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Response of Phytoplankton to Changes in Hydrographic Properties in A Subtropical Embayment in the Sea of Oman

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ABSTRACT

This paper discusses six years of phytoplankton response to the hydrographic properties of a subtropical embayment in the sea of Oman from April 2006 through April 2011. A total of 278 dinoflagellate and diatom taxa were recorded during a study The Dinophyceae contributed the highest number of species (166) followed by Bacillariophyceae (112). The number of genera present was largest during the Southwest Monsoon (SWM) followed by the Northeast Monsoon (NEM) and lowest during the Spring Intermonsoon (SPIM) with considerable interannual variability. Dinoflagellates were the most important group in the Bay of Bandar Khayran. They constituted 59.7 % of the total species identified in the Bay and dominated the total phytoplankton population most of the years with 83% of the total abundance. Diatoms were the second important group and contributed 40.3 % to the total species identified in the Bay and only 17% of the total abundance during the study period. Diatoms were observed in higher abundance during 2006 and 2010 than in the rest of other years, particularly during NEM and SWM when silicate concentrations was elevated. Increases in diatom abundance and their association with nutrients and silicate were coupled primarily with a decrease in temperature. A weak association was found between dinoflagellate species and nutrients. The small size dinoflagellates (15-55 μm) dominated the population and persisted annually. This implies a minor effect of grazing pressure on these species beside their less demand on high nutrients concentrations.

Key Words: Sea of Oman; Arabian Sea; Monsoon and Up-welling; Diatoms; Dinoflagellate.

INTRODUCTION

Phytoplankton are the key components in aquatic ecosystems and therefore knowledge of the seasonal cycle of species composition, productivity and biomass are essential for understanding ecosystem dynamics. In contrast to most tropical waters that have small seasonal changes compared to temperate and polar systems, the tropical Arabian Sea and the Sea of Oman experience large and distinct temporal and spatial patterns of variability in primary productivity that result directly from monsoonal forcing of the upper ocean (Barber et al. 2001, Piontkovski et al. 2011). There are two seasonal monsoon periods named after the wind direction, the southwest monsoon (SWM) in summer and the northeast monsoon (NEM) in winter and two intermonsoon periods, the spring intermonsoon (SPIM) and the fall intermonsoon (FIM). Nutrient enrichment from upwelling along the southern Omani coast during the strong SWM and to a lesser extent fertilization of waters from winter convective mixing create a strong seasonal cycle in nutrient supply, and consequently alternating conditions of nutrient sufficiency during the two monsoons and oligotrophy during the two intermonsoon periods. Spatially contrasting nutrient environments are also evident along a 1000 km transect at 65°E from the nutrient rich southern coastal region to more oligotrophic conditions in the central portion of the Arabian Sea (Barber et al. 2001, Marra and Barber 2005, Piontkovski and Claereboudt 2012).

The SWM is followed by the FIM period (October-December) when the wind speeds decrease significantly. Solar heating and weak winds result in shallow mixed layers and nutrient depletion, and consequently relatively low primary productivity (Banse 1987, Marra and Barber 2005). During the NEM in winter when the temperature difference between land and sea is smaller, there is a reversal of the wind direction from southwestern to northeastern. During the NEM, deep convective mixing provides nutrients to the upper mixed layers and the nutrient enrichment extends 400-1000 km offshore, so that winter productivity in the Arabian Sea can also be relatively high (Banse 1987, Banse and English 2000, Piontkovski et al. 2011, Piontkovski et al. 2013). The spring intermonsoon period (April-June) after the NEM, leads to a period of relatively low wind velocities and calm seas resulting in low seasonal phytoplankton abundance.

The seasonal pattern of diatoms and dinoflagellates along with the important chemical and physical variables are not commonly available for the Sea of Oman. The few available studies have been short term and only over one annual cycle (Al-Azri et al. 2007, Al-Hashmi et al. 2012). This study investigates the species composition and seasonal abundance of diatoms and dinoflagellates in the shallow Bandar Khayran Bay in the Sea of Oman on the northeast coast of Oman in relation to the physical and chemical parameters that affect phytoplankton abundance and distribution during 2006-2011.

METHODOLOGY

Four field samplings were conducted in Bandar Khayran Bay, a shallow and isolated inlet along the coast of Muscat at 23°30’26”N and 58° 43’48”E (maximum depth, 16 m) The Bay is mainly a fishing area with high potential for tourism development (Figure 1).

Field collection and analysis

Samples were collected twice a month from April 2006 through April 2011 from a single location in Bandar Khayran Bay (Figure 1C) from 1 and 10 m. Since this shallow bay is usually well mixed, only data from 1 m are shown. Temperature, salinity, oxygen and depth were measured with an Idronaut-Ocean Seven 316 CTD probe fitted with an additional sensor for chlorophyll *a* fluorescence. Subsurface water samples that were representative of the mixed layer were collected with Niskin bottles for the analyses of nitrate + nitrite, ammonium, phosphate and silicate. After collection, water samples were immediately frozen for storage. They were later thawed and analyzed for nutrients using a 5-channel SKALAR FlowAccess auto-analyzer according to the procedures described in Strickland and Parsons (1972) and modified by the manufacturer of the analyzer (Skalar Analytical 1996).

For phytoplankton species identification and cell counts, water samples (250 ml) were collected and preserved with 2% Lugol’s iodine solution. Samples were allowed to settle and were concentrated into 20 mm diameter tubes. Prior to taxonomic analysis, samples were further concentrated using a reverse filtration cone fitted with 1 μm pore-diameter Nucleopore filter (Sorokin et al. 1975). Cells were counted in a Nauman chamber (0.04-0.75 ml) using an inverted Olympus microscope (model IX50). The cell counts (N/ml) were determined using the formula: N= (nK) where n is the abundance of cells of the given species in a sample; K is the coefficient for the given sample. A coefficient K was calculated for each sample: K= (Vs/Vc)/Vf, where Vs is sample volume, Vc is subsample volume, Vf is the volume of filtered water. Species identification was based on the following references: Sournia 1986, Round et al. 1990, Tomas et al. 1997 and G´omez et al. 2010).

Zooplankton samples were collected using a Bongo net (mouth surface area: 0.125 m^2), with a 150 μm mesh and equipped with a Hydrobios digital flowmeter. The net was towed obliquely at a speed of one knot from near the bottom to the surface. Samples were transferred to 0.5L bottles and preserved in 5% borate-buffered formaldehyde for later analysis. In the laboratory, the plankton were identified to the genus level and then counted under a stereomicroscope after sub-sampling.

Principle component analysis (PCA) in Primer 6 (Warwick and Clarke 1991) was used to correlate phytoplankton community structure with environmental variables (temperature, salinity, nitrate + nitrite, ammonium, silicate and phosphate). The data were first log X^{+1} transformed to reduce the effect of a very abundant species. Data were normalized before PCA analysis. Correlations were established using Spearman rank correlation. Simpson’s biodiversity index was used as a measure of biodiversity of phytoplankton (Simpson 1949).

Data on the zonal and meridional components of wind speed were retrieved from the NCAR/NCEP

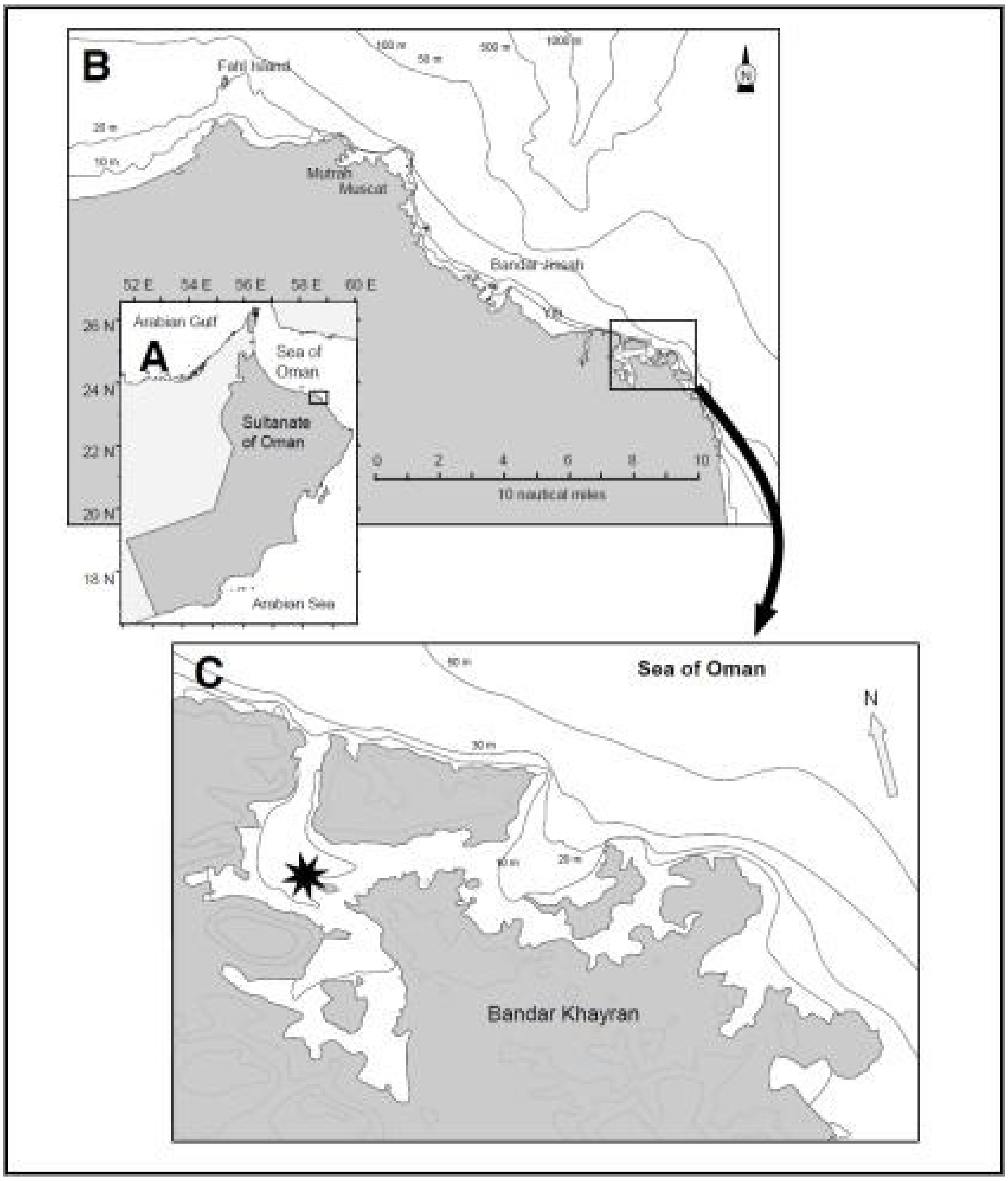

Figure 1. Map of Oman (A), Muscat coast (B) Bandar Khayran Bay (C).

reanalysis database (Kistler et al. 2001), in which the daily averages of wind speed at 10 m above sea level were extracted for the Sea of Oman region with coordinates 22.5-25.0°N; 57.5-60.0°E. Satellite-derived (9 km spatial resolution MODIS Aqua) monthly level-3 products for chlorophyll *a* were obtained to assemble a time series for the region. These products are available from NASA Ocean Color Group (http://oceancolor.gsfc.nasa.gov). Monthly time series were acquired using the GES-DISC Interactive Online Visualization and Analysis Infrastructure software as part of the NASA's Goddard Earth Sciences Data and Information Services Center. Monthly time series of particulate organic matter, and mixed layer depth were retrieved from the NASA Ocean Biogeochemical Model, which is a coupled, three-dimensional, 14 vertical layer model incorporating general circulation, biogeochemical, radiative components and assimilating monthly global products (Gregg 2008). The model is driven by wind stress, shortwave radiation and sea surface temperature. The assimilation process has an algorithm of constant readjustment of the model parameters, based on the chlorophyll data acquired by the satellite sensors. It is assumed that oceanic radiation is driven by water scattering, absorption, dissolved organic matter, and optical properties of the phytoplankton group.

RESULTS

Seasonal Cycle of Physical and Biogeochemical Parameters

Monthly sea surface temperature (SST) distribution shows the classical semi-annual heating and cooling pattern during the sampling period from 2006 to 2011 (Figure 2A). SST increased from March through July and reached its annual peak value (~31°C) in July but rapidly dropped by about 3°C in August. During July and August, the interannual variability was large (2-3°C). After a mid-summer cooling in August, a secondary warming phase began and lasted through October. The winter cooling phase began in November and the SST continued to decrease until February when the SST reached its annual minimum (23.8°C). Satellite SST, obtained from NOAA coral bleaching program, off Muscat (Figure 3) showed that summer 2008 experienced intense mid-summer cooling compared to the other years. Monthly sea surface salinity (no graph) varied in a small range between 36.5 and 36.7 ppt. from December through April. The peak of salinity was recorded during October and November reaching 37 ppt.

Surface concentrations of dissolved oxygen where higher during winter with minimal interannual variability (5.5-6.4 ml.L-1) and larger interannual variability during summer (4-6.4) (no graph). The winds are offshore for a large part of the year, from February till October, with peak speeds (~4.5 m s^{-1}) in August (Figure 2B). The direction of the winds changes to onshore in November and continue until January with increasing magnitude towards the end of winter. A gradual shift from onshore to offshore begins in February.

In general, nitrate and ammonium concentrations were <1 µM except during winter months (December-February) when they increased to >5 and >4 µM respectively (Figure 4A) and interannual variability was high in winter and low during June. Phosphate was higher (~0.8 to 1.3 µM) in winter with minimal interannual variability during winter (January-February) (Figure 5A). In contrast in summer, phosphate decreased and remained low (<0.4 µM). During the winter-to-summer transition, the interannual variability of phosphate was high. Silicate concentration was >1 µM all year and was the lowest during May and June (Figure 5B). Higher concentrations were observed during the two monsoons (August and September ~2.5 µM and January and February ~2 µM).

N:P ratios were generally <16:1 except in February when median values ranged between 8 and 20 and during July when ratios ranged from 5 to 17 (Figure 6A). N:Si ratios (normally 1:1) were generally >1, except in August and September 2006 when median values were 0.7 to 1.9 respectively (Figure 6B).

Surface chlorophyll *a* (Chl-*a*) showed only a 2-fold range (0.4-0.8 mg m^{-3}), except for the highest annual peak in February (1.2 mg m^{-3}) (Figure 7). The lowest concentrations (0.4 mg m^{-3}) occurred in May (inter-monsoon) and then increased in late summer (September) to 0.8 mg m^{-3}.

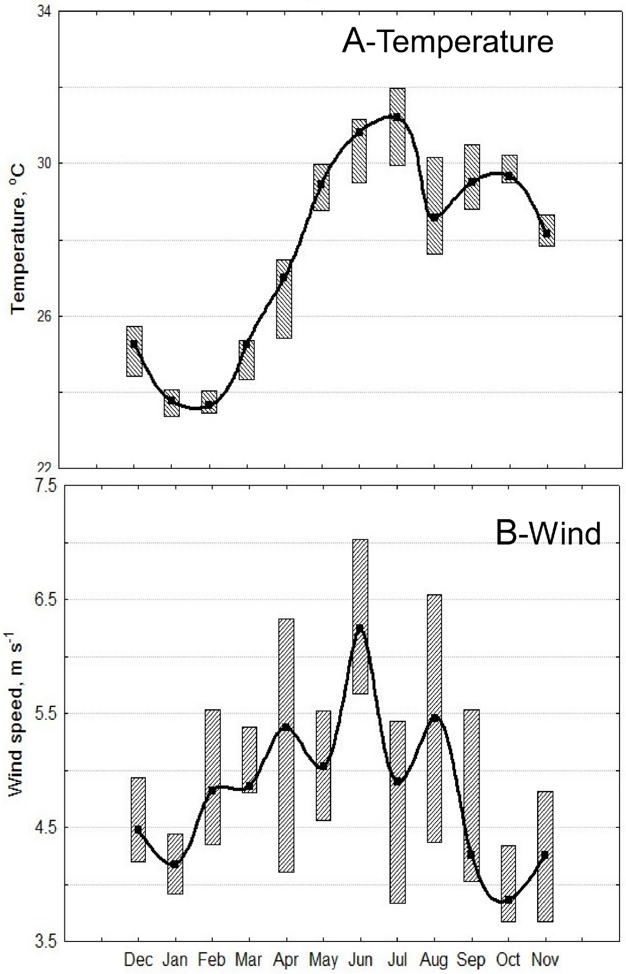

Figure 2. Monthly median and range (25-75%) of: (A) sea surface temperature, (B) Meridional component of mean monthly wind speeds off the Muscat region from 2006-2011.

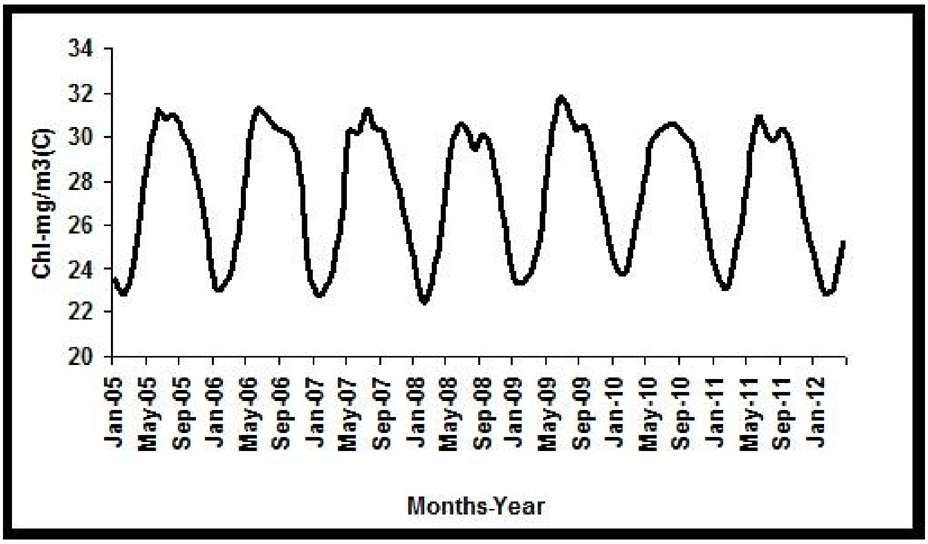

Figure 3. A) Interannual variation in SST off-shore of Muscat from 2005-2011 (from NOAA coral bleaching program).

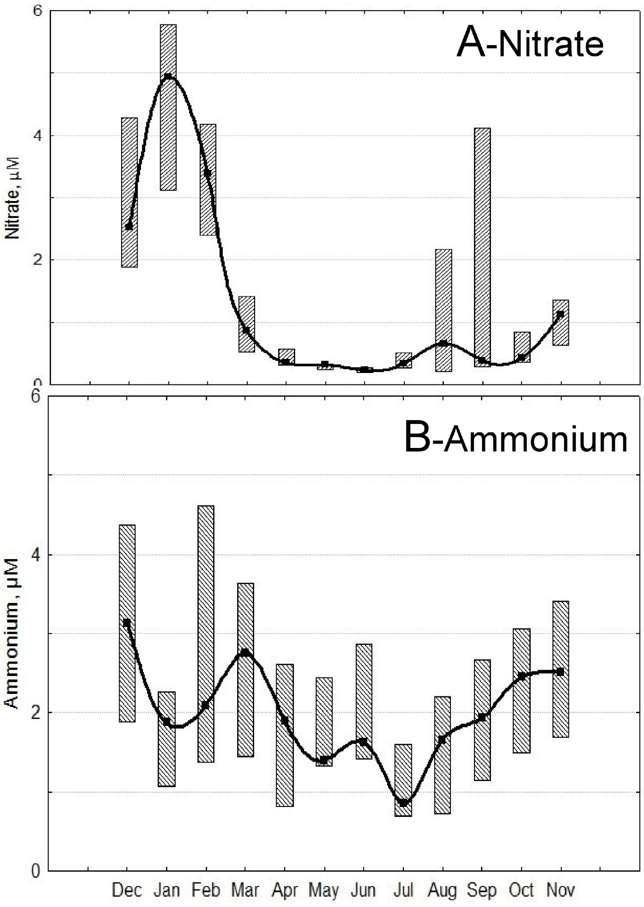

Figure 4. Median and the range (25-75%) in monthly: A) nitrate, B) ammonium concentrations, 2006-2011.

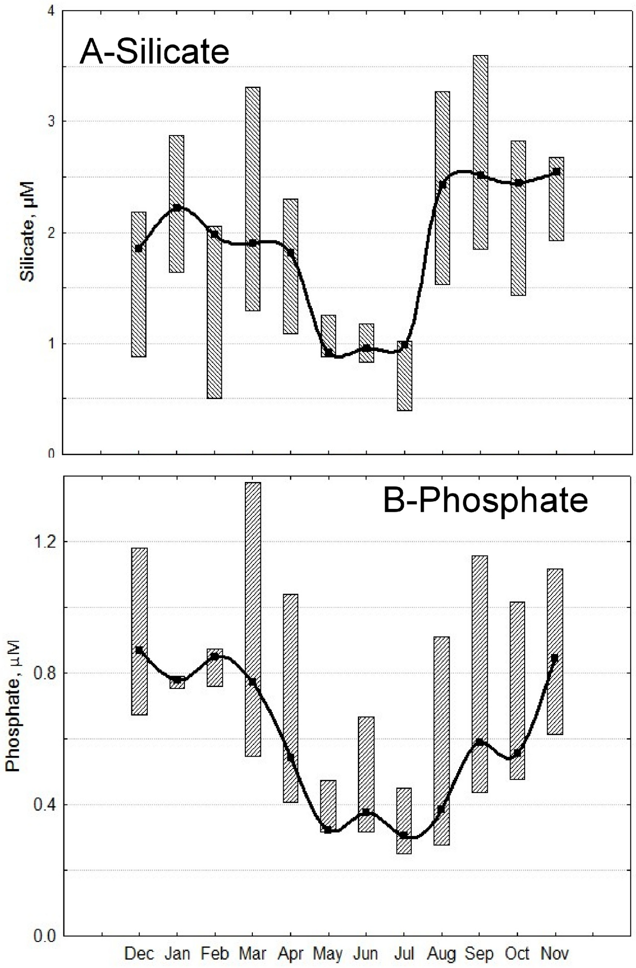

Figure 5. Median and the range (25-75%) in monthly: A) phosphate and B) silicate concentration 2006-2011.

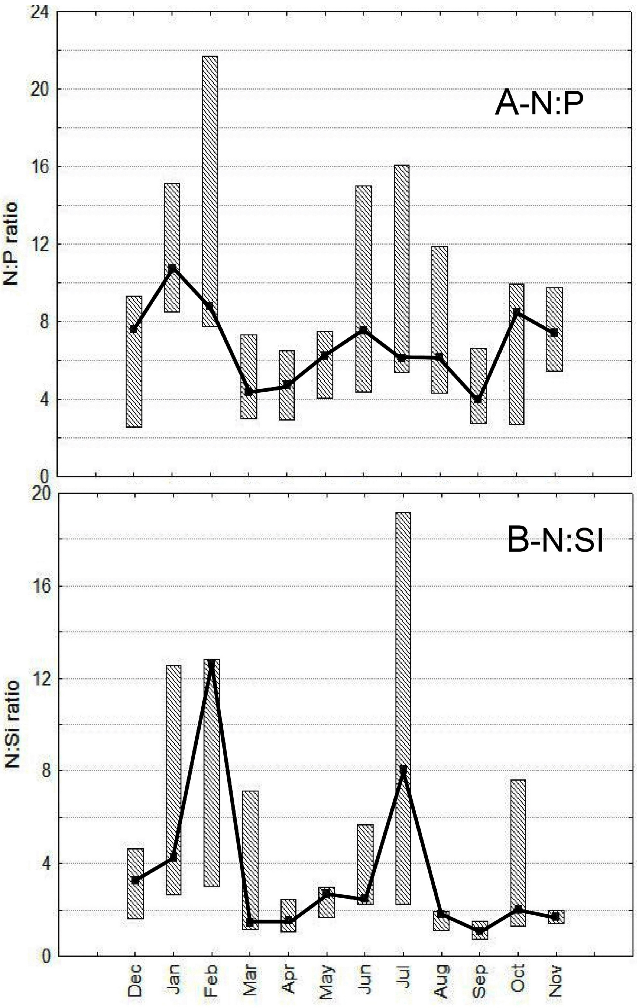

Figure 6. Median and the range (25-75%) for nutrient ratios: A) N:P and B) N:Si where N = NO3 + NH4, 2006-2011.

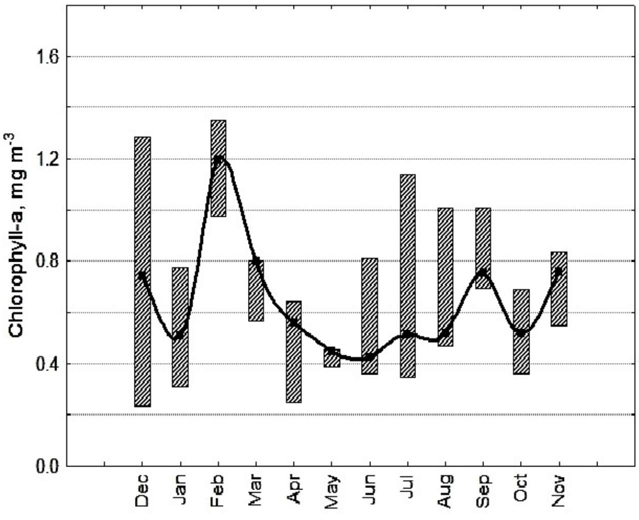

Figure 7. Median and the range (25-75%) in monthly surface (1 m) Chl-a , 2006-2011.

Phytoplankton Species

Qualitative and Quantitative Fluctuations

A total of 278 dinoflagellate and diatom taxa were recorded during the 6 year study and the Dinophyceae contributed 166 species followed by the Bacillariophyceae (112).

Large fluctuations were observed in total phytoplankton abundance with a minimum of 859 cells L^{-1} and a maximum of 47 x 10^3 cells L^{-1} (Figure 8A). Particularly high monthly average counts of 12.7 x 10^4 and 40.3 x10^4 cells L^{-1} were found during the diatom bloom of *Leptocylindrus danicus* in August 2006 and the major and widespread *Cochlodinium polykrikoides* bloom in December 2008, respectively. The monthly average abundance during 2006-2011 ranged between 3670 $\pm$ 2370 to 12,800 $\pm$11,150 cells L^{-1} (Figure 8A). With the exception of the two above mentioned unusual blooms observed in June 2006 and December 2008, the annual cycle of phytoplankton abundance showed two periods of high cell counts in March and September, similar to chlorophyll (Figure 7). The highest fluctuations in species abundance and the number of taxa were more pronounced during the SWM than the NEM

On average, phytoplankton species richness was higher during the SWM and NEM than during the two intermonsson periods, FIM and SPIM: 4.8 and 4.4, versus 3.3 and 2.1, respectively. The large dissimilarity in phytoplankton assemblages that dominated during different years was determined by the simper test Primer (average 69.5). Out of 118 samples, only a few species, mostly dinoflagellates, were present, namely: *Prorocentrum minimum* (Pavillard) J.Schiller*, Gymnodinium* sp F.Stein*, Scrippsiella trochoidea* (Stein) Loeblich III, *Noctiluca scintillans* (Macartney) Ehrenberg, *Gymnodinium simplex* (Lohmann) Kofoid & Swezy and *Prorocentrum micans* Ehrenberg. These species were present at least 38 times in the 118 samples (Figure 9). The most important taxa that contributed >15% to the total abundance each year are listed in Table 1. These species were responsible for 29.5% of similarity among years.

Dinophyceae

Dinoflagellates were the most important group in the Bandar Khayran Bay. They constituted 60% of the total species identified in the bay and dominated the total phytoplankton assemblage most of the year, comprising 83% of the total abundance.

Dinoflagellates were observed during all sampling periods, but were more abundant in March and August

Table 1. Taxa contributing >15% to the total abundance (cells L^{-1}). empty cells=no data

Year	Species	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
2006	*Chaetoceros sp.*					0	0	746	213	0	0	1172	0
	Leptocylindrus danicus					0	0	746	138816	6178	0	0	0
	Leptocylindrus minimus					0	0	0	13206	30246	0	0	0
	Pachyneis gerlachii					0	0	0	0	1917	0	0	0
	Pseudo-nitzschia pungens					0	0	0	23411	213	0	0	0
	Thalassionema nitzschioides					0	320	3834	1249	213	426	0	0
	Thalassiosira sp.					0	0	1172	392	213	0	0	0
	Gymnodinium simplex					276	213	320	107	213	0	1811	320
	Gymnodinium sp.					1010	1491	959	1602	852	1172	639	533
	Gyrodinium pingue					138	0	320	107	107	0	320	320
	Prorocentrum minimum					1794	213	1385	2889	1598	2343	1172	746
	Prorocentrum gracile					107	5964	0	0	213	213	213	0
	Prorocentrum micans					138	107	0	0	0	533	0	107
	Scrippsiella trochoidea					458	0	533	499	852	959	426	213
2007	*Guinardia delicatula*	0	213	426	0	1065	0	0	0	0	213	0	0
	Thalassionema nitzschioides	0	0	0	0	1065	2769	0	107	0	0	0	0
	Gymnodinium simplex	533	852	959	852	852	1065	320	1278	0	852	107	959
	Gymnodinium sp.	533	852	1917	1172	1598	3195	852	848	320	1491	528	107
	Gymnodinium uberrimum	0	0	0	0	0	0	9585	0	2876	0	0	0
	Noctiluca scintillans	211	1095	979	248	8	56	123	8628	731	18	69	1884
	Prorocentrum minimum	1278	320	4895	3621	426	852	4260	852	3408	852	1065	1385
	Prorocentrum gracile	107	0	0	5325	1277	426	107	0	107	107	107	0
	Prorocentrum micans	0	0	2343	320	0	426	533	107	533	426	0	0
	Scrippsiella trochoidea	107	320	1065	213	213	0	1385	0	959	107	746	533
2008	*Cylindrotheca closterium*	0	0	0	0	0	0	0	0	0	320	0	0
	Dactyliosolen fragilissimus	0	0	0	0	320	0	0	0	0	0	0	0
	Guinardia flaccida	0	320	0	0	0	426	0	0	0	0	0	0
	Cochlodinium polykrikoides	0	0	0	0	0	0	0	0	0	0	0	109000
	Gymnodinium simplex	0	0	0	107	0	0	426	1278	533	639	0	426
	Gymnodinium sp.	320	107	320	107	639	533	852	2982	2237	1278	2769	1491
	Noctiluca scintillans	1337	21	336	1	0	0	0	0	0	0	0	0
	Prorocentrum minimum	426	746	1917	959	533	4260	4260	3302	4260	533	4686	7242
	Prorocentrum micans	0	0	852	1278	0	320	0	0	0	0	746	533
	Scrippsiella trochoidea	213	0	107	107	0	107	426	1917	2345	320	213	107
2009													
	Gymnodinium simplex	0	426	1065	0	0	213	426	2556	639	107	213	0
	Gymnodinium sp.	639	426	2556	426	852	0	1065	2343	426	320	746	1172
	Gyrodinium pingue	533	0	0	0	213	213	107	0	107	0	320	107
	Heterocapsa triquetra	0	0	0	0	0	0	0	213	0	0	0	213
	Prorocentrum minimum	320	1065	5219	1917	2663	6177	959	1704	7668	2450	213	426
	Prorocentrum micans	0	0	2769	639	639	1065	959	0	3089	107	0	107
	Protoperidinium breve	0	0	107	2343	213	0	0	213	426	0	0	0
	Protoperidinium sinaicum	0	0	0	0	213	213	533	639	107	0	0	0
	Scrippsiella trochoidea	0	0	3408	852	7881	2556	426	3621	6923	746	213	0
2010	*Chaetoceros compressus*		0	0	0	0	0	0	0	0	6603	0	0
	Chaetoceros pseudocurvisetus		0	0	0	0	0	0	0	0	7136	0	0
	Chaetoceros sp.		0	0	0	0	0	0	0	0	1065	1065	0
	Chaetoceros tortissimus		0	0	0	0	0	0	0	0	1065	1065	0
	Pseudo-nitzschia delicatissima		0	0	0	21194	426	0	0	0	0	0	0
	Thalassiosira eccentrica		0	0	213	107	0	107	0	0	0	0	213
	Thalassiosira sp.		107	213	0	0	0	0	0	0	0	0	0
	Diplopsalis lenticula		107	0	0	0	0	0	0	0	0	0	0
	Gymnodinium sp.		320	0	1491	426	426	1598	1065	426	1065	0	1065
	Noctiluca scintillans		833	0	2	43	8	85	0	98	53	3	54
	Ornithocercus magnificus		0	0	0	0	0	0	0	0	0	107	0
	Ornithocercus thurnii		0	0	0	0	0	0	0	0	0	107	0
	Prorocentrum minimum		1172	4899	1278	1811	3195	2556	2556	1065	3195	1704	320
	Prorocentrum gracile		107	213	0	107	0	0	213	0	107	0	0
	Prorocentrum micans		107	0	0	533	213	533	0	107	320	0	0
	Protoceratium areolatum		0	0	0	0	0	0	0	0	0	0	2769
	Protoperidinium minusculum		0	2556	0	0	0	533	0	0	0	107	0
	Scrippsiella trochoidea		0	3408	0	959	852	1278	825	533	639	0	320
2011	*Guinardia striata*	0	9053	0	0								
	Helicotheca tamesis	0	0	2130	0								
	Gymnodinium sp.	533	3302	1278	1385								
	Prorocentrum minimum	2024	2556	4260	320								
	Scrippsiella trochoidea	320	2556	1065	2769								

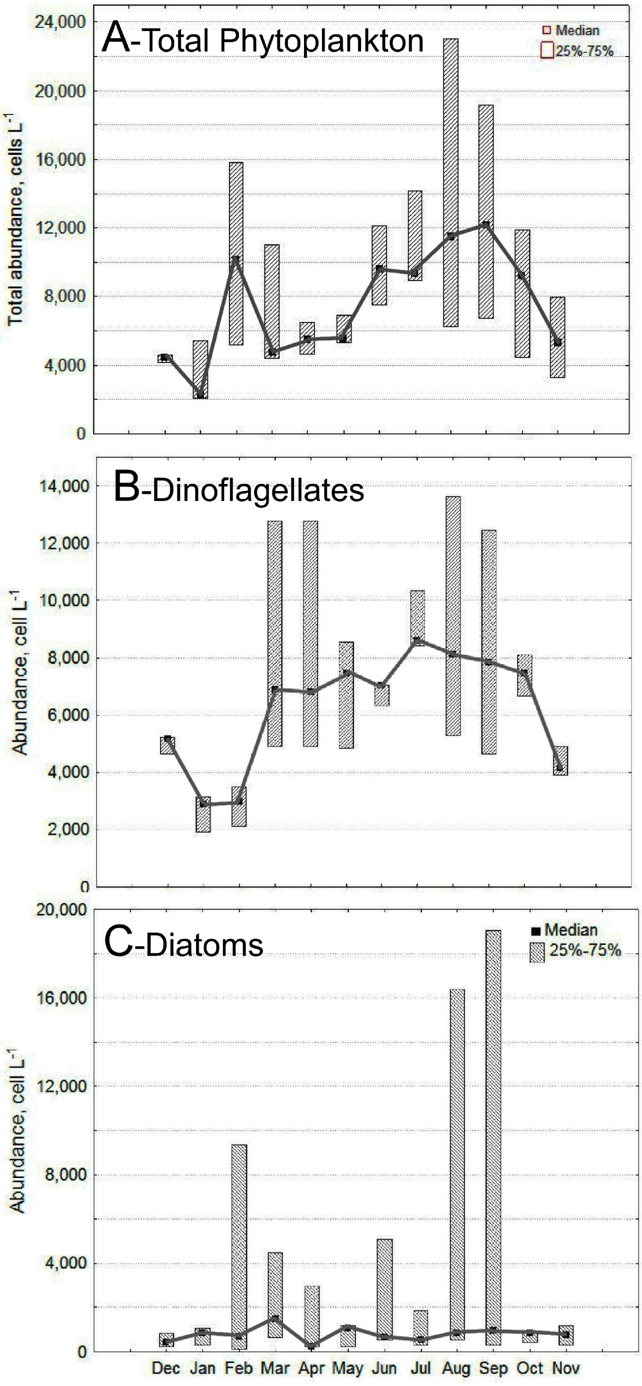

Figure 8. Median and the range (25-75%) in monthly total abundance of: A) total cell abundance, B) dinoflagellates, and C) diatoms , 2006-2011.

(NEM and SWM) (Figure 8B). Excluding the *Cochlodinium polykrikoides* Margalef bloom of 2008, dinoflagellates showed higher abundance in 2007 and 2009 with a 17% increase, compared to the rest of the years (Table 1).

During the NEM, *Noctiluca scintillans* was more abundant when SST was ~23°C than during the SWM when SST was >30oC (Figure 10).

Bacillariophyceae

Diatoms were the second most important group and contributed 40% to the total species identified in the bay comprising only 17% of the total abundance. Diatoms showed higher abundance during 2006 and 2010 than the rest of the other years (Figure11). The highest counts were in October, 2006 and in March and October of 2010 with an average of 40,000 cells L^{-1} (Figure 11). Generally, diatoms were more abundant during February-March and August-September (Figs. 8C and 11; NEM and SWM respectively) and appeared to be major contributors to the high Chl-*a* during the two monsoon periods.

The highest abundance of diatoms occurred in 2006, even excluding the *Leptocylindrus danicus* Cleve bloom and after this bloom, a dramatic decrease of >47% in 2007, 2008 and 2009 occurred in diatom abundance, followed by a recovery in 2010 (Figure 11). In 2006, diatoms were dominated by *Leptocylindrus danicus, L. minimus* Gran, *Pseudo-nitzschia pungens* (Grunow ex Cleve) Hasle and *Chaetoceros* spp. Ehrenberg. In 2010, *Pseudo-nitzschia delicatissima* (Cleve) Heiden and *Chaetoceros* spp. contributed significantly to the total diatom population in 2010. During 2006 and 2010, the higher nutrients likely contributed to the higher abundance of diatoms for both years compared to the other years.

Zooplankton

Zooplankton occurred in high abundance and were represented by several taxonomic groups. Copepods comprised the major part of total zooplankton abundance and exhibited a peak in September (Figure 12).

Principal Component Analysis

Principal component analysis of the major phytoplankton groups showed that high Chl-*a* was associated with diatoms and diatoms were dependent on silicate (Figure 13). The increase in diatom abundance and its association with phosphate, ammonium and silicate were coupled primarily with a decrease in temperature (e.g. upwelling). A weak association was found between dinoflagellates (except *Noctiluca scintillans*) and nutrients. No clear association was found between copepod abundance and diatoms.

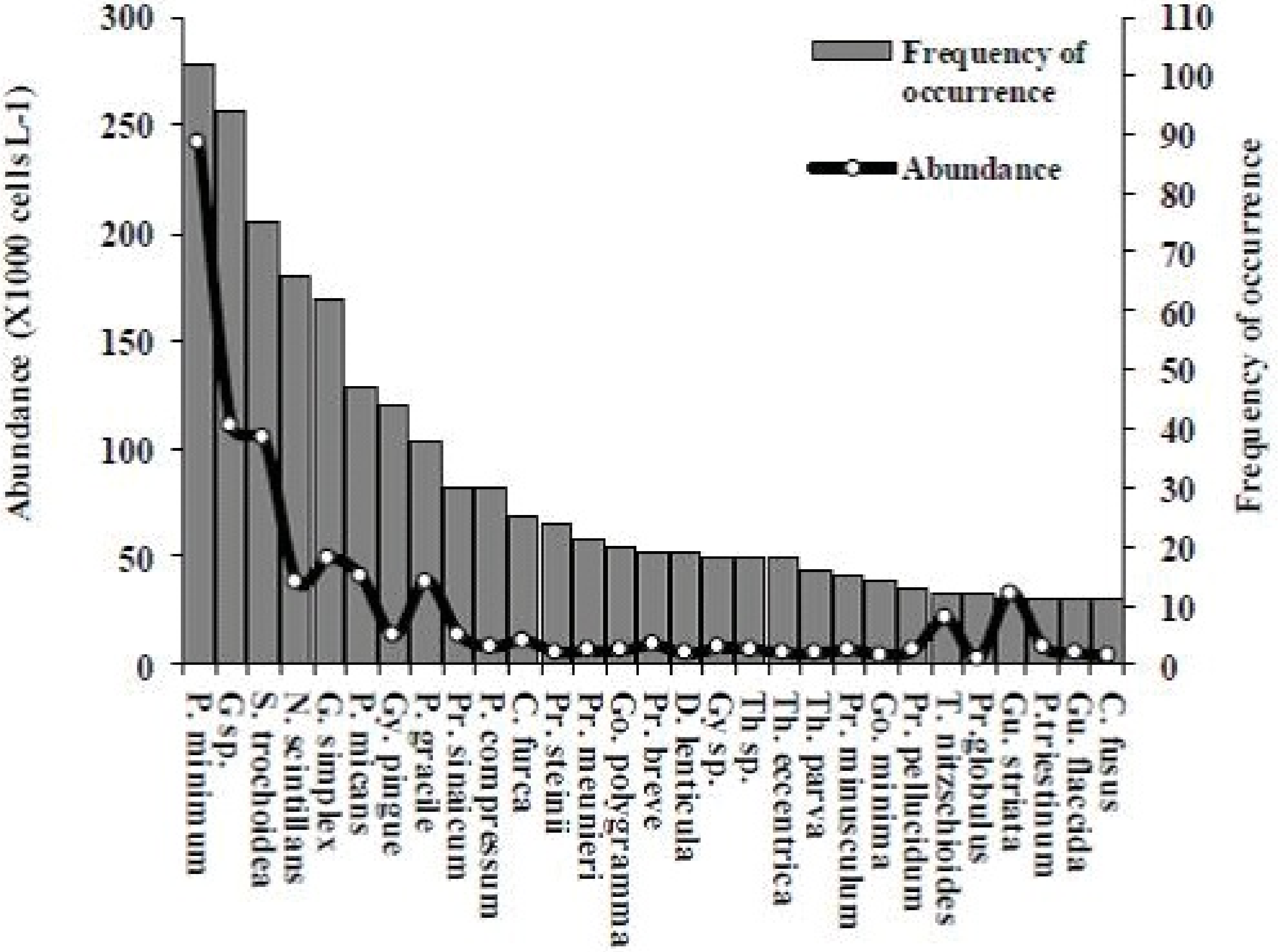

Figure 9. Abundance of species and their frequency of occurrence during 2006-2011.
P. = Prorocentrum, G = Gymnodinium, S. = Scrippsiella,.N.= Noctiluca, Gy.=.Gyrodinium,.Pr.= Protoperidinium,.C.= Ceratium, Go.= Gonyaulax, D. = Diplopsalis, Th. = Thalassiosira, T.= Thalassionema, Gu. = Guinardia.

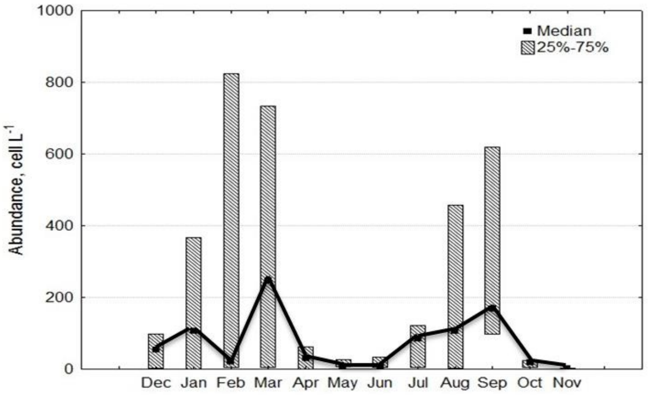

Figure 10. Median and range (25-75%) of monthly abundance of *Noctiluca scintillans* (2006-2011).

DISCUSSION

During the SWM and NEM monsoons, phytoplankton abundance increased in Bandar Khayran Bay (Figure 8). The extremely high variability observed was due to the more than 100-fold increase in phytoplankton numbers at the start of the SWM and NEM monsoons and the sharp decrease towards the end of the monsoons. During both seasons, the concentration of nutrients increased abruptly and remained relatively high during the NEM in winter. The increase in surface nutrient concentrations was associated with meridional winds turning onshore in November-January. Higher nutrient concentrations in winter were attributable to deep convective mixing

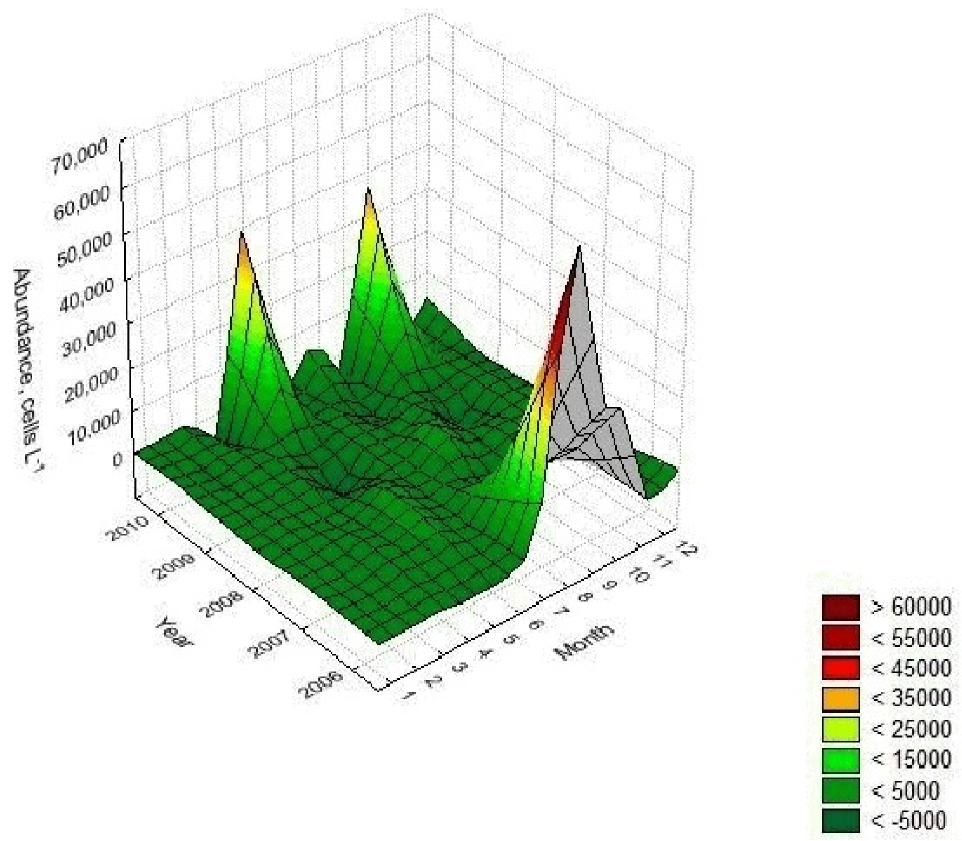

Figure 11. Average monthly and annual abundance of diatoms during 2006-2010.

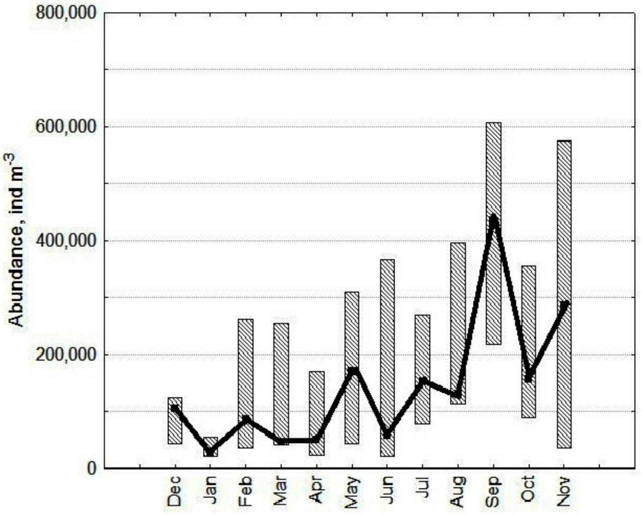

Figure 12. Median and the range (25-75%) in monthly copepod abundance, 2006-2011.

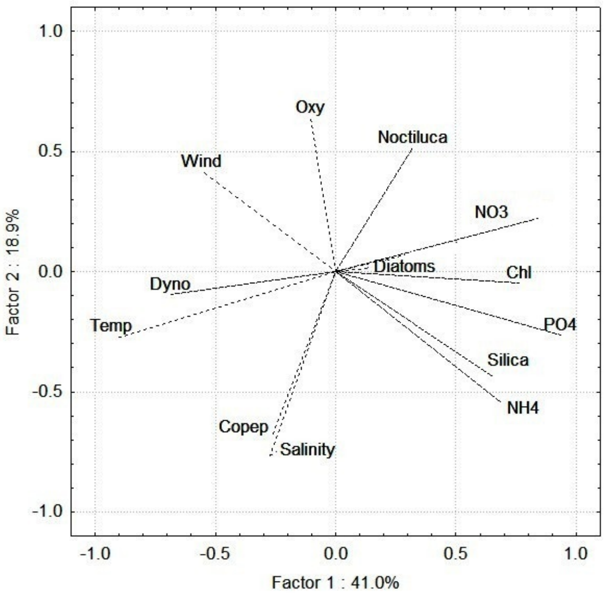

Figure 13. PCA analysis showing the grouping diatoms and dinoflagellates, and their relationship to the environmental parameters: Temp: temperature; Oxy: oxygen; Chl: Chl-a; NH4: ammonium; PO_4: phosphate; NO_3:nitrate; Silica: Silicate; :Diatoms; Dyno: Dinoflagellates; copep copepods.

forced by winter cooling of surface water that resulted in increased phytoplankton abundance in the Bay. The increase in nutrient concentrations in August was due to the injection of cold water produced by upwelling along the Omani coast. These increased nutrients also resulted in an increase in the number of phytoplankton genera and thus higher species richness. The annual vertical movement of the deep chlorophyll maximum (DCM) appears to be related to the heating and cooling phases, while the Chl-*a* in the DCM was influenced by the thermohaline structure and nutrient availability. However, no classical species succession (i.e. diatoms followed by dinoflagellates) was clearly observed.

In 2006, an alternate cycle between diatoms and dinoflagellates was observed. Dinoflagellates such as *Gymnodinium* sp. *Prorocentrum minimum* and *Pr. gracile* dominated the SPIM (May –June) while the diatoms, mainly *Guinardia striata, Leptocylindrus danicus*, *L. minimus* and *Pseudo-nitzschia pungens,* dominated the SWM (July-September) phytoplankton assemblage. Changes in phytoplankton composition often coincided with changes in cell size, because the increased surface-to-volume ratio of small cells is advantageous under low nutrient concentrations (Chisholm and Morel 1991). High nutrient concentrations and turbulence during the SWM and NEM support the growth of larger fast growing species such as diatoms. However, diatom abundance decreased and diatoms were replaced by dinoflagellates, especially *Scrippsiella trochoidea,* even during the NEM (Table 1). The increased N:Si (Figure 6B) due to low Si of <2 μM (Figure 5B) might have suppressed diatoms dominance and favored non-silicious phytoplankton (Riegman 1991, Smayda 1990).

Also during 2010, diatoms were dominant, but during two different seasons, May (SPIM) and early October (late SWM). *Pseudo-nitzschia delicatissima* dominated in May, while in October *Chaetoceros compressus* and *Chaetoceros pseudocurvisetus* dominated. Even though the NEM assemblage of diatoms were characterized by a mixture of different taxa, *Guinardia striata* dominated and comprised ~20% of the total phytoplankton assemblage.

Diatoms were more dominant than dinoflagellates in 2006 and 2010 due to high nutrients availability. The increased abundance in October coincided with high nutrient concentrations: 10.5 μM nitrate and 3.8 μM silicate in 2006 and 19.2 μM nitrate and 9.2 μM silicate in 2010. Not surprisingly, a strong correlation was found between the abundance of the dominant diatoms and silicate concentrations (Figure 13). Diatoms generally have faster growth rates than other phytoplankton groups when nutrients and light are optimal (Brand and Guillard 1981). This increase in diatoms abundance was not locally restricted because high diatom abundance was also found at Fahal Island, 8 km away from the Bandar Khayran Bay (pers. obs.). The dominance of diatoms during February, March and early October was also reported in 2001 both inside and outside the Bay (Al-Hashmi et al. 2010).

Higher abundance of diatoms compared to dinoflagellates was reported (AL-Azri et al. 2010) during most months (February-March; July-September, 2004-2006). This dominance of diatoms was not seen in 2007-2009 when the phytoplankton population was entirely dominated by dinoflagellates. The SWM of 2007 was preceded by Cyclone Gonu which resulted in an early and massive bloom of *Noctiluca scintillans* that dominated the entire Sea of Oman including the Bandar Khayran Bay (Al-Hashmi et al. 2015). The mixing by the typhoon may have lowered the water temperature, below *N. scintillans* upper threshold of 25-30ºC, allowing it to bloom. Since diatoms are the favorite food source for *N. scintillans*, they may have actively grazed the diatoms and controlled the abundance of diatoms (Harrison et al. 2011). Similarly, a *Cochlodinium polykrikoides* bloom dominated the sea of Oman from October, 2008 to February, 2009 outcompeting other organisms including diatoms (Al-Azri et al. 2014).

Dinoflagellates dominated even during summer and this is a common feature of Muscat coastal waters (Al-Azri et al. 2010). Due to their vertical migration capability, dinoflagellates often dominate under highly stratified low nutrient concentrations (Margalef 1978, Lalli and Parsons 1997) as well as at higher temperatures (Boney 1989) In addition, 50% of the dinoflagellates are at least partially heterotrophic organisms, which feed on diatoms that they can capture in trailing filaments (Van den Hoek et al. 1995).

The dinoflagellate assemblages that dominated and persisted annually were: *Prorocentrum minimum, Gymnodinium* sp. *Scrippsiella trochoidea, Gymnodinium simplex* and *Prorocentrum micans.* Phytoplankton assemblages selected under uniform environmental conditions are likely to share similar characteristics and adaptation strategies (Margalef 1978). All of these dinoflagellates (except *Noctiluca scintillans*) are very small 15-5 µm, which allows them to take up nutrients even at very low concentrations, a selective advantage in oligotrophic waters (Linventon 2001). Also these species are known to tolerate a broad range of temperature variability (Wang et al. 2007) and grow better under high light or warm temperatures (Heil et al. 2005). Moreover, species like *Pr. minimum, Gymrodinium simplex, Scrippsiella trochoidea* and *Noctiluca scintillans* are phagotrophic and therefore they are not completely reliant on inorganic nutrients (Burkholder 2008, Lalli and Parsons 1997).

Besides the above dominant dinoflagellates*, Noctiluca scintillans* also occurs frequently in the bay. It is known to form green blooms twice a year: late SWM (September-October) and NEM (January-February) in the Sea of Oman (Al-Azri et al. 2007, Gomes et al. 2008). However, no bloom was observed in 2008 due the intense *Cochlodinium polykrikoides* bloom from November 2008 to January 2009 (Al-Hashmi 2015).The green color is due to the symbiotic green autotrophic prasinophyte *Pedinomonas noctilucae* ®. Subrahmanyan) Sweeney inside the *N. scintillans* cell *(*Harrison et al. 2011). The association between green *Noctiluca* and Chl-*a* is due to the contribution of the green symbiont to the chlorophyll concentration (Sweeney 1976, Elbrachter et al. 1989, Hausmann et al. 2003).

In natural waters, phytoplankton biomass and size distribution are controlled to a large extent not only by nutrient availability, but also by grazing pressure from zooplankton and other filter feeders (Sarnelle 1993, Kivi et al. 1993). It is known that small cells are generally better competitors for nutrients than larger cells, but they may be more readily grazed than larger cells (Riegman et al. 1993, Edgar and Green 1994). Even though no clear association was found between phytoplankton (diatoms and dinoflagellates) and copepod abundance (Figure 13), highest copepod abundance occurred in September (Figure 12) following the highest abundance of phytoplankton that occurred in August (Figure 8). Copepod biomass in the bay was found to be far lower than in the open, off-shore Muscat waters (Al-Hashmi 2014). This could be because the coral community in the bay causes a decline in the copepod population and hence a reduction in grazing pressure (Holzman et al. 2005). Phytoplankton regulation by zooplankton was reported to be weaker in tropical waters than is generally seen in temperate regions (Von Ruckert and Giani 2008). However, no conclusion can be made on the grazing effect of zooplankton on phytoplankton in the bay since the study did not investigate the microzoplankton and other size classes of zooplankton.

SUMMARY

The coast of Muscat (Sea of Oman) possesses a diverse assemblage of phytoplankton with a total of 278 taxa identified. Species composition of the phytoplankton communities showed large seasonal variability. This variability is strongly associated with thermal stratification and nutrient concentrations in the waters in and around Bandar Khayran Bay. The monsoonally-driven semi-annual warming and cooling has a profound impact on the patterns of phytoplankton biomass. The phytoplankton dynamics may be influenced more by silicate limitation than nitrogen since NH_4 is surprisingly high particularly after *N. scintillans* bloom decay and also this may reflect active grazing. Since phytoplankton usually take up NH_4 before NO_3, it is not likely that NO_3 limitation occurs when there is sufficient ambient NH_4. Heterotrophic dinoflagellates constantly dominated the phytoplankton community when nutrients are low, while diatoms were only dominant when silicate is sufficient during the SWM of 2006 and 2010. Blooms of *Noctiluca scintillans* were observed only during January and September. The increase in optimum biological and hydrographic factors play a major role in the bloom formation of *Noctiluca scintillans* and its spatial distribution.

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