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A preliminary study on the environmental factors triggering frequent bloom of diatom *Asterionellopsis glacialis* (Castracane) Round 1990 along west coast of Bay of Bengal

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A time-series observation of *Asterionellopsis glacialis* (Castracane) Round 1990 bloom in the surf zone of east coast of India and associated physico-chemical parameters, was carried out during pre-monsoon period (May 2018). This study also reviews the species status as a surf-zone diatom and its temporal characteristics. Referring to the earlier study, the temporal characteristic of *A. glacialis* bloom in Indian context can be classified as "sporadic" due to the alteration of blooming community and may be also further investigated for its seasonality as the bloom mostly observed during the pre-monsoon season. Among the nutrients, silicate is identified as a major factor controlling the bloom of *A. glacialis*. The present study highlights the introduction of biogenic silica attributed to precipitation induced land runoff and the effect of wind as important environmental factors responsible for *A. glacialis* proliferation in nearshore waters of east coast of India.

[**Keywords**: Algal bloom, *Asterionellopsis glacialis*, Bay of Bengal, Silicate, Wind]

Introduction

Surf-zone diatoms are responsible for discoloration of near shore waters, especially the surf-zone[1]. The discoloration caused by these diatoms could be considered to be either a "bloom" such as "surf bloom" as in South Africa or "oceanic bloom" as in India or an "accumulation" as in South America and Australia[2]. The patch formation by these diatoms is due to their ability to rise to the surface trapped in between air bubbles that are formed when waves break[3]. These diatoms are the major primary producers in this region and represent a potential and efficient source of energy for different trophic levels of the food chain including the interstitial fauna and decomposers[1]. The blooming of surf-zone diatoms is also known to attract certain fishes especially mullets[3]. The patches formed by diatoms are not permanent features of the surf-zone, rather considered as temporal phenomena of the bloom, and is influenced by four peculiar characteristics of the surf-zone diatom, such as "diel" (cell patches form in the morning and wane at dusk before disappearing by nightfall), "mesoscale" (regular periodicity of appearance and disappearance), "seasonality" (occurrence reported during particular season) and "sporadic" (sporadic alteration of blooming community)[1,4].

Seven species have been identified globally as surf-zone diatoms *viz. Anaulus australis* Drebes & Schulz, 1989; *Asterionellopsis glacialis* (Castracane) Round 1990; *Asterionellopsis socialis* (J. C. Lewin & R. E. Norris) R.M. Crawford & C. Gardner, 1997; *Attheya armata* (T. West) R. M. Crawford, 1994; *Aulacodiscus johsonii* Arnott ex Pritchard, 1861; *Aulacodiscus kittonii* (Janisch) Sims & Holmes (1983) and *Aulacodiscus petersii* Ehrenberg, 1845[(refs. 3,5)]. *A. glacialis* is described as a non-toxic bloom forming species producing dark greenish-brown patches in water[6]. Global occurrence of their blooms has been reported at latitudes between 24°49′ N and 34°42′ S (Fig. 1). Their blooms has been observed from six countries namely New Zealand[2], Australia[2,7], India[8-16], Pakistan[6], South Africa[2,17] and Brazil[2,3,18,19].

In India, the diatom (*A. glacilais*) bloom has been recorded exclusively from east coast, located at Gopalpur, Rushikulya estuary, Bahuda estuary, Visakhapatnam, Vellar estuary and Kalpakkam[8-11,13-15].

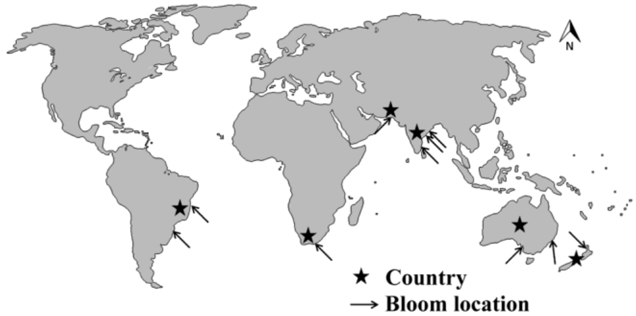

Fig. 1 — Global occurrence of *Asterionellopsis glacialis* blooms between 1954 and 2017

The present study evaluates the interrelationship between the environmental variables and *A. glacialis* bloom occurred during pre-monsoon or summer season (May 2018) in nearshore waters of Gopalpur, east coast of India. In addition, the collected data is compared with the earlier reports of *A. glacialis* bloom from India to quantify its temporal characteristics in the Indian coast.

Materials and Methods

Bloom of *A. glacialis* was observed while regular field visits during May, 2018 in surf-zone waters of Gopalpur (19º15′30″ N, 84º54′43″ E), east coast of India. The site is located at a close proximity with estuaries (Rushikulya and Bahuda) draining into the Bay of Bengal. The study region experiences three distinct seasons such as pre-monsoon (March-June), monsoon (July-September) and post-monsoon (October-February)[11]. The field data was collected from the peak of the bloom to waning of the bloom period. Field surveys were carried out twice a day (morning 7:30 AM and evening 4:30 PM) during 9 – 15, 22 – 23 and 28 May 2018. Samples were collected from a fixed location in the surf zone. Salinity and water temperature were recorded by using water quality probe (Hannah HI98914). Dissolved Oxygen (DO) concentration was measured by adopting Winkler's titrimetric method[20]. Water samples for the estimation of dissolved inorganic nutrients (nitrite, nitrate, ammonium, phosphate, silicate) were collected in pre-cleaned plastic bottles, filtered through a glass fiber filter (GF/F) paper and then analyzed in a spectrophotometer following standard methods[20]. Estimation of chlorophyll-*a* (Chl-*a*) concentration was analyzed by following Parsons *et al*.[21]. A known volume of water sample was filtered through a glass fiber filter (GF/F) paper. Subsequently, the filter papers were extracted in 90 % acetone. After 24 hours of extraction period, the absorbance of the supernatant was measured using UV-Visible spectrophotometer (LABMAN, LMSP-UV1000B).

The phytoplankton samples were collected through a hand-held plankton net (65 µm) by filtering a known volume of water by using a bucket. The collected plankton samples were preserved with Lugol's iodine solution for further analysis. An aliquot of sample was taken in Sedgwick Rafter chamber and observed under a compound light microscope (Olympus CKX53SF) and identified up to the genus level referring standard identification keys[22]. The cell concentration was expressed as cells l^{-1}.

In order to delineate the spatial spread of the bloom, daily Chl-*a* products of ocean colour sensor Moderate Imaging Spectroradiometer onboard Aqua satellite (MODISA) was averaged for May 2018 with aid of SeaDAS (v. 7.5) software. The sensor default atmospheric correction scheme and bio-optical algorithm were applied for retrieval of Chl-*a*. The rain gauge measured rainfall data was acquired from the Indian Meteorological Department (IMD) regional centre, Gopalpur. Wind speed and direction were extracted from Advanced Scatterometer (ASCAT) with 0.25 degree resolution. Pearson correlation matrix was performed to understand the relation between chemical and biological parameters.

Results

Environmental variables such as DO, water temperature, salinity, nutrients (nitrite, nitrate, ammonium, phosphate and silicate) recorded during the study period are presented in Figure 2. During the study period, the salinity ranged between 29.00 – 33.89 psu (32.99±1.07) and water temperature within 25.60 – 30.01 °C (27.87±1.29). DO concentration varied within 5.95 – 7.58 mg l^{-1} (6.47±0.57) with maximum record during 10th May evening and minimum during 23rd May. Inorganic dissolved macronutrients such as nitrite, nitrate, ammonium, phosphate and silicate varied within 0.19 – 1.61 µmol l^{-1} (0.75±0.41), 0.76 – 5.39 µmol l^{-1} (3.14±1.59), 0.11 – 0.77 µmol l^{-1} (0.24±0.15), 0.34 – 1.98 µmol l^{-1} (1.08±0.67) and 2.08 – 18.54 µmol l^{-1} (8.92±5.59), respectively. The concentration of the nitrite and nitrate showed a continuous fluctuating pattern with higher concentration during day and lower during evening. Though their concentration decreased during evening, it again increased in the next day morning

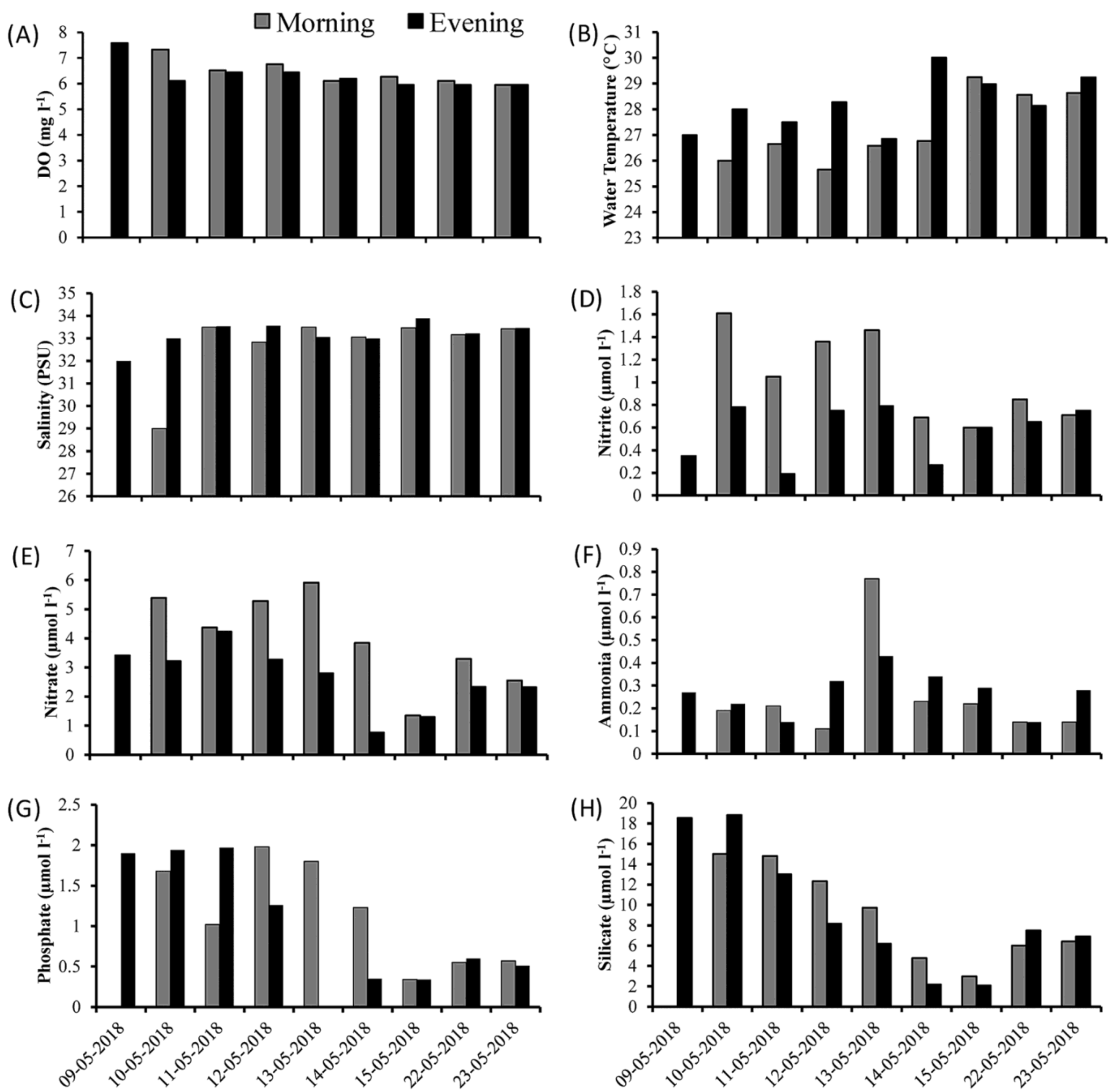

Fig. 2 — Environmental variables recorded from Gopalpur coast during the study period

throughout the study. However, the concentration of silicate showed a similar trend as nitrite and nitrate with higher concentration during morning, with constant decrease in their concentration day by day. No such pattern was observed for phosphate and ammonium concentrations. During the study period (May 2018), rainfall was observed only on 10th May (1.8 mm) and 12th May (2.8 mm).

The cell concentration of *A. glacialis* was higher in the evening as compared to the morning hours (Fig. 3). Chlorophyll-*a* concentration ranged between 0.41 – 18.84 mg m^{-3} where maximum concentration was recorded on 9th May evening and minimum during 14th May morning. The cell concentration of phytoplankton recorded during the study is presented in Table 1. Monospecific bloom of

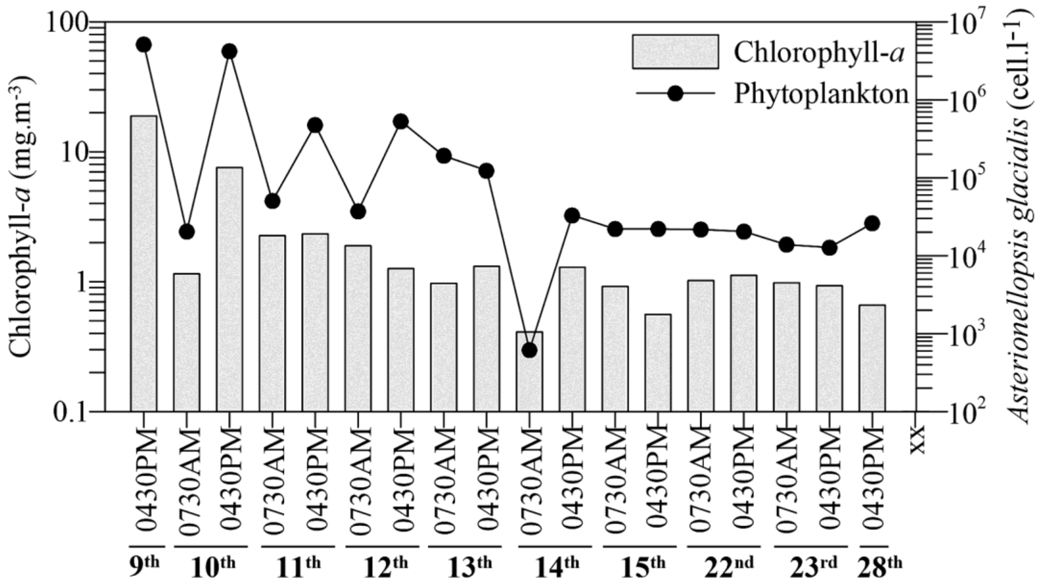

Fig. 3 — Cell abundance of *Asterionellopsis glacialis* and chlorophyll-*a* concentration during the study period

Table 1 — Cell density (cells l^{-1}) of major phytoplankton species during the study period

Date	Time	*Asterionellopsis glacialis*	*Pseudonizschia* sp.	*Noctiluca* sp.	*Chaetoceros* spp.	*Coscinodiscus* sp.
9th-May	4:30PM	5160000	-	0	-	-
10th-May	7:30AM	20400	-	36	-	12
	4:30PM	4220000	-	0	-	-
11th-May	7:30AM	50300	-	24	-	60
	4:30PM	477000	-	0	-	50
12th-May	7:30AM	37200	-	0	-	385
	4:30PM	531000	-	0	-	150
13th-May	7:30AM	191000	-	0	-	-
	4:30PM	124000	-	15	60	60
14th-May	7:30AM	620	-	120	-	40
	4:30PM	33000	29000	3000	6000	-
15th-May	7:30AM	22000	48000	6000	4000	2000
	4:30PM	22000	36000	-	-	-
22nd-May	7:30AM	21666	-	-	50	2166
	4:30PM	20500	-	-	2750	-
23rd-May	7:30AM	13833	-	-	500	16666
	4:30PM	12780	-	-	1560	1200
28th-May	4:30PM	26000	600	-	-	-

A. glacialis was observed during 9th and 10th May evening and 13th May morning. However, *A. glacialis* did not only dominate in the phytoplankton sample, other phytoplankton also occasionally dominated. Other phytoplankton species recorded during the study with low to medium cell concentration are *Chaetoceros* sp., *Coscinodiscus* sp., *Noctiluca* sp., and *Pseudonitzschia* sp. Maximum cell concentration (5.16×10^6 cells l^{-1}) of *A. glacialis* was observed on 9th May evening. On 14th May morning (7:30 AM), the cell concentration declined drastically to 620 cells l^{-1}. In the evening, the concentration of *A. glacialis* again increased to 3.3×10^4 cells l^{-1} with an appearance of other phytoplankton species such as *Pseudonitzschia* sp. (2.9×10^4 cells l^{-1}), *Noctiluca* sp. (3×10^3 cells l^{-1}) and *Chaetoceros* spp. (6×10^3 cells l^{-1}). The cell concentration of *Pseudonitzschia* sp. (4.8×10^4 and 3.6×10^4 cells l^{-1}) was higher than that of *A. glacialis* (2.2×10^4 cells l^{-1}) during 15th May morning and evening, respectively. However, *A. glacialis* again dominated in subsequent days. Cell concentration of *Coscinodiscus* sp. was high

(1.66×10^4 cells l^{-1}) in the morning of 23 May, however *A. glacialis* again dominated (2.6×10^4 cells l^{-1}) on 28th May evening. Additionally, *Ceratium* spp., *Pleurosigma* sp., *Navicula* sp., *Cylindrotheca* sp. and *Rhizosolenia* spp. were recorded with very low cell concentration.

The satellite-retrieved monthly average (May, 2018) Chl-*a* concentration was 0.65±0.07 mg m^{-3}. The satellite image shows low Chl-*a* concentration in the offshore waters (red box, Fig. 4). It could not detect the surf zone Chl-*a*. Therefore, it can be said that the bloom is confined in a narrow patch of nearshore waters.

The wind direction over the study region clearly showed south-south-west that is towards the coast with higher magnitude on 8th May (Fig. 5). Whereas, on 13th May, wind was from west and away from the coast. On the other days, the magnitude of the wind was relatively low.

From the correlation analysis (Table 2), it was observed that Chl-*a* is the better representation of phytoplankton abundance (r = 0.931, n = 17, p < 0.01). Nitrate-phosphate and silicate-phosphate showed positive correlation implying that all three have a common source. Chlorophyll-*a* is correlated positively with silicate (r = 0.645, n = 17, p < 0.01) and also with phosphate (r = 0.467, n = 17) but with p = 0.059. Significant correlation between Chl-*a* and silicate suggest silicate may be the controlling parameter for the bloom. The N:P ratio (4.54±1.71) was always lower than Redfield ratio (N:P = 16) suggesting that dissolved inorganic nitrogen as the limiting factor. The Si:N ratio (2.14±1.05) was greater than Redfield ratio (Si:N = 1) suggesting that silicate is not the limiting factor for the phytoplankton production.

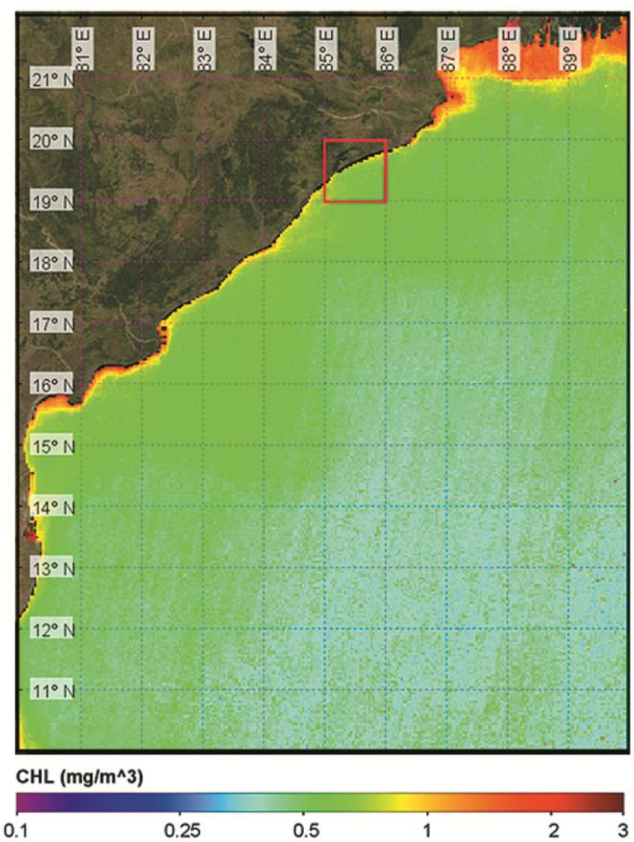

Fig. 4 — Monthly average (May, 2018) satellite (Moderate Imaging Spectroradiometer onboard Aqua satellite) retrieved chlorophyll-*a* concentration in Gopalpur coast, western Bay of Bengal

Earlier reports of *A. glacialis* bloom along the Indian coast was collected along with the cell concentration, Chl-*a* concentration and environmental parameters, and compared with the data collected during the present study (Table 3). The values of parameters such as DO and nutrients were taken on the day having highest cell density of *A. glacialis* per liter during the recorded bloom period, whereas the values mentioned in other units are converted to mg l^{-1} and µmol l^{-1}, respectively. In Indian waters, the bloom of *A. glacialis* was recorded from estuaries, surf-zones as well as from the offshore waters. It was observed that all the earlier bloom records of *A. glacialis* are restricted to the east coast of India and most of the records are from the South Odisha region (Rushikulya estuary, Gopalpur and Bahuda estuary). Majority of the blooms are recorded during the pre-monsoon period (March-June) and most of the records are during May. The cell concentration of *A. glacialis* ranged between 1.52×10^4 to 54.5×10^6 cells l^{-1}. Water temperature ranged between 24.1 – 30.0 °C, salinity ranged between 19.9 – 35.1 psu and DO ranged between 2.95 – 7.98 mg l^{-1}. Similarly, nutrients like nitrite, nitrate, phosphate and silicate ranged between 0.002 – 6.11 µmol l^{-1}, 0.01 – 13.25 µmol l^{-1}, 0.002 – 1.9 µmol l^{-1} and 0.29 – 200 µmol l^{-1}, respectively. Chlorophyll-*a* concentration ranged between 2.4 – 132.1 mg m^{-3}.

Discussion

In Indian context, the blooms of *A. glacialis* have been reported from estuary, surf-zone and offshore waters as well. The bloom has been reported from estuaries such as Rushikulya, Bahuda and Vellar[9,11,13] and from the off-shore waters of Visakhapatnam, Kalpakkam and Gopalpur[8,14,23]. The present study confirms the occurrence of *A. glacialis* bloom in the

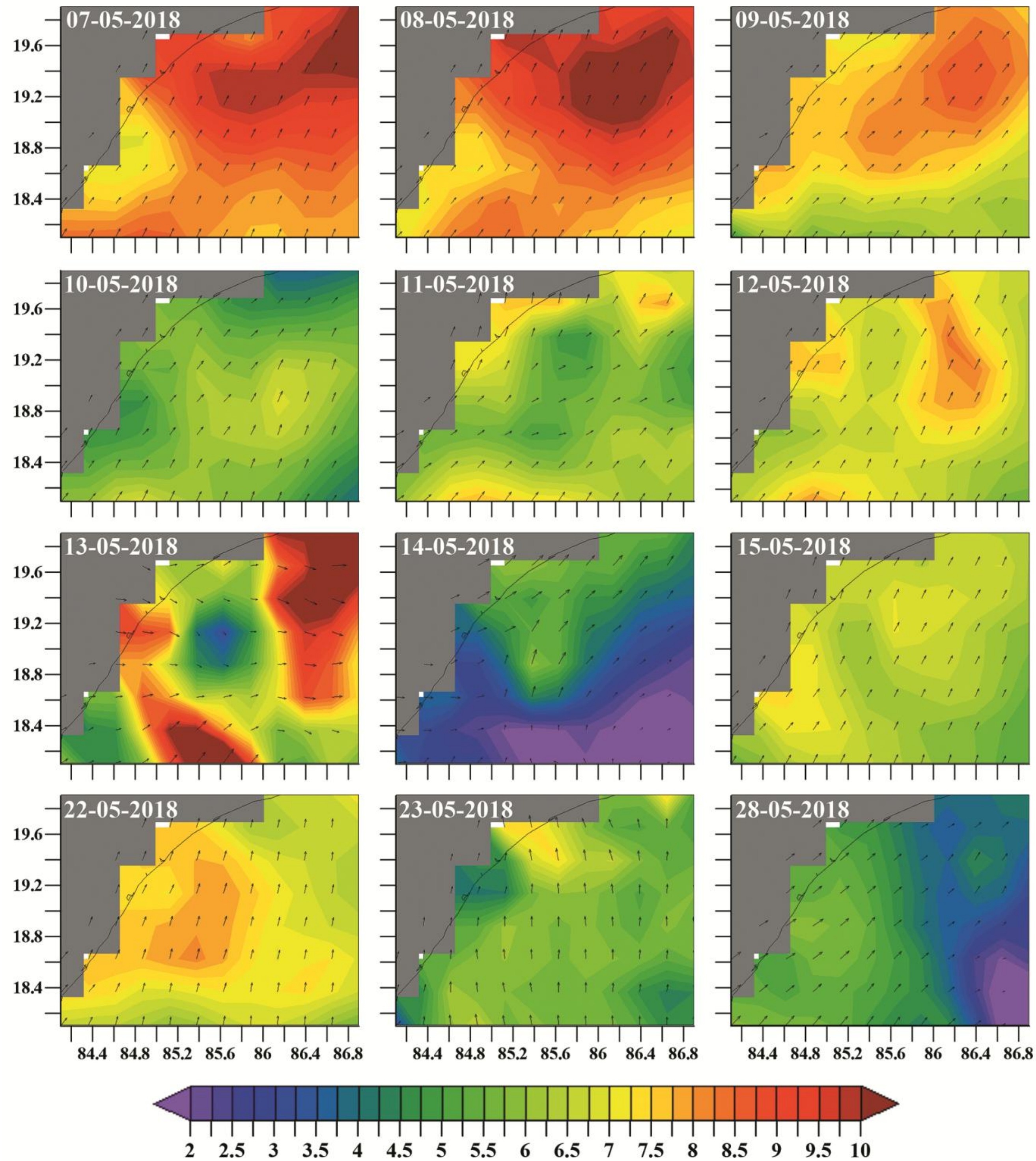

Fig. 5 — Wind direction (arrow marks) overlaid on wind speed (in m/s, the filled colour patten) during bloom period in coastal waters of Gopalpur, east coast of India. X and Y axes represent longitude (degree east) and latitude (degree north), respectively

surf-zone of Gopalpur. Odebrecht *et al*.[5] briefed that there are seven species which have been designated as surf-zone diatoms and *A. glacialis* is one among them. As the bloom of *A. glacialis* has also been reported from the estuaries and off-shore waters, considering the same as surf-zone diatom is probably uncertain.

The cell concentration of *A. glacialis* was observed high in evening and low in morning during the peak

Table 2 — Pearson correlation matrix of major chemical and biological parameters (n = 17, **$p < 0.01$, *$p < 0.05$)

	Cell density	Nitrite	Nitrate	Ammonium	Phosphate	Silicate
Chlorophyll-*a*	.931**	-.226	.096	.002	.467	.645**
Cell density		-.209	.069	.028	.509*	.673**
Nitrite			.749**	.284	.388	.340
Nitrate				.247	.813**	.663**
Ammonium					.164	-.040
Phosphate						.834**

Table 3 — Comparative table with water quality parameters and cell density of *Asterionellopsis glacialis* bloom along Indian coast

Location	Month	Max cell density (cells l^{-1})	Water temperature (°C)	Salinity (psu)	DO (mg l^{-1})	Nitrite (µmol l^{-1})	Nitrate (µmol l^{-1})	Ammonium (µmol l^{-1})	Phosphate (µmol l^{-1})	Silicate (µmol l^{-1})	Chl-*a* (mg m^{-3})	Reference
Off Visakhapatnam	April	93.2×10^6	24.1	34.81	2.96	-	-	-	1.75	25	36.0	Subba Rao[8]
Vellar Estuary	October	0.0152×10^6	28.0	19.9	-	3.0	24.8	-	1.20	48.1	-	Mani *et al.*[9]
RushikulyaEstuary	April-May	0.0852×10^6	29.0	34.1	7.97	0.19	0.42	-	1.07	6.29	-	Panigrahy & Gouda[11]
Gopalpur	March-May	~0.12×10^6	29.2	33.8	7.85	-	~0.4	-	~0.2	~4.0	~60	Choudhury & Panigrahy[10]
Covelong (Chennai)	May	0.3×10^6	30.0	35.15	7.93	0.13	0.21	-	0.01	7.12	2.49	Rajendran & Kannan[12]
Bahuda Estuary	May	2.14×10^6	29.5	31.26	6.13	<0.01	0.43	-	0.42	28.73	-	Mishra & Panigrahy[13]
Off Kalpakkam	May	54.5×10^6	32.0	35.6	4.0	0.4	3.0	-	0.9	9.0	~20	Satpathy & Nair[14]⋆
Gopalpur	March-April	27.3×10^6	26.37	31.35	7.98	<0.01	0.02	-	<0.01	0.29	132.2	Sasamal *et al.*[15]
Kalpakkam	January	56.3×10^6	26.2	32.8	7.2	0.07	1.32	0.00	0.75	3.45	15.9	Sahu *et al.*[16]
Gopalpur	May	5.16×10^6	27	32	7.5	0.35	3.41	0.27	1.9	18.54	18.8	Present study

⋆Provided parameter values are not clear

of the bloom period when cell concentration was high (9th to 13th May). This can be explained by considering the wind factor. In morning times, the wind was low, so the *A. glacialis* chains got dispersed in near shore waters; while in afternoon time, when the wind speed was high, the chains started to aggregate near the beach water. *Asterionellopsis* is thermophilic in nature and exhibits higher growth rate over short time period[24,25]. Literature review also depicts the same with occurrence of the species bloom in the study region mostly during pre-monsoon when the water temperature is relatively high. Therefore, the higher temperature during the afternoon is probably the factor resulted in rapid multiplication of cells and hence increased their population during the evening time.

The patches formed by surf-zone diatoms can be classified as four major temporal characteristics such as diel, mesoscale, seasonality and sporadic[1,4]. The seasonality feature stands for occurrence of the bloom of particular species during a particular season. Along the Indian coast, the blooms of *A. glacialis* are reported to occur mostly during the pre-monsoon season (March to June) with peak during May. However, more extensive year-round studies are required to confirm the seasonality feature for occurrence of the species bloom along the Indian coast as Sahu *et al.*[16], reported a bloom of *A. glacialis* during the winter/ post-monsoon season (January) from the coastal waters of Kalpakkam, Tamil Nadu, India.

Additionally, *A. glacialis* is not the permanent dominant species during the bloom period as noticed during the present study. The community alters between dominancy of *A. glacialis*, *Pseudonitzschia* sp. and *Coscinodiscus* sp. The phenomenon which comprises the sporadic alteration of blooming community is classified as “sporadic” variability. So the study concludes that the bloom of *A. glacialis* in the Indian context can be classified as both seasonal and sporadic.

Earlier reports suggest that the upwelling and wind are the factors which trigger the bloom of *A. glacialis*[19,26]. Gouda & Panigrahy[26] reported that, the upwelling brings the much required nutrients from the sub-surface layer which enhances the concentration of *A. glacialis*. An earlier study reported that wind also plays a significant role in accumulating the *A. glacialis* cells along the surf-zone and thus, majorly attributes in controlling their concentration and variability[19]. The concentration of *A. glacialis* during the present study was high on 9th May. The wind direction plots depict that on 8th May 2018, wind was from south-south-west *i.e.* an onshore wind with higher magnitude. The density of *A. glacialis* was relatively low during 14th morning and the wind direction plots show that on 13th May, wind was from west and away from the coast. This supports the finding of Odebrecht *et al*.[19] that wind factor plays a crucial role in the accumulation of *A. glacialis*. The correlation matrix suggests the common sources of nitrate, phosphate and silicate. The summer season have least river drainage from the watershed. Therefore, the major source of nutrients here would be from wind-induced water column mixing or upwelling that replete the surface water nutrients.

It was also observed that silicate exhibited a good correlation with Chl-*a* (r = 0.645, $p < 0.01$, n = 17) and cell density (r = 0.673, $p < 0.01$, n = 17). The concentration of *A. glacialis* was high on 10th May when the concentration of silicate was also relatively high. The rainfall recorded during the 10th May might be another factor which probably introduced the terrigenous biogenic silica into the system thus boosting the multiplication of *A. glacialis*.

Conclusion

A time series study was undertaken in Gopalpur coast during pre-monsoon season to unravel the environmental factors triggering recurrent blooms of the diatom *A. glacialis*. From the study, the following conclusions were obtained - (i) the bloom of *A. glacialis* is "sporadic" and may be "seasonal" as well in the Indian context as revealed from the present study and earlier reports, (ii) the wind played a significant role in bloom formation by cell accumulation and nutrient replenishment, (iii) upsurge in *A. glacialis* abundance is also correlated to the concentration of silicate as the coastal water possibly received an input of terrigenous biogenic silica due to rainfall-induced land run-off and upwelling.

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Conflict of Interest

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Author Contributions

SP: Field survey, data acquisition and manuscript preparation; SP, BKS, SKB & KCS: Data analysis, data interpretation, manuscript preparation and critical analysis.

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