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Understanding the response of phytoplankton to the cyclonic event Sitrang: A case study in the Hooghly estuary of Sundarban Bay of Bengal region

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Abstract: The study aims to investigate the impact of tropical cyclone Sitrang on the phytoplankton community and water quality parameters at estuarine zone of Hooghly River near Namkhana region of Sundarban. Focusing on the response of diatom and dinoflagellates to this post-monsoonal cyclone this study tries to address the questions regarding short-term ecological effects, including changes in water quality, shifts in the phytoplankton composition and abundance, and the potential factors driving these changes. Water samples were collected for consecutive three days before and six days after the occurrence of the Sitrang in October 2022. A substantial drop in pH, DO, and temperature after the immediate passage of the cyclone along with increased salinity, chlorophyll-a content, inorganic macronutrients, and TDS were observed. The cyclone led to a significant reduction in phytoplankton diversity, while concurrently causing a notable increase in their abundance. Prior to the cyclone 45 species of diatoms and 8 species of dinoflagellates were observed which was reduced to 25 and 6 species after the cyclone. Post-cyclonic period exhibited high predominance of dinoflagellates especially *Tripos* sp., and *Noctiluca scintillans* (4.3×10^3 cells/L). Canonical correspondence analysis (CCA) revealed nitrate and salinity are the major factors influencing phytoplankton abundance. The notable phenomenon of massive increase in the number of *Tripos furca* (2.04×10^4 cells/L) suggests their favourable growth condition triggered by the cyclone. Due to the rising intensity of cyclones in the Indian Sundarbans, close monitoring and continuing research is essential for a thorough understanding of phytoplankton dynamics.

Introduction

Cyclonic storms are frequent occurrences in the Bay of Bengal, with significant implications for marine and coastal ecosystems (Mohanty, 1994). The high velocity of winds and huge amounts of rainfall associated with the storm severely affect the water quality. Cyclones passing the coastal and marine areas brought physical perturbation including upwelling, vertical mixing, terrestrial water runoff, and sediment resuspension that feed the euphotic layer with nutrients (Subrahmanyam et al., 2002). As a result, biomass and productivity of phytoplankton considerably rise. However, cyclones can also have negative consequences for phytoplankton. The strong winds and turbulent conditions associated with cyclones can disrupt the upper ocean layer, mixing and dispersing phytoplankton populations (Hallegraeff, 2010). Depending on the characteristics of the cyclone and the pre-cyclonic ocean condition, cyclone-induced changes can vary significantly in terms of severity and even the scale of alterations (Mallin, 2002). Cyclones can diminish overall phytoplankton biomass and affect the stability of the marine food web. Additionally, excessive rainfall and runoff from the storm can introduce pollutants and sediment into coastal waters, potentially

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impacting phytoplankton growth and health (Wetz and Yoskowitz, 2013; Du et al., 2020). Increased nutrient content in the upper-lit zone can intensify proliferation of phytoplankton which sometimes results in harmful algal bloom (Miller et al., 2006; Tsuchiya et al., 2014; Srichandan et al., 2021). Harmful algal bloom can deplete the oxygen level and directly impact fish, shellfish, and other aquatic animals. This can have cascading effects on higher trophic levels and food web (Anderson, 2009).

The Sundarban, located in the coastal region of the Bay of Bengal is prone to cyclones due to its geographical location (Halder et al., 2021). The Bay of Bengal is a semi-enclosed tropical ocean basin that experiences heavy monsoon influences and gets significant amounts of freshwater from river flow and rainwater (Sahoo and Bhaskaran, 2016). In particular Bay of Bengal experiences two primary cyclonic seasons: pre-monsoon (April–May) and post-monsoon (October–November). During the post-monsoon, high sea surface temperatures, adequate moisture, and instability in the atmosphere support the formation of cyclonic systems. These systems are known as "post-monsoon depressions" or "post-monsoon cyclones which bring heavy rainfall and strong winds to coastal regions, chiefly affecting parts of eastern India (Girishkumar and Ravichandran, 2012). Hooghly River estuary is the confluence of freshwater from the river and saline water from the Bay of Bengal, creating a unique and dynamic ecosystem that supports a variety of flora and fauna. This estuarine water also plays a significant role in the economy and livelihoods of the local communities. It supports fishing activities, providing a source of income for many people living along its shores (Mitra and Zaman, 2016). Understanding how tropical cyclones impact phytoplankton can provide valuable insights into the dynamics of estuarine ecosystems of the Sundarban region and their responses to extreme weather events. The effects of cyclone-induced shifts in phytoplankton can contribute to our knowledge of the resilience and vulnerability of these ecosystems in the face of changing climatic implications in a broader aspect. With the increasing frequency and intensity of cyclones due to climate change, there is a growing need for vast studies to understand how estuarine ecosystems respond and adapt.

Sitrang, the tropical cyclone named by Thailand, actually emerged on 17th October, 2022, offshore of the Andaman and Nicobar Islands near the Bay of Bengal. A low-pressure area of the atmosphere developed into a depression, which later developed into a deep depression on 22nd October, and on October 23rd, it became more powerful and attained the status of a cyclonic storm. Sitrang was supposed to develop into a powerful cyclone but failed to happen due to the dry air rise. Though the storm made landfall in Bangladesh and dissipated on 25th October, but also impacted the study area of Hooghly Estuary (Fig. 1). IMD data revealed a rainfall of 4.51 mm on 24th October and 19.8 mm on 25th October in the study area.

Materials and Methods

In this study, we have conducted regular field investigations from 21st to 30th of October before and after the passage of tropical cyclone Sitrang in the estuarine waters around Namkhana region of Sundarban. A flowchart of the proposed research methodology is given in Fig. 2.

Study Area

The study area (Fig. 3) was the connecting riverine zone between Hooghly River and Hatania-Doyania River and offshore of the Bay of Bengal. This region is ecologically significant and unique due to its position and plays a crucial role in terms of mixing of freshwater and high tidal sea water, and nutrient transport. Additionally, the river channel serves as a local harbor for trawlers and motorized fishing boats since it is exposed to the sea at both ends. Anthropogenic wastewater and local drainages are discharged directly into the river, raising nutrient load of the study area. Surface water samples were taken from three sites [Station-1 (21.76056, 88.23628 near Namkhana Bridge), Station-2 (21.754776, 88.267445 near Madanganj), Station-3 (21.727693, 88.266245 near Dwariknagar Ferryghat)]. Map of the study area was made with the help of QGIS 3.22.2.

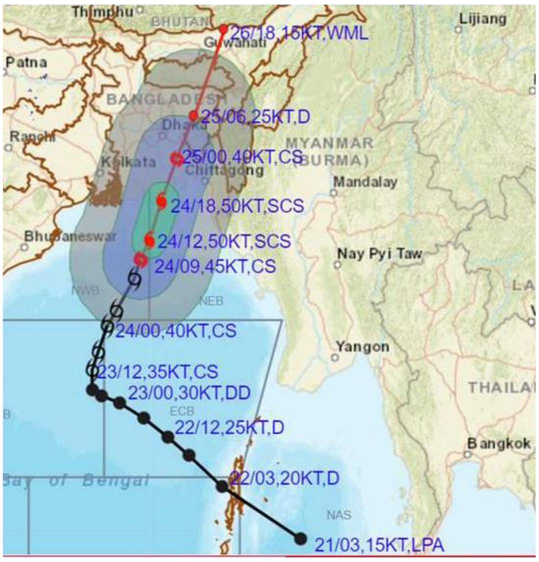

Figure 1. Track of the cylcone Sitrang (Image obtained from RSMC-New Delhi, Tropical Cyclone Advisory No.8 based on 0900 UTC of 24.10.2022)

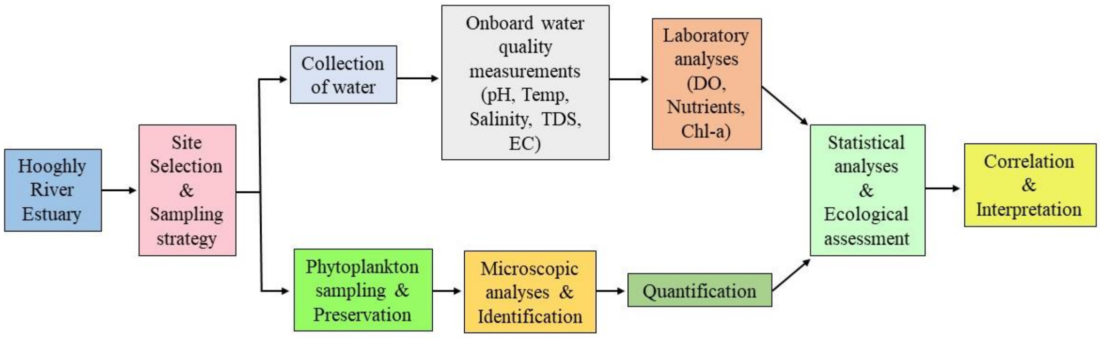

Figure 2. Proposed methodology

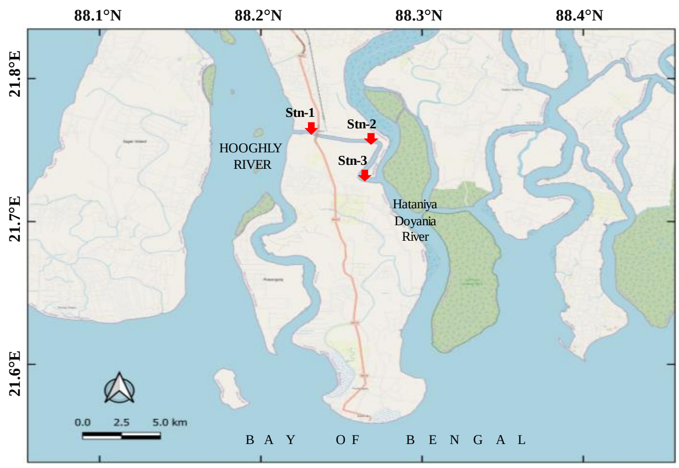

Figure 3. Map of the Study Area

Water parameters analyses

Temperature, pH, EC, TDS, and Salinity were measured on the spot using a digital instrument of HANNA (Model No- HI98130). Dissolved oxygen (DO) was determined following Winkler's method (1888). Phosphate was determined by treating it with molybdic acid, ascorbic acid, and trivalent antimony, and the absorbance was recorded spectrophotometrically (Grasshoff et al., 1999). Silicate content in water was assessed using molybdic solution, and the resulting blue-colored complex was quantified spectrophotometrically (Grasshoff et al. 1999). Nitrate was determined through diazotization reaction with sulphanilamide in an acid solution and coupled with naphthylethylenediamine which formed azo dye, and the absorbance was measured spectrophotometrically (Grasshoff et al., 1999). Chlorophyll-a was analyzed following the acetone extraction procedure by the use of Whatman GF/F filter paper (Pore size: 0.7 µm, diameter: 47 mm) and absorbance measured in UV-Vis spectrophotometer (Parsons et al., 1984).

Phytoplankton sampling and analyses

50 Litres of surface water were sieved through a bolting silk (mesh size 20µm) and transferred into collecting bottles. Samples were labelled with a number, date, and time and preserved with 3% formaldehyde solution. This study is mainly focused on dinoflagellates and diatoms. Phytoplankton samples were observed under compound light microscope (Leica DMi8) for identification purpose. Species identification and nomenclature were carried out using published literature (Hasle et al., 1996; Gómez, 2013) as well as several website sources (algeabase and WoRMS). For quantification, 1 ml of concentrated sample was taken in Sedgwick Rafter counting chamber and counting was done in triplicate and their mean was taken for numerical analysis.

Diversity indices and statistical analyses

Margalef richness index (D), Shannon-Weiner diversity index (H′) and Pielou's evenness index (J′) formula were applied to assess the diversity. Two-tailed unpaired t-test was employed to test the significance of different data on numerical cell abundance and daily water parameters before and after the cyclone. Graphical representations were prepared using MS Excel 2016. Through PAST software version 4.13 canonical correspondence analysis (CCA) was performed using the relative abundance of most occurring phytoplankton taxa in both pre-cyclonic and post-cyclonic observations with different environmental variables and expressed as triplot.

Results

Water parameters

Surface water temperature showed a narrow variation and ranged between 28.5 to 29.5°C during pre-cyclonic period and just after the immediate passage of the Sitrang a lowered water temperature between 27.4 to 27.8°C was observed at different stations. pH of water showed very little fluctuation and ranged between 7.13 – 7.53, and dissolved oxygen content of 5.8 – 6.8 mg/L was observed before the cyclone. After the immediate passage of cyclone, a considerable drop in pH (lowest 6.8), and dissolved oxygen (lowest 4.2 mg/L) were observed but these conditions were soon recovered, and a rising pattern was visible across the afterward observations. Hydrological condition of the Hooghly Estuary slightly

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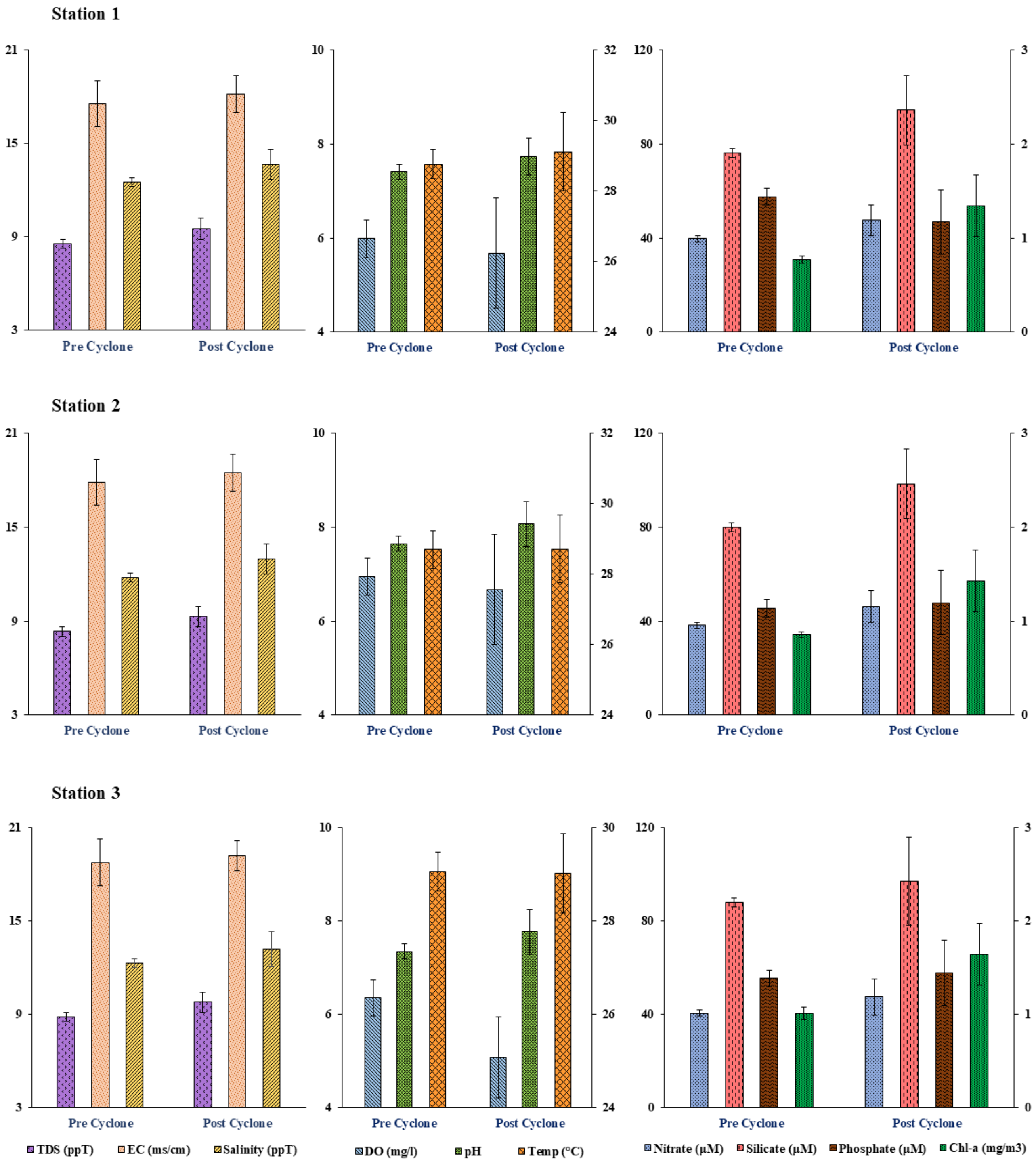

Figure 4. Water quality parameters at different stations before and after the cyclone

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Table 1. Relative abundance (%) of documented species of diatom and dinoflagellates at three stations in pre and post-cyclone

		Station-1		Station-2		Station-3	
Class	**Species**	**Pre**	**Pos**	**Pre**	**Pos**	**Pre**	**Pos**
Bacillariophyceae	*Amphora* sp.	0.84	0.34	1.22	-	1.21	-
	Asterionella japonicus	5.00	4.34	4.02	1.78	2.31	2.92
	Bacillaria paxillifer	1.09	-	0.90	-	1.60	0.76
	Bacteriastrum hyalinum	0.91	-	-	-	1.50	0.31
	Chaetoceros compressus	3.50	4.02	4.77	4.45	3.14	4.22
	Chaetoceros danicus	4.08	3.18	3.02	2.24	2.36	2.67
	Chaetoceros debilis	2.78	2.67	2.64	2.53	1.66	1.09
	Chaetoceros decipiens	2.31	2.17	2.14	2.45	1.68	0.7
	Chaetoceros castracanei	1.76	1.00	2.11	1.7	1.09	0.43
	Chaetoceros lorenzianus	1.83	-	-	-	0.98	-
	Coscinodiscus centralis	4.80	4.1	4.59	3.82	3.34	4.54
	Coscinodiscus concinnus	5.46	3.67	6.36	5.12	4.12	3.15
	Coscinodiscus eccentricus	3.40	3.27	5.05	3.67	2.35	1.36
	Coscinodiscus gigas	1.05	0.45	-	-	1.78	1.12
	Coscinodiscus perforatus	-	-	-	-	1.11	-
	Cyclotella caspia	2.51	3.08	2.27	1.11	1.52	1.07
	Cyclotella striata	1.23	1.28	-	-	2.50	1.05
	Ditylum brightwellii	3.32	3.09	1.85	1.5	2.35	2.23
	Eucampia zodiacus	1.11	-	1.19	1.1	1.34	-
	Fragilaria gracilis	-	-	1.08	-	1.68	0.89
	Lauderia annulata	1.12	0.66	3.78	2.5	3.11	3.39
	Leptocylindrus danicus	1.45	-	0.66	-	2.86	0.12
	Leptocylindrus minimus	-	-	-	-	1.12	-
	Navicula spp	1.67	1.08	1.74	1.88	2.40	2.44
	Nitzschia acicularis	1.45	0.98	0.68	0.76	2.61	1.34
	Nitzschia acuminata	-	-	1.89	1.34	1.67	1.12
	Odontella longicruris	-	-	-	-	2.12	2.45
	Odontella mobiliensis	1.67	0.85	1.85	1.65	1.48	1.52
	Odontella sinensis	2.18	1.97	2.91	2.45	2.43	2.87
	Palmerina hardmaniana	2.25	2.34	2.32	1.35	2.06	1.41
	Pinnularia ambigua	2.61	-	1.76	-	1.12	0.45
	Pinnularia viridis	1.67	-	1.09	-	1.01	-
	Planktoniella blanda	2.96	1.38	2.12	1.85	1.03	0.78
	Planktoniella sol	2.18	2.43	1.64	1.56	1.46	1.56
	Pleurosigma elongatum	2.12	-	2.06	1.08	3.20	1.52
	Pseudonitzschia sp	0.24	-	-	-	0.07	-
	Rhizosolenia imbricata	-	-	1.08	-	1.68	0.89
	Rhizosolenia setigera	1.38	0.65	1.45	1.18	2.17	2.27
	Rhizosolenia styliformis	-	-	-	-	2.28	1.56
	Skeletonema costatum	0.56	0.34	1.66	-	0.45	-
	Synedra oxyrhynchus	-	-	-	-	1.18	0.67
	Thalassionema frauenfeldtii	0.96	0.45	2.17	0.56	1.95	2.14
	Thalassionema nitzschioides	-	-	0.67	-	1.23	-

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	Thalassiosira condensata	-	-	-	-	0.98	1.12
	Thalassiothrix longissima	1.98	0.68	4.76	4.43	3.05	2.15
Dinophyceae	*Noctiluca scintillans*	3.72	8.59	3.76	9.56	2.96	9.27
	Prorocentrum micans	1.59	-	1.19	-	1.17	0.17
	Protoperidinium depressum	0.25	-	0.28	0.02	0.20	0.02
	Tripos furca	4.25	29.4	3.92	26.98	3.13	23.2
	Tripos fusus	3.74	4.49	2.14	4.67	2.17	4.31
	Tripos lineatus	4.25	5.34	4.76	3.4	2.88	2.97
	Tripos mulleri	2.5	0.55	1.79	0.78	1.71	0.38
	Tripos trichoceros	3.18	1.14	3.17	0.53	2.48	0.29
		100.00	100.00	100.00	100.00	100.00	100.00

changed over the course of post-cyclonic period. Salinity, EC, and TDS followed an increasing trend along with instant elevation. Salinity varied from 11.9 to 12.4 psu before the cyclone which was increased after the cyclone and more or less ranged from 12.4 – 14.8 psu in all stations, while the highest salinity of 15.1 psu was recorded from Station-1. EC increased and a maximum of 21.1 mS/cm was reached just after the Sitrang. Short-term noticeable rise of TDS from 8.25 ppT to 10.52 ppT was documented at Station-1 while it was 8.03 to 10.3 ppT for Station-2 and 8.5 to 10.8 ppT for Station-3. Before the cyclone lowest nitrate content of 38.1 µM was observed at Station-1, while just after the cyclone maximum nitrate 58.2 µM was recorded at Station-3. Phosphate content generally ranged more or less between 1.05 – 1.95 µM in all Stations after the cyclone whereas prior to cyclone it ranged between 1.03 – 1.5 µM. Silicate content drastically rose after the cyclone and reached a maximum of 130 µM (at Station-3) where the minimum value of 73.6 µM was seen before cyclone. A two-fold increase of chlorophyll-a in surface water was also recorded after the cyclonic event, with the highest being 2.12 mg/mm3 in Station-3 and the lowest being 0.8 mg/mm^3 before the cyclone at Station-1. Station-wise variation in all water parameters is given in Fig. 4.

Phytoplankton abundance and composition

Following the cyclonic phase, phytoplankton abundance increased significantly. A sum total of 6.88 – 8.62 ×10^3 cells/L of phytoplankton cells was observed before the cyclone with diatoms making up the bulk (86%) of the total phytoplankton biomass, however in post-cyclonic period a total of 1.23 – 5.57 ×10^4 cells/L of phytoplankton were found where dinoflagellate cells increased dramatically sharing 48% of total abundance. Post-cyclonic investigation revealed dinoflagellate cell density increased 2-10 fold, while diatoms increased only 1-3 fold. Before the hit of cyclone 45 species of diatoms and 8 species of dinoflagellates were observed which was reduced to 25 and 6 species. Among the diatoms *Coscinodiscus* sp. and *Chaetoceros* sp. were most abundant while in dinoflagellates *Noctiluca scintillans*, *Tripos* spp. prevailed the estuarine water. Station-3 had the highest abundance when comparing the total phytoplankton (Station-3>Station-1>Station-2). A checklist of all documented species along with their relative abundance before and after the cyclone was given in Table 1.

Diversity indices and statistics

Prior to the cyclone, Shannon-Weiner Diversity Index (H′) was highest (2.927) and it was reduced to lowest 2.463 after the cyclone. Maximum value of Pielou's Equitability Index (J′) calculated was 0.933 for pre cyclone which became 0.785 after (Fig. 5). Margalef Richness Index (D) also followed a similar trend of decrease in the post-cyclonic phase. Triplot of CCA constructed by the relative abundance and physicochemical data for pre and post-cyclonic periods showed constrained ordination where CCA first and second axes had the eigenvalue of 0.1556 and 0.0322 able to show a cumulative 85.6% of the variance (Table 2). The results of t-test indicate significant changes in several water parameters (salinity, TDS, nitrate, silicate, Chl-a) after the cyclone (Table 3). Mean cell abundance following the cyclone was also statistically significant (for diatoms t = – 4.32, df = 5, p = 0.008 and dinoflagellates t = – 3.37, df = 5, p = 0.019).

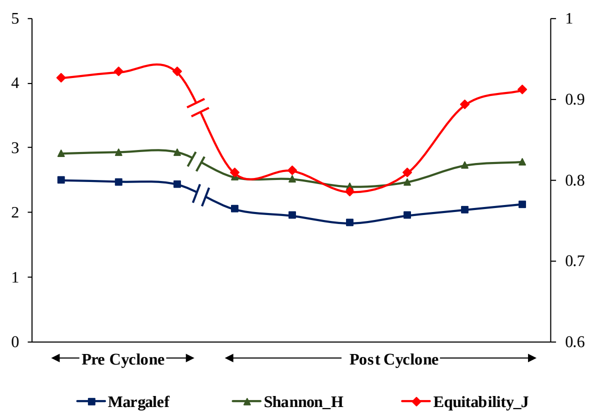

Figure 5. Diversity indices before and after the cyclone (line breakage indicate cyclonic day)

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Table 2. Eigenvalues and constrained inertia of the CCA

Axis	Eigenvalue	% of constrained inertia	% of cumulative inertia
1	0.15569	70.91	70.91
2	0.032233	14.68	85.59
3	0.013851	6.31	91.90
4	0.00784	3.57	95.47
5	0.006108	2.78	98.25
6	0.002566	1.17	99.42
7	0.001285	0.59	100.00

Table 3. t-test results of different water quality parameters between pre-cyclonic and post-cyclonic observations at different sites of the study area

	Station-1			Station-2			Station-3		
Parameters	***t***	**df**	***p***	***t***	**df**	***p***	***t***	**df**	***p***
Temperature	– 0.603	7	0.566	– 0.029	6	0.978	0.104	7	0.920
pH	– 1.533	7	0.169	– 1.724	7	0.129	– 1.724	7	0.129
DO	0.523	7	0.618	0.469	7	0.654	0.469	7	0.654
Salinity*	– 2.436	7	0.047	– 2.436	7	0.047	– 2.436	7	0.047
Nitrate*	– 2.524	6	0.046	– 2.524	6	0.046	– 2.524	6	0.046
Phosphate	1.291	4	0.268	– 0.350	6	0.738	– 0.350	6	0.738
Silicate*	– 2.715	5	0.039	– 2.715	5	0.039	– 2.715	5	0.039
Chl-a*	– 3.867	5	0.011	– 3.867	5	0.011	– 4.090	6	0.007
EC	– 0.531	3	0.632	– 0.531	3	0.632	– 0.531	3	0.632
TDS*	– 2.626	7	0.034	– 2.626	7	0.034	– 2.626	7	0.034

*significant (as $p < 0.05$)

Discussion

As a river empties into an estuary, the hydrodynamics become complex due to tidal influences, river flow variability, and estuarine geometry. However, the cyclone-induced disturbances led by heavy rainfall and intense wind, increase nutrient and sediment transport and thus create a more complicated and dynamic situation (Schafer et al., 2020). After the hit of Cyclone Sitrang environmental conditions of the estuary shifted to a more mixed condition over different sampling sites. Post-cyclonic observations revealed slight temperature declining conditions, which was insignificant as per the paired t-test, but the water temperature is a key factor that can influence phytoplankton abundance and distribution. Phytoplankton distribution is often influenced by temperature stratification as it affects nutrient availability and light penetration. Temperatures below the optimal range can limit the growth rates of many phytoplankton species (Wiltshire et al., 2008). Though the optimal temperature for phytoplankton growth can vary depending on the species, it often falls within the range of around 10°C to 25°C. This temperature range allows for efficient photosynthesis and metabolic processes (Langdon, 1988; Claquin et al., 2008; Xiao et al., 2018). Moderate temperature range of 27.4 to 30.1°C after the cyclone along with the nutrients and other factors must have positively impacted the phytoplankton growth and abundance.

After the cyclone, pH of the estuarine water decreased immediately but gradually rose towards the alkaline conditions and stayed a little high for few days suggesting the alkaline nature of estuarine water. Decreased pH after the cyclone might have been a short-term impact of Sitrang. Previous studies on cyclones affecting Hooghly Estuary also revealed an increase in pH of water (Mitra et al., 2011).

Salinity, electrical conductivity (EC), and total dissolved solids (TDS) all are interrelated and used to characterize the amount of dissolved salts in water (Rusydi, 2018). Different species of phytoplankton have varying levels of salinity tolerance. Some species are adapted to thrive in low salinity conditions, while others are more sensitive and require higher salinity (Alkawri et al., 2010). Various phytoplankton species have a

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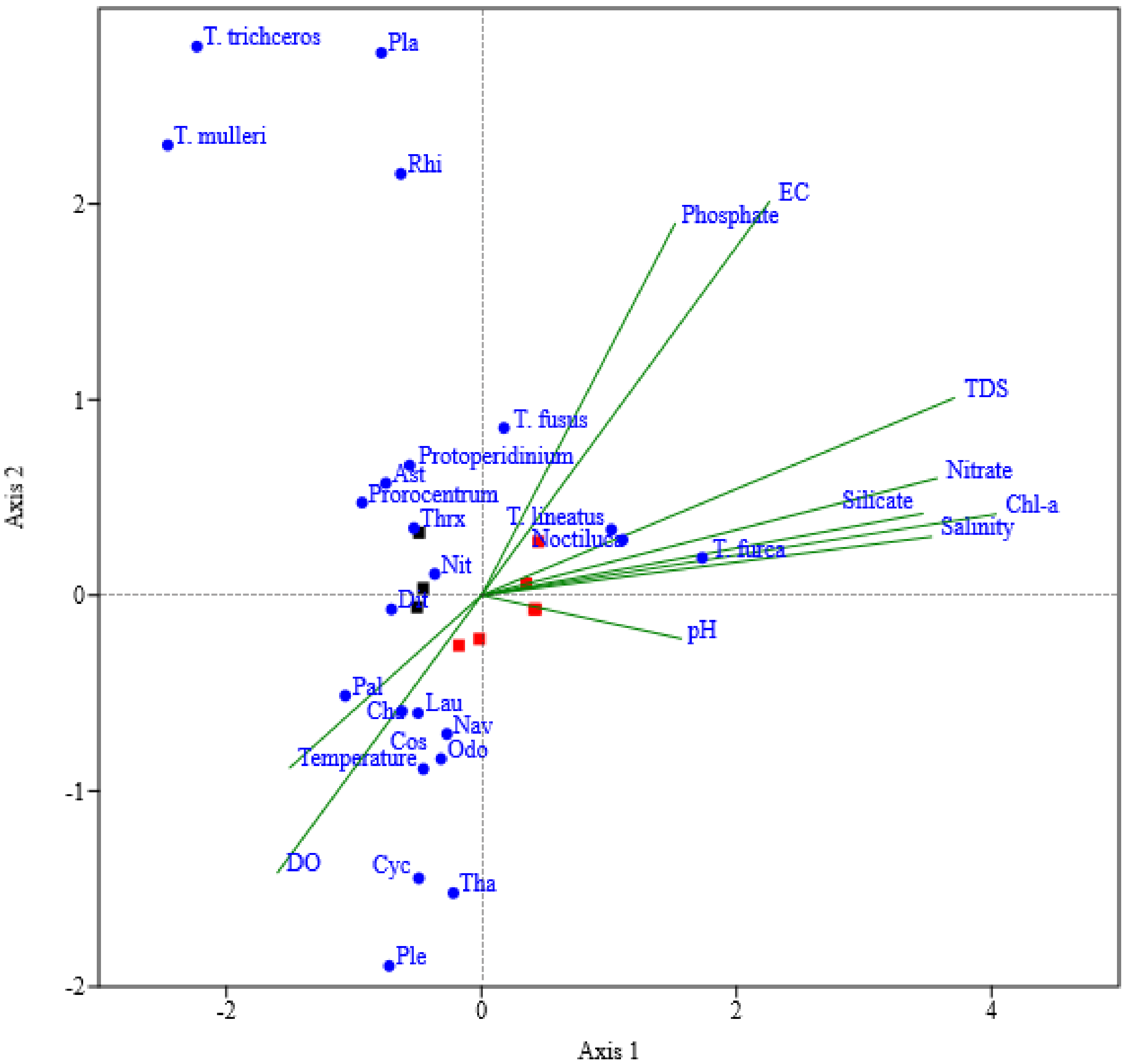

Figure 6. CCA Triplot obtained from relative abundance of most observed dinoflagellates and diatoms with water parameters before and after cyclone (Red square = Post-cyclonic observations, Black square = Pre-cylonic observations, Cha = *Chaetoceros* sp., Cos = *Coscinodiscus* sp., Lau = *Lauderia* sp., Pal = *Palmerina* sp., Rhi = *Rhizosolenia* sp., Dit = *Ditylym* sp., Pla = *Palnktoniella* sp., Cyc = *Cyclotella* sp., Odo = *Odontella* sp., Ast = *Asterionella* sp., Tha = *Thallaisonema* sp., Thrx = *Thallasiothrix* sp., Nav = *Navicula* sp., Nit = *Nitszchia* sp., Ple = *Pleurosigma* sp., Protoperidinium = *Protoperidinium depressum*, Prorocentrum = *Prorocentrum micans*, Noctiluca = *Noctiluca scintillans*, T. = *Tripos*)

competitive advantage over others in high salinity conditions, leading to shifts in the community composition (Qasim et al., 1972). Change in low to high salinity and TDS condition during the post-cyclonic period was statistically significant. These results are corroborated with the previous studies on cyclone-induced water quality shifting of Hooghly estuary (Paul et al., 2020; Mitra et al., 2020). Enormous quantities of runoff from the nearby lands and wind mixing of the water column possibly contributed to the high TDS levels while the intrusion of large amounts of saltwater due to storm surge is a definite cause of the increased salinity state of the study area (Choudhury et al., 2015; Das et al., 2016). In tropical estuary phytoplankton community structure is influenced by the salinity gradient and nutrient content while the phytoplankton abundance is regulated by grazing pressure (Bharathi et al., 2022). Cyclone-induced physical stress and increased salinity might have a negative impact on phytoplankton grazers and predators, thus influencing the overall phytoplankton dynamics (Paul et al., 2020).

Post-cyclonic observations revealed a very high abundance of dinoflagellates especially *Tripos* spp., and *Noctiluca scintillans* than diatoms in all sampling sites. Sudden changes in salinity can stress phytoplankton, impacting their physiological processes (Peierls et al.,

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2003). *Noctiluca scintillans* and *Tripos furca* are known for their ability to tolerate a wide range of salinity conditions, including both low and high salinities (Smalley et al., 2002; Al-Azri et al., 2007). *Noctiluca scintillans* can outcompete other phytoplankton species in high-salinity environments. Its ability to tolerate salinities gives it a competitive advantage over other organisms that may be less adapted to such conditions (Baliarsingh et al., 2016). Thus *Noctiluca scintillans* (4.3×10^3 cells/L) and *Tripos furca* (2.04×10^4 cells/L) having the highest cell count among dinoflagellates during post-cyclone phase led to shifts in phytoplankton community composition and overall ecosystem dynamics. For instance, following the passage of cyclone Phailin, a significant change in the phytoplankton composition, such as a switch from diatom to a dinoflagellate-dominated system, was also noted previously (Srichandan et al., 2015).

Chlorophyll-a (Chl-a) can be used as a proxy of phytoplankton biomass or productivity in aquatic environments. After the cyclonic period, near about two to three-fold significant increase in Chl-a content was noticed. The high rise in Chl-a levels (2.76 mg/m^3) was attained in two days owing to the high abundance of phytoplankton. Chl-a content of water might be driven by a combination of nutrient enrichment due to vertical mixing in the water column that deliver nutrients from below to the euphotic zone and precipitation-induced surface runoff that redistribute nutrient in the upper layer. This observation of Chl-a enhancement after the cyclonic period was consistent with previous investigations of cyclones like Phallin (in October 2013), Hudhud (in October 2014), and Bulbul (in November 2019) that occurred in post-monsoon (Lotliker et al., 2014; Chacko, 2017; Hoque et al., 2022). In summary, the concentration of phytoplankton chlorophyll-a is strongly correlated to the availability of macronutrients, particularly nitrogen and phosphorus. Nutrient inputs can influence the growth, composition, and productivity of phytoplankton communities after the cyclone and ultimately increase different phytoplankton pigments, especially Chl-a content and thus shaping the overall health and functioning of estuarine ecosystems (Baliarsingh et al., 2021).

Following the cyclone there was a noticeable increase in macronutrient concentrations in the estuary. Elevated levels of nitrate, phosphate, and silicate, can be attributed to several factors related to the cyclone, such as increased runoff, sediment erosion, upwelling, nutrient redistribution, organic matter input, and changes in salinity (Herbeck et al., 2011). This increased supply of nutrients can stimulate phytoplankton growth and promote blooms. However, if the cyclone-induced turbidity persists, it may limit the availability of light necessary for phytoplankton to utilize these nutrients effectively (Vidya and Das, 2017). Increased macronutrient concentrations after the cyclone can boost short-term productivity, but the long-term effects depend on the estuarine characteristics, nutrient profile, species interactions, and human influences (Paerl et al., 2006). Tropical cyclones quickly (within a week) enhance phytoplankton productivity and bloom development when light constraint is not a concern. This is because wind-driven nutrient resuspension plays a significant role to achieve the condition (Wetz and Paerl, 2008). Cyclones that take place from October to December make the phytoplankton blooms more intense. The upwelling process, which transports the nutrient-rich deep water to the euphotic zone by a variety of methods, causes the bloom to develop (Vinayachandran et al., 2003; Reddy et al., 2008).

Tripos furca and *Tripos fusus* are known to thrive in harsh environmental conditions and when the environment becomes favourable can multiply rapidly leading to shifts in the composition and diversity of phytoplankton communities (Baek et al., 2008). Studies revealed phytoplankton taxa that seem to thrive under post-cyclone conditions (i.e., low light levels, elevated nutrient concentrations), particularly the harmful Dinophyceae species. Because many of these organisms are nutritionally mixotrophs, they may supplement their energy needs in low-light environments by using organic materials, giving them an advantage over other phytoplankton-like diatoms (Burkholder et al., 2008). Prior to the cyclonic event *Coscinodiscus, Ditylum, Planktoniella, Rhizosolenia, Chaetoceros, Lauderia* were the most abundant diatom taxa. As a result of the cyclonic event, diatom numbers increased from 6.39×10^3 to 2.62×10^4 cells/L, and the community structure and species composition differed since several species were absent from the study. However, in the case of dinoflagellates community structure changed a little because *Protoperidinium* sp. and *Prorocentrum* sp. were decreased in numbers or absent in many observations while all the other dinoflagellate species rose dramatically. Changes in community structure, especially in diatom and dinoflagellates, can have implications for higher trophic levels in the food web and overall ecosystem functioning. Diatoms generally predominate the estuarine and coastal waters of northeast Bay of Bengal although there have been reports of Dinoflagellate predominance on occasional events (Baliarsingh et al., 2018; Padhi et al., 2021). Cyclonic winds also have a significant influence on the phytoplankton community. Sitrang was comparatively weaker cyclone but the average wind speed of Sitrang was recorded 80 – 90 km/h and maximum 110km/h. In the study area, these winds might have impacted the temporal and spatial distribution of *Tripos* or *Noctiluca scintillans* through dispersion (Miyaguchi et al., 2006).

CCA triplot (Fig. 6) showed several environmental factors such as temperature, DO, and pH having both negative loadings on first and second axis but salinity, TDS, EC, macronutrients, and Chl-a have positive loadings. Macronutrients particularly nitrate and silicate and salinity bear the highest positive score and act as the key factors regulating the increased phytoplankton abundance in the post-cyclonic phase. Entire diatom taxa and few dinoflagellate species exhibited negative scores on first axis. It might be due to their comparatively lower abundance than the others after the cyclone. Three species of *Tripos* namely *T. furca*, *T. lineatus*, *T. fusus*, and *Noctiluca* bears significant positive score suggesting the post-cyclonic conditions favouring their opportunistic growth and sustenance in the study area. According to Huynh et al., (2022), salinity and nitrate are the two most important environmental factors for the high growth of *T. furca* and *T. fusus* in coastal water. Dissolved nitrate is a major source of nitrogen for phytoplankton and plays a vital role in promoting their growth and productivity, on the contrary, silicate content is the primary driver for influencing diatom growth. Several workers have suggested the role of dissolved inorganic nitrogen, temperature, and mesohaline state of water drives the excessive dinoflagellate growth (Doblin et al., 2006; Zhou et al., 2017; Gobler et al., 2012). Studies have also shown that estuarine zones with high nitrate availability have a high abundance of dinoflagellates especially the cosmopolitan species *T. furca* (Canini et al., 2013).

For a better understanding of the phytoplankton dynamics of the Hooghly River estuary due to tropical cyclones, it is important to take into account the changes in biomass and composition of both cyclonic events and long-term climatic trends. Also, it is essential to remember that the actual response of phytoplankton to cyclones is complicated and can differ greatly depending on regional and local factors. A comprehensive knowledge of the complex interactions between phytoplankton dynamics and Tropical Cyclones may be achieved by a combination of mixed-field observations, remote sensing data, and numerical modeling. This approach can guide effective management strategies that aim to both protect estuarine ecosystems and minimize the potential consequences of phytoplankton blooms.

Conclusion

Hooghly estuarine region of Sundarban represents one of the most valuable aquatic resources in the world both ecologically and economically. Tropical cyclone Sitrang brought significant changes in environmental conditions that triggered phytoplankton growth. The phytoplankton community in the estuary went through a severe ecological disturbance, involving a significant fall in species diversity and evenness, but individual populations particularly the dinoflagellates were at their maximums. These short-term changes are part of the natural variability of estuarine and coastal ecosystems, and they play an important role in shaping the overall ecological dynamics. The rapid change from low to high abundance of *Noctiluca* and *Tripos furca* raises concerns about the potential susceptibility of Harmful Algal Bloom (HAB) formation in the near future. Such rapid shifts in population dynamics can indicate conditions conducive to the proliferation of these harmful species, leading to the formation of HABs. Such HAB occurrence not only poses a threat to the estuarine ecosystem, rather also will seriously affect the monetary sustainability of the region leading to a severe socio-economic crisis.

Though the study of cyclone-induced impacts on phytoplankton communities holds promise for understanding marine and estuarine ecosystem dynamics, it also faces challenges related to the complex nature of ecosystems, data limitations, and the intricacies of extreme weather events. Studies with short periods of timeframe only provide valuable insights about the immediate impacts of the cyclone on estuarine ecosystems. Thus, long-term investigations are required to develop a clear scenario instead of a skewed conclusion. Implementation of sustainable coastal management practices, regular basis water quality monitoring, and further advanced research can suggest future directions that will lead to a more comprehensive understanding of phytoplankton dynamics.

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Conflict of interest

All the authors declare that there is no conflict of interest.

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