

TOWARDS ECOSYSTEM MODELLING: IMPACT OF COASTAL PROCESSES ON BIOGEOCHEMISTRY ALONG THE INDIAN COAST

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

by

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Certificate

This is to certify that the thesis titled '**Towards ecosystem modelling: Impact of coastal processes on biogeochemistry along the Indian coast**' being submitted by **Kunal Ajit Madkaiker** to the Indian Institute of Technology Delhi for the award of the degree of **DOCTOR OF PHILOSOPHY** is a record of original bonafide research carried out by him. Kunal has worked under our guidance and supervision and has fulfilled the requirements for the submission of this thesis. The results contained in this thesis have not been submitted in part or in full to any other University or Institute for the award of any degree or diploma.

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Kunal Ajit Madkaiker

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.

सार

उष्णकटिबंधीय तटीय महासागरों में पारिस्थितिक तंत्र की गतिशीलता को समझने के लिए तटीय भौतिक प्रक्रियाओं और जैव-भूरासायनिक परिवर्तनशीलता के बीच अंतःक्रिया का अध्ययन अत्यंत महत्वपूर्ण है। उत्तर भारतीय महासागर (NIO) जिसमें अरब सागर (AS) और बंगाल की खाड़ी (BoB) सम्मिलित हैं, तीव्र मानसूनी प्रभाव, मीठे जल का प्रवाह और ऋतु आधारित तटीय परिसंचरण द्वारा नियंत्रित होता है, जो पोषक तत्वों की आपूर्ति तथा जैव उत्पादकता को विनियमित करता है। यद्यपि यह क्षेत्र पारिस्थितिक और जलवायु दृष्टि से अत्यंत महत्वपूर्ण है, फिर भी तटीय परिवहन, जैव-भूरासायनिक चक्रों और पारिस्थितिक प्रतिक्रियाओं के बीच पारस्परिक संबंध अभी भी स्पष्ट रूप से परिभाषित नहीं हैं। इस शोधप्रबंध में यह अध्ययन किया गया है कि भौतिक प्रक्रियाएँ किस प्रकार NIO के जैव-भूरासायनिक स्वरूप को प्रभावित करती हैं। इसके लिए उच्च-रिज़ॉल्यूशन ($1/20^\circ$) वाले क्षेत्रीय कॉन्फ़िगरेशन में मैसाचुसेट्स इंस्टीट्यूट ऑफ टेक्नोलॉजी जनरल सर्कुलेशन मॉडल (MITgcm) का उपयोग किया गया है, जिसमें दो प्रमुख जैव-भूरासायनिक मॉड्यूल डिज़ॉल्व्ड इनऑर्गेनिक कार्बन (DIC) और बायोजियोकेमिस्ट्री विथ लाइट, आयरन, न्यूट्रिएंट्स एंड गैसेज़ संस्करण 2 (BLINGv2) एकीकृत किए गए हैं। इन सिमुलेशनों को 2001-2020 की अवधि के जलवायुगत बलन क्षेत्रों द्वारा संचालित किया गया है, जो इस क्षेत्र की औसत अवस्था का प्रतिनिधित्व करते हैं।

इस अध्ययन के प्रथम घटक में तटीय परिवहन और उसके अरब सागर तथा बंगाल की खाड़ी के मध्य बेसिन-स्तरीय आदान-प्रदान माग पर प्रभाव पर ध्यान केंद्रित किया गया है। तटीय धाराएँ जलद्रव्यमान और ट्रेसरों के पार-बेसिन आदान-प्रदान की प्रमुख चालक के रूप में कार्य करती हैं। अध्ययन से यह स्पष्ट हुआ कि भारतीय प्रायद्वीप के साथ मौसमी रूप से उलटने

वाली तटीय धाराएँ ऊष्मा और लवणता के पार्श्वीय पुनर्वितरण को नियंत्रित करती हैं। पूर्वी तट के साथ धारा-प्रवाह की तीव्रता और मौसमी परिवर्तनशीलता अधिक पाई गई, जिसका कारण उत्तर की ओर बहने वाली पश्चिमी सीमा धारा और भूमध्यरेखीय दिशा में बहने वाली पूर्वी भारतीय तटीय धारा है। पश्चिमी तट का परिवहन आंतर-ऋतुकालिक दोलनों से प्रभावित पाया गया। अरब सागर में देशान्तर दिशा में ऊष्मा परिवहन बंगाल की खाड़ी की तुलना में अधिक है। दोनों बेसिन ग्रीष्म मानसून के दौरान ऊष्मा स्रोत तथा शीत ऋतु में ऊष्मा अवशोषक के रूप में कार्य करते हैं, जिससे इनका वायुसागर और ऊष्मीय विनियमन होता है।

तटीय आदान-प्रदान की इस समझ के आधार पर, अध्ययन के दूसरे घटक में कार्बोनेट रसायन तंत्र का परीक्षण किया गया है, जिसमें सतही DIC और क्षारीयता (ALK) के बजट पर विशेष ध्यान दिया गया है। सिमुलेशनों से यह स्पष्ट हुआ कि AS और BoB में सतही DIC और ALK के स्थानिक तथा मौसमी वितरण भिन्न हैं, जो अपवेलिंग, जैविक अवशोषण और मीठे जल के प्रवाह के पारस्परिक प्रभाव को दर्शाते हैं। अरब सागर में प्रबल अपवेलिंग और वायु-समुद्र CO₂ विनिमय के कारण सतही DIC का स्तर अधिक पाया गया, जबकि बंगाल की खाड़ी में मीठे जल के पतलेपन और स्तरीकरण के कारण DIC का स्तर निम्न रहा। अध्ययन में DIC और ALK की भिन्नता को नियंत्रित करने वाले प्रमुख भौतिक और जैविक चालकों की पहचान की गई और कार्बन की बफरिंग क्षमता का आकलन रिवेल फैक्टर के माध्यम से किया गया। उच्च रिवेल फैक्टर वाले क्षेत्र कम बफरिंग क्षमता को दर्शाते हैं, विशेषकर उत्तरी बंगाल की खाड़ी में जहाँ प्रमुख नदियाँ अपने जल का विसर्जन करती हैं। यह विश्लेषण इस क्षेत्र के कार्बोनेट तंत्र की समग्र समझ प्रदान करता है, जो भौतिक चालकों और रासायनिक प्रतिक्रियाओं के बीच संबंध स्थापित करता है।

अध्ययन का तीसरा घटक तटीय जैव-भूरासायनिक प्रक्रियाओं पर मीठे जल की परिवर्तनशीलता के प्रभाव की जाँच करता है, विशेषकर यह कि नदीय प्रवाह और वर्षा किस प्रकार स्तरीकरण, पोषक तत्व उपलब्धता और कार्बन विनिमय को प्रभावित करते हैं। इसके लिए मीठे जल में परिवर्तन को सम्मिलित करने वाले संवेदनशीलता प्रयोगों का एक समूह संचालित किया गया। परिणामों से पता चलता है कि बंगाल की खाड़ी में प्रबल लवणीय स्तरीकरण के कारण युफोटिक क्षेत्र में पोषक तत्वों की पुनः आपूर्ति सीमित होती है, जिससे उत्पादकता अपेक्षाकृत कम रहती है। इसके विपरीत, अरब सागर में ऊर्ध्वाधर मिश्रण, तटीय अपवेलिंग और पार्श्वीय पोषक तत्वों का प्रवाह उच्च उत्पादकता बनाए रखता है। घटे हुए मीठे जल के प्रयोगों में, अधिक मिश्रण के कारण तटीय क्षेत्रों में पोषक तत्वों की उपलब्धता और उत्पादकता में वृद्धि देखी गई। तथापि, अधस्तलीय कार्बन के ऊपर उठाव से सतही pH में कमी आई, जिससे यह स्पष्ट हुआ कि जैविक वृद्धि और अम्लीकरण के बीच संतुलन मौजूद है। बड़े हुए मीठे जल के प्रयोगों में, उत्पादकता घट गई जबकि सतही pH में वृद्धि हुई क्योंकि ऊर्ध्वाधर कार्बन विनिमय कम हुआ। इन प्रवृत्तियों के अनुरूप फाइटोप्लैंकटन का ऊर्ध्वाधर वितरण भी परिवर्तित हुआ कम बैरियर लेयर मोटाई (BLT) की स्थिति में छोटे और बड़े फाइटोप्लैंकटन की जैवभार में वृद्धि हुई, जबकि अधिक BLT की स्थिति में यह घट गई।

अंतिम घटक में प्रकाश अवरोधन की जैव-भूरासायनिक प्रतिपुष्टि का विश्लेषण किया गया है, जिसे सामान्यतः स्व-छायांकन कहा जाता है। इसके लिए दो संवेदनशीलता प्रयोग किए गए एक में प्रकाश अवरोधन को मनिज़ा एट अल. (2005) के अनुसार परिवर्तनीय माना गया और दूसरे में इसे स्थिर रखा गया। तुलना से यह ज्ञात हुआ कि स्व-छायांकन प्रकाश और पोषक तत्व क्षेत्रों की ऊर्ध्वाधर संरचना को परिवर्तित करता है, जिससे उत्पादकता प्रोफाइल प्रभावित होती है। परिवर्तनीय प्रकाश अवरोधन को शामिल करने से अधस्तलीय क्लोरोफिल अधिकतम का अनुकरण अधिक यथार्थ पाया गया। विश्लेषण

यह भी दर्शाता है कि स्व-छायांकन ऊर्ध्वाधर पोषक तत्व प्रवणता को प्रभावित करता है, जिससे प्रकाश और पोषक तत्व सीमाओं के बीच ऊर्ध्वाधर युग्मन का प्रदर्शन सुधरता है। यह अध्ययन इस बात पर बल देता है कि क्षेत्रीय जैव-भूरासायनिक मॉडलों में उत्पादकता और अधस्तलीय प्रकाश उपलब्धता के बीच प्रतिपुष्टियों का सटीक निरूपण अत्यंत आवश्यक है।

समग्र रूप से, इस शोधप्रबंध के चारों घटक यह एकीकृत समझ प्रस्तुत करते हैं कि भौतिक प्रक्रियाएँ भारतीय तटीय जल की जैव-भूरासायनिक अवस्था को किस प्रकार प्रभावित करती हैं। यह संश्लेषण दर्शाता है कि परिसंचरण, स्तरीकरण, मीठे जल और प्रकाश अवरोधन के परस्पर प्रभाव क्षेत्रीय उत्पादकता, कार्बन चक्रण और बफ़रिंग क्षमता को नियंत्रित करते हैं। यद्यपि मॉडल सिमुलेशन जलवायुगत बलों पर आधारित हैं और औसत अवस्था का प्रतिनिधित्व करते हैं, फिर भी ये भारतीय तट के साथ देखी गई जैव-भूरासायनिक परिवर्तनशीलता को व्याख्यायित करने का एक ठोस आधार प्रदान करते हैं। यह अध्ययन भारतीय तटीय जल में BLINGv2 जैव-भूरासायनिक मॉड्यूल के प्रथम क्षेत्रीय कार्यान्वयन और अनुकूलन का उदाहरण प्रस्तुत करता है, जो अन्य उष्णकटिबंधीय क्षेत्रों या युग्मित जलवायु परिदृश्यों तक विस्तारित किया जा सकता है। भौतिक और जैव-भूरासायनिक प्रक्रियाओं के अंतर्संबंधों को स्पष्ट कर, यह कार्य उन पारिस्थितिक और सामाजिक-आर्थिक रूप से महत्वपूर्ण क्षेत्रों के लिए पारिस्थितिक तंत्र मॉडलों की पूर्वानुमान क्षमताओं को सुदृढ़ करने में योगदान देता है, जहाँ प्रेक्षणात्मक कवरेज अभी भी सीमित है।

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List of abbreviations and acronyms

Abbreviation	Full Form
ACE	Anticyclonic Eddy
AFT	Alongshore Freshwater Transport
AHT	Alongshore Heat Transport
ALK	Total Alkalinity
AR6	Sixth Assessment Report
AS	Arabian Sea
A_T	Total Alkalinity Concentration
AVT	Alongshore Volume Transport
Bio-Argo	Biogeochemical Argo
BLINGv2	Biogeochemistry with Light, Iron, Nutrients, and Gases Version 2
BLT	Barrier Layer Thickness
BoB	Bay of Bengal
BoBPS	Bay of Bengal Process Studies
BOBBLE	Bay of Bengal Boundary Layer Experiment
CaCO_3	Calcium Carbonate
CATDS	Centre Aval de Traitement des Données SMOS
CE	Cyclonic Eddy
Chl	Chlorophyll
CMEMS	Copernicus Marine Environment Monitoring Service
CMEMS-LSCE-FFNN	CMEMS Global Ocean Surface Carbon
CMIP5 / CMIP6	Coupled Model Intercomparison Project Phase 5 / Phase 6
CO_2	Carbon Dioxide
CORA	Coriolis Ocean Dataset for ReAnalysis
CTRL	Control Simulation
DIC	Dissolved Inorganic Carbon
DOP	Dissolved Organic Phosphorus
DON	Dissolved Organic Nitrogen
EAPS	Earth, Atmospheric, and Planetary Sciences
ECCO	Estimating the Circulation and Climate of the Ocean

EEZ	Exclusive Economic Zone
EICC	East Indian Coastal Current
EKE	Eddy Kinetic Energy
ENSO	El Niño-Southern Oscillation
ESM	Earth System Model
ERA5	ECMWF Reanalysis 5
FW	Freshwater Flux
Fe	Iron
GEBCO	General Bathymetric Chart of the Oceans
GEOTRACES	Marine Biogeochemical Cycles of Trace Elements and Isotopes
GEOSECS	Geochemical Sections
GHR SST	Group for High-Resolution SST
GO-SHIP	Global Ocean Ship-based Hydrographic Investigations Program
GLOBIO-L4	OCEANCOLOUR_GLO_BGC_L4_MY_009_104
GPM	Global Precipitation Measurement
H200 / H1200	HYCOM transport integrated over 200 m / 1200 m
HCO_3^-	Bicarbonate Ion
HYCOM	HYbrid Coordinate Ocean Model
IIOE	International Indian Ocean Expedition
INC-HYC	INCOIS-HYCOM
INCOIS	Indian National Centre for Ocean Information Services
INCOIS-GODAS	INCOIS Global Ocean Data Assimilation System
IPCC	Intergovernmental Panel on Climate Change
IOD	Indian Ocean Dipole
ITCZ	Intertropical Convergence Zone
JGOFS	Joint Global Ocean Flux Study
KPP	K-profile parameterization
k_λ	Light attenuation coefficient at wavelength λ
$k_{\text{sw}(\lambda)}$	Attenuation by pure seawater at wavelength λ
LP	Large Phytoplankton
M200 / M1200	MITgcm transport integrated over 200 m / 1200 m

MDJWF	Modified Jackett-McDougall Equation of State
MEFT	Meridional Eddy Freshwater Transport
MEHT	Meridional Eddy Heat Transport
MITgcm	Massachusetts Institute of Technology General Circulation Model
MHT	Meridional Heat Transport
MLD	Mixed Layer Depth
MPI	Message Passing Interface
MULTBIO-3D	MULTIOBS_GLO_BIO_BGC_3D_REP_015_010
MUR	Multi-scale Ultra-high-resolution SST
N^2	Brunt-Väisälä Frequency
NAS	Northern Arabian Sea
NCP	Net Community Production
NEAS	Northeastern Arabian Sea
NEFT	Net Eddy Freshwater Transport
NEHT	Net Eddy Heat Transport
NFT	Net Freshwater Transport
NHT	Net Heat Transport
NIO	North Indian Ocean
NPZD	Nutrient-Phytoplankton-Zooplankton-Detritus
NPP	Net Primary Production
NVT	Net Volume Transport
NWBoB	Northwestern Bay of Bengal
O_2	Oxygen
OceanSODA	Ocean Surface pCO_2 / Carbon Dataset
OMZ	Oxygen Minimum Zone
OpenMP	Open Multi-Processing
ORAS4	Ocean Reanalysis System 4
OSCAR	Ocean Surface Current Analyses Real-time
PAR	Photosynthetically Active Radiation
pCO_2	Partial Pressure of CO_2
$P (PO_4^{3-})$	Phosphate

POP2-MARBL	Parallel Ocean Program version 2-Marine Biogeochemistry Library
psu	Practical Salinity Unit
PW	Petawatt
R	Pearson Correlation Coefficient
R_f	Revelle Factor
RAMA	Research Moored Array for African-Asian-Australian Monsoon Analysis
RMSE	Root Mean Square Error
RMSD	Root Mean Square Deviation
ROMS	Regional Ocean Modelling System
Sbio	Biological Cycling (Soft Tissue)
SCaCO ₃	Biological Cycling of Hard Tissue
SCM	Subsurface Chlorophyll Maximum
SEAS	Southeastern Arabian Sea
SGD	Submarine Groundwater Discharge
Si (SiO ₄ ⁻)	Silicate
SLD	Sri Lankan Dome
SMAP	Soil Moisture Active Passive
SMOS	Soil Moisture and Ocean Salinity
SODA	Simple Ocean Data Assimilation
SOCAT	Surface Ocean CO ₂ Atlas
SOOP	Ship of Opportunity Program
SP	Small Phytoplankton
SST	Sea Surface Temperature
SSS	Sea Surface Salinity
Sv	Sverdrup
SWBoB	Southwestern Bay of Bengal
TAF	Transformation of Algorithms in Fortran
TAMC	Tangent Linear and Adjoint Model Compiler
TropFlux	Tropical Fluxes
WBC	Western Boundary Current
WICC	West Indian Coastal Current

WOA	World Ocean Atlas
ZEFT	Zonal Eddy Freshwater Transport
ZEHT	Zonal Eddy Heat Transport