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Research Article

Seasonal and Spatial Variability of Chlorophyll-*a* in Response to ENSO and Ocean Current in the Maritime Boundary of Bangladesh

Tamanna Fardoshi,[1] **Md Rony Golder**,[1] **Muhammad Abdur Rouf**,[1] **and Md Masud-Ul-Alam**[2]

[1]*Fisheries and Marine Resource Technology Discipline, Khulna University, Bangladesh*
[2]*Oceanography and Hydrography Department, BSMR Maritime University, Bangladesh*

Correspondence should be addressed to Muhammad Abdur Rouf; roufku@yahoo.com

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Chlorophyll-*a* (Chl-*a*) and its correlation with different parameters are one of the major indicators to understand marine ecosystems. This study was conducted to explore the seasonal and spatial variability of Chl-*a* at three different stations (onshore, midshore, and offshore) across the maritime boundary of Bangladesh in the northern BoB with its response to the surface current speed and recent ENSO (El Niño/La Niña-Southern Oscillation) events by using satellite data. Moderate resolution imaging spectroradiometer (MODIS) aqua satellite level-3 data of Chl-*a* was used in this study. Ocean currents datasets were obtained from the Asia-Pacific Data Research Center (APDRC) live access service, LAS8.6.13 of NOAA (National Oceanic and Atmospheric Administration), whereas the SST anomalies dataset was collected from NOAA Climate Prediction Center. This study revealed that the onshore region showed the highest (1.121 mgm^{-3}) abundance of Chl-*a*, whereas the offshore region showed the lowest (0.136 mgm^{-3}). The offshore and midshore regions showed a homogenous distribution of Chl-*a*, whereas the observed trend of seasonal fluctuation was southwest monsoon > postmonsoon > northeast monsoon > premonsoon. There is a seasonal variation in the relationship between Chl-*a* and surface current speed, with moderate correlations during northeast (Dec-Feb) and premonsoon (Mar-May). The effect of ENSO on Chl-*a* was observed as insignificant ($P > 0.05$) in the northern BoB. However, Chl-*a* variability in response to ENSO events across the northern region of BoB requires more investigation.

1. Introduction

Chlorophyll–*a* (Chl-*a*) is an accessory photosynthetic pigment [1, 2] found in all green plants, cyanobacteria, and phytoplankton. The presence of Chl-*a* is considered as a good indicator of ocean health [3] as well as its distribution, variability, and correlation pattern with different parameters have been used to understand primary productivity [2, 4, 5], biological and ecosystem response [6], and ecological variations of the marine environment which are primarily influenced by Chl-*a* fluctuation [7, 8]. Investigating the variability of chlorophyll-a (Chl-*a*) across the oceans has important implications. It allows us to assess the availability of fishery resources and promote the development of marine aquaculture [9]. Furthermore, it provides valuable insights into the spatial abundance of fish [10], as regions with high Chl-*a* abundance serve as fertile feeding grounds for marine ecosystems [11]. Decision-makers can utilize the spatial variability of Chl-*a* to evaluate the health and productivity of phytoplankton-dependent marine ecosystems. In addition, information on Chl-*a* concentration is vital for studying ocean primary production, the biophysical state of water bodies, and conducting fisheries research. In fact, understanding the phytoplankton spatial variability at a diverse scale is essential for suggesting the growth, dispersion, and survival of planktonic species [12, 13] throughout the oceans.

Several studies have been conducted over the Bay of Bengal (BoB) to investigate Chl-*a* distribution in response to various physical and biological parameters [14–16], such as the annual and seasonal variability of Chl-*a* in the shelf region of the northern BoB [17], the bathymetric features of BoB [18], the validation of Chl-*a* in this region [19], biological productivity [20], hydrography, and circulation of BoB [21], particularly in the southwest and western areas of BoB [19, 22–26]. In addition, a few studies [27, 28] investigated the phytoplankton distribution in the Arabian Sea, which is close to the BoB. However, the seasonal and spatial variability of Chl-*a* is yet to be explored particularly across the maritime boundary of Bangladesh in the northern BoB at different depths and distances from the coast. On the other hand, the BoB experiences significant climatic events such as the Indian Ocean Dipole (IOD), the El Niño-Southern Oscillation (ENSO), and the Madden-Julian Oscillation (MJO), [29–31] prompting investigations into their potential impacts on the BoB. Studies have examined the relationship between El Niño and IOD [32], the variability of sea surface temperature during ENSO and IOD events [33], and conducted time-series analysis of chlorophyll-a (Chl-*a*) with respect to IOD events [34]. Additionally, researchers have explored the influence of ENSO on Chl-*a* variability in the Maluku Sea [35] and the South China Sea [36]. However, the specific impact of ENSO on Chl-*a* variability in the maritime boundary of Bangladesh remains unexplored.

This study is aimed at investigating the seasonal and spatial variability of Chl-*a* at the three different stations representing onshore, midshore, and offshore, having different depths across the maritime boundary of Bangladesh in the northern BoB and its correlation with the ocean current and significant climatic events like ENSO to comprehend the ENSO influence on Chl-*a* abundance across the regions. Marine Fisheries Research in Bangladesh requires a site-specific view of seasonal trends of Chl-*a* distribution to the extent of primary productivity across the maritime boundary of Bangladesh in the northern BoB, along with the impact of the major climatic event on it. This study will help to identify the most productive region in Bangladesh's maritime boundary with higher fish abundance and healthier marine ecosystems. This will be accomplished by assessing the concentration of Chl-*a*, which is an indicator of phytoplankton abundance. Demonstrating the impact of global climatic phenomena like El Niño and La Niña on the health of the marine ecosystem across Bangladesh's maritime boundary is another significant implication of this research.

2. Materials and Methods

This study was conducted to investigate the comparison of Chl-*a* distribution in different depths and its seasonal variation in the maritime boundary of Bangladesh in the BoB. The three stations: onshore (depth 100-150 m), midshore (200-1000 m), and offshore (1000-2000 m) occupied different depths and were selected, and each station in the study area covers 500 m^2, as depicted in Figure 1.

Level 3 mapped (SMI) with 4 km resolution monthly, and annual Chl-*a* data were collected from MODIS-aqua satellite (https://oceancolor.gsfc.nasa.gov) for estimating seasonal and spatial variability of Chl-*a* considering our study areas from July 2002 to June 2020. The MODIS-aqua Chl-*a* datasets were processed and analyzed by using SeaDAS 7.5.3, developed by NASA for processing, displaying, analyzing, and quality control of ocean color data [17]. Four seasons were recognized as premonsoon (March, April, and May), southwest monsoon (June, July, August, and September), postmonsoon (October and November), and northeast monsoon (December, January, and February) [17, 37] to investigate the seasonal variability of Chl-*a* in this study. Surface and meridional current datasets were retrieved directly from the Asia-Pacific Data Research Center (APDRC) live access service, LAS8.6.13 of NOAA (National Oceanic and Atmospheric Administration) (http://apdrc.soest.hawaii.edu/). For measuring the relation between ONI and Chl-*a*, we used a 3-month running mean of ERSST.v5 SST anomalies for ten years (2010-2019) of Niño 3.4 area (5° S–5° N, 170–120° W) as ONI (Oceanic Nino Index). The monthly mean of SST anomalies data was provided by NOAA, Climate prediction center (https://origin.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ONI_v5.php) based on centered 30-year base periods updated every five years. ONI value was plotted with a monthly mean of Chl-*a* anomalies data set for 19-year (2002-2019) base periods to project the relation between them. In an Oceanic Nino Index (ONI) that is above or below the threshold of +0.5°C or −0.5°C, respectively, El Niño and La Niña conditions are considered to be in progress [33]. The SST anomaly threshold is considered as weak (0.5 to 0.9), moderate (1.0 to 1.4), strong (1.5 to 1.9), and very strong events (≥2.0). All statistical analysis was conducted using IBM SPSS software (version 25) and Minitab (Version 17).

3. Results and Discussion

3.1. Seasonal and Spatial Variability of Chl-a. The spatial variability of Chl-*a* and its seasonal distribution in the onshore, offshore, and midshore regions for 19 years (July 2002 to June 2020) in the maritime boundary of Bangladesh are depicted in Figure 2. The highest Chl-*a* (1.121 $mg\text{-}m^{-3}$) was observed in the onshore region. The lowest Chl-*a* (0.136 mgm^{-3}) was observed in the offshore region. Chl-*a* ranged from 0.280 to 1.121 mgm^{-3}, 0.136 to 0.320 mgm^{-3}, and 0.136 to 0.238 mgm^{-3} over the onshore, midshore, and offshore regions, respectively. The average Chl-*a* was observed comparatively lower in midshore ($0.235 \pm 0.05\ mgm^{-3}$) and offshore ($0.181 \pm 0.03\ mgm^{-3}$) regions than in onshore ($0.558 \pm 0.30\ mgm^{-3}$) of the northern BoB. Chl-*a* variability was found to be significantly different ($F_{(2,645)} = 47.126$, $P < 0.001$) among the regions (onshore, midshore, and offshore). Post hoc comparisons using the Tukey (LSD) test indicated that the Chl-*a* of the onshore region was significantly different ($\boldsymbol{P} < 0.001$) from

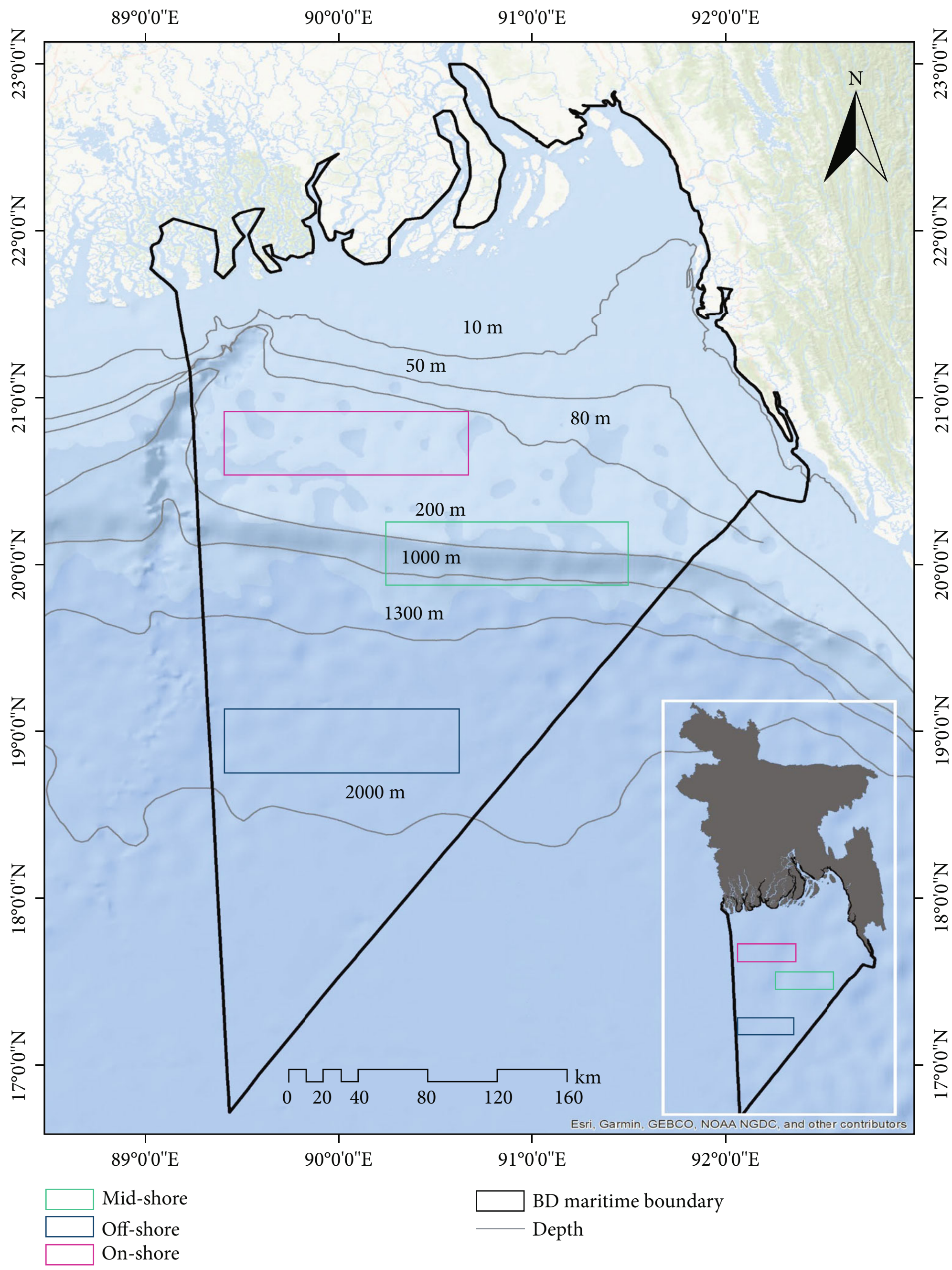

Figure 1: The study area in the maritime boundary of Bangladesh in the northern BoB where the three stations, onshore, midshore, and offshore, are depicted as three quadrangles of different colors.

the midshore and offshore regions. In addition, the observed Chl-*a* distribution was found almost homogenous in the offshore and midshore regions. In the case of seasonal variation, Chl-*a* fluctuated widely during southwest monsoon among the stations, mostly in the onshore region. During the onset of this season (Jun), the value of Chl-*a* was recorded lowest (0.136 mgm^{-3}), whereas the highest value of Chl-*a* was 1.121 mgm^{-3} at the end of the southwest monsoon (Sep). In the premonsoon, variation of Chl-*a* overall the regions was observed comparatively lower. Chl-*a* in the study area was found significantly different ($F = 25.638$, $P < .0001$) among the seasons. Post hoc comparisons using the Tukey (LSD) test indicated that the Chl-*a* of the southwest monsoon was significantly different ($P < .0001$) from the premonsoon, postmonsoon, and northeast monsoon.

As the Chl-*a* during southwest monsoon was observed to be significantly different from the other three seasons, it can be concluded that Chl-*a* at Bangladesh maritime boundary in the northern BoB showed a significant seasonal variability during the investigation period. Observed seasonal variability of Chl-*a* showed a maximum in the onshore region with the following seasonal trends: southwest monsoon > postmonsoon > northeast monsoon > premonsoon. In Figure 3,

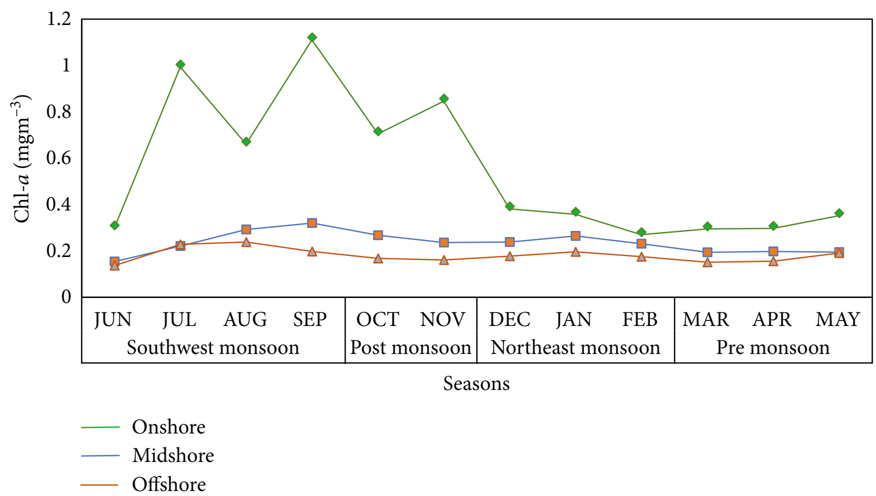

Figure 2: Seasonal and spatial trend of Chl-*a* (July 2002-June 2020) in the maritime boundary of Bangladesh.

monthly chronological Chl-*a* satellite images showed the Chl-*a* variability and its distribution patterns over the respective regions in the northern BoB for 19 years (July 2002–June 2020).

As with seasonal distribution, the annual trend also showed the most variability of Chl-*a* over the onshore region depicted in Figure 4. In the onshore region, the annual time series data (2002–2020) showed a complex variability of Chl-*a*. The maximum and minimum annual average of Chl-*a* was 1.11 mgm^{-3} in 2004 in the onshore region and 0.09 mgm^{-3} in 2002 in the offshore region, respectively.

The northern BoB is a complex and dynamic region, with spatial variability in Chl-*a* concentration influenced by a range of physical, chemical, and biological factors [5, 6, 16, 38, 39] including light availability, nutrient availability, the presence of other organisms, temperature, currents, and monsoon-driven upwelling [37, 40–43]. However, the spatial distribution of Chl-*a* concentration in the northern BoB is not uniform [44, 45]. Satellite remote sensing data shows that the highest Chl-*a* concentrations are found in the coastal waters where river discharge and upwelling are strongest [26, 46, 47]. Chl-*a* concentration gradually decreases with increasing distance from the coast and is lowest in the central BoB, where nutrient availability is limited [26, 44, 45, 48].

This study has demonstrated that the concentration of Chl-*a* at Bangladesh's maritime boundary in the northern BoB exhibits significant seasonal and spatial variability. The highest Chl-*a* was observed in the onshore region (depth 100-150 m) during the southwest monsoon (June–September). In this study, the onshore region occupying the lower distance from the coast in northern BoB is supposed to receive a higher percentage of river discharge than the midshore and offshore regions during the southwest monsoon. In this season (Jun-Sep), the major river system Ganges-Brahmaputra-Meghna (GBM) which is adjacent to the maritime boundary of Bangladesh experiences a significant amount of rainfall which results in the highest amount of river discharge [18, 21, 45, 49]. In the aftermath, the highest Chl-*a* production has been observed in the onshore region during this season (Jun-Sep). Additionally, factors including light availability, nutrient availability, the presence of other organisms, SST, currents, monsoon-driven upwelling, rainfall, and river discharge [5, 6, 16, 38–40, 43, 49] do not remain constant all year round which eventually results in seasonal fluctuations of Chl-*a* in the onshore region. However, the depth starts to increase sharply after 200 meters where the midshore region starts, eventually reaching 2000 meters near the continental shelf, making the offshore and midshore areas less productive due to the deepest topography [15, 16, 26, 46].

A significant seasonal variation of Chl-*a* has been observed throughout the year due to the periodically reversing monsoon system in the BoB which distinguishes it from all other oceans. [50–52]. In addition, seasonal variations of Chl-*a* across the northern BoB is strongly related to the river runoff, lower SST, and coastal plumes [19, 38–40]. In this study, the southwest monsoon (June-September) is characterized as the most productive season. During the summer monsoon (June-September), increased wind-driven upwelling along the eastern coast of India brings nutrient-rich waters to the surface, leading to increased Chl-*a* concentrations in the northern BoB region [1, 14, 16, 23]. The season (Jul-Sep) has higher river discharge [17] enriched with higher amounts of nutrients like nitrate, silicon, and phosphate [34] due to river runoff following monsoonal rainfall [1] that causes a substantial increase of Chl-*a* abundance during this season. [23, 37, 42]. Plenty of nutrients are deposited along with the sediments to the Bangladesh coast in the northern BoB from the confluence of two major river systems: the Ganges and the Brahmaputra system and the whole Ganga-Brahmaputra-Meghna [23, 37, 41] during the southwest monsoon [38]. However, a recent study [17] for the years 2012-2017 at the shelf region in the northern BoB found a decreasing trend of Chl-*a* during the premonsoon due to the lower wind speed and rise in temperature. The same trend was observed for the year 1999-2000 by Nagamani et al. [24]. An increase in SST and a decrease in wind speed were also reported as the reasons behind the lower abundance of Chl-*a* in the premonsoon [17, 24].

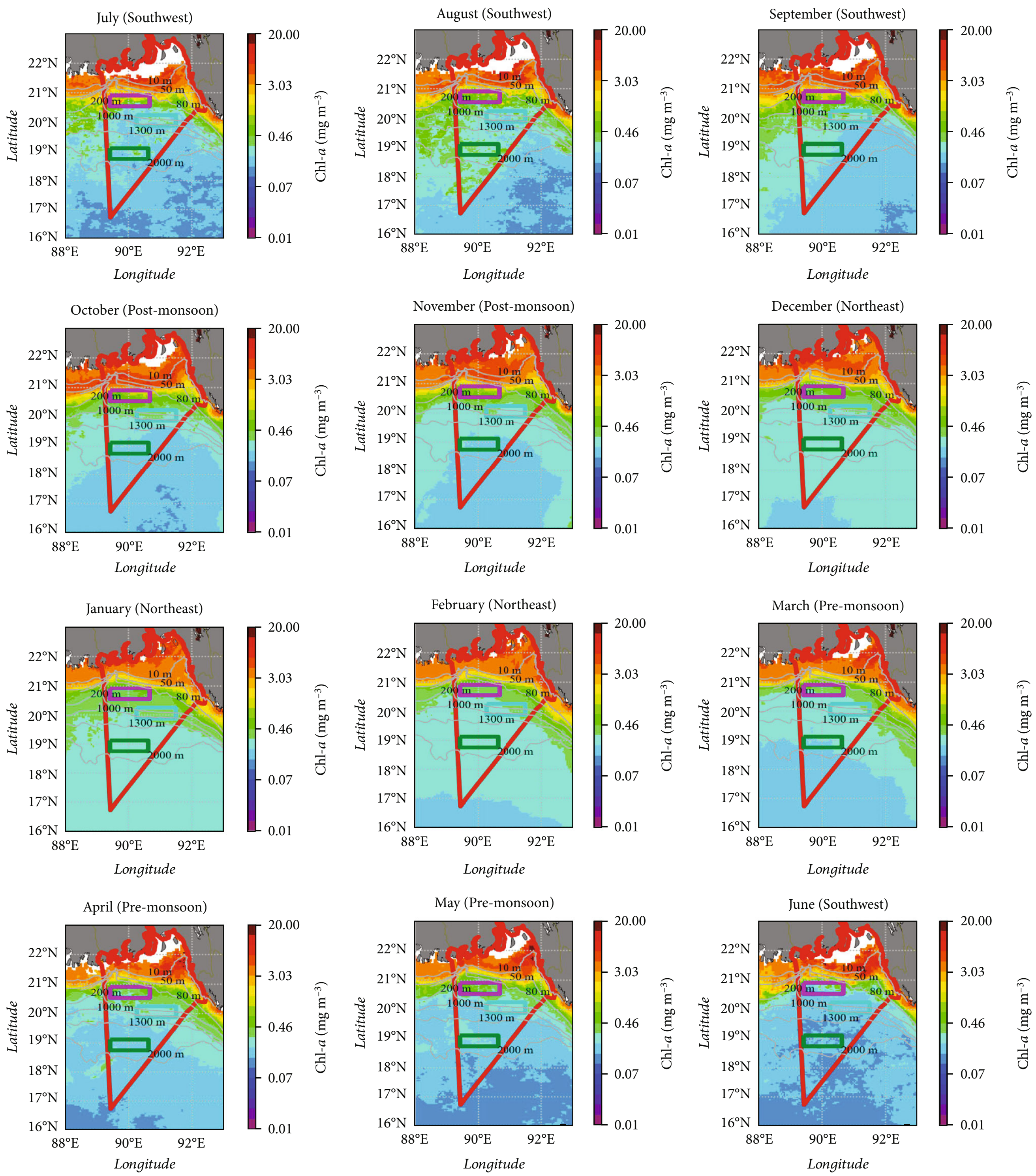

Figure 3: Composite image of monthly average Chl-*a* for 19 years (July 2002-2020) in the maritime boundary of Bangladesh in the northern BoB.

The concentration of Chl-*a* in the onshore region showed continuous fluctuations throughout the southeast and postmonsoon period (Figure 2). Fluctuations in Chl-*a* levels primarily result from variations in the system's ecology and the biological response to the physical and chemical environment [7, 8]. In this study, the Chl-*a* concentration began to rise from the onset of the monsoon and reached its peak in September. However, in August, which is typically the peak of the monsoon season, the concentration of Chl-*a* suddenly dropped in onshore as a consequence of reduced light availability due to increased cloud cover [23], and rainfall causes turbidity [38], which can limit photosynthesis in phytoplankton [53], leading to a decrease in Chl-*a* production.

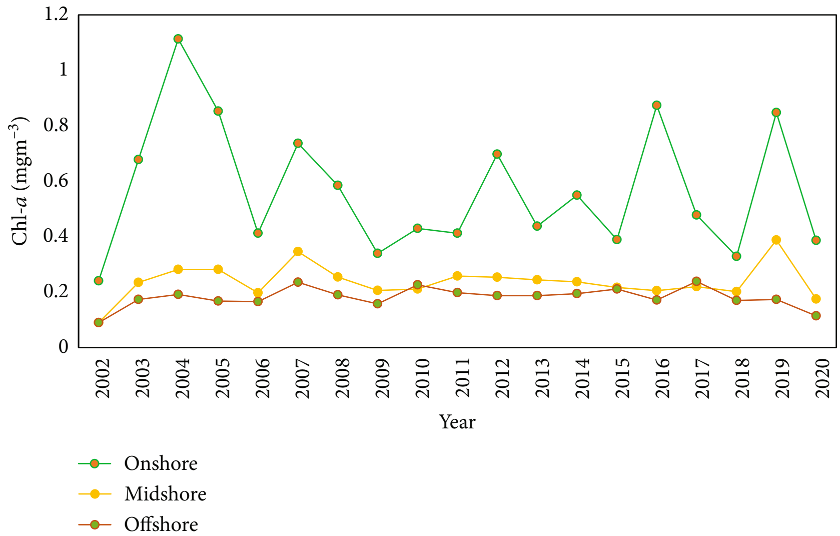

Figure 4: Annual trend of Chl-*a* (2002-2020) in different locations over the maritime boundary of Bangladesh.

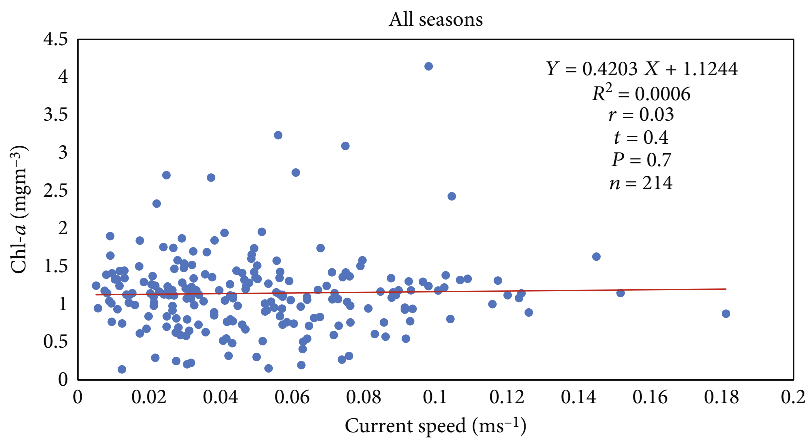

Figure 5: Seasonal relationship between Chl-*a* (mgm^{-3}) (all seasons) and current speed ms^{-1}.

The seasonal and annual time series showed analogous spatial variability in Chl-*a* concentration across the study areas. For the annual time series data (2002–2020), the variability of Chl-*a* fluctuated most in the onshore region with having a relatively higher concentration than in midshore and offshore regions (Figure 4). In addition, the Chl-*a* variability during (2002–2020) showed almost a homogenous distribution in the midshore and offshore regions. The onshore region is more vulnerable to changes in factors including sea surface temperature (SST), rainfall, river discharge, nutrient availability, and coastal upwelling [53–58]. The combined influence of these factors can significantly impact the growth of phytoplankton over the years. Consequently, the onshore region experiences significant fluctuations in Chl-*a* concentration compared to the midshore and offshore regions during the period from 2002 to 2020. Furthermore, the annual average of Chl-*a* from 2002 to 2020 shows a decline of Chl-*a* concentration (Figure 4). There has been an observed declining trend of the annual average of Chl-*a* in the BoB over the past few decades [17, 53, 59–61]. Significant decrease of dissolved inorganic nitrogen and phosphorus in the Bay of Bengal [58], as well as rising SST due to climate change [53, 58, 59], and changes in precipitation patterns [53] are the reasons that contribute to this annual decline.

3.2. Relation between Chl-a and Ocean Current Speed in Bangladesh Maritime Boundary. This study used a monthly average dataset of Chl-*a* and the current speed dataset with the timeline of July 2002–June 2020 to determine the relation between them in the study area. While conducting the investigation, the Chl-*a* dataset was used from the entire maritime boundary of Bangladesh.

A weak positive correlation ($b = 0.42$, $R^2 = 0.0006$, $r = 0.03$) was found between seasonal Chl-*a* and current speed in the maritime boundary of Bangladesh in the northern BoB (Figure 5). The P value (>0.05) indicates a nonsignificant relationship between Chl-*a* and the current speed. The regression model was found as $\mathrm{Chl} - a = 1.124 + 0.420^{*}$current speed. The analysis suggests that there is a weak relationship between Chl-*a* and current surface current speed when considering all seasons combined.

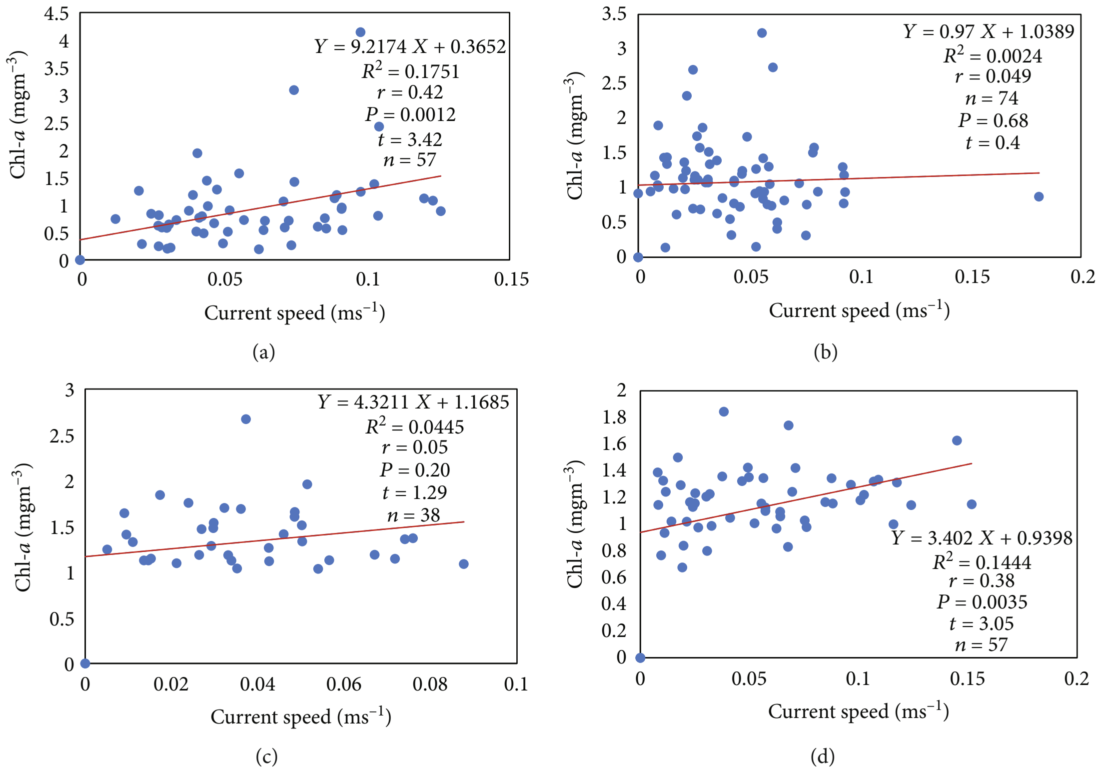

Figure 6: Relationship between Chl-*a* and current speed in (a) premonsoon, (b) southwest monsoon (c) postmonsoon, and (d) northeast monsoon seasons.

The relationship between the seasonal Chl-*a* and the surface current speed of different seasons was determined by the same linear regression (Figure 6). The results indicate that the relationship between Chl-*a* and surface current speed varies depending on the season. A nonsignificant ($P > 0.05$) but a weak positive correlation was found between Chl-*a* and the current speed for the southwest monsoon (June-September) and postmonsoon (October-November). However, a moderate positive correlation was found between the seasonal Chl-*a* and the surface current speed during the northeast (Dec-Feb) season (Figure 6) which is statistically significant ($r = 0.38$, $b = 3.40$, $P < 0.05$). During premonsoon (Mar-May), the relationship was also observed as significant ($P < 0.05$) and moderately positive ($r = 0.42$, $b = 9.21$). Overall, these results suggest that there is a moderate positive relationship between Chl-*a* and surface current speed in the maritime boundary of Bangladesh in the northern BoB where seasonal variation is salient.

Table 1 suggests that the relationship between Chl-*a* and the surface current speed is not constant throughout the year. This is likely due to the variation of different factors throughout the year (such as temperature, stratification, winds, upwelling, and vertical mixing), exerting greater or lesser influences on Chl-*a* concentrations at different times [62–67]. In this study, the correlation between Chl-*a* and surface current speed is moderately positive during the northeast and premonsoon season which typically occurs between February and May in the Indian Ocean region. During premonsoon, the surface currents are dominated by the northeast monsoon winds, coastal boundary currents, and offshore Ekman transport [61], creating upwelling that brings nutrient-rich deep water to the surface [64, 68] which enhances the growth of phytoplankton, leading to higher Chl-*a* concentrations [62, 65, 68]. In contrast, the correlation between Chl-*a* concentration and the surface current speed is comparatively weaker during the southwest monsoon season (June to September) due to the increased mixing of the water column resulting from monsoon winds and associated rainfall. This increased mixing can reduce the concentration of nutrients in surface waters, thereby limiting the growth of phytoplankton during southwest monsoon [64, 69].

3.3. ENSO Effect over Chl-a Distribution in the Northern BoB. Intensity and trend of El Niño and La Niña events from 2010 to 2019 following the ONI time series index (SSTA) are depicted in Figure 7. The high value of ONI (≥2.5°C) was observed from November 2015 to February 2016, as seen in Figure 7, and can be considered as one of the most potent El Niño since 1990 and is considered one of the most significant El Niño events after 1950 [33].

A nonsignificant negative relation ($r = -0.07$, $P = >0.05$) was found between SST anomalies (yearly average of 3 months running mean) and Chl-*a* in the northern BoB (Figure 8). This analysis reveals that the 10-year (2019-2010) ONI (Oceanic Nino Index) of the Nino 3.4 region has a very negligible influence on yearly Chl-*a* distribution in the maritime boundary of Bangladesh. While investigating the seasonal effect (Figure 9), a negative correlation was also found in the seasonal distribution of Chl-a (Figure 9) in the study area, whereas the *P* value (>0.05)

Table 1: Statistical analysis between Chl-*a* and surface current speed following seasonal monthly average data.

Time series	Intercept	Coefficient (*b*)	R^2	Sig (*P* value)	Correlation coefficient *r*
Southwest monsoon (Jun-Sep)	1.038	0.97	0.002	0.68	0.05
Postmonsoon (Oct-Nov)	1.168	4.32	0.04	0.20	0.05
Northeast (Dec-Feb)	0.939	3.40	0.14	0.003	0.38
Premonsoon (mar-may)	0.365	9.21	0.18	0.001	0.42
All season (2002-2020)	1.13	0.420	0.0006	0.7	0.03

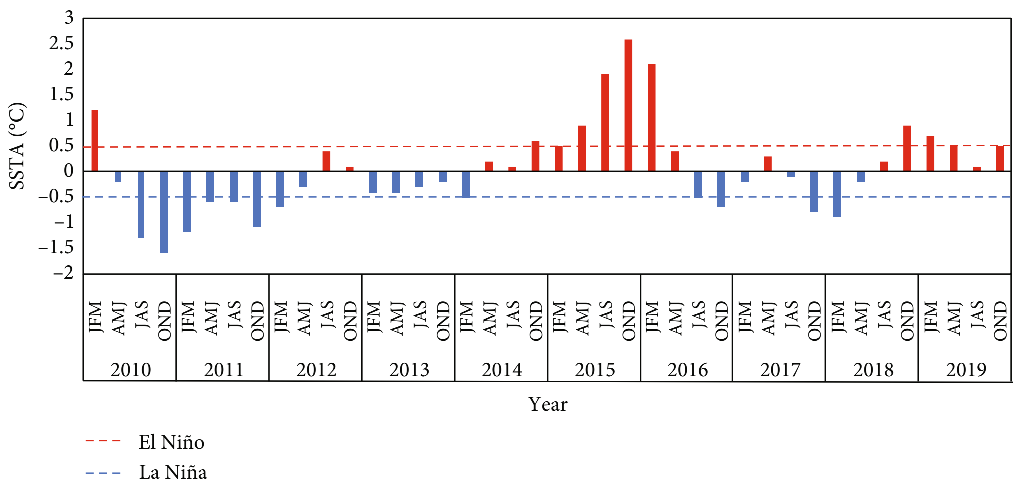

Figure 7: ONI time series (3 months running mean) during 10 years (2010-2019).

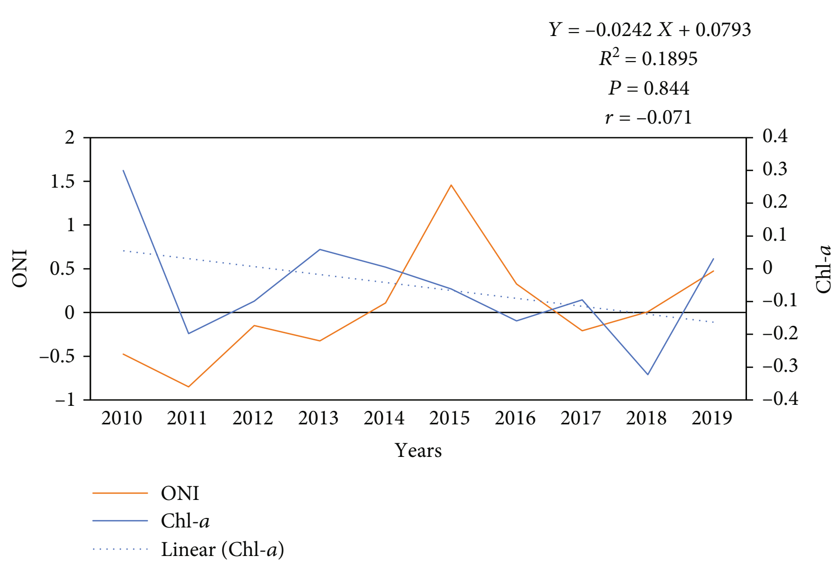

Figure 8: Annual effect of ENSO on Chl-*a* anomaly.

indicates a nonsignificant relation between SST anomalies (monthly average) and seasonal Chl-*a* variation. The BoB undergoes significant global climatic events like El Niño [70–72]. The high value of ONI (>2.5°C), which was observed from November 2015 to February 2016, represents one of the most potent El Niño since 1990 and is considered one of the most significant El Niño events after 1950 [33]. This study reveals that the ENSO event in the 2015-2016 (strong El Niño in 2016) session has a negligible influence on Chl-a seasonal variation pattern also in the following years 2017 (La Nina period) in the maritime boundary of Bangladesh in the northern BoB as it has brought no significant change on Chl-a distribution in this area. The magnitude of Chl-*a* anomalies has changed but not significantly even after the El Nino period (2015-2016).

So, this study reveals that the ENSO event in 2015-16 did not alter the seasonal variability and annual trend of Chl-*a* in the maritime boundary of Bangladesh. ENSO effects are

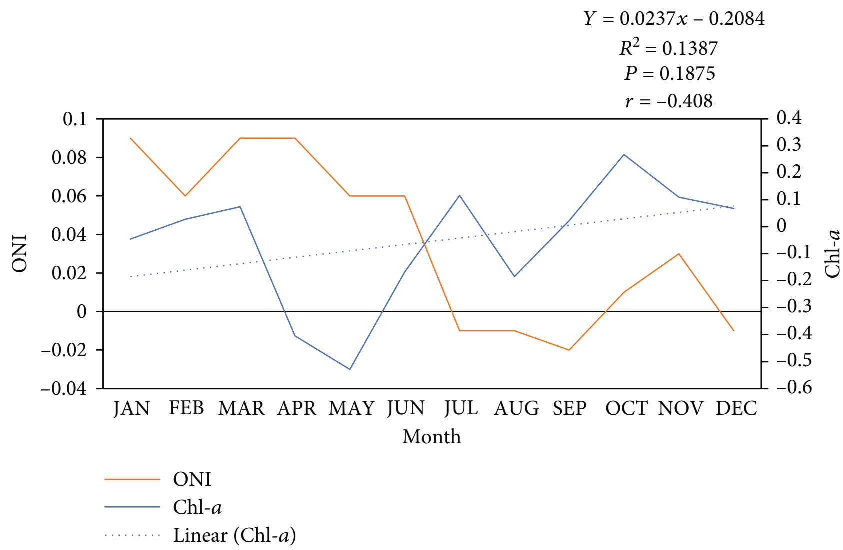

Figure 9: Seasonal effect of ENSO on Chl-a anomaly (2010-2019).

usually observed on large ocean basins like the Pacific, where warming or cooling due to the El Niño and La Niña events are highly associated with the global average surface temperature (NOAA http://climate.gov). The ENSO effect also brought no change in the seasonal variability of Chl-*a* in the Maluku Sea [35] and the South China Sea [36]. The ENSO has the most considerable impact on the Pacific Ocean Basin's tropics [73–75]. The equatorial Pacific Ocean is the epicenter of ENSO activity [74]. The ENSO influence has been observed mainly in the tropics and subtropics with high latitudes surrounding the Pacific regions [73, 74]. The fluctuation of global marine Chl-*a* in response to ENSO events could not be taken into account in a small domain like Bangladesh maritime boundary. The impact of ENSO on Chl-*a* distribution might be understood better in the large ocean domain [74, 76].

4. Conclusion

This study reveals the seasonal and spatial variability of Chl-*a* in three separate regions in the maritime boundary of Bangladesh in the northern BoB and its response to surface current and significant climatic events like ENSO. The highest Chl-*a* was observed in the onshore region over the maritime boundary of Bangladesh during the southwest monsoon, whereas the lowest was in the offshore region. The observed Chl-*a* abundance was almost homogenous in the offshore and midshore regions. Therefore, the onshore region has a higher level of primary productivity than offshore and midshore regions which is likely to have higher fisheries abundance and diversity. Additionally, observed seasonal variability of Chl-*a* showed a maximum fluctuation in the onshore region with the following seasonal trends: southwest monsoon > postmonsoon > northeast monsoon > premonsoon. The relationship between Chl-*a* and surface current speed varies by season and is comparatively stronger during the premonsoon season than other time series throughout the year, and the weakest correlation is observed when considering all seasons combined. ENSO event of 2015-2016 did not change the seasonal variability and annual trend of Chl-*a* of this area. The entire study is based on secondary data; however, in situ-based primary data might yield more accurate findings.

Data Availability

The Chl-a, SST anomalies, and current data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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The authors would like to thank the NASA (National Aeronautics and Space Administration) ocean color site (https://oceancolor.gsfc.nasa.gov) for providing the Chl-*a* dataset. The authors would like to express gratitude to the Live access service, APDRC LAS8.6.13, and especially to NOAA, the Climate Prediction Center (https://origin.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ONI_v5.php), for providing the monthly mean of SST anomalies.

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