

Towards ecosystem modelling: Impact of coastal processes on biogeochemistry along the Indian coast

Abstract

Understanding the interplay between coastal physical processes and biogeochemical variability is central to the ecosystem dynamics in tropical coastal oceans. The North Indian Ocean (NIO), comprising the Arabian Sea (AS) and the Bay of Bengal (BoB), is characterized by strong monsoonal forcing, freshwater input, and seasonally varying coastal circulation, which together regulate nutrient supply and productivity. Despite its ecological and climatic importance, the linkages between coastal transport, biogeochemical cycling, and ecosystem response remain inadequately constrained for the Indian coastal waters. This thesis investigates how physical processes influence the biogeochemical state of the NIO by using a high-resolution ($1/20^\circ$) regional configuration of the Massachusetts Institute of Technology general circulation model (MITgcm) integrated with its biogeochemical modules, namely the Dissolved Inorganic Carbon (DIC) and the Biogeochemistry with Light, Iron, Nutrients and Gases Version 2 (BLINGv2). The simulations are driven by climatological forcing fields (2001-2020), providing a representation of the mean state of the region.

The first component of this work focuses on coastal transport and its influence on basin-scale exchange pathways between the AS and BoB. Coastal currents act as a key driver for the cross-basin exchange of water masses and tracers. The study demonstrates that the seasonal reversal of coastal currents along the Indian peninsula exerts a major control on the lateral redistribution of heat and salinity. The alongshore volume transport on the eastern coast is stronger with high seasonal variability due to the poleward-flowing Western Boundary Current (WBC) and equatorward-flowing East Indian Coastal Current (EICC). West coast transport is influenced by large intraseasonal oscillations. The meridional heat transport over the AS is stronger than that over the BoB. Both basins act as a heat source during the summer monsoon and a heat sink during the winter, which ventilates and regulates the basin.

Building on the understanding of coastal exchanges, the second component examines the carbonate chemistry system, focusing on the surface DIC and Alkalinity (ALK) budgets. The simulations reveal distinct spatial and seasonal patterns in surface DIC and ALK across the AS and BoB, depicting the interplay of coastal upwelling, biological uptake, and freshwater inputs. The AS exhibits higher surface DIC associated with strong upwelling and air-sea CO₂ exchange, while the BoB shows lower DIC values consistent with freshwater dilution and stratification. The study quantifies the dominant physical and biological drivers of DIC and ALK variability and evaluates the buffering capacity of carbon using the Revelle factor. Regions of high Revelle factor correspond to reduced buffering, particularly in the northern BoB, where major rivers discharge into the bay. This analysis provides a clear understanding of the regional carbonate system, linking physical drivers to its chemical responses in the region.

The third component examines the impact of freshwater variability on coastal biogeochemistry, focusing on how river runoff and precipitation modulate stratification, nutrient availability, and carbon exchange. For the analysis, a set of sensitivity experiments is undertaken to incorporate freshwater perturbations. The model experiments show that the strong haline stratification in the BoB reduces nutrient resupply to the euphotic zone, leading to lower productivity relative to the AS. Conversely, in the AS, vertical mixing, coastal upwelling, and lateral advection of nutrients sustain higher productivity. In the reduced freshwater experiments, enhanced nutrient availability resulting from higher mixing increased productivity in coastal regions. However, the upward transport of subsurface carbon also lowered surface pH, indicating a trade-off between biological enhancement and increased surface acidification. In the increased freshwater experiment, productivity was suppressed, while surface pH increased due to reduced vertical carbon exchange. Vertical phytoplankton responses are consistent with these trends, with small and large phytoplankton biomass increasing under weaker Barrier Layer Thickness (BLT) and decreasing under enhanced BLT.

The final component explores the biogeochemical feedback of light attenuation on phytoplankton variability, commonly referred to as self-shading. Two sensitivity experiments are conducted: one using variable light attenuation, as described by Manizza et al. (2005), and another with constant attenuation. The comparison highlights that self-shading varies the vertical structure of light and nutrient fields, thereby influencing productivity profiles. Including variable light attenuation results in a more realistic subsurface chlorophyll maximum with higher accuracy. The analysis also indicates that self-shading influences the vertical nutrient gradients, i.e., the nutriclines, improving the representation of vertical coupling between light and nutrient limitation. This study, therefore, demonstrates the importance of accurately accounting for the feedback between productivity and subsurface light availability in regional biogeochemical models.

Collectively, the four components of the thesis provide an integrated understanding of how physical processes influence the biogeochemical state of the Indian coastal waters. The synthesis reveals that the interaction between circulation, stratification, freshwater, and light attenuation regulates regional productivity, carbon cycling, and buffering capacity. The model simulations, although based on climatological forcings and thus representative of the mean state, provide a basis for interpreting observed biogeochemical variability along the Indian coast. The study also represents the first regional implementation and optimization of the BLINGv2 biogeochemical module in the Indian coastal waters, providing a framework that can be extended to other tropical regions or coupled climate scenarios. By resolving the interplay of physical and biogeochemical processes in the Indian coastal waters, this work contributes toward improving the capabilities of ecosystem models in a region where observational coverage remains limited, but the ecological and socio-economic stakes are high.