Oscillations in phytoplankton community in a monsoon influenced tropical estuary

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Abstract

In a monsoon-affected tropical-estuary, oscillations in freshwater discharge during monsoon shifted the phytoplankton blooms from those adapted to low-salinities to high-salinities and vice versa. Salinity stratification during monsoon (onset and restart after an intermittent break) favored diatom (*Skeletonema*) bloom in low-saline surface-waters. In high-saline, nutrient-rich bottom-waters, *Fragilariopsis* (diatom) bloom was observed during onset of monsoon and persisted till the end of monsoon. The break period in monsoon altered the phytoplankton community leading to mixed species bloom of large-sized diatoms and harmful dinoflagellates (*Gymnodinium catenatum* and *Cochlodinium polykrikoides*) under high-saline, nutrient-poor, non-stratified and transparent water-column. Such oscillations in community should be considered for better understanding the biogeochemistry of monsoon influenced tropical estuaries. The occurrence of harmful dinoflagellate, *C. polykrikoides*, could be the first report from this region. The dominance of *Skeletonema* is determined positively by the extent of low-saline stratified condition whereas most of the observed taxa were favored by high-saline, nutrient-poor and transparent waters.

Key words: estuary, phytoplankton, diatoms, dinoflagellates, monsoon, non-monsoon

1. Introduction

The phytoplankton community determines the quality of estuarine waters because they respond quickly to environmental changes and in turn, influence the environment. Until recently, numerous studies on phytoplankton ecology have focused on primary production and its role in the global ecosystem functioning. Recently, concerned with the global increase in harmful algal blooms/red tide phenomenon, studies related to dynamics of phytoplankton population have gained importance. Phytoplankton abundance and species composition in an estuarine ecosystem are closely linked to various physical (advection, light, temperature salinity, etc), chemical (pH, nutrients) and biological (grazing) factors as well as interactions among them. Hence the continual documentation of phytoplankton population dynamics along with relevant environmental variables can offer important information on water quality. Such an approach can signal any drastic changes occurring within an aquatic ecosystem and also provide evidence to the causes of changes. Phytoplankton community, a source of organic carbon and energy for higher trophic levels, ultimately determines the success of fisheries. The understanding of phytoplankton dynamics is, therefore, central to the understanding of how estuarine ecosystems work and how they respond to environmental stresses imposed by natural and anthropogenic activities (Cloern, 1979).

Zuari estuary, located along the central-west-coast of India, Goa, is a dynamic aquatic ecosystem exhibiting a strong seasonal gradient, both in environmental variables and plankton assemblages, because of the tight physico-chemical and biological coupling. The Zuari River originates in the Western Ghats and extends up to 70km before meeting the Arabian Sea. The width and depth of the mouth is ~5.5km and ~5-6m respectively. This area is strongly influenced by the southwest monsoon and the changes associated with its onset have marked effects on the phytoplankton community, food-web and production (Devassy and Goes, 1988; Bhattathiri et al., 1976). During this period, a surplus amount of freshwater, influx from land run-off from the river and precipitation (~275 cm), is added to the estuary resulting in marked changes in the physico-chemical characteristics of the water. Based on this, one year has been classified into three seasons (monsoon:June-September, post-monsoon:October-January; pre-monsoon:February-May). Since there are only few studies in this region an investigation was carried out to evaluate the environmental influence on the oscillations in phytoplankton community in a monsoon influenced tropical estuary.

2. Materials and Methods

Monthly sampling of surface and bottom (~1m above bottm) water for a period of 17 months was carried out from September-1999 to January-2001 in the Zuari estuary at a fixed location (Longitude: $73.00^0$59'E; Latitude: $15.00^0$25'N). Details of the methodology employed for sampling and analyses of environmental parameters such as temperature, salinity, nutrients and Secchi disc depth during the study period have been given elsewhere (Patil and Anil, 2008). The oxygen-saturation was calculated using temperature, salinity and dissolved oxygen values (Benson and Crause, 1984). Chlorophyll *a* was determined by 90% acetone extraction method. Water samples (1-L) fixed with Lugol's iodine was used for numeration of phytoplankton populations (triplicates). Phytoplankton were identified based on the standard identification keys. Univariate measures (species-count, Shannon–Wiener diversity, species-richness and evenness) were calculated using PRIMER ver.5.

3. Results

3.1 Environmental conditions

During the observation period, the temperature ranged from 28 – 33^0C and 22 – 31^0C in surface and bottom waters respectively. Low salinity ranging from 15 to 19 ppt was recorded during the monsoon. During the post and pre-monsoon months the salinity ranged from 25 to 35 ppt.

The nitrate concentration ranged between 0.4 and 8 mM with peak values in April, July and December 1999. Nitrite levels ranged between 0.01 and 0.68 mM being highest in the pre-monsoon period (March). During May 1999, a rise was detected in phosphate concentration. Silicate concentrations were highest in the monsoon (July 1999). The observed low salinity, high nitrate and silicate concentrations were due to considerable land run off during the monsoon season.

3.2 Phytoplankton community

In the present study, 136 (83-diatoms, 44-dinoflagellates; 9-others) phytoplankton species have been recorded. Altogether 121 species in surface (77-diatoms, 34-dinoflagellates; 9-others) and 118 species in bottom (77-diatoms, 34-dinoflagellates; 6-others) waters have been recorded. Among the phytoplankton, diatoms>dinoflagellates dominated the community (Fig. 1a,b), whereas silicoflagellates, blue green algae formed a minor component.

In this investigation, two phytoplankton blooms resulting in high chlorophyll values were observed as a recurrent feature of the annual cycle (Fig.2j). The first bloom was observed when there was a break in rainfall (July-2000) or after the end of southwest monsoon (November-1999 and October-2000) and the second bloom was observed during pre-monsoon (March-2000) (Figs. 1,2j). Interestingly these blooms were coincided with low-nutrient, predominantly saline and transparent water conditions (Figs.1-2). These blooms resulted in maximum phytoplankton diversity, species-count, evenness and species-richness (Fig.1a'-b'). The first bloom was dominated by large-size diatoms (*Chaetoceros curvisetus*, *Leptocylindrus danicus*, *Licmophora juergensii*, *Navicula transitans* var. *derasa* f. *delicatula*, *Skeletonema costatum*, *Fragilariopsis* sp., *Thalassionema nitzschioides*) and harmful dinoflagellats (*Gymnodinium catenatum* and *Cochlodinium polykrikoides*) only during monsoon break (July-2000) (Fig. 1a-b). During onset (June-2000) and restart (August-2000) of monsoon, a single-species bloom of *S.costatum* was observed causing drastic decline in species count, diversity, species richness and evenness in surface waters whereas *Fragilariopsis* bloomed only during June-2000 in the bottom waters (Fig. 1a-b). Maximum abundance was observed in surface rather than bottom waters during June-2000 and August-2000 (Fig.1a-b). Such differences in community were mainly due to existence of stratification till early post-monsoon season (except July-2000) which was evident from temperature, salinity and DO profiles (Fig.2). The second bloom was dominated by *Chaetoceros curvisetus*, *C.lorenzianus*, *C.diversus*, *Thalassinema nitzschioides*, *Guinardia flaccida*, *Cylindrotheca closterium*, *Pleurosigma angulatum*, *Navicula transitans* var. *derasa* f. *delicatula*, *S.costatum* and *Asterionellopsis glacialis* (Fig. 1a,b). In November-2000, the phytoplankton population declined (Fig.1) that coincided with a sudden increase in turbidity (Fig.2d). Despite nitrate concentration being high twice during the same time of the year, December (1999 and 2000), *Thalassionema* was the single most dominant in year 1999 whereas during 2000 the community was dominated by many species (Figs.1-2). In January-2001, a single-species bloom of *Thalassiosira* was observed in surface and bottom waters (Fig.1a-b).

3.3. Relationship between environment and phytoplankton species composition

To evaluate the relationship between the dominant phytoplankton species (>4%) and various observed water and meteorological parameters a Canonical Correspondence Analysis (CCA) was performed on log transformed data using the Multi-Variate Statistical Package program version 3.1. In the CCA biplot for surface water, the 8-axis explained 95.8% of the relationship between phytoplankton species and monsoon driven environmental conditions. The first two-axes of the CCA biplots (Fig. 2k,l) explaining approximately 50% revealed that salinity is the most important environmental variable. Nutrients, water transparency, solar radiation and rainfall are the other important environmental parameters influencing the phytoplankton community. Two groups of phytoplankton species can be distinguished based on their responses to environmental settings. Group-I comprised of only *Skeletonema* and showed preference to nutrient rich low saline (~16) surface waters. *Skeletonema* thrive well during onset as well as restart of freshwater discharge after an intermittent monsoon break (Fig.2k,l). Group-II consisted of diverse assemblage of phytoplankton species that favored nutrient-poor, high-saline ($\geq$30) and transparent waters (Fig.4l). The species located on the upper left quadrant preferred phosphate-poor conditions whereas the species located in the lower left quadrant preferred nitrogen- and silicate-poor conditions. The Group-II species dominated the phytoplankton community during monsoon breaks and non-monsoon periods. Group-II species, excluding *Leptocylindrus*, *Cerataulina* and *Eucampia*, located in the upper left quadrant of the biplot were related to higher oxygen saturation whereas the reverse was true for the species located in other quadrants.

In the CCA biplot for bottom waters, the 8-axis explained 92.7% of the relationship between phytoplankton species and environmental conditions. The first two-axis of the CCA biplots explaining approximately 45% revealed that temperature, salinity, nutrients, water transparency, solar radiation and rainfall are the important environmental parameters influencing the phytoplankton community of the bottom waters (Fig.2m,n). Three phytoplankton groups were identified based on their responses to environmental settings. Group-I species preferred low-temperature, relatively lower-salinity (unlike surface waters) and elevated nutrient concentrations. These species were dominant during monsoon period. Group-II species, which are located in the lower half of the biplot favoured less transparent and nitrate- and silicate-poor waters whereas group-III species were related with phosphate-poor conditions. These species dominated during non-monsoon periods. Group-I species, located in the upper half of the biplot were related to lower oxygen saturation whereas the reverse was true for the species located in other quadrants. *Skeletonema*, a group-II species was also found to dominant during restart of monsoon after an intermittent monsoon break.

4. Discussion

The results revealed that the oscillations in freshwater discharge during monsoon have a pronounced influence on phytoplankton community. With the onset of monsoon, the study site experiences high freshwater influx (Shetye et al., 1995) at a flow rate of >10,000 ML day^{-1} when most of the annual precipitation occurs over the catchment area (Unnikrishnan et al., 1997). Such an increased freshwater influx resulted in the development of stratification with nutrient-rich low-saline surface and high-saline, low-temperature and DO in the bottom-waters (Figs. 2a-c). CCA indicated that the prevalence of low-salinity due to freshwater discharge is an important environmental factor influencing native phytoplankton community (Figs.2l). The flow pattern affects the biomass through physical flushing as well as by controlling the salinity and nutrient gradients to which the cells are exposed. Under stratified conditions, diatom blooms in surface (*Skeletonema*) and bottom (*Fragilariopsis*) waters caused a difference in univariate measures between depths (Fig. 1).

After consistent rainfall, there was no or less rainfall for 18 days before July-2000 sampling. During this period even the influence of freshwater discharge at the study site was negligible and this phase of negligible rainfall and freshwater discharge is considered as monsoon break. Under such conditions *Skeletonema* and *Fragilariopsis* bloom, observed in June-2000, declined (Figs. 1a-b). The change in environmental conditions like rise in salinity due to reduced freshwater discharge and nitrate depletion might be the reason for the decline of the blooms (Figs. 2b,f). Subsequent to decline of these blooms, a mixed species bloom of large-sized diatoms and harmful dinoflagellates (*Cochlodinium polykrikoides* and *Gymnodinium catenatum*) resulted in high chlorophyll and oxygen-saturation (>100%), indicating production was dominant than respiration (Figs. 2d,j). Mixed bloom also caused an increase in the phytoplankton diversity, species numbers, evenness and richness and this increase was mainly due to diatoms (Fig. 1). Interestingly mixed bloom was observed even though the system was nitrate limited i.e. NO_3:PO_4 ration <1 (data not shown). This is possibly because the species are well adapted in predominantly saline, nutrient-poor and transparent waters. For eg. *Chaetoceros curvisetus* (Anderson and Roels, 1981).

Since *C.polykrikoides* a ‘red tide’ causing organism and also known to kill fish was not reported in previous studies (Devassy and Goes, 1988; Krishnakumari et al., 2002) we assume that the occurrence of this species in this study could be the first report from this region. While the work related to phytoplankton dynamics in this region is limited it is difficult to ascertain its origin. Through culture experiments it is known that *C.polykrikoides* prefer high-salinity, temperature and irradiance for growth (Kim et al., 2004). In this study, under bloom conditions the water temperature and salinity were ~29 ^{0}C and ~33 which were similar to elsewhere during the occurrence of *C.polykrikoides* red tide in the field. With the restart of freshwater discharge, *C.polykrikoides* bloom was terminated and this kind of decline is generally associated with the formation of specialized resting cysts which then form large inocula to cause a massive bloom under similar environmental conditions. In subsequent year (October-2001), after monsoon, *C. polykrikoides* bloom was reported by a team from National Institute of Oceanography, Goa (Bhat and Matondkar, 2004) indicating that this bloom might have stemmed from the remains of preceding year. D’Silva et al. (D’Silva et al., 2008) based on ^{210}Pb dating of cores collected from this region, revealed that the cysts of *C. polykrikoides* were recorded recently (year 1982).

With the restart of the freshwater discharge after an intermittent break (August-2000), stratified conditions similar to that formed during onset of the monsoon prevailed (Fig. 2a-c). Once again *S.costatum* bloom was observed under less transparent and low-saline surface waters (Figs. 1a,2b,2d). This bloom might have stemmed from the benthic propagules (BP) of previous bloom which was observed during the onset of monsoon (Patil and Anil, 2008). Moreover the low nitrate concentrations observed during this period indicated its utilization during bloom development. These observations revealed that the phytoplankton growth, which is largely controlled by environmental factors (salinity, light, nutrients and transparency), can then develop into a bloom any time only if environmental conditions are conducive. The results of bloom development during the monsoon (Fig.1) are opposite to the findings of scientists (Devassy and Goes, 1988; Krishnakumari et. al., 2002) who worked in the same estuarine system. In their study, the lowest cell counts/abundance was observed during monsoon season in the year 1980 and 1998. They reported that poor growth conditions (like lowered light and salinity regimes caused by monsoon events) and the absence of species, which can bloom under such conditions, are the cause for the low counts. Whereas in the present study during monsoon, single as well as multi species blooms of diatoms and dinoflagellates were observed. Blooming of *Skeletonema* during monsoon under low saline condition is also reported elsewhere along the west coast of India (Subrahmanyan, 1959; Gopinathan, 1974, Mitbavkar and Anil, Patil and Anil 2005). Although blooms were observed during monsoon, the total phytoplankton diversity indices remained low (June-2000 and August-2000), except during monsoon break (July-2000), compared to post and pre-monsoon seasons (Fig. 1a'-b').

As the season progressed towards post-monsoon, the blooms as well as number of species triggered by monsoon events declined (Fig. 1). Several loss processes such as grazing, dormancy followed by sedimentation, competition etc. could be the reason. A parallel investigation conducted revealed increased abundance of diatom benthic-propagule, dominated by *Skeletonema* and *Fragilariopsis* in the study site (Patil and Anil, 2008) further indicating that sedimentation is one of the important loss processes. Moreover in this region, diatom abundance results in higher population density of zooplankton during early post-monsoon months. The report on zooplankton community from this region indicates that copepods constitute the dominant group (Padmavati and Goswami, 1996); in addition, they are the major herbivores grazing on phytoplankton blooms (Smetacek, 1985; Kiørboe and Nielsen, 1994). Even oxygen saturation decreases by 20-30%, indicating dominance of respiration over production (Fig. 2d). Hence, it is hypothesize that sedimentation and grazing could be the major processes responsible for the decline of blooms.

During post-monsoon of the year 1999-2000 and 2000-01 phytoplankton composition showed an inter-annual variability. During 1999-2000 post-monsoon, phytoplankton community was dominated by *Cerataulina*, *Coscinodiscus*, *Ditylum*, *Leptocylindrus*, *Thalassionema* and *Chaetoceros* whereas during 2000-01 community was dominated by *Skeletonema*, *Thalassionema*, *Chaetoceros* and *Thalassiosira* (Fig. 1a-b). Such inter-annual variability can be attributable to variations in nutrient concentrations as well as in the magnitude of water transparency (Fig. 2e-i). Interestingly, during November (both years), the dinoflagellate population declined and this decline was due to decline in phosphate concentrations in surface waters (Fig. 2g). During the subsequent month (December), in both the years, nutrient concentration increased and water transparency decreased (Fig. 2e-i). Earlier (Nair, 1980) reported two peaks of zooplankton production, one in November and the other in March/April. Higher zooplankton population results in ammonia-rich fecal matter and this might undergo nitrification in the presence of excess oxygen leading to high-nitrates. Similar observations from the study area have reported that these high concentrations were of local origin (Qasim and SenGupta, 1981). The lowering of temperature and water transparency during those months highlights the prevalence of winter mixing. Such nutrient input and variability in water transparency, during post- and pre-monsoon will influence phytoplankton species composition, bloom development, biomass and production. Despite nitrate concentration increased twice during the same time of the year (December 1999 and

2000), *Thalassionema* was the single most dominant in year 1999 whereas during 2000 the community was dominated by many species. *Ceratium furca*, a dinoflagellate, responded similarly even though total dinoflagellates responded positively during both the years (Fig.1). Although a large number of taxa were benefited due to nutrient input in the subsequent month (January) *Thalassiosira* bloom was evident only in the year 2001 (Fig. 1a-b). Monthly sampling from a single station could be one of the reasons for the missing of diatom blooms, as blooms are known to occur on a time scale of few days to weeks.

During early pre-monsoon, the phytoplankton population was evenly distributed even though phytoplankton abundance, species count and richness were low (Fig. 1a'-b'). The increased grazing pressure (oxygen saturation <100%) could be the reason for such low abundance. In the subsequent month (March-2000) a mixed bloom of phytoplankton dominated by diatoms was observed. During this period, community structure between water depths differed (Fig. 1a-b). The dominance of *Nitzschia angularis* in bottom waters was the main cause for such differences. Surface bloom was dominated by *Chaetoceros*, *Pleurosigma*, *Nitzschia*, and *Guinardia* whereas in bottom waters *Nitzschia*>*Chaetoceros*>*Pleurosigma* dominated the phytoplankton community. Dominance of pennate diatoms (*Pleurosigma*) probably indicates benthic seeding. Among the dinoflagellates, *C.furca* and *Prorocentrum gracile* were dominant. The increase in abundance and species number during this time further reveals preference for the prevailing environmental conditions like high-salinity, temperature, DO and transparent water column. These blooms resulted in high chlorophyll and oxygen-saturation (>100%) showing maximum production (Fig. 2d,j). The decline of *C.curvisetus* bloom (Fig. 2a-b), on both occasions (March-2000 and August-2000), was coupled with increase in the abundance of bethic propagule (data not shown) and decrease in water transparency. The freshwater discharge or benthic resuspension could be cause for reduced transparency and probably these processes might have triggered *Chaetoceros* bloom to undergo sporulation or be flushed out physically from the surface. Finally this study concludes that the changes in freshwater discharge during monsoon resulted in the phytoplankton communities/blooms shifting from those adapted to low-salinities/high-salinities and vice versa. In view of the rising trends in the frequency and magnitude of extreme rain events observed over central India from 1951-2000 (Goswami et al. 2006), studies relevant to phytoplankton dynamics is important to decipher changes in the marine ecosystem functioning.

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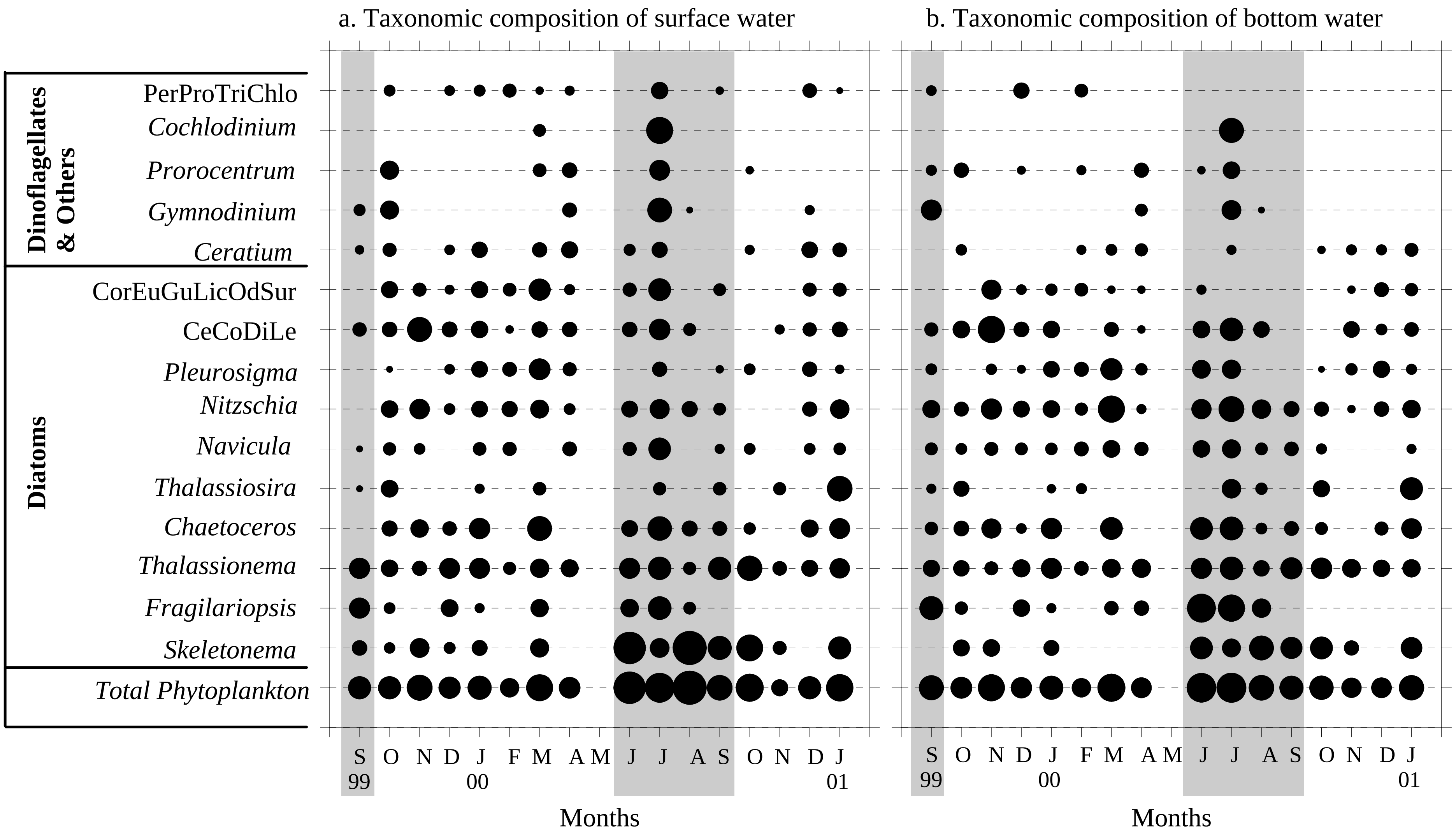
Figure legends

Figure 1. Temporal variation of the contribution of dominant taxa (log(X+1) transformed abundance values) to the phytoplankton community (surface-a; bottom-b). CeCoDiLe-Cerataulina>Coscinodisucs>Ditylum>Leptocylindrus, CorEuGuLicOdSur-Corethron>Euccampia>Guinardia>Licmophora>Odontella>Surirella, PerProTriChlo-Peridinium>Protoperidinium>Trichodesmium> Chlorogloea. Maximum symbol height-5.99%.

Figure 2. Temporal variations in the univariate measures of total phytoplankton community (surface-a; bottom-b).

Figure 3. Temporal variations in water parameters (a-i) and Chlorophyll *a* concentrations (J)

Figure 4. Ordination diagrams for species: l-n), months: k-m) based on Canonical Correpondence Analysis-CCA of the phytoplankton species. The hydrological (Temp-temperature, Sal-salinity, DO-Dissolved oxygen, NO_3-nitrate, NO_2-nitrite, PO_4-phosphate, SiO_3-silicate, Osat-oxygen saturation, SD-Sechi disc depth) and meteorological variables (WD-wind direction, WV-wind velocity, RF-Rainfall, SH-Sunshine hours, DL-Day length, SR-Solar radiation, AT-Air temperature, RH-Relative humidity, Atmp-Atmospheric pressure) are indicated by arrows. Species codes are *Skeletonema*-Ske, *Fragilariopsis*-Fra, *Thalassionema*-Thx, *Chaetoceros*-Cha, *Thalasssiosira*-Tha, *Navicula*-Nav, *Nitzschia*-Nit, *Pleurosigma*-Ple, *Cerataulina*-Cer, *Coscinodisucs*-Cos, *Ditylum*-Dit, *Leptocylindrus*-Lep, *Corethron*-Cor, *Euccampia*-Euc, *Guinardia*-Gui, *Licmophora*-Lic, *Odontella*-Odt, *Surirella*-Sur, *Ceratium*-Cer, *Gymnodinium*-Gym, *Cochlodinium*-Coc, *Prorocentrum*-Pro, *Peridinium*-Per, *Protoperidinium*-Pro, Trichodesmium-Tricho, Chlorogloea-Chlo. General grouping of species and months are indicated. See text for interpretation of ordination diagrams. Note: For the analysis, average values (7 consecutive days, prior to and inclusive of the sampling day) of meteorological data have been used. Shaded region represents monsoon season.



a. Taxonomic composition of surface water
b. Taxonomic composition of bottom water
Dinoflagellates & Others
PerProTriChlo
Cochlodinium
Prorocentrum
Gymnodinium
Ceratium
Diatoms
CorEuGuLicOdSur
CeCoDiLe
Pleurosigma
Nitzschia
Navicula
Thalassiosira
Chaetoceros
Thalassionema
Fragilariopsis
Skeletonema
Total Phytoplankton
S O N D J F M A M J J A S O N D J
99 00 01
Months

Fig. 1.

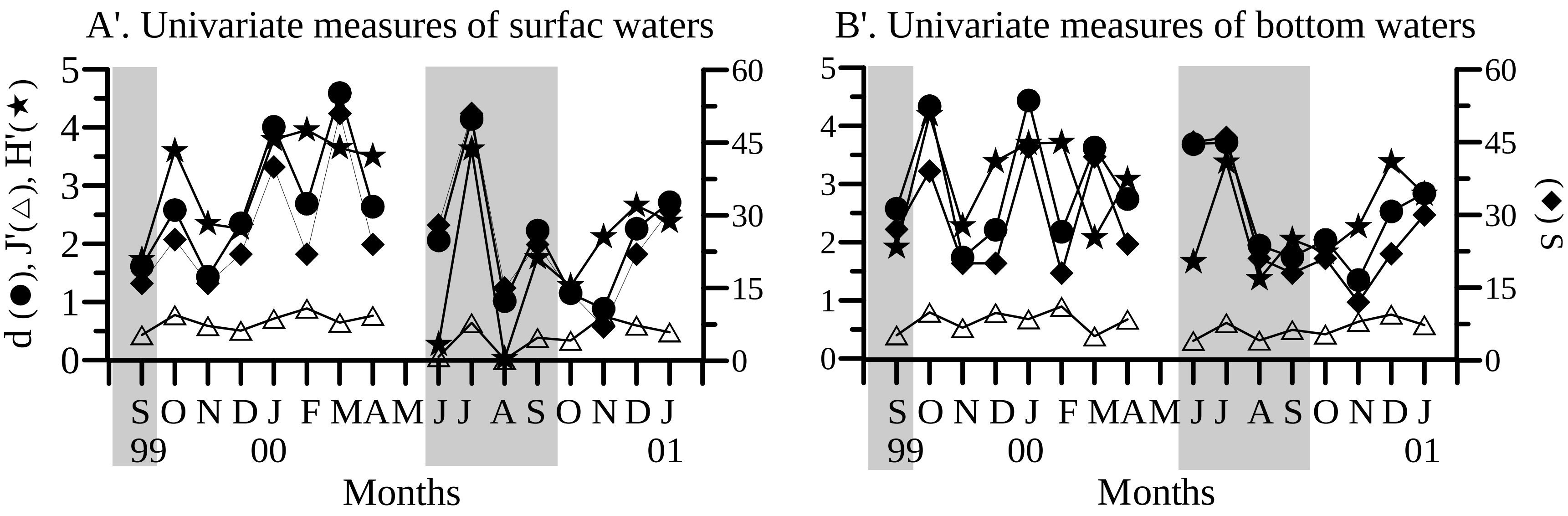
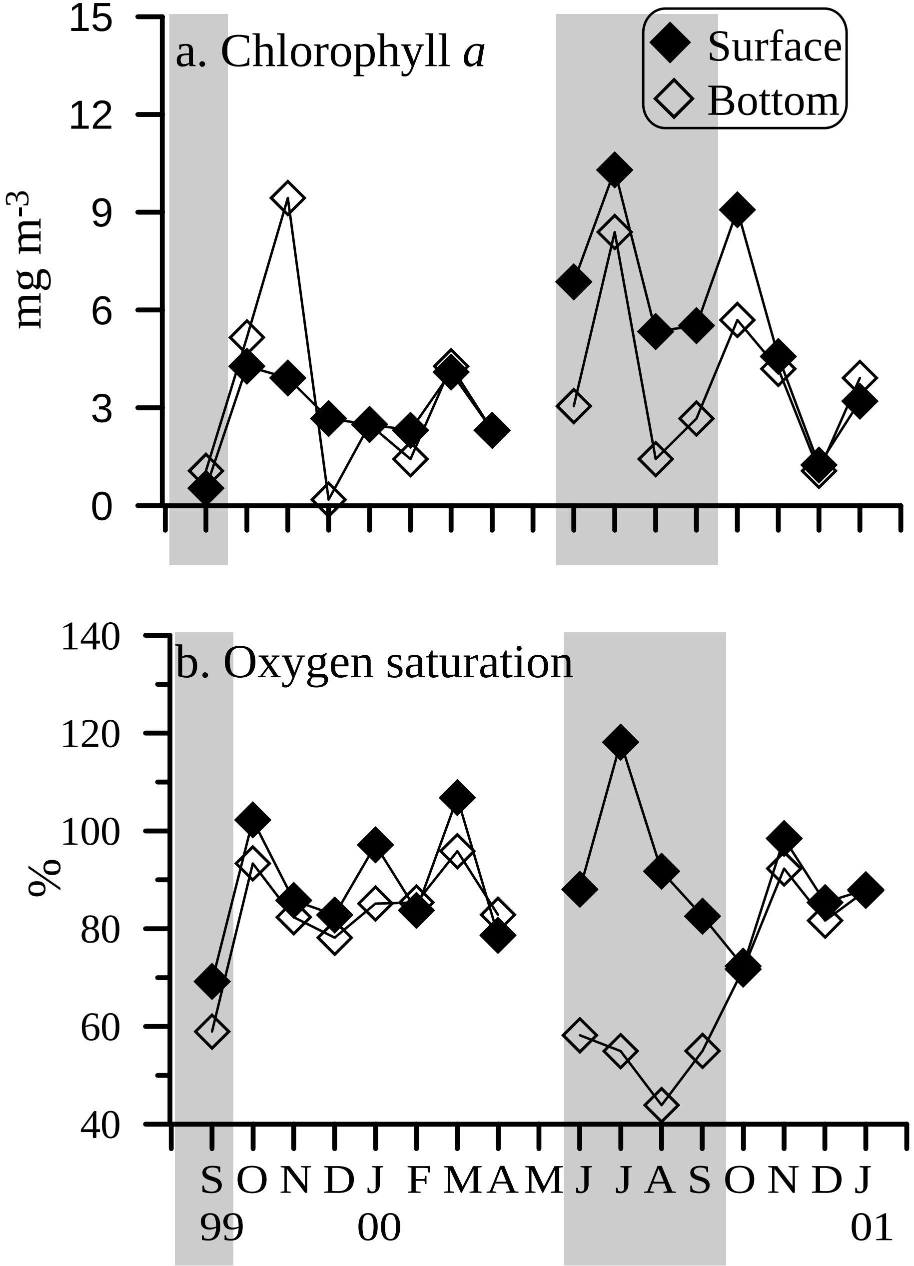

A'. Univariate measures of surfac waters
B'. Univariate measures of bottom waters
d (●), J'(△), H'(★)
S (◆)
S O N D J F M A M J J A S O N D J
99 00 01
Months

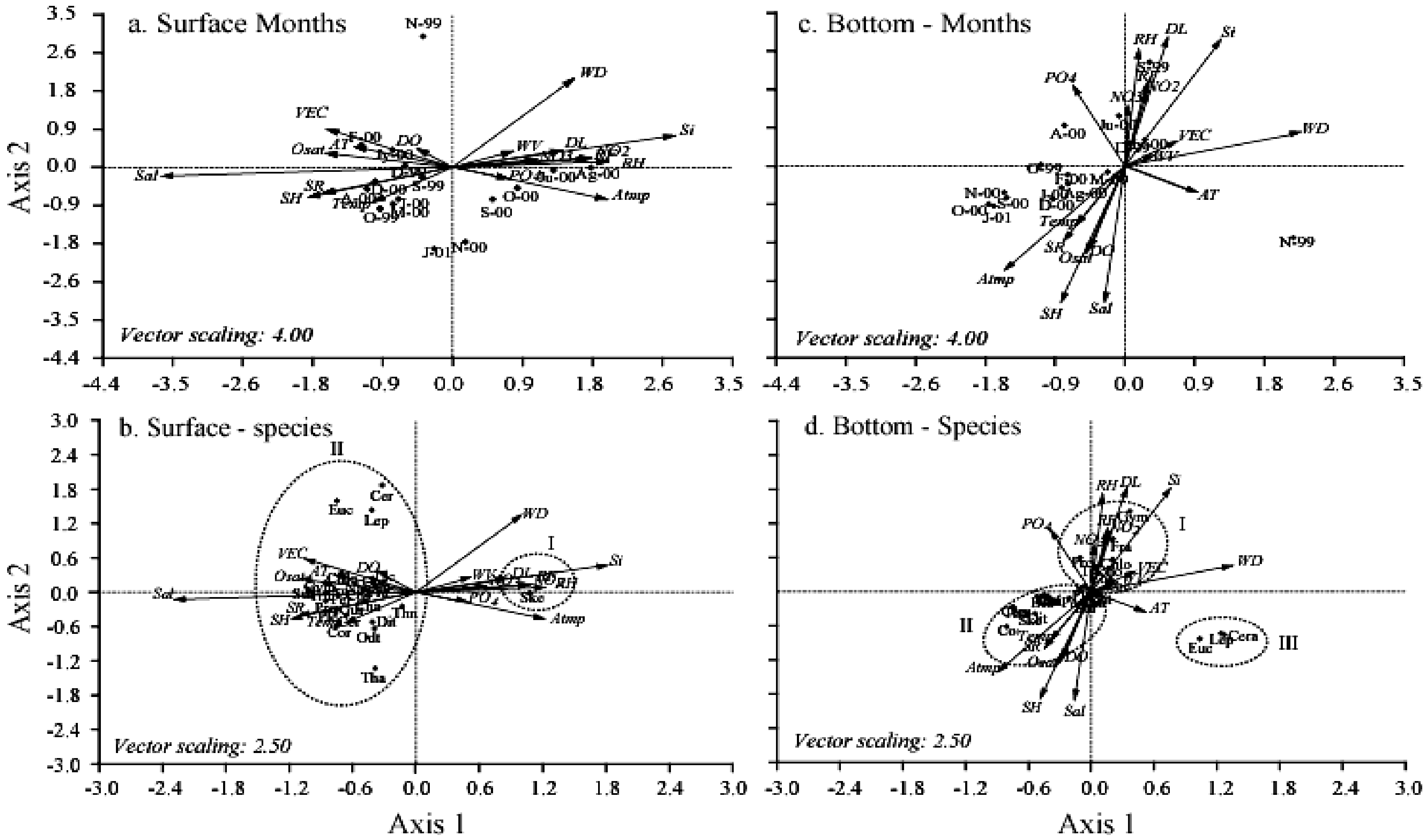
Fig. 2.

1



a. Chlorophyll *a*
Surface
Bottom
mg m-3
15
12
9
6
3
0
b. Oxygen saturation
%
140
120
100
80
60
40
S O N D J F M A M J J A S O N D J
99
00
01

Fig. 3.



a. Surface Months
c. Bottom - Months
b. Surface - species
d. Bottom - Species
Vector scaling: 4.00
Vector scaling: 2.50
Axis 1
Axis 2

Fig. 4.