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Seasonal variability of phytoplankton in a coastal lagoon and adjacent open sea in Pakistan

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Abstract: The coast of Pakistan (North Arabian Sea) is under the influence of the seasonal cycle of monsoons, which may result in 2 periods of elevated phytoplankton productivity, one during the north-east monsoon (December–February) and the other during the south-west monsoon (May–September). In the present study, elevated primary productivity in the Miani Hor Lagoon and adjacent open sea off Pakistan was found during the south-west monsoon (May–September) and spring inter-monsoon (March–April). The lowest phytoplankton abundance was recorded in the north-east monsoon period at both collection sites. A total of 65 species of diatoms and 32 species of dinoflagellates were identified in the lagoon. In the open sea, 63 species of diatoms and 23 species of dinoflagellates were present. No significant differences were found in salinity, dissolved oxygen, pH, or nitrite, ammonium, or phosphate concentrations during the different seasons at the 2 sites. Temperature and chlorophyll-a varied significantly ($P < 0.001$) between the seasons, with temperature being highest during the south-west monsoon period and chlorophyll-a during the spring inter-monsoon period. Diatoms showed a statistically significant positive correlation with temperature and a negative significant correlation with salinity. Further studies are needed along the coast of Pakistan in order to understand the dynamics of phytoplankton in this part of the North Arabian Sea.

Key words: Seasonal abundance, species diversity, physicochemical parameters, phytoplankton

1. Introduction

The Arabian Sea, a part of the Northern Indian Ocean, is known for its seasonality characterised by reversing summer and winter monsoonal wind patterns and associated upwelling. Reversal in surface circulation during monsoons (Wrytki, 1973; Banse, 1987), seasonality in the nutrient distribution (Banse, 1987), and irradiance (Brock et al., 1994) have important effects on the primary production in the Arabian Sea. The reversal of monsoon winds changes the circulation pattern of the Arabian Sea, which can drive seasonality in abundance of phytoplankton, the primary producers of the marine food webs (Dwivedi et al., 2006). The Arabian Sea is bordered by Pakistan to the north, by India to the east, and the Arabian Peninsula to the west.

The coastline of Pakistan is 1050 km long, of which 250 km belongs to Sindh Province and 800 km to Balochistan Province (Figure 1). The Indus Delta of the Sindh coast is covered with dense growth of mangroves (Saifullah, 1982), while only 3 small pockets of mangroves are present along the coastline of Balochistan (Mirza et al., 1988). These are Miani Hor, Kalmat Khor, and Gawatar Bay. Miani Hor is a lagoon situated about 90 km away from Karachi on the eastern part of the Balochistan coast and is an important fishing centre. Extremely little published information is available on the fauna and flora of this area (Ahmed & Ayub, 1996, 1999; Chaghtai et al., 1995, 2002; Ahmed & Abbas, 1999). Although literature on the distribution, seasonal abundance, and biomass of phytoplanktons in the Arabian Sea is available (Subrahmanyan et al., 1975; Kuz'-menko, 1977; Banse, 1987; Brock et al., 1991; Brock and McClain, 1992; Pant, 1992; Tarran et al., 1999; Sawant & Madhupratap, 1996; Hirawake et al., 1997; Brown et al., 1999; Sarangi et al., 2005; Dwivedi et al., 2006), no study has covered the North Arabian Sea along the Pakistan coast. Like the rest of the Arabian Sea, this coast is also under the influence of monsoonal winds, which are expected to drive 2 periods of elevated primary productivity, one during the south-west monsoon and other during the north-east monsoon. Keeping in view that no information on the qualitative and quantitative characteristics of the phytoplankton community is available from this area of the North Arabian Sea, the present study aimed to characterise and understand the seasonal variability of phytoplankton abundance and chlorophyll-a concentration in the Miani Hor Lagoon and the open sea adjacent to it. The variability of phytoplankton was also studied in relation to physical and chemical factors.

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2. Materials and methods

Monthly sampling was carried out for 11 months (September 2003–August 2004) at 2 sites, the Miani Hor Lagoon and the open sea adjacent to it (Figure 1). Sampling was not possible in July 2004 due to the roughness of the sea and a ban on operation of boats in the sea. Collection of samples was conducted at both stations between 0900 and 1200 hours with a boat towing a phytoplankton net (mesh size of 50 µm) horizontally along 100 m in the subsurface (0.5 m) water. While towing, the boat during was maintained at a uniform speed (4 knots). The filtrate from the plankton net was transferred to a 1-L jar and immediately fixed with 4% formalin.

2.1. Study area

Miani Hor (25°31′N, 66°20′E) is a swampy lagoon and an active fishing centre, located about 90 km north-west of Karachi, on the coast of Balochistan (Figure 1). It is approximately 60 km long and 7 km wide on average, reaching up to 10 km wide at some locations. The lagoon lies parallel to the Arabian Sea, to which it is connected by a 4-km wide mouth. Tides are semidiurnal with a tidal range of average 2.12 m. Here the climate is very arid, with less than 200 mm of rain per year (Saifullah & Rasool, 2002). The sources of fresh water for Miani Hor are the seasonal run-off rivers of Porali and Windor (Hussain, 1998). Miani Hor is the only locality along Pakistan's coast where 3 species of mangrove trees co-exist: *Avicennia marina*, *Ceriops tagal*, and *Rhizophora mucronata*. The lagoon is considered relatively free from any kind of industrial pollution (Saifullah et al., 2002) as no industrial facilities are found near the area. However, domestic waste disposal and accumulated solid waste debris have been shown as growing problems in the Miani Hor Lagoon (Qureshi et al., 2002). Sampling stations were selected to represent the lagoon (site 1) and the adjacent open sea (site 2); see Figure 1. The distance between site 1 and site 2 is about 15 km.

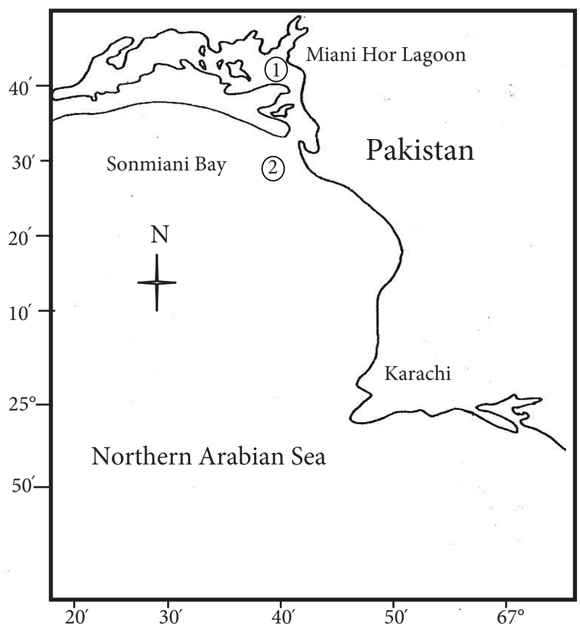

Figure 1. Map of sampling sites: 1. Maini Hor Lagoon; 2. Open sea.

2.2. Physical and chemical parameters

Water temperature, salinity, and pH were measured in situ with a thermometer, an ATAGO S/Mill-E refractometer, and a portable Jenway pH meter, respectively. Samples were collected from the subsurface water for the analysis of chemical parameters. Dissolved oxygen was analysed by the Winkler method (Strickland & Parsons, 1972). Chlorophyll-a, nitrite, nitrate, ammonium, and phosphate were estimated following the methods described in Strickland and Parsons (1972).

2.3. Identification of phytoplankton

Samples of phytoplankton were identified from the following literature: Chaghtai and Saifullah (1988, 2001), Hoque et al. (1999), Richard (1987), and Fritsch (1961).

2.4. Quantitative phytoplankton estimation

Phytoplankton samples were fixed with formaldehyde in the field in jars of 1-L capacity and then counted in the laboratory. Total phytoplankton abundance was calculated as cells L^{-1} and is expressed in terms of percentage composition. As each genus was represented by a large number of species, the counting was done for each genus instead of each species. In order to check the seasonal abundance of phytoplankton, seasons were divided into autumn inter-monsoon (October–November), north-east monsoon (December–February), spring inter-monsoon (March–April), and south-west monsoon (May–September) (Figure 2).

2.5. Statistical analyses

Two-way ANOVA was used to test for differences in physical and chemical parameters with sites and seasons as factors. Tukey's test was used to determine which factors were

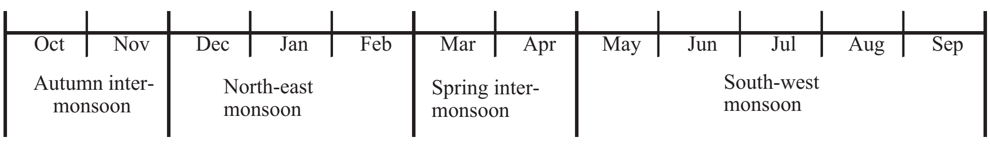

Figure 2. Division of months into different seasons.

significantly different. Correlation coefficients (Pearson) between the diatoms and dinoflagellate density and the various physiochemical parameters were computed. The data were analysed using SPSS version 14.0. Changes in phytoplankton dynamics were examined using Shannon-Weiner diversity (H') and evenness (J) (Zar, 1996). The numbers of species were referred to as species richness (Magurran, 1998).

3. Results

3.1. Physical and chemical parameters

Water temperature ranged between 21 and 33 °C in the lagoon and between 20 and 32 °C in the adjacent open sea. No significant differences in temperature were found between the 2 sites while temperature varied significantly ($P < 0.001$) between the seasons (Table 1), being lowest during the north-east monsoon period (December–February) (Table 2). Salinity ranged between 35 and 40 in the lagoon and between 35 and 42 in the open sea. No significant difference ($P > 0.05$) in salinity was found between sites or between seasons (Tables 1 and 2). pH value was similar at the 2 sites, but it was significantly ($P < 0.01$) different between seasons (Table 1). The pH was higher during the spring inter-monsoon as compared to the other seasons, when it was similar (Table 2). Dissolved oxygen in the subsurface water ranged between 4.0 and 5.7 mL L^{-1} in the lagoon and between 4.1 and 5.3 mL L^{-1} in the open sea. No significant difference was found in the concentration of dissolved oxygen at the 2 sites or between the different seasons (Tables 1 and 2).

Table 1. Two-way analysis of variance to test differences in physical and chemical parameters at 2 sites during different seasons.

Physical and chemical parameters	Source of Variation	df	F ratio	P value
Temperature	Site	1	0.047	NS
	Season	3	14.213	0.000
	Site & season	3	0.019	NS
Salinity	Site	1	0.269	NS
	Season	3	1.662	NS
	Site & season	3	0.234	NS
pH	Site	1	0.012	NS
	Season	3	5.154	0.013
	Site & season	3	0.324	NS
Oxygen	Site	1	0.071	NS
	Season	3	1.572	NS
	Site & season	3	0.887	NS
Chlorophyll-a	Site	1	0.123	NS
	Season	3	5.093	0.014
	Site & season	3	0.102	NS
Nitrite	Site	1	0.155	NS
	Season	3	0.767	NS
	Site & season	3	1.073	NS
Nitrate	Site	1	0.421	NS
	Season	3	6.031	0.007
	Site & season	3	0.045	NS
Ammonium	Site	1	0.217	NS
	Season	3	0.433	NS
	Site & season	3	0.771	NS
Phosphate	Site	1	0.021	NS
	Season	3	1.686	NS
	Site & season	3	2.229	NS

Significant at $P < 0.05$ level; NS = not significant.

Table 2. Average values of physical and chemical parameters in the lagoon and open sea during the study period.

Seasons	Temp. (°C)	Salinity	pH	Oxygen (mg L^{-1})	Chl.-a (μg L^{-1})	Nitrite (μg L^{-1})	Nitrate (μg L^{-1})	Ammonia (μg L^{-1})	Phosphate (μg L^{-1})
Lagoon									
Autumn inter-monsoon	26.8^{a}	38.0^{a}	7.6^{a}	4.1^{a}	5.4^{b}	0.058^{a}	4.765^{b}	0.252^{a}	0.220^{a}
North-east monsoon	22.3^{b}	39.3^{a}	7.5^{a}	4.9^{a}	1.4^{a}	0.031^{a}	2.116^{c}	0.278^{a}	0.256^{a}
Spring inter-monsoon	28.0^{a}	38.0^{a}	7.8^{b}	4.4^{a}	8.1^{c}	0.037^{a}	0.391^{a}	0.468^{a}	0.405^{a}
South-west monsoon	30.0^{a}	36.3^{a}	7.5^{a}	4.2^{a}	1.7^{a}	0.048^{a}	1.174^{a}	0.342^{a}	0.162^{a}
Open sea									
Autumn inter-monsoon	27.0^{a}	39.0^{a}	7.5^{a}	4.7^{a}	4.8^{b}	0.058^{a}	4.209^{b}	0.465^{a}	0.847^{a}
North-east monsoon	22.3^{b}	38.7^{a}	7.5^{a}	4.6^{a}	1.4^{a}	0.073^{a}	1.740^{c}	0.850^{a}	0.139^{a}
Spring inter-monsoon	28.0^{a}	38.5^{a}	7.8^{b}	4.2^{a}	9.6^{c}	0.021^{a}	0.279^{a}	0.270^{a}	0.009^{a}
South-west monsoon	29.8^{a}	37.3^{a}	7.5^{a}	4.3^{a}	2.9^{a}	0.042^{a}	0.385^{a}	0.171^{a}	0.124^{a}

Abbreviations: Temp. = Temperature; Chl.-a = Chlorophyll-a. Values in column with different superscripts (a, b, c) are significantly different ($P < 0.05$). Values with similar superscripts are not significantly different.

No significant differences were found in concentrations of nitrite, nitrate, ammonium, or phosphate between the lagoon and the open sea (Table 1). The concentrations of nitrite, ammonium, and phosphate were found to be similar during different seasons; however, the concentrations of nitrate were significantly ($P < 0.001$) higher during the autumn inter-monsoon and during the north-west monsoon period (Table 2).

No significant difference was found in the chlorophyll-a concentration at the 2 sites (Table 1). Chlorophyll-a concentration showed seasonal variations (Table 1). Similar concentrations were observed during the north-east and south-west monsoon periods, while significantly higher values were found during the spring inter-monsoon and autumn inter-monsoon (Table 2).

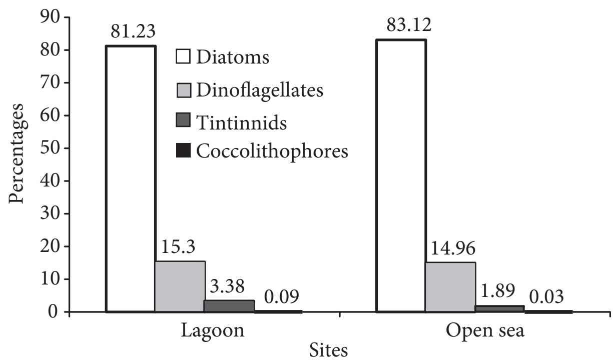

Figure 3. Percentages of the different plankton groups collected from the Miani Hor Lagoon and adjacent open sea during the period from September 2003 to August 2004.

3.2. Phytoplankton composition and abundance

Species of diatoms, dinoflagellates, coccolithophores, and tintinnids (<0.1%) were encountered in the samples collected from the lagoon and adjacent open sea (Figure 3). Diatoms (Bacillariophyceae) and dinoflagellates (Dinophyceae) were further investigated in this study. Both in the lagoon and in the open sea, the highest phytoplankton abundances were found during the south-west monsoon followed by the spring inter-monsoon (Figure 4). During the latter period, bloom of phytoplankton was determined by an increase in the population of the dinoflagellate *Noctiluca scintillans* in May at both sites. The lowest phytoplankton abundance was recorded during the north-east monsoon period at both collection sites. A total of 65 species of diatoms and 32 species of dinoflagellates were identified in the lagoon (Table 3). In the open sea, 63 species of diatoms and 23 species of dinoflagellates were found (Table 3). Some genera were represented by a large number of species, while others were represented by only 1 or 2 species (Table 3). Most species of diatoms and dinoflagellates were common at both sites. In the lagoon, the main genera were *Ceratium* (20 species), *Rhizosolenia* (12 species), *Chaetoceros* (9 species), *Nitzschia* (9 species), *Peridinium* (8 species), and *Coscinodiscus* (7 species). In the open sea, the main genera were *Ceratium* (13 species), *Rhizosolenia* (11 species), *Coscinodiscus* (8 species), *Chaetoceros* (7 species), *Nitzschia* (6 species), and *Peridinium* (6 species). Species specifically found in the lagoon included *Gossleriella tropica*, *Navicula* sp., *Gonyaulax polyedra*, and *G. monocantha*, while *Cyclostephanos dubius*, *Druridgea* sp., *Bacteriastrum* sp., and *Diplopsalis* sp. were specific to the open sea (Table 3).

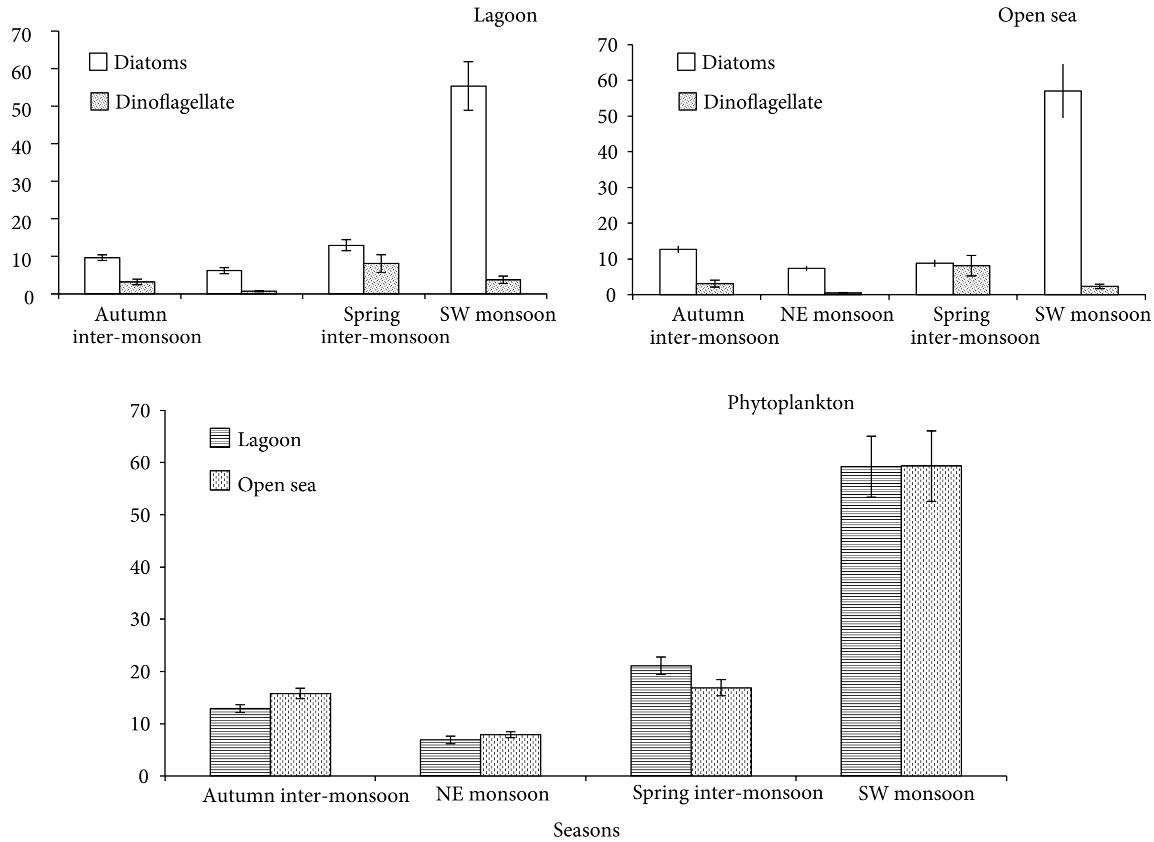

Figure 4. Seasonal abundance of total population of diatoms and dinoflagellates in the Miani Hor Lagoon and adjacent open sea.

Table 3. List of phytoplankton species found in the Maini Hor Lagoon and adjacent open sea during the period from September 2003 to August 2004.

Taxa	Lagoon	Open sea
Bacillariophyceae		
Coscinodiscus radiatus Ehrenberg	+	+
C. marginatus Ehrenberg	+	+
C. jonesianus (Greville) Ostenfeld	+	+
C. lineatus Ehrenberg	-	+
C. nodulifer A.W.F.Schmidt	+	+
C. nitidus W.Gregory	+	+
C. subtilis Ehrenberg	+	+
C. excentricus Ehrenberg	+	+
Gossleriella tropica Schutt	+	-
Hemidiscus sp. Wallich	+	+
Actinocyclus octonarius Ehrenberg	+	+
Cyclotella comta (Ehrenberg) Kutzing	+	+
Cyclostephanos dubius (Hustedt) Round	-	+
Lauderia annulata Cleve	+	+
Melosira moniliformis (O.F.Muller) C.Agardh	+	+
Druridgea sp. De Toni	-	+
Hyalodiscus radiatus (O'Meara) Grunow	+	+

Table 3. (Continued).

Species	Lagoon	Open sea
Podosira stelliger (J.W.Bailey) A.Mann	+	+
Dactyliosolen sp. Castracane	+	+
Guinardia flaccida (Castracane) H.Peragallo	+	+
Leptocylindricus danicus Cleve	+	+
Corethron sp. Castracane	+	+
Rhizosolenia robusta G.Norman ex Ralfs	+	+
R. styliformis Brightwell	+	+
R. castracani H.Peragallo	+	-
R. firma G.H.H.Karsten	+	+
R. shrubsolei Cleve	+	+
R. stolterfothii H.Peragallo	+	+
R. fragilissima Bergon	+	+
R. cylindrus Cleve	-	+
R. imbricata Brightwell	-	+
R. calcar avis Schultze	+	+
R. setigera Brightwell	+	+
R. crassispina Schroeder	+	+
R. alata Brightwell	+	-
R. hebetata J.W.Bailey	+	-
Biddulphia mobiliensis (J.W.Bailey) Grunow	+	+
B. granulata Roper	+	+
Hemiaulus membranaceus Cleve	+	+
H. sinensis Greville	+	+
Anaulus sp Ehrenberg	+	+
Cerataulina pelagica (Cleve) Hendey	+	+
Cerataulina sp. H.Peragallo ex Schütt	-	+
Eucampia zodiacus Ehrenberg	+	+
E. cornuta (Cleve) Grunow	+	+
Odontella regia (Schultze) Simonsen	+	+
Chaetoceros curvisetus Cleve	+	+
C. teres Cleve	-	+
C. brevis F.Schütt	+	-
C. eibenii Grunow	+	-
C. externus Gran	+	+
C. mitra (J.W.Bailey) Cleve	+	+
C. decipiens Cleve	+	+
C. costatus Pavillard	+	+
C. diversus Cleve	+	+
C. constrictum Gran	+	-
Bacteriastrum sp. Shadbolt	-	+
Ditylum brightwellii (T.West) Grunow	+	+
Thalassionema nitzschioides (Grunow) Mereschkowsky	+	+
Navicula sp. Bory	+	-
Pleurosigma acutum Norman ex Ralfs	+	+
P. olescurium	+	+
P. tenuissimum W.Smith	+	+
P. affine Grunow	-	+
P. spencerii (Bailey ex Quekett) W.Smith	-	+

Table 3. (Continued).

Species	Lagoon	Open sea
P. littorale W.Smith	+	-
Nitzschia socialis Gregory	+	-
N. distans Gregory	+	-
N. linearis W.Smith	+	-
N. sigma (Kützing) W.Smith	+	+
N. angularis W.Smith	+	+
N. ventricosa Kitton	+	+
N. obtusa W.Smith	+	+
N. insignis Gregory	+	+
N. seriata P.T.Cleve	+	+
Dinophyceae		
Ceratium furca var. *furca-eugrammum* Sournia	+	+
C. fusus var. *seta* (Ehrenberg) Sournia	+	+
C. longirostrum Gourret	+	+
C. breve var. *parallelum*	+	+
C. extensum (Gourret) Cleve	+	+
C. belone Cleve	+	+
C. dens Ostenfeld & Schmidt	+	-
C. lunula Schimper ex Karsten	+	+
C. kofoidii Jorgensen	+	-
C. falcatum (Kofoid) E.G.Jorgensen	+	-
C. trichoceros (Ehrenberg) Kofoid	+	+
C. massiliense var. *massiliense* Sournia	+	+
C. horridum var. *buceros* (Zacharias) Sournia	+	-
C. tripose var. *atlanticum* Ostenfeld	+	+
C. declineatum Karsten	+	-
C. deflexum (Kofoid) Jorgensen	+	+
C. contortum (Gourret) Cleve	+	+
C. contrarium (Gourret) Pavillard	+	+
Ceratium sp.	+	-
Peridinium depressum Bailey	+	+
P. conicum (Gran) Ostenfeld & Schmidt	+	+
P. truncatum H.W.Graham	+	-
P. oceanicum VanHoffen	+	+
P. granii Ostenfeld	+	+
P. pentagonum Gran	+	+
P. hirobis Abe	-	+
P. steinii Jorgensen	+	-
P. oblongum (Aurivillius) Cleve	+	-
Diplopsalis sp. Bergh	-	+
Dinophysis miles Cleve	+	+
D. caudata Saville-Kent	+	+
Gonyaulax polyedra (*Lingulodinium polyderum*) (Stein) Dodge	+	-
G. monacantha Pavillard	+	-
Noctiluca scintillans Macartney	+	+

Abbreviations: + present, - absent.

In the lagoon, diatoms were significantly correlated with salinity (r = –0.802; P = 0.003), but not with temperature (r = 0.548; P = 0.081) (Table 4). In the open sea, correlations between diatoms and salinity (r = –0.683; P = 0.020) and between diatoms and temperature (r = 0.649; P = 0.031) were both statistically significant. Dinoflagellates and chlorophyll-a showed statistically significant correlations in the lagoon (r = 0.894; P = 0.001) and in the open sea (r = 0.920; P = 0.001). The other parameters, including oxygen, nitrite, nitrate, ammonium, and phosphate, showed no significant correlations with diatoms or dinoflagellates (Table 4).

3.3. Seasonal variation in phytoplankton abundance

During the autumn inter-monsoon, the population of phytoplankton was dominated by the diatoms *Coscinodiscus jonesianus* and *C. marginatus* (25.1%), followed by species of *Nitzschia* (13.4%) in the lagoon (Table 5; Figure 5). In the open sea, *Coscinodiscus radiatus* and *C. jonesianus* were the dominant forms, accounting for 28.3% of the total phytoplankton abundance, followed by *Anaulus* sp. (17.2%) and *Dinophysis miles* (16.5%). During the north-east monsoon period, species of *Coscinodicus* and *Buddulphia mobiliensis* were abundant at both sites; however, in the open sea, species of *Rhizosolenia* (15.6%) and *Hemidiscus* sp. (21.0%) were also found in relatively large numbers. During the spring inter-monsoon, the phytoplankton population was dominated by species of *Rhizosolenia* (32.6%) and the harmful marine dinoflagellate *Noctiluca scintillans* (27.7%) in the lagoon and by *Noctiluca scintillans* (42.1%) and species of *Coscinodiscus* (26.0%) in the open sea. During the south-west monsoon period, the dominant genus at both sites was *Coscinodiscus* (>50%) (Table 5; Figure 6).

3.4. Species richness and diversity

The average diversity index and evenness value recorded in the lagoon were 0.60 and 0.55, respectively, and in open

Table 4. Pearson's correlation between diatoms and dinoflagellates and various physical and chemical parameters in the Miani Hor Lagoon and open sea.

Locations		Diatoms	Dino.	Temp.	Salinity	Chl.-a	Oxygen	NO_2	NO_3	NH_4	PO_4
Lagoon											
Diatoms	Pearson Correlation	1.000	–0.130	0.554	–0.802**	–0.255	–0.423	0.404	0.150	0.117	–0.393
	Significance (2-tailed)		0.703	0.077	0.003	0.449	0.195	0.218	0.660	0.731	0.232
	N	11	11	11	11	11	11	11	11	11	11
Dinofla-gellates	Pearson Correlation	–0.130	1.000	0.369	–0.147	0.894**	0.098	0.065	–0.188	0.029	0.594
	Significance (2-tailed)	0.703		0.263	0.665	0.001	0.775	0.850	0.579	0.933	0.054
	N	11	11	11	11	11	11	11	11	11	11
Open sea											
Diatoms	Pearson Correlation	1.000	–0.309	0.649*	–0.683*	–0.122	–0.382	–0.129	0.170	–0.229	0.244
	Significance (2-tailed)		0.355	0.031	0.020	0.722	0.246	0.704	0.618	0.499	0.469
	N	11	11	11	11	11	11	11	11	11	11
Dinoflag-ellates	Pearson Correlation	–0.309	1.000	0.168	0.119	0.920**	–0.162	–0.216	–0.097	–0.175	–0.023
	Significance (2-tailed)	0.355		0.622	0.727	0.001	0.634	0.524	0.777	0.608	0.946
	N	11	11	11	11	11	11	11	11	11	11

Abbreviations: Dino. = Dinoflagellates; Temp. = Temperature; Chl.-a = Chlorophyll-a **Correlation is significant at the 0.01 level,
*Correlation is significant at the 0.05 level.

Table 5. Seasonal changes in the dominant phytoplankton in the Miani Hor Lagoon and adjacent open sea.

Seasons	Miani Hor Lagoon	Adjacent open sea
Autumn inter-monsoon	*Coscinodiscus jonesianus*, *C. marginatus*, *Cyclotella comta*, *Anaulus* sp., *Nitzschia obtusa*, *N. seriata*, *N. angularis*, *Ceratium furca* var. *furca-eugrammum*, *Dinophysis miles*	*Coscinodiscus radiatus*, *C. jonesianus*, *Cyclotella comta*, *Biddulphia mobiliensis*, *Anaulus* sp., *Dinophysis miles*
North-east monsoon	*Coscinodiscus jonesianus*, *C. nodulifer*, *C. nitidus*, *Biddulphia mobiliensis*	*Coscinodiscus radiatus*, *C. jonesianus*, *Hemidiscus* sp., *Rhizosolenia robusta*, *R. styliformis*, *R. stolterfothii*, *Biddulphia mobiliensis*
Spring inter-monsoon	*Rhizosolenia robusta*, *Noctiluca scintillans*, *Nitzschia angularis*, *N. seriata*, *Ceratium fusus* var. *seta*	*Coscinodiscus jonesianus*, *C. nitidus*, *Rhizosolenia styliformis*, *R. firma*, *R. stolterfothii*, *Noctiluca scintillans*, *Ceratium fusus* var. *seta*
South-west monsoon	*Coscinodiscus nitidis*, *C. radiatus*, *C. marginatus*, *C. jonesianus*, *Rhizosolenia robusta*, *R. firma*, *Chaetoceros mitra*, *C. diversus*, *C. decipiens*	*Coscinodiscus jonesianus*, *C. nitidis*, *C. radiatus*, *C. marginatus*, *C. lineatus*, *Chaetoceros mitra*, *C. diversus*, *C. constrictus*

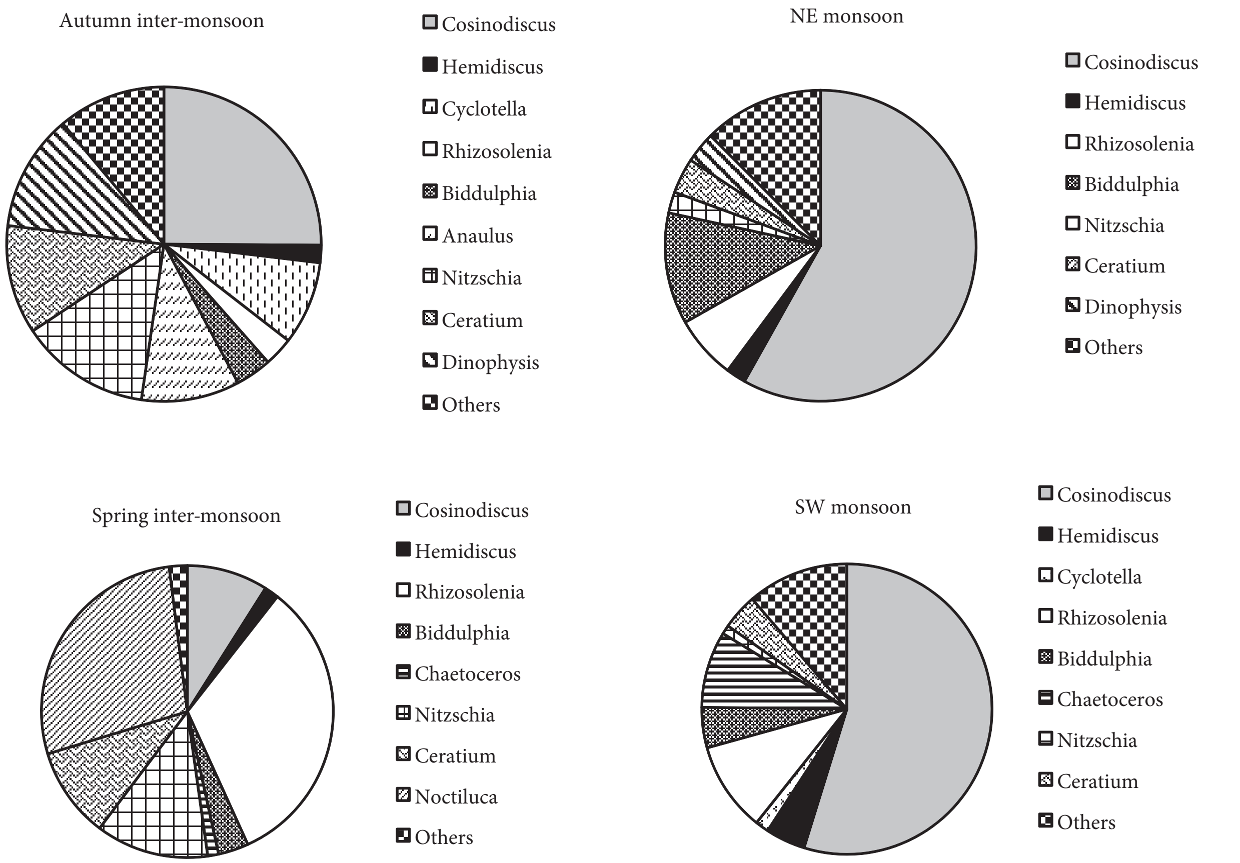

Figure 5. Seasonal abundance of phytoplankton genera in the Miani Hor Lagoon.

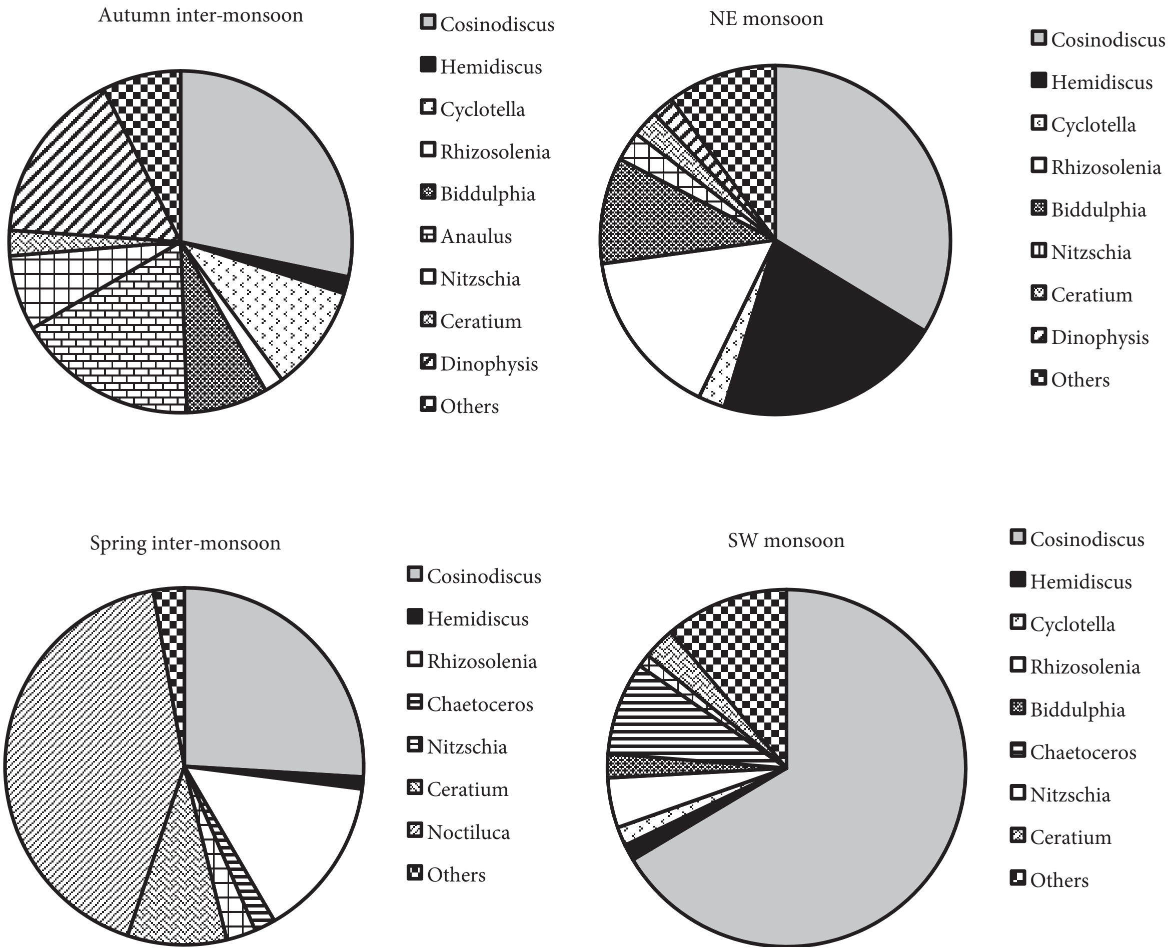

Figure 6. Seasonal abundance of phytoplankton genera in the open sea.

sea were 0.58 and 0.54, respectively. The diversity index ranged between 0.23 and 0.96 and evenness index between 0.28 and 0.79 in the lagoon (Figure 7). The diversity and evenness index ranged between 0.22 and 0.92 and between 0.21 and 0.76, respectively, in the open sea (Figure 7). There was a significant correlation (Pearson's) between diversity index and evenness index in the Miani Hor Lagoon ($r = 0.969$; $P < 0.001$; $n = 11$) and in the open sea ($r = 0.937$; $P < 0.001$; $n = 11$). However, there was no significant correlation ($r = 0.599$; $P > 0.05$; $n = 11$) between species diversity index and species richness in the lagoon, while in the open sea this relationship was significant ($r = 0.633$; $P < 0.05$; $n = 11$). There was no significant correlation ($P > 0.05$) between evenness index and species richness at either site.

4. Discussion

In the present study, 98 phytoplankton species of Bacillariophyceae (diatoms) and Dinophyceae (dinoflagellates) were recorded from the Miani Hor Lagoon and 85 species in the open sea. Diatom species were more diverse and abundant compared to dinoflagellates. The phytoplankton composition in the lagoon and open sea was dominated by diatoms. The peak in diatom abundance occurred during the south-west monsoon period, whereas dinoflagellates were more abundant during the spring inter-monsoon. Solak et al. (2012), while studying the diatoms from Felent Creek, Turkey, reported that species richness was mostly higher in winter than in summer. To date, no information has been reported about the phytoplankton composition and abundance in the Maini Hor Lagoon and the adjacent open sea; therefore, the present observations form a baseline for future study in this area of the North Arabian Sea.

The highest abundance of phytoplankton was recorded during the south-west monsoon (May–September), followed by the spring inter-monsoon (March–April). A number of studies have reported such phytoplankton abundance during the south-west monsoon season, along the south-west coast of India (Rajagopalan et al., 1992), in the coastal waters of south Kanara in India (Prabhu & Reddy, 1987), and in waters of the Indo-Pakistan shelf

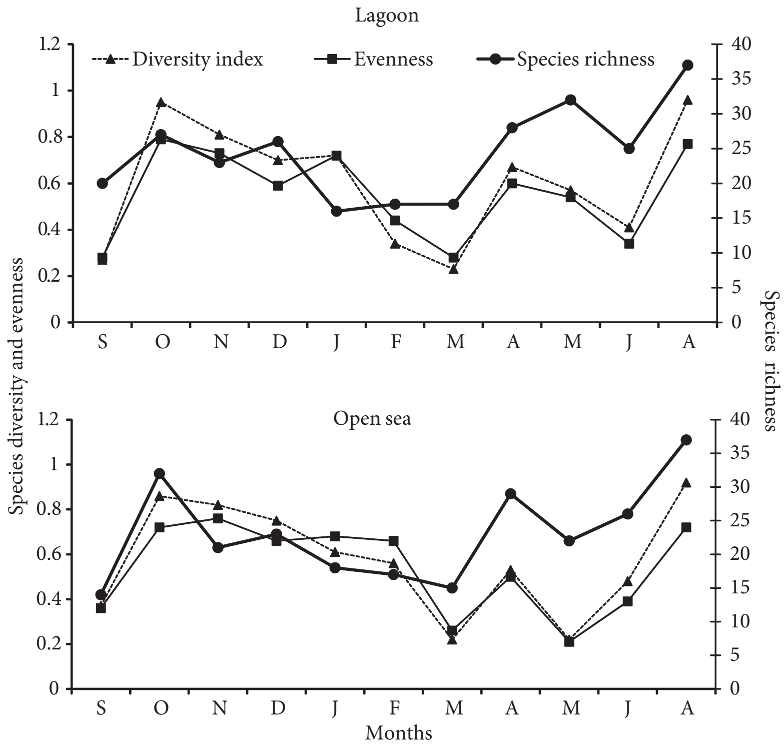

Figure 7. The species diversity and evenness index and species richness in the Miani Hor Lagoon and open sea during the period from September 2003 to August 2004.

(Kuz'-menko, 1977). Brock and McClain (1992) reported an increased concentration of phytoplankton from May through September along the Omani coast in the north-western Arabian Sea that extended into the open sea by upward nutrient fluxes forced by coastal upwelling and offshore Ekman pumping. Two periods of elevated phytoplankton productivity, one during the north-east monsoon (November–February) and the other during the south-west monsoon (June–September), were reported on the west coast of India (Parab et al., 2006).

The spring inter-monsoon bloom of phytoplankton in the present study may be related to temperature, which suddenly increased in March–April (28 °C) compared to lower average temperature (22.3 °C) during the north-east monsoon in December–February. Recent studies reported that algal bloom in the North Arabian Sea develops every year during February–March and this was correlated to north-easterly trade winds and sea surface temperatures (Sarangi et al., 2005; Dwivedi et al., 2006). Brock et al. (1994) showed that the maxima of phytoplankton production in the North Arabian Sea occur during both summer and winter monsoons, which are separated by low production during autumn and spring inter-monsoons. However, this mixed layer primary production differed by region in the Arabian Sea due to varying monsoon influence and circulation dynamics.

In the present study, the low phytoplankton biomass and high nitrate concentrations during the autumn inter-monsoon suggest that active grazing populations may be responsible for preventing diatom/dinoflagellate populations from flourishing in the area. This study is similar to the study by Parab et al. (2006) from the west coast of India (eastern Arabian Sea) where low phytoplankton biomass and high ammonium concentrations indicated that active grazing populations may be responsible for preventing the phytoplankton populations from blooming in the area during the early north-east monsoon. Similarly, Goericke (2002) concluded that phytoplankton biomass in the monsoonal Arabian Sea was not limited by the availability of inorganic nutrients but controlled by the grazers. Furthermore, Goericke (2002) supported the hypothesis that phytoplankton abundance and community structure in the high-nutrient low-chlorophyll areas of the monsoonal Arabian Sea are controlled by top-down forces (i.e. grazing) rather than bottom-up forces (i.e. availability of nutrients).

Diversity is dependent on key ecological processes such as competition, predation, and succession, and therefore changes in these processes can alter the species diversity index through changes in evenness (Stirling & Wilsey, 2001). The species diversity index of plankton communities in estuaries can serve as an indicator that the ecosystem is under the influence of pollution stress or eutrophication (Telesh, 2004). Lower species Shannon-Wiener diversity index values (ranging from 0.23 to 0.96) in the lagoon indicated that the area is under the influence of pollution. Similarly, the low species diversity index in the open sea adjacent to the Miani Hor Lagoon showed that this open water is under the influence of lagoon water and that the domestic waste waters entering the lagoon have now spread to the adjacent open sea. Similarly, Balloch et al. (1976) recognised the Shannon-Wiener diversity index as a suitable indicator for water quality and Wu (1984) also established that the value of diversity index of a community in less polluted waters would be higher. However, a low species diversity index also showed that there is domination by a few species in the area (Margalef, 1978), which is evident in our study where several species were present but were dominated by a small number species. Our analysis showed a significant correlation between diversity index and evenness but the relationship between species richness and the diversity index was not so significant. This relationship is similar to that in the study by Reed (1978), who found that diversity indices were closely related to evenness, whereas species numbers (richness) were unimportant in determining species diversity for plankton and microbenthos.

Additional surveys of the seasonal phytoplankton abundance in the inshore and offshore waters of the North Arabian Sea along the coast of Pakistan are needed to better understand the dynamics of phytoplankton in this area.

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