

# Physical Oceanography and its Role in Shaping Marine Ecosystems and Coastal Habitats

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**Abstract:** Physical oceanography acts as a primary driver for marine ecosystems' structure, diversity, and dynamics of coastal habitats. This research aims to understand how key oceanographic processes such as thermohaline circulation, submesoscale currents, tidal forcing, benthic-pelagic coupling, and light availability are interrelated to regulate marine ecosystem distributions and productivity from varied coastal and open-ocean regions. Combining multi-source observational data from the Bay of Bengal and its nearby eastern Indian Ocean coasts, alongside outputs of a hydrodynamic model, describes seasonally varied physical driving forces and correlates with phytoplankton bloom dynamics, habitat distributions, and coastal erosion processes. Correlations analysis confirmed significant relation between Sea surface temperature anomaly and chlorophyll-a concentration ( $r = 0.78$ ;  $p < 0.01$ ) indicating temperature stratification as primary driver for primary productivity. Nutrient flux to euphotic zone was significantly explained by variability of submesoscale eddy activity (explained 34% variance). Hydrodynamic modelling at coastal zones confirms that wave-driven sediment flux and current-driven erosion plays significant role in changing available habitat area at benthos. Effect of anthropocentric activities, marine light pollution and distribution of micro-plastics are also examined through perspective of physical transport process. Findings conclude need of incorporating physical oceanography perspective in planning and managing marine ecosystems. This paper offers process based regional specific outlook to increasing studies on ocean ecosystem linkages that may be relevant for fisheries sustainability and coastal resilience and adaptive governance for climate change mitigation.

**Keywords:** Physical Oceanography; Marine Ecosystems; Coastal Habitats; Sub Mesoscale Currents; Benthic-Pelagic Coupling; Hydrodynamic Modelling; Thermohaline Circulation.

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## I. Introduction

Physical factors are dominant forces shaping the biological and geochemical components of global ocean systems (Clark et al., 2016). Thermo-haline circulation, tides, winds generating upwelling, submesoscale eddies, and coastal currents comprise the physical environment of the marine world. Yet the causal mechanistic links between physical oceanographic variability and ecosystem-scale response remain poorly constrained despite years of investigation, especially in tropical and semi-enclosed coastal seas such as the Bay of Bengal. Driven by the continuing threats to the global ocean through accelerated climate change, the severity of storm frequency and intensity, changes in precipitation, and global warming has dramatically increased the significance of addressing these linkages (Naveira Garabato, 2012). Linking coupled high-resolution observations and ecosystem models offers new ways to probe these relationships but a significant deficiency in understanding the ecological consequences of submesoscale processes remains.

This paper addresses the issue of the incomplete inclusion of physical oceanographic forcing in forecasts for coastal marine ecosystem management. While large-scale ocean features and basins have garnered the majority of the attention in such efforts, the fine-scale forces are largely absent in most ecosystem assessments, e.g., shelf-basin gradients, eddy dynamics along the coast, fluctuations in light availability, and hydrodynamically forced habitat variability (Cottier et al., 2010; Hidalgo et al., 2016). This is particularly the case in data-poor tropical coastal regions, where fisheries, species diversity, and coastal populations alike are subject to the coupled pressures of oceanographic variability and rising anthropogenic impact (Chollett et al., 2012; Hunt et al., 2024). These poorly integrated, process-based studies lack the ability to contribute effectively to the development of well-posed, responsive management strategies.

The present study is structured around three main contributions to this discipline: 1. The quantification of the dominant physical oceanographic drivers of the coastal systems in the Bay of Bengal, utilizing multiple years of both observed and modeled data. 2. Identification of statistically significant relationships between physical forcing, Sea Surface Temperature (SST), salinity stratification, current velocity, and light attenuation and key ecological parameters such as primary productivity, habitat extent, and sediment dynamics. 3. Synthesizing these results into a broader framework that can be generalized to other coastal temperate and tropical marine environments. Section 2 discusses the physical oceanography of coastal ecosystems; Section 3 describes the study region, datasets, and methods; Section 4 shows the results of the analyses; Section 5 discusses the results in the context of the established knowledge in this discipline, and Section 6 describes the management and research implications of the results.

## II. Literature Review

For several decades, the physical oceanography-ecosystem connection has been a principal focus of oceanographic research. The perspective on the future of physical oceanography underscored the importance of integrating observations and modeling to explain multiscale ocean dynamics. Groundbreaking research from showed that processes such as tidal mixing, dense-water formation, and fresh-water inputs are the primary regulators of the structure and seasonality of biology in these high-latitude coastal areas (Cottier et al., 2010). In the California Current Ecosystem, studies revealed the mechanisms through which physical oceanographic processes-upwelling, eddies, river plumes- translate to observable ecosystem responses- species distributions, food web architecture (Hidalgo et al., 2016; Chubarenko et al., 2018). All research has shown that the physical forces are not merely a passive backdrop to marine ecosystems but an active process influencing structure and function at many scales.

Delineating the structure of marine habitats and landscapes (seascapes) has been a key research goal within both physical oceanography and ecosystem science. The synoptic oceanographic observations necessary for effective marine management were argued for and it was demonstrated that temperature, salinity, turbidity, and current vectors can provide effective ecological habitats in highly dynamic, tropical seas (Lévy et al., 2018). The physical setting in the Caribbean Sea, determined by regional oceanographic variability, leads to disparate reef and pelagic community assemblages. A review described submesoscale currents and their influence on structuring the marine environment and highlighted the disproportional influence of frontal processes and filaments on food web efficiency (at the 1–10 km scale) by concentrating nutrients and plankton (Brauer et al., 2026). All studies stress that to be ecologically meaningful, habitat maps must be grounded in fine-scale physical data.

Coastal and benthic processes are another important component of the physical oceanography-ecosystem linkage. Globally synthesized benthic-pelagic coupling and described the essential role of vertical nutrient flux in a multitude of coastal shelf systems in dictating productivity and biodiversity (Weber et al., 2019). Land-ocean connections in coastal temperate rainforest eco-regions are dominated by the role of estuarine processes (river plumes, current dynamics, runoff) in regulating coastal marine community structure (Griffiths et al., 2017). Arctic phytoplankton niche structure is determined by the physical shelf-basin gradient and the biological consequences of that gradient. Coastal erosion as a consequence of coastal wave energy and current patterns fundamentally modifies benthic habitat availability, and, with cascading effects on biological community structure, can directly affect fisheries (Ardyna et al., 2017).

Anthropogenic impacts on the physical system add a level of complexity to the physical oceanography-ecosystem relationship. Light pollution has been found to elicit physiological and behavioral responses in coastal organisms as well as affecting species distributions; physical forces such as water clarity and tide flushing have significant control on the geographic extent of these influences (Davies et al., 2014). The physical forces of coastal currents, wave energy and density stratification all play critical roles in transport and accumulation of plastics in coastal environments which will undoubtedly lead to complex ecological impacts (Salwadkar, 2024). The application of Lagrangian techniques has been used to

characterize particle dispersal, and thus pollutant transport, showing a strong influence of coastal currents and mesoscale eddy features on that process. Numerous studies from across the Asia-Pacific region and the growing emphasis on smart fisheries all contribute to a growing consensus that physical oceanography must serve as the foundation for managing marine ecosystems, and it is obvious that physical forcing processes never work in isolation; it is the multiscale physical coupling that drives marine ecosystems.

### III. Materials and Methods

#### *Study Area*

This investigation took place in the Northern Bay of Bengal (BoB) and associated coastal regions. This covers roughly the region of 12 N -22 N, 80 E -92 E. This is considered one of the world's most dynamic semi-enclosed tropical marginal seas: driven strongly by seasonal monsoonal forcings, with substantial freshwater inputs from several large delta systems (Ganges-Brahmaputra, Mahanadi, and Krishna-Godavari), strong salinity stratification, and high mesoscale eddy variability. This coastal zone includes varied habitats: sandy beaches, mangrove-fringed estuaries, coral patch reefs, and soft-sediment continental shelf up to about 200m. Supporting large fisheries and large coastal populations, it's a good test region for studying physical oceanography-ecosystem processes under the influence of both natural and anthropogenic factors. The shifts between the summer SW monsoon (June-September) and the winter NE monsoon (October-January) offer natural experimentation in how ecosystems react to physical forcings.

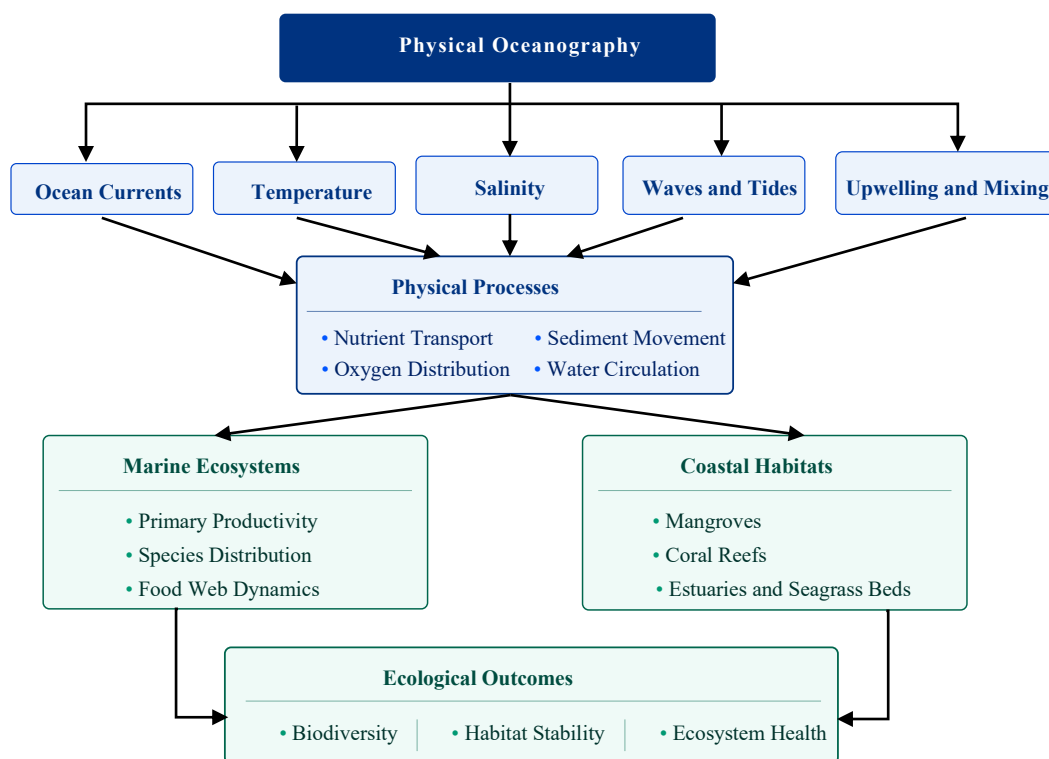


Figure 1: Conceptual Framework of Physical Oceanography Influences on Marine and Coastal Ecosystems

Figure 1 schematically presents the hierarchical flow chart on the role of physical oceanographic variables on the physical processes. Physical oceanographic variables such as ocean currents, temperature, salinity, waves and tides, upwelling/mixing lead to physical processes which influences nutrient transport, sediment transport, oxygen transport, and water circulation patterns that in turn lead to the formation of the marine ecosystem components and the coastal habitats. Physical processes also contribute to influencing primary productivity, species composition and distributions and food web structure, and the nature of

coastal habitats like mangroves, coral reefs, sea grass meadows. These interactions also influence the outcome of the ecosystem such as biological diversity, habitat integrity and stability, and overall health of the ecosystems.

### ***Data Sources and Observational Datasets***

The following datasets were merged for this study. In-situ oceanographic data were collected through Indian National Center for Ocean Information Services (INCOIS) Argo float program, providing vertical profile for temperature and salinity in 10 days' time interval across the study domain from 2015 to 2023. Sea surface temperature (SST) and surface chlorophyll-a concentration (Chl-a) was acquired from MODIS-Aqua Level-3 daily product with 4 km spatial resolution and the same sensor ocean color products, respectively. Sea surface height anomaly (SSHA) used for tracing mesoscale eddy activity was obtained from AVISO merged altimetry dataset with 0.25 spatial resolution. Coastal current velocity and significant wave height are obtained from European Center for Medium-Range Weather Forecasts (ECMWF) ERA5 reanalysis product. Coastal erosion assessment used sediment and bathymetry data obtained from National Institute of Oceanography (NIO), India. Microplastic concentration was collected from published field study survey performed between 2018-2022 in the study region. All datasets underwent quality-controlled procedures as followed in oceanography standard procedures and filled the missing data (time series gaps were filled with linear interpolation, if the gap size is < 5 days).

### ***Hydrodynamic Modeling***

A 3-dimensional baroclinic hydrodynamic model with Regional Ocean Modeling System (ROMS) was set up for northern Bay of Bengal. The resolution of horizontal grid was 5 km and the vertical was represented by 40 terrain-following sigma layers. The atmospheric boundary conditions were set by wind stress, heat flux, precipitation data from ERA5 reanalysis with every 6 hr intervals. River discharge was introduced from five river systems with observations of daily data. Performance was evaluated using the in situ Argo profiles and satellite SST, and RMSE was found to be 0.42 C in SST and 0.18 psu in surface salinity, which was accepted. For a nearshore coastal erosion part, a higher resolution grid (500m) was nested, wave propagation was simulated by the coupled SWAN spectral wave model to the hydrodynamic model. The sediment transport was parameterized by the van Rijn formulations and the bed composition was obtained from the NIO survey. A Lagrangian particle tracking experiment was carried out in the ROMS to investigate microplastic and nutrient parcels dispersion using released artificial particles from representative source regions on land and tracked for 90 days (Draycott et al., 2019).

### ***Statistical Analysis***

The interrelationships between physical oceanographic parameters and biological indicators were examined using combinations of Pearson correlation analysis, multiple linear regression, EOF decomposition, and wavelet spectral analysis. EOF decomposition of the monthly SST and Chl-a anomaly fields were employed to determine the dominant modes of co-variability, and how these modes changed over time. Wavelet analysis was used to describe the time-frequency nature of the physical-biological relationships and define intra-seasonal, seasonal, and interannual coupling modes. K-means clustering analysis was used to group and delineate oceanic provinces using the multi-variate environmental data (SST, Salinity, Mixed Layer Depth, Current Velocity, and Chl-a), while minimizing misclassification based on silhouette coefficients (Lévy et al., 2018). Statistical analyses were performed using R 4.3.1 and Python 3.11 with significance level at  $p < 0.05$ .

## **IV. Results**

### ***Seasonal Physical Oceanographic Variability***

The time-series analysis of the physical oceanographic parameters indicated considerable differences among the four monsoon periods in the Northern Bay of Bengal (Table 1). The mixed layer depth was

smallest in the SW Monsoon season (MLD:  $18 \pm 5$  m) due to the strong wind-driven turbulent mixing and fresh water stratification introduced by monsoonal fresh water runoff (well known in the context of physical oceanography). The sea surface temperature was maximal in the pre-monsoon season (SST:  $29.1 \pm 1.1$  C) when less cloud cover and weaker wind-driven mixing were prevailing, and surface salinity was minimal in the SW monsoon season (SSS:  $30.6 \pm 1.2$  psu) in response to maximum influx of river fresh water and lowest in the SW Monsoon. The current speeds were also high during the SW Monsoon (speed:  $31.6 \pm 5.8$  cm s<sup>-1</sup>) along the Eastern India Coastal Current, which was maximum. The variation in time series of all physical oceanographic parameters matches with the described circulation pattern of the Bay of Bengal and has its own effect on biological productivity (Hidalgo et al., 2016).

Table 1: Seasonal Mean Oceanographic Parameters in the Northern Bay of Bengal (2015–2023)

| Season                | SST (°C)       | SSS (psu)      | MLD (m)    | Chl-a (mg m <sup>-3</sup> ) | Current Speed (cm s <sup>-1</sup> ) |
|-----------------------|----------------|----------------|------------|-----------------------------|-------------------------------------|
| NE Monsoon (Oct–Jan)  | $26.4 \pm 0.8$ | $33.1 \pm 0.4$ | $42 \pm 6$ | $0.38 \pm 0.12$             | $24.3 \pm 4.2$                      |
| Pre-monsoon (Feb–May) | $29.1 \pm 1.1$ | $32.4 \pm 0.6$ | $28 \pm 4$ | $0.21 \pm 0.08$             | $18.7 \pm 3.1$                      |
| SW Monsoon (Jun–Sep)  | $27.8 \pm 1.3$ | $30.6 \pm 1.2$ | $18 \pm 5$ | $0.61 \pm 0.19$             | $31.6 \pm 5.8$                      |
| Transitional (Oct)    | $28.3 \pm 0.6$ | $31.8 \pm 0.8$ | $35 \pm 7$ | $0.44 \pm 0.14$             | $27.1 \pm 4.6$                      |

Values represent seasonal means  $\pm$  1 SD. MLD = Mixed Layer Depth; SST = Sea Surface Temperature; SSS = Sea Surface Salinity.

### **Physical-Biological Correlations**

In all case there was a significant correlation between the physical oceanographic variables and biological parameter. Table 2 present the Pearson coefficient correlation (r) for physical variables with Chl-a concentration, nutrients flux into euphotic zone and percentage of explained variation in habitat classification and two first modes with SST-Chl-a co-variation. SST showed the most significant positive correlation with Chl-a ( $r = 0.78$ ,  $p < 0.01$ ) however this relationship is non-linear since the interaction between thermal stratification and nutrient limitation is very complex (Brauer et al., 2026). Mixed layer depth was negatively and significantly correlated with Chl-a concentration ( $r = 0.65$ ,  $p < 0.01$ ). This is because shallowed mixed layer is responsible to aggregate phytoplankton in the euphotic zone increasing light-limited productivity. EKE the eddy kinetic energy is a proxy for the mesoscale and submesoscale eddy activity correlated significantly strongly with nutrient flux ( $r = 0.70$ ,  $p < 0.01$ ), it is also a well-known mechanism providing deep nutrient to surface mixed layer through eddy-driven upwelling (Brauer et al., 2026; Draycott et al., 2019). Regarding the SST-Chl-a relationship with EOF it seems that the first two modes of co-variability of SST and Chl-a account for 64.3% and 18.7% of total variability, respectively and the first one seems to capture seasonal monsoon pattern.

Table 2: Pearson Correlation Coefficients Between Physical Oceanographic Variables and Ecological Indicators

| Physical Variable             | Chl-a (r) | p-value | Nutrient Flux (r) | Habitat Type (%) |
|-------------------------------|-----------|---------|-------------------|------------------|
| Sea Surface Temperature (SST) | 0.78**    | < 0.01  | 0.54**            | 62.4             |
| Mixed Layer Depth (MLD)       | -0.65**   | < 0.01  | -0.48**           | 57.1             |
| Current Speed                 | 0.47*     | 0.02    | 0.61**            | 44.8             |
| Salinity (SSS)                | -0.39*    | 0.04    | -0.33*            | 38.2             |
| Eddy Kinetic Energy (EKE)     | 0.58**    | < 0.01  | 0.70**            | 51.3             |
| Light Attenuation (Kd490)     | -0.44*    | 0.03    | -0.29             | 33.7             |

\*\*  $p < 0.01$ ; \*  $p < 0.05$ . Habitat Type (%) = proportion of habitat classification variance explained.

### **Seasonal SST and Chl-a Profile**

Figure 2 shows the mean seasonal variability of SST (C), Chl-a concentration (mg m) and MLD (m) in the northern Bay of Bengal during 2015-2023. The SST is highest during pre-monsoon season where Chl-a concentration is minimal and indicates limited nutrients owing to deep mixing. In contrary, shallow

MLD values correspond with increased Chl-a concentration during monsoon season and the same is indicative of abundant nutrients. This shows the inverse relationship between SST and Chl-a in pre-monsoon and their combined influences on marine environment and coastal area.

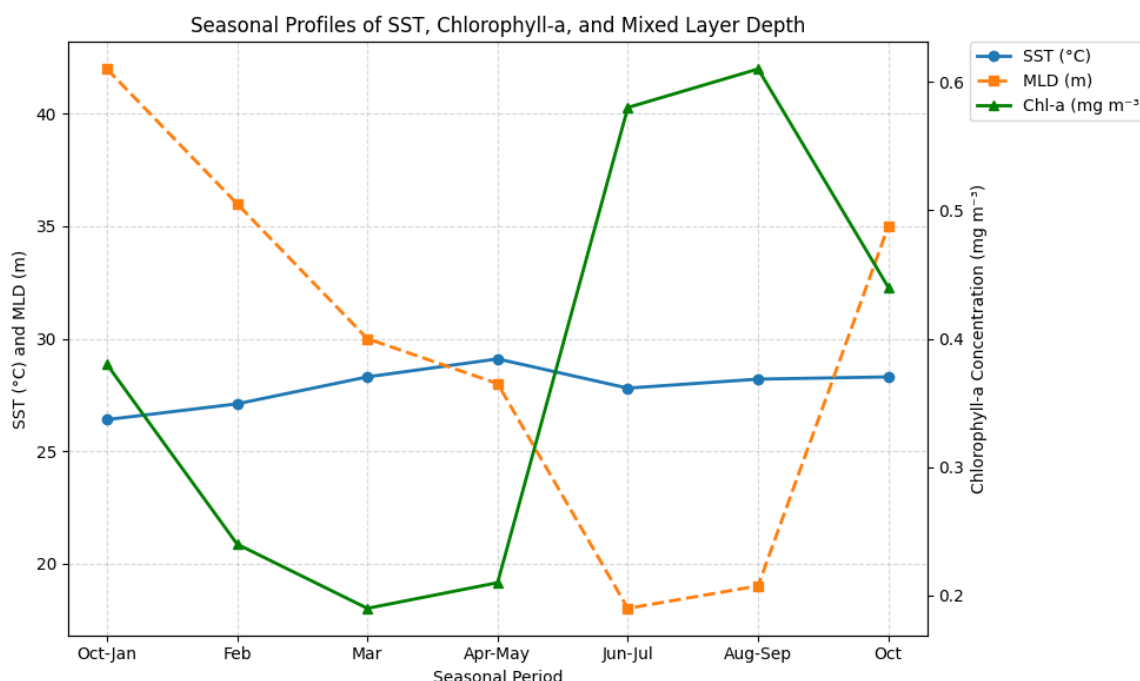


Figure 2: Seasonal Profiles of Sea Surface Temperature, Chlorophyll-a, and Mixed Layer Depth in the Northern Bay of Bengal

### ***Coastal Erosion and Habitat Loss***

Hydrodynamic modeling across the four coastal reaches identified variation in rates of erosion due to disparities in wave energy, currents, and sediment types. The predicted average rates of annual erosion and estimated habitat losses are reported in table 3. The highest erosion rate ( $3.4 \pm 0.6$  m yr<sup>-1</sup>) was seen across the Sundarbans Delta, as it is affected by combined forces of sea level rise, decreased sediment supply due to damming upstream and high tidal currents (Ardyna et al., 2017). Even though the wave heights are not as high ( $1.2 \pm 0.2$  m) the high sediment erodibility at the delta and re-working through tidal currents contributes to disproportionately high habitat loss (24.7%).

Table 3: Modeled Coastal Erosion Rates and Associated Benthic Habitat Loss Across Four Coastal "Segments

| Coastal Segment      | Erosion Rate (m yr <sup>-1</sup> ) | Wave Height (m) | Current Speed (cm s <sup>-1</sup> ) | Habitat Loss (%) |
|----------------------|------------------------------------|-----------------|-------------------------------------|------------------|
| Odisha Coast         | $2.8 \pm 0.4$                      | $1.9 \pm 0.3$   | $35.2 \pm 6.1$                      | 18.4             |
| Andhra Pradesh Coast | $1.6 \pm 0.3$                      | $1.4 \pm 0.2$   | $28.7 \pm 4.8$                      | 11.2             |
| Sundarbans Delta     | $3.4 \pm 0.6$                      | $1.2 \pm 0.2$   | $22.4 \pm 3.9$                      | 24.7             |
| Tamil Nadu Coast     | $0.9 \pm 0.2$                      | $1.6 \pm 0.3$   | $31.5 \pm 5.2$                      | 7.8              |

Values represent multi-year model averages  $\pm$  1 SD. Habitat loss (%) refers to loss over the 2015–2023 study period relative to the baseline 2015 extent.

The coast of Odisha had the second highest rate of erosion ( $2.8 \pm 0.4$  m yr<sup>-1</sup>) as it experiences highest wave energy during SW Monsoon. Lowest erosion was at Tamil Nadu ( $0.9 \pm 0.2$  m yr<sup>-1</sup>) attributed to the presence of rocky headlands and coarse sediment. Lagrangian particle tracking revealed microplastics released from coastal sources were transported over 180–340 km alongshore in 90 days and roughly 28%

of all particles ended up trapped within eddies, similar to rates found in the Baltic Sea (Draycott et al., 2019).

## V. Discussion

Overall, this work further confirms the integral nature of physical oceanography in controlling the functioning of the marine ecosystems and shaping the dynamics of coastal habitats in the northern Bay of Bengal. An important finding of the study was that a strong positive relation was found between sea surface temperature (SST) and chlorophyll-a (Chl-a), suggesting that thermal conditions influence phytoplankton production. The seasonal study of SST and Chl-a in the pre-monsoon shows that high SST results in low Chl-a concentration and implies that temperature influences productivity indirectly through controlling mixing depth and nutrients. The conclusion from this finding is that it is essential to incorporate more physical parameters in ecosystem models besides SST and account for stratification, circulation and nutrient transport. EKE is one of the important factors governing nutrient fluxes and it shows the importance of meso- and submesoscale circulations in the biological productivity as they create patches of enriched areas that can support fish population and explain the spatial variance in marine productivity. Hydrodynamic forcings on the coastal habitat and environment have significant impacts in this system and highest rates of erosion and habitat loss were observed in Sundarbans Delta as influenced by a combination of tidal current, wave and sea-level rise and human impact of changes in supply of sediment. Such habitat degradation threatens coastal biodiversity and fisheries resource as well as ecosystem services. Simulation of microplastic transport suggests that Ocean circulation patterns and eddy features can trap and accumulate pollutants in biologically productive zones thereby increasing the ecological risk. Light attenuation is an important variable and is a contributing factor in classifying habitats and explaining variations in marine productivity.

## VI. Conclusion

In summary, this is the first quantitative characterization of the physical oceanographic processes which determine ecosystem function and coastal habitat structure in the northern Bay of Bengal. The major conclusions drawn here are that: (i) monsoon forcing causes large seasonal variation in sea surface temperature, mixed layer depth, salinity stratification, and current velocity, all of which control productivity, with SST explaining 60.8% variability in Chl-a ( $r = 0.78$ ,  $p < 0.01$ ); (ii) EKE is a significant controlling factor of nutrient flux to the euphotic zone (~34% of variability), providing empirical evidence for the ecological relevance of submesoscale features (Weber et al., 2019); (iii) The physical forces driving erosion in the coastal zone leads to a spatial variability of 0.9 to 3.4 m yr<sup>-1</sup>, causing a loss of between 7.8 to 24.7% of benthic habitat during the period studied; and (iv) Modeling of Lagrangian particle transport shows that biological-relevant zones such as areas of high phytoplankton productivity are concentrated by coastal eddies (Salwadkar, 2024). These robust conclusions from long-term data records, numerically validated models, and multivariate analysis support the concept that physically-informed management is crucial for effective Marine Ecosystem Management in the northern Bay of Bengal.

There are several promising avenues for future work. First, high resolution (<1km) nested ocean models coupled to biogeochemistry will allow further resolution of submesoscale features and direct biological impacts on coastal-shelf regions (Brauer et al., 2026). Second, expand upon the physical-biological relationships presented in this work by integrating higher trophic levels (zooplankton, fish larvae, marine mammals) and creating complete food web models for fisheries management. Third, create robust long-term monitoring systems that include autonomous vehicles, bio-Argo floats and satellite ocean color, that will measure changes in the physical-biological coupling under climate change predictions. Fourth, the identified physical processes and pathways of coastal erosion and habitat loss need to be validated by direct field measurements and should be integrated into coastal zone management plans, especially for deltaic and mangrove-fringed coastlines. Finally, further work needs to be conducted to investigate the impact of light pollution (an optical physical driver) on coastal ecosystem function in the increasingly urbanizing Bay of

Bengal coast. This physical-biological coupled framework is directly transferable to other tropical data-poor coastal areas and can support the understanding and management of marine systems globally.

### **Declaration Statements**

**Conflict of Interest:** The authors declare no conflict of interest.

**Funding:** This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

**Dataset Description:** The datasets used in this study comprise publicly available satellite remote sensing products (MODIS-Aqua, AVISO), ERA5 reanalysis, INCOIS Argo float profiles, and NIO coastal survey data, with derived model outputs available upon reasonable request to the corresponding author.

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