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Spatio-temporal variations of phytoplankton assemblage in coastal waters of Maharashtra, north-eastern Arabian Sea

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ABSTRACT

Seasonal variations in phytoplankton species and abundance along the coast of Maharashtra from two different locations (Mumbai and Ratnagiri) and depths were investigated during August 2014-May 2017. A total of 84 species of phytoplankton were recorded from the region out of which 67 were diatoms, 16 dinoflagellates and one blue green alga. Seventy-five and 60 species of phytoplankton were recorded from Ratnagiri and Mumbai respectively. Diatoms dominated the phytoplankton community (81.7-93.3%) followed by dinoflagellates (4.7-7.2%) and blue green algae in both locations. Maximum phytoplankton density was recorded during post-monsoon season followed by pre-monsoon and monsoon seasons at Mumbai and Ratnagiri. Highest average phytoplankton cell density recorded was 9.09×10^4 cells l^{-1} and 4.06×10^4 cells l^{-1} during post-monsoon season at Ratnagiri and Mumbai respectively. Maximum cell density was observed at 20 m depth from Mumbai and Ratnagiri. *Thalassiosira subtilis*, *Trieres mobiliensis*, *Skeletonema costatum*, *Coscinodiscus centralis* and *Ditylum brightwelli* were the most abundant phytoplankton species recorded at Mumbai, whereas *Chaetoceros curvisetus*, *S. costatum*, *Trichodesmium erythraeum*, *Chaetoceros lorenzianus* and *Ditylum brightwelli* were abundant in Ratnagiri waters. The blue green alga, *T. erythraeum* was abundantly recorded during pre-monsoon season. Species diversity index (H') ranged from 4.72 to 5.52 and was higher during post-monsoon season compared to pre-monsoon and monsoon. Highest phytoplankton diversity was observed at 20 m depth compared to 40 m depth.

Keywords: Arabian Sea, Diversity, Mumbai, Phytoplankton, Ratnagiri

Introduction

Arabian Sea is one of the most sensitive ecosystems, playing a crucial role in regulation of earth's climate and atmospheric chemical composition through biogeochemical ocean-atmosphere transfers (Naqvi and Jayakumar, 2000). The north-eastern coast of Arabian Sea is a complex, dynamic and biologically productive ocean system. Phytoplankton abundance and biomass fluctuations in north-eastern Arabian Sea are intensely linked to strong winds blowing during south-west and north-east monsoons. The south-west monsoon (summer monsoon, May to September) is the time of an equatoward current along the west coast of India resulting in upwelling phenomenon (Shetye *et al.*, 1990). This wind driven upwelling in northeastern Arabian Sea during summer monsoon results in rapid isotherm movements and cooling of surface waters (Banse and English, 1993, 2000; Madhupratap *et al.*, 1996; Kumar *et al.*, 2001a; Smitha *et al.*, 2008) driving nutrient rich water into the euphotic zone (Banse, 1987). Due to the high degree of seasonality in the physico-chemical environment and abundance of phytoplankton, the primary producers of marine food chain in Arabian Sea, are subjected to the semi-annual reversal of monsoon winds and coastal currents (Dwivedi *et al.*, 2006; Naqvi *et al.*, 2006).

Ocean margins including continental shelf and adjacent slope waters are highly productive, contributing 25-50% of total oceanic primary production (Walsh, 1988). Biological productivity of coastal waters marked by increased phytoplankton growth, chlorophyll-*a* and gross primary productivity, is greatly influenced by denser nutrient-rich water brought to the surface during upwelling (Kumar *et al.*, 2001a; Habeebrehman *et al.*, 2008). Aquatic organisms including zooplankters, fishes and heterotrophic aquatic organisms sustain on phytoplankton for their energy needs and thus phytoplankton becomes an important component of the food chain as primary producers (Price, 2001; Tas and Gonulol, 2007; Essien and Antai, 2008; Saravanakumar *et al.*, 2008; Bharali *et al.*, 2010). These primary producers support marine fisheries and fishery potential predictions (Falkowski *et al.*, 1998; Mathivanan *et al.*, 2007).

Spatiotemporal variations in phytoplankton species distribution occurs due to hydrographical factors and indicates water quality of the environment (Liu *et al.*, 2004). Due to their sensitivity and rapid response to the changed environmental conditions, phytoplankton composition and abundance are considered as natural bio-indicators of water quality (Gharib *et al.*, 2011). Considering frequent variations in environmental parameters, studies on phytoplankton community structure, changes in their spatio-temporal distribution, abundance and diversity are indicators of environmental health and biological integrity (Hardikar *et al.*, 2017). Phytoplankton diversity represents health and productivity of an aquatic ecosystem and monsoon events occurring along Indian coast greatly influence phytoplankton diversity (D'Costa and Anil, 2010; Satpathy *et al.*, 2010). Magurran (1988) stated that phytoplankton diversity studies are essential to understand community structure, stability and resilience of community against impairments. Additionally, biological productivity of nearshore waters is also influenced by freshwater influx from major riverine systems, dense urbanisation and agricultural and industrial runoffs transporting nutrient rich organic matter to the Arabian Sea.

Coastal areas along the 720 km Maharashtra coast are gaining importance due to rapid urbanisation, industrialisation and developmental activities, causing damage to the marine ecosystem and diversity. These activities decrease resilience of coastal ecosystems and their vulnerability to anthropogenic pressures and climate change effects increases (Bijlsma *et al.*, 1995). Mumbai is a developing, densely populated and urbanised settlement on the northern part of Maharashtra coast, intensively exposed to sewage and anthropogenic effluents, whereas Ratnagiri is a developing city on the southern coast of Maharashtra. However, Ratnagiri is also developing as a hub for industrial activities. Both locations are of utmost importance due to major fishing activities concentrated along north-west coast of India. Though several researchers have studied phytoplankton diversity in nearshore waters along the coast of Maharashtra in earlier years (Nair *et al.*, 1980; Ramaiah and Ramaiah, 1998; Tiwari and Nair, 1998; 2002; Kumar *et al.*, 2015a; b; Shahi *et al.*, 2015; Hardikar *et al.*, 2017; Khot *et al.*, 2018) the variability of phytoplankton in the coastal waters of Maharashtra is poorly recorded. Hence the aim of the study was to look into phytoplankton abundance, diversity and seasonal variation in phytoplankton community composition in coastal waters off Mumbai and Ratnagiri.

Materials and methods

Study area and sampling strategy

The present investigation was conducted at Mumbai and Ratnagiri along Maharashtra coast, north-eastern Arabian Sea. Fig. 1 depicts two depth contour stations, at each location selected for sampling, Mumbai 20 m (18°51'49.2"N 72°41'31.1"E), Mumbai 40 m (18°55'38.9"N 72°32'36.9"E), Ratnagiri 20 m (17°03'26.3"N 73°12'43.3"E) and Ratnagiri 40 m (17°03'59.7"N 73°06' 48.7"E).

Samples from Ratnagiri waters were collected during August 2014-May 2017 from onboard *M. F. V. Narmada* and from Mumbai waters during January 2015-May 2017 from onboard *M. F. V. Vaishnavi Mata*. Sampling was not done during June and July due to rough sea conditions and seasonal fishing ban along the west coast. Data was compiled and analysed season-wise: post-monsoon (POM: October to January), monsoon (MON: August to

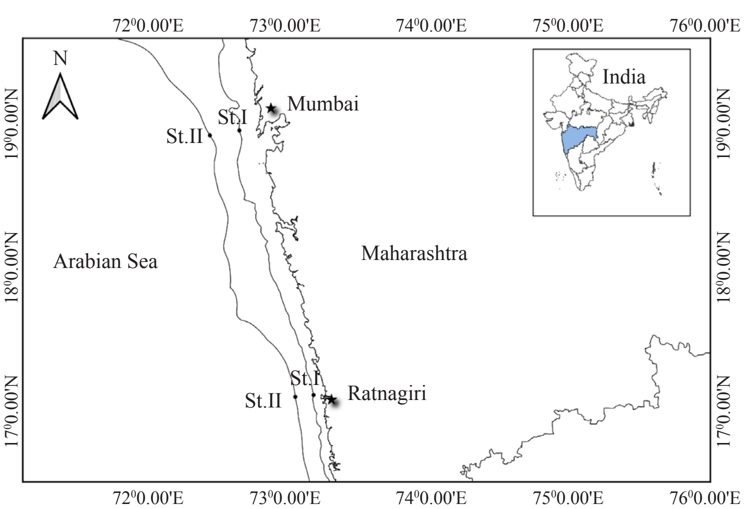

Fig. 1. Map showing sampling locations off Mumbai and Ratnagiri

September) and pre-monsoon (PRM: February to May) (Srinath *et al*., 2003).

Phytoplankton sample collection and analysis

Phytoplankton samples at each location were collected from surface using phytoplankton net (mesh size 50 µ). The net was towed from the fishing vessel and filtered phytoplankton biomass was preserved onboard using 1% Lugol's iodine solution and 4% formalin until analysis (Robin *et al*., 2010; Karthik *et al*., 2012).

Phytoplankton samples collected were allowed to settle and 1 ml of concentrated sample was examined under inverted binocular microscope using Sedgewick rafter cell. Total phytoplankton cell density was expressed in cell numbers per liter (Latif *et al*., 2013; Minu *et al*., 2014). Taxonomic identification to species level for phytoplankton recorded during the study was done following published literature (Venkataraman, 1939; Subrahmanyan, 1946; Desikachary, 1959; Gopinathan, 1984; Desikachary and Sreelatha, 1989; Tomas *et al.*, 1997; Al-Kandari *et al.*, 2009). Scientific nomenclature of phytoplankton species recorded was revised as per Algaebase (Guiry and Guiry, 2020).

Hydrobiological analysis

In situ water parameters *viz*, sea surface temperature, pH, salinity, turbidity and total dissolved solids were recorded onboard during phytoplankton sample collection. Multiparameter (WTW 320 i) and Eutech Cyberscan water testing meter were used for recording sea surface temperature, pH, salinity and total dissolved solids. Turbidity was recorded using Eutech (TN-100) turbidity meter. Dissolved oxygen was estimated following Winkler's titration (APHA, 2005). Chlorophyll-a was estimated using acetone extraction method (APHA, 2005).

Statistical analysis

Phytoplankton community structure and variations in season-wise and depth-wise phytoplankton cell density were analysed using MS-Excel. To evaluate difference in phytoplankton abundance among seasons and depths, one-way ANOVA was done using SPSS (version 25).

Univariate diversity indices Shannon-Weiner Diversity Index (H'), Margalef's species richness index (d), Pielou's evenness (J') and Simpson Dominance Index (1- λ') with respect to phytoplankton abundance among depth and seasons at both locations were analysed using PRIMER v7 (Clarke and Gorley, 2015).

$$H' = \Sigma[(pi) * \log(pi)]$$

$$d = (S-1) / \log N$$

$$J' = H' / \log_2 S$$

$$1 - \lambda' = 1-\sum ni (ni - 1) / N (N-1)$$

where, 'S' is the total number of species, 'N' is the total number of individuals of all species in the sample, 'ni' is the number of individuals of a species in the sample and Pi = ni/N proportion of the sample for the i^{th} species. K-dominance plot, Bray-Curtis Similarity and SIMPER were figured based on square root transformed data using Primer v7. Cluster analysis using complete linkage method was performed based on Bray Curtis similarity to determine similarities in plankton occurrence among sampling stations and seasons. Similarity in species between Mumbai and Ratnagiri and identification of discriminating species were studied from similarity percentage (SIMPER) analysis.

Results

Hydrobiological parameters

Seasonal variations in hydrobiological parameters of water samples collected during the present study are presented in Table 1. Average sea surface temperature ranged from 25.00 to 31.80ºC and 26.00 to 32.50ºC, at Mumbai and Ratnagiri respectively. Highest sea surface temperature was observed during PRM season compared to POM and MON seasons. pH values ranged between 7.34 and 8.33 at Mumbai and between 7.42 and 8.45 at Ratnagiri. Highest pH was observed at Ratnagiri during PRM season. Seasonal variation in pH values was observed and lower pH was observed during MON. Salinity varied from 29.20 to 36.80 ppt during the study. Comparatively higher salinity values were observed at Mumbai during PRM season. Lowest salinity values were observed during MON season at Mumbai and Ratnagiri. Dissolved oxygen content ranged between 3.95 and 6.10 mg l^{-1} at Mumbai whereas at Ratnagiri DO values varied between 3.88 and 6.40 mg l^{-1}. Highest dissolved oxygen values were recorded during PRM season compared to POM and MON seasons at Mumbai and Ratnagiri. Chlorophyll-*a* showed seasonal variation at Mumbai and Ratnagiri. Higher chlorophyll-*a* concentrations were observed during POM season. At Mumbai, chlorophyll-*a* ranged from 1.35 to 5.37 mg C m^{-3} which were slightly lower than chlorophyll-*a* concentration observed at Ratnagiri (1.90 to 6.00 mg C m^{-3}). Highest turbidity and total dissolved solids content were observed during MON followed by PRM and POM seasons at Mumbai and Ratnagiri.

Phytoplankton species composition

A total of 84 species of phytoplankton belonging to 32 orders, 41 families and 54 genera were identified (Table 2). Out of these, 67 species were diatoms (Classes Bacillariophyceae, Coscinodiscophyceae and Mediophyceae), 16 were dinoflagellates (Classes Dinophyceae and Noctilucoohyceae) and one species of blue green alga (Class Cyanophyceae). Diatom species

Table 1. Seasonal variations in the physico-chemical characteristics (Mean±SE) at Mumbai and Ratnagiri during the study period

Location	Depth (m)	Season	SST	pH	SAL	DO	CHL	TDS	TBD
Mumbai	20 m	MON	28.65±0.56	7.92±0.10	31.30±1.14	4.61±0.34	3.78±0.28	40.57±2.68	10.71±3.11
		POM	28.01±0.63	8.01±0.08	33.92±0.30	4.84±0.16	4.16±0.29	33.09±3.53	6.72±0.96
		PRM	28.67±0.58	8.09±0.07	35.18±0.23	5.12±0.12	3.82±0.31	31.08±3.78	7.95±0.93
	40 m	MON	29.00±0.52	7.96±0.15	32.58±0.65	4.86±0.33	3.15±0.12	42.75±3.16	8.55±3.02
		POM	27.86±0.64	8.03±0.09	34.40±0.21	5.05±0.20	3.43±0.23	27.86±3.53	5.04±0.74
		PRM	29.31±0.59	8.11±0.08	35.39±0.25	5.14±0.19	3.38±0.30	30.75±3.53	6.49±1.42
Ratnagiri	20 m	MON	28.13±0.30	8.10±0.13	30.89±0.57	4.41±0.20	3.07±0.14	30.04±3.43	5.37±0.62
		POM	28.51±0.37	8.11±0.04	33.59±0.21	5.32±0.09	4.30±0.27	25.16±2.55	2.45±0.27
		PRM	30.24±0.46	8.13±0.06	34.79±0.19	5.78±0.09	3.76±0.20	27.37±3.21	3.58±0.58
	40 m	MON	27.58±0.31	8.07±0.14	31.53±0.50	4.67±0.22	2.29±0.13	29.14±2.99	4.14±0.86
		POM	28.19±0.45	8.11±0.05	34.13±0.18	5.37±0.09	3.86±0.16	25.75±1.78	2.13±0.39
		PRM	30.18±0.44	8.15±0.05	35.18±0.19	5.99±0.09	3.01±0.24	28.39±3.09	2.75±0.45

Table 2. Depth-wise occurrence of phytoplankton species recorded off Mumbai and Ratnagiri

Species	Mumbai 20 m	Mumbai 40 m	Ratnagiri 20 m	Ratnagiri 40 m
Amphiprora alata	+	+	+	-
Amphora angusta	+	+	-	-
Ardissonea formosa	+	+	-	-
Asterionellopsis glacialis	+	+	+	+
Asteromphalus flabellatus	-	-	+	+
Bacteriastrum delicatulum	+	+	+	+
Bacteriastrum hyalinum	+	+	+	+
Bellerochea malleus	+	+	+	-
Biddulphia biddulphiana	+	-	-	-
Cerataulina bergonii	+	+	-	-
Chaetoceros affinis	+	+	+	+
Chaetoceros coarctatus	+	+	+	+
Chaetoceros curvisetus	+	+	+	+
Chaetoceros decipiens	+	+	+	+
Chaetoceros diversus	-	-	+	+
Chaetoceros lorenzianus	+	+	+	+
Corethron hystrix	-	-	+	-
Coscinodiscus centralis	+	+	+	+
Coscinodiscus marginatus	+	+	+	-
Coscinodiscus radiatus	+	+	+	+
Cyclotella striata	+	+	+	+
Cylindrotheca closterium	+	+	-	-
Ditylum brightwellii	+	+	+	+
Eucampia zodiacus	+	+	+	+
Fragilariopsis oceanica	+	+	+	+
Grammatophora oceanica	-	-	+	+
Guinardia flaccida	+	+	+	+
Guinardia striata	-	-	+	-
Gyrosigma balticum	+	+	+	+
Helicotheca tamesis	-	-	+	+
Hemiaulus hauckii	-	-	+	+
Hemiaulus membranaceus	-	-	+	+
Hemiaulus sinensis	+	+	-	-

Contd............

Species	Mumbai 20 m	Mumbai 40 m	Ratnagiri 20 m	Ratnagiri 40 m
Lampriscus shadboltianum	-	-	+	+
Lauderia annulata	-	-	+	+
Leptocylindrus danicus	+	+	+	+
Licmophora abbreviata	+	+	+	+
Licmophora juergensii	-	-	+	+
Lyrella clavata	-	-	+	+
Melosira sulcata	-	-	+	+
Navicula directa	+	+	+	-
Navicula distans	+	+	+	+
Neocalyptrella robusta	+	+	+	+
Nitzschia longissima	+	+	+	+
Nitzschia sigma	+	+	+	+
Odontella aurita	-	-	+	+
Odontella sinensis	+	+	+	+
Planktoniella sol	+	+	+	+
Pleurosigma elongatum	+	+	+	+
Pleurosigma normanii	+	+	+	+
Proboscia alata	+	+	+	+
Pseudo-nitzschia seriata	+	+	+	+
Rhizosolenia imbricata	-	-	+	-
Rhizosolenia setigera	+	+	+	+
Rhizosolenia stolterfothii	-	-	+	+
Skeletonema costatum	+	+	+	+
Surirella fluminensis	+	-	+	-
Synedra ulna	+	+	+	-
Thalassionema frauenfeldii	+	+	+	+
Thalassionema nitzschioides	+	+	+	+
Thalassiosira decipiens	-	-	+	+
Thalassiosira eccentrica	+	+	+	+
Thalassiosira subtilis	+	+	+	+
Thalassiothrix longissima	+	+	+	+
Triceratium favus	-	-	+	-
Triceratium reticulatum	+	-	-	-
Trieres mobiliensis	+	+	+	+
Amphidinium carterae	+	+	-	-
Dinophysis caudata	+	+	+	+
Dinophysis miles	+	+	+	+
Noctiluca scintillans	-	-	+	+
Ornithocercus magnificus	-	-	+	-
Prorocentrum micans	+	+	+	+
Protoperidinium biconicum	+	+	-	-
Protoperidinium depressum	+	+	+	+
Protoperidinium oceanicum	-	-	+	+
Pyrophacus horologium	+	+	+	+
Pyrophacus steinii	-	-	+	-
Tripos brevis	+	+	+	+
Tripos furca	+	+	+	+
Tripos fusus	+	+	+	+
Tripos massiliensis	-	-	+	+
Tripos muelleri	-	-	+	+
Trichodesmium erythraeum	+	+	+	+

belonging to Class Mediophyceae (9 orders, 14 families, 19 genera) were dominant at all stations followed by diatoms of Class Bacillariophyceae (10 orders, 12 families, 17 genera). Among dinoflagellates, majority of the species recorded were from Class Dinophyceae represented by 5 orders, 6 families and 7 genera. Only one dinoflagellate, *Noctiluca scintillans* was recorded from Class Noctilucoohyceae. Depth-wise occurrence of phytoplankton species off Mumbai and Ratnagiri are given in Table 2.

At Mumbai, 60 phytoplankton species were recorded, out of which 49 were diatoms (19 orders, 26 families, 37 genera), 10 were dinoflagellates (5 orders, 6 families, 6 genera) and one was a blue green alga. Phytoplankton cell density varied between 1.62 to 6.47 x 10^4 cells l^{-1} recorded at 20 m depth and 0.58 to 3.84 x 10^4 cells l^{-1} at 40 m depth. Seasonal variations were observed with respect to phytoplankton cell density. High species count with cell density was observed during POM season with 56 species. Mean cell density of phytoplankton was high during POM season (4.06±0.50 x 10^4 cells l^{-1}) followed by PRM season (3.07±0.22 x 10^4 cells l^{-1}) and MON season (1.93±0.13 x 10^4 cells l^{-1}) at 20 m depth. Mean cell density of phytoplankton during POM, PRM and MON seasons was 2.25±0.36 x 10^4 cells l^{-1}; 1.59±0.15 x 10^4 cells l^{-1} and 0.71±0.07 x 10^4 cells l^{-1} respectively at 40 m depth station of Mumbai (Fig. 2).

Group-wise percentage composition of phytoplankton species is presented in Table 3. Diatoms were abundant throughout the year and trend of diatom abundance at 20 m depth was PRM>MON>POM whereas at 40 m depth station, trend of diatoms abundance was POM>MON>PRM. Dinoflagellates were abundant during POM and MON season compared to PRM season. One-way ANOVA revealed significant difference ($p<0.05$) in total cell density, diatoms, dinoflagellate and blue green alga density between 20 and 40 m depth stations. Highest phytoplankton cell density was recorded during POM when compared to MON season ($p<0.05$). One-way ANOVA revealed significant difference ($p<0.05$) in diatom cell density (POM and MON), dinoflagellate cell density (PRM, POM and MON) and blue green algae cell density (PRM and POM) among seasons.

Diatoms *T. subtilis*, *T. mobiliensis*, *S. costatum*, *C. centralis, D. brightwellii*, *Pseudo-nitzschia seriata, Chaetoceros lorenzinus, C. curvisetus*, *Coscinodiscus radiatus* and *Fragilariopsis oceanica* were abundant at Mumbai. *T. subtilis, T. mobiliensis* and *C. centralis* were abundant throughout all the seasons. *Leptocylindrus danicus* was prevalent during MON season and *S. costatum* was abundant during POM season and least observed during MON season. *Tripos furca* and *Dinophysis miles* were major dinoflagellate species contributing to the phytoplankton community structure at Mumbai. *T. erythraeum* was abundantly observed only during PRM season especially at 40 m depth stations during the present study.

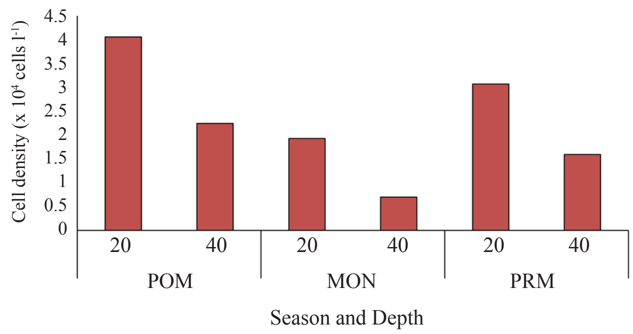

Fig. 2. Season-wise and depth-wise average phytoplankton cell density recorded at Mumbai

Table 3. Season-wise abundance (%) of phytoplankton groups recorded at each station

Mumbai	MON 20 m	MON 40 m	POM 20 m	POM 40 m	PRM 20 m	PRM 40 m
Bacillariophyceae	25.9%	26.2%	24.1%	20.5%	20.7%	19.4%
Coscinodiscophyceae	7.9%	8.5%	15.7%	13.9%	11.9%	9.7%
Mediophyceae	59.5%	58.9%	53.3%	60.6%	63.6%	57.5%
Dinophyceae	6.6%	6.4%	6.9%	5.0%	3.3%	2.0%
Noctilucoohyceae	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Cyanophyceae	0.0%	0.0%	0.0%	0.0%	0.5%	11.4%
Ratnagiri						
Bacillariophyceae	19.0%	23.7%	16.6%	20.2%	11.3%	17.0%
Coscinodiscophyceae	7.7%	6.8%	5.7%	7.8%	5.4%	7.2%
Mediophyceae	70.5%	65.9%	61.6%	57.7%	53.2%	54.7%
Dinophyceae	2.8%	3.6%	4.5%	6.8%	2.4%	4.6%
Noctilucoohyceae	0.0%	0.0%	2.7%	1.9%	6.2%	4.3.%
Cyanophyceae	0.0%	0.0%	8.8%	5.6%	21.4%	12.2%

Higher species richness was observed at Ratnagiri with 75 phytoplankton species recorded during the present study period. Among these, 60 were diatoms (29 orders, 38 families, 48 genera), 14 were dinoflagellates (5 orders, 6 families, 7 genera) and one, blue green alga.

Maximum mean cell density of phytoplankton was 7.79±0.60 x 10^4 cells l^{-1} recorded at 20 m depth station whereas mean cell density of phytoplankton was 1.84±0.18 x 10^4 cells l^{-1} at 40 m depth. Phytoplankton abundance varied between 0.81 x 10^4 (PRM in May at 40 m) and 17.57 x 10^4 cells l^{-1} (POM in November at 20 m). Average phytoplankton abundance at both depth stations depicted a trend as POM>PRM>MON (Fig. 3). Maximum mean cell density of phytoplankton was recorded at 20 m depth during POM season (9.09±1.32 x 10^4 cells l^{-1}) followed by PRM season (7.10±0.57 x 10^4 cells l^{-1}) and MON season (6.57±0.45 x 10^4 cells l^{-1}). Similarly, at 40 m depth highest mean cell density was recorded during POM season (2.43±0.32 x 10^4 cells l^{-1}) followed by PRM season (1.67±0.20 x 10^4 cells l^{-1}) and MON season (0.98±0.05 x 10^4 cells l^{-1}).

Diatoms dominated in all the seasons, showing maximum abundance during MON season followed by POM and PRM seasons (Table 3). Dinoflagellate cell density showed a trend as PRM (8.7%) > POM (7.5%) > MON (2.9%) in total phytoplankton biomass. However, dinoflagellates belonging to Class Dinophyceae were abundantly observed during POM followed by PRM and MON season. *N. scintillans* was abundant during PRM season and absent during MON season. Blue green alga was abundant during PRM season at both stations compared to POM season.

One-way ANOVA revealed significant difference ($p<0.05$) in total cell density, diatoms, dinoflagellate and blue green alga density among 20 and 40 m depth stations at Ratnagiri. No significant difference ($p>0.05$) was observed in total cell density and diatom cell density

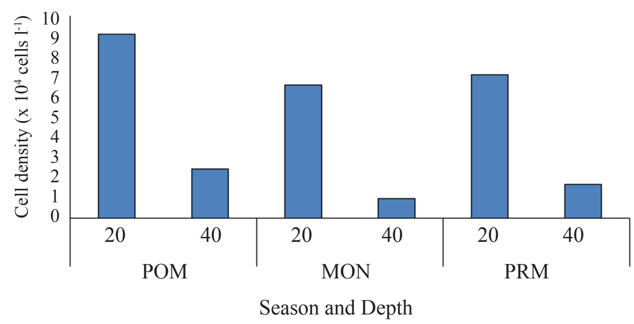

Fig. 3. Season and depth-wise average phytoplankton cell density recorded at Ratnagiri

among seasons. However, one-way ANOVA revealed significant difference in dinoflagellate cell density (PRM and MON) and blue green algae cell density (PRM and MON) among seasons.

C. curvisetus, S. costatum, T. erythraeum, C. lorenzianus, D. brightwellii, T. mobiliensis, P. seriata, F. oceanica, N. scintillans and *C. affinis* were the most abundant diatoms recorded at Ratnagiri during the present study. *N. scintillans* blooms were observed during PRM season off Ratnagiri. Dinoflagellates *T. furca* and *D. miles* were also abundant.

Species diversity indices

Univariate biodiversity indices estimated to understand variation between phytoplankton diversity and seasonal changes (Fig. 4) indicated similar pattern in Mumbai and Ratnagiri. Highest Shannon-Weiner diversity (H´), Margalef's species richness (d´) and Simpsons dominance (1-λ´) was observed during POM season followed by PRM and MON season.

Variations ($p<0.05$) in diversity indices among 20 and 40 m depth was observed at Mumbai and Ratnagiri. Highest diversity indices were recorded at 20 m depth stations at both places. Seasonal variation was recorded

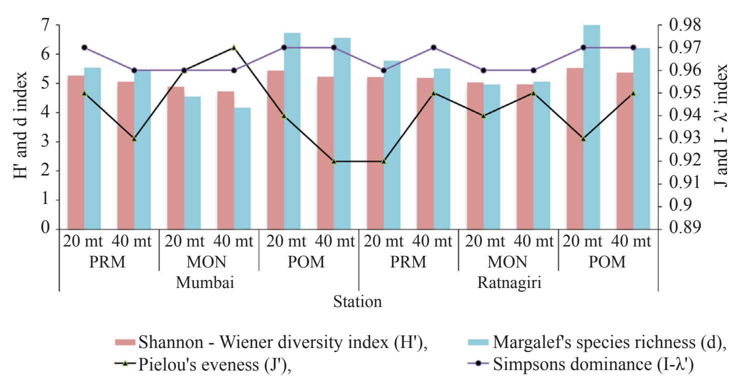

Fig. 4. Seasonal variations in diversity indices recorded during the present study

($p<0.05$) only for Pielou's evenness at Mumbai between PRM and MON. One way ANOVA revealed highest diversity at Ratnagiri during POM season ($p<0.05$) for Margalef's species richness, Shannon-Weiner diversity index and Simpson's dominance. Seasonal variation was not observed ($p>0.05$) for Pielou's eveness at Ratnagiri.

The cumulative dominance plots (Figs. 5 and 6) agree with the observations on species diversity indices. K-Dominance plot shows presence of maximum species diversity during POM season at 20 and 40 m depth stations at Mumbai and Ratnagiri. Cluster analysis reveals resemblance of samples among them for certain species. Ordination separated phytoplankton assemblage of 20 and 40 m depth stations of Mumbai during MON season (73.15% similarity) and phytoplankton assemblage of 40 m depth station of Ratnagiri during MON season (58.42% similarity) from remaining stations at 45.05% similarity (Fig. 7). Highest similarity in phytoplankton assemblage was observed among 20 and 40 m depth stations during POM season (80.34% similarity) at Mumbai followed by phytoplankton assemblage at 40 m depth station during POM and PRM season (77.14% similarity).

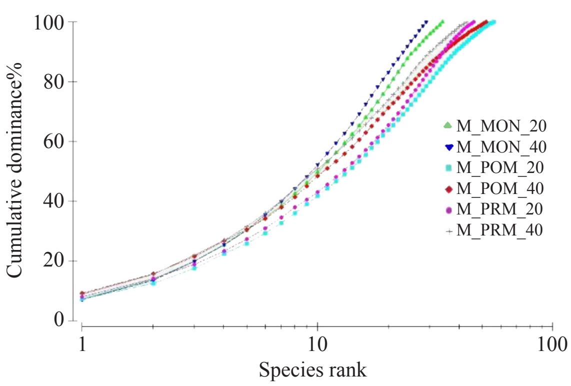

Fig. 5. K-Dominance plot for phytoplankton species recorded at Mumbai

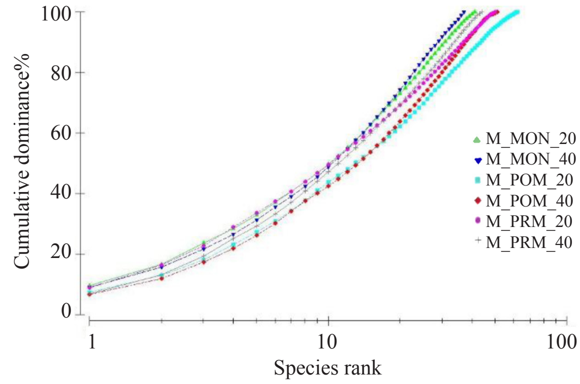

Fig. 6. K-Dominance plot for phytoplankton species recorded at Ratnagiri

SIMPER analysis

Results of SIMPER analysis and discrimination between groups is shown in Table 4. Analysis of similarity percentage showed 49.34% dissimilarity between phytoplankton abundance at Mumbai and Ratnagiri; *T. subtilis*, *T. mobiliensis*, *C. centralis* and *L. danicus* were characteristic of the coastal waters off Mumbai while *C. curvisetus*, *C. lorenzianus*, *S. costatum*, *D. brightwelli*, *P. seriata* and *T. erythraeum* were the species contributing to the dissimilarity from Ratnagiri waters.

Discussion

Phytoplankton density was higher during POM and PRM seasons compared to MON season. Similar observations revealing higher phytoplankton cell density during

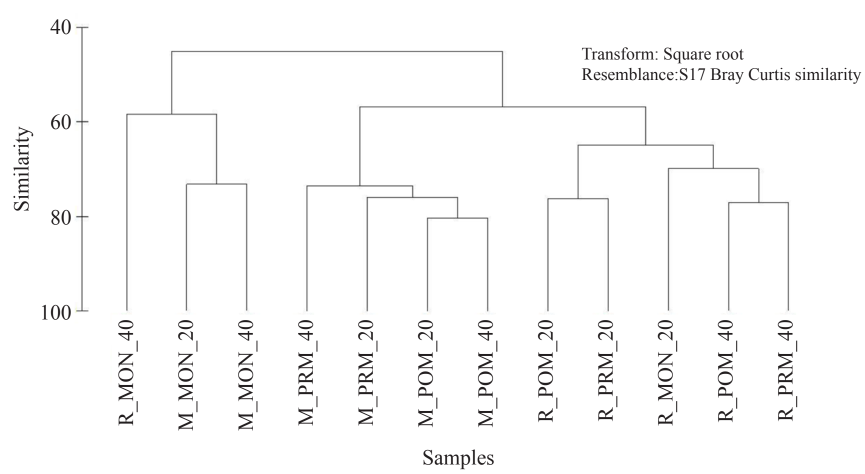

Fig. 7. Dendrogram showing Bray-Curtis similarities of phytoplankton assemblage observed at different sampling stations in different seasons at Mumbai and Ratnagiri

Table 4. SIMPER analysis displaying the average abundance of the most abundant phytoplankton species (contributing at least 1% of the dissimilarity) between Mumbai and Ratnagiri

Species	Mumbai	Ratnagiri			
	Av. Abund.	Av. Abund.	Av. Diss.	Contrib%	Cum%
Chaetoceros curvisetus	71.77	271.32	3.33	6.76	6.76
Trichodesmium erythraeum	31.93	170.16	2.52	5.11	11.87
Chaetoceros lorenzianus	77.01	204.97	2.28	4.63	16.50
Thalassiosira subtilis	186.38	64.51	2.26	4.59	21.09
Skeletonema costatum	109.82	213.51	2.02	4.10	25.19
Noctiluca scintillans	0.00	94.69	1.46	2.96	28.14
Chaetoceros affinis	19.10	93.10	1.23	2.50	30.64
Ditylum brightwellii	88.81	149.63	1.22	2.47	33.10
Rhizosolenia stolterfothii	0.00	67.91	1.18	2.38	35.49
Leptocylindrus danicus	71.73	18.00	1.16	2.36	37.84
Chaetoceros coarctatus	16.81	81.49	1.16	2.36	40.20
Trieres mobiliensis	140.10	130.60	1.14	2.31	42.51
Gyrosigma balticum	70.72	13.86	1.09	2.20	44.71
Coscinodiscus centralis	108.07	87.02	1.00	2.03	46.74
Pseudo-nitzschia seriata	86.98	129.31	1.00	2.03	48.77

Average dissimilarity = 49.34. Av.: Average; Abund.: Abundance; Diss.: Dissmilarity; Cum.: Cumulative

winter (POM) season compared to summer (PRM) and MON season have been described in previous studies from west coast of India (Rajasekar *et al.*, 2010; Rai and Rajashekhar, 2014, 2015; Temkar *et al.*, 2015). Rajesh *et al.* (2002) observed more phytoplankton production when salinity and other hydrological parameters were in stable condition. Higher phytoplankton cell density observed during non-monsoon seasons may be due to stability of water columns (Shruthi and Rajashekhar, 2013) and influx of nutrients from surface runoff to the coastal areas (Kumar *et al.*, 2015a). In the present study, lower sea surface temperature and salinity was observed during MON season which can be attributed to rainfal and dilution of seawater. Perumal *et al.* (2009) recorded lowest phytoplankton abundance during MON season as consequence of abrupt changes in environmental conditions, lower salinity and temperature. Also cloudy weather and decreased transparency might be the reason behind declined phytoplankton abundance during the season. Low pH values observed during MON season in the present study may be due to seawater dilution, lower temperature, minimal salinity and lower primary production (Rajasekar *et al.*, 2010; Minu *et al.*, 2014; Rai and Rajashekhar, 2014, 2015). Chlorophyll-*a* biomass was in accordance with the phytoplankton abundance at Mumbai and Ratnagiri.

Higher turbidity and total dissolved solids recorded during MON season can be attributed to freshwater influx heavily laden with silt (Garg *et al.*, 2006) and in PRM season as a result of increased wave action resulting in turbulence in coastal waters leading to stirring of bottom sediments (Nixon, 1988).

During winter season, increased strength of winds in Arabian Sea drives enhanced evaporative cooling, leading to convective mixing. This convective mixing enahances nutrient supply to euphotic zone from subsurface and increased dust input during winter which boosts iron induced fertilisation supporting increased phytoplankton biomass (Banse, 1987; Madhupratap *et al.*, 1996; Kumar and Prasad, 1996; Kumar *et al.*, 2001b; Kumar *et al.*, 2010). Parab *et al.* (2006) observed two peaks of phytoplankton productivity, one during November to February and other during June to September along west coast of India. In the present study, two peaks of phytoplankton were observed, one during November to December and second during February to April.

Diatoms were abundantly recorded from all the stations during the different seasons at Mumbai and Ratnagiri followed by dinoflagellates. Similar trend was observed along west coast of India in previous studies (Venkataraman, 2005; Paniadima *et al.*, 2006; Saravanakumar *et al.*, 2008; Raveesha *et al.*, 2010; Kaladharan *et al.*, 2011; Robin *et al.*, 2013; Shruthi and Rajashekhar, 2013; Rai and Rajashekhar, 2015; Temkar *et al.*, 2015, Hardikar *et al.*, 2017; Khot *et al.*, 2018; Krishnankutty *et al.*, 2019). Latif *et al.* (2013) observed diatoms to be more diverse and abundant in lagoon and open sea compared to dinoflagellates along coast of Pakistan. Dominance of diatoms reflects ecologically rich and sound coastline able to support large ecosystem (Temkar *et al.*, 2015). Abundance of diatoms throughout all seasons may be due to the capability of diatoms to thrive well in varying environmental conditions (Shruthi and Rajashekhar, 2013). *Ceratium* and *Dinophysis* were commonly occuring dinoflgellates recorded in previous studies (Trigueros and Orive 2001; Selvaraj *et al.*, 2003; Madhav and Kondalarao, 2004; Rai and Rajashekhar, 2014; Krishnankutty *et al.*, 2019).

T. subtilis and *T. mobiliensis* were available throughtout all seasons. *S. costatum* was also available throughout all seasons however, maximum availabilty was observed during POM season. These observations agree with dominance of *Thalassiosira* sp., *S. costatum*, *Pseudo-nitzschi*a sp., *Biddulphia* sp. and *Coscinodiscus* sp. along the coast of Mumbai documented in previous studies (Ramaiah *et al.*, 1998; Tiwari and Nair, 1998, 2002; Kumar *et al.*, 2015a; b; Shahi *et al.*, 2015). Being a euryhaline species *S. costatum* (Rijstenbil, 1988) was observed throughout all seasons with maxima during POM season (Gonzalves, 1947; Qasim, 1972; Tiwari and Nair, 2002; Khot *et al.*, 2018).

Among diatoms, *C. curvisetus*, *C. lorenzianus* and *S. costatum* were abundant at Ratnagiri. *S. costatum* prevailed during MON and POM seasons. Robin *et al.* (2010) reported *C. lorenzianus* as the abundant species recorded from all stations up to 40 m depth off Karnataka and Kerala during their observations. Nair *et al.* (1980) also reported *Chaetoceros* spp. as abundantly available along Ratnagiri coast. Rai and Rajashekhar (2014) reported *Biddulphia mobiliensis, C. curvisetus, S. costatum* and *Licmophora abbreviata* as abundantly available diatoms off Kerala. Khot *et al.* (2018) also recorded the abundant availability of *Chaetoceros* spp. during PRM and POM sesasons and of *S. costatum* during POM season from Ratnagiri waters. Similar observations regarding abundance of *Chaetoceros* spp. and *S. cotstaum* from Malvan waters was also made by Hardikar *et al.* (2017).

The dinoflagellate, *N. scintillans* was abundantly recorded during PRM season at Ratnagiri during the present study. *N. scintillans* blooms in nearshore waters of Arabian Sea have earlier been reported during PRM season (Devassy and Nair, 1987; Matondkar *et al.*, 2004; Matondkar *et al.*, 2007; Gomes *et al.*, 2008; Sulochanan *et al.*, 2014). However, Dwivedi *et al.* (2012) rejected adverse impacts of *N. scintillans* blooms on zooplankton and fish population in northern Arabian Sea. *T. erythraeum* was the only cyanobcteria recorded and was predominantly observed in PRM season during the present study. However, it was also recorded during POM season at Ratnagiri. Predominance of *T. eruthraeum* during PRM season and availabiltiy during POM season has been documented in previous studies also (Nair *et al.*, 1980; Sawant and Madhupratap; 1996; Matondkar *et al.*, 2007; Robin *et al.*, 2010). Dominance of filamentous algae like *Trichodesmium* sp. is usually seen in warm, nutrient-poor nearshore waters lacking circulation and oceanic gyres (Jeffrey, 1995).

In the present study, higher diversity indices were observed during POM season and lowest during MON season. These findings are in accordance with the observations of Rai and Rajashekhar (2015); Shruthi and Rajashekhar (2013). Minu *et al.* (2014) reported higher diversity indices during POM season followed by PRM and MON at 10 and 20 m depth stations off Kochi. Krishnankutty *et al.* (2019) observed maximum species count/diversity during POM season. Shannon-Wiener diversity index is a suitable water quality indicator and diversity value for less polluted water will be higher (Balloch *et al.*, 1976; Wu, 1984). High value of diversity indices represent a healthy ecosystem whereas low values indicate degraded state of ecosystem (Manna *et al.*, 2010). However, dominanc of a few species in the area also reveals low species diversity index (Margalef, 1968). Lower diversity is observed when one of few species dominate in the community (Gao and Song, 2005). Higher Shannon-Weiner index represents equally abundant species and it decrease as relative abundance of species moves away from evenness due to environmental disturbances (Kumar *et al.*, 2015a). Low value of Shannon-Weiner diversity indices during MON sesason is due to dilution of water (Rajagopal *et al.*, 2010). Higher diversity indices are observed at offshore stations compared to nearshore stations (Hardikar *et al.*, 2017; Khot *et al.*, 2018). In the present study, lower diversity indices observed at 40 m depth stations could be atrributed to dominance of a few species compared to 20 m depth stations. Higher diversity during POM and PRM seasons compared to MON may be due to high phytoplankton species count and cell density which is equally distributed among all species.

Phytoplankton abundance is closely related to environmetal parameters and in the present study also the seasonal variations in abundance could be attributed to the changes in hydrographical parameters prevailing in the coastal waters. This study on the seasonal variation of phytoplankton abundance will be useful to predict future environmental changes in the waters as well as form a baseline for predictive modelling studies on fishery resources. Further studies in relation to environment would help in identifying the mechanisms that explain phytoplankton fluctuations in the coastal waters.

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References

APHA 2005. *Standard methods for the examination of water and wastewater,* 21st edn. American Public Health Association/ American Water Works Association/Water Environment Federation, Washington DC, USA, 1220 pp.

Balloch, D., Davies, C. E. and Jones, F. H. 1976. Biological assessment of water quality in three British rivers: The North Esk (Scotland), the Ivel (England) and the Taff (Wales). *Wat. Poll. Cont.*, 75: 92-114.

Banse, K. 1987. Seasonality of phytoplankton chlorophyll in the central and northern Arabian Sea. *Deep Sea Res. Part A. Ocaen. Res. Pap.,* 34: 713-723. https://doi.org/10.1016/0198-0149(87)90032-X.

Banse, K. and English, D. C. 1993. Revision of satellite-based phytoplankton pigment data from the Arabian Sea during the northeast monsoon. *Mar. Sci.* I (*Pakistan*), 2: 83-103.

Banse, K. and English, D. C. 2000. Geographical differences in seasonality of CZCS-derived phytoplankton pigment in the Arabian Sea for 1978-1986. *Deep-Sea Res. II*, 47: 1623-1677.

Bharali, J., Baruah, B. K. and Sharma, H. P. 2010. A study on plankton population of the wetlands of Kaziranga national park. *Poll. Res.*, 29(2): 199-209.

Bijlsma, L., Ehler, C. N., Klein, R. J. T., Kulshrestha, S. M., McLean, R. F., Mimura, N., Nicholls, R. J., Nurse, L. A., Perez Nieto, H., Stakhiv, E. Z., Turner, R. K. and Warrick, R. A. 1995. Coastal zones and small Islands. In: Watson, R. T., Zinyowera, M. C. and Moss, R. H. (Eds.), *Climate change 1995: Impacts, adaptations and mitigation of climate change - scientific-technical analyses.* Contribution of working group II to the Second Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, UK, p. 289-324.

Clarke, K. R. and Gorley, R. N. 2015. *PRIMER v7: User manual/Tutorial (Plymouth Routines in Multivariate Ecological Research). PRIMER-E,* Plymouth, UK.

D'Costa, P. M. and Anil, A. C. 2010. Diatom community dynamics in a tropical, monsoon- influenced environment: West coast of India, *Cont. She. Res.*, 30(2): 1324-1337.

Desikachary, T. V. 1959. *Cyanophyta.* Indian Council of Agricultural Research, New Delhi, India, 686 pp.

Desikachary, T. V. and Sreelatha, P. M. 1989. *Oamaru Diatoms*. J. Cramer, Berlin, 330 pp.

Devassy, V. P and Nair, S. R. S. 1987. Discolouration of water and its effect on fisheries along the Goa coast. *Mahasagar*, 20(2): 121-128.

Dwivedi, R. M., Raman, M., Parab, S., Matondkar, S. G. P. and Nayak S. 2006. Influence of northeasterly trade winds on intensity of winter bloom in the Northern Arabian Sea. *Curr. Sci.*, 90(10): 1397-1406.

Dwivedi, R. M., Chauhan, R., Solanki, H. U., Raman, M., Matondkar, S. G. P., Madhu, V. R. and Meenakumari, B. 2012. Study of ecological consequence of the bloom (*Noctiluca miliaris*) in offshore waters of the Northern Arabian Sea. *Indian J. Geo-Mar. Sci.*, 41(4), 304-313.

Essien, J. P. and Antai, S. P. 2008. Microalgae biodiversity and biomass status in Qua Iboe Estuary mangrove swamp, Nigeria. *Aqua. Ecol.*, 42(1): 71-81. DOI:10.1007/s10452-007-9083-5.

Falkowski, P. G., Barber, R. T. and Smetacek, V. 1998. Biogeochemical controls and feedbacks on ocean primary production. *Science*, 281(5374): 200-206. doi:10.1126/science.281.5374.200.

Gao, X. and Song, J. 2005. Phytoplankton distributions and their relationship with the environment in the Changjiang estuary, China. *Mar. Poll. Bull.*, 50(3): 327-335. DOI:10.1016/j.marpolbul.2004.11.004.

Garg, R. K., Saksena, D. N. and Rao, R. J. 2006. Assessment of physico-chemical water quality of Harsi Reservoir, district Gwalior, Madhya Pradesh. *J. Ecophys. Occu. Heal.*, 6(1): 33-40.

Gharib, S. M., El-Sherif, Z. M., Abdel-Halim, A. M. and Radwan, A. A. 2011. Phytoplankton and environmental variables as a water quality indicator for the beaches at Matrouh, South-eastern Mediterranean Sea, Egypt: An assessment. *Oceanologia*, 53(3): 819-836. https://doi.org/10.5697/oc.53-3.819.

Gomes, H. R., Goes, J. I., Matondkar, S. G. P., Parab, S. G., Al-Azri, A. R. N. and Thoppil, P. G. 2008. Blooms of *Noctiluca miliaris* in the Arabian Sea - An *in situ* and satellite study. *Deep Sea Res. Part I: Ocean. Res. Pap.*, 55(6): 751-765.

Gonzalves, E. A. 1947. Variations in the seasonal composition of the phytoplankton of Bombay Harbour. *Curr. Sci.*, 16(10): 304.

Gopinathan, C. P. 1984. A systematic account of the littoral diatoms of the southwest coast of India. *J. Mar. Biol. Ass. India*, 26(1&2): 1-31.

Guiry, M. D. and Guiry, G. M. 2020. *AlgaeBase*. World-wide electronic publication, National University of Ireland, Galway. http://www.algaebase.org; searched on 7 January 2021.

Habeebrehman, H., Prabhakaran, M. P., Jacob, J., Sabu, P., Jayalakshmi, K. J., Achuthankutty, C. T. and Revichandran, C. 2008. Variability in biological responses influenced by upwelling events in the Eastern Arabian Sea. *J. Mar. Sys.*, 74(1-2): 545-560.

Hardikar, R., Haridevi, C. K., Chowdhuri, M., Shinde, N., Ram, A., Rokade, M. A. and Rakesh, P. S. 2017. Seasonal distribution of phytoplankton and its association with physico-chemical parameters in coastal waters of Malvan, west coast of India. *Env. Mon. Ass.*, 189(4): 1-16. DOI:10.1007/s10661-017-5835-4.

IBM Corp. 2017. *IBM SPSS Statistics for Windows, Version 25.0*. IBM Corp., Armonk, New York, USA.

Jeffrey, S. L. 1995. *Marine biology function, biodiversity, ecology.* Oxford University Press, New York, USA, 420 pp.

Kaladharan, P., Zacharia, P. U. and Vijayakumaran, K. 2011. Coastal and marine floral diversity along Karnataka coast. *J. Mar. Biol. Ass. India*, 53(1): 121-129.

Al-Kandari, M., Al-Yamani, F. Y. and Al-Rifaie, K. 2019. *Marine phytoplankton atlas of Kuwait's waters*. Kuwait Institute for Scientific Research, Kuwait, 344 pp.

Karthik, R., Arun Kumar, M., Sai Elangovan, S., Siva Sankar, R. and Padmavati, G. 2012, Phytoplankton abundance and diversity in the coastal waters of Port Blair, South Andaman Island in relation to environmental variables. *J. Mar. Biol. Ocean.*, 1(2): 1-6. DOI:10.4172/2324-8661.1000102.

Khot, M., Sivaperumal, P., Jadhav, N., Chakraborty, S. K., Pawase, A. and Jaiswar, A. K. 2018. Diversity and composition of phytoplankton around Jaitapur coast, Maharashtra, India. *Indian J. Geo Mar. Sci.*, 47(12): 2429-2441.

Krishnankutty, S., Joseph, C. A., Vincent, P. D., Jabir, T., Vishnu, P. S., Saramma, A. V. and Mohamed Hatha, A. A. 2019. Hydrographic, seasonal diversity, distribution and abundance of phytoplankton in coastal waters off Cochin south-eastern Arabian Sea. *Indian J. Geo Mar. Sci.*, 48(3): 319-326.

Kumar, J., Deshmukhe, G., Dwivedi, A., Surya, S., Sreekanth, G. B. and Singh, S. K. 2015a. Seasonal and spatial variation of microalgal abundance and chlorophyll a concentration in intertidal rocky pools along Mumbai coast, India. *Indian J. Geo Mar. Sci.*, 44(3): 421-427.

Kumar, J., Deshmukhe, G. and Chakraborty, S. K. 2015 b. Influence of hydrological parameter on phytoplankton diversity, abundance and productivity of Vasai Creek, Mumbai, India. *J. Kalas. Sci.*, 3(3): 11-21.

Kumar, S. P. and Prasad, T. G. 1996. Winter cooling in the northern Arabian Sea. *Curr. Sci.*, 71(11): 834-841.

Kumar, S. P., Roshin, R. P., Narvekar, J., Dinesh Kumar, P. K. and Vivekanandan, E. 2010. What drives the increased phytoplankton biomass in the Arabian Sea? *Curr. Sci.*, 99(1): 101-106.

Kumar, S. P., Madhupratap, M., Kumar, M. D., Muraleedharan, P. M., D'Souza, S. N., Gauns, M. and Sarma, V. V. S. S. 2001a. High biological productivity in the central Arabian Sea during the summer monsoon driven by Ekman pumping and lateral advection. *Curr. Sci.*, 81(12): 1633-1638.

Kumar, S. P., Ramaiah, N., Gauns, M., Sarma, V. V. S. S., Muraleedharan, P. M., Raghukumar, S., Kumar M. D. and Madhupratap, M. 2001b. Physical forcing of biological productivity in the Northern Arabian Sea during the Northeast monsoon. *Deep-Sea Res. II,* 48(6): 1115-1126.

Latif, S., Ayub, Z. and Siddiqui, G. 2013. Seasonal variability of phytoplankton in a coastal lagoon and adjacent open sea in Pakistan. *Turk. J. Bot.*, 37(2): 398-410. https://doi.org/10.3906/bot-1201-6.

Liu, D. Y., Sun, J., Liu, Z., Wei H. and Zhang, J. 2004. The effects of spring-neap tide on the phytoplankton community development in the Jiazhou Bay, China. *Acta Ocea. Sin.*, 23(4): 687-697.

Madhav, V. G. and Kondalarao, B. 2004. Distribution of phytoplankton in the coastal waters of East coast of India. *Indian J. Mar. Sci.*, 33(3): 262-268.

Madhupratap, M., Kumar, S., Bhattathiri, P. M. A., Kumar, M. D., Raghukumar, S., Nair, K. K. C. and Ramaiah, N. 1996. Mechanism of the biological response to winter cooling in the northeastern Arabian Sea. *Nature,* 384: 549-552.

Magurran, A. E. 1988. *Ecological diversity and its measurement*. Princeton University Press, Princeton, New Jersey, USA, 179 pp.

Manna, S., Chaudhuri, K., Bhattacharyya, S. and Bhattacharyya, M. 2010. Dynamics of Sundarban estuarine ecosystem: eutrophication induced threat to mangroves. *Sal. Sys.*, 6: 8-24. doi: 10.1186/1746-1448-6-8.

Margalef, D. R. 1968. *Perspectives in ecological theory*. University Chicago Press, Chicago, USA, 111 pp.

Mathivanan, V., Vijayan, P., Sabhanayakam S. and Jeyachitra, O. 2007. An assessment of plankton population of Cauvery River with reference to pollution. *J. Env. Biol.*, 28(2): 523-526.

Matondkar, S. G. P., Bhat, S. R., Dwivedi, R. M. and Nayak, S. R. 2004. Indian satellite IRS-P4 (OCEANSAT), Monitoring algal blooms in the Arabian Sea. IOC-UNESCO, *Harmful Algae News*, 26: 4-5.

Matondkar, S. G. P., Dwivedi, R. M., Parab, S., Pednekar, S., Mascarenhas, A., Raman, M. and Singh, S. 2007. Phytoplankton in the northeastern Arabian Sea exhibit seasonality. The International Society for Optical Engineering, *SPIE Newsroom* 10.1117/2.1200703.0616, 1-4.

Minu, P., Shaju, S. S., Muhamed Ashraf, P. and Meenakumari, B. 2014. Phytoplankton community characteristics in the coastal waters of the southeastern Arabian Sea. *Acta Ocea. Sin.*, 33(12): 170-179. DOI:10.1007/s13131-014-0571-x.

Nair, S. R., Achuthankutty, C. T., Nair, V. R. and Devassy, V. P. 1980. Plankton composition in the coastal waters between Jaigarh and Rajapur along west coast of India. *Mahasagar-Bull. Nat. Inst. Oceano.*, 13(4): 343-352.

Naqvi, S. W. A. and Jayakumar, D. A. 2000. Ocean biogeochemistry and atmospheric composition: Significance of the Arabian Sea. *Curr. Sci.*, 78: 289-299.

Naqvi, S. W. A., Naik, H., Jayakumar, D. A., Shailaja, M. S. and Narvekar, P. V. 2006. Seasonal oxygen deficiency over the western continental shelf of India. In: Neretin, L. N. (Ed.), *Past and Present Water Column Anoxia*, *NATO Science Series, IV. Earth and Environmental Sciences, vol. 64*, Springer, Netherlands, p. 195-224.

Nixon, S. W. 1988. Physical energy inputs and the comparative ecology of lake and marine ecosystems. *Limnol. Ocean.*, 33(4): 1005-1025.

Paniadima, A., Kannapiran, E. and Vareethiah, K. 2006. Seasonal variation of phytoplankton in Chinnathurai coast along southwest coast of India. *J. Mar. Biol. Ass. India*, 48(2): 161-165.

Parab, S. G., Prabhu, M. S. G., Gomes, H. R. and Goes, J. I. 2006. Monsoon driven changes in phytoplankton populations in the eastern Arabian Sea as revealed by microscopy and HPLC pigment analysis. *Cont. Shelf. Res.*, 26(20): 2538-2558.

Perumal, V. N., Rajkumar, M., Perumal, P. and Rajasekar, K. T. 2009. Seasonal variation of plankton diversity in the Kuduviyar Estuary, Nagapattinam, South-east coast of India. *J. Env. Biol.*, 30(6): 1035-1046.

Price, A. R. G. 2001. The marine food chain in relation to biodiversity. *The Sci. World J.*, 1: 579-587. DOI 10.1100/tsw.2001.85.

Qasim, S. Z. 1972. Some observations in *Trichodesmium* blooms In: Desikachari, T. V. (Ed.), *Taxonomy and biology of blue green algae*, University of Madras, Chennai, India, p. 433-438.

Rai, S. V. and Rajashekhar, M. 2014. Seasonal assessment of hydrographic variables and phytoplankton community in the Arabian Sea waters of Kerala, Southwest coast of India. *Braz. J. Ocea.*, 62(4): 279-293.

Rai, S. V. and Rajashekhar, M. 2015. Ecological measurements of phytoplankton communities in the Arabian Sea water off Kerala and Karnataka coasts (South India). *Alg. Stud.*, 149(1): 39-60.

Rajagopal, T., Thangamani, A., Sevarkodiyone, S. P., Sekar, M. and Archunan, G. 2010. Zooplankton diversity and physico-chemical conditions in three perennial ponds of Virudhunagar District, Tamil Nadu. *J. Env. Biol.*, 31(3): 265-272.

Rajasekar, K. T., Rajkumar, M., Jun, S., Prabu, V. A. and Perumal, P. 2010. Seasonal variations of phytoplankton diversity in the Coleroon coastal water, South-East coast of India. *Acta Ocea. Sin.*, 29(5): 97-108.

Rajesh, K. M., Gowda, G. and Mridula, R. M. 2002. Primary productivity of the brackishwater impoundments along Nethravathi Estuary, Mangalore in relation to some physico-chemical parameters. *Fish. Tech.*, 39(2): 85-87.

Ramaiah, N., Ramaiah, N. and Nair, V. R. 1998. Phytoplankton characteristics in a polluted Bombay harbor-Thana-Bassein creek estuarine complex. *Indian J. Mar. Sci.*, 27(3&4): 281-285.

Raveesha, K. P., Mohan, A., Chethan, N., Katti, R. J. and Reddy, H. R. V. 2010. Community structure of net phytoplankton along surf zone of Mangalore during southwest monsoon season. *Indian J. Mar. Sci.*, 39(3): 445-448.

Rijstenbil, J. W. 1988. Selection of phytoplankton species in culture of gradual salinity changes. *Neth. J. Sea Res.*, 22(3): 291-300. DOI:10.1016/0077-7579(88)90031-2.

Robin, R. S., Vishnu Vardhan, K., Muduli, P. R., Rajkumar, J. S. I. and Palanisami, S. 2010. Vertical distribution of biological characteristics and phytoplankton community structure in the shelf waters off Southwest coast of India. *Int. J. Curr. Res.*, 8: 16-34.

Robin, R. S., Vishnu Vardhan, K., Muduli, P. R., Jaikumar, M., Karthikeyan, P., Suresh Kumar, C. and Saravana Kumar, C. 2013. Influence of coastal and backwaters coupling on sustenance of high nutrients and organic production along the Southeast Arabian Sea. *Mar. Sci.*, 3(3): 79-90.

Saravanakumar, A., Rajkumar, M., Thivakaran, G. A. and Serebiah, J. S. 2008. Abundance and seasonal variation of phytoplankton in the creek waters of Western mangrove of Kachchh-Gujarat. *J. Env. Biol.*, 29(2): 271-274.

Satpathy, K. K., Mohanty, A. K., Natesan, U., Prasad, M. V. R. and Sarkar, S. K. 2010. Seasonal variation in physicochemical properties of coastal waters of Kalpakkam, East coast of India with special emphasis on nutrients. *Env. Mon. Ass.*, 164: 153-171.

Sawant, S. and Madhupratap, M. 1996. Seasonality and composition of phytoplankton in the Arabian Sea. *Curr. Sci.*, 71(11): 869-873.

Selvaraj, G. S. D., Thomas, V. J. and Khambadkar, L. R. 2003. Seasonal variation of phytoplankton and productivity in the surf zone and backwater at Cochin. *J. Mar. Biol. Ass. India*, 48: 9-19.

Shahi, N., Godhe, A., Mallik, S. K., Härnström, K. and Nayak, B. B. 2015. The relationship between variation of phytoplankton species composition and physico-chemical parameters in northern coastal waters of Mumbai, India. *Indian J. Geo-Mar. Sci.*, 44(5): 673-684.

Shetye, S. R., Gouveia, A. D., Shenoi, S. S. C., Sundar, D., Michael, G. S., Almeida A. M. and Santanam, K. 1990. Hydrography and circulation off the West coast of India during the south-west monsoon. *J. Mar. Res.*, 48: 359-378.

Shruthi, M. S. and Rajashekhar, M. 2013. Ecological observations on the phytoplankton of Netravati-Gurukrupa Estuary, south west coast of India. *J. Mar. Biol. Ass. India*, 55(2): 41-47. doi: 10.6024/jmbai.2013.55.2.01768-07.

Smitha, B. R., Sanjeevan, V. N., Vimalkumar K. G. and Revichandran, C. 2008. On the upwelling off the southern tip and along the west coast of India. *J. Coastal Res.*, 24(4): 95-102.

Srinath, M., Pillai, V. N., Vivekanandan, E. and Kurup, K. N. 2003. Demersal fish assemblages of the south-west coast of India. In: Silvestre, G., Garces, L., StobutzkiI, Ahmed, M., Valmonte-Sanos, R. A., Luna, C., Lachica-Alino, L., Munro, P., Christensen, V. and Pauly, D. (Eds.), *Assessment, management and future directions for coastal fisheries in Asian countries*, World Center Conference Proceedings, 67: 163-186.

Subrahmanyan, R. 1946. A systematic account of the marine plankton diatoms of the Madras coast. *Proc.eedings of Indian Acad. Sci. B.,* 24(4): 85-197.

Sulochanan, B., Dineshbabu, A. P., Saravanan, R., Bhat G. S. and Lavanya, S. 2014. Occurrence of *Noctiluca scintillans* blooms off Mangalore in the Arabian Sea. *Indian J. Fish.*, 6(1): 42-48.

Tas, B. and Gonulol, A. 2007. An ecologic and taxonomic study on phytoplankton of a shallow lake, Turkey. *J. Env. Biol.*, 28(2): 439-445.

Temkar, G. S., Abdul Azeez, P., Sikotaria, K. M., Brahmane, V. T., Metar, S. Y., Gangan, S. S. Mathew, K. L. and Desai, A. Y. 2015. Correlation of phytoplankton density with certain hydrological parameters along the coastal waters of Veraval, Gujarat. *J. Mar. Biol. Ass. India*, 57(2): 65-74.

Tiwari, L. R. and Nair, V. R. 1998. Ecology of phytoplankton from Dharamtar Creek, west coast of India. *Indian J. Mar. Sci.*, 27(3&4): 302-309.

Tiwari, L. R. and Nair, V. R. 2002. Plankton biodiversity of Dharamtar Creek adjoining Mumbai Harbour. In: Quadros, G., Athalye, R. P. and Bandodkar, B. N. (Eds.), *Proceedings of the National Seminar on Creeks, Estuaries and Mangroves-Pollution and Conservation*, p. 96-102.

Tomas, C. R. 1997. *Identifying marine phytoplankton*. Academic Press, California, USA, 876 pp.

Trigueros, J. M. and Orive, E. 2001. Seasonal variations of diatoms and dinoflagellates in a shallow, temperate estuary, with emphasis on neritic assemblages. *Hydrobiologia*, 444(1): 119-133. DOI: 10.1023/a:1017563031810.

Venkataraman, G. 1939. A systematic account of some south Indian diatoms. *Proceedings of the Indian Academic Science*, 10(6): 293-368.

Venkataraman, K. 2005. Coastal and marine biodiversity of India. *Indian J. Mar. Sci*., 34(1): 57-75.

Walsh, J. J. 1988. On the nature of continental shelves. Academic Press, New York, USA, 520 pp.

Wu, J. T. 1984. Phytoplankon as bioindicator for water quality in Taipei. *Bot. Bull. Acad. Sin.*, 25(2): 205-214.

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