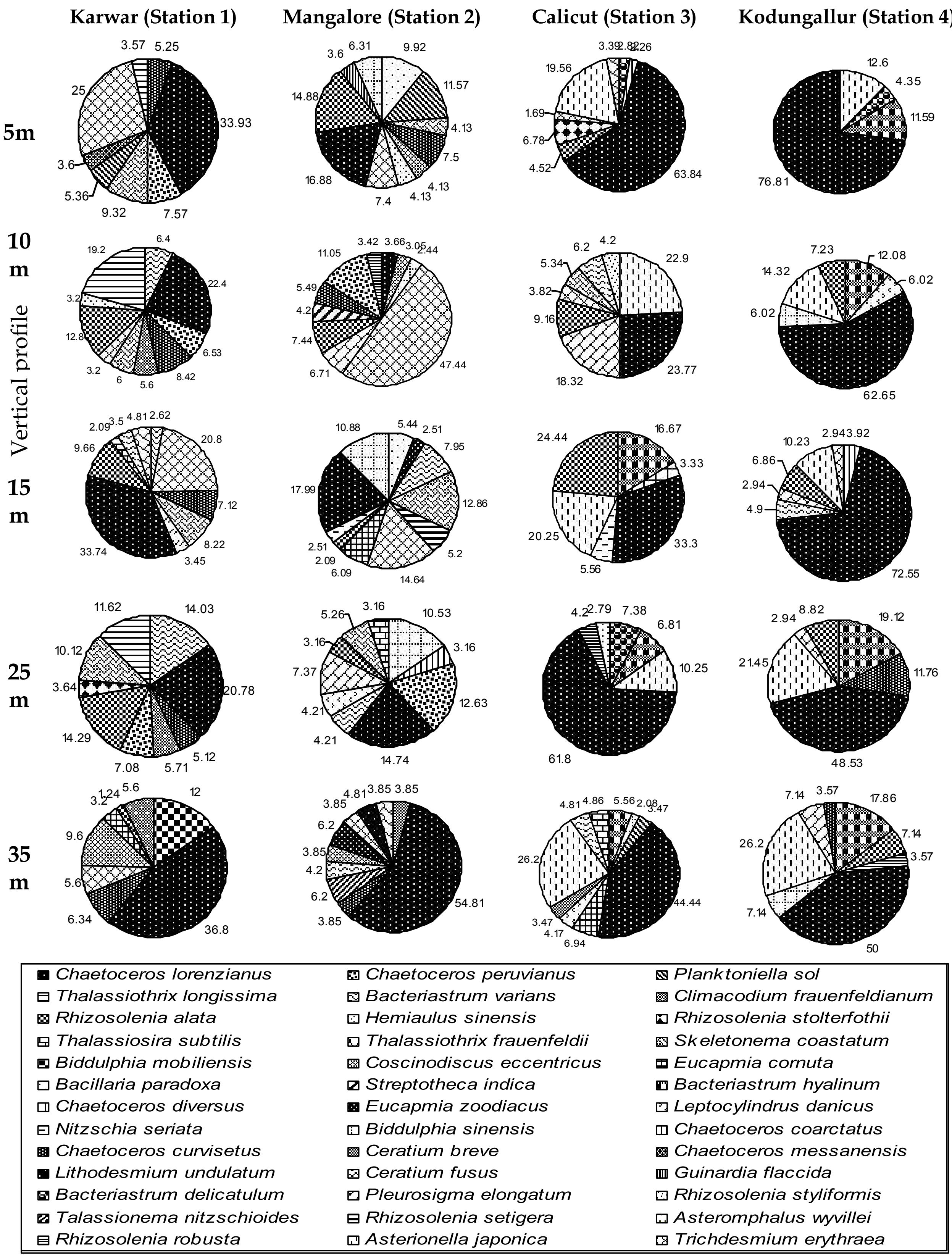


Fig.8. Percentage compositions of major algal species at various stations at each depth

importance in assessing the biological health and hence a detailed study of nutrient distribution with respect to photosynthetic rate and phytoplankton standing crop is required to understand dynamic marine ecosystem. Primary productivity was maximum at 10 to 15 m water except at stn 3, where the maximum at 5 m depth. According to Devassy and Goes, 1991 photosynthetic rates were invariably higher at subsurface depths corresponding to 30 and 60% of the incident irradiance. This is in accordance with phytoplankton and nutrient distribution (Table 1). A definite link between primary production and demineralization by zooplankton is considered to exist (e.g., Goldman, 1985). In contrast, in the subsurface chlorophyll maximum, the phytoplankton production is controlled by light and nutrient supply at deeper waters. In upper mixed layer, phytoplankton profiles might be primarily determined by a depth differential in herbivore grazing (Longhurst, 1976) and nutrient supply, which is excreted by zooplankton apart of nutrients from land origin (Dugdale and Goering, 1967). This may enhances the phytoplankton standing crop and thereby the corresponding organic production. The present study corroborate with the fact that photosynthetic rates are invariably higher at sub surface waters corresponding to 30 to 60% of the incident irradiance and with optimum nutrient distribution (Devassy and Goes, 1991). A definite link between primary production and demineralization by zooplankton exist (Goldman, 1985). The present results show high significant correlation between primary productivity and chlorophyll *a*, between chlorophyll a and nitrate were observed. (Bhargava *et al.,* 1978) did similar type of observation at southern Arabian Sea. A significant positive correlation between primary productivity and chl. *a* and phytoplankton density and negative correlation between primary productivity and nutrient concentration was established.

Phytoplankton species distribution revealed 67 species of phytoplankton belonging to 3 taxonomic groups, (Sarojini and Sharma, 2001) made similar observation at east coast waters of India. Earlier reports suggested a stratification of diatoms with depth and higher abundance at subsurface water compared to surface (Sawan and Madhupratap, 1996). In the upwelling conditions, phytoplankton growth rate varied with groups. Diatoms were found to be important, although they were patchily distributed (Burkill, 1999). They always had higher growth rate (Garrison *et al.,* 2000) than dinoflagellates and silicoflagellates. Malone (1980) reported that larger diatoms of predominate in highly productive areas such as upwelling systems. Initial dominance of flagellates (nanoplankton) was completely taken over by diatoms during upwelling. However, at some locations phytoplankton, other than diatoms (green flagellates) were dominant, largely due to the differences in the rate of nitrate assimilation. This was accompanied by a concomitant shift in the vertical distribution of the chlorophyll maximum, which moved from the surface to form SCM.

Peak phytoplankton established within and below the pycnoline / nitrocine, suggesting a low vertical dispersion of particles in this layer due to lower particle sedimentation rate and consequent temporary aggregation within the pycnocline and enhance growth condition due to irradiance and nutrient availability. Formation and persistence of thin layers phytoplankton in coastal ocean can result in various physical processes (Franks, 1995). High biogeochemical activities (Hanson and Donaghay, 1998) have been quantified within those thin layers, were as dense concentrations of phytoplankton are often locked in this layers (Rines *et al.,* 2002). Below 15 m, it was determined that some colonies of *Chaetoceros* formed abundant. The slow settling of *Chaetoceros* cells may be due to their long hair like spines, which increase the friction and lower sinking rates. Phytoplankton can accumulate at the base of the mixed layer and below the pycnocline through a reduction in sinking velocity as they enter a region of greater density and velocity. Moreover, sinking rates of marine diatoms vary widely within density gradients depending on their physiological state and on nutrient availability (Passow, 1991). From the results it is clear that maximum phytoplankton standing crop was in direct relation with chlorophyll and nutrient concentration. The dinophyceae representatives were present throughout the water column in all stations except stn. 4. *Trichdesmium erythraeum* was the only one representative of class cynophyceae and it was more predominant in 10 and 15m depth of Karwar and Mangalore. According to (Jeffrey, 1995) filamentous *Trichdesmium* is found in the nutrient-poor waters of the warm near-shore waters of restricted circulation and nutrient poor waters of oceanic gyres. Cyanobacteria well known for their ability to atmospheric nitrogen fixation, in which gaseous nitrogen is converted to NH_4^+, (ammonium ion), and is then available for incorporation in to amino acids and proteins. In some seas, nitrogen fixation by *Trichodesmium* is responsible for as much as 20% of input of nitrogen in to phytoplankton.

Vertical stratification of some phytoplankton species was well pronounced. Organisms such as *Ceratium furca, Bacteriastrum varians*, *Ceratium breve*, *Corethron hystrix*, *Guinardia flaccida*, *Oxytoxum scolopax*, *Lithodesmium undulatum*, *Talassionema nitzschioides, Rhizosolenia crassispina*, *Ceratium trichoceros* and *Ditylum brightwelli* were found only from 10m onwards. This behavior might be due to photo- inhibition at surface and shade adaptation at subsurface depths (Devassy and Goes, 1991). In marine ecological research, multivariate methods (through clustering and ordination) provide useful for detecting difference in the biotic structure between samples in space and time or changes over time (Clarke and Warwick, 1994). The main purpose of any community analysis has always been always been to investigate patterns among communities taking in to account species richness and diversity, special distribution and or relating given association to environmental gradients (Wilbur and Travis, 1984). In this context, some key studies exist for phytoplankton dealing with multivariate methods as with a few in land and coastal waters (e.g. Matta and Marshall, 1984; Van Tongeren *et al.,*1992 ; Varis, 1991; Madhu *et al.,* 2007).

On the basis of phytoplankton abundance data and species association patterns, it is possible to distinguish different phytoplankton communities (depth and area-ways) along south west coast of India. while *Chaetoceros peruvianus, Chaetoceros curvisetus, Skeletonema costatum, Thalassiothrix longissima, Bacteriastrum* *varians, and Rhizosolenia alata* were found characterizing the shelf waters of Karnataka (Karwar and Mangalore), *Asterionella japonica* was the discriminating species for shelf waters Kerala (Calicut and Kodungallur).The investigations have shown presence of discrete assemblage of phytoplankton in relation to prevailing hydrographic condition. Mechanism responsible to such differences could be many and diverse. Physical accumulation of suspended loads in coastal water brought through river discharge impinging photosynthetic activity, local upwelling controlled by climatic events (e.g., prevailing wind systems), seasonal nutrient enrichment or impoverishment, difference in growth rate of individual planters, zooplankton gazing pressure (Burkill, *et al.,*1987) and salinity variations due marginal stress from the fresh water inputs (Robin, *et al.,* 2003). Changes in phytoplankton community structure across water column noticed during this study could be matched with differing salinity and nutrient concentrations. (Clark and Warwick, 1994) explained that the biotic data could be matched with a set of environmental variables measured at the same set of sites corresponding to the biota.

CONCLUSION

Latitudinal variations in primary productivity and pigment concentration along SW of India (Arabian Sea) indicate that shelf waters of state of Karnataka (12-14 ^{o}N) is more productive than shelf waters of state of Kerala shelf waters (10-11^{o} N). Summer monsoon associated with cloudy rough sea weather conditions and turbid mixed layer prevailing in the Kerala shelf waters might have contributed to this observation. Results clearly indicate that deeper waters (10-15 m) are more productive than upper waters (5 m) with respect to pigment concentration, species diversity and net productivity. In conclusion, we contend that phytoplankton abundance and biomass could be affected by its spatial variability in community structure with species specific association (e.g., depth ways) and largely with respect to differences in the hydrographical conditions. The study provide baseline Knowledge on the productivity, pigment concentration and Phytoplankton community structure and quantity of phytoplankton biomass available for marine food web with respect to various depths, which could give new insight to the future ecological assessment of coastal and shelf waters.

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