

Phytoplankton species assemblages and their relationship to hydrographic factors—a study at the old port in Mangalore, coastal Arabian Sea.

Karolina Härnström^{1,2*}, Indrani Karunasagar¹, Anna Godhe^{1,2}

¹ Dept. of Fishery Microbiology, College of Fisheries, Karnataka Veterinary Animal and Fisheries Sciences University, PB No 527, Mangalore 575 002, India

² Dept. of Marine Ecology, University of Gothenburg, Box 461, SE 405 30 Göteborg, Sweden
[Email:karolina.harnstrom@marecol.gu.se]

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Several environmental variables were monitored and water samples were examined from over a period of 17 days in December 2005 and January 2006 to understand the taxonomic structure of coastal phytoplankton communities at a coastal site near Mangalore. The phytoplankton community was characterized by identifying and quantifying microalgal taxa; in conjunction, also determined Chl *a*, inorganic nutrients, oxygen, salinity, temperature, total bacteria, and tidal range. Canonical correspondence analysis (CCA) was used to trace temporal phytoplankton community changes, and to examine the relationships between species composition and environmental factors. These variables were subjected to analysis, pairwise, to identify correlations. The species diversity of the phytoplankton community changed rapidly, and high species diversity coincided with significantly higher relative diatom abundance, and lower species diversity coincided with significantly higher proportions of phytoplankton taxa other than diatoms and dinoflagellates. In addition, the Chl *a* concentration was positively correlated to the relative proportion of dinoflagellates. The relative abundance of some species was dependent on specific environmental variables, such as *Chaetoceros tenuissimus* that was found inversely correlated to salinity. We also found that the stage of the tides may have implication on the sampling, because it has an influence on species diversity and the proportion of specific microalgal groups. At declined water level, the relative proportion of diatoms and dinoflagellates was low, and generally the Chl *a* concentrations were also lower during low tide.

[Key words: Phytoplankton, monsoon, upwelling, hydrography, salinity]

Introduction

Marine phytoplankton communities usually comprise several taxonomic groups, and contribute to primary production and interaction between trophic levels¹. Primary production varies with season, and this can be ascribed to variation in nutrient access, light, and temperature². Seasonal patterns include changes in phytoplankton diversity, composition, biovolume, and importantly, the magnitude of primary production; but the photosynthetic response to limiting factors might be regulated by changes in species composition and diversity³. Thus, in order to better understand the dynamics of marine ecosystems, it is necessary to accurately quantify phytoplankton biomass and to determine community composition at the species level, and to place both in the context of local hydrography.

The freshwater phytoplankton communities India, in e.g. ponds, rivers, and lakes, of India have been widely investigated, especially in the southern part of

the country⁴, but the marine environment has been less extensively studied. Among marine systems, tropical waters have comparatively small seasonal changes; but brief growth increments, separated from the annual average, are frequent⁵. Changes in phytoplankton growth in the Arabian Sea vary seasonally and are driven primarily by the monsoons, but spatial variations are also caused by upwelling and mesoscale eddies⁶. On a large scale, phytoplankton productivity increases during the cooling northeast monsoon (November–February) and during the southwest monsoon (June–September), when upwelling occurs⁷. Because of these semi-annual reversals of monsoons, primary production in the Arabian Sea is amongst the highest in the world⁸. Despite this, phytoplankton communities in marine tropical areas are known to be less dynamic than in temperate waters, from an annual perspective, with smaller seasonal changes in net phytoplankton growth⁵. On shorter scales, however, variability does occur, and brief pulses of increased growth are quite common. For example, a study on the central Indian

*Corresponding author

west coast recorded a great variability in phytoplankton counts between locations that were closely situated⁹. Furthermore, the fluctuations were observed over several months, with different intensities of variation, and they were tied to local upwelling.

Coastal waters off Mangalore provide for a multi-species fishery, and the area is known as one of the largest upwelling systems in the world¹⁰. Upwelling occurs in late summer (peak in August), and this results in elevated nutrient concentrations and high productivity. In winter, during the northeast monsoon, the area have showed variable abundance of both diatoms and dinoflagellates, often replaced by *Trichodesmium* spp (Cyanophyceae)^{11, 12}.

As demonstrated in other geographical areas and in a variety of habitat types, freshwater influence is known to have a profound effect on phytoplankton biomass, productivity, and community composition¹³. Short-term phytoplankton blooms are often triggered by differences in salinity, or from the resultant water column stratification. Indeed, in some areas, temporal change of the phytoplankton community are very dynamic because of short-term tidal variability¹⁴; but other factors, such as zooplankton grazing and exchange between sediment and water column, also affect species diversity¹⁵. Different environmental factors in the coastal SE Arabian Sea, e.g. salinity, temperature, and sedimentation, are influenced by tidal forces; but offshore, this influence is not significant¹⁶. Studies on diatoms in the Zuary estuary, further north in Goa, showed that variation in salinity directly influenced the diatom abundance, with increasing numbers in high salinities¹⁷.

The purpose of this study was to investigate the taxonomic composition of coastal phytoplankton assemblages and how hydrographic factors influence these. Few studies of this kind have been carried out in the area, and gaining more insight into the influence of different environmental factors on phytoplankton community development is of great interest. In the present study the phytoplankton community have been characterised by quantifying and identifying microalgal taxa. Also several environmental variables have been monitored simultaneously during the observation period.

Materials and Methods

The Netravathi River enters the Arabian Sea near (~ 2 km) Mangalore, the sampling site of this study

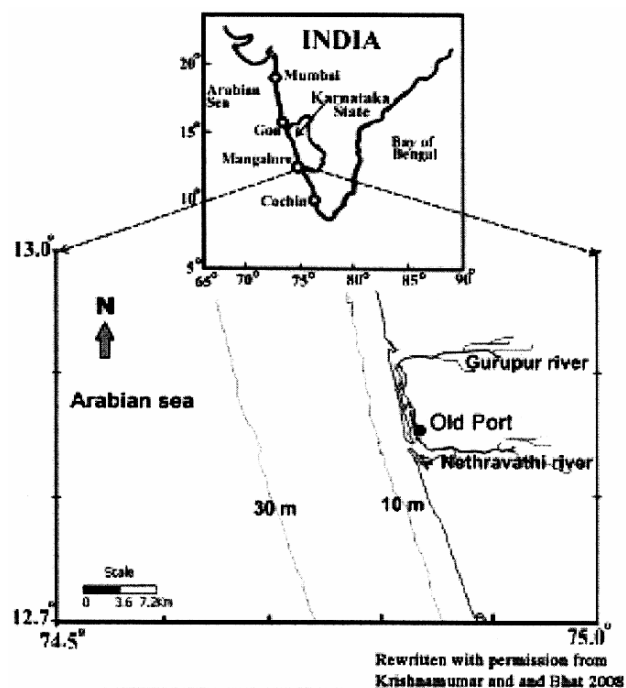


Fig. 1— Map of sampling location.

(Fig. 1). The coastal area is affected by tides, and consequently the estuarine and oceanic waters are mixed; during low tide, fresh water from the river is mixed with seawater.

Water sampling was carried out at the old port of Mangalore, Karnataka (12°52'N, 74°53'E), from December 28, 2005, to January 13, 2006. Samples were collected using a water sampler (Aquatrap, 2.5 l, Partex Products), then transferred to black, light-protected bottles, and immediately transported to the laboratory, where they were processed. The water samples were used for phytoplankton identification and quantification, and for analyzing environmental variables. The sampling was conducted at the same station every second or third day between 10 and 11 AM, irrespective of state of tide.

Inorganic nitrate, ammonia, and silicate were analyzed four times during the sampling period (Dec. 28, Jan. 2, Jan. 6, and Jan. 13). The concentrations of inorganic nitrate, ammonia, and silicate were monitored with Merck Spectroquant® kits (Merck KGaA) and quantified in a spectrophotometer (Spectroquant® NOVA 60, Merck KGaA, NO₃; detection range 3.2-223.7 μM, NH₄; detection range 11.1-105.3 μM, SiO₂; detection range 0.1-140.8 μM). Phosphorus concentrations were quantified using the ascorbic acid method¹⁸, and oxygen concentration by Winkler's titration¹⁹. Salinity

was measured by a conventional refractometer (Erma), and pH by a pH meter (MKVI Systronics). Surface water temperature was measured *in situ* by a thermometer. Mangalore tide plotter was downloaded from Mobile Geographics' web site (<http://www.mobilegeographics.com>), and tidal extremes and heights at 11 AM for all sampling dates were incorporated in the data analysis. Total bacterial counts were estimated by DAPI staining of formalin-fixed samples (3%), following standard protocols²⁰. For estimations of chlorophyll *a* (Chl *a*) concentrations, 2 × 200 ml from each sample was filtered onto Whatman GF/F filters. Chl *a* was extracted in 7 ml of 90% acetone, and kept in 10-ml tubes over night at 4°C. After extraction, 1.5 ml was centrifuged at 4000 rpm for ten minutes, and thereafter the concentrations were measured on a spectrophotometer (Shimadzu Corporation). Chl *a* calculations were based on equations from Parsons *et al.*²¹.

The phytoplankton identification and quantification and evaluation of potential grazers, have been carried out with the 200 ml of seawater was preserved with Lugol's solution. Samples of 50 ml were settled overnight in sedimentation chambers²² for subsequent microscopic analysis using an inverted light microscope (Zeiss Axiovert 25) at 200 to 400 × magnifications. A minimum of 300 living cells was counted in each chamber. Species identification was based on relevant literature^{23, 24, 25, 26, 27}. Some species belonging to particular diatom genera, e.g. *Skeletonema*, can be correctly identified only by electron microscopy²⁸. This was beyond the scope of this study, and therefore such specimens were identified to genus level using light microscopy (LM), and specimens belonging to the same morphospecies, were universally denoted, e.g. *Skeletonema* sp. When two different unidentified morphospecies of the same higher taxa were detected, they were numerically denoted e.g. Diatom sp. 1, Diatom sp. 2. Dimension of all recorded taxa were measured, and biovolumes were calculated using formulas for the geometric shapes closely approximating the taxa²⁹.

The diversity of the phytoplankton community was estimated by calculation of Shannon's diversity index (H')³⁰. Correlations were investigated by using Spearman and Pearson correlation coefficients. Significance level for the tests was defined as $p < 0.05$. The analyses were made using SPSS 11.0.4 for Mac OS X (SPSS Inc., Chicago, IL, USA).

Internal gradient analysis was used to trace temporal phytoplankton community changes, and to examine the relationships between composition of species and environmental factors. CCA (CANOCO version 4.5³¹) was selected as the unimodal response model, since the gradient was more than two standard deviations. The CCA integrated 11 environmental variables and 25 taxa having over 1% relative abundance. None of the data were weighted. CCA was run constrained to each environmental variable in turn to determine the amount of variation that can be accounted for by that variable. Since CANOCO cannot determine the ordination axes' significance, a Monte Carlo test was used to evaluate the significant relationship between environmental and species data. Significance of the CCA axes was tested with 499 permutations.

Results

Chlorophyll *a* concentrations during the period ranged from 1.67 $\mu\text{g l}^{-1}$ to 4.87 $\mu\text{g l}^{-1}$ (Fig. 2A, Table 1). The highest concentration was observed on Dec. 30, and thereafter a decline followed with a second, smaller Chl *a* concentration peak on Jan. 11. Due to the influence of freshwater input from the Netravathi River, the salinity fluctuated at the sample site (32–36, Table 1). The salinity was high, but within normal range for the dry season (November–May) when rainfall is rare, and runoff from the river is less¹⁰. The tidal height oscillated between 0.5 and 1.25 m. The range in pH was between 7.78 and 7.97, and temperature varied between 23° and 24°C. At high tides, the salinity, pH, and Chl *a* concentrations were generally high. All inorganic nutrient concentrations varied moderately (Table 1). A decrease towards the end of the period was noticed in both silicate and nitrate concentrations (data not shown). Phosphorus was the limiting nutrient for phytoplankton growth, with an average Redfield ratio of 589³². Oxygen concentrations varied between 3.84 and 5.66 ml l^{-1} (Table 1).

Table 1— Ranges of environmental variables

Variable (unit)	Min/Max
Chl <i>a</i> ($\mu\text{g l}^{-1}$)	1.67-4.87
PO ₄ (μM)	0.01-0.09
NH ₄ (μM)	16.67-61.11
NO ₃ (μM)	9.68-17.74
SiO ₂ (μM)	9.93-24.47
O ₂ (μM)	3.84-5.66
Salinity (PSU)	32-36
pH	7.78-7.97
Temp (°C)	23-24
Total bacteria	47515-178181
Tide (m)	0.5-1.25

Diatoms dominated the eukaryotic phytoplankton community throughout the investigated period (diatom abundance: $1.57\text{--}6.02 \times 10^5$ cells l^{-1} , Fig. 2B; proportion of diatoms: 24–79%, Fig. 2E). Total phytoplankton biovolumes varied from $0.39 \text{ mm}^3 \text{ l}^{-1}$ to $6.94 \text{ mm}^3 \text{ l}^{-1}$ (Fig. 2C), with the lowest record on Jan 4, and the highest record just two days later. In total, 73 of the encountered phytoplankton taxa were identified to species level; 46 of these were diatoms, and 22 were dinoflagellates. Other recorded taxa were, for example, *Dictyocha fibula* and cf. *Fibrocapsa japonica* (Table 2).

Many diatom species, including *Nitzschia* spp., *Chaetoceros brevis*, *Chaetoceros curvisetus*, and

Guinardia sp., were recorded in large numbers on Jan 2, when diatom reached its first abundance maximum (Fig. 2B). Other species, like *Chaetoceros tenuissimus* and two unidentified small diatoms, displayed higher densities during the second diatom abundance maximum on Jan. 9. *Chaetoceros tenuissimus* was not found at all during the high tide peak on Jan. 2 (Fig. 2D). Between the two peaks of diatom abundance, a short period of lower diatom abundances followed (Fig. 2B). Simultaneously, an increase in biovolumes was recorded (Fig. 2C), which coincided with high abundance of *Cerataulina pelagica*, a relatively large diatom that was dominating the water column on Jan. 6.

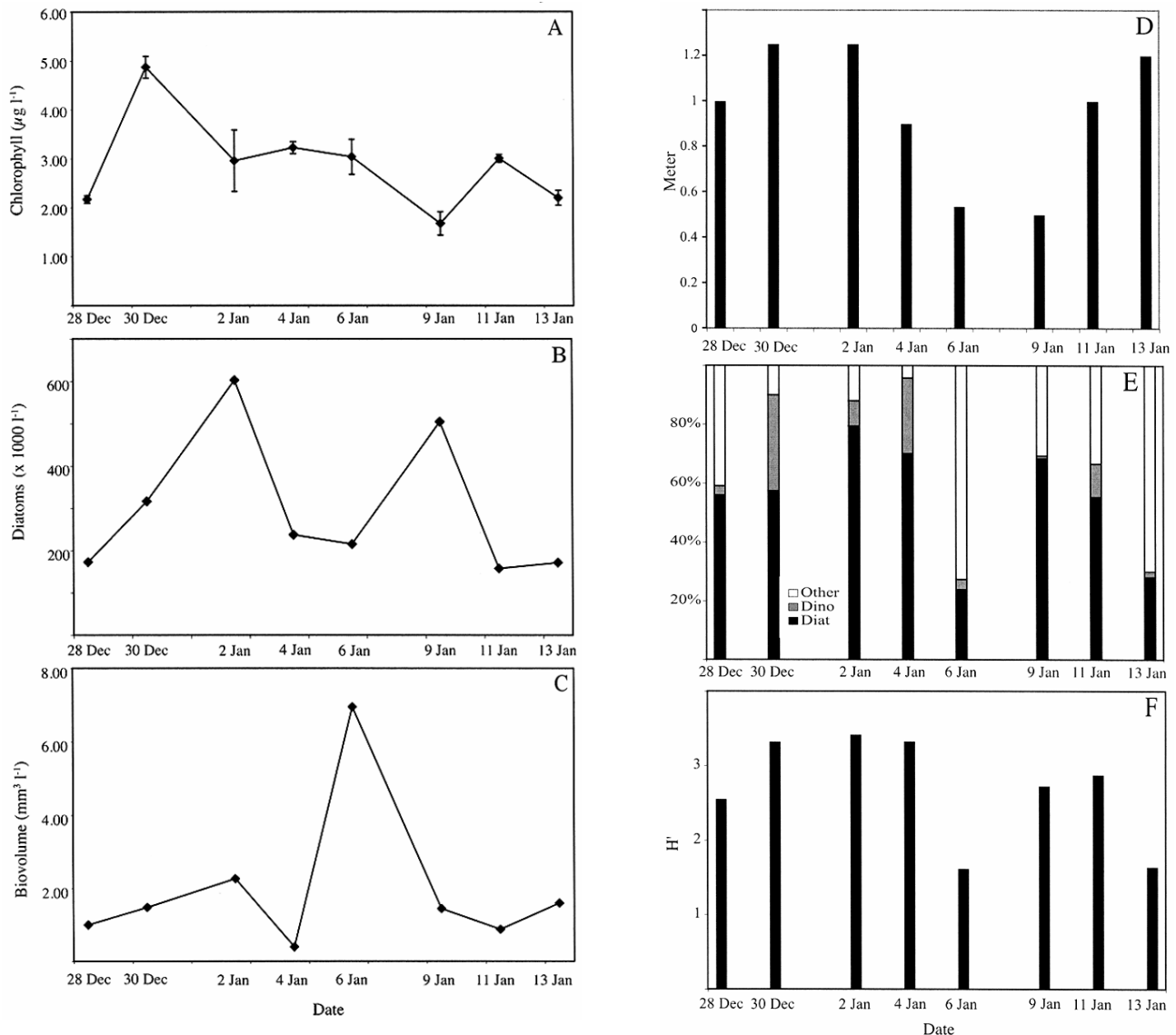


Fig. 2 A.— Chlorophyll *a* concentrations. B. Diatoms per litre. C. Total biovolume of phytoplankton. D. Tidal amplitude. E. Relative proportion of diatoms, dinoflagellates and other groups. F. Shannon's diversity index.

Table 2—Phytoplankton taxa identified in this study

Taxa	Auktor	Range (min-max cells l ⁻¹)
Bacillariophyceae		
<i>Actinocyclus ehrenbergii</i>	Ralfs 1861	0-1963
<i>Asterienelliopsis glacialis</i>	(Castracane) Round 1990	0-27475
<i>Bacteriastrium furcatum</i>	Shadbolt 1854	0-250
<i>Bacteriastrium hyalinum</i>	Lauder 1864	0-981
<i>Bacteriosira fragilis</i>	(Gran) Gran 1900	0-9813
<i>Biddulphia mobiliensis</i>	Grunow 1882	0-350
<i>Biddulphia rhombus</i>	(Ehrenberg) Smith 1856	0-981
<i>Biddulphia sinensis</i>	Greville 1866	0-50
<i>Cerataulina pelagica</i>	(Cleve) Hendey 1937	0-84388
<i>Chaetoceros affinis</i>	Lauder 1864	0-3925
<i>Chaetoceros brevis</i>	Schiitt 1895	0-21588
<i>Chaetoceros compressus</i>	Lauder 1864	0-1600
<i>Chaetoceros costatus</i>	Pavillard 1911	0-23550
<i>Chaetoceros curvisetus</i>	Cleve 1889	0-27475
<i>Chaetoceros decipiens</i>	Cleve 1873	0-650
<i>Chaetoceros laciniosus</i>	Schiitt 1895	0-100
<i>Chaetoceros lorenzianus</i>	Grunow 1863	0-9813
<i>Chaetoceros mitra</i>	(Bailey) Cleve 1896	0-3925
<i>Chaetoceros simplex</i>	Ostenfeld 1901	0-3925
<i>Chaetoceros socialis</i>	Lauder 1864	0-11775
<i>Chaetoceros subtilis</i>	Cleve 1896	0-1963
<i>Chaetoceros tenuissimus</i>	Meunier 1913	0-78500
<i>Chaetoceros wighamii</i>	Brightwell 1856	0-300
<i>Climacodium fraudenfeldianum</i>	Grunow 1867	0-3925
<i>Coscinodiscus concinnus</i>	Smith 1856	0-981
<i>Coscinodiscus radiatus</i>	Ehrenberg 1841	0-4906
<i>Cylindrotheca closterium</i>	(Ehrenberg) Lewin & Reimann 1964	5888-57894
<i>Dactyliosolen fragilissimus</i>	(Bergon) Hasle 1997	0-500
<i>Dactyliosolen phuketensis</i>	(Sundstrom) Hasle 1997	0-3925
<i>Ditylum brightwellii</i>	(West) Grunow 1883	0-981
<i>Eucampia cornuta</i>	(Cleve) Grunow 1883	0-1963
<i>Eucampia zodiacus</i>	Ehrenberg 1840	0-20025
<i>Fragilaria striatula</i>	Lyngbye 1819	0-13738
<i>Guinardia cf. cylindrus</i>	(Cleve) Hasle 1997	0-41213
<i>Guinardia striata</i>	(Stolterfoth) Hasle 1997	0-5888
<i>Hemiaulus hauckii</i>	Grunow ex Van Heurck 1882	0-7850
<i>Hemiaulus sinensis</i>	Greville 1865	0-200
<i>Leptocylindrus danicus</i>	Cleve 1889	0-15700
<i>Leptocylindrus minimus</i>	Gran 1915	0-33363
<i>Melosira nummuloides</i>	Agardh 1824	0-100
<i>Meuniera membranacea</i>	(Cleve) Silva 1996	0-200
<i>Phaeodactylum tricorutum</i>	Bohlin 1897	0-2944
<i>Rhizosolenia faeroensis</i>	Ostenfeld 1903	0-1963
<i>Skeletonema tropicum</i>	Cleve 1900	0-25513
<i>Thalassionema nitzschioides</i>	(Grunow) Mereschkowsky 1902	0-3925
<i>Thalassiosira pseudonana</i>	Hasle & Heimdal 1970	4906-29438

Table 2— Phytoplankton taxa identified in this study—*Contd*

Taxa	Auktor	Range (min-max cells l ⁻¹)
Dinophyceae		
<i>Amylax cf. triacantha</i>	(Jorgensen) Soumia 1984	0-2944
<i>Ceratium furca</i>	(Ehrenberg) Claparede & Lachmann 1859	0-700
<i>Ceratium lineatum</i>	(Ehrenberg) Cleve 1899	0-1962.5
<i>Ceratium pentagonum</i>	Gourret 1883	0-150
<i>Cochlodinium citron</i>	Kofoid & Swezy 1921	0-981.25
<i>Dinophysis caudata</i>	Saville-Kent 1881	0-200
<i>Dinophysis ovum</i>	Schlitt 1895	0-250
<i>Gonyaulax spinifera</i>	(Claparede & Lachmann) Diesing 1866	0-5888
<i>Gonyaulax verior</i>	Soumia 1973	0-100
<i>Akashiwo sanguineum</i>	(Hirasaka) Hansen & Moestrup 2000	0-200
<i>Gyrodinium spirale</i>	(Bergh) Kofoid & Swezy 1921	0-1963
<i>Heterocapsa niei</i>	(Loeblich III) Morrill & Loeblich III 1981	0-50
<i>Karenia mikimotoi</i>	(Miyake & Kominami ex Oda) Hansen & Moestrup 2000	0-47100
<i>Polykrikos schwarzii</i>	Biitschli 1873	0-50
<i>Prorocentrum gracile</i>	Schlitt 1895	0-3925
<i>Prorocentrum lima</i>	(Ehrenberg) Dodge 1975	0-981
<i>Prorocentrum micans</i>	Ehrenberg 1833	0-3925
<i>Prorocentrum minimum</i>	(Pavillard) Schiller 1933	0-1963
<i>Protoperidinium mite</i>	(Pavillard) Balech 1974	0-100
<i>Protoperidinium steinii</i>	(Jorgensen) Balech 1974	0-1963
<i>Protoperidinium subinermis</i>	(Paulsen) Loeblich III 1969	0-981
<i>Scrippsiella trochoidea</i>	(Stein) Balech ex Loeblich III 1965	0-14719
Dictyophyceae		
<i>Ciliophrys infusionum</i>	Cienkowski 1876	0-50
<i>Dictyocha fibula</i>	Ehrenberg 1837	0-981
Raphidophyceae		
<i>cf. Fibrocapsa japonica</i>	<i>Toriumi & Takano 1973</i>	0-3925
Prasinophyceae		
<i>Pterosperma polygonum</i>	<i>Ostenfeld 1902</i>	0-50
Others		
<i>Myrionecta rubra</i>	(Lohmann 1908) Jankowski 1976	0-50

The Shannon's index varied between 1.62 (Jan. 6) and 3.42 (Jan. 2), where the first index value indicates low species diversity, and the latter a much higher diversity. When the diversity index was high, the proportion of diatoms was also significantly higher ($p < 0.01$). Conversely, with a low species diversity index, significantly higher relative abundances were observed for phytoplankton groups other than diatoms and dinoflagellates ($p < 0.01$) (Figs 2E–F). High Chl *a* concentrations were significantly correlated with high relative proportion of dinoflagellates ($p < 0.01$,

Figs 2A and 2E). At the time of highest and lowest dinoflagellate proportions (Dec. 30 and Jan 9, respectively), the Chl *a* concentrations were 4.87 $\mu\text{g l}^{-1}$, and 1.67 $\mu\text{g l}^{-1}$ respectively. There was a tendency toward correspondence between high Shannon's index, high Chl *a* concentration, high diatom abundance, and high tide (Figs 2A, 2B, 2D, and 2F), but no significant correlation was detected.

The CCA was significant ($P = 0.006$, Monte Carlo). Eigenvalues of axes 1 ($\lambda_1 = 0.452$), 2 ($\lambda_2 = 0.332$), 3 ($\lambda_3 = 0.220$) and 4 ($\lambda_4 = 0.212$) explained 90.1% of the

Table 3— Interset correlations of environmental variables with axes

Variable	Axis 1 ($\lambda_1=0.452$)	Axis 2 ($\lambda_2=0.332$)	Axis 3 ($\lambda_3=0.220$)	Axis 4 ($\lambda_4=0.212$)
Chl a	-0.60	0.71	0.31	0.16
PO ₄	-0.50	-0.29	-0.59	-0.54
NH ₄	-0.28	-0.35	-0.16	0.38
NO ₃	-0.55	-0.50	-0.45	-0.06
SiO ₂	-0.37	-0.56	-0.31	-0.20
O ₂	-0.19	-0.14	0.06	0.08
Salinity	-0.88	0.05	0.12	0.45
pH	-0.91	-0.01	0.10	0.39
Temp	-0.90	0.00	0.13	0.40
Tot. bact.	0.02	0.20	-0.63	-0.38
Tide	-0.75	0.36	-0.43	0.34

Table 4— Correlation among environmental and nominal variables used in canonical correspondence analysis

	Chl a	PO ₄	NH ₄	NO ₃	SiO ₂	O ₂	Salinity	pH	Temp	Tot. bact.	Tide
Chl a	1										
PO ₄	-0.18	1									
NH ₄	-0.16	0.09	1								
NO ₃	-0.18	0.76	0.33	1							
SiO ₂	-0.24	0.43	0.45	0.90	1						
O ₂	0.00	0.06	0.33	-0.25	-0.43	1					
Salinity	0.68	0.10	0.37	0.39	0.39	0.14	1				
pH	0.64	0.19	0.38	0.46	0.43	0.14	0.99	1			
Temp	0.65	0.15	0.37	0.44	0.44	0.12	1.00	1.00	1		
Tot. bact.	-0.13	0.50	-0.05	0.47	0.47	-0.66	-0.22	-0.19	-0.21	1	
Tide	0.62	0.35	0.25	0.43	0.29	0.08	0.77	0.76	0.74	0.21	1

cumulative variance in species data and 90% of the relation between species and environmental data (Table 3). The ranks of the environmental variables contributing to this data were (1) pH, (2) temperature, (3) salinity, (4) tide, (5) Chl *a*, (6) nitrate, (7) phosphorus, (8) silicate, (9) total bacteria, (10) ammonia, and (11) oxygen. The CCA showed a high correlation between silicate and nitrate, and between temperature, pH, and salinity, but the correlations between the other variables were moderate or low (Table 4). Therefore, the individual effects of collinear variables, e.g. nitrate with strong collinearity to silicate, are difficult to determine. The species–environmental correlations for all axes were high, all of them having a value of 1. On the basis of interset correlations, pH and temperature had the strongest correlation to axis 1, Chl *a* to axis 2, total bacteria to axis 3, and phosphorus to axis 4 (Table 3).

The length of the environmental arrows and their orientation on the Canoco biplot indicate their relative

importance to each axis. Environmental arrows represent a gradient, where the mean value is located at the origin, and the arrow points in the direction of its increase (Fig. 3). Most species were strongly correlated to nutrients (bottom left of the Canoco biplot, Fig. 3) or Chl *a* (top left of the Canoco biplot, Fig. 3). Negatively correlated to the environmental variables tide and Chl *a*, were taxa such as *Entomoneis* sp., *Cylindrotheca closterium*, *Navicula* sp., and various, small unidentified flagellates, of which many are associated with benthic environments. Most species belonging to the genus *Chaetoceros* showed significant correlation to salinity, tide, and Chl *a*. An exception was *Chaetoceros tenuissimus*. Two small (ca. 3 μ m) unidentified diatom species and *C. tenuissimus* were inversely correlated to salinity. Many species had affinity for higher nutrient concentrations, e.g. *Skeletonema* sp., *Nitzschia* sp., *Fragilaria striatula*, and *Cerataulina pelagica*.

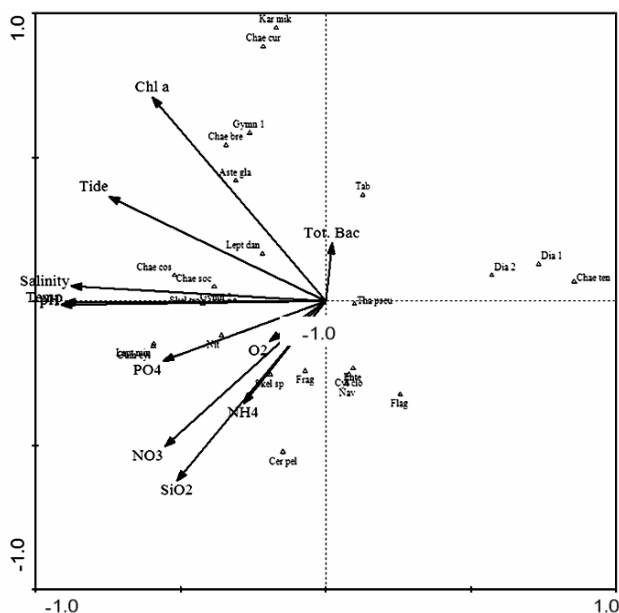


Fig. 3— CCA biplot for species abundance and environmental variables. Abbreviations are: Aste gla= *Asterionellopsis glacialis*, Cer pel= *Cerataulina pelagica*, Chae bre= *Chaetoceros brevis*, Chae cos= *Chaetoceros costatus*, Chae cur= *Chaetoceros curvisetus*, Chae soc= *Chaetoceros socialis*, Chae ten= *Chaetoceros tenuissimus*, Cy clo= *Cylindrotheca closterium*, Dia 1= Unidentified diatom sp.1, Dia 2= Unidentified diatom sp.2, Ente= *Entomoneis* spp., Flag= Unidentified flagellates, Frag= *Fragilaria* spp., Guin cyl= *Guinardia* cf. *cylindrus*, Gymn 1= *Gymnodinium* sp. 1, Gymn 2= *Gymnodinium* sp. 2, Kar mik= *Karenina mikimotoi*, Lept dan= *Leptocylindrus danicus*, Lept min= *Leptocylindrus minimus*, Nit= *Nitzschia* spp., Nav= *Navicula* spp., Skel sp= *Skeletonema* sp., Skel tro= *Skeletonema tropicum*, Tab= *Tabellaria* sp., Tha pseu= *Thalassiosira pseudonana*

Leptocylindrus minimus and *Guinardia* cf. *cylindrus* were clustered more specifically with phosphorus (Fig. 3).

Discussion

In this study it is demonstrated that the species composition of the phytoplankton community changes over very short time periods, and that the relative abundance of each species might be dependent on particular environmental variables. It has been observed that the species diversity of the phytoplankton community may fluctuate rapidly. It is observed that high species diversity coincided with significantly higher relative diatom abundance, and lower species diversity coincided with significantly higher proportions of phytoplankton taxa other than diatoms and dinoflagellates. In addition, the Chl *a* concentration was positively correlated to the relative proportion of dinoflagellates. It is also observed that the stage of the tides may have implication on the sampling, resulting in an influence on species

diversity and the proportion of specific microalgal groups. At declined water level, the relative proportion of diatoms and dinoflagellates was low, and generally the Chl *a* concentrations were also lower during low tide.

Marine water is constantly mixed with fresh water from Netravathi River, at the sampling site, a process enhanced by tidal forces. A positive relationship between Chl *a* and species diversity was observed. It was not possible to draw any conclusions on the individual effects of salinity and temperature because of the collinearity of these variables. Since temperature fluctuations were very small and the effects of the tidal range were strong, salinity has a more pronounced individual effect on the phytoplankton species composition at this specific site. Duarte *et al.*³ recorded, in a previous study from Portugal, the lowest diversities in a coastal lagoon nearest to the opening to the sea, and hypothesized, opposite to the results from our study, that pelagic marine ecosystems have increased production associated with decreasing diversity, i.e. Chl *a* and diversity are negatively correlated. Moreover, the same authors saw, in their study, correlations between high diversity, high diatom abundance, increased water temperature, and salinity. They also found that the changes in photosynthetic parameters (e.g. photosynthetic rate and light saturation index) did not appear to affect the phytoplankton community function over large time scales but definitely affected it on a daily basis. Phytoplankton blooms in estuaries are sometimes dominated by one or just a few species and are spatially patchy³³. Changes in species composition over short times and distances, can be reflected by variation in nutrient and Chl *a* concentrations. In the present study, the major taxonomic groups constituting the phytoplankton community also influenced the diversity index. The most notable characteristic was a higher diversity coinciding with high relative diatom proportion, and decreased diversity during relatively low proportion of diatoms and dinoflagellates. There is significant correlation between Chl *a* concentration, and the relative abundance of dinoflagellates. In a different study conducted in the harbour in Alexandria, a correlation between high Chl *a* concentrations and high species diversity was found³⁴. This particular study also showed that taxonomic groups other than dinoflagellates and diatoms had the largest effect on the Chl *a* concentrations.

In this short-term study, we did not find a significant correlation between any particular inorganic nutrient and the density of specific groups of phytoplankton. Nitrogen and/or phosphorus are considered to constitute the limiting nutrients in many marine environments³⁵. In a study on seasonal variation of primary production off the Mangalore coast, low phosphate and nitrate concentrations were recorded throughout the year, but with nitrogen as the most significant limiting nutrient¹⁰. This study recorded overall high nitrogen concentrations; and the Redfield ratios between silicate, nitrate, and phosphorus reveal that phosphorus was limiting, which most probably affects the phytoplankton community. The higher relative abundance of diatoms throughout the sampling period, could be a consequence of the relatively high silicate concentrations and the generally faster growth rate in diatoms³⁶. Dinoflagellates on the other hand, normally thrive in stratified water where both nitrogen and phosphorus concentrations are moderate to high³⁷. Since stratification probably is low in the tidal influenced and busy port area, and phosphate concentrations limited, this might also have affected the relative composition of dinoflagellates and diatoms, favouring the latter.

Total biovolumes were calculated on every sampling occasion. This study was carried out during a rather short period of time and the fluctuations of most environmental parameters, excluding the records of individual species, were minor. Hence, we could not reveal any significant correlation between any of the other hydrographic parameters and biovolumes. In general, tropical or subtropical phytoplankton assemblages display high species richness, with somewhat lower numerical abundances compared to temperate waters. Warm waters are also known to be less viscous than cold water, favouring species with a larger surface to volume ratio³⁸. Biovolume was neither correlated to Chl *a*, diversity, or proportions of any major groups, but the exceptional high value on Jan. 6 was a consequence of high abundance of *Cerataulina pelagica* cells in the water mass, recorded just after the shift from high to low tide. Since the individual biovolume of each cell of this species is relatively large, they had a great influence on the total biovolume. When other species might have problems adjusting to new conditions, like the shift in tide, it could be explained by this opportunistic species managing to bloom during a

short period. In one study, *Cerataulina pelagica* was observed to form dominating blooms, but required salinity above 20¹⁵. *C. pelagica* constituted one of four species with probabilities of increasing the biomass proportion significantly above 50% in a very short time span. However, as sampling was conducted at one spot only, it is difficult to say whether a bloom was sampled, or if the high concentration of this particular species was due to spatial patchiness.

The results in this study indicated that tides might have an influence on the composition of the phytoplankton community, not only at a higher taxonomic level, but also at the species level. Therefore, the results of e.g. weekly or monthly sampling may be affected, and it is especially important to consider this when working in certain areas, with tidal influence. In just a matter of days, a shift in species composition was noticed, which has also been recorded from previous studies³. During high tide, the marine influence in the sampling area was greater. In general, the CCA biplot showed a pattern where high Chl *a* concentration, high tide, high salinity, high temperature, and many planktonic diatoms were correlated (Fig. 3). All nutrients and oxygen clustered together. All of these environmental variables are of importance, with Chl *a* strongly correlated with most of the observed *Chaetoceros* species. As shown in the biplot, total bacterial counts correlated with Chl *a* concentration but seemed to be little influenced of the phytoplankton community. This is differing from what we have seen in a previous study, where total bacteria and Chl *a* correlate, and the total bacterial community was influenced by the taxonomic composition of the phytoplankton community (Rehnstam-Holm, submitted)³⁹.

A shift in some species was noticed at low tide, when conditions changed to more brackish-like; and some of these species—*Chaetoceros tenuissimus*, various small flagellates (ca. 3µm), and two different unidentified small diatom species—had higher relative abundance around Jan. 9. *Chaetoceros tenuissimus* is known to be associated with fjords and other typically brackish water environments (<http://www.smhi.se>). The recording of small diatoms, which were more abundant during low tide, might rather be a consequence of the overall low phosphate concentration. It is well known that smaller cells more easily take up traces of nutrients when concentrations are low^{40, 41}. Some species are negatively correlated to

tidal height, i.e. *Entomoneis* sp., *Cylindrotheca closterium*, *Navicula* sp., and various small-identified flagellates. These taxa are associated with benthic environments, and this might influence the outcome of the CCA, since these species have the ability to attach to their substrate and might be less- or differently affected by tide-associated effects compared to the planktonic taxa.

Conclusions

The present study infers that in addition to other factors, small-scale hydrographic changes affect the composition of the phytoplankton community. Several factors were tightly coupled: high species diversity, increased diatom and dinoflagellate abundances, and Chl *a*. Even though species occurrences and abundances were correlated with particular environmental factors, the patterns in the community structure that we observed in this study seem more apparent at higher taxonomic levels (e.g. diatoms and dinoflagellates). Beside this tide was important, and this could have implications on phytoplankton sampling in general, since short-term patchiness of phytoplankton distribution is common.

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