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Spatio-temporal Variations in Sea-Surface-Temperature and Salinity Level in the Northern Bay of Bengal between 2016 and 2020

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Abstract

The Bay of Bengal (BoB) is a continuum receiving numerous major rivers including the Mahanadi, Godavari, Krishna, Kaveri, Ganges, Brahmaputra, Meghna, and many more others. The river outputs are greatly impacted by the dynamic circulation system along the shelf. As anticipated, the freshwater influx from rivers leads to lower salinities and shallower mixed layers. Yet, the effect of this extra freshwater input into the bay is unexpectedly complex. Meanwhile, the considerable freshwater flow from these rivers transforms the density and dynamic height of the receiving seas, potentially influencing primary productivity in the northern BoB. Various observational, reanalysis, and satellite datasets—such as river discharge, temperature, salinity, density, and chlorophyll concentration—are analyzed using heterogeneous correlation methods. The data sources include the Copernicus Marine Environment Monitoring Service and ERA-Interim. It highlights that Classic estuarine two-layer circulation during monsoonal period is one of the significant consequences of river plume influence on continental shelf. Coriolis force, which is governed by earth rotation, monsoonal effect and buoyant river plumes are what makes this discovery so significant. This study indicates that the highest variability in Sea Surface Salinity (SSS) is found near the mouths of the major rivers, such as the Ganges-Brahmaputra-Meghna (GBM) in the northern BoB and the Irrawaddy in the northern Andaman Sea. There's also notable variation along the western boundary of the basin, though to a lesser extent. The results show a large increase in surface salinity along the Bangladeshi coast especially in the eastern part in near future, which may affect the area of fresh water plume-suggesting that variations in river flow can significantly influence the dynamic marine ecosystems of the northern BoB during the time period between 2016 and 2020. These modifications are anticipated to cause considerable alterations in the coastal aquatic ecosystems in coastal areas.

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Introduction

Bangladesh is known as the world's largest deltaic plain, located where the Ganges, Brahmaputra, and Meghna (GBM) rivers and their tributaries converge, forming the GBM basin. This most dynamic tide dominated delta drains both the northern and southern Himalayan slopes. The estuary systems in this area are responsible for distributing the roughly drains 1 billion tons of silt and 1.18 trillion m^3 of water into the Bay of Bengal (BoB) brought in by this flow each year (Islam *et al*., 2009). Although the Lower Meghna is the primary channel for transferring flow and sediments, numerous cross-connecting waterways in Bangladesh's south-west also contribute to the flow and sediment transport (Kida and Yamazaki, 2020).

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The BoB is a major source of freshwater export, with the northern region experiencing the lowest salinities, especially from June to October, due to the monsoon rains and the GBM delta. This freshwater spreads southward along the coasts, mixing slowly with the saltier water below, creating a distinct mixed layer depth (MLD). Below this layer, a warmer, saltier barrier layer exists, hindering vertical water and heat mixing and nutrient transfer to the sunlit surface. This stratification reduces productivity in the central Bay but increases it along the coastal margins, driven by coastal upwelling and river plumes. (Largier, 2020).

The BoB's dynamics are further influenced by the Indian Monsoon, Indian Ocean Dipole (IOD), and El Niño-Southern Oscillation (ENSO), affecting wind, rainfall, and circulation patterns. These factors affect BoB circulation patterns through variations in surface wind, rainfall, and marine circulation. Due to this climate variability the Bay is already experiencing sea level rise, posing a significant threat to coastal communities in Bangladesh. Due to increased flooding depth, area, and maximum wave height, sea level rise in the twenty-first century is projected to be between 0.5 and 1.7 meters. (Kay *et al*.).

The dynamics of influence of estuarine flow have been extensively studied across various regions, shedding light on the complex interactions between oceanic and riverine forces. In the West Florida shelf, (Weisberg *et al*., 2005) highlighted the role of momentum and buoyancy fluxes in driving ocean circulation, with significant implications for wintertime conditions on the East Coast continental

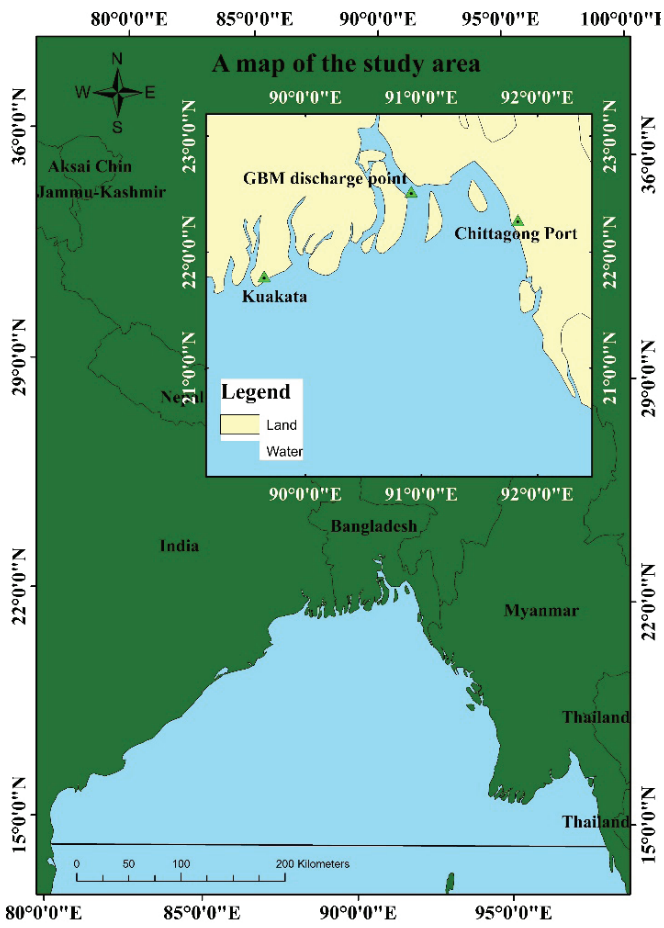

Figure 1. The northern BoB (marked above the dashed line, Latitude: 14°N to 24°N; Longitude: 80°E to 99°E). In the inset map the GBM discharge mouth is shown with surrounding landmarks

shelf. Similarly, in East China, the Changjiang river emerges as a major driver of shelf circulation, leading to enhanced cross-shelf exchange and subsurface intrusion due to bottom Ekman transport (Akhter *et al*., 2021; Chowdhury *et al.*, 2021; Wu and Wu, 2018) as only a few local, short-term studies have been performed. Hence, this study investigates a comprehensive basin-wide framework of the seasonal variations in the chlorophyll-a concentration, its dominant external forcing, and the internal dynamics of the Bay of Bengal. Multivariate empirical orthogonal function decomposition and heterogeneous correlation analyses are applied to numerous observational, reanalysis, and satellite datasets, including chlorophyll-a, nutrients, temperature, salinity, turbidity, and wind stress curl datasets collected from various sources, including the Copernicus Marine Environment Monitoring Service, World Ocean Atlas, and ERA-Interim. This study suggests that the chlorophyll-a concentrations at both the surface and the subsurface chlorophyll-a maximum (SCM). This highlights the need to delve deeper into the influence of river plumes on shelf dynamics, an area that remains largely unexplored. In the BoB, research using models like the Regional Ocean Modeling System (ROMS) has demonstrated how seasonal river inputs shape the formation and spread of plume systems, impacting salinity distribution and stratification.(Jana *et al*., 2015) two parallel climatological simulations (with and without rivers. However, there remains a need to explore the reciprocal influence of shelf circulation on riverine dynamics, particularly in mega-deltas like the GBM delta.

However, the effect of this additional freshwater inflow into the bay is unexpectedly surprising. As a result, with the aim of better describing shelf circulation in the BoB, The primary goal of this research is to comprehensively analyze the physical forcing behind variations in currents over inter-annual, seasonal, and inter-seasonal time scales. Furthermore, the study aims to assess how these interactions influence primary productivity in the northern BoB.

The present research focuses on the Northern BoB, that is located, in the north and is bordered by Bangladesh, India, and Myanmar. The bay is roughly 1500 km wide extended approximately between the latitudes 14°N to 24°N (Figure 1).

Materials and Methods

For this study, river discharge data in the northern BoB were sourced from the Bangladesh Water Development Board (BWDB) for the years 2016 to 2020.The study utilizes satellite datasets including SSS, Sea Surface Temperature (SST). SSS and SST data from CMEMS cover the period from 2016 to 2020 with a resolution of 0.25° × 0.25° and depths up to 220 meters.

Field observations and sample collection were conducted from January 11 to 13, 2023, along the coastal region from Maheshkhali to Teknaf. To clarify this approach, I initially collected secondary data from 2016 to 2020 to observe and analyze trends over this period. Subsequently, I gathered data in 2023 to facilitate a comparative analysis and evaluate any significant changes or trends over the intervening years Water quality data were gathered using multiparameter instruments, and water samples were collected in white plastic bottles for laboratory analysis of nutrients. Lab analysis included nitrite determination using the Ferrous Sulfate Method at a wavelength of 371 nm, phosphate determination via the Phosver 3, Ascorbic Acid method at 490 nm, and ammonium determination using the USEPA Nessler Method 8038 (Klein and Gibbs, 2017) wastewater and seawater. Distillation is required for wastewater and seawater. 1 USEPA accepted for wastewater analysis (distillation required at 380 nm). Sample preparation involved blank preparation and spectrophotometer readings for each analysis.

The methodology section outlines the approach taken in the study from 2016 to 2020 to analyze the spatial distribution and seasonal variation of physico-chemical parameters in the study domain. The study divides time into four seasons: (winter, spring, summer, and fall). The analysis tools used included MATLAB R2020a for numerical computations and visualization, ArcGIS 10.7.1 for mapping and spatial analysis, and Python 3.10 for general-purpose analysis, particularly for computing SST data and Dipole Mode Index (DMI) values for the IOD region from 2011 to 2020.

Results and Discussion

Observation on spatial distribution and inter-annual variation of physical parameters

The study focuses on the spatial distribution and temporal variation of SSS and SST in the BoB from 2016 to 2020. Both SSS and SST exhibit a gradient from south to north (Figure 2). The fresher surface waters in the northern BoB contribute to intense haline stratification and the formation of a barrier layer, resulting in high SST, especially above 28°C (Figure 2.b).

The variability in SSS in the BoB is influenced by large

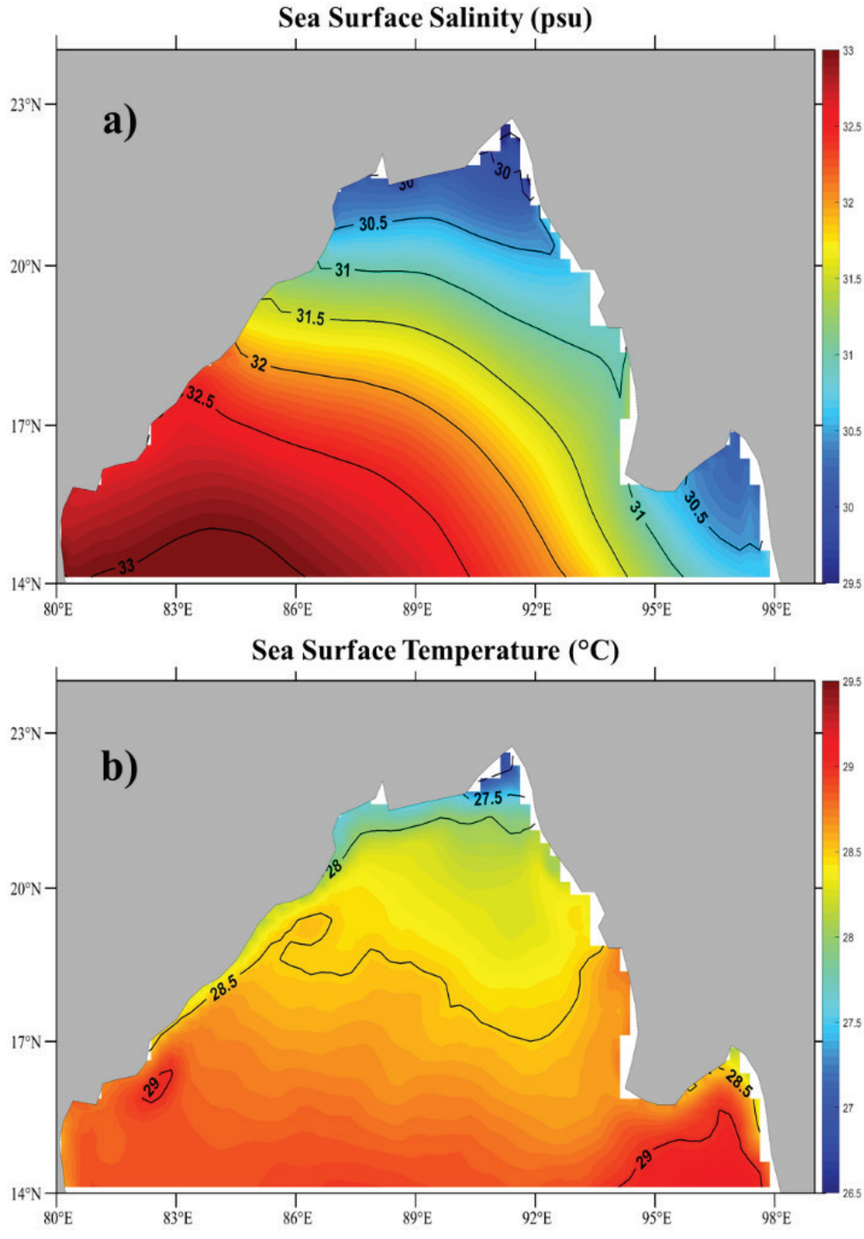

Figure 2. Spatial variations in annual mean SSS and SST of the northern BoB between 2016 and 2020. The same problem appears

riverine inputs, creating significant salinity gradients near major river mouths and along the western boundary of the basin. SSS increases gradually from northeast to southwest at the continental shelf, with the western coast exhibiting the highest salinity. Inter-annual variations in temperature and salinity are evident, with the distribution of temperature showing distinct changes (Figure 3), influenced by IOD events (Khan *et al.*, 2021; Lu and Ren, 2020; Vinayachandran *et al.*, 2007). Among the all years salinity suddenly increase in 2018 but temperature remains comparatively low in that year (D'Addezio and Subrahmanyam, 2016; Kumari *et al.*, 2018).

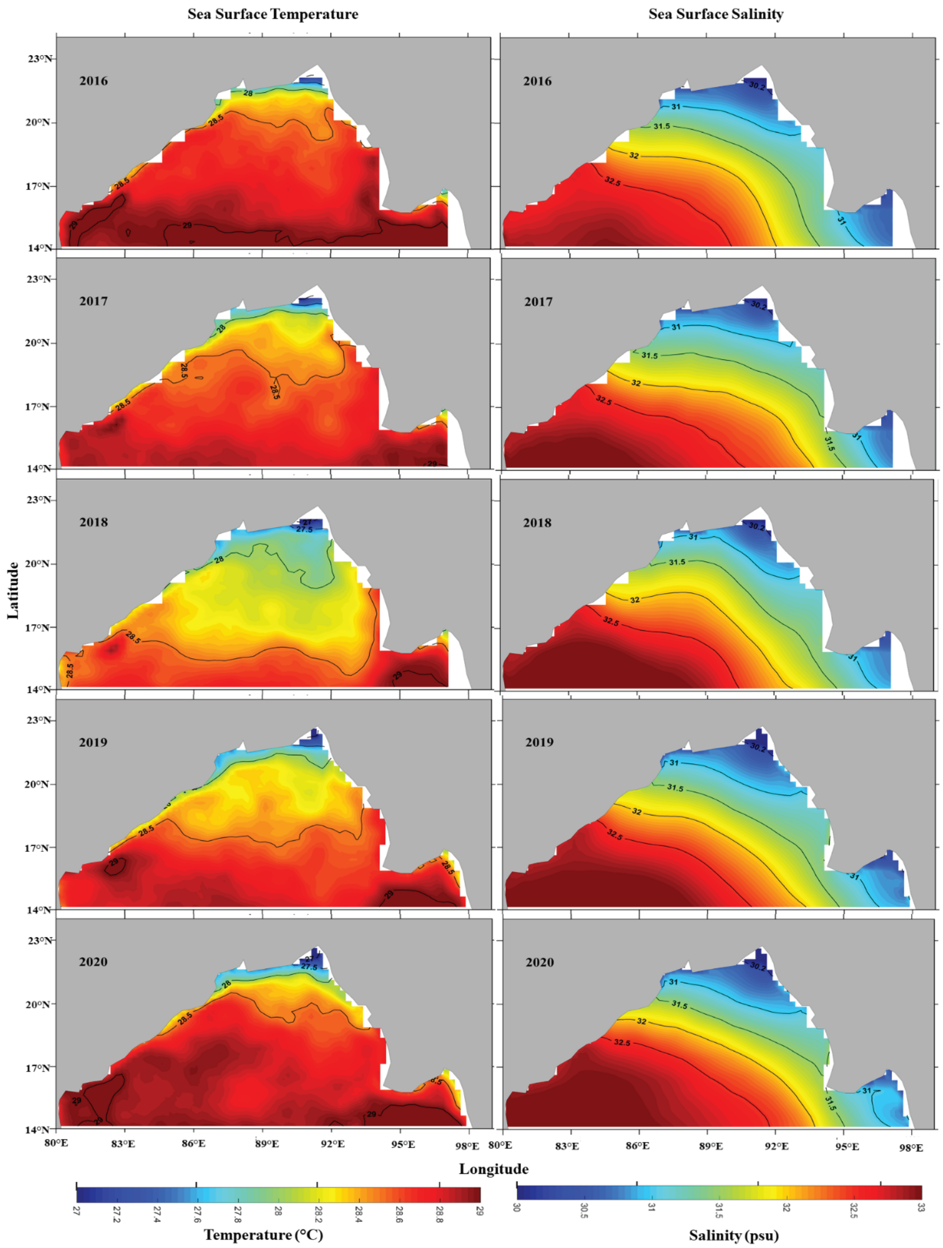

Figure 3. Inter-annual variation (time period from 2016 to 2020) of SST [on the left] and SSS [on the right]

As we know 2016-17 faces strong negative IOD causing high temperature in the northern BoB (Lu *et al*., 2018). Then there is a temperature shift causing positive IOD in 2019 and thus resulting in a temperature decrease in 2018 in Figure 3 (Lu and Ren, 2020)which has induced severe climate impacts around the Indian Ocean basin. In this study, the cause for 2019 IOD event and the related mechanism are explored. We find that the remarkable strengthening of Australian high and weakening of sea level pressure over South China Sea/Philippine Sea have been evidently visible since May 2019. Such a record-breaking interhemispheric pressure gradient (IHPG.

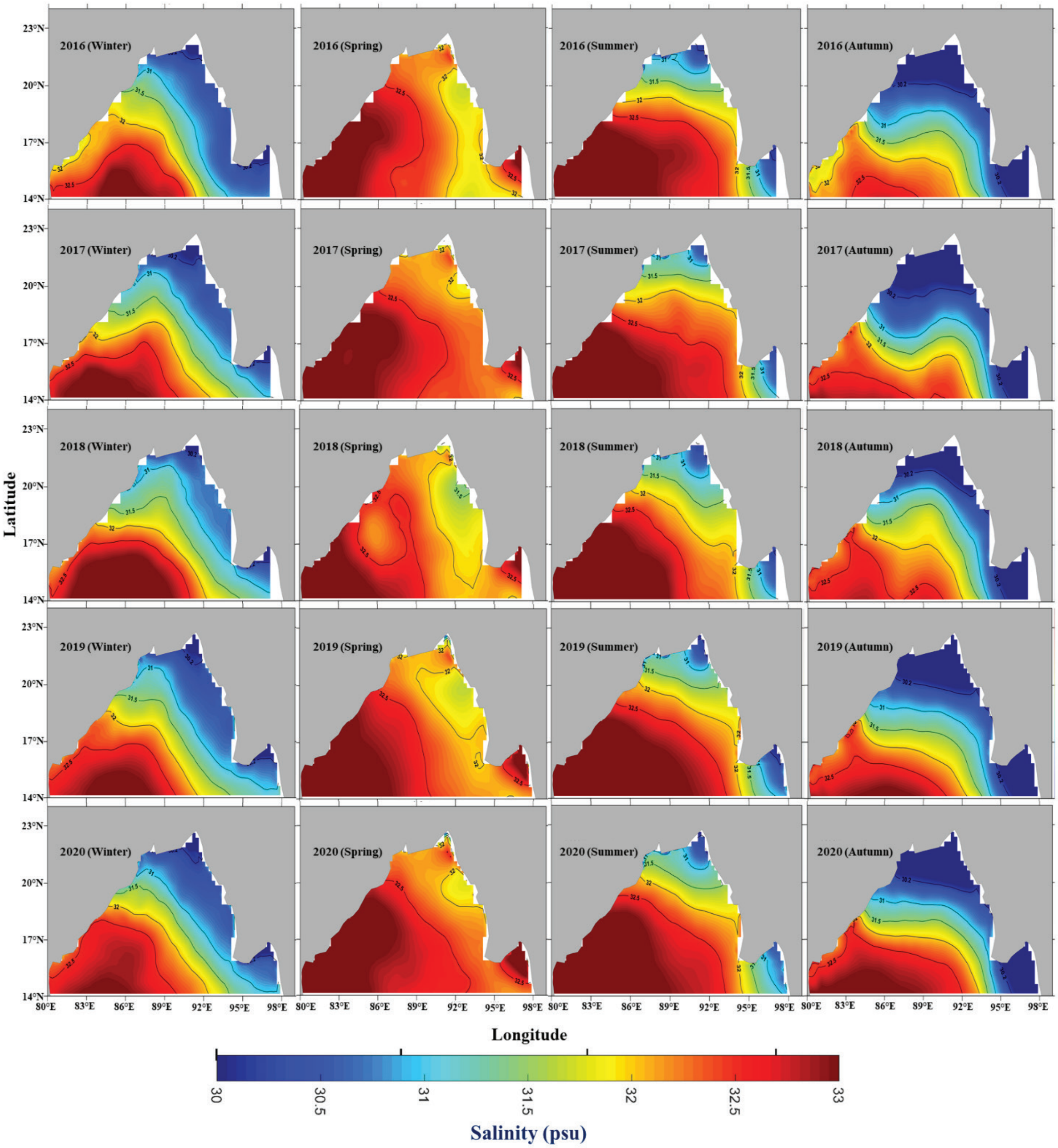

Figure 4. Seasonal distribution of SSS (psu) in the northern BoB for the time period from 2016 to 2020

The BoB experiences pronounced seasonal fluctuations in SSS and SST, particularly around the GBM shelf and the east coast of India, driven by the Indian monsoon's freshwater flow (Figure 4). From June to August, a stretch of low-salinity water develops in the northeastern BoB. Despite increased heat absorption due to riverine input, SST remains only marginally lower due to efficient entrainment cooling, latent heat loss, and penetrative radiation. Freshwater levels remain high until November, after which salinity rises during the winter-spring season. By November, the freshwater tongue extends southward to 10°N. Spring exhibits high SSS distribution in the northern BoB, peaking in 2020. Conversely, summer of 2016 sees a strong concentration of salinity exceeding 33 psu. Autumn records very low salinity, especially in the northern bay, while 2017 exhibits large areas of low salinity during this season. Overall, salinity tends to be lowest in autumn, rising through winter to peak in spring before decreasing again in summer.

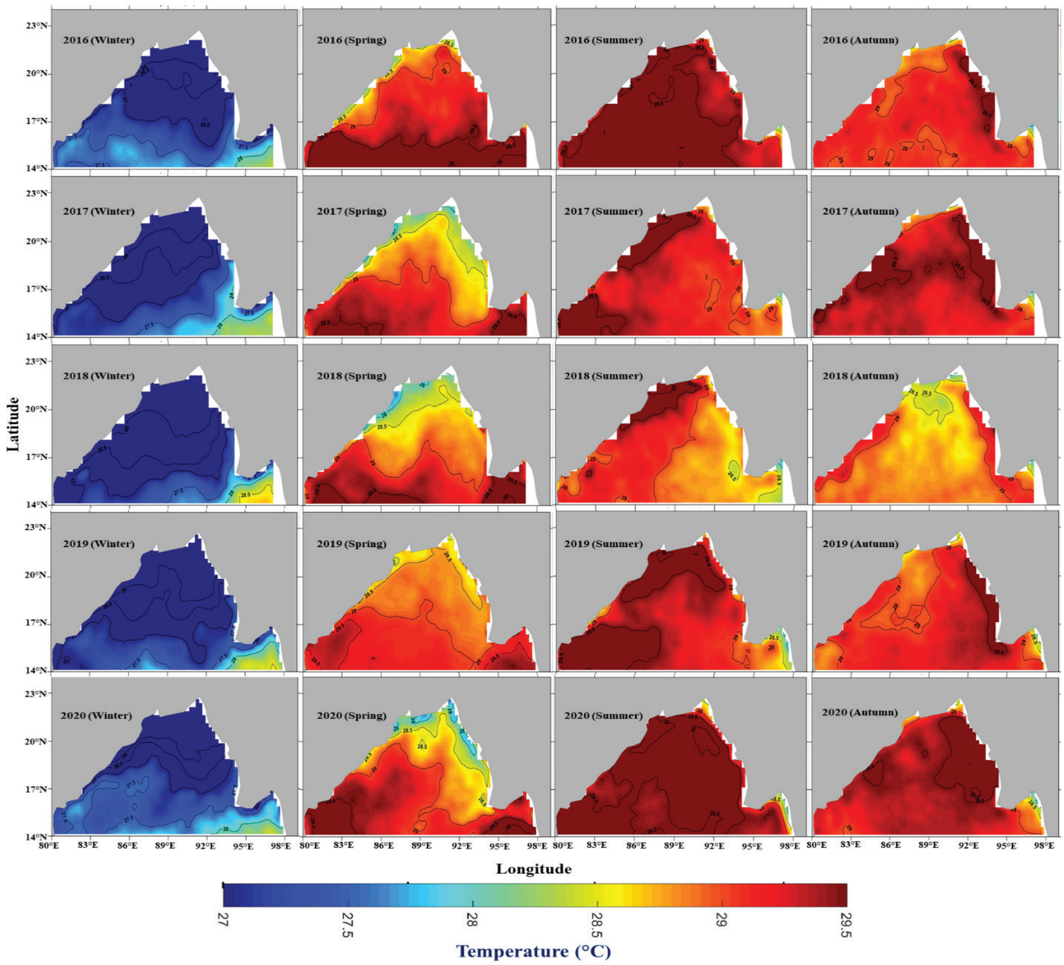

Figure 5. Seasonal distribution of SST (°C) in the northern BoB for the time period from 2016 to 2020

SST displays seasonal variations (De Boyer Montégut *et al*., 2007), with lowest temperatures during winter and highest during summer (Figure 5). Notably, 2020 shows a consistently high temperature distribution across all seasons compared to other years, with 2018 showing a low distribution. Variations are evident from one season to another, with the northern bay showing higher variation than the southern bay in seasonal observations.

Relationship between salinity, precipitation and density

Time series analysis reveals well-defined seasonality in precipitation variations, which closely correspond with fluctuations in salinity, density, and river discharges in the northern BoB (Figure 6). Maximum salinity, river discharge, and precipitation occur during the monsoonal period, particularly peaking in May, July, and August, respectively. Conversely, minimum values are observed in October and November for salinity, precipitation, and river discharges. Density exhibits a reversal pattern, reaching its highest crest in February and lowest point in November.

Geographically, the northern BoB experiences a broad range of salinities due to the convergence of freshwater from river mouths and oceanic water (Kida and Yamazaki, 2020; Shetye *et al.*, 1996). The seasonally reversing monsoonal wind system significantly impacts salinity and precipitation rates, with heavy rainfall during the monsoon period leading to high river discharge rates and freshwater intrusion into the northern Bay. This results in a low-salinity plume that drifts over surrounding waters or spreads as a coastal current (Geyer *et al.*, 2004). After the monsoon period, salinity and density gradually increase during winter-spring, while precipitation and river discharge rates decrease. This persistence of freshwater until November, followed by an increase in salinity, defines the seasonal patterns of the northern BoB.

Vertical profiling, observation on MLD

Five stations were taken for the observation on vertical distribution of chlorophyll-a associated with temperature, salinity and density. Station 1 and 2 are taken at southern edge (14°15´N, 89°15´E, and 14°30´N, 85°00´E) of northern BoB (figure 7.a, 7.b), from these stations 1 is the southernmost point in the mid longitude of northern BoB.

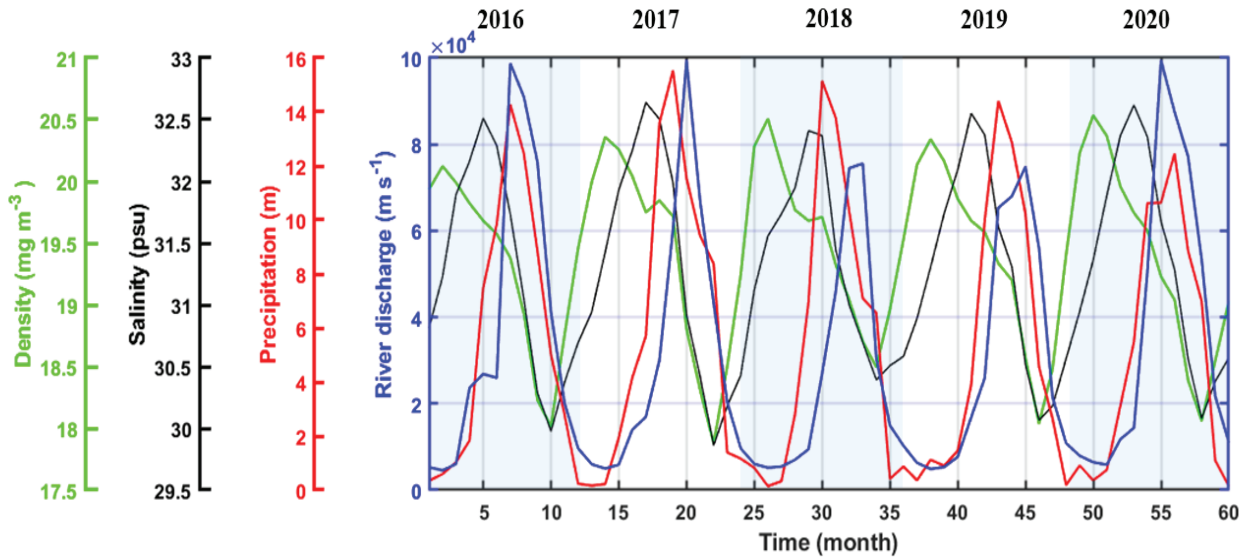

Figure 6. Time series analysis for density (mg m^{-3}), salinity (psu), precipitation (meter) and river discharge (m s^{-1}) in the northern BoB for the time period from 2016 to 2020

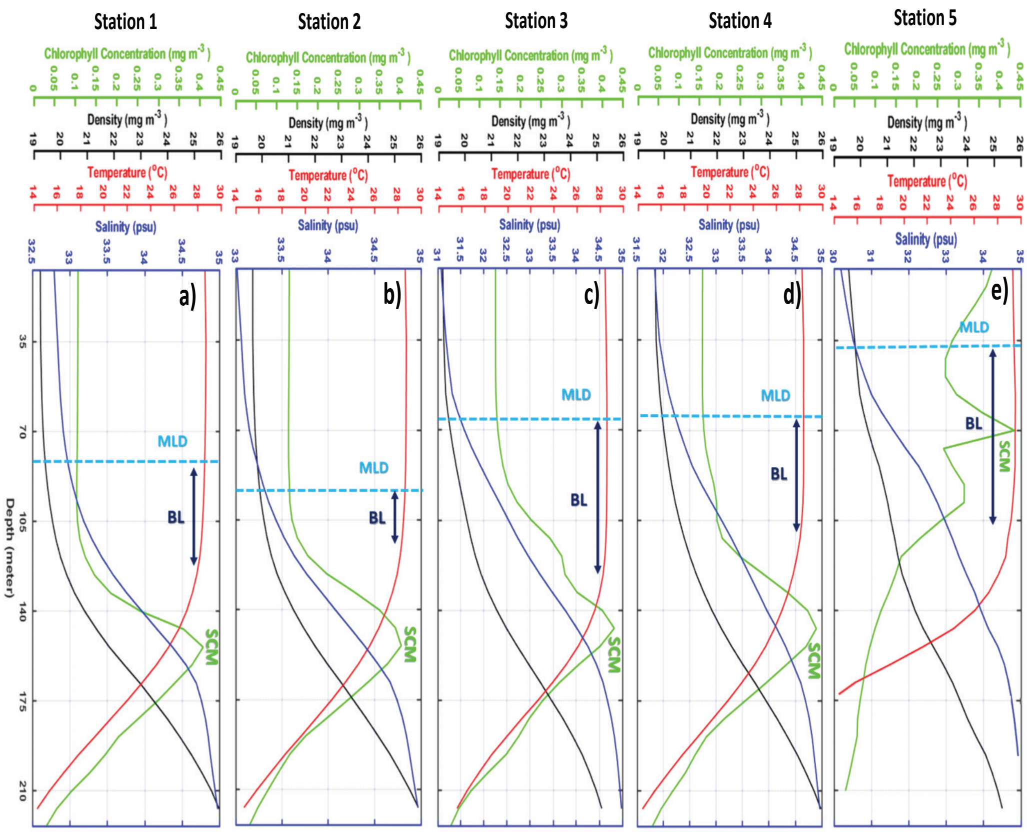

Figure 7. Typical vertical profiles with temperature (◦C), salinity (psu) and density (mg m^{-3}), and mixed layer depth (meter) of stations 1-5 [marked above the vertical profile] in the northern BoB with a mean climatology for the year 2016 to 2020. Mixed layer depth (as MLD), barrier layer (as BL) and subsurface chlorophyll-a maxima (as SCM) marked in the Figures

These stations shows the deepest MLD formation due to reduced freshwater flux and decreased mixing relative to coastal areas (Chowdhury *et al*., 2021; Kara *et al.*, 2000). Station 3 and 4 are taken at mid latitude (18°00´N, 93°00´E, and 18°00´N, 89°15´E) of northern BoB (Figure 7.c, 7.d), where station 3 is near the Myanmar coast and station 4 is in the middle bay. MLD is shallower than the southern points which may be influenced by the shallow bathymetry and increased mixing. Last point (station 5) is taken near the Bangladesh coast (21°15´N, 89°15´E), at the mouth of Swatch of no Ground (figure 7.e). This station shows the shallowest MLD compared to all stations which indicating significant river discharge influence, which results in enhanced mixing in the upper oceanic layer (Kataoka *et al.*, 2023; Vissa *et al*., 2013; Yesubabu *et al*., 2020) the WRF model is initialized without coupling. In the second experiment, the WRF-OML model is initialized by prescribing the MLD as a constant depth of 50 m (MLD-CONST).

Conclusions

This research delves into the spatial distribution and inter-annual variations of essential physical parameters, specifically SSS and SST, in the BoB covering a five-year span from 2016 to 2020. Our findings offer significant insights in to the complex dynamics of this critical marine ecosystem. Our analysis of SSS and SST highlighted distinct spatial gradients, influenced by oceanic rainfall and runoff from major rivers like the Ganges, Brahmaputra, and Irrawaddy. The influx of fresher surface waters in the northern BoB caused strong haline stratification, which contributed to the formation of a barrier layer, subsequently affecting the distribution of SST. Additionally, we observed significant inter-annual variations in SSS and SST, with distinct patterns emerging in different regions of the northern BoB.

Our time series analysis highlighted the seasonal variability of physical parameters, including precipitation, river discharge, salinity, and density. Notably, monsoonal periods were associated with peak values of these parameters, indicating the strong influence of riverine freshwater on shelf circulation. Moreover, examination of physico-chemical properties and vertical profiling revealed spatial heterogeneity in pH, dissolved oxygen, salinity, density, and nutrient concentrations along the GBM shelf region.

The discussion underscored the importance of understanding the complex interplay between riverine freshwater and oceanic forces in shaping the BoB ecosystem. (De Boyer Montégut *et al*., 2007; Jana *et al*., 2015)two parallel climatological simulations (with and without rivers. These interactions have significant implications for primary productivity, nutrient cycling, and ecological balance in the region (Correll, 1999; Narvekar and Prasanna Kumar, 2014; Neto *et al*., 2015) understanding the spatio-temporal dynamics of coastal phytoplankton dynamics is challenging due to the multiple environmental factors involved. Here, we use remote sensing and geostatistical techniques to demonstrate the influence of key environmental variables (i.e. sea surface temperature; current intensity; wind speed; photosynthetically active radiation and flow of larger rivers. Furthermore, our findings have practical implications for resource management, conservation efforts, and climate change adaptation in the BoB.

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Declaration

The authors declare that this research findings reported in this article do not have any conflicting interest.

Author's contributions

Resources for data analysis were assembled, and the research was supervised by Maria Zaman. Literature review, writing, and functional acquisition were performed by Azam Chowdhury, Tasin Sumaia Khan, and Maria Zaman. Data collection, statistical analysis, and map generation were carried out by Ashraful Moontahab and Tasin Sumaia Khan. The manuscript was critically reviewed by Azam Chowdhury and Maria Zaman. The completed manuscript has been read and approved by all authors.

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