

The Indian Ocean Bubble 2



Dear IIOE-2 Members,
Greetings from the Indian Ocean!

Welcome to the June 2026 issue of **IO-Bubble**. This edition brings together a diverse collection of articles that showcase the breadth of research, innovation, and collaboration across the Indian Ocean under the IIOE-2 framework.

In this issue, readers will explore topics ranging from ocean governance and the Biodiversity Beyond National Jurisdiction (BBNJ) Agreement to international collaborations supporting IIOE-2. We feature new research on Indian Ocean climate variability, salinity stratification, monsoon-driven processes, and ocean biogeochemistry, alongside advances in ocean observations, artificial intelligence, and marine technology.

The issue also highlights studies on marine pollution, phytoplankton, seagrass ecosystems, and capacity-building initiatives through the ECOP India Report, reflecting our shared commitment to sustainable ocean science and the development of future ocean professionals.

We sincerely thank all our contributors for sharing their valuable work and look forward to your continued participation in strengthening the IIOE-2 community.

We hope you enjoy this issue.

On behalf of the IIOE-2 PO team
N. Kiran Kumar, Hrishikesh D. Tambe and Aneesh Lotliker

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Ocean Climate Dynamics and Predictability

Evaluation of Indian Ocean Dipole Predictability in DCPD-CMIP6 Decadal Hindcast Simulations

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Importance of predicting the Indian Ocean Dipole

The Indian Ocean Dipole (IOD) (Saji et al., 1999; Webster et al., 1999) is a dominant mode of climate variability that strongly influences rainfall, drought, and marine conditions across the Indian Ocean rim countries. Positive IOD events often bring heavy rainfall to East Africa while reducing the concurrent impacts of El Niño on the Indian summer monsoon and causing droughts over parts of Australia. These impacts have significant socioeconomic consequences, especially agriculture, water resources, and fisheries. Improving the predictability of the IOD is therefore critical for advancing climate services and decision-making in the Indian Ocean region, aligning closely with the objectives of the International Indian Ocean Expedition – 2 (IIOE-2).

The predictability challenge

Despite its importance, predicting the IOD has remained a major scientific challenge. Unlike El Niño, which can often be predicted at least a year in advance due to strong ocean memory in the Pacific (Latif et al., 1998; Zhao and Hendon, 2009), the IOD exhibits limited predictability. (Luo et al., 2008). One of the potential reasons is the presence of a ‘winter predictability barrier’ (Liu et al., 2017; Feng and Duan, 2018). During boreal winter, air–sea coupling weakens, subsurface ocean signals decay rapidly, and atmospheric variability introduces noise. These factors, collectively reduce the signal-to-noise ratio, making it difficult for models to capture the onset and evolution of IOD events beyond a few months. Interestingly, a recent study (Feba et al., 2021) shows that at least two of the coupled models from the CMIP5 decadal hindcasts have the prediction skill of IOD well beyond a year, to be clear, on decadal time scales up to 7–8 years, and these lead skills pertain to the phase of the IOD events.

Can we predict IOD years in advance?

Recent advances in climate modelling, particularly through the Decadal Climate Prediction Project (DCPP) under CMIP6 (Boer et al., 2016; Eyring et al., 2016), offer new opportunities to explore long-lead predictability. In this study, we analyzed 12 state-of-the-art coupled climate models to assess their ability to predict IOD events across lead times of up to 10 years. The results reveal a striking contrast: while most models show little or no skill beyond short lead times, a few models demonstrate significant prediction capability. In particular, CanESM5 and, to some extent, NorCPM1 exhibit robust skill in predicting IOD events even 8–10 years after initialization.

Figure-1 illustrates the correlation between observed and model-derived IOD indices across different lead times. The standout performance of CanESM5 highlights the potential for decadal predictability when models adequately represent key oceanic processes. CanCM4, an earlier version of CanESM5, also showed strong potential (Feba et al., 2021).

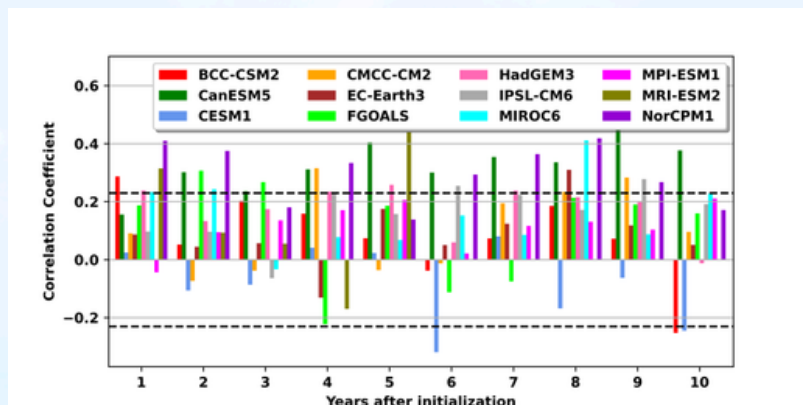


Figure-1: Prediction skill of IOD for the CMIP6 models across lead years (Paul et al., 2026)

What potentially limits interannual predictability of the IOD?

Our analysis of CMIP6-DCPP models reveals a clear asymmetry in predictability between the SSTA of the western and the eastern equatorial Indian Ocean. The western Indian Ocean exhibits stronger ocean–atmosphere coupling and retains subsurface memory, making it more predictable. In contrast, the eastern Indian Ocean is more strongly influenced by atmospheric noise and complex regional processes such as the Indonesian Throughflow (Shi et al., 2012; Doi et al., 2017). This asymmetry limits the overall skill of IOD prediction on interannual time scales because the dipole index depends on both regions.

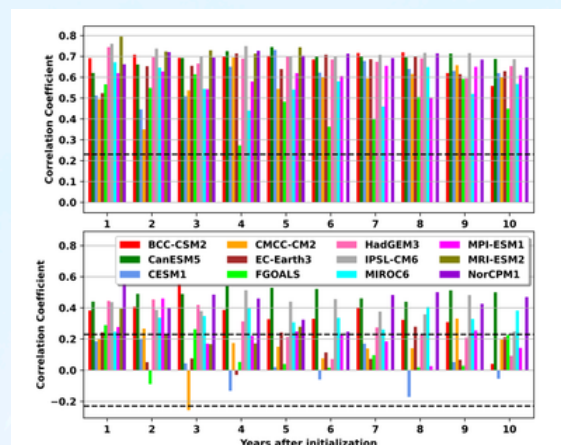


Figure-2: Prediction skill of SST anomalies in the western and the eastern equatorial Indian Ocean across lead times.

Figure-2 shows the prediction skill of sea surface temperature (SST) anomalies in the western and eastern equatorial Indian Ocean from CMIP6 decadal hindcast models. Correlation coefficients between model simulations and observations are shown as a function of lead time. The dashed lines indicate the 90% confidence threshold. The western Indian Ocean exhibits consistently higher predictability compared to the eastern Indian Ocean.

Although most models can reproduce the dipole-like spatial pattern of IOD variability, they differ in the magnitude and structure of variability. This indicates that capturing the pattern alone is not sufficient; accurate representation of the underlying dynamics is equally important.

A surprising source: the Southern Ocean

One of the most intriguing findings of this study is the role of remote oceanic signals originating in the Southern Ocean (Feba et al., 2021). In CMIP6-DCPP models as well, we identify subsurface temperature anomalies at depths of 300–800 m that propagate eastward along the Antarctic Circumpolar Current. These signals subsequently move northward toward the western Indian Ocean and influence surface conditions several years later. This pathway suggests that the Southern Ocean acts as a reservoir of long-term memory, capable of preconditioning the tropical Indian Ocean well in advance of IOD events

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Impacts of Salinity Stratification on Diurnal and Sub-seasonal SST warming in the Northern Indian Ocean

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Freshwater discharge into the Bay of Bengal from the north peaks between August and November by surging river run-offs and monsoon rains (Sengupta et al., 2016). Mesoscale ($O(100)$ km) eddies and wind-driven Ekman currents redistribute this light and buoyant riverwater throughout the Bay, extending its influence to the Southern Bay (Sree Lekha et al., 2018). Meanwhile, the East India Coastal Current, coupled with coastal Kelvin and downwelling Rossby waves, shuttles this freshwater into the Arabian Sea (Hormann et al., 2019). This distribution alters vertical stratification, forming salinity-stratified barrier layers and sub-mesoscale fronts ($O(1-10)$ km) that regulate upper-ocean heat storage and exchange (Ramachandran et al., 2018). The peak of freshwater dispersal within the Northern Indian Ocean (NIO) coincides with the spring inter-monsoon warming (Vinayachandran et al., 2007).

During this period, persistent clear skies and light winds (< 6 m/s) trigger a net heat gain (90% of the days), forming the NIO mini-warm pool. These conditions also foster the development of Diurnal Warm Layers (DWLs), which are anomalously warm surface layers with high SST amplitudes (difference between afternoon SST and early-morning SST). Together, the mini-warm pool and its embedded DWLs act as primary heat sources for atmospheric convection. On diurnal to intra-seasonal scales, this thermal energy influences pre-monsoon tropical cyclone intensification as well as the eventual onset and evolution of the monsoon (Kerhalkar et al., 2025; Pradhan et al., 2022; Rao et al., 2015)

While surface forcing suggests a uniform one-dimensional heating process, remote sensing reveals a far more heterogeneous reality (Figure-1a,e). Across scales of less than 100 km, we observe significant spatial gradients: intra-seasonal (15–60 day) baseline SST (or T_f) warming rates and differences in diurnal SST amplitudes (T_{diurnal}) can vary spatially by $O(1^\circ\text{C})$.

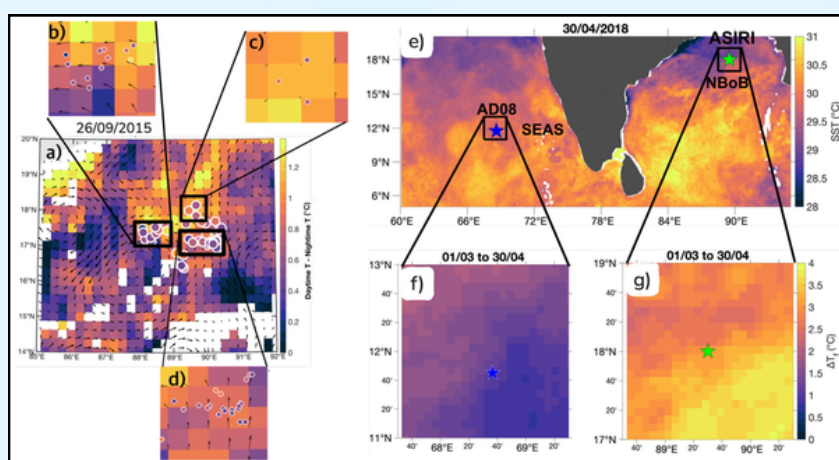


Figure-1: (a) Difference between daytime and nighttime temperatures on 26 September 2015 from AMSR-2, with colored circles denoting the same quantity from in-situ drifters.(b), (c), (d) Zoomed views of regions within the boxes in a). Black arrows indicate the geostrophic currents on 26 September 2015, while the white points in (a) indicate missing data. (e) SST of the Northern Indian Ocean on 30 April 2018 from OISST. The blue and green stars indicate the AD08 mooring in SEAS and ASIRI Mooring in NBoB respectively. (f) and (g) Change in SST from 01 March to 30 April 2018 within the boxes in vicinity of the moorings as indicated in (a). Adapted from Kerhalkar, et al., 2026a and Kerhalkar, et al., 2026b.

These observations raise questions regarding the drivers of spatial variability in T_{diurnal} as well as T_f , particularly the role of the region's unique salinity stratification. While SST evolution is traditionally governed by surface fluxes, wind speeds, and water clarity, the North Indian Ocean's salinity structure adds a layer of complexity. Co-located with the observed SST differences are surface salinity differences of $O(2$ g/kg) and mixed-layer depth variability of $O(25$ m). Simultaneously, lateral wind speed differences of $O(2$ m/s) suggest that small-scale air-sea flux gradients are also at play. Together, these factors imply that the thermal heterogeneity is driven by a tight coupling between atmospheric forcing and the underlying oceanic salinity structure.

To address these questions, we utilized a combination of high-resolution in-situ observations and numerical simulations using the General Ocean Turbulence Model (GOTM), which parameterizes upper-ocean mixing through various turbulence closure schemes. The observational data stems from long-term, heavily instrumented moorings and cutting-edge instruments deployed during extensive fieldwork under India-US collaborative projects (ASIRI-OMM Wijesekera et al., 2016, MISOBBoB-OMM Shroyer et al., 2021, and EKAMSAT, Johnson et al., 2025). These deployments included surface drifters measuring sea-surface temperature and salinity, alongside Drogued-Buoy Air-Sea Interaction Systems (D-BASIS). The D-BASIS platform combines surface moorings with wave-powered "wirewalkers" to profile upper-ocean temperature, salinity, and velocity every 10 minutes, while ship-board FastCTD systems provided horizontal snapshots of the upper ocean at 200-meter resolution (Figure-2, Kerhalkar, et al., 2026a).

INTERNATIONAL INDIAN OCEAN EXPEDITION - II

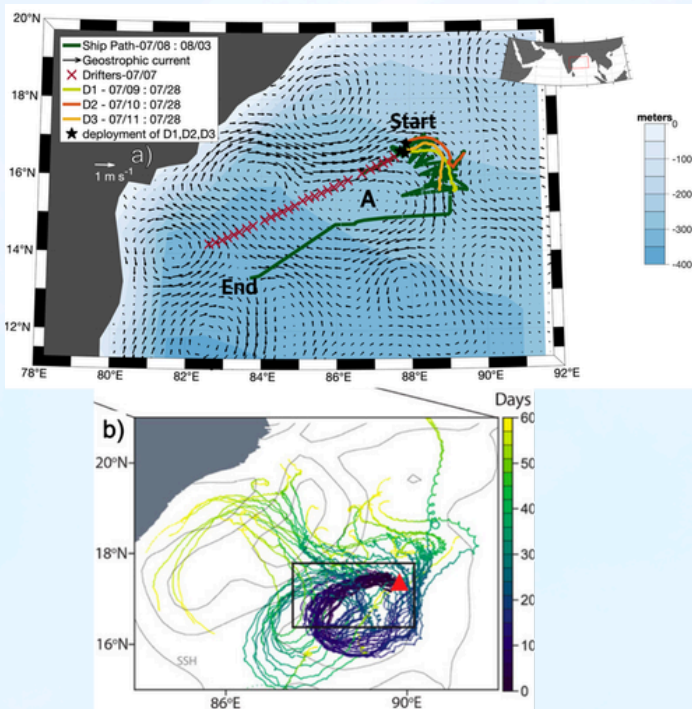


Figure-2: a) Map of the Bay of Bengal displaying various assets used for sampling during the MISO-BoB Intensive Observational Period (IOP) in 2019. The legend provides information about the deployment dates and positions of drifters. It also includes deployment positions, paths, deployment dates, and recovery dates for the D-BASIS profilers (D1, D2, D3). The map also illustrates the ship's route and sampling dates. The background colors represent the bathymetry of the Bay, while the background arrows depict geostrophic currents averaged over a ten-day period from 15-24 July 2019. The letter A indicates the anticyclonic eddy along which the drifters moved. Adapted from Kerhalkar, et al., 2026a. b) Two months of drifter trajectories released at the red triangle overlaid onto CMEMS sea level anomalies with days after deployment are shown in color. Adapted from Essink et al., 2022.

In a recent study (Kerhalkar, et al., 2026a), we show that remote sensing significantly underestimates the spatial variability in diurnal cycle amplitudes (Figure-1 b,c,d). Using our dense instrument network, we identified median and extreme spatial differences in T_{diurnal} of 0.2 C and 1.6 C respectively, over scales under 100 km (Figure-3 a). Drifter data specifically linked increasing salinity gradients to spatial differences in T_{diurnal} of about 0.2 C (Figure-3 c). By using GOTM to isolate individual drivers, we found that winds and water clarity each modulate T_{diurnal} by 0.3-0.5 C, while salinity stratification and heat fluxes each contribute 0.1-0.2 C. Crucially, this sensitivity only emerges when the initial mixed layer is shallow (< 14 m). While median spatial differences can be explained by any one of these four factors, the extreme T_{diurnal} difference of 1.6 C require their combined influence contribution, highlighting the intense variability of air-sea interaction at small scales. This small-scale variability was further evidenced by a network of three D-BASIS units separated by only 30 km. Both observations and corresponding GOTM simulations showed that the vertical extent of the diurnal warm layer deepening is modulated by O(10 m) due to localized wind shifts and underlying salinity stratification. FastCTD measurements revealed that this stratification was driven by a combination of synoptic cold-pool events and the mesoscale salinity field as it was modulated by eddy action (Figure-4). Essentially, even across short distances, the depth of solar heating is dictated by how localized winds interact with the pre-existing oceanic patchiness.

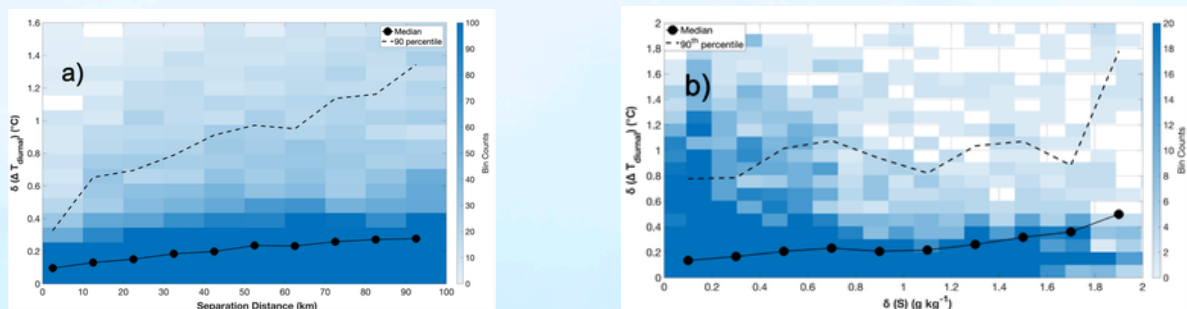


Figure-3: a) Binned scatter plot of spatial differences in diurnal SST magnitudes between drifter pairs versus their separation distances for 01 September to 30 November 2015 (11,186 observations). Color indicates the number of observations per bin (every 10 km and 0.1C). Solid lines with circle markers show the median values in each separation-distance bin while dashed lines indicate the 90th percentile values in each bin. b) is the same as a) except the spatial differences in diurnal SST magnitude is binned as a function of salinity differences. Adapted from Kerhalkar, et al., 2026a

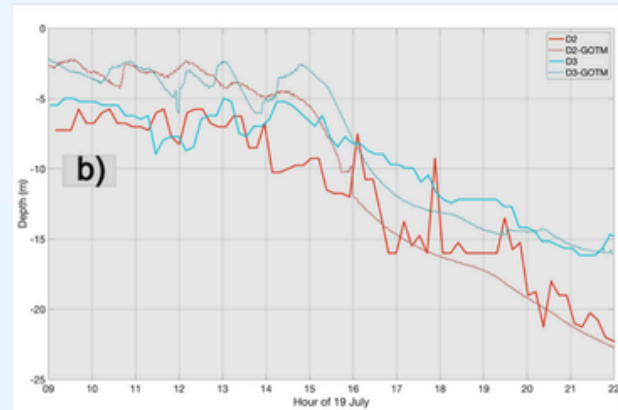
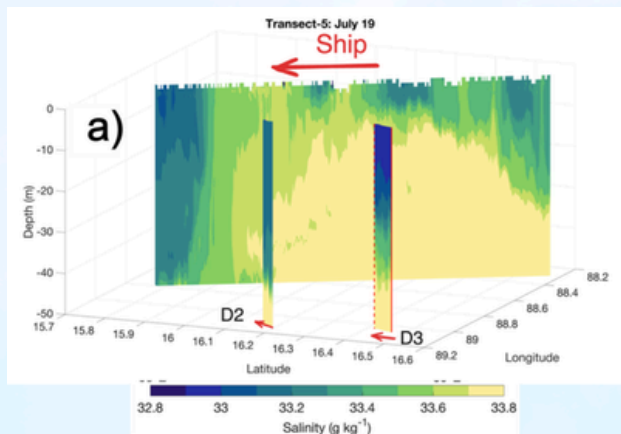


Figure-4: a) 3-D plots of the salinity from ship transect as well as sections sampled from D2 and D3 during the same time. b) Solid lines indicate the observed DWL depths at D2 and D3, while the dashed lines indicate the DWL depths from the corresponding GOTM simulations on 19 July 2019. Time series are shown in local time (IST).

Adapted from Kerhalkar, et al., 2026a

The impact of salinity stratification extends beyond diurnal cycles into the longer-term evolution of baseline SST (T_f). By trapping both daytime heating and nighttime cooling over a comparatively stratified layer, salinity can drive significant lateral variability in T_f . To evaluate this, we conducted a suite of 1-D GOTM simulations forced with realistic surface fluxes from NIO moorings (AD08 in the Arabian Sea and WHOI mooring in the Bay of Bengal). These simulations reveals differences of 0.2-0.5 C in T_f over 14-21 days due to salinity stratification differences (Kerhalkar, et al., 2026b), partly explaining trends observed in remote sensing (Figure-1 f,g, Figure-5 a,b). As with the diurnal warming, this variability is only evident when initial mixed layers are shallow (< 14 m). Interestingly, the role of salinity stratification on the T_f is contrasting; in the Arabian Sea scenario, the stratified case warms less than the unstratified case (Figure-5 f). In the Bay of Bengal, however, the stratified case fluctuates, exhibiting both higher and lower warming rates than the unstratified case at different times (Figure-5 e). Through idealized GOTM simulations, we demonstrate that the relative warming of a stratified case compared to an unstratified one is highly sensitive to the net surface heat flux and the water's optical properties. Under high daily mean net heat flux and turbid conditions, stratified layers warm more effectively because the trapped daytime heating overpowers nighttime cooling. This suggests that in regions with strong salinity fronts (such as the NIO, especially during the mini-warm pool), elevated heat fluxes and turbidity can actually enhance density contrasts across the front (Figure-6). Conversely, under lower heat fluxes or clearer water, the initial salinity front may become partially density-compensated. In these scenarios, the more efficient nighttime cooling over a stratified layer overpowers daytime heating, leading to reduced relative warming.

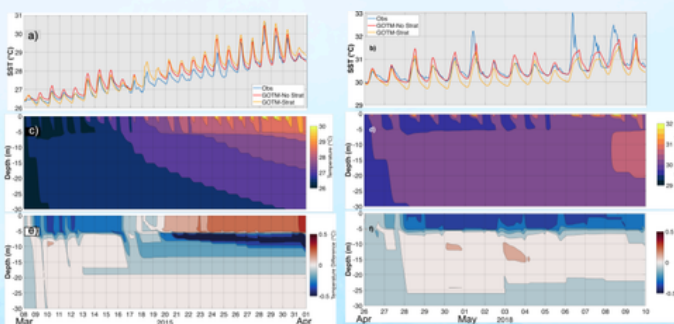


Figure-5: a) Observed SST from ASIRI mooring (in blue), modeled SST assuming no salinity stratification (in red) as well as modeled SST assuming salinity stratification (in yellow) between 08 March and 01 April 2015. c) Modeled temperature profiles assuming salinity for the same time period. (e) Difference in temperature between stratified and unstratified simulations. Red color indicates that the salinity-stratified case is warmer than non-salinity-stratified case. b) ,d) ,f) is the same as a), c), e) except for AD08 mooring between 26 April and 10 May 2018. Adapted from Kerhalkar, et al., 2026b.

To quantify this, we derived an analytical expression for the daily-mean net heat flux threshold above which salinity stratification triggers greater surface warming (equations-4,5 in Kerhalkar, et al., 2026b) . Validated by our 1-D simulations, this threshold is governed by water clarity, mixed-layer depth, and solar radiation, typically varying between 107-180 Wm^{-2} . Ultimately, this framework explains how bio-physical coupling and salinity determine varying intensities of upper-ocean heating.



Figure-6: Schematic explaining the Arabian Sea and Bay of Bengal scenarios shown in Figure-5.

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Biogeochemistry, Hypoxia, and Acidification

Monsoon Upwelling, Hypoxia and Acidification: Tracking Carbon Stress on the Southeastern Arabian Sea Shelf

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The southeastern Arabian Sea shelf is one of the most dynamic and biogeochemically active coastal regions in the northern Indian Ocean. Every year, the summer monsoon drives coastal upwelling along the southwest coast of India, bringing cooler, nutrient-rich subsurface waters onto the continental shelf. This process supports high biological productivity, but it also brings a hidden cost: the same waters are often low in oxygen, enriched in dissolved inorganic carbon (DIC), and naturally more acidic. The result is a seasonal episode of multiple stressors - hypoxia, acidification, and elevated carbon dioxide (CO₂) - that can strongly affect marine ecosystems.

In their recent study published in *Marine Chemistry*, V. Sudheesh and G.V.M. Gupta examine how these coupled processes shape the inorganic carbon system over the southeastern Arabian Sea shelf. Using repeat shipboard observations through 2012 along two coastal transects - Kochi in the southern eastern Arabian Sea and Mangalore in the central eastern Arabian Sea - the authors provide one of the clearest seasonal descriptions so far of how upwelling alters carbonate chemistry, oxygen conditions, and CO₂ dynamics in this monsoon-driven shelf ecosystem.

The study is built on a valuable observational design. The Kochi shelf was sampled ten times across a full annual cycle (Kochi Time Series – KoTS), while the Mangalore transect was sampled during key seasonal windows representing spring intermonsoon, summer monsoon, and winter monsoon. At both locations, stations extended from nearshore to outer shelf waters (13 - 100 m depth), allowing the authors to track both vertical and cross-shelf gradients. This repeated, shelf-scale perspective is particularly important in the eastern Arabian Sea, where upwelling intensity, freshwater influence, and oxygen stress can vary sharply over short distances and between seasons.

A central message of the paper is that seasonality exerts a dominant control on shelf carbonate chemistry. During the non-upwelling (oxic) period, the inorganic carbon system is relatively stable, and much of the variability in DIC and total alkalinity (T_{Alk}) can be explained by conservative water-mass mixing. In simple terms, the chemistry during these months is largely controlled by the mixing of different water masses, especially fresher waters influenced by Bay of Bengal-derived inputs and more saline Arabian Sea shelf waters. When the authors normalize DIC and T_{Alk} to a common salinity (nDIC₃₅ and nT_{Alk35}), much of the apparent variability is reduced, showing that salinity-driven mixing is a dominant control outside the upwelling season.

That picture changes dramatically during the summer monsoon (June–September). With the onset of upwelling, oxygen-poor and DIC-rich subsurface waters are transported onto the shelf. These waters increase subsurface carbon concentrations, lower pH, and intensify oxygen depletion. The authors show that even after removing salinity effects, salinity-normalized DIC remains strongly elevated, especially below about 40 m depth, where nDIC₃₅ increases from ~1950–2000 μmol kg⁻¹ near the surface to >2100–2200 μmol kg⁻¹ in deeper shelf waters. This is a key result because it shows that the carbon build-up is not simply the result of freshwater dilution or mixing, it reflects a real accumulation of inorganic carbon linked to upwelling and respiration.

The study argues convincingly that this carbon accumulation follows a two-stage mechanism. First, physical advection brings CO₂-rich, oxygen-deficient subsurface waters from the oxygen minimum zone (OMZ) onto the shelf. Second, biological amplification occurs as microbial respiration further consumes oxygen and adds CO₂ within the stratified shelf system. This interpretation is supported by the positive relationship between apparent oxygen utilisation (AOU) and nDIC₃₅, indicating that oxygen consumption is associated with additional DIC enrich-

ment. Importantly, the authors avoid oversimplifying this as purely local respiration; instead, they emphasize the combined effect of imported DIC-rich source waters and subsequent in situ remineralisation. This makes the paper especially strong from a process-based perspective.

Another important contribution of the study is its analysis of carbonate buffering capacity. While DIC shows strong seasonal enhancement during upwelling, total alkalinity varies much less, even though some alkalinity generation may occur under low-oxygen conditions through anaerobic processes. Because DIC increases more strongly than T_{Alk} , the TAlk:DIC ratio declines during the summer monsoon, indicating a reduction in the system's buffering capacity. In practical terms, this means shelf waters become more sensitive to additional CO_2 accumulation, making pH fall more easily and increasing vulnerability to acidification. The authors show that this weakened buffering is also reflected in a higher Revelle factor, another sign that the system becomes less able to absorb carbon without large chemical change.

The ecological significance becomes especially clear when looking at carbonate mineral saturation states. During non-upwelling months, shelf waters remain comfortably supersaturated with respect to calcite and aragonite, conditions generally favorable for calcifying organisms. But during the summer monsoon, saturation states decline sharply. The paper reports that under severe upwelling conditions, when pCO_2 exceeds $1000 \mu atm$, calcite saturation (Ω_{Ca}) can fall to around 2.5, while aragonite saturation (Ω_{Ar}) can decline to around 1.5. These values are still above undersaturation, but they represent a substantial loss of carbonate chemical "comfort zone," particularly for sensitive calcifiers such as pteropods, foraminifera, larval molluscs, and echinoderms.

The seasonal CO_2 signal is equally striking. Surface waters in the region are often a source of CO_2 to the atmosphere, but the strength of this source changes markedly through the year. On the Kochi shelf, surface pCO_2 values increase sharply during peak upwelling, reaching very high and spatially variable levels, with some surface waters exceeding $1200 \mu atm$ in June. Subsurface maxima are even higher. These observations confirm that the southeastern Arabian Sea shelf is not only a zone of seasonal acidification and deoxygenation, but also an active coastal CO_2 outgassing region during monsoon forcing.

What makes this study especially relevant for IIOE-2 is that it highlights the eastern Arabian Sea as a natural laboratory for multiple stressors in the Indian Ocean. Unlike many coastal hypoxic systems worldwide that are heavily driven by anthropogenic eutrophication, the eastern Arabian Sea represents a system where monsoon-driven physical forcing, natural OMZ dynamics, and shelf biogeochemistry interact to create recurring seasonal extremes. Yet these natural processes do not make the system less important in the climate context, if anything, they make it more valuable for understanding how warming, stratification, and future changes in monsoon behavior may amplify oxygen loss and acidification.

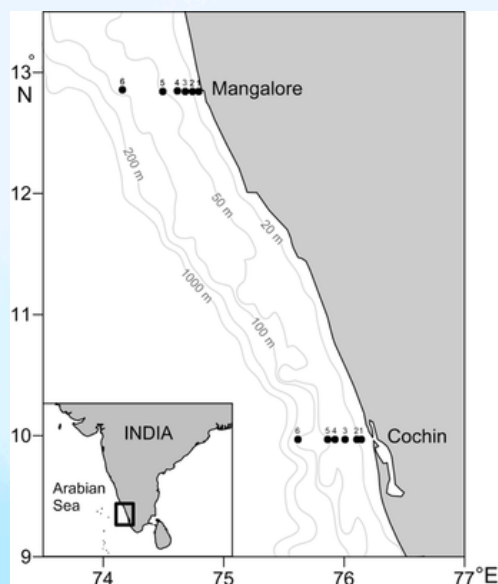


Figure-1: Study area in the eastern Arabian Sea showing the sampling stations (1-6). Depth contours indicate the bathymetric depth of the water column at each location.

Overall, this paper provides a strong mechanistic framework for understanding how upwelling, deoxygenation, and acidification are tightly coupled on the southeastern Arabian Sea shelf. It shows that seasonal carbon stress is not just a simple mixing problem, but the outcome of linked physical transport and biological transformation. For the Indian Ocean community, this is an important contribution because it moves beyond describing low oxygen alone and places the eastern Arabian Sea firmly in the broader global conversation on coastal multiple stressors, carbonate-system vulnerability, and ecosystem resilience.

This study was conducted at the Centre for Marine Living Resources and Ecology (CMLRE) as part of the Marine Living Resources (MLR) Programme of the Ministry of Earth Sciences (MoES), India, under the SIBER-India Programme.

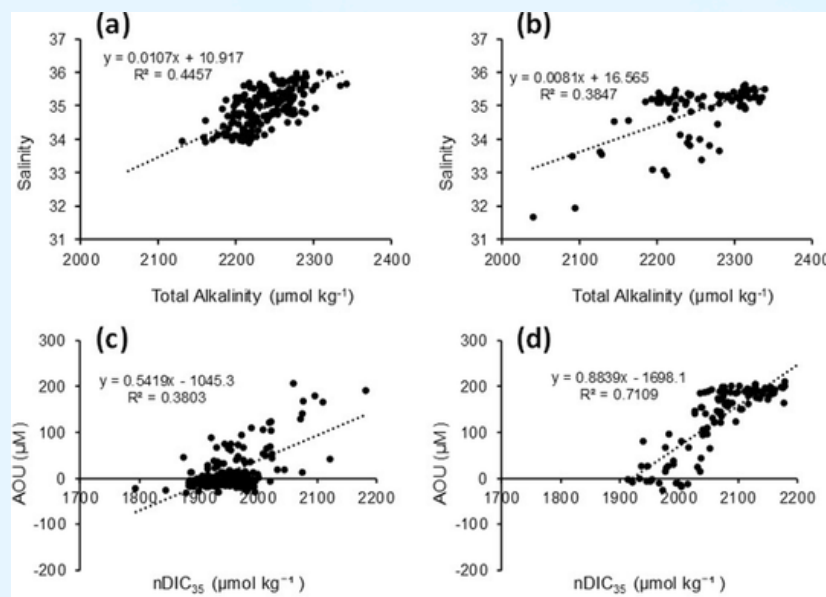


Figure-2: Relationship between salinity versus total alkalinity (T_{Alk}) during the non-monsoon season (a) and the summer monsoon season (b), indicating that alkalinity is largely controlled by conservative water-mass mixing. Apparent oxygen utilisation (AOU) and salinity-normalised dissolved inorganic carbon (nDIC₃₅) during the non-monsoon season (c) and the summer monsoon (d), showing that DIC enrichment persists after salinity normalisation and remains positively associated with oxygen consumption.

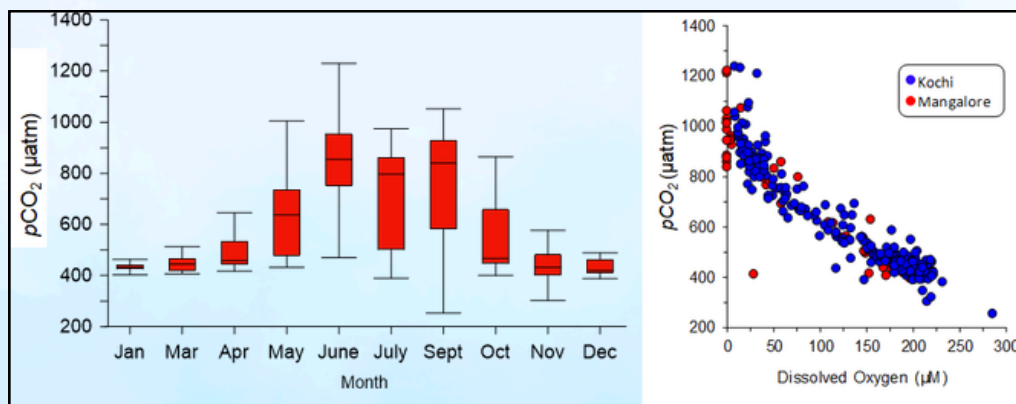


Figure-2: Monthly $p\text{CO}_2$ (μatm) variability and its relationship with DO in the SEAS



Marine Pollution and Conservation

Microplastic Pollution In The Bay of Bengal: A Case Study of Nijhum Island

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Introduction

Plastic is something that we use literally in everything in our daily lives, from brushing our teeth in the morning to going to sleep. It has become an integral part of lives due to it being cheap and easy to manufacture. We are already aware of plastic pollution in the environment and its deadly consequences but we are barely aware of microplastic pollution, which is even more concerning. Unlike plastics which are visible to naked eye, microplastics are not. Any plastic particle less than 5 mm in size is defined as microplastics by the scientists. Since, microplastics pollution is happening worldwide in every ecosystem including marine environment, so being a student of Oceanography, I wanted to know about its impact in the coastal area of Bangladesh, more particularly the small Island called Nijhum located in the Bay of Bengal. The reason I chose this location is that, it has a small population and it is one of the least tourist heavy places in Bangladesh. So, I wanted to see how much microplastic pollution happens in such a place like this.

This study basically followed this simple design:

Sampling → Drying → Density Separation → Digestion → Filtration → Microscopic Analysis → ATR-FTIR

Materials and Methods

Study Area

Nijhum Island located within the central coastal zone, adjacent to the Meghna estuary channel in the mouth of Bay of Bengal, roughly 2 km southwest of Hatiya Island. The Island roughly has an area of 163.45 sq km², of which only about 38.65 sq km² is dry land. It hosts various species such as spotted deer, fish, shrimp, crab, rays etc that are important for the local ecology. It was designated as a national park in April, 2001 to protect its marine biodiversity and ecosystems by the Bangladesh Government. The local economy is mainly dependent on fishing, cultivation and livestock grazing. An outline of the sampling location and sampling stations of Nijhum Island has been shown in Figure-1.

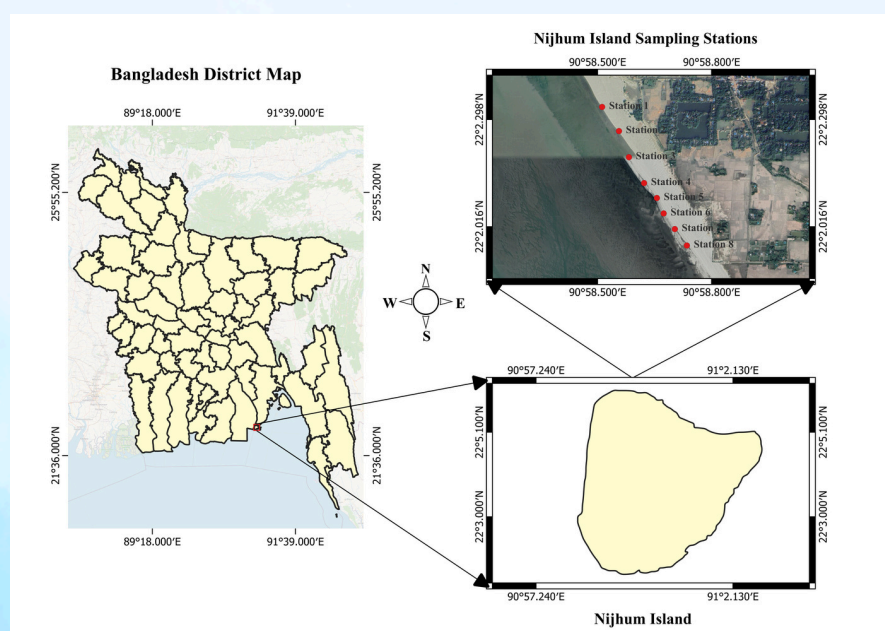


Figure-1: Study Area of Nijhum Island and Sampling Stations

Sample Collection

I collected sand samples from Nijhum Island on 27th of October in 2025 with the help of one of my fellow classmates. From the sampling site only 8 samples were collected from the intertidal zone because this is the most polluted zone in terms of microplastics pollution of a beach. The study area covered mainly Nama Bazar sea beach area of Nijhum Island. Sampling was conducted with my classmate early in the morning based on the tidal data as we had to collect samples from the intertidal zone which stays exposed only during the low tide. The sampled stations are Nijhum Island = Station 1, Station 2, Station 3...so on and so forth (see Table 1). Samples were collected using a clean stainless steel (to avoid plastics contamination) scooper from an area of around 15 cm² with a 40 ± 2 feet distance apart from each station resulting in each sample of 300±50 g sand. Finally I labeled the samples properly and wrapped them in well sealed and clean aluminum foils to prevent any sort of contamination and then they were taken to the laboratory promptly.



Figure-2: Author Collecting Beach Sand Samples With a Stainless Steel Scooper

Station ID	Latitude	Longitude
Station 1 (Nama Bazar Beach)	22°02'19.87" N	90°58'30.72" E
Station 2 (Nama Bazar Beach)	22°02'16.06" N	90°58'33.38" E
Station 3 (Nama Bazar Beach)	22°02'11.94" N	90°58'34.95" E
Station 4 (Nama Bazar Beach)	22°02'07.85" N	90°58'37.35" E
Station 5 (Nama Bazar Beach)	22°02'05.49" N	90°58'38.97" E
Station 6 (Nama Bazar Beach)	22°02'03.06" N	90°58'40.44" E
Station 7 (Nama Bazar Beach)	22°02'00.59" N	90°58'42.20" E
Station 8 (Nama Bazar Beach)	22°01'58.00" N	90°58'44.10" E

Table-1: Nijhum Island Sampling Stations

Sample Preparation (Drying)

The collected samples were dried using an oven at 90° in the oven/dryer for 24 hours. But before doing this, I took the samples out of the foil bags and spread them out on steel trays. This method (oven drying) is a fundamental method in microplastic research because it ensures consistent mass distribution of the sand and eases the density separation process. Additionally this is the preferred method because it is faster and can be better controlled in terms of airborne microplastic contamination.

Density Separation: Floatation Method

From each of the samples, only 200 ± 2 g of sand were weighted and proceeded with density separation process. Then samples were combined with the brine solution of ZnCl_2 . I used 500 milliliter of distilled water with 350 ± 2 g of ZnCl_2 to prepare the brine solution with the help of the magnetic stir machine. After that the samples were kept in rest so that the sand particles could settle for 24 hours in order to have the floatation process complete.

Optimization of Digestion (Hydrogen peroxide treatment)

Once the floatation was complete the samples were moved from one beaker to another using a pipette and threw away all the leftover sand. Then 100 mL of 30% H_2O_2 was added to each beaker considering the water quality and amount to break down the organic matter (e.g. plant debris, biological material). I chose H_2O_2 due to its effectiveness compared to NaOH , H_2SO_4 , HNO_3 , and HCl in terms of removing organic matters. In order to complete the digestion the beakers were then covered with aluminum foils and placed inside the incubator at 65°C for 24 hours.

Filtration

Finally I did the filtration procedure which was done after the completion of the digestion process. Vacuum filtration method was used for this. I used a vacuum pump with vacuum stand and cellulose nitrate filter paper with pore size $0.45 \mu\text{m}$ to filter the samples for the filtration. After the filtration was complete, the filter papers were placed onto glass petri dishes and covered with aluminum foils with proper labeling.

Microscopic Analysis

OPTIKA Stereo Microscope from Italy was used to look at the filter papers, with the aid of a C-B5+ 5.1 MP CMOS to capture images of suspected plastic particles at 4X magnification. These images were used to categorize and determine the microplastics based on their characteristics. Eventually I grouped them based on their type, color, shape, size and polymer type. Common types of MPs such as Fibers, Films, Fragments, and Beads were found.

Identification of Polymer Type Using ATR-FTIR Spectrometer

I used a custom polymer library and Attenuated Total Reflectance Fourier Transform Infrared (ATR-FTIR) instrument (Agilent Cary 630 FTIR Spectrometer, USA) to identify the polymer type of each microplastics. The spectra were acquired within the interval of 4000 cm^{-1} to 650 cm^{-1} .

Results

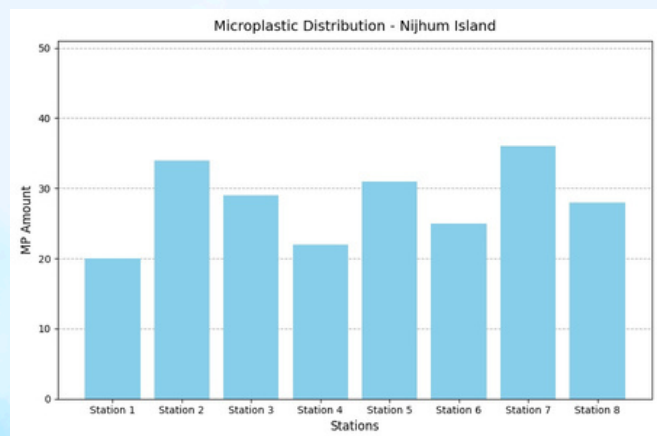


Figure-3: Bar Diagram of Microplastic Distribution In Nijhum Island

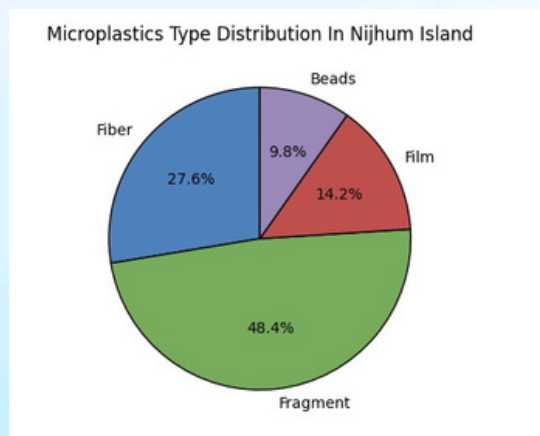


Figure-4: Microplastics Type Distribution in Nijhum Island

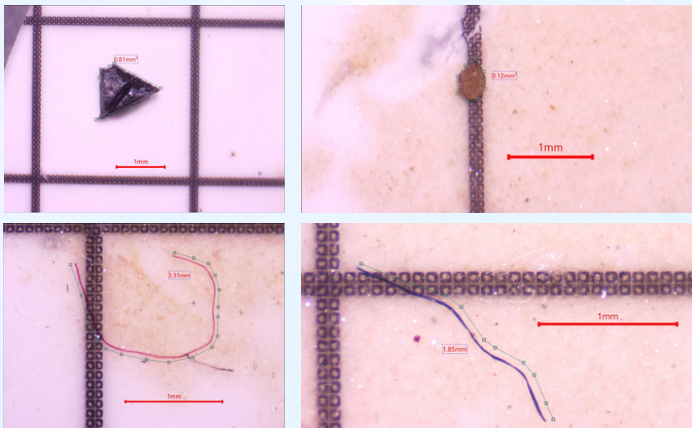


Figure-5: Different Types of Microplastics (size, shape, color)

Nijhum Island Stations	MP Amount
Station 1	20
Station 2	34
Station 3	29
Station 4	22
Station 5	31
Station 6	25
Station 7	36
Station 8	28
Total	225

Table-2: Abundance of Microplastics In Nijhum Island

FRTIR-ATR Result

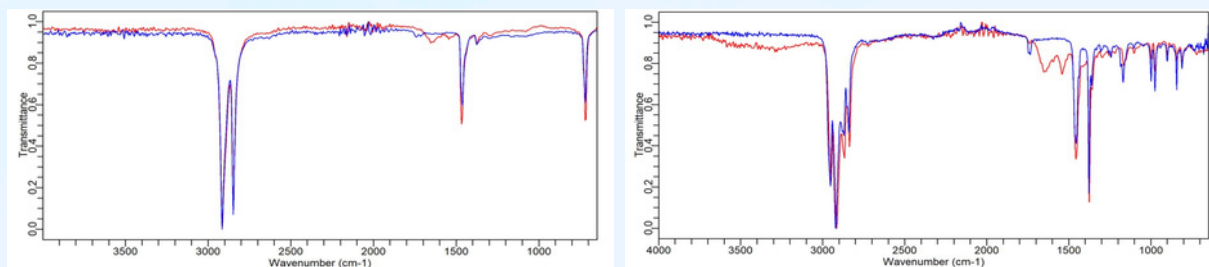


Figure-6: ATR-FTIR infrared spectra were identified mainly as: (a)- Polyethylene (Placed on Top), (b)- Polypropylene (Placed right below (a)).

Discussion

I found different amounts and types of microplastics in the beach sand samples of Nijhum Island. This basically proves how widespread the problem is. Just because Nijhum Island has a small population and smaller area it doesn't mean that the island is free of pollution. So, finding the causes and routes of microplastics pollution is crucial for coming up with effective and sustainable ways to prevent it.

Conclusion

My study sheds light on the microplastics pollution in Nijhum Island, but further monitoring and assessment is required to see how things change over time and how well mitigation strategies are working. We should undertake the effects of microplastics pollution on marine ecosystem health and their possible toxicity with further investigation.



Assessment of Poly-Aromatic Hydrocarbon sources in surface sediments along the Kenyan coast using PMF

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Aim: Polycyclic Aromatic Hydrocarbons (PAHs) were analyzed in surface sediments from selected locations along the Kenyan coastline, including Mwache Creek, Tudor Creek, Mida Creek, and the Sabaki River estuary. These sites exhibit varying degrees of contamination and diverse anthropogenic sources (Figure 1). The sixteen US EPA priority PAHs, together with alkylated phenanthrenes, were quantified across these locations, which range from highly impacted zones to relatively remote and protected marine ecosystems

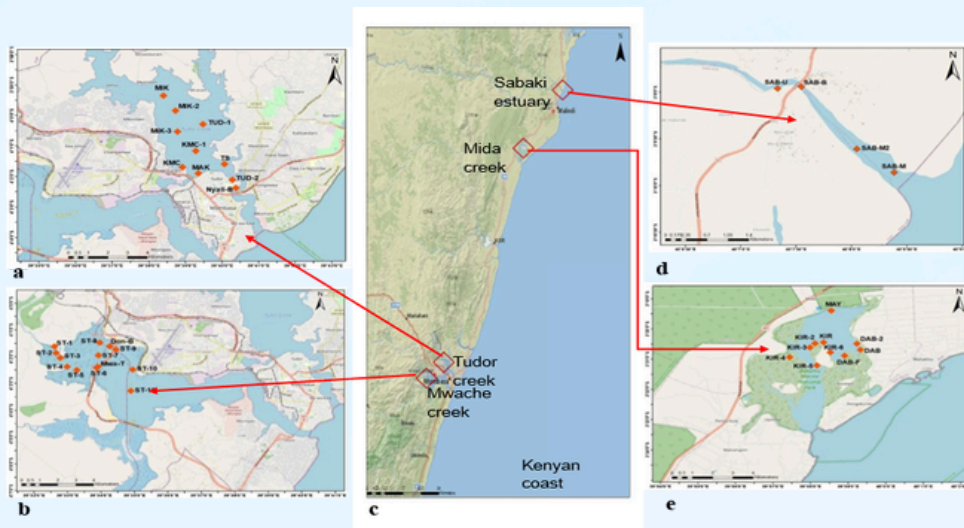


Figure-1: Map of the study area in the western Indian Ocean, Kenya. a) urbanized Tudor creek, b) Mwache creek both affected by port activities in Mombasa, c) the Kenyan coast, d) Sabaki River mouth and e) Mida creek Natural Park.

Across the 37 sampling stations, total concentrations of parent PAHs ranged between 0.94 and 99.02 ng g⁻¹. Alkylated PAHs, predominantly methyl-phenanthrenes, were exclusively detected in sediments from Mwache Creek at concentrations varying from 1.06 to 5.56 ng g⁻¹. Elevated PAH concentrations in Mwache Creek and Tudor Creek are likely linked to their proximity to pollution hotspots such as Kilindini Harbor, the densely populated city of Mombasa, the nearby airport, and heavily trafficked road networks. In contrast, Mida Creek exhibited much lower PAH concentrations, consistent with its status of Marine National Park and Reserve characterized by limited urban development and fewer emission sources. Similarly, reduced PAH levels were recorded in the Sabaki River estuary. The results demonstrated a predominance of high molecular weight (HMW) PAHs, particularly in Mwache and Tudor Creeks, where concentrations exceeded those measured in Mida Creek and the Sabaki estuary. Diagnostic ratios of parent PAHs, including Fla/(Fla+Py), Ph/(Ph+An), BbF/BkF, BaA/(BaA+Chr), and IP/BghiP, suggested that pyrolytic processes were the predominant source of contamination across the study sites. To further determine PAH sources, Positive Matrix Factorization (PMF) analysis was performed on the dataset. The first four PMF factors indicated petroleum-related contamination at several sites within Mwache Creek, alongside significant pyrolytic sources such as biomass combustion, maritime operations, and vehicular emissions. Pyrolytic PAHs originating from gasoline, diesel combustion, and biomass burning were more prevalent than petrogenic PAHs, with the latter contributing only 15.44% to the total contamination. Evidence of petrogenic PAHs was identified solely in Mwache Creek, likely due to activities associated with Kilindini Harbor and local fishing vessels. The PMF model attributed the major pyrolytic contributions to gasoline combustion (35.54%) and biomass burning (31.09%), followed by diesel engine emissions (17.93%).

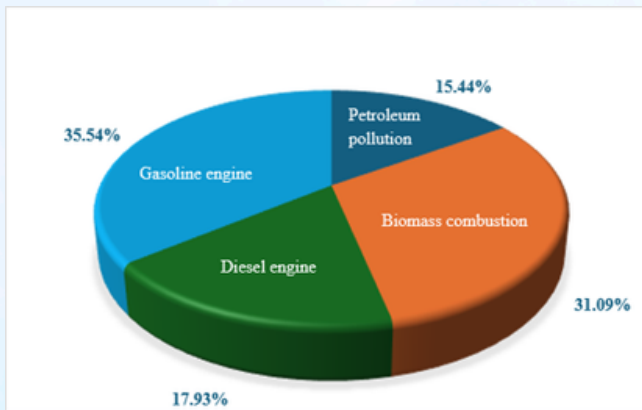


Figure-2: Pie chart of the relative contribution of major PAH sources along the Kenyan coast in surface sediments obtained from PMF.

Summary: These findings emphasize the influence of anthropogenic activities along the Kenyan coast, distinguishing urban-industrial emissions around Mombasa from those in less developed coastal areas. Within the framework of blue economy development, continuous monitoring of PAHs along the Kenyan coastline—particularly around Mombasa—is strongly recommended, alongside assessments of their bioaccumulation in commercially important marine species. Furthermore, given the planned construction of the Mwache Dam, which is expected to alter the transport and accumulation of sediment-associated PAHs within adjacent mangrove wetlands, this dataset provides a crucial baseline for evaluating future anthropogenic impacts on water resources and marine ecosystems.



Biodiversity, Taxonomy, and Emerging Technologies

An Absorption-Based Bio-Optical Framework for Phytoplankton Size Class Retrieval in the Arabian Sea

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Phytoplankton are microscopic marine organisms that form the foundation of marine food webs and play an important role in regulating ocean productivity, biogeochemical cycling, and climate processes. Through photosynthesis, they contribute significantly to the biological carbon pump by facilitating the transfer of atmospheric carbon dioxide from surface waters to deeper ocean layers. Variability in phytoplankton community structure directly influences marine ecosystem functioning, trophic interactions, and carbon export efficiency. In marine ecosystems, phytoplankton communities are broadly categorized into pico-phytoplankton, nano-phytoplankton, and micro-phytoplankton groups based on cell size, with each group performing distinct ecological and biogeochemical functions. Pico-phytoplankton generally dominate low-nutrient oligotrophic waters, whereas micro-phytoplankton are commonly associated with nutrient-rich bloom conditions and enhanced carbon export. Nano-phytoplankton frequently occupy transitional ecological conditions between these two extremes. In the Arabian Sea, phytoplankton dynamics are strongly influenced by monsoon-driven physical and biogeochemical processes such as convective mixing, coastal upwelling, stratification, mesoscale circulation, and nutrient entrainment. These processes create highly dynamic environmental conditions that support contrasting phytoplankton communities across seasons and regions of the basin. During winter and pre-monsoon periods, enhanced nutrient availability promotes intense phytoplankton blooms dominated by larger micro-phytoplankton communities, whereas stratified oligotrophic conditions favour pico-phytoplankton dominance in offshore waters. Understanding these ecological transitions is essential for improving knowledge of ecosystem functioning and climate-related changes in the northern Indian Ocean. Conventional ship-based observations provide valuable insights but remain limited in spatial and temporal coverage. In this context, ocean-colour remote sensing combined with bio-optical measurements offers an effective approach for monitoring phytoplankton variability at synoptic scales. This collaborative study involving researchers from INCOIS, NCPOR, and Columbia University utilized in situ phytoplankton absorption measurements collected during six research cruises conducted between 2016 and 2024 across the Arabian Sea. Sampling covered productive bloom waters, oligotrophic offshore regions, and transitional environments influenced by varying nutrient availability and monsoonal forcing. Water samples collected during these cruises were analysed for phytoplankton absorption properties and diagnostic pigments using advanced laboratory techniques. Phytoplankton absorption spectra were measured using the quantitative filter technique with a UV-Visible spectrophotometer equipped with an integrating sphere, while pigment analyses were performed using high-performance liquid chromatography (HPLC) following internationally established analytical protocols. Pigment samples from the RR2306 cruise were additionally processed at NASA Goddard Space Flight Center using standardized methods widely adopted in global ocean-colour validation studies. The resulting dataset provided an excellent opportunity to examine the optical variability and phytoplankton community structure of the Arabian Sea across multiple ecological regimes (Figure-1).

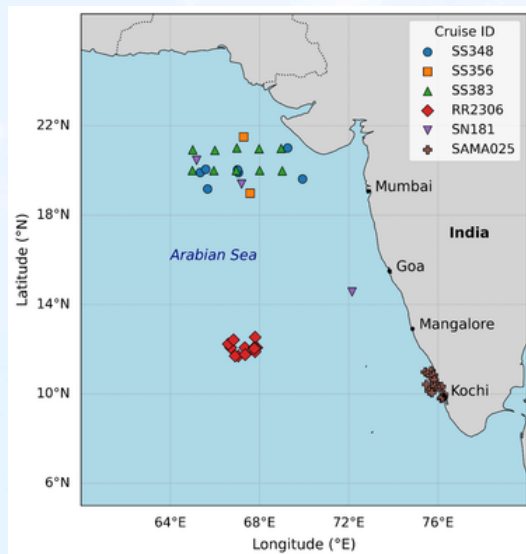


Figure-1: Study area map showing cruise tracks and sampling stations across the Arabian Sea

Result & Discussion

The study investigated how phytoplankton absorption properties vary in relation to changes in phytoplankton community structure and productivity. A strong relationship was observed between phytoplankton absorption at 443 nm ($a_{ph}(443)$) and the spectral slope between 443 and 510 nm, providing a reliable optical basis for distinguishing pico-, nano-, and micro-phytoplankton communities in the Arabian Sea. These absorption-based classifications were validated using co-located HPLC pigment observations, allowing direct comparison between optical measurements and pigment-derived phytoplankton community composition (Figure-2). The results showed that low phytoplankton absorption values coupled with steeper blue-region spectral slopes were generally associated with pico-phytoplankton communities characteristic of oligotrophic offshore waters, whereas higher absorption values and lower spectral slopes were linked to micro-phytoplankton communities typically observed under bloom conditions and nutrient-rich environments. Nano-phytoplankton communities displayed intermediate optical characteristics and frequently occurred in transitional regions influenced by moderate nutrient availability. Analysis of phytoplankton absorption spectra revealed systematic differences in both spectral magnitude and spectral shape among the observed phytoplankton communities. Productive bloom conditions dominated by micro-phytoplankton exhibited stronger absorption peaks and greater spectral variability associated with elevated pigment concentrations and accessory pigments, while pico-phytoplankton-dominated oligotrophic waters displayed lower absorption magnitudes and steeper spectral slopes characteristic of smaller cells with reduced pigment packaging effects. Nano-phytoplankton communities occupied an intermediate optical range and frequently overlapped with adjacent groups, reflecting their transitional ecological behaviour (Figure 3).

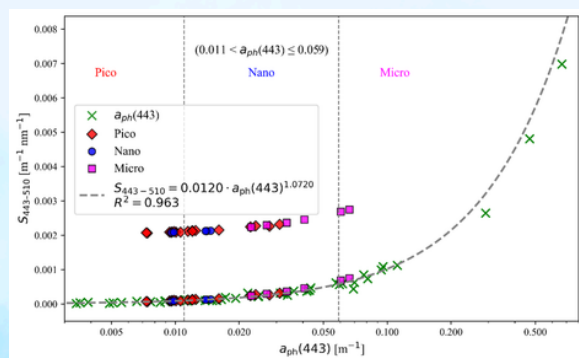


Figure-2: Relationship between $a_{ph}(443)$ and spectral slope ($S_{443-510}$) showing separation of pico-, nano-, and micro-phytoplankton communities

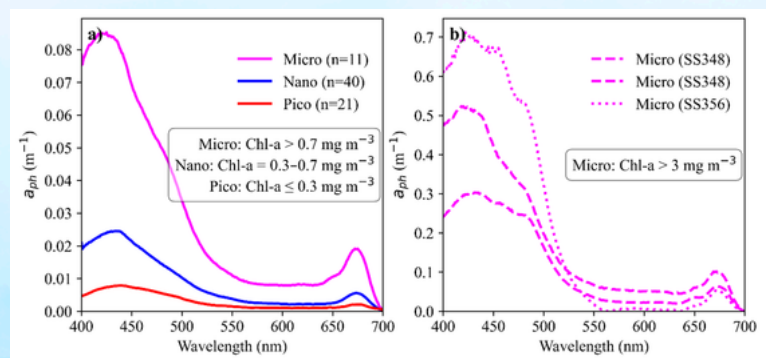


Figure-3: Mean phytoplankton absorption spectra representing pico-, nano-, and micro-phytoplankton optical signatures

The study also examined the fractional contribution of pico-, nano-, and micro-phytoplankton communities along the phytoplankton absorption gradient and identified a clear ecological transition across productivity regimes. Pico-phytoplankton dominated low-absorption offshore waters, whereas micro-phytoplankton increasingly dominated under high-biomass bloom conditions. Nano-phytoplankton contributions peaked under moderate absorption conditions, representing transitional ecological states between oligotrophic and bloom environments. To evaluate the robustness of the framework, the regional absorption-based model was compared with previously published global phytoplankton size class models based on both absorption and chlorophyll relationships. The Arabian Sea model demonstrated improved agreement with in situ observations and lower uncertainty relative to global formulations when applied to the regional dataset. Existing global models often overestimated or underestimated phytoplankton groups because they were developed using datasets from oceanic regions with different ecological and optical characteristics. In contrast, the regionally tuned framework developed in this study more accurately represented the optical behaviour of Arabian Sea phytoplankton communities and significantly improved the representation of transitional nano-phytoplankton assemblages that are generally difficult to resolve using chlorophyll-based approaches alone. These findings highlight that phytoplankton absorption properties provide a stronger and more direct link to phytoplankton community structure than bulk chlorophyll concentrations and therefore offer a more reliable basis for studying ecosystem variability in optically complex marine environments.

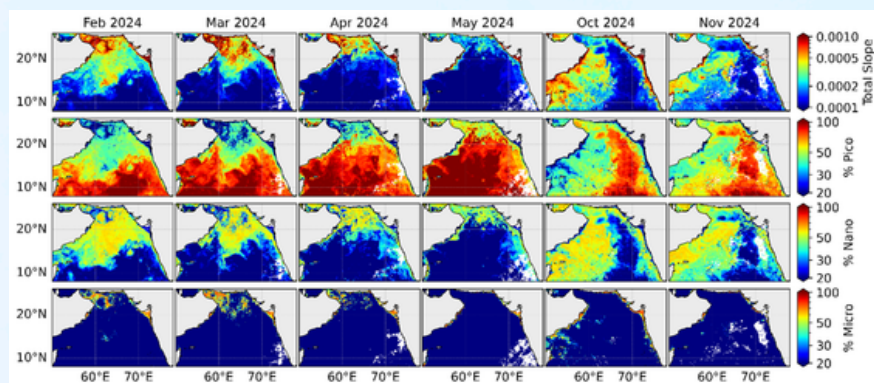


Figure-4: Satellite-derived seasonal maps of pico-, nano-, and micro-phytoplankton distributions across the Arabian Sea

The empirical relationships derived from the in situ observations were subsequently applied to satellite-derived VIIRS phytoplankton absorption products to generate synoptic-scale maps of phytoplankton community structure across the Arabian Sea during 2024 (Figure.4). The satellite-derived monthly composites revealed pronounced spatial and seasonal variability in phytoplankton distributions throughout the basin. Offshore waters of the central Arabian Sea were consistently dominated by pico-phytoplankton communities under oligotrophic conditions, whereas enhanced contributions from micro-phytoplankton communities were observed in the northern Arabian Sea during productive winter and pre-monsoon bloom periods. Nano-phytoplankton communities were commonly detected along coastal and peripheral regions influenced by moderate nutrient inputs and mixing processes. Seasonal variability associated with the monsoon cycle produced strong changes in phytoplankton community structure across the study region. Winter mixing and nutrient enrichment supported larger micro-phytoplankton communities in productive northern waters, while stratified offshore regions favoured pico-phytoplankton groups adapted to nutrient-poor environments. Satellite-derived distributions further highlighted regional contrasts between the northern Arabian Sea, the western Arabian Sea near the Somali coast, and the oligotrophic offshore basin. Validation against co-located HPLC pigment observations demonstrated good agreement between satellite-derived phytoplankton classifications and in situ measurements, confirming the applicability of the developed framework for large-scale monitoring of phytoplankton variability in the Arabian Sea. The study further demonstrates the importance of combining in situ bio-optical observations, pigment analysis, and satellite remote sensing to improve understanding of ecosystem variability and climate-driven changes in marine productivity across the northern Indian Ocean. The

ability to retrieve pico-, nano-, and micro-phytoplankton distributions using regionally tuned optical relationships provides significant advantages for long-term ecosystem monitoring, ocean-colour applications, and marine biogeochemical studies in rapidly changing environments such as the Arabian Sea.

Conclusion

This study demonstrates that phytoplankton absorption properties provide a robust and regionally optimized framework for distinguishing pico-, nano-, and micro-phytoplankton communities in the Arabian Sea. The strong relationship between $a_{ph}(443)$ and spectral slope enabled effective characterization of phytoplankton community structure across contrasting ecological regimes. Validation using HPLC pigment observations and satellite-derived VIIRS products confirmed the applicability of the framework for monitoring large-scale spatial and seasonal variability in phytoplankton distributions. The integration of in situ bio-optical observations, pigment analysis, and satellite remote sensing offers an effective approach for ecosystem monitoring and understanding climate-driven changes in marine productivity and biogeochemical processes in the northern Indian Ocean.

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Using AI to Study Fish Colour Patterns in the Indian Ocean — A Student's Research Perspective

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Background

Working on a marine-related research project a while back was what first made me take the Indian Ocean seriously — not as something you pass on the way somewhere, but as an active, deeply complex system that we still know surprisingly little about. One thing that kept coming up during that work was fish — specifically, how little standardised, large-scale data exists on Indian Ocean fish species, and how much of what we do know was collected through surveys that are expensive, slow, and hard to repeat consistently.

Fish colouration has always been used as a primary identification feature. Colour patterns, spot arrangements, stripe geometry, and iridescence are all genuinely diagnostic — they vary between species, between sexes, between populations in different geographic zones, and sometimes in response to environmental stress. Marine

biologists have known this for a long time. The difficulty is that manually documenting colour across thousands of specimens, from photographs taken under varying underwater conditions by different equipment, is not something that scales well. This is where the research idea began.

The project currently being developed by the author explores whether machine learning — specifically convolutional neural network (CNN) based image classification — can be used to analyse fish colour patterns systematically, with the Indian Ocean as the primary focus region. This article describes the motivation, the approach, the limitations that are honestly quite significant at this stage, and why the work feels worth pursuing regardless.

What the Research is Trying to Do

The core idea is fairly straightforward. CNNs are a class of deep learning model that have become the standard tool for image-based classification across many fields — from medical imaging to satellite land cover analysis. They work by learning hierarchical visual features from labelled training data: in this case, photographs of fish labelled by species. A well-trained model can then take a new, unlabelled image and predict the species based on what it has learned about colour and pattern.

What makes this different from a simple colour-matching exercise is that CNNs pick up on spatial relationships within the image — not just that a fish is blue, but where the blue sits relative to other features, how it transitions at the edges, what texture sits underneath it. These are the kinds of subtle differences that a trained taxonomist notices but that are very hard to encode explicitly into a rule-based system. Deep learning handles them implicitly through the training process.

The proposed pipeline has three stages. First, fish images from Indian Ocean sources are collected, preprocessed to correct for underwater colour distortion, and labelled. Second, a CNN model is trained on this dataset to classify species from image data alone. Third — and this is the part the author finds most interesting — the model outputs a detailed colour descriptor for each image, which is essentially a quantitative fingerprint of that individual's surface pigmentation. These descriptors can then be compared across specimens, populations, and locations to ask questions about colour variation that would be impractical to answer through manual analysis.

Why This Matters for the Indian Ocean

The Indian Ocean is not the most studied ocean basin. Relative to the Pacific and Atlantic, it has received less long-term systematic research attention, and the biodiversity data that does exist is unevenly distributed — concentrated around a few well-studied reef systems and coastal zones, with large gaps in the deep water and open ocean regions. At the same time, it is surrounded by countries where fisheries are central to food security and livelihoods, and where the effects of climate change on marine ecosystems are being felt sharply.

A tool that can work with existing photographic data — images already sitting in institutional databases, published papers, and citizen science archives — without requiring new field surveys for every question you want to answer, has real practical value in this context. One of the underappreciated things about the Indian Ocean right now is that there is actually quite a lot of imagery available, generated by research cruises, reef monitoring programmes, and recreational diving communities. The bottleneck is not the images themselves but the capacity to analyse them at scale.

Citizen science is worth taking seriously here. Platforms that aggregate diver-submitted photographs of marine life have built up substantial libraries of Indian Ocean species imagery. Reef fish communities around the Lakshadweep archipelago, the Andaman and Nicobar Islands, and the Maldivian atolls are photographed regularly by divers whose primary motivation is not scientific documentation but who nevertheless produce taxonomically valuable material. If standardised image submission protocols can be introduced and linked to a classification system, this represents a genuinely large and geographically distributed data source that institutional research alone could not easily replicate.

A Related Application: Natural Pigment Identification

A secondary direction that came out of reading around fish pigmentation biology is the potential connection to natural dye research. Fish produce a range of structurally complex pigments — carotenoids, melanins, porphyrins — some of which have properties that are of commercial and pharmaceutical interest. There is an active research area around finding marine-sourced natural pigments as alternatives to synthetic dyes, which carry significant environmental costs in both production and end-of-life disposal.

The relevance to the colour classification work is that a model characterising surface spectral properties in detail is, indirectly, generating information about likely pigment composition. Species whose colour descriptors indicate high concentrations of specific pigment classes could be identified as candidates for targeted biochemical extraction studies — making what is currently a largely intuition-driven search process more systematic. This is a longer-term application rather than the immediate focus of the work, but it is one the author intends to develop as the core framework matures.

Challenges and Current Limitations

The main problem right now is data, and it would be misleading to describe the project as being in a comfortable position with respect to that. Building a training dataset of adequately labelled, high-quality underwater photographs covering a representative range of Indian Ocean fish species is genuinely difficult. Some species have many well-documented images; others barely have any. Deep-water species, which may be among the most scientifically interesting, are the least photographed.

Image quality is a separate but connected challenge. Underwater photography is not like surface photography — colour information degrades with depth in predictable but location-specific ways, and images taken in the clearer waters of the open Arabian Sea look very different from those taken in the more turbid nearshore zones of the Bay of Bengal. Preprocessing approaches that correct for these differences exist, but they need to be adapted and tested specifically for Indian Ocean conditions rather than simply borrowed from work done in other marine contexts.

There is also an important question about how this kind of tool gets used responsibly. If the pigment identification application is developed further, the risk of creating new extraction pressure on already-stressed fish populations is real and has to be taken seriously. Any deployment of AI-generated biodiversity data in contexts where it could inform harvesting or commercial exploitation needs conservation safeguards built in from the start, not added as an afterthought.

Looking Ahead

The immediate priorities for this work are dataset assembly, architecture selection, and establishing image preprocessing protocols suited to Indian Ocean conditions. Collaboration with institutions that hold existing survey imagery — and that might be willing to share it under appropriate data agreements — would make a substantial difference to how quickly the training dataset can be built to a useful size.

Further ahead, the most interesting direction would be integrating colour descriptor outputs with concurrent oceanographic data. If species colour variation can be correlated with sea surface temperature anomalies, depth profiles, or chlorophyll concentration — all of which are increasingly available through remote sensing platforms and Argo float networks operating in the Indian Ocean — the framework starts to become a tool not just for identification but for environmental monitoring. That is a more ambitious goal than the current stage of the work warrants, but it is what motivates the foundational steps being taken now.

The Indian Ocean has a lot still to give up in terms of biological knowledge. This research is a small attempt to develop tools that can help with that, starting from where a student can reasonably start — with existing images, open-source model architectures, and the conviction that the question is worth asking.



Observational Infrastructure and Regional Collaboration

Deployment of a first Directional Wave Rider Buoy (DWR4) in the Port Area of Port Louis, Mauritius

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Mauritius has an Exclusive Economic Zone of approximately 2.2 million square kilometres and with such a vast maritime area, the ocean plays a fundamental role in the economic, environmental and social development of the island. As a Small Island Developing State (SIDS), Mauritius depends heavily on the ocean mainly for maritime trade, fisheries, tourism and emerging blue economy activities. Furthermore, Mauritius island is subject to global phenomena such as climate change, rising sea levels, extreme ocean events and coastal erosion which highlight the urgent need for improved ocean observation systems and real-time ocean monitoring capabilities.

As global climate conditions continue to evolve, there is an increasing need to adapt coastal and ocean management policies accordingly; therefore, monitoring wave parameters is essential for providing the scientific information required to support informed and climate-resilient decision-making. In this context, Mauritius achieved an important milestone through the successful deployment of a first Directional Wave Rider (DWR4) buoy near the entrance of the Port Area in Port Louis.

The deployment of the WAMAN (WAVE Monitoring Along Near-shore) DWR4 buoy was carried out through a collaborative partnership between the Prime Minister's Office (PMO) of Mauritius, through the Department for Continental Shelf, Maritime Zones Administration and Exploration (CSMZAE), partnered with the High Commission of India (Mauritius) and the Indian National Centre for Ocean Information Services (INCOIS), India. This initiative forms part of broader efforts to improve maritime safety, and manage marine resources in Mauritius.

Importance of Wave Monitoring in Mauritius

The island of Mauritius is strategically located in the southwest Indian Ocean which is often influenced by dynamic oceanographic and meteorological conditions. The coastal zones are often exposed to a range of climatic events such as cyclones, storm surges, heavy swells and strong currents that can significantly impact fisheries, coastal infrastructure, navigation safety and recreational activities among others.

The Port Area serves as a critical gateway for maritime traffic and economic activity. Safe vessel navigation and efficient port operations depend largely on accurate and timely information relating to sea state conditions which include wave height, wave direction and surface current. Furthermore, monitoring of sea surface temperature data provides valuable insight on potential coral bleaching events, as prolonged periods of elevated sea surface temperature are among the primary drivers for coral stress and bleaching.

The deployment of a Directional Wave Rider 4 buoy marks a major achievement for Mauritius to monitor ocean conditions continuously and in near real-time. The data generated from the buoy is supporting institutions,

researchers and maritime stakeholders in Mauritius to better understand the ocean and respond effectively to any hazardous ocean event.

The Directional Wave Rider 4 (DWR4)

The Directional Wave Rider 4 (DWR4) integrates the following measurements:

- wave height;
- surface current;
- wave direction;
- water temperature.

Deployment

The DWR4 buoy was successfully deployed on 25 June 2025 near the entrance of Port Louis harbour at Latitude 20° 08' 33.54" S and Longitude 57° 28' 55.63" E, and anchored at a depth of approximately 17 metres. INCOIS nominated two scientists to facilitate and support deployment operation in Mauritius. The deployment operation was conducted jointly by officers of CSMZAE and the two scientists from INCOIS, with the support from the National Coast Guard and the Ministry of Agro-Industry, Food Security, Blue Economy and Fisheries (Blue Economy and Fisheries Division) of Mauritius (Table-1).

Attribute	Description
Platform ID	MRU_PL01
Platform type	Moored directional wave buoy
Platform model	Datawell Directional Wave Rider DWR4
Deployment Site	Port Louis (Mauritius)
Coordinates (WGS84)	Latitude: 20° 08' 33.54" S, Longitude: 57° 28' 55.63" E
Depth	Approx 17m
Deployment Date	25/6/2025
Contact	Department for Continental Shelf, Maritime Zones Administration & Exploration (CSMZAE)
Email	mzadministration@govmu.org
Purpose	Continuous monitoring of wave conditions for navigation safety, operational forecasting, and coastal resilience applications

Table-1: Deployment information for the Directional Wave Rider (DWR4) buoy

Data Dissemination

The CSMZAE is planning to provide access to real-time data and other relevant statistics from the DWR4 buoy using the Mauritius Ocean Observatory E-platform (E-platform, Deployment)

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The E-platform has been established by CSMZAE to centralize data pertaining to the maritime zones of the Republic of Mauritius. The E-platform supports data discovery, access and sharing among researchers, institutions and users involved in ocean management, policy and planning.

The integration of wave buoy data will complement the core aim of the E-platform by providing users with access to the in-situ ocean observations. A dedicated dashboard is currently being developed which will allow users to visualize, download, and explore historical records of wave parameters, and use this data to support research and informed ocean management and planning.

A user manual is also being drafted to guide users in accessing, visualizing, and downloading data from the DWR4 buoy on the E-Platform.



Capacity Building, Science-to-Policy, and Early Career Networks

Biodiversity Beyond National Jurisdiction (BBNJ): Opportunities and challenges for India

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Abstract

The Agreement under the United Nations Convention on the Law of the Sea on the Conservation and Sustainable Use of Marine Biological Diversity of Areas Beyond National Jurisdiction (BBNJ Agreement, 2023), commonly known as the High Seas Treaty, represents a historic milestone in global ocean governance. The agreement establishes an international framework for the conservation and sustainable use of marine biodiversity in areas beyond national jurisdiction (ABNJ). For India, a major maritime nation with expanding interests in ocean science, marine biotechnology, and the blue economy, the BBNJ Agreement presents both opportunities and governance challenges. The treaty is structured around four pillars: marine genetic resources and benefit sharing, area-based management tools, environmental impact assessments, and capacity building and technology transfer. This article evaluates the implications of the BBNJ Agreement for India, focusing on opportunities for scientific advancement, marine biotechnology development, and leadership in international ocean governance. It also examines institutional, legal, and strategic challenges associated with implementing the agreement. Strategic policy recommendations are proposed to enable India to effectively engage with the emerging BBNJ governance regime while safeguarding national interests and contributing to global marine biodiversity conservation.

Introduction

Covering approximately 71% of the Earth's surface, the global ocean constitutes the planet's largest biosphere and plays a fundamental role in regulating climate, sustaining biodiversity, and supporting human societies. Ocean systems regulate global biogeochemical cycles, influence atmospheric processes, and sustain food security and livelihoods for billions of people worldwide.

Historically, coastal seas and continental shelf regions have been governed by national jurisdictions. In contrast, vast portions of the ocean remain beyond national jurisdiction. These regions, known as Areas Beyond National Jurisdiction (ABNJ), comprise roughly two-thirds of the ocean surface or 95% of the ocean volume and include both the high seas water column and the seabed beyond national continental shelves (1). ABNJ contain highly diverse ecosystems such as seamounts, hydrothermal vents, and deep-sea plains that harbour unique biological communities and largely unexplored genetic diversity.

ABNJ harbors extraordinary biodiversity composed of an estimated 2.2 million marine species and a trillion microorganisms (2). They are promising sources of novel pharmaceuticals, industrial enzymes, nutraceuticals, and biomaterials. Advances in deep-sea exploration technologies have increased access to these environments, intensifying scientific and commercial interest in marine genetic resources. This drives the requirement for international governance frameworks over the ABNJ.

Despite their ecological and economic significance, governance of ABNJ has historically been fragmented. Existing legal instruments under the United Nations Convention on the Law of the Sea (UNCLOS) regulate specific activities such as shipping, fisheries, and seabed mining, but they do not comprehensively address biodiversity conservation in international waters. After nearly two decades of negotiations, the international community adopted the Agreement under the United Nations Convention on the Law of the Sea on the Conservation and Sustainable Use of Marine Biological Diversity of Areas Beyond National Jurisdiction in 2023 (3). Commonly referred to as the BBNJ Agreement or High Seas Treaty, the instrument establishes mechanisms to strengthen international cooperation for conserving and sustainably using biodiversity in ABNJ. The agreement complements

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existing UNCLOS frameworks and contributes to implementation of the United Nations Sustainable Development Goals (SDGs), particularly SDG 14 (Life Below Water), SDG 13 (Climate Action), and SDG 17 (Partnerships for the Goals). Healthy ocean ecosystems regulate climate through carbon sequestration, heat absorption, and oxygen production, making marine conservation essential for climate stability.

India, with a coastline exceeding 7,500 kilometres and a maritime jurisdiction covering approximately 2.02 million km², has substantial interests in ocean governance. India's Exclusive Economic Zone (EEZ) extends 200 nautical miles from its coastline and includes waters surrounding the Andaman and Nicobar Islands and Lakshadweep archipelago. India also holds exploration rights over approximately 75,000 km² in the Central Indian Ocean Basin through contracts with the International Seabed Authority. India's expanding blue economy initiatives, marine research programs, and deep-ocean exploration missions align closely with the objectives of the BBNJ Agreement. Its deep ocean fishing fleets operate in high seas adjacent to the EEZ and research vessels conduct expeditions in the international waters (4). However, effective participation in the treaty regime will require institutional coordination, legal reforms, technological investments, and active engagement in international governance mechanisms.

The BBNJ Agreement rests on four pillars namely, Marine Genetic Resources (MGRs) and benefit sharing, Area Based Management Tools (ABMTs), Environment Impact Assessment (EIA), and Capacity Building and Technology Transfer (CBTT).

MGRs and benefit sharing

Marine genetic resources (MGRs) refer to genetic material derived from marine organisms that contains functional units of heredity with actual or potential value. These resources include genetic material from marine microorganisms, invertebrates, and other organisms inhabiting deep-sea ecosystems (3,5).

The BBNJ Agreement establishes an international framework for accessing and utilizing MGRs in ABNJ while promoting equitable benefit sharing among nations. Under the agreement, no state may claim sovereignty over marine genetic resources found in ABNJ. Activities related to these resources are expected to benefit humankind as a whole, with particular consideration for developing countries. However, it does not formally designate MGRs as common heritage (6).

Benefit sharing under the treaty includes both monetary and non-monetary mechanisms. Monetary benefits may arise from commercial utilization of marine genetic resources while non-monetary benefits include access to biological samples and scientific data including genetic sequence data, participation in research activities, technology transfer, and training opportunities.

Monetary mechanisms are implemented in a phased manner. In phase I, the developed member states should make annual voluntary contributions to a special fund as they have dominated deep-sea bioprospecting and marine biotechnology development historically. Phase II mandates that the Conference of Parties (COP) shall decide on modalities for monetary benefit-sharing from MGR utilization. This approach balances the voluntary contributions advocated by the developed nations and monetary benefit-sharing of commercial biotechnologies developed by developing nations advocated by developing states (7,8). To ensure compliance towards benefit-sharing obligations, the agreement includes provisions for sharing digital sequence information (DSI) of the MGRs (9,10). The clearing-house mechanism can track the DSI of MGR samples throughout the value chain from collection to potential commercialization.

Provisions of non-monetary benefits aim to democratize access to marine biodiversity research and reduce technological disparities between developed and developing nations. Developing nations often lacked access to research vessels, advanced laboratories, and bioinformatics infrastructure required to participate in these activities. The BBNJ framework attempts to promote equitable access to marine scientific research opportunities. It includes access to MGR samples, participation in scientific activities, access to scientific results and data, strengthening research capabilities of developing states, technology transfer on fair and most favorable terms, and capacity building.

For India, access to marine genetic resources presents opportunities to expand marine biotechnology industries. As a nation with significant scientific capacity, India can leverage its national institutions and universities to support the burgeoning marine biotechnology sector to provide exclusive marine science programs. India can also launch its own research programs to harvest the potential of MGRs. Participation in the BBNJ framework can substantially enhance India's research capabilities through capacity building and collaborative research, technology transfer, and unrestricted access to MGR samples from ABNJ. India's pharmaceutical and biotechnology sectors may benefit from marine-derived compounds with applications in medicine, industrial biotechnology, and environmental technologies. Participation in international research collaborations may strengthen India's scientific capabilities in genomics, bioinformatics, and marine natural product discovery. The Agreement's benefit-sharing framework ensures that even where initial discovery occurs elsewhere. However, ensuring transparency in the collection and utilization of marine genetic resources remains a challenge. India may face difficulties in monitoring resource access and ensuring equitable sharing of benefits derived from commercial applications. The standardized batch identifier system provides a tracking mechanism, but its effectiveness relies on universal adoption and honest reporting.

Area-Based Management Tools (ABMTs)

The BBNJ Agreement focuses on conservation of bioresources in the ABNJ using ABMTs. These tools include spatial management measures such as marine protected areas (MPAs) designed to conserve biodiversity and regulate human activities in ecologically significant marine regions (11). Implementation and enforcement of ABMT measures primarily fall under the responsibility of flag states, although international cooperation is expected to support monitoring and compliance mechanisms.

The agreement establishes procedures for proposing, evaluating, and designating ABMTs in areas beyond national jurisdiction. Proposals for MPAs undergo scientific and technical review followed by consideration by the Conference of Parties (COPs). Criteria for evaluation include ecological significance, biodiversity richness, ecosystem vulnerability, and ecological connectivity.

The BBNJ Agreement legitimizes to facilitate India's expanding presence in ABNJ. Increasing maritime activity, resource exploration, and geopolitical competition in the region highlight the importance of cooperative ocean governance frameworks. Active participation in BBNJ governance institutions by participation in the COP, subsidiary bodies, and regional consultations would enhance India's profile in global ocean governance.

As MPAs are established in the Indian Ocean and other regions, opportunities emerge for sustainable ocean tourism, marine wildlife observation, and scientific tourism. India's existing coastal and island tourism infrastructure could expand to serve this niche market, generating revenue while promoting ocean conservation awareness (12).

Environmental Impact Assessments

BBNJ Agreement mandates prior Environmental Impact Assessment (EIA) for any planned activities in ABNJ that may cause significant pollution or harmful changes to marine ecosystems. The EIA framework requires assessment reports be made publicly available through a Clearing-House Mechanism, ensuring transparency and facilitating international review and informed decision-making. It is mandatory to consider ecosystem resilience, and cumulative environmental impacts. Strategic environmental assessments may be conducted to evaluate broader regional environmental trends.

For India, implementing EIA requirements for activities conducted by national entities in ABNJ will require enhanced technical expertise in environmental monitoring, oceanographic modelling, and ecosystem assessment.

Capacity Building and Technology Transfer (CBTT)

The Agreement requires substantial enhancement in the technical capacities of the developing states especially

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in marine science and research capabilities, data management and application, development and implementation of ABMTs, conduct of EIAs, and monitoring, control, and surveillance of activities in ABNJ.

India's existing marine research infrastructure, including initiatives such as the Deep Ocean Mission, provides a strong foundation for participation in these initiatives. However, its institutional architecture and legal framework are fragmented and designed primarily for domestic implementation. BBNJ obligations require a centralized ocean governance authority capable of coordinating across ocean science, foreign affairs, environmental protection, fisheries, shipping, and defense. India may also need to adapt existing legal frameworks to regulate activities of Indian entities operating in ABNJ and ensure compliance with benefit-sharing obligations. Its existing Biological Diversity Act, 2002 should be extended to resources accessed from ABNJ too.

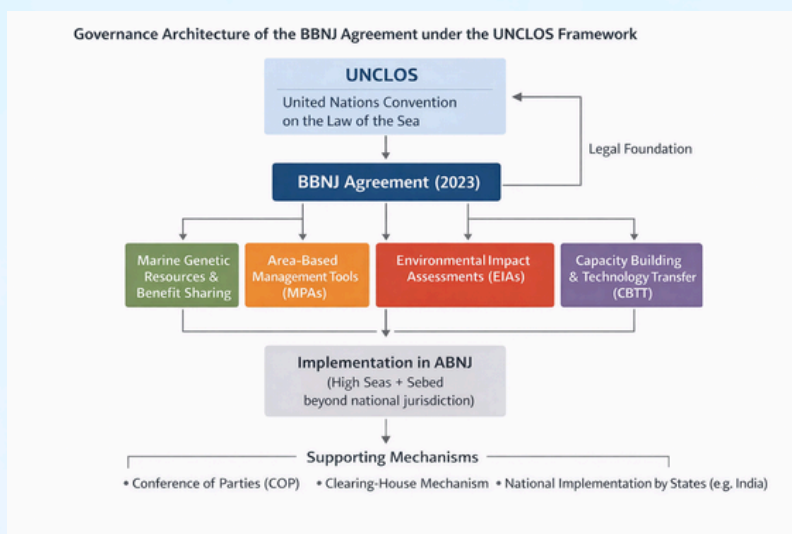


Figure-1: Governance architecture of the BBNJ Agreement under the UNCLOS framework showing the four operational pillars and their implementation in areas beyond national jurisdiction (ABNJ).

Challenges of India

As a developing nation with a growing population and expanding economy, India faces the fundamental challenge of balancing ocean conservation imperatives with its development needs. It must ensure that ABMTs and EIA procedures do not become barriers to reasonable resource utilization as the BBNJ Agreement focuses more on conservation. This requires active participation in developing implementation guidelines, ensuring that conservation measures are science-based, proportionate, and considerate of its needs. The transition to sustainable ocean practices requires extra investments particularly for supporting the affected communities and industries. Fishing communities dependent on high seas fisheries may face restrictions as MPAs are established. Seabed mining operations must meet stringent environmental standards, potentially increasing costs and timelines. This transformation may strain financial resources..

As a developing state party with significant capacity, India must contribute substantially to the Agreement's financial mechanism as significant investments in research infrastructure, monitoring systems, data management platforms, and human resource development. It may require additional resources for ABNJ-specific research, monitoring of foreign activities in the Indian Ocean region, participation in international scientific collaborations, and development of ABMT proposals for ecologically significant areas adjacent to India's EEZ.

Participation in the Clearing-House Mechanism requires technical capacity for data submission, retrieval, and utilization. For EIA procedures for Indian entities operating in ABNJ India needs technical expertise in environmental assessment methodologies, baseline data collection, and impact prediction. India's existing Deep Ocean Mission needs to be restructured to accommodate non-domestic priorities to meet BBNJ obligations.

Recommendations for India

Considering the provisions, India should move strategically to take full advantages of the BBNJ Agreement. The following recommendations are made to safe guard India's interests in the ABNJ in the Indian Ocean.

1. Ratification: Under the Vienna Convention on the Law of Treaties (13), signature in an agreement indicates a nation's consent to negotiate and support for the treaty's objectives. It has to be ratified for binding obligations. India has signed the high seas treaty and has appointed a 12-member committee to review its implications, identifying necessary legislative amendments, proposing new statutory frameworks, and recommending institutional arrangements for implementation. For India, ratification should be preceded by enactment of core implementing legislation addressing jurisdictional provisions for Indian entities operating in ABNJ, benefit-sharing obligations and mechanisms, EIA procedures for activities in international waters, compliance and enforcement provisions, institutional responsibilities and coordination mechanisms, and financial arrangements for contributions to BBNJ mechanisms. It is recommended that India expedite and move decisively towards ratification while ensuring thorough domestic preparation. Any delays might risk excluding India from early COP sessions where foundational decisions on implementation guidelines, benefit-sharing modalities, and institutional arrangements are made. Early ratification would enable India to participate as a full party with voting rights.

2. Establishment of a National Ocean Governance Authority: India should establish a centralized National Authority with coordinating responsibility across all ocean-related matters. This authority, possibly reporting directly to the Prime Minister's Office, would integrate currently fragmented functions to provide strategic direction for Blue Economy development, coordinate BBNJ implementation across ministries, represent India in international ocean governance forums, and manage the national Clearing-House Mechanism node.

3. Enhancement of Deep-Sea Research and Monitoring Capabilities: India should invest more in deep-sea research beyond the scope of current Deep Ocean Mission. It is recommended to expedite the development and deployment of MATSYA-6000 (4); expand autonomous underwater vehicle fleets for surveillance and research; develop advanced sensors and monitoring systems for ABNJ; establish long-term observational networks in strategically significant areas; and build capacity for collection, characterization, and storage of MGR.

These capabilities enable India to contribute meaningfully to global ocean knowledge and claim legitimate stake in MGR benefits. It provides strategic advantages to India in critical marine areas positioning it as a leader in marine technology capable of generating export revenue and attracting international research collaborations.

4. Developing Strategic Regional Leadership in the Indian Ocean: The Indian Ocean witnesses complex geopolitical dynamics with increasing presence of extra-regional powers and dual-use technologies or activities with potential military applications around EEZs. To safeguard its strategic interests, India should engage with other Indian Ocean rim states, to ensure that regional perspectives are reflected in BBNJ implementation decisions made through voting. India may conduct regional capacity-building programs for neighboring countries, and offer its research infrastructure for regional scientific collaborations. It may also propose ABMTs for ecologically significant areas in the Indian Ocean high seas, and promote the Indian Ocean Rim Association (IORA) as a coordination platform for BBNJ matters.

5. Prioritisation of Marine Biotechnology Development: To take full advantage of the treaty, India should establish a dedicated a National Marine Biotechnology Mission focusing on MGR research and commercialization including development of a national MGR repository. India's scientific capacity, pharmaceutical industry strength, and biodiversity richness position it favorably to become a significant player in marine biotechnology. Early investment in this sector can yield substantial economic returns while contributing to global health and sustainability objectives.

6. Active engagement in BBNJ Institutional Development: India should actively participate in all BBNJ institutions and mechanisms including the Scientific and Technical Body, Access and Benefit-Sharing Committee,

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and other subsidiary bodies and working groups. Active engagement enables India to shape implementation details, protect national interests, build international credibility, access capacity-building resources, and ensure that developing nations' perspectives are reflected in decisions. Passive participation or delayed engagement would cede influence to early movers and potentially result in frameworks less favorable to India's interests.

7. Addressing Stakeholder Concerns: successful implementation of BBNJ Agreement requires addressing concerns of diverse domestic stakeholders including, fishing communities, scientific community, industry people, and civil society organizations. Alternative livelihood should be ensured for fishers losing livelihoods due to fishing restrictions under potential ABMTs. India should develop programs where restrictions are necessary, and advocate for exemptions for small-scale and subsistence fishing where appropriate. Researchers should be made aware of access procedures, and obligations. Mining, shipping, and biotechnology companies must be provided with predictable regulatory frameworks. India should establish mechanisms for civil society input for BBNJ implementation, support transparency through public access to EIA documents and decision-making processes and recognize civil society contributions to ocean conservation.

Stance of major maritime nations

For India, the BBNJ Agreement provides both challenges and opportunities. While cooperation is the slogan, India should watch for the stance of other major maritime nations to safeguard its interests in the ABNJ regions. China expressed its strategic maritime ambitions and commitment to demonstrating leadership in global environmental governance by signing and ratifying the BBNJ Agreement in December 2025. It became the first permanent UN Security Council member to participate in the Agreement. China's extensive deep-sea research capabilities, substantial fishing fleet operating in international waters, and ambitious Belt and Road maritime investments all are expected to be benefitted from active participation in BBNJ institutions. Being an advanced maritime nation, the US generally supported the BBNJ negotiations. However, it hasn't signed the Agreement. Its concerns could be potential conflicts with its existing fisheries and shipping regulations, implications for military operations in international waters, obligations about benefit-sharing for already developed MGRs, and domestic political opposition to new international treaties requiring Senate ratification. Collective approach of the European Union include substantial financial contributions to BBNJ implementation, leadership in proposing ABMTs, and commitment to transparent benefit-sharing from MGR commercialization (14). Small Island Developing States (SIDS) like Palau, Fiji, and the Maldives, have been among the most ardent supporters of the BBNJ Agreement, recognizing that healthy high seas directly affect the marine resources within their EEZs. Many SIDS ratified quickly, seeing the Agreement essential for protecting their marine heritage and ensuring equitable benefit-sharing.

Conclusion

The BBNJ Agreement ultimately reflects humanity's growing recognition that the high seas, long treated as a limitless common, require active stewardship for present and future generations. For India, with its ancient maritime heritage, growing Blue Economy, and emerging great-power status, leadership in this stewardship represents not only a strategic imperative but also a moral responsibility. As a major maritime nation with significant interests in ABNJ, the Agreement presents both opportunities and challenges to India.

The opportunities include India's enhanced access to marine genetic resources in the ABNJ, which can accelerate the development of its marine biotechnology sector. Participation in ABMT strengthens India's strategic presence in critical ocean areas. The provisions for capacity-building and technology transfer in the Agreement complement India's existing infrastructures and policies. Engagement with BBNJ institutions enhances India's profile in global ocean governance and enables protection of national interests. The challenges are equally significant. Legislative and institutional gaps must be addressed through comprehensive reforms. Enforcement and compliance in vast, remote ocean areas require enhanced capabilities. Geopolitical complexities demand strategic diplomacy and coalition-building. Balancing conservation and consumption of resources for developm-

ent needs careful evaluation of competing priorities. The path forward demands expedited yet thorough preparation, establishment of centralized ocean governance authority, enhanced deep-sea capabilities, regional leadership, marine biotechnology prioritization, and active participation in BBNJ institutions. Early and effective engagement can position India as a leader in implementing this landmark treaty, advancing both national interests and global ocean conservation objectives. Delayed or passive participation risks ceding influence to early movers and missing opportunities to shape the future of ocean governance.

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Contribution of Monaco Explorations to IIOE-2 Objectives in the Indian Ocean

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As part of Monaco Explorations' contribution to the objectives of the Second International Indian Ocean Expedition (IIOE-2) and to the advancement of scientific knowledge and ocean governance in the Indian Ocean, several major initiatives were implemented following the Monaco Explorations Indian Ocean Expedition 2022.

One of the main achievements was the publication of a special issue in the international scientific journal Deep Sea Research Part II. During its 12th meeting held on 22 March 2023, the Expedition Advisory Committee agreed to prepare a special issue bringing together the scientific outputs of the expedition and enhancing the visibility and coherence of the various research projects conducted during the expedition. A publication group composed of Committee members and project leaders was established to identify the most appropriate journal based on accessibility, readership, impact factor, and publication costs.

Following this process, Deep Sea Research Part II was selected. The special issue, entitled Deep Sea Research Part II: Tropical Studies in Oceanography, Volume 224, December 2025, 105551, includes eight scientific articles together with an editorial paper highlighting scientific cooperation and knowledge development in the Mascarene Basin and Plateau in support of ocean governance.

The published papers address a broad range of priority topics for the Western Indian Ocean, including benthic biodiversity on the Saya de Malha Bank, phytoplankton biomass distribution, coral thermal stress responses, deployment strategies for biogeochemical floats, plastic pollution and its interactions with corals, genetic origins of juvenile green turtles, and the establishment of a global coral biobank. One article was also dedicated to awareness-raising, communication strategies, and public outreach activities developed during the expedition.

The special issue was fully published in February 2026. All papers are freely accessible for one year on the dedicated journal webpage: Deep Sea Research Part II – Special Issue. Printed copies of the special issue will also be produced for communication and dissemination purposes.

In addition to these scientific publications, a Science to Policy Workshop (S2PW) was jointly organised by Monaco Explorations, the Government of Mauritius, and the Government of Seychelles. The workshop took place in Port-Louis, Mauritius, from 12 to 14 November 2025.

The objectives of the workshop were to:

- inform stakeholders of the latest scientific findings from the expedition;
- analyse the implications for regional management and governance;
- propose concrete recommendations for policy and action relevant to Mauritius, Seychelles, and regional ocean governance stakeholders;
- foster regional and international collaboration for ocean stewardship.

The S2PW gathered around 50 participants, including representatives from the Governments of Mauritius and Seychelles, scientific project leaders, representatives of regional and international organisations such as WIOMSA, Nairobi Convention, SIOFA, IOTC, IUCN, and IORA, as well as members of the MEIO Expedition Advisory Committee, invited experts, and Monaco Explorations staff members.

The workshop agenda included presentations on major global ocean governance issues, including the UNCLOS BBNJ Agreement, as well as scientific presentations on the expedition results. Brainstorming, discussion, drafting, and reporting sessions enabled participants to develop a set of recommendations aimed at strengthening the integration of scientific knowledge into policy processes, enhancing regional collaboration, and identifying potential financing mechanisms for conservation and sustainable development.



The participants of the Science to Policy Workshop.

Through these scientific and policy-oriented initiatives, Monaco Explorations contributed to strengthening scientific knowledge of the Western Indian Ocean, promoting science-based decision-making, and fostering regional cooperation for sustainable ocean governance.



Early Career Ocean Professionals (ECOP) India Node activities and updates

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So, what exactly is ECOP India? Ever heard of it?

Nearly five years ago in the year 2021, a framework for global collaboration in Ocean Science was put forth. It was named the United Nations Decade of Ocean Science for Sustainable Development (2021-2030), in short, the UN Decade. The UN general assembly tasked the Intergovernmental Oceanographic Commission (IOC) of UNESCO, to coordinate the preparations for the framework and its implementation since it is the only UN body responsible for supporting global ocean science and services. IOC with its entire gamut of senior and experienced scientists began their endeavours of coordinating with regional and international organizations, policymakers, non-profit agencies, community leaders and all kinds of stakeholders.

During the first global planning meeting it was recognized that the early career representation at the global platform is significantly limited and therefore to remedy the situation the Early career ocean professionals (ECOP) working group was conceived which later turned into a full fledged global programme of the UN Decade. An ECOP was defined as anyone who self-identifies as being early in their career, within 10 years or less of professional experience in any field related to the ocean. The aim for the ECOP programme was to increase ECOP representation at planning meetings, identify the various needs and perspectives of ECOPs through global surveys and connective networks and finally integrate their insights in planning phases. Through the global programme many regional and national nodes of the ECOP programme started to be established. This way the regions could be easily connected to the global programme and function in coordination, while being autonomous themselves. It took quite a lot of time before the India node could be established.

The ECOP Programme in India gained popularity among young ocean researchers as early as 2021, largely through their exposure to talks delivered by UNESCO officials at international conferences. In 2021, a small group

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of researchers got together from a number of oceanographic institutes across India and produced a short video on the occasion of World Ocean Day on how their research contributes to the seven Outcomes of the UN Ocean Decade. That's how the ECOP Programme gained momentum in India. The national ECOP India node was formalized in November 2024. Between 2021 and 2024, a few important national events were organized under the global banner of ECOP and under the leadership of Dr. Trishneeta Bhattacharya and Dr. Sunanda Narayanan (at that time still in their Ph.D. and now postdoctoral research fellows), who later on became the coordinators for the ECOP India node.

Currently, the ECOP India node has nearly 650 registered members from all over the country. After the establishment of the node, we organized the first ECOP India workshop in Hyderabad, India on 5-6th June 2025, in association with the Decade collaborative centre for the Indian Ocean region (DCC-IOR), bringing together researchers, ocean literacy advocates, community leaders and other stakeholders. We regularly organize national workshops, surveys, competitions and ocean literacy seminars. There are very few early career networks in India and also globally. Therefore we often partner with other such networks in India; like the Early Career Scientists Network (ECSN) to organize webinars by young researchers on topics of recent academic interests. To register for these webinar series please fill out the form at Register here:

<https://docs.google.com/forms/d/15Sw3F7jmo4y1Pj1vZWmYALhTL-D-p6kSLJW7B1Q4OOY/>

We also recently launched our latest Ocean decade activity C-TIDE (Cultivating Tomorrow's Innovators Decade) India. This activity contributes to building an inclusive and engaging platform for ECOPs across the country. A key initiative under this program is Chai & Curiosity, a YouTube-based podcast series that features Indian early career researchers sharing their academic journeys, along with insights into scholarships, funding opportunities, and career pathways at both national and international levels.

The youtube channel can be found here: <https://www.youtube.com/@BrewingCuriosity-s5f>

The platform also actively engages with audiences by inviting questions related to academic growth, mental well-being, career development, and opportunities in ocean sustainability. These questions are addressed in episodes through discussions with experienced researchers and senior scientists. In addition, the initiative develops accessible animation content to promote ocean science awareness. Interested individuals can submit their questions at india@ecopdecade.org, and are encouraged to stay connected for upcoming content and opportunities. We have launched a coordination campaign in all oceanographic institutes across India to reach out to students interested in oceanography and its allied field where an interested candidate may act as a nodal coordination officer between that institute and ECOP India. Through this campaign we could form links between established researchers and the students in their post-graduation who might want to take up ocean research as a career. This way the young researchers who are moving closer to seniority could easily pass on their knowledge and expertise to the younger upcoming students interested in research and keep the network going. People wanting to connect or contribute to our initiatives can also send in their suggestions and queries to the same email address. Our social media platforms are fairly easy to access. A quick and easy ECOP India search would take you to our pages on Facebook, Instagram, X, and LinkedIn. Our official webpage can be found here: <https://www.ecopdecade.org/india/>. To join ECOP India and remain updated about all the latest events organized by us, please register here:

https://ba32fe97.sibforms.com/serve/MUIEAMBGzBvcjQyY4b9dDF1F34DL0aKC4b6Qj6edwGA54uiJA2_zqAljCqRg482nN9GXmftbef4uwE6cKFfVjMrnb73iPyqzff_XrqY1N9lhj0y_fwzVDMFxBsBi_gafHiBNbLzTOwaFELKgwv3oDA2E1VKL2dvCoyx-JLvUvnbDBPeaXkWU2DdeleoYjto4wpTAhpK08ON3M17z

We are constantly looking for ways to grow and connect. We are also looking for interns who could help us in our activities. The position is remote and unfortunately currently unpaid. If we find funds we would surely open up many more lucrative opportunities. In the meantime, if you think you can contribute your time and expertise to ECOP India activities in any way, please do not hesitate to reach out to us!



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