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ORIGINAL RESEARCH ARTICLE

Asterionellopsis glacialis (Family: Fragilariaceae, Class: Bacillariophyceae, Phylum: Ochrophyta) bloom and its impact on plankton dynamics at Kalpakkam (Bay of Bengal, Southeast coast of India)

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Abstract An intense bloom of *Asterionellopsis glacialis* (Family: Flagilariaceae; Class: Bacillariophyceae; Phylum: Ochrophyta) was observed in the near-shore waters at Kalpakkam, Tamil Nadu. Proliferation was supported by the favorable temperature, salinity, and nutrient levels in the coastal waters prevailing in the post-northeast monsoon period. BIOENV analysis and PCA confirmed salinity and nitrate as the key environmental factors responsible for the *A. glacialis* abundance. Cluster analysis further supported the distinct state of coastal water during the bloom with respect to physicochemical properties. The bloom period was floristically and faunistically richer than the pre- and post-bloom periods. The cluster and nMDS analysis confirmed the effects of bloom on plankton dynamics in the near-shore waters at Kalpakkam. The dominance of meroplankters especially, Cirripedia nauplii and Bivalvia larvae over Copepoda during the peak bloom period, was a significant result of the study. PCA ordination plot for the quantitative aspects of phytoplankton and zooplankton groups further supported the above observation. Among Copepoda, Cyclopoida and Poecilostomatoida (mostly carnivorous) exceeded the Calanoida (mostly herbivorous) during the peak bloom period unlike the reverse trend observed during other periods. Fish eggs and larvae were available in substantial numbers

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during the bloom which indicated their proliferation in the presence of the blooming diatom standing stock as the food material.

1. Introduction

Phytoplankton blooms have become regular phenomena in the coastal marine environment due to the eutrophication caused by anthropogenic impacts and natural events such as upwelling and water currents (Jocelyn et al., 2000; Rao, 1969). Margalef (1978) also recognized that the most important features governing bloom are turbulence and advection, as they decide the plankton mass how long to stay at the photic zone and in favorable environmental conditions. Phytoplankton blooms generally take place in coastal waters in a nutrient-enriched environment in the presence of light. The bloom is usually of a variety of colors, i.e., from green to red. *Trichodesmium erythraeum*, blue-green algae, is a very common bloom-forming species along the Indian coasts. However, diatom blooms are very meager along this coast. Among diatoms, blooms of *Asterionellopsis glacialis* have been reported from different parts of Indian coasts. Rao (1969) reported the bloom of *A. glacialis* in the coastal waters of Visakhapatnam for the first time. Subsequently, *A. glacialis* bloom was reported from the Vellar river estuary, Tamil Nadu coast (Mani et al., 1986), from coastal waters of Orissa (Choudhury and Panigrahy, 1989; Mishra and Panigrahy, 1995; Panigrahy and Gouda, 1990). The occurrence of *A. glacialis* bloom was also reported from Kalpakkam coast, Tamil Nadu by Satpathy and Nair (1996). The bloom of marine phytoplankton is becoming a cosmopolitan phenomenon and has spread across all the latitudes (Bhat et al., 2006). The increased appearance of phytoplankton blooms in the coastal and offshore waters of India, as reported by various studies during recent times (D'Silva et al., 2012; Latha et al., 2014; Mohanty et al., 2010; Sahu et al., 2016) has threatened the marine ecosystems. Impacts of bloom on marine fishing activities have long been reported from Indian waters (Nagabhushanam, 1967; Prabhu et al., 1971). Human health hazards arisen from bloom-infested waters have also been reported (Karunasagar et al., 1984, 1998) from India. During our regular coastal water monitoring program, *Asterionellopsis glacialis* bloom was encountered (January 2015) in the coastal near-shore zone of Kalpakkam (12°33′N Lat.; 80°11′E Long.). The bloom patches were brownish colored and were observed in the surf zone. The bloom was observed to be extended to ~10 km along the coastline. Besides, blooms of Dinophyta *Noctiluca scintillans* (Sargunam et al., 1989) and Cyanobacteria *Trichodesmium erythraeum* (Mohanty et al., 2010; Satpathy et al., 2007) have also been reported from coastal waters of Kalpakkam. Interestingly, though *Asterionella* bloom has been reported about six times from the Indian coastal waters, all the bloom events for this species occurred in the Bay of Bengal (BOB) coast. Most of the diatom blooms have no direct harmful impact on the economy but generally alter the physicochemical and biological properties of water and consequently affect flora and fauna (Campbell, 1996). The present investigation focused on describing the phyto- and zoo-plankton community structure along with the abiotic factors measured during the *A. glacialis* bloom encountered at Kalpakkam coast, BOB. Recent observations on phytoplankton blooms from Indian coastal waters (Jyothibabu et al., 2017; Roy et al., 2016; Sarma et al., 2020; Shanmugam et al., 2017; Sridevi et al., 2019) have mainly concentrated on physicochemical aspects and remote sensing data. Apart from the reports from the 1990s to 2000s, some of which dealt with phytoplankton and rarely included zooplankton, recent studies in this regard are very scarce (Baliarsingh et al., 2016; Srichandan et al., 2019). Moreover, although phytoplankton blooms have been reported earlier from this coast, those investigations only emphasized physicochemical aspects. Hence, there is a paucity of information regarding plankton, particularly zooplankton community organization during such blooms. Besides, an effort has been made to determine the spatial extent and dynamics of the bloom by satellite sensor-derived Chl-*a* images, which provide quick and effective means to detect and monitor bloom formation.

2. Material and methods

2.1. Study area

Kalpakkam (12°33′N Lat. and 80°11′E Long.) is situated about 70 km south of Chennai metro city, southeast coast of India. It is an emerging hub of nuclear installations. It harbors Madras Atomic Power Station (MAPS), Prototype First Breeder Reactor (PFBR), First Breeder Fuel Cycle Facility (FRFCF — under construction), Indira Gandhi Centre for Atomic Research (IGCAR), and desalination plant (Nuclear Demonstration & Desalination Plant, NDDP). The bloom was encountered during the regular coastal water monitoring program (December 2014—January 2015) near the seawater intake of MAPS, which is ~500 m away from the shore (Figure 1). Water column depth near the sampling location is about 8 m, and tides are small (0.3—1.5 m; micro-tidal). The surf zone is ~100 m at this location. In this part of the south-eastern Indian peninsula, three seasons are observed annually according to the wind regime (i) pre-monsoon (PRM) or southwest monsoon (SWM) (June—Sept.), (ii) Northeast monsoon (NEM) (October to January) and (iii) post-monsoon (POM)/summer (February—May) (Sahu et al., 2015). The coastal current at Kalpakkam is bidirectional, northerly from February to October (speed of 0.2—1.8 km/h) and southerly from October to February (speed 0.1—1.3 km/h). Southerly (~0.5 million m^3/y) and northerly littoral drift (~1 million m^3/y) takes place at this location due to monsoon winds (10—40 km/h). The surface seawater temperature (SST) shows bimodal oscillation with two annual peaks

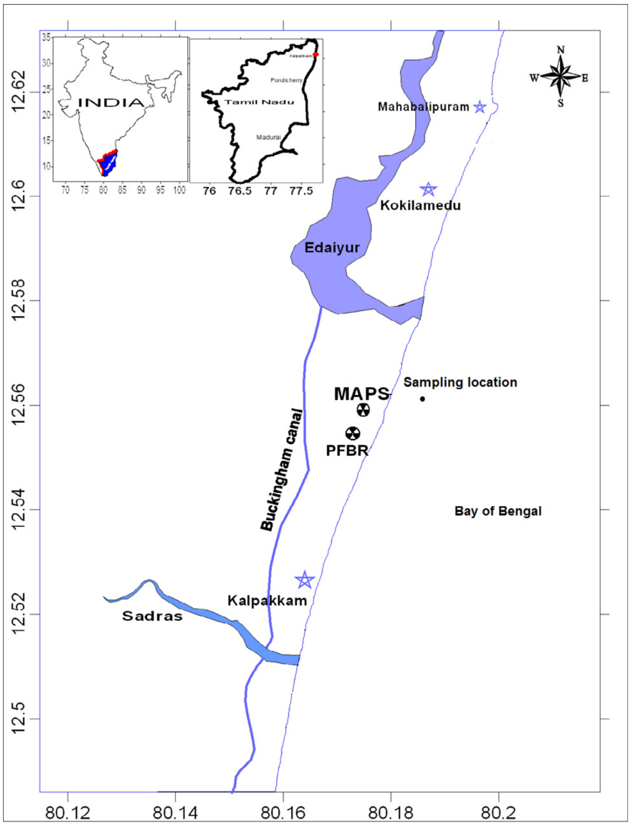

Figure 1 Study area showing the sampling location, Kalpakkam coast, east coast of India.

(April/May, August/September) and two minima during December/January and June/July (Satpathy and Nair, 1990). This region receives about 65% of total rainfall (~1250 mm) during the dominant NEM period. Monsoonal rain and the monsoon-dependent wind and current reversals drastically affect the coastal water ecology (Satpathy et al., 2009, 2010). Also, the Sadras and the Edaiyur backwater systems present at this location play an important role in the coastal ecology by discharging a large amount of freshwater mainly during the NEM period.

2.2. Methods

Surface water was collected daily during the bloom (14th to 19th January 2015), and post-bloom (20, 21 and 23 January 2015) periods, whereas weekly samples were collected before bloom during regular monitoring program (24 December 2014; 12 January 2015) and those were considered as pre-bloom samples. Samples were analyzed for physicochemical parameters. Dissolved Oxygen (DO) was measured using Winkler's titrimetric method (Parsons et al., 1984). Salinity was estimated by Knudsen's argentometric titration (Grasshoff et al., 1983) and CyberScan PCD 5500 multi-parameter probe was used for measurement of pH (accuracy of ±0.01). Micro-nutrients such as nitrate, ammonia, silicate, phosphate, total Nitrogen (TN), and total phosphorous (TP) were estimated following standard methods of Grasshoff et al. (1983) and Parsons et al. (1984). Chl-*a* and phaeopigments were estimated by the spectrophotometric method of Parsons et al. (1984). Chemito Spectrascan UV 2600 spectrophotometer was used for all the spectrophotometric analyses. Utermohl's sedimentation technique (Vollenweider, 1974) was used for phytoplankton abundance estimation. The settled phytoplankton was counted using Sedgwick Rafter cell under an inverted research microscope (Zeiss Axiovert 40) using magnification up to 1000×. Phytoplankton was identified up to species level using taxonomic literature (Desikachary, 1987; Fristch, 1935; Subramanian, 1968, 1971; Tomas, 1996). The horizontal hauling method of zooplankton sample collection was adopted in the study using a conical zooplankton net (200 μm mesh size) fitted with the Hydro-Bios flow meter. 5% neutralized formaldehyde was used to preserve the zooplankton samples and then examined for quantitative and qualitative aspects using a zooplankton counting chamber at a magnification of 200× under an inverted microscope. Zooplankton identification (up to species level) was carried out using standard literature (Bradford-Grieve, 1994; Conway et al., 2003; Kasturirangan, 1963; Newell and Newell, 1967). The bigger individuals were counted separately after sorting them out from the sample. The zooplankton abundance was presented in terms of organisms 10 m^{-3}. Zooplankton biomass, dry weight (g. dry wt. 10 m^{-3}), was estimated after filtering through the plankton net (200 μm mesh size). The residuals were oven-dried for 24 h at 80°C, then stored for 2 hours in a desiccator at room temperature and weighted with a Sartorius analytical microbalance (±0.01 g accuracy).

Species diversity indices such as species diversity (D), species richness (R), and evenness (J) were estimated using the formulae of Gleason (1922), Shannon and Weaver (1963), and Pielou (1966), respectively. To get an insight into the interrelation between bloom and various physicochemical parameters, principal component analysis (PCA) and Pearson's correlation matrix analysis was performed by using XLSTAT Pro. Hierarchical cluster analysis (HCA) and non-metric multidimensional scaling (nMDS) were performed using PRIMER v6.0 (Plymouth Routines in Multivariate Ecological Research) to establish the relations between the phyto- and zooplankton species during different bloom phases. The potential relationships between the bloom and other biotic and abiotic parameters were assessed using BEST submodule BIOENV (biota-environment correlation analysis) of PRIMER v6.0 to explore (Clarke and Gorley, 2006). Pre-treatment of all data was carried out as required for the above analyses (Xu et al., 2008). To determine the spatial distribution of the *A. glacialis* bloom, satellite Chl-*a* and sea surface temperature (SST) images retrieved from NASA Moderate Resolution Imaging Sensor (Modis/Terra) were analyzed for the study period.

3. Results and discussion

3.1. Environmental variables

Relatively low water temperature was observed during the bloom period (26.1—27.4°C) as compared to pre-bloom (27.5—27.8°C) and post-bloom (27.6—28.2°C) periods (Table 1). To get a broader picture, the in situ temperature was compared with the satellite data. The near-shore

Table 1 Summary of environmental variables observed during the *Asterionellopsis glacialis sensu lato* bloom in the coastal waters of Kalpakkam (Temperature — °C, Salinity — PSU, dissolved oxygen — mg l^{-1}, nutrients (nitrate, ammonia, total nitrogen, phosphate, total phosphorus, silicate — μ mol l^{-1}).

	Temp	pH	Salinity	DO	Nitrate	Phosphate	Ammonia	Silicate	TN	TP
Pre-bloom period										
24th Dec.	27.8	8.0	32.4	5.8	0.86	0.08	0.24	4.56	8.56	0.52
12th Jan. M	27.5	8.1	32.7	6.2	1.12	0.12	0.05	3.42	6.89	0.48
Bloom period										
14th Jan. M	27.2	7.9	32.6	7.1	1.18	0.07	0	3.90	7.06	1.64
17th Jan. M	26.2	7.7	32.8	7.2	1.32	0.75	0	3.45	40.26	7.03
17th Jan. AN	27.6	7.7	33.4	7.4	1.05	0.50	0	6.60	2.49	1.10
18th Jan. M	26.1	8.0	31.9	8.0	1.18	0.55	0	3.90	13.28	0.68
19th Jan. M	27.4	7.8	32.6	7.6	1.68	0.05	0	3.23	8.09	0.05
Post-bloom period										
20th Jan. M	28.2	8.0	32.8	6.1	1.53	0.21	0.12	3.75	9.52	0.72
21st Jan. M	27.9	8.1	33.7	5.7	1.24	0.18	0.05	3.59	8.67	0.42
23rd Jan. M	27.6	8.1	33.1	5.4	1.42	0.24	0.08	3.87	9.23	0.57

Table 2 Correlation matrix (Pearson).

Variables	Temp	pH	DO	Phosphate	Silicate	TN	TP	*A. glacialis* density	Phyto density	Zoopl. density	Chl *a*
Temp.	**1**										
pH	0.378	**1**									
Salinity	0.530	−0.014									
DO	**−0.690**	**−0.687**	**1**								
Nitrate	0.046	−0.095	0.104								
Phosphate	**−0.697**	−0.506	0.456	**1**							
Ammonia	**0.550**	0.457	**−0.691**	−0.416							
Silicate	0.178	−0.395	0.151	0.251	**1**						
TN	**−0.658**	−0.391	0.202	**0.685**	−0.362	**1**					
TP	**−0.598**	**−0.575**	0.251	**0.708**	−0.114	**0.928**	**1**				
A. glacialis density	**−0.670**	**−0.618**	0.411	**0.599**	−0.123	**0.822**	**0.939**	**1**			
Phyto density	**−0.745**	**−0.664**	**0.542**	**0.618**	−0.103	**0.786**	**0.895**	**0.987**	**1**		
Zoopl. density	−0.159	**−0.675**	**0.558**	**0.552**	**0.776**	−0.066	0.119	0.130	0.198	**1**	
Chl-*a*	**−0.570**	**−0.592**	0.258	**0.627**	−0.131	**0.892**	**0.990**	**0.963**	**0.919**	0.098	**1**
Phaeopigments	**−0.583**	−0.603	0.275	**0.670**	−0.074	**0.883**	**0.989**	**0.963**	**0.922**	0.156	**0.997**

Values in bold are significantly different from 0 with a significance level alpha=0.1 (variables which developed significant correlations only are given in the table).

waters of the north Tamil Nadu coast showed a relatively low SST, about 0.8 to 1.2°C lower than that of the offshore regions (Figure 2a—b), indicating the upwelling process is taking place in the coastal zone during this season. Many workers have reported coastal upwelling during pre-SWM and SWM along the east coast of India (La Fond, 1957, 1958; Murty and Varadachari, 1968). The cooling of water along the south Andhra coast and north Tamil Nadu coast was suggested as the factor responsible for algal bloom formation in this region (Mishra et al., 2006). The 3-day composite image of SST during January 14—16th, 2015, showed lower values (range: 25—26°C) in the coastal waters than in the non-blooming offshore water mass (≥26.5—28°C). Moreover, a negative correlation ($r = -0.670$; $p = 0.03$) in between *A. glacialis* abundance and temperature (Table 2) indicated the association of the bloom with upwelling. The concentration of DO was also relatively high during the bloom period, and it showed a positive correlation ($r = 0.542$; $p = 0.09$) with phytoplankton abundance. Similarly, the DO contents increased during the blooms of *Noctiluca* (Sargunam et al., 1989) and *Asterionella* (Choudhury and Panigrahy, 1989; Gouda and Panigrahy, 1990; Mishra et al., 2006; Misra and Panigrahy, 1995; Sasmal et al., 2005), although severe Oxygen depletion has also been recorded (1.25 ml l^{-1}) during *Noctiluca* bloom reported from south-western India coast (Naqvi et al., 1998). Nitrogen and Phosphorus released from the algal biomass during bloom lead to the observation of relatively high values of these nutrients during the peak bloom phase (Table 1). The above observation was supported by strong positive correlations of TN and TP with the abundance of phytoplankton and pigment concentrations ($p = 0.0001$). Similar observations of an increase in phosphate concentration have been reported during phytoplankton blooms from various Indian

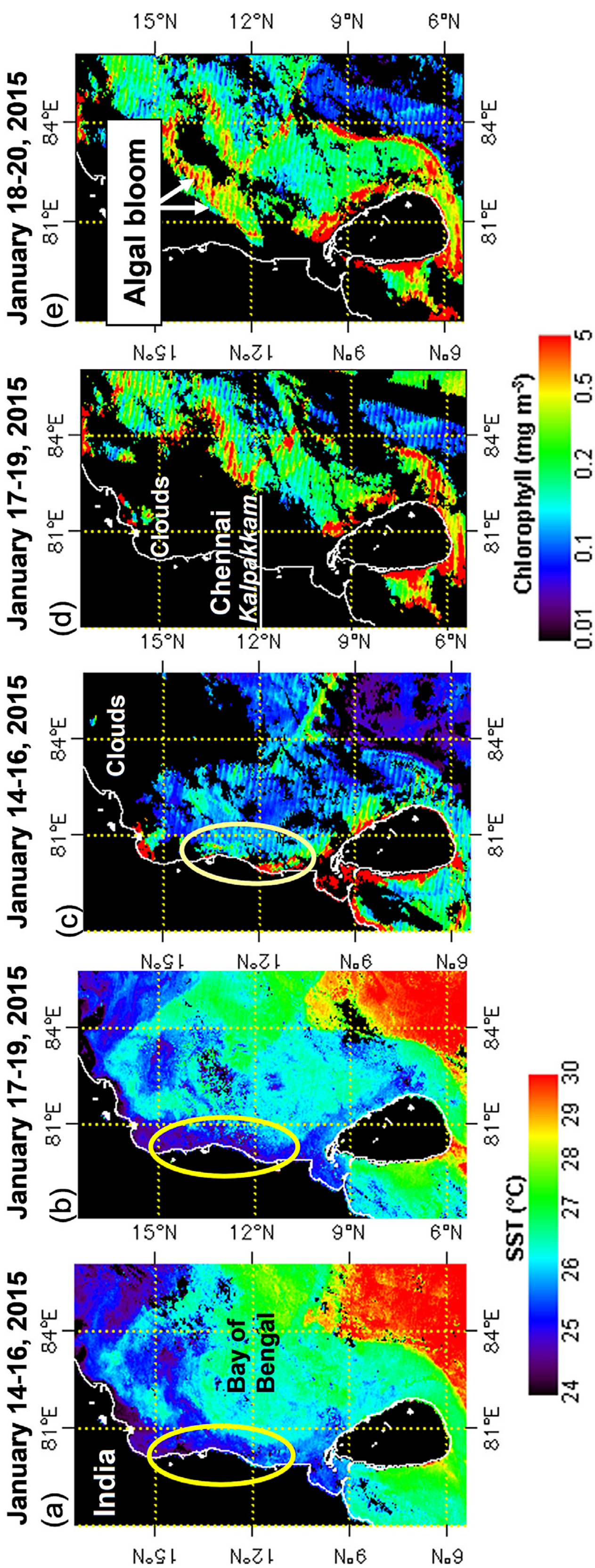

Figure 2 NASA MODIS-Terra satellite sensors derived 3-day composite images of SST (a—b) indicate the cooling zones and chlorophyll images (c—e) reflect the phytoplankton bloom water along southwest Bay of Bengal.

coastal waters (Dharani et al., 2004; Raghuprasad and Jayaraman, 1954; Sahayak et al., 2005; Satpathy and Nair, 1996). Though silicate is used by diatoms to synthesize the siliceous frustules, visible variation in concentrations of silicate during this study was not observed. Silicate, being one of the most important nutrients, regulates the growth of diatoms and ultimately phytoplankton blooms, as it gets depleted during the bloom occurrence (Choudhury and Panigrahy, 1989; Gouda and Panigrahy, 1990; Mishra et al., 2006; Mishra and Panigrahy, 1995; Rao, 1969; Sasmal et al., 2005). In contrast, silicate increased during dinoflagellate and cyanobacteria blooms reported from BOB (Dharani et al., 2004; Raghuprasad and Jayaraman, 1954; Sargunam, 1989; Satpathy et al., 2007).

The highest Chl-*a* content (15.99 mg m^{-3}) was recorded on 17th January (Table 3), coinciding with the highest phytoplankton abundance. However, on 18th and 19th January the abundance was still high, although the Chl-*a* concentration decreased significantly. It suggested that the exponential growth phase of the bloom had already passed during its observation and it was in the waning phase. Further, relatively high phaeopigment concentrations observed during the bloom period depicted that bloom biomass was declining. Similar observations of the rapid disappearance of blooms from the coastal water of India have also been reported (Mishra et al., 2006; Mohanty et al., 2010; Satpathy et al., 2007). Chl-*a*, as well as phaeopigments, showed strong positive correlations ($p= 0.0001$) with the phytoplankton abundance during the study. The satellite Chl-*a* images indicated three types of water mass (Figure 2c—e): (i) patches with red and yellow color, where the concentration of Chl-*a* was 0.30—5.0 mg m^{-3} indicated the presence of a highly eutrophic/bloom water mass, (ii) green patches with Chl-*a* concentration of 0.1—0.3 mg m^{-3} indicated the presence of non-bloom but eutrophic/productive water mass and (iii) cyan and blue color patches with Chl-*a* concentration: 0.01—0.10 mg m^{-3} characterized a low productive/oligotrophic water mass. Composite satellite images for Chl-*a* for 14—16th January 2015 showed that its concentration was relatively high along the southern Andhra Pradesh coast and northern Tamil Nadu waters. It indicated that the bloom was extended to a broad region (Figure 2c). In situ values of chlorophyll measured in the study corroborated with values obtained from satellite images. During the post-bloom period, the absence of the bloom in the coastal waters and distribution of irregular stripes of bloom biomass in the offshore regions of the study area was noticed from the combined images of 17—20th January (Figure 2d—e).

3.2. Phytoplankton composition

Based on the concentration of *A. glacialis* (Table 3), the period of observation was divided into 3 phases, pre-bloom (December 2014—early January 2015), bloom (14th January—21st January 2015), and post-bloom (January end—early Febuary 2015). A total of 120 species consisting of: 105 diatoms (Phylum: Ochrophyta, Class: Bacillariophyceae) — 38 Pennate diatoms (Order: Pennales) and 67 Centric diatoms, (Order: Centrales), 12 dinoflagellates (Phylum: Dinoflagellata), two cyanobacteria (Phylum: Cyanobacteria; Class: Cyanophycae) and one chlorophyta (Phylum: Chlorophyta) were observed, with the remarkable difference be-

Table 3 Summary of plankton dynamics observed during the *Asterionellopsis glacialis* bloom in the coastal waters of Kalpakkam.

	A. glacialis cells L^{-1}	Phytoplankton cells L^{-1}	Zooplankton cells L^{-1}	Chl *a* mg m^{-3}	Phaeopigments mg m^{-3}
Pre-bloom period					
4th Dec	15600	215000	46890	1.98	2.64
12th Jan M	21566	168500	42055	2.15	2.42
Bloom period					
14th Jan M	29513333	33926667	52604	5.87	7.83
17th Jan M	56284000	57956000	59198	15.99	21.59
17th Jan AN	7386667	11406667	90180	3.21	5.2
18 Jan M	8006667	16633333	62792	1.54	2.67
19th Jan M	2153333	8479999	57475	1.54	1.29
Post-bloom period					
20th Jan M	24400	154533	53406	1.89	2.35
21st Jan M	18444	137460	56410	2.25	3.46
23rd Jan M	21040	204500	48950	1.68	1.97

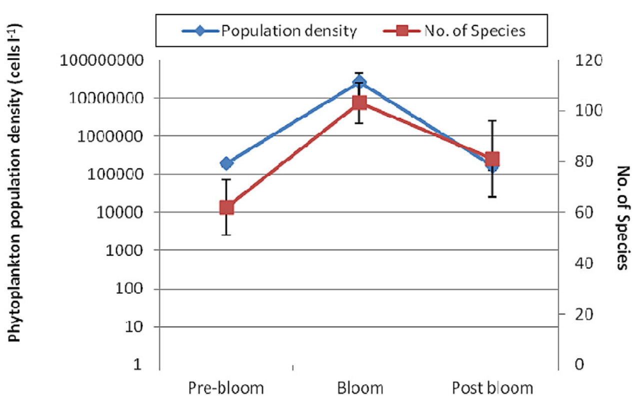

Figure 3 Population density and number of species of phytoplankton during different phases of bloom.

tween the three phases. The bloom phytoplankton assemblage was floristically richer (103 species) compared to the pre-bloom (62 species) and post-bloom period (81 species) (Figure 3). HCA and nMDS analysis for the phytoplankton community structure during the three phases of bloom developed seven phytoplankton groups (Figure 4—5). These groups were characterized by the presence of phytoplankton species exclusively during pre-bloom (4 species), bloom (5 species), post-bloom (9 species), pre-bloom+bloom (31 species), pre-bloom+post-bloom (5 species), bloom+post-bloom (45 species) and pre-bloom+bloom+post-bloom (22 species). These combinations showed that most of the species which thrived during the bloom period survived the impact of the bloom. Interestingly, the highest number of exclusive phytoplankton species were observed to be present during post-bloom observations (9 species). The above observations showed that the bloom had influenced the phytoplankton dynamics at the Kalpakkam coast. Out of the 22 species of phytoplankton found throughout the study, *Bacteriastrum delicatulum*, *Biddulphia heteroceros*, *B. iddulphia mobiliensis*, *B. iddulphia sinensis*, *Chaetoceros curvisetus*, *Chaetoceros lorenzianus*, *Chaetoceros socialis*, *Nitzschia panduriformis*, *Pleurosigma formosum* and *Skeletonema costatum* contributed significantly to the abundance during all three periods. The above species are common in tropical coastal waters and are available throughout the year (Achary et al., 2014; Sahu et al., 2013). Scrutiny of data showed that the number of both Pennales (pre-bloom — 17; post-bloom — 26) and Centrales (pre-bloom — 36; post-bloom — 45) increased from pre-bloom to post-bloom period. Others gave similar increased species numbers during *A. glacialis* bloom (Mishra et al., 2006; Mishra and Panigrahy, 1995) and bloom of other phytoplankton species (Mohanty et al., 2010; Satpathy et al., 2007). Similarly, the number of Dinoflagellata species increased from 5 during the pre-bloom period to 9 during bloom, and subsequently, it decreased to 7. It indicated that Dinoflagellata, which are generally abundant in oligotrophic oceanic waters, could have been transported to the coastal waters by current and circulation patterns (Sahu et al., 2014).

The abundance of *A. glacialis* with respect to total phytoplankton is depicted in Figure 6. The total phytoplankton abundance (cells l^{-1}) showed a sharp increase from 1.6×10^5 to 5.7×10^7 during different bloom phases. The numerical abundance of phytoplankton was found to be the highest when the *A. glacialis* reached the bloom phase, with 97.1% contribution to the total phytoplankton population. The lowest abundance was observed in December 2014, when the *A. glacialis* population was only about 10% of the phytoplankton cells. The abundance grew rapidly during the bloom period and declined from January end onwards. A vigorous multiplication of *A. glacialis* was noticed from 14^{th} January to 21^{st} January 2015 and during this period, its contribution to total abundance was about 64.5%. The abundance of other phytoplankters was found sporadically. Such a monospecific bloom of *A. glacialis* has been already reported along the Visakhapatnam coast (Rao, 1969), off Gopalpur (Choudhury and Panigrahy 1989; Mishra et al. 2006). The relative abundance of other species during the pre-bloom period was about 90%, which declined to 2.9% during the peak bloom. The contribution of other species increased from the end of January 2015 and was found to be ~86.8%.

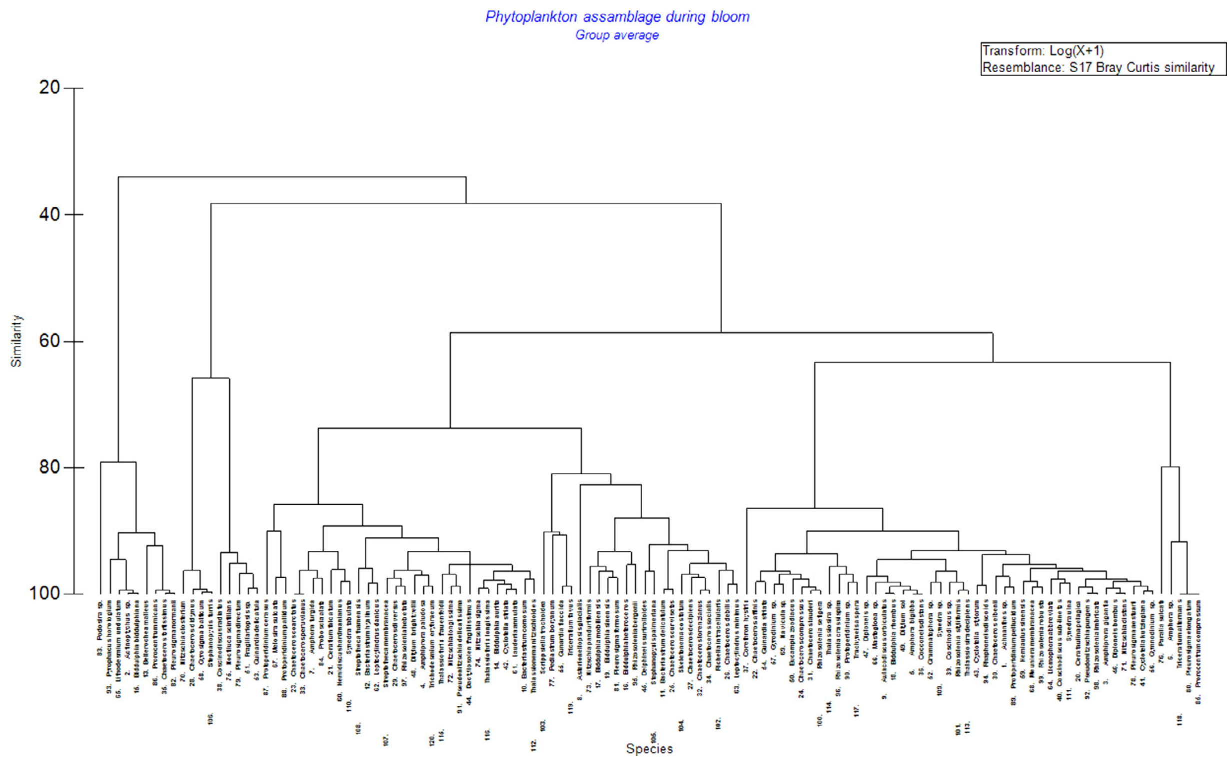

Figure 4 Hierarchical cluster analysis of phytoplankton species abundance during the study period (numerical digit given against each species is serial number of the species).

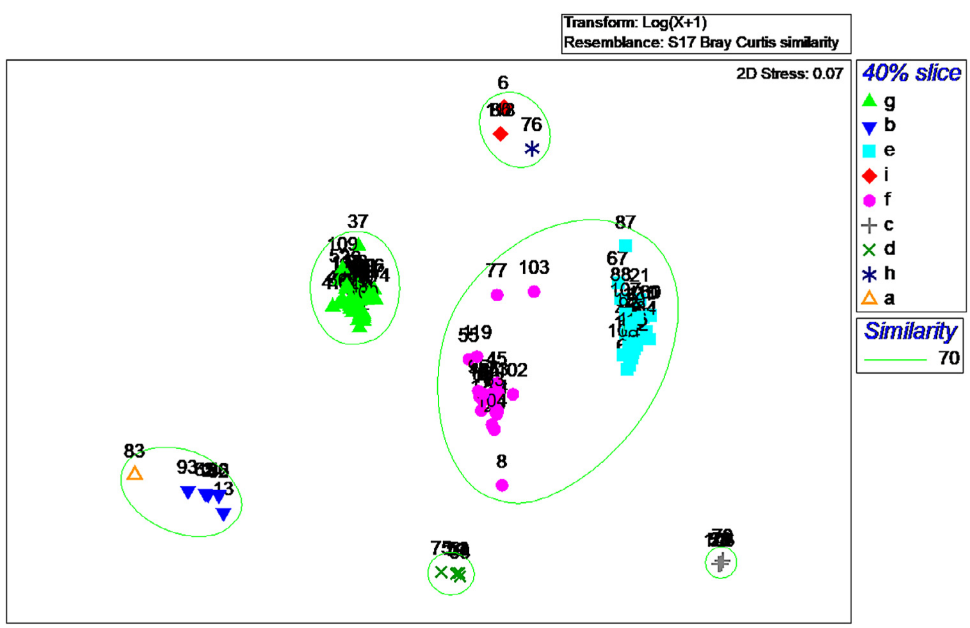

Figure 5 Non-metric multidimensional scaling (nMDS) of phytoplankton species showing the species associations (numerical digits represent the species serial numbers as given in Figure 4).

3.3. Zooplankton composition

Phytoplankton bloom has long been known to change the aquatic ecosystem drastically with respect to physicochemical and biological properties (Landsberg, 2002; Shumway, 1990; Smayda, 1989). It has been reported that nutrients enrichment in the coastal water takes place in this region due to monsoon precipitation, which leads to spring outbursts of phytoplankton that subsequently affects the zooplankton composition and distribution (Padmavati and Goswami, 1996; Satpathy and Nair, 1996). Zooplankton community in this study comprised of 67 taxa out of which 57

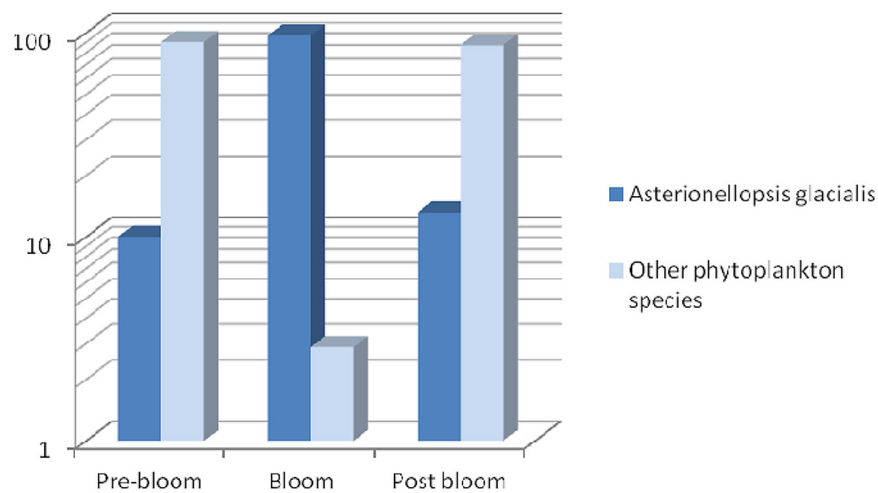

Figure 6 Relative abudance of *Asterionellopsis glacialis* and other phytoplankters in coastal waters of Kalpakkam during different phases of bloom.

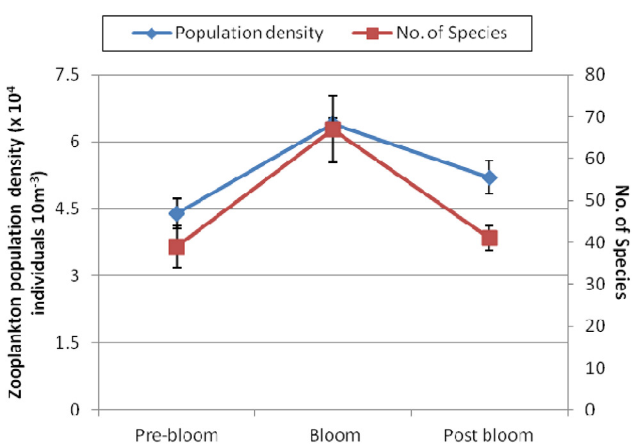

Figure 7 Population density and number of species of zooplankton during different period of bloom.

were identified (39 holoplankters, 13 meroplankters, five benthopelagic forms), with Copepoda the dominant component including 24 species, followed by 15 non-copepod holoplankton (NCH). The highest number of Copepoda species (24) coincided with the peak bloom followed by pre-bloom (13) and post-bloom (10) observations. In general, a relatively high number of zooplankters species was observed during the bloom phase (Figure 7), as it was already observed during a *Trichodesmium erythraeum* bloom at Kalpakkam coastal waters (Sahu et al., 2015). Copepod nauplii and Copepodites, i.e., juveniles of various copepod groups (Calanoida, Cyclopoida, and Harpacticoida) were recorded during all three periods, and ovigerous females of *Oithona rigida, Oithona similis, Pseudodiaptomous serricaudatus*, and *Euterpina acutifrons* were commonly found. Zooplankton of pre-bloom and post-bloom periods was represented mainly by *Bestiolina similis, Paracalanus parvus, Oithona rigida, Centropages tenuiremis*, among Copepoda, and Gastropoda and Polychaeta larvae and fish eggs among meroplankton. During the peak bloom period, meroplankters (Cirripedia nauplii, Bivalvia larvae), Copepoda (*Bestiolina similis, Oithona* spp.) and the Appendicularia *Oikopleura dioeca* were the most common forms. The HCA and nMDS analyses showed zooplankton assemblage was different in terms of species richness than the phytoplankton assemblage. Zooplankton taxa were organized into four groups (Figure 8—9) viz., common taxa occurred during all three phases of bloom (23), bloom and post-bloom (15), bloom and pre-bloom (12) and exclusively in the bloom period (12). No species were found to be present exclusively during the pre-bloom, post-bloom and pre-bloom+post-bloom period. The above analysis indicated that the zooplankton species present during the pre-bloom thrived well in addition to a few more species, especially the meroplankton, added during the bloom period. On the other hand, it also indicated no drastic change in zooplankton species succession in the post-bloom phase, as there were no new species found in the post-bloom period.

Zooplankton abundance increased during the bloom period (6.4×10^4 individuals 10 m^{-3}) compared to the pre-bloom (4.4×10^4 individuals 10 m^{-3}) and post-bloom (5.2×10^4 individuals 10 m^{-3}) periods (Figure 7). However, the contribution of Copepoda was the lowest during the bloom (~31%) and relatively high during pre-bloom (~68.5%) and post-bloom (~48.9%) periods (Figure 10). Among Copepoda, Calanoida were dominant (avg. 20% of the total zooplankton population), especially with species of the families Paracalanidae and Acrocalanidae, contributing respectively with ~7% and ~9% to the zooplankton assemblage during the peak bloom period, when Cyclopoida and Poecilostomatoida (~19.5%) exceeded the Calanoida (~17%). Calanoida are the most abundant Copepoda in the world Ocean, and the observed decrease in their abundance could be due to predation by Cyclopoida and Poecilostomatoida. The highest zooplankton abundance during the bloom period was associated with meroplankters, especially Cirripedia nauplii and Bivalvia larvae. Among meroplanktonic components, Cirripedia nauplius, Bivalvia larva, and Gastropoda larva contributed 25%, 14.5%, and 6% of meroplankton density respectively during the bloom period. A subsequent decrease in their abundance was observed during the post-bloom period (Cirripedia nauplius — 17%, Bivalvia larva

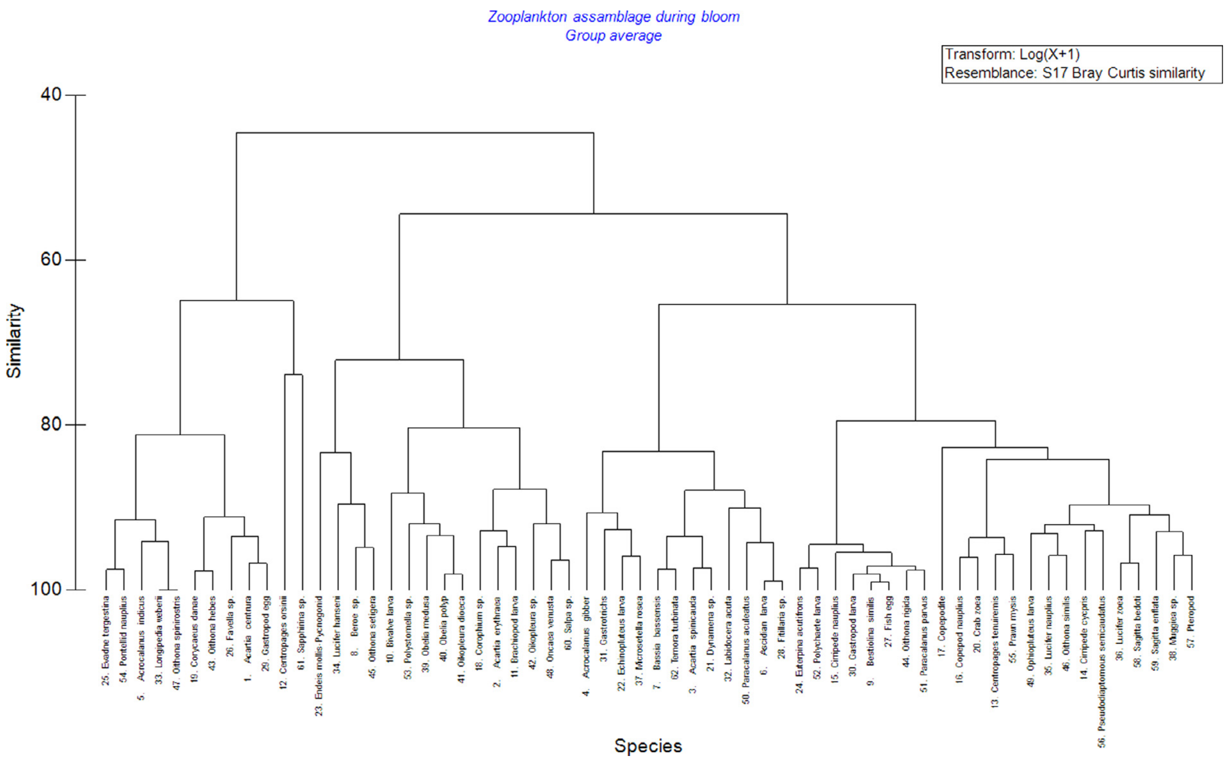

Figure 8 Hierarchical cluster analysis of zooplankton species abundance during the study period (numerical digit given against each species is serial number of the species).

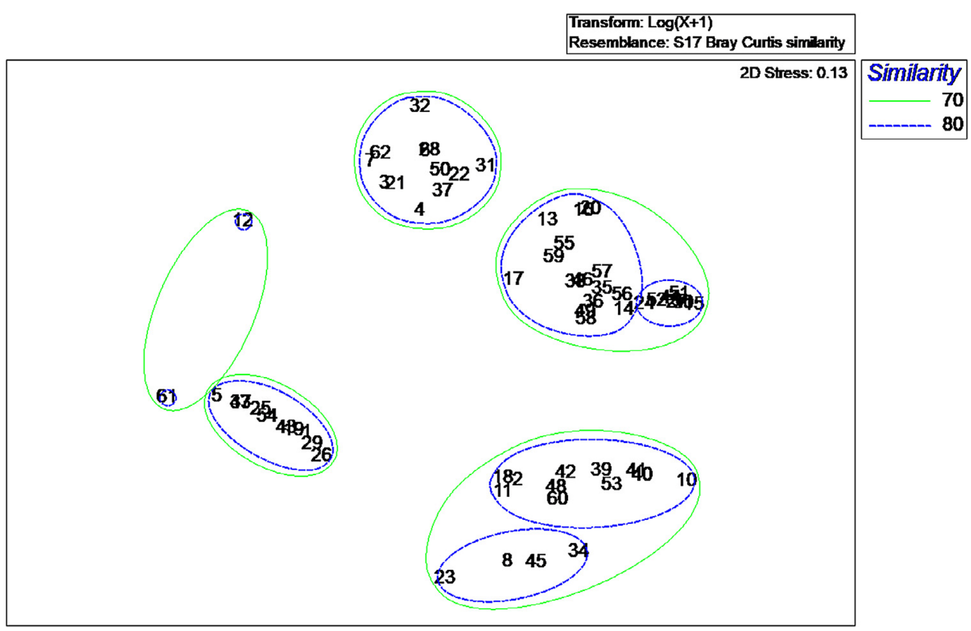

Figure 9 Non-metric multidimensional scaling (nMDS) of zooplankton species showing the species associations (numerical digits represent the species serial numbers as given in Figure 8).

— 10.5%, and Gastropoda larva — 4%). The present study area, with sporadic reefs and power plant-related marine structures, harbors a sizable population of barnacles (sessile Cirripedia) and Bivalvia. The larvae of the localized population of barnacles and bivalves thrived well during the above period as the blooming species *A. glacialis* could have served as the principal food source. Moreover, the increased reproductive capacity of adults during the availability of plenty of food could be another probable cause for the observed increased density of cirripede nauplii during the bloom and post-bloom periods. Naupliar release in barnacles coinciding with phytoplankton blooms have been reported by Barnes (1962) and Starr et al. (1991), and a similar reproduction behavior for urchins and mussels has also

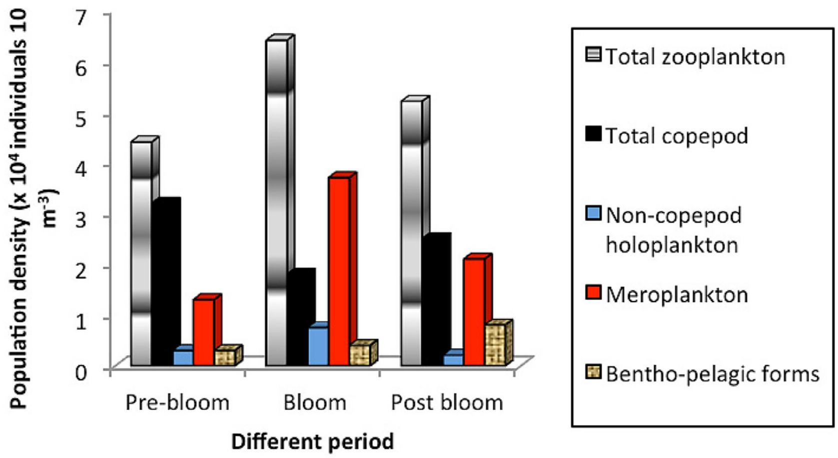

Figure 10 Population density of different groups of zooplankton during the study period.

been observed. Meroplankton showed its highest dominance during the peak bloom period. Fish eggs and larvae were available in substantial numbers during the bloom which indicated their proliferation in diatom standing stock as the food material (Padmakumar et al., 2010). Among NCH, major forms were *Oikopleura dioeca, Lucifer hansenii,* and *Sagitta bedoti*, etc. which all together contributed ~9—10% of the zooplankton assemblage.

The present study was compared with an event of *Trichodesmium* bloom from the same coastal area to find out any similarities or dissimilarities with respect to zooplankton community structure during the blooms. Although *Asterionellopsis glacialis* (Phylum: Ochrophyta; Class: Bacillariophyceae) and *Trichodesmium* (Phylum: Cyanobacteria) are not in the same group of phytoplankton, their blooming creates almost similar kind of environment in the coastal milieu, where qualitative aspects (number of species) of zooplankton showed relatively comparable trends. In the present study, during the peak bloom period, *Bestiolina similis* and *Oithona* spp. were very commonly found in the Copepoda community, whereas, during *Trichodesmium erythraeum* bloom (Sahu et al., 2015), *Canthocalanus pauper, Parvocalanus crassirostris, Pseudodiaptomous serricaudatus, Temora turbinata, Labidocera pavo, Pontellopsis scotti, Pontella securifer, Oithona hebes* were the common forms in Copepoda. Meroplankton population showed Cirripedia nauplii, Gastropoda larvae and Bivalvia larvae were the commonly occurring forms during *A. glacialis* bloom, which is comparable with Sahu et al. (2015), where a unique grouping of various crustacean meroplankters (nauplius, protozoea, post-zoea, mysis, etc.), Bivalvia veliger larvae, Polychaeta larvae and Cirripedia nauplii was reported. However, Echinodermata larva was the meroplankton form that appeared exclusively during the peak bloom period of *T. erythraeum* and neither in pre-bloom nor in the post-bloom period the same has appeared. In non-Copeoda holoplanktonic group, *Oikopleura dioeca* was frequently observed form during the bloom phase in the present study, which is the dominant form during *Trichodesmium* bloom (Sahu et al., 2015) also along with *Sagitta* sp. and two Cladocera species i.e., *Penilia avirostris* and *Evadne tergestina*. These above-mentioned comparisons between two bloom periods from the same location signify the prevalence of similar coastal water quality caused due to such bloom events.

Zooplankton (g 10 m^{-3} dry weights) biomass, which ranged from 0.35—0.62, exhibited almost the same variation trend as population density. The observed lowest value during the pre-bloom period coincided with the lowest abundance of zooplankton and the highest biomass during the bloom period could be ascribed to the overwhelming abundance of cirripede nauplii and bivalve larvae. Previous literature, on the contrary, showed phytoplankton proliferation during the post-monsoon period leading to the observation of higher zooplankton biomass in the near-shore region of SW-BOB (Sahu et al., 2013).

4. Diversity indices

Measurement of the relationship between qualitative and quantitative numbers of a community is known as species diversity. It is known to be low in a physically controlled system (Odum, 1971). Variations in species diversity indices in the present study indicated the change in phytoplankton and zooplankton community structure during different bloom phases. The phytoplankton diversity presented maximum values during the bloom period (4.87) and the lowest (1.05) during the pre-bloom period. The values of species richness and evenness were in tune with phytoplankton species diversity: the lowest (0.07) and highest (3.21) species richness was observed respectively during the pre-bloom and bloom period; evenness values remained low (0.08) during the pre-bloom period, and maximum (0.9) during the bloom period. Similarly, zooplankton diversity (3.1) and richness (2.8) were highest during the peak bloom period and lowest (2.1 and 1.4, respectively) during the post-bloom period. A steady trend was observed for Evenness values throughout the study, and it ranged from 0.3-0.6. This was in tandem with the number of species and population abundance, i.e., essentially due to the abundance of Copepoda such as, Cyclopoida and Poecilostomatoida and meroplankton such as Bivalvia larva and Cirripedia nauplius.

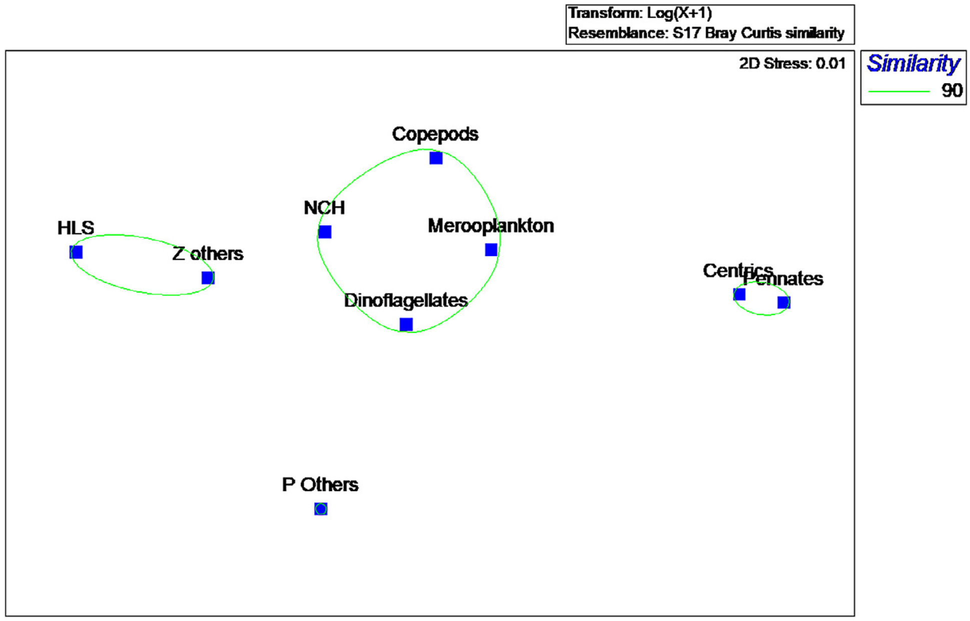

Figure 11 Non-metric multidimensional scaling (nMDS) showing the interrelation between phytoplankton and zooplankton groups during the study.

5. Interrelations between phyto- and zooplankton groups

For assessing the interrelation between phytoplankton and zooplankton during the study, both were segregated into groups. Phytoplankton species were grouped into centric diatoms (Order: Centrales), pennate diatoms (Order: Pennales), Dinoflagellata, others (Cyanobacteria, Chlorophyta, etc.). Similarly, zooplankton species were grouped as Copepoda, meroplankton, non-copepod holoplankton (NCH), holoplankton larval stages (HLS), and others (Gastrotricha, Polystomella — Phylum: Protozoa, Class: Rhizopoda; Obelia — Phylum: Cnidaria, Class: Hydrozoa, etc.). The nMDS analysis with cluster overlay (Figure 11) showed a distinct pattern. Centric (Order: Centrales) and Pennate (Order: Pennales) diatoms were clubbed together indicating their co-occurrence during the study period. Copepoda, meroplankton, Dinoflagellata, and NCH which were encountered with relatively high diversity during the bloom, formed a separate group. HLS and other zooplankton formed a separate group which was commonly observed throughout the study period. With respect to quantitative aspects, the factor plane distribution of plankton groups in the PCA with Varimax rotation showed the overall impact of the bloom on the plankton community. It was observed that Copepoda that contributed significantly (~68.5%) to the zooplankton abundance during the pre-bloom period were negatively loaded on PC1 as well as PC2 (Figure 12). All the other groups of phyto- and zooplankton were positively loaded on both the PCs, which indicated the general increase in abundances of all these groups during the bloom period.

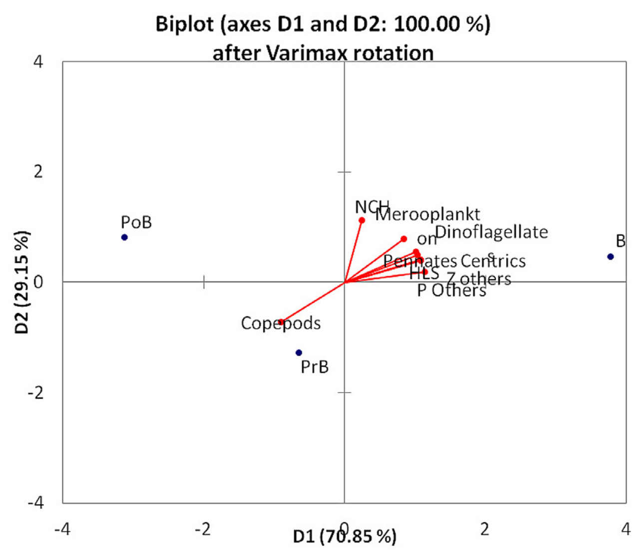

Figure 12 PCA ordination with Varimax rotation, showing the overall impact of the bloom on the plankton community (phyto- and zooplankton are given in groups).

5.1. Classification of bloom periods

Cluster analysis carried out for water quality characteristics supported the observation of temporary change in coastal water characteristics during the bloom period (Figure 13). It showed that the bloom period alone formed a separate cluster whereas; pre- and post-bloom periods formed the other cluster. It can be inferred from the above that either the bloom had altered the physicochemical properties of coastal water or the entire coastal water mass carrying the bloom was drifting along the coast during the observation. The sharp changes in water quality and plankton community structure during the bloom phase indicated the second hypothesis. Similar observations of sudden appearance and disappearance of blooms have been attributed to the drifting water mass that carried the bloom along with it (Mohanty et al., 2010; Satpathy et al., 2007).

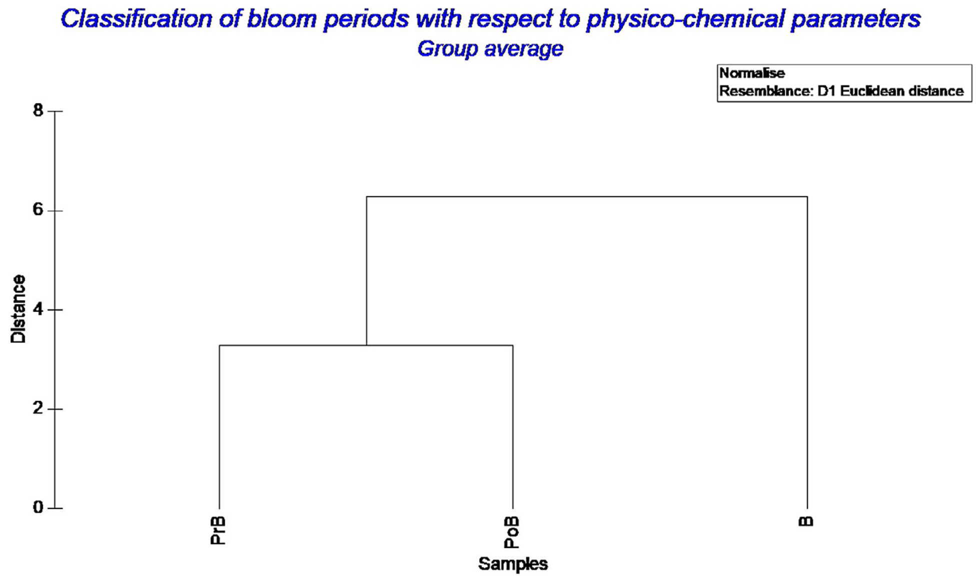

Figure 13 Classification of bloom periods with respect to physico-chemical parameters showing the changes in coastal water characteristics during the bloom.

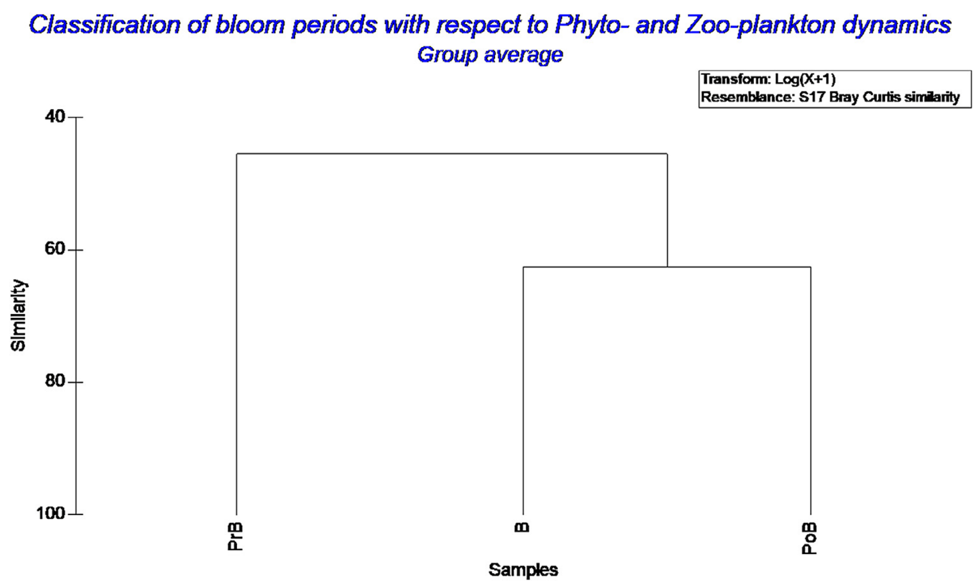

Figure 14 Classification of bloom periods with respect to phyto- and zooplankton dynamics observed during the bloom.

Cluster analysis with respect to phyto- and zooplankton dynamics during the three phases of bloom developed two clusters. Unlike the classification of bloom phases concerning physicochemical parameters, where the bloom period was observed to be a separate entity, the pre-bloom period was found to be different from the other two periods in this case (Figure 14). The bloom and post-bloom periods were more similar to each other with respect to the commonness in species between these two periods. The above observation attributed to the fact that 45 phytoplankton species and 15 species of zooplankton were common between bloom and post-bloom period (Figures 4 and 8), which are the highest among all the combinations possible among the three phases of bloom, except common species found during all the phases.

5.2. Interrelations between bloom and other parameters

Multivariate statistical analyses are considered to be more useful for detecting the variations in complicated data containing biotic and abiotic variables. The usefulness of multivariate analyses to analyze spatiotemporal variations between communities and their variations with changing ecological and climatic conditions has been depicted by various authors (Hourston et al., 2009; Jiang et al., 2011a,b, 2012; Kim et al., 2007; Xu et al., 2011a,b,c). Biota-environment (BIOENV) analysis was carried out to find the correlations between phytoplankton abundances and environmental variables observed during the bloom period (Table 4). The BIOENV analysis aims to select a set of abiotic param-

Table 4 The best results.

No.	Vars	Corr. Selections
1	1.000	Nitrate
2	1.000	Salinity, Phosphate
2	1.000	Salinity, Ammonia
2	1.000	Salinity, Zooplankton
3	1.000	Salinity, nitrate, Phosphate
3	1.000	Salinity, Nitrate, Ammonia
3	1.000	Salinity, Nitrate, TN
3	1.000	Salinity, Nitrate, Zooplankton
4	1.000	Temperature, Salinity, Nitrate, Phosphate
4	1.000	Temperature, Salinity, Nitrate, Ammonia

eters that significantly impact the distribution patterns of phytoplankton groups in the community. The BIOENV test was carried out by maximizing the Spearman rank correlation between the resemblance matrices of environmental and biotic variables (Euclidean distance) and community abundances (Bray-Curtis distance) (Izquierdo and Guerra-García, 2010). Results of BIOENV analysis (with maximum ten variable combinations) confirmed that a set of variables, such as salinity, nitrate, phosphate, ammonia, zooplankton, TN, and temperature, is related to the *A. glacialis* abundance. Even though ten variable combinations were chosen for BEST analysis, the results were truncated at a maximum of four parameters combination, indicating that all the studied parameters were not important with respect to the bloom formation. Salinity and/or nitrate seems to have played important roles in the proliferation of *A. glacialis* or the bloom formation as these were the only two parameters found in all the combinations of BEST results which has also been reported by others (Baliarsingh et al., 2016; Srichandan et al., 2019) as the controlling factor of blooms.

Principal component analysis for both planktonic and environmental variables yielded two PCs. These two PCs contributed to 100% of the variance and indicated that the state of the coastal environment during the study could be divided broadly into two periods. The PC1, which contributed 81.77% of the variance, represented the bloom and post-bloom period with significant positive/negative factor loadings of all the variables except salinity and nitrate (Figure 15). The second PC was positively loaded with salinity and nitrate, representing the pre-bloom period. Thus, PCA results indicated a change in salinity and nitrate that mainly influenced the bloom formation in the coastal waters. The above observations corroborated the results of BIOENV results.

6. Conclusion

Optimum temperature, salinity, and nutrient levels prevailed during the post-northeast monsoon period, led to the appearance of *A. glacialis* bloom in the coastal waters of Kalpakkam. Results of BIOENV analysis and PCA confirmed that salinity and/or nitrate played important roles in the proliferation of *A. glacialis* or the bloom formation. Cluster analysis further supported the distinct state of coastal water during the bloom pertaining to physicochemical properties. The cluster and nMDS analysis confirmed a considerable impact of the bloom on the plankton dynamics in the coastal waters of Kalpakkam. The peak bloom period was characterized by the dominance of meroplankters especially, Cirripedia nauplii and Bivalvia larvae over Copepoda. Among Copepoda, Cyclopoida and Poecilostomatoida (mostly carnivorous) exceeded the Calanoida population (mostly herbivorous) during the peak bloom period. The observations were supported by the PCA ordination plot for the quantitative aspects of phytoplankton and zooplankton groups. Such alterations in the plankton community structure could be attributed to the intra- and inter-community interactions of plankton assemblages in the ambiance. Coastal waters thus demand continuous monitoring to find out the impact of such phenomenon and its relation to alteration in the ecosystem either due to natural processes or anthropogenic activities.

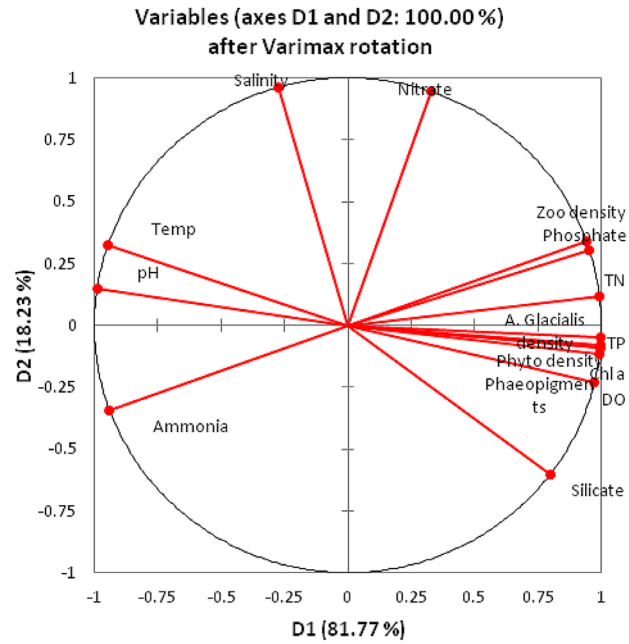

Figure 15 PCA ordination with vectors for both planktonic and environmental variables indicating the probable cause of bloom in the coastal waters.

Declaration of competing interest

The authors declare that there is no conflict of interest in this manuscript.

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