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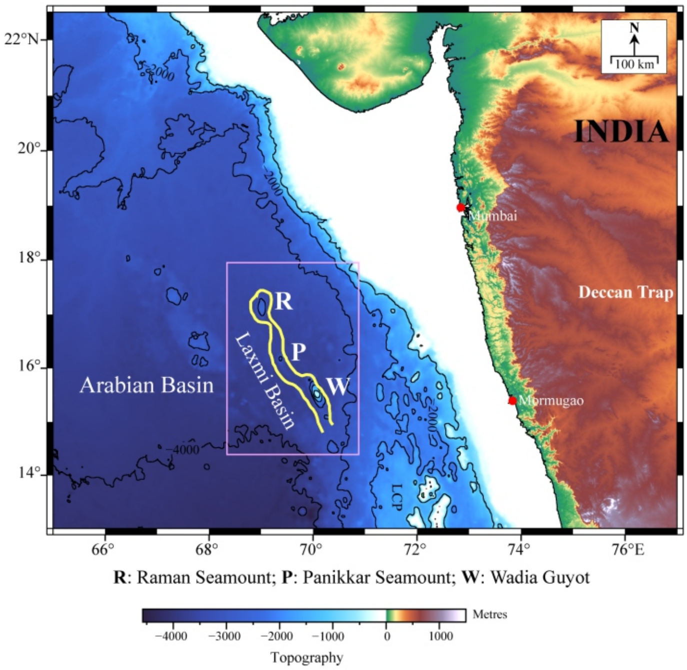

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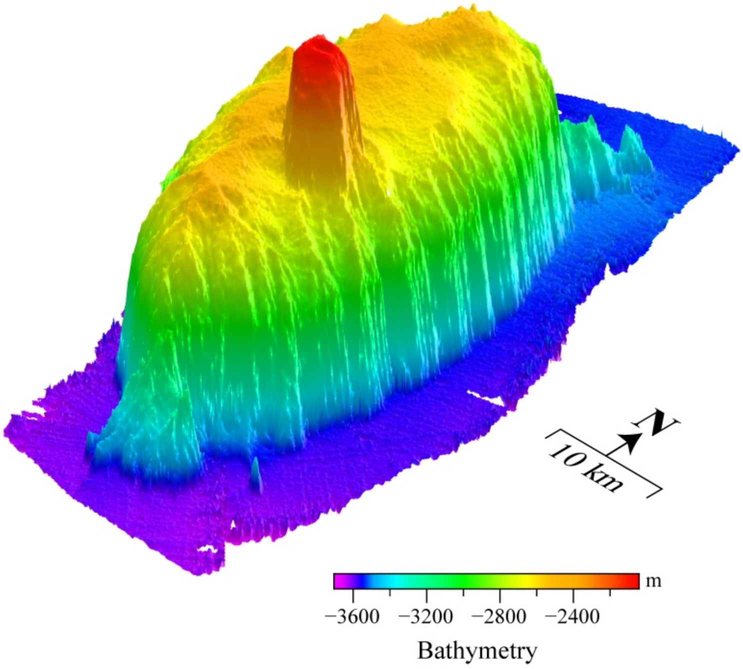

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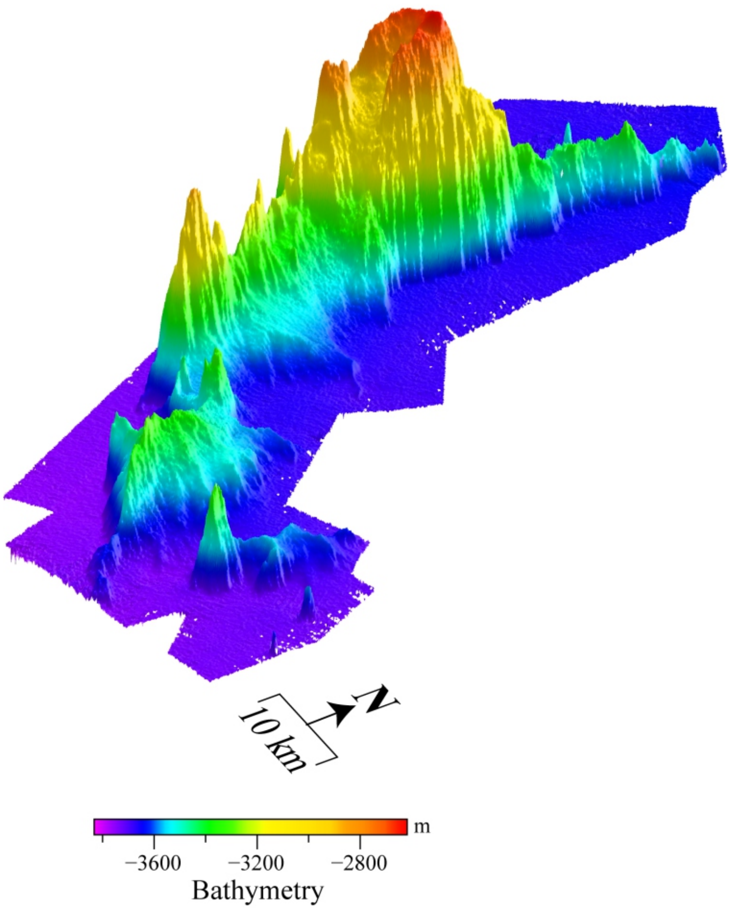

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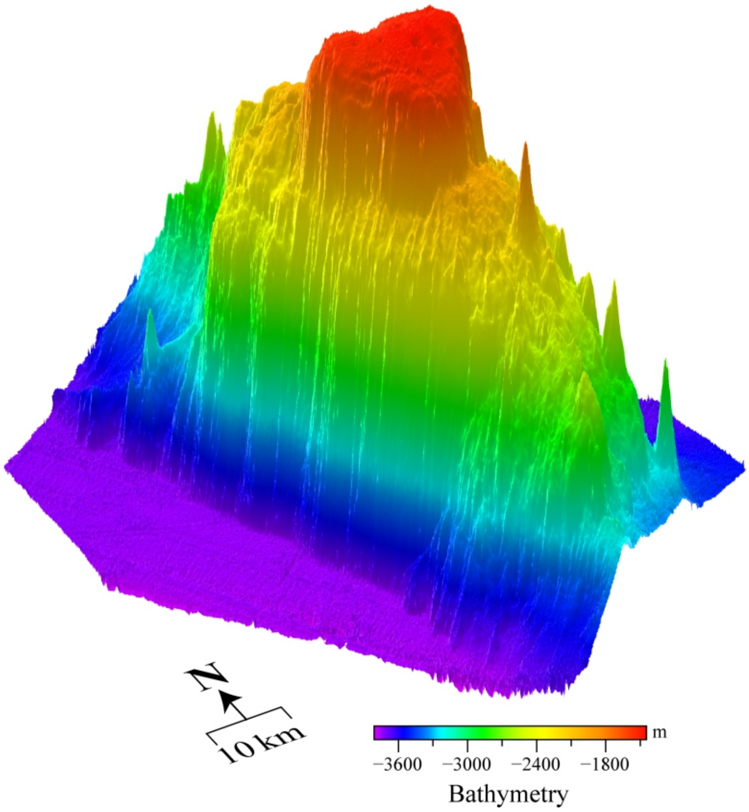

Rapid warming of the Arabian Sea in recent years



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Abstract

The Arabian Sea (AS) has emerged as a significant warming hotspot over recent decades and is projected to experience strong warming in the upcoming decades. Since 2000, the northern AS has experienced intensified warming, with the rate of warming has doubled compared to the period 1976-1999. The highest warming is observed during the summer monsoon season in the post-2000 years (2000-2023) at a rate of 0.025°C per year. Maximum warming has occurred below the climatological thermocline to depths of up to 200 m in the southern basin, whereas in the northern AS, core warming is located at depths of 100-200 m. Surface winds have sharply declined in the northeastern AS, and the presence of easterly wind anomalies in the northern AS has weakened the summer monsoon winds and cyclonic circulation in the central basin. This, in turn, has strengthened the northeastward wind-driven Ekman transport towards the northeastern AS. Surface heat fluxes also have contributed enhanced heat accumulation over the northeastern AS. Reduced evaporative cooling and the weakening of upper ocean vertical mixing due to declining winds have contributed to the faster warming of northern AS in recent years. Therefore, local air-sea interaction processes play a crucial role in the non-homogeneous regional warming, which has adverse impacts on the marine ecosystem and significant socioeconomic consequences far beyond the Indian Ocean realm.

Keywords: Arabian Sea, Indian Ocean, summer monsoon, thermocline, Ekman transport

1. Introduction

The global annual mean sea surface temperature (SST) and upper ocean heat content in 2023 were the highest ever recorded by modern instruments (Cheng et al., 2024). The Indian Ocean (IO) showed continued heat uptake especially the western half leading to the rapid warming and accelerated sea level rise in the AS (Albert et al. 2023). The ocean warming and associated monsoon variability makes Indian subcontinent more prone to the impacts of climate change disasters such as extreme precipitation, landslides, floods, heat waves, etc.. The warming of the AS is also blamed for promoting the formation of deep cloud systems, which leads to intense rainfall along the west coast of India over shorter durations and increases the likelihood of landslides. Ocean warming elevates atmospheric temperatures and increases atmospheric humidity due to higher evaporation from the Earth's surface, particularly the ocean. These reactions occur simultaneously worldwide, leading to heavy rainfall and saturating soils and bedrock with water. This series of natural responses can trigger landslides and debris flows in various forms, not only on land but also in oceanic areas and large lake regions (Kitazato 2024).

Kumar et al. (2009) demonstrated that the AS has undergone a regional climate shift since 1996, accompanied by a five-fold increase in the occurrence of intense cyclonic storms. Recently, Albert et al. (2023) attributed the rapid warming of the Arabian Sea post-2000 to increased heat content associated with decreasing trends in outward longwave radiation (OLR). This study examines the warming of the AS and possible mechanisms over the 24 years post-2000, compared with the trends during the 24 years pre-2000 (1976-1999).SST trends are estimated using the extended reconstructed SST version 5 (ERSSTv5; Smith et al., 2008) for the period 1976-2023. ERSST includes observations from the International Comprehensive Ocean-Atmosphere Data Set release 3.0 and near-surface Argo buoy data. Upper ocean temperature and thermocline depth information are obtained from the European Centre for Medium-Range Weather Forecasts (ECMWF) ocean reanalysis system 5 (ORAS5) datasets. Surface winds, air-sea heat fluxes, and cloud cover datasets are extracted from the ECMWF Reanalysis version 5 (ERA5) monthly reanalysis product (Hersbach et al., 2020). Trend values are computed using the Theil-Sen trend estimator method, and statistical significance is determined using the Mann-Kendall test.

2. Results

The western half of the IO, particularly the AS, has experienced dramatic warming of both surface and subsurface waters in recent years (Albert et al., 2023; Kumar et al., 2009). The rapid warming of the AS during post-2000 has been particularly notable in the northeastern region, which has warmed at a rate of 0.03°C/yr higher than during the pre-2000 years (Fig. 1a & b). Both the summer and winter monsoon

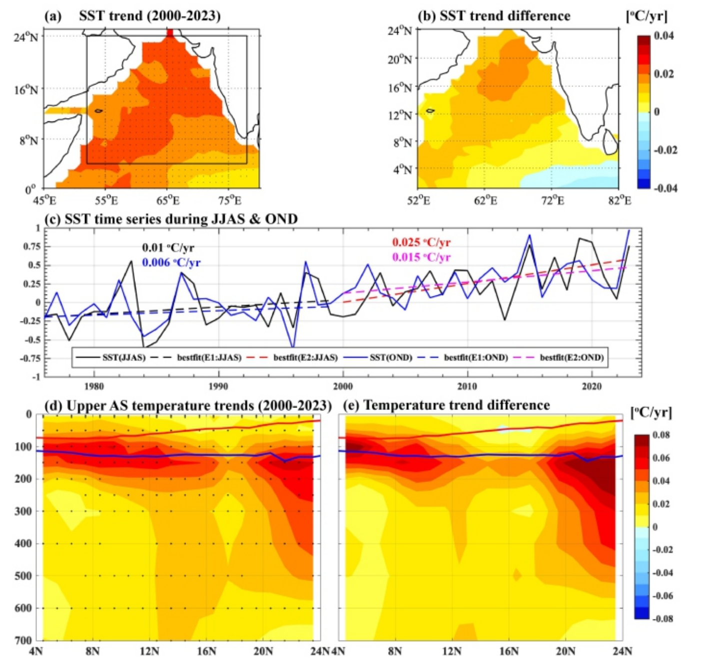

Fig. 1. (a) SST trends over the AS during 2000-2023, (b) trend difference between post-2000 (1976-1999) years and pre-2000 years (2000-2023). (c) Time series of SST averaged over the AS (region highlighted in Fig. 1a) during JJAS and OND, (d) depth-latitude sections of temperature trends and (e) trend difference between post-2000 and pre-2000 obtained from the region highlighted in Fig. 1a. Red and blue lines indicate the depth of 26o isotherm and 20o isotherm as first and second climatological thermocline depth respectively in Fig. 1d and 1e. Statistical significance of trend values in Fig. 1a and 1d are highlighted by black dots.

seasons show warming of the AS, with the most rapid warming occurring during the JJAS (June to September) period in both pre-2000 and post-2000 years. SST warming in post-2000 years has been twice as fast as in pre-2000 years for both seasons. Regions north of 15°Nhave experienced intensified warming post-2000 compared to the southern AS, with warming extending to depths of 500 meters along the meridional section between 18°N and 24°N. In contrast, post-2000 warming of subsurface layers up to 200 meters has been observed over the AS south of 16°N. Significant warming of subsurface layers near the climatological thermocline may suppress the cooling of surface through vertical processes (Fig. 1d & e).

Surface winds have shown a sharp declining trend, with the most significant changes observed in the northern and eastern AS during the post-2000 period. This decrease in wind field has a significant impact on warming through reduced evaporation, shoaling of the mixed layer, reduced vertical mixing due to suppressed upwelling, and decreased heat divergence. Notably, the summer monsoon winds have sharply decreased north of 16°N due to the predominance of northeasterlies, while showing an increasing trend over the central AS (Fig. 2a & b). Easterly winds along the eastern AS during the summer monsoon are associated with a weakened Walker circulation and a westward shift of convection in the IO(Sharma et al. 2022). In contrast, the northeast monsoon winds have shown a decreasing trend in the central and southern Arabian Sea. Due to the presence of intensified easterlies, the northwestern and eastern AS regions have shown strengthening winds during the post-2000 period (Fig. 2c & d). A weak cyclonic circulation formed in the AS is associated with the predominance of northeasterlies and southwesterlies in the southern AS. This contributes to Ekman convergence northeastward in the AS north of 12°N and southwestward south of this latitude (Fig. 2e & f).

A key characteristic of IO warming is the persistent increase in temperature trends over the decades unlike to the

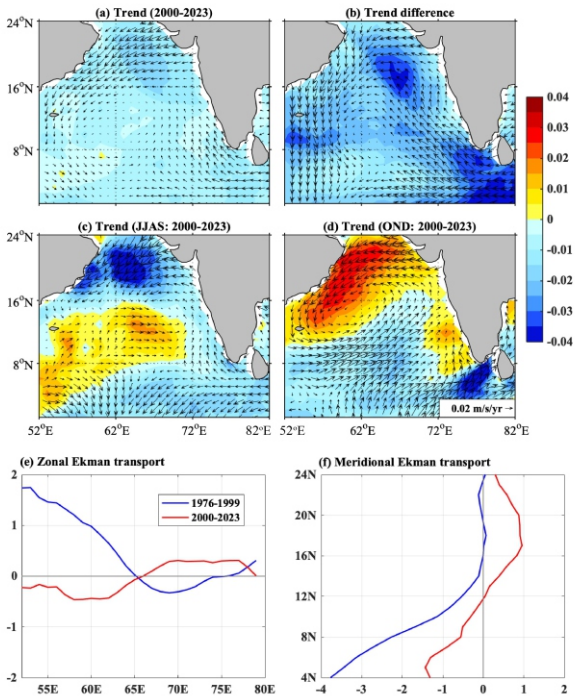

Fig. 2. Surface wind speed trends (m/s/yr) during (a) post-2000, (b) difference between wind speed trends between post-2000 and pre-2000 years, (c) JJAS, (d) OND wind speed trends during post-2000 years. (e) Meridionally integrated zonal Ekman transport, and (f) Zonally integrated meridional Ekman transport trends (10-3 Sv/yr) during pre-2000 and post-2000 years.

tropical ocean basins. The robust oceanic warming pattern and consequent extreme regional precipitation eventsarise due to the slower rate of heat release from the ocean compared to the rapid heat accumulation (Oh et al. 2024). The Greenhouse gas forcing warms the atmosphere, which then influences the ocean through changes in surface fluxes. This heat is transferred from the mixed layer, causing the deeper ocean to warm. The net heat gain predominantly contributes to the warming of deep ocean and increase in ocean heat content. Fig.3 shows increasing trend of surface net heat gain which is controlled by the LHF trend to the larger extent. The reduction in net shortwave into the ocean associated with increase in cloud cover over northern AS is balanced by decreasing trend of longwave radiation out of the ocean. Reduction of evaporative heat loss has contributed to the basin wide increase in total net heat gain by the AS. The declining trend of LHF even with the continuous warming of AS and which has contributed to the depletion of regional moisture supply towards central Indian landmass (Bajrang et al. 2023). The reduction in evaporation in the AS is possibly due to rise of atmospheric moisture content in response to the surface warming. Hence, weakening of winds and surface heat fluxes contributed to the intensified warming pattern during the post-2000 years compared to pre-2000 years.

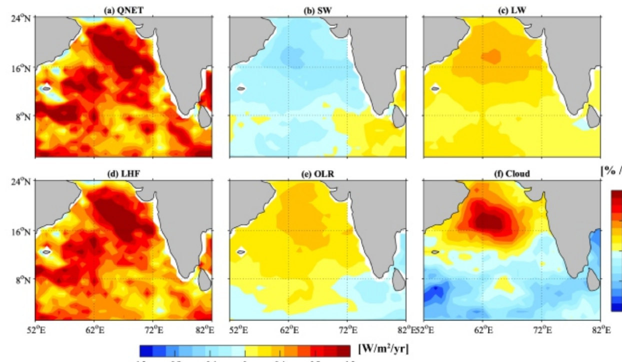

Fig. 3. Fluxes trend differences between 2000-2023 and 1976-1999. Sign convention is positive when ocean gains heat.

3. Conclusions

The northern AS has warmed at the rate of 0.025°C/yr during 2000-2023 and which is 0.015°C/yr higher than the warming rate during 1976-1999. Warming has been penetrated to the deeper layers in the AS north of 16°N and strong warming of post-2000 is occurred in the subsurface layers between 100-200 m depth in the southern AS. Both the summer and winter monsoon seasons experience two-fold increase in SST trends during the post-2000 years and former characterise sharp increase of 0.025°C/yr. In line with the warming, basin wide reduction in wind speed is observed with maximum reduction over eastern AS due to the easterlies and which contributed to weak cyclonic circulation in the central AS. This anomalous wind field has contributed to the intensified Ekman convergence towards northeastward in the northern basin which has contributed to the heat accumulation there during post-2000. Due the increased cloudiness, shortwave radiation into the ocean has reduced over northern AS and which is offset by suppressed OLR and evaporative cooling leading to heat gain over northern basin during the post-2000 years. The latent heat flux has shown basin wide declining trend with maximum amplitude located towards the northeastern AS and leading to highest surface net heat accumulation over there. The reduction of latent heat loss can be attributed to declined wind speed over AS. Present study suggest that local air-sea interaction processes over the AS has contributed to the intensified warming during post-2000 compared to pre-2000 years.

Acknowledgements

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Marine Renewables – Our Research Experiences

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Assessment of marine energy potential along India's vast coastline is crucial for evaluating the feasibility, scale, and economic viability of renewable energy projects. These assessments provide detailed insights into key areas with high energy potential, seasonal variations, and to propose any systems that can optimize energy extraction while serving other purposes, such as coastal protection. As for as tidal energy concerned, regions such as the Gulf of Kutch, Gulf of Khambhat, and the Andaman Islands have been focal points due to their substantial tidal ranges and strong currents. As part of the research efforts, we have estimated the spatial and temporal variations of the tidal energy power potential along these regions, using region-specific numerical models, as the tidal hydrodynamics of these individual regions are unique. The in-house developed numerical models were validated with available in-situ measured tidal levels and currents. Mimicking spatially varying tidal-amplifications in Khambhat and Kutch region in the numerical model is challenging and successfully estimated the tidal energy potential through systematic calibrations. Our model results show that maximum power densities of about 600W/m² and 4500W/m², for Kutch and Khambhat regions respectively. The Andaman Islands, which heavily rely on diesel generators for power, face high costs and environmental challenges in transporting fuel from the mainland. Keeping this our mind, we assessed the tidal current potential around the Andaman Islands, using numerical model. The tidal current based power densities estimated to exceed 1.5 kW/m², which can potentially be harvested using existing tidal turbines proven to perform in low cut-in speeds; such as AR1500, Sabella D10, and Tocardo T2, in any pilot projects.

We have successfully mapped the wave energy potential along our country's Exclusive Economic Zone (EEZ), including the Lakshadweep and Andaman & Nicobar Islands, using ERA-Interim reanalysis datasets. Along the west coast, average wave power ranges from 10–15 kW/m. Southern regions, including the Andaman and Nicobar Islands, exhibit even higher wave power potential, emphasizing their suitability for wave energy projects. In another independent research study, we captured the seasonal variations of the wave energy potential, along East coast of India. As it is realised that the wave energies are maximum predominantly during monsoon season, we suggest to adopt dual-purpose systems; combining coastal protection with energy extraction technologies to maximize efficiency and sustainability.Our past research studies reveal the promising potential of marine renewable energies along Indian coastline that may lead to development of efficient and sustainable energy projects, contributing significantly to India's renewable energy goals.

On the other hand, using the existing physical model facilities at IIT Bombay, we have successfully carried out research studies, primarily focusing on wave energy conversion concepts. Unlike the northern latitudes, India's coastline is not naturally gifted with high wave energy potentials, hence, the economic viability of wave energy converters (WEC) can only be enhanced by integrating them with coastal protection. Such dual-purpose infrastructure shall not compromise any performance characteristics, urging a thorough research investigation before implementation. Through a comprehensive experimental research study, we assessed wave energy trapped within a vertical porous chambered breakwater, thus leading to a quasi-resonance condition (CBW) and using heaving WEC models. The study involves estimation of hydrodynamic performance of the breakwater as well as the WEC. Our study has revealed that the optimal chamber width, matches the resonant period of the incident wave, significantly improves the energy absorption efficiency. Also, incorporating the WEC reduces the reflection characteristics of the breakwater. We tested different types of floating WEC models, such as sphere, plate and cylindrical shapes, integrated with CBW to assess and compare its efficiencies. Our study reveals that there is a significant increase in efficiencies of WEC when placed inside the chamber of CBW, as compared to their stand-alone models and maximum of about 60% is observed.

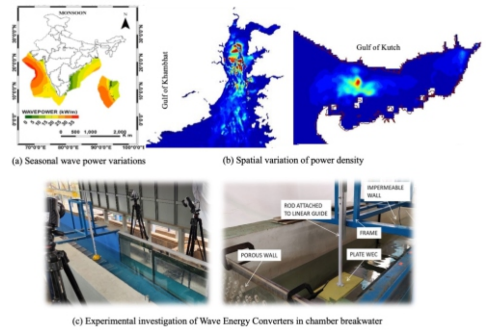

Fig. 1. Glimpses of our marine renewable research results

We are currently working on how to improve the efficiency of power extraction by adopting optimal power take off systems. Thus, integrating the wave energy converter with the chambered breakwater system has several shared benefits and improves economic benefits by reducing construction and maintenance costs. The proposed systems have broad applications in harnessing ocean renewable energy and developing coastal protective structures. It can serve as a multipurpose structure, primarily aimed at protecting the coast against erosion while capturing wave energy seasonally. These systems are ideal for areas of medium wave energy potential and the development of green ports.

This article is based on the following papers:

Aiswaria, K, Balaji, R. & Sarkar, D. (2023). Integration of wave energy devices with chambered breakwater, Journal of Ocean Technology, vol. 18 no. 1 (energy from the ocean), 84-100.
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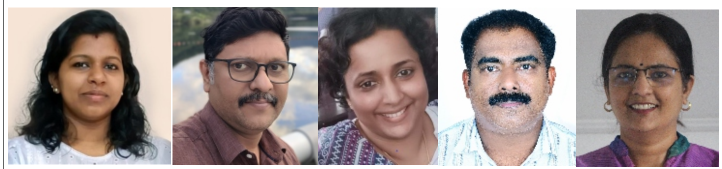
Research Highlights

Potentials of environmental DNA metabarcoding to unveil the biodiversity of deep-sea ecosystems



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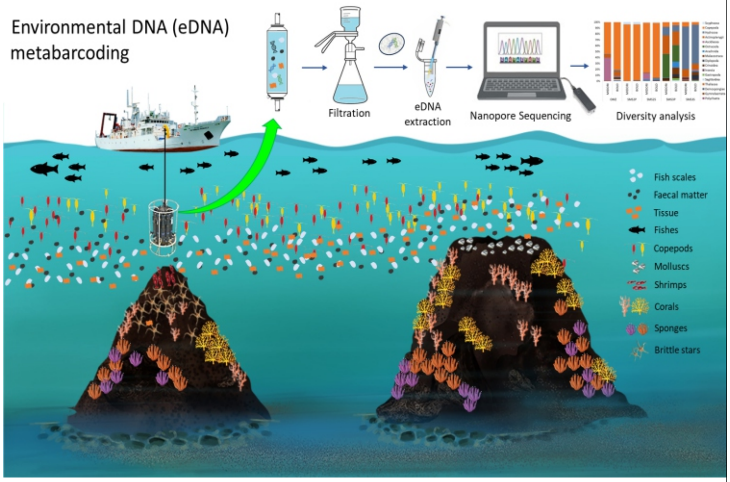
This article is based on the following papers:

Devika Raj K., Anas Abdulaziz, Jasmin C., Jaleel K.A. & Menon. N. (2024). Unveiling the Faunal Diversity in the Water Column Adjacent to Two Seamounts in the Deep Arabian Sea Using Environmental DNA Metabarcoding, Journal of Marine Science and Engineering, 12(6), 971.
Devika Raj K., Jasmin C., Jaleel K.A. & Anas Abdulaziz. (2023). Diversity assessment of deep-sea organisms from Seamounts of Arabian Sea using environmental DNA metabarcoding. Conference proceedings, 8th National Conference of Ocean Society of India (OSICON-23) (Abstract ID: ABS-07-0364). This paper bagged the 'Best Oral Presentation Award' in OSICON-23 under the sub-theme 'Biodiversity and Ecology'

The deep-sea environment covers about two-thirds of the Earth's surface and contains various specialized ecosystems, including seamounts. However, the diversity of organisms living in these ecosystems is not well-documented. One of the main challenges in studying the diversity of deep-sea ecosystems is the need for intact samples and specialists to identify each group of organisms. The environmental DNA (eDNA) metabarcoding approach can help address this challenge. It enables the identification of entire groups of organisms present in the ecosystem using a small quantity of DNA extracted from water samples. This method offers high sensitivity, eliminates the need to sacrifice animal life for documentation, reduces reliance on specialized taxonomic experts, and can be automated, making it a valuable tool for ecological research. The identification sensitivity greatly depends on the availability of reference sequences in publicly available databases such as NCBI-GenBank and BOLD Systems.

In 2022, we conducted a study using environmental DNA(eDNA) to investigate the diversity of animals in the water column surrounding the summits of two seamounts off the coast of Mangalore in the Southeast Arabian Sea (Devika et al., 2024). The cytochrome oxidase I (COI) gene from the eDNA was amplified and sequenced using Oxford Nanopore Technologies. The seamounts, SMS2 and SMS3 (Bijesh et al., 2018), emerged from a depth of approximately 1400 meters and were found to be intersected by the oxygen minimum zone (OMZ) at depths of 340 and 440 meters, respectively. The analysis of diversity indices (Shannon entropy and Chao index) of eDNA sequences revealed a higher richness and evenness of biodiversity in the water column adjacent to the summit and periphery of SMS2 compared to SMS3. The COI gene sequences were analyzed and organized into molecular operational taxonomic units (MOTUs), resulting in the identification of nine phyla: Crustacea, Chordata, Cnidaria, Mollusca, Chaetognatha, Echinodermata, Porifera, and Annelida. Crustacea was the dominant phylum, with copepods being the most abundant class in the water column around SMS2, while phylum Cnidaria and phylum Chordata were dominant in SMS3. A considerable number of MOTUs did not show similarity with known COI gene sequences, indicating that most of the organisms in this region are unknown to us. This might be due to the lack of molecular phylogeny data for deep-sea taxa in databases, making it difficult to match the queried sequence data. The COI gene sequence dataset has an advantage over conventional morphology-based ones, and it will prove more useful as these databases strengthen. Additionally, biodiversity comparisons based on MOTUs and taxonomic assignments, even with a few sequences, are useful in identifying spatial differences in biodiversity between seamounts.

Overall, the manuscript emphasizes the significance of eDNA metabarcoding techniques in understanding the diversity of organisms in deep-sea ecosystems. While the value of eDNA-based tools in biodiversity monitoring is well recognized, their application in documenting deep-sea organisms is not widely utilized, primarily due to the lack of reference sequences for comparison in global databases. As a result, a combination of traditional and molecular taxonomy of marine organisms is necessary to enhance the use of eDNA in diversity studies, which could simplify surveillance efforts in the future.



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A brief report of the beach cleaning programme of Ocean Society of India conducted on 8 June 2024 - World Oceans Day 2024

Ocean Society of India, with funding from Ministry of Earth Sciences, celebrated the World Oceans Day 2024 by conducting beaching cleaning programmes and awareness programme. Beaches of all maritime states of India and Diu, the Union Territory were concentrated in the programme on 8 June 2024. A total of 23 beaches, namely, Chopati-Veraval, Dumas (Gujarat); Gomtimatha (Diu) Murud, Bhatye, Vengurla (Maharashtra); Caranzalem (Goa); Aligadda, Tonka (Karnataka); Ponnani, Puthuveypu, Thrikkunnapuha, Sanghumughom (Kerala); Pudumadom, Broken Bridge – Thiruvanmiyur, Kovalam (Tamil Nadu); Chinna veerapattinam (Puducherry); NTR beach, RK beach (Andhra Pradesh); Paradeep, Chandipur (Odisha); Boguran Jalpai and Talsari (West Bengal) were selected. Accordingly, 23 co-ordinators from 23 premier institutions in the country voluntarily came forward in the massive programme. The efforts done by all these institutions are praiseworthy. The data collected are abridged below-

On this day 31.39 km length of beach were cleaned. The width of beaches ranged from 100 m to 250 m. A total of 2287 participants (in the age group 8-75 yrs.) voluntarily involved in the programme. Total waste collected was to the tune of 8166 kg within a short period of 1 to 1.5 hours. Some beaches took more hours for participants to completely clean the beaches. The wastes were segregated into plastic, Glass, Foam plastics, metal, paper, clothes, wood particles, rubber and miscellaneous (including microplastics). This was based on protocol designed for the purpose. Waste belonging to wood particles, paper and clothes were accounted as biodegradable.

The salient observations include the following-

- Almost all beaches are highly polluted
- Higher rate of waste accumulation was reported from Kovalam and Ponnani Beaches and lower rate from R K Beach and Dumas beach
- Based on the waste accumulation level the vulnerable beaches are : Chopati – Veraval, Aligadda, Ponnani and Puthuveypu beaches.
- Chandipur beach is peculiar where even building materials are discarded. It is a serious fact.
- Higher level of plastic waste was recorded in almost all beaches constituting more than 50% from beaches – Aligadda, Bhatye, Dumas, Tonka, Kovalam, Paradeep, Thrikkunnapuzha, Boguran Jalpai and Talsari.
- Glass waste has been reported from all beaches indicating glass bottles discarded after liquor consumption in beaches (possible in tourism spots)
- Rubber waste (mostly chappals) has been reported from Aligadda, Ponnani, Puthuveypu, NTR, RK beaches in large quantity
- Plastic waste from fishing sector has been reported in almost all stations.
- Plastic waste generated from food related sources was on a higher level in Dumas, Murud, Bhatye (maximum), Vengurla, Sanghumughom, NTR, Paradeep and Chandipur
- Biodegradable waste on higher scale was reported from Kovalam, Carenzalem beaches
- Amazingly high level of waste plastic bottles was observed in NTR, Paradeep, Chandipur beaches.

From the data collected during the current endeavour and from similar efforts, the following recommendations are proposed.

- Initiate reusing of plastic products that we purchase.
- Recycling of waste plastic is another method of reducing pollution
- Switching to biodegradable packaging and helping in ways to reduce plastic pollution.
- Single use of plastic may be abandoned and its place use environment friendly products
- Use cloth bags, metal containers instead of plastic bags and containers
- Organize river, estuaries and ocean clean ups regularly. There are machines which are employed to clean water and oceans.
- Every activity in rivers, estuaries and beaches should be regulated with practical policies with the main objective of controlling pollution.
- Upcycling of old items to make them more appealing or useful.
- Place permanent bins for collecting plastic in places where crowds assemble and periodic removal
- Encourage plastic substitutes
- Make use of waste plastics for value added products such as fuel production and so on
- Develop a route map for plastics from production to recycle
- Varkala Beach of Kerala and R K Beach of Andhra Pradesh are following periodic beach cleaning. At R K Beach, introduced machines to clean beach every week is an adoptable mechanism.
- If the local self-governments with the special funding support from Governments come forward, the entire beaches could be kept clean and declare as the first country with clean beaches
- Local fishermen and local people may be entrusted with this job as service to society for keeping nature clean and an income generating affair.

Media gave wide publicity for the programme in all stations. This has given wide appreciation to OSI, Ministry of Earth Sciences and all the premier institutions in the country who took part in the massive programme. Ministry of Earth Sciences funded the programme.

Prof. Dr. K. V. Jayachandran, National Co-ordinator of the Progrmme, GC member, OSI & Honorary Professor, University of Kerala

OSI Webinar Series (April-June, 2024)

April 2024

Topic: Urban sprawl and coastal protection structures - Challenges and Opportunities to coastal biodiversity

Speaker: Dr. Prince Prakash Jebakumar, NIOT Chennai

Date & Time: 26 April, 2024 (Friday), 1600-1700 IST

About the Talk

Urbanization along the coast has led to man-made structures on beaches, altering habitats and separating populations. The foreign nature of coastal protection structures on natural beaches tends to cause ecological changes. A 1076 km Tamil Nadu coastal stretch was studied for its impact on coastal biodiversity. Epibiota and marine growth settlement were analyzed. Habitat modification hosts alien species from shipping ballast water, and an eco-friendly technology is being introduced.

June 2024

Topic: Recent Advances in Ocean and Climate Research for Sustainable Developments: The Evolution of Digital Twins

Speaker: Prof. Swadhin K. Behera, JAMSTEC, Japan

Date & Time: 07 June, 2024 (Friday), 1630-1730 IST

About the Talk

Extreme ocean and climate events are affecting the socio-economies of many regions around the world. Understanding and predicting these phenomena are crucial for sustainable development. While numerical models are already used for ocean and climate simulations and predictions, digital twins offer a comprehensive framework with AI/ML and interactive interfaces. These enable researchers, policymakers, and industries to gain unprecedented insights into the complexities of the terrestrial and marine environments like never before. By integrating diverse data streams, such as oceanographic measurements, weather forecasts, marine life behavior, and vessel movements, this framework plays a transformative role in making informed decisions for sustainable resource management, disaster response, and environmental conservation.

Articles/research highlights of general interest to the oceanographic community are invited for the next issue of the Ocean Digest. Contributions may be emailed to osioceandigest@gmail.com

Cover Photo: *3D view of the Raman Seamount, Panikkar Seamount, and Wadia Guyot located in the Laxmi Basin, Arabian Sea, depicting the morphology of these anomalous seafloor features*

Image credit: Dr. Yatheesh Vadakkeyakath, Principal Scientist, CSIR-National Institute of Oceanography, Dona Paula, Goa - 403 004, India

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