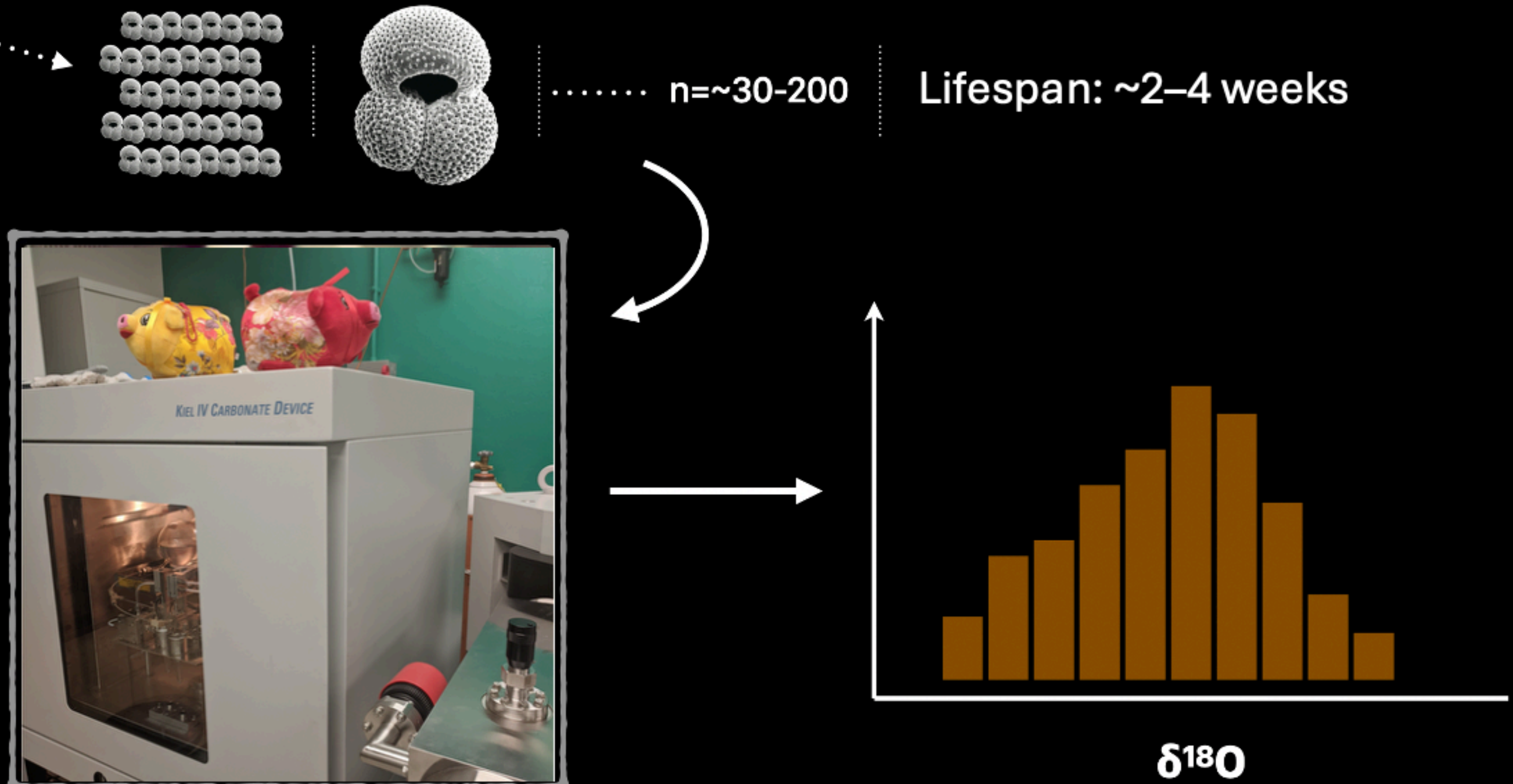


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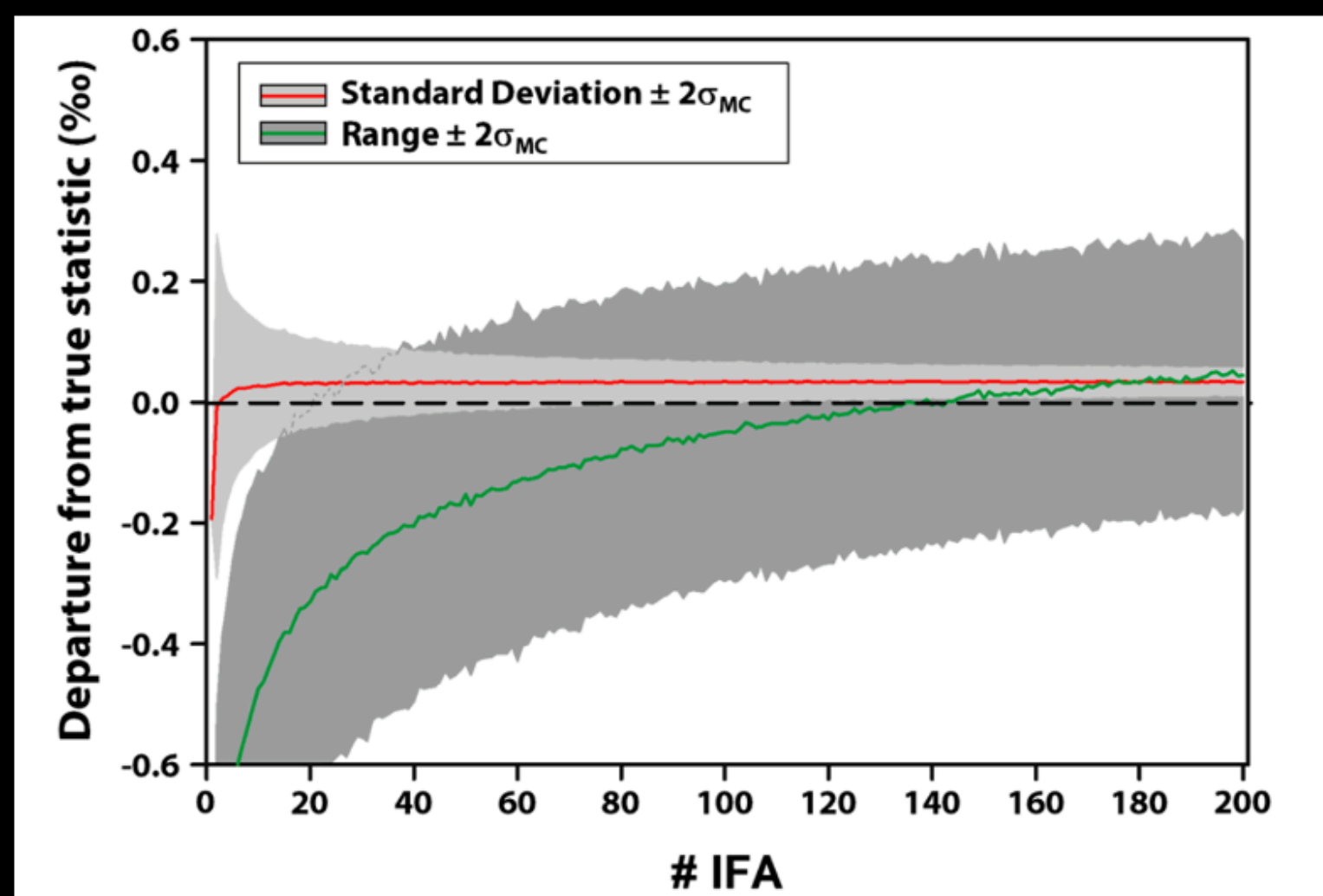


$$\delta^{18}\text{O} = f(T, \delta^{18}\text{O}_{\text{sw}})$$

Individual Foraminiferal Analyses



G. ruber
(White)



Editorial

Understanding Our Oceans: From Past Climate to Future Sustainability

The ocean is not merely a vast reservoir of water; it is an active component of the Earth system, regulating climate, sustaining biodiversity, supporting livelihoods, and influencing the intensity and variability of the Indian summer monsoon. Yet, despite significant advances in ocean observations and modelling, many aspects of ocean–atmosphere interactions and their responses to a changing climate remain uncertain. This issue of Ocean Digest, brings together diverse perspectives on these challenges, highlighting how scientific investigations, technological innovation, and emerging research talent can contribute to a more sustainable ocean future. Our invited article, “Shell by Shell: How Unicellular and Microscopic Foraminifera Constrain Large-Scale Ocean–Paleomonsoon Linkages in the Northern Indian Ocean,” explores how individual foraminiferal analysis (IFA) can reveal the history of monsoon–ocean interactions. By measuring the oxygen isotopic composition of individual microscopic shells preserved in marine sediments, scientists can reconstruct past ocean conditions and investigate changes in upper-ocean stratification. The article highlights contrasting responses in the Arabian Sea and Bay of Bengal, shaped by monsoon winds, upwelling, and freshwater discharge. These findings are particularly relevant today, when monsoon behaviour remains difficult to predict and climate variability, including El Niño–Southern Oscillation (ENSO), complicates seasonal outlooks. Understanding past monsoon variability provides a longer-term perspective against which present observations and climate-model simulations can be evaluated. Although past climate records cannot provide straightforward forecasts, they help us identify mechanisms, assess the range of natural variability, and better understand how the monsoon–ocean system may respond to future climate change.

Complementing this palaeoceanographic perspective, our article on concrete 3D printing for coral reef restoration in the Andaman Islands demonstrates how engineering and marine science can work together to address contemporary environmental challenges. The development and deployment of bio-inspired artificial reef structures illustrate the potential of advanced manufacturing to create habitats that support marine colonisation and biodiversity. Initial observations following deployment are encouraging, while continued monitoring will be essential to assess long-term ecological benefits. This initiative also underscores the importance of collaboration among research institutions, technology developers, and field scientists in translating scientific ideas into practical conservation solutions.

The student contribution, examining the sensitivity of the upper-ocean response to the K-profile parameterisation (KPP) shape function during Cyclone Hudhud, further enriches this issue. By exploring how ocean-model formulations influence simulated cooling, heat content, and vertical mixing, the study highlights the importance of improving our representation of air–sea interactions during extreme weather events. Such investigations are valuable for advancing ocean modelling and understanding the coupled processes that influence tropical cyclones.

Together, these contributions demonstrate the breadth of contemporary ocean science—from reconstructing climate histories locked in microscopic shells to designing marine habitats and refining numerical models. The regular sections of Ocean Digest further extend this engagement by bringing readers closer to developments, activities, and perspectives across the ocean-science community.

As we confront a future of increasing climatic and ecological uncertainty, sustained observations, long-term records, interdisciplinary research, and technological innovation will be indispensable. I hope this issue stimulates curiosity, encourages scientific dialogue, and reinforces our collective commitment to understanding and protecting the ocean.

Happy reading!
Editorial Team
Ocean Digest



Cover page:

Tiny shells of planktonic foraminifera preserve valuable clues to the history of our oceans and monsoon systems. The cover illustrates how Individual Foraminiferal Analysis (IFA) transforms these microscopic archives into a powerful tool for reconstructing past ocean conditions. After recovery from marine sediment cores, individual foraminiferal tests are carefully selected and their calcium carbonate shells analysed using an isotope-ratio mass spectrometer. The instrument measures stable oxygen isotope ratios ($\delta^{18}\text{O}$), providing information about the temperature and isotopic composition of the seawater in which the organisms calcified.

Unlike conventional bulk analysis, which combines multiple shells into a single measurement, IFA generates a distribution of isotope values from individual specimens. The upper-panel schematic depicts this transition from individual shells through mass spectrometric measurement to a population-level $\delta^{18}\text{O}$ distribution. The spread, shape and overlap of these distributions reveal environmental variability that a single average may conceal.

Applied to the northern Indian Ocean, IFA offers new insights into contrasting upper-ocean stratification in the Arabian Sea and Bay of Bengal. Differences between surface- and subsurface-dwelling species help distinguish the influences of monsoon-driven wind mixing, upwelling and freshwater discharge. By examining these shell-by-shell records across the Holocene, scientists can better understand past monsoon–ocean interactions and evaluate how the northern Indian Ocean may respond to future climate change.

Picture credit: Kaustubh Thirumalai

Shell by shell: how unicellular and microscopic foraminifera constrain large-scale ocean–paleomonsoon linkages in the northern Indian Ocean



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Abstract:

Though the Arabian Sea and Bay of Bengal—the two major basins of the northern Indian Ocean—together span less than 2% of the global ocean surface, they collectively sustain fisheries accounting for more than 10% of the global marine catch. Indian Summer Monsoon (ISM) winds, rainfall, and runoff influence the physical oceanography and marine biogeochemistry of this region’s upper-ocean waters. How climate change will alter the ISM and its impacts on the northern Indian Ocean is uncertain, partly due to the short instrumental record. On the other hand, paleoceanographic records offer a longer-term, geological-scale perspective. Planktic foraminifera, unicellular protists that drift in the upper ocean and build microscopic calcium carbonate shells (‘tests’) over a few weeks to a month, sink to the seafloor upon death and preserve the properties of the waters in which they calcified. Retrieved from marine sediment cores, these shells are classically analyzed in bulk—pooling many individuals per sample to generate one measurement before moving downcore. Here, I focus on a related-but-different approach: individual foraminiferal analyses (IFA), in which individual foraminiferal shells from the same sedimentary sample are measured separately to build a population of proxy values for an interval that represent sub-decadal signals. Statistics drawn from IFA populations are revealing the complex oceanographic history of the northern Indian Ocean across the Holocene epoch. These paleoceanographic clues help elucidate “out-of-sample” ocean-climate dynamics of this region across altered global states and help validate mechanisms relevant for future changes.

Introduction

The Arabian Sea and Bay of Bengal comprise the two largest basins of the northern Indian Ocean. Sunlit waters here sustain unique marine ecosystems fueled by substantial biological productivity, which help support numerous fisheries in the region that cater to the economies and protein needs of densely populated countries flanking the Indian Ocean rim. Under present-day conditions, the dominant climatic driver of the physical and biological oceanography of this marine domain is the Indian Summer Monsoon (ISM) phenomenon (Qasim, 1977). During late April and May, strong winds from the Southern Hemisphere cross the equator into the southwestern Arabian Sea, curve northeastward towards the Indian subcontinent, and ultimately help sustain rainfall over the subcontinent from June till September. ISM winds extract moisture from the Arabian Sea, heightening sea-surface salinity (SSS) in this basin (Fig. 1). The southwesterly winds bring rain over the western Ghats and western–northern India, whereas on the eastern margin, low-pressure convective systems form in the Bay of Bengal and bring rainfall to the Indo-Gangetic Plains and northeastern part of the subcontinent (Mahendra et al., 2026). Convection across the subcontinent generally subsides by October as the land temperature cools and winds change direction, and most of the ISM runoff flows into the Bay of Bengal during boreal autumn, discharging enormous amounts of freshwater into the Bay of Bengal—establishing it as one of the freshest oceanic basins on the planet (Fig. 1).

These seasonal ISM processes exert a tight control on the oceanography of the northern Indian Ocean. In the Arabian Sea, alongside high SSS values, monsoon winds churn upper-ocean waters and promote upwelling in the western part of the basin, inducing relatively cooler sea-surface temperatures (SST) and a deep mixed layer (Fig. 1). These processes elevate nutrient availability in sunlit waters and support biological production in the region. Conversely, in the coastal Bay of Bengal, freshwater discharge induces strong stratification, which inhibits upper-ocean mixing, nutrient delivery from depth, and adversely impacts primary productivity.

Accordingly, how the ISM will be altered under anthropogenic global warming, and in turn, how this will affect stratification, nutrient delivery, and biological production in the northern Indian Ocean are central questions of ecological and socioeconomic importance. Whereas coupled ocean-atmosphere models project thermodynamic ISM intensification under a weakened circulation regime, biogeochemical projections of changes in the northern Indian Ocean are highly uncertain (Kwiatkowski et al., 2020). Unfortunately, reliable pre-21st-century instrumental coverage of ocean temperature, salinity, and production is too brief to ground-truth model simulations and is already entangled with anthropogenic influences to provide independent tests for validation.

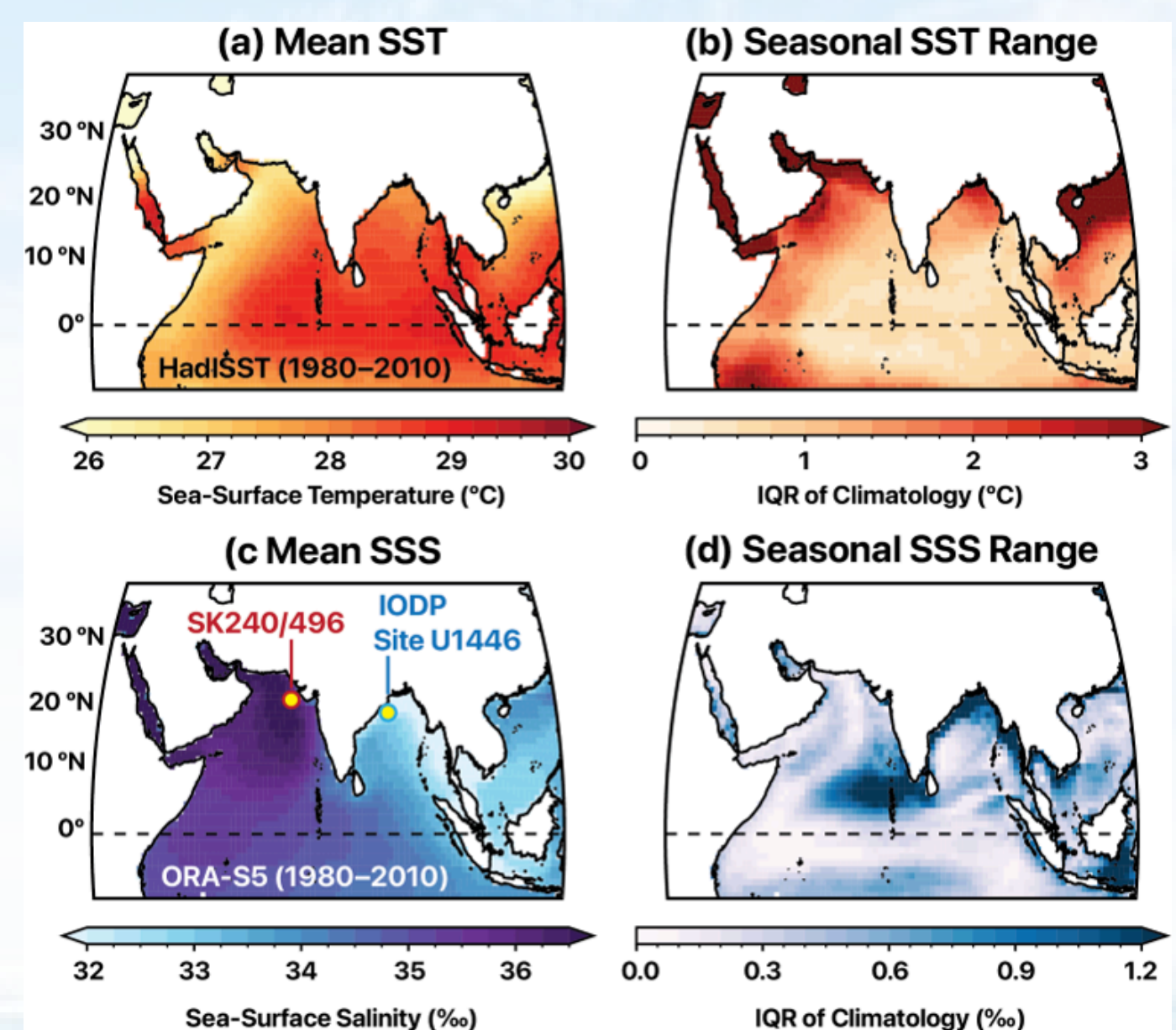


Fig. 1. Modern mean-state and seasonal variability of sea-surface temperature and salinity across the northern Indian Ocean. (a) Mean annual sea-surface temperature (SST; °C) and (b) seasonal SST range across the tropical and northern Indian Ocean, calculated from monthly HadISST1 fields over 1980–2010 (Rayner et al., 2003). Seasonal variability is expressed as the interquartile range (IQR) of the monthly climatology at each grid point, thereby emphasizing the amplitude of the seasonal cycle. (c) Mean annual sea-surface salinity (SSS; ‰) and (d) corresponding seasonal SSS range, calculated from monthly ORAS5 ocean-reanalysis fields over the same 1980–2010 interval (Zuo et al., 2019), with seasonal variability again expressed as the IQR of the monthly climatology. The locations of sediment core SK240/496 in the northeastern Arabian Sea (red/yellow marker) and IODP Site U1446 in the northwestern Bay of Bengal (blue/yellow marker) are indicated in (c). These sites occupy contrasting hydrographic regimes: the northern Arabian Sea is characterized by relatively saline surface waters and pronounced SST seasonality associated with monsoon-driven air–sea heat exchange and wind forcing, whereas Site U1446 lies within the comparatively fresh northern Bay of Bengal, where strong seasonal freshwater input produces pronounced SSS variability.

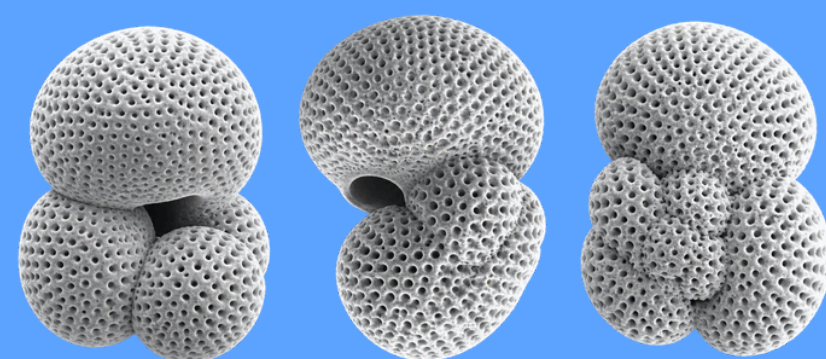
Windows into the ancient past

The paleoceanographic record provides a way around this problem. Past Earth-climate states contain different climate forcing factors such as changes in Earth-orbital configurations, ice-sheet extents, greenhouse gas concentrations, and sea levels relative to present-day conditions, providing natural experiments to examine how global climate change impacts regional oceanography, free from dominant anthropogenic contamination. The present interglacial, or the Holocene epoch, spanning ~11,700 years before present (hereafter kyr BP), has drawn particular attention because the early Holocene (~9-10 kyr BP) featured much stronger summer insolation ($>35 \text{ W/m}^2$) in the Northern Hemisphere. This forcing is thought to have strengthened the monsoon circulation, providing an ideal experiment to investigate monsoon sensitivity to forcing because ice sheets, sea level, and greenhouse gases were relatively similar to preindustrial levels (Kutzbach, 1981). Delineating the stratification history of the Arabian Sea and Bay of Bengal from proxy records during the early Holocene—when the ISM is thought to have been intensified relative to present-day conditions—will help establish a strong model validation target and help resolve how monsoon-ocean dynamics change under strong climate forcing. Even though there is evidence of decoupling between orbital insolation over the Holocene and ISM strength (Naik et al., 2017; Kumar and Ramesh, 2017; Thirumalai et al., 2025), as isolated intervals of interest, the early versus late Holocene time slices allow us to investigate how stratification changed under strong (early Holocene) and weak (late Holocene) orbital forcing.

Marine sediment cores are the go-to archives for investigating oceanic change over hundreds to thousands of years: particles and microfossils rain onto the seafloor and accumulate continuously, providing a sedimentary record of change over geological time. Indeed, interest in the northern Indian Ocean as a paleoceanographic laboratory is not new (Cullen, 1981), with early studies targeting ISM changes gleaned from the marine record over glacial-interglacial cycles (Prell et al., 1980; Clemens et al., 1991).

Over the past three decades, several coastal Indian sediment core records have been developed using geochemical proxy variations of microfossil planktic foraminifera to investigate how ISM changes over the Holocene influenced northern Indian oceanography (Sijinkumar et al., 2016; Kumar and Ramesh, 2017; Naik et al., 2017; Aravind et al., 2026). Planktic foraminifera are unicellular zooplankton that drift in the surface and subsurface ocean (depth dependent on species) with a lifespan of a few weeks to months, after which their calcium carbonate shells (called tests)—whose chemistry captures the seawater properties—fall to the seafloor (e.g., Spero, 1998). Several monospecific individual tests are pooled together per sample to generate a geochemical proxy measurement (aka “multi-test approach”) of paleoceanographic parameters thought to be representative of the time interval captured by the sediment sample. This approach provides continuous downcore measurements of planktic foraminiferal $\delta^{18}\text{O}$ over time, with sample resolution (how many years per sediment core depth) dictated by the sedimentary environment at that site (Thirumalai et al., 2013).

A widely applied proxy for the multi-test approach is the stable oxygen isotopic composition (reported in $\delta^{18}\text{O}$ values) of foraminiferal calcite as an indicator of upper-ocean hydrography. Foraminiferal calcite $\delta^{18}\text{O}$ is sensitive to both calcification temperature and seawater $\delta^{18}\text{O}$ values (a proxy for salinity; Saraswat et al., 2013). Temperature is inversely correlated to foraminiferal $\delta^{18}\text{O}$ (higher $^{18}\text{O}/^{16}\text{O}$ ratios get incorporated into calcite precipitating under colder conditions due to thermodynamic considerations), and salinity via seawater $\delta^{18}\text{O}$ is positively correlated with foraminiferal $\delta^{18}\text{O}$ (terrestrial freshwaters are depleted in ^{18}O relative to oceanic waters). In spite of >30 planktic foraminiferal $\delta^{18}\text{O}$ records developed in the eastern Arabian Sea and coastal Bay of Bengal, uncertainty still persists regarding how early Holocene ISM changes altered ocean stratification (Sijinkumar et al., 2016; Kumar and Ramesh, 2017; Thirumalai et al., 2025; Aravind et al., 2026). Uncertainties arise due to chronology/dating and sedimentary intactness, but also because of changes in foraminiferal depth habitats, ecology, and phenology (Thirumalai et al., 2013). The lack of independent temperature constraints to separate seawater $\delta^{18}\text{O}$ signals from calcification temperature additionally complicates interpretation of multi-test foraminiferal $\delta^{18}\text{O}$ records—particularly in the dynamic Indian margin setting, with strong seasonal currents and coastal upwelling (Sarkar et al., 2000; Saraswat et al., 2013; Naik et al., 2017; Kumar et al., 2019).



How many foraminiferal shells are needed for a robust signal?

Whereas conventional or multi-test foraminiferal analysis (sometimes called “bulk” analysis) uses many shells from a sedimentary sample to obtain one measurement per sedimentary sample, individual foraminiferal analyses (IFA) uses multiple measurements of individual tests to generate distributions of data within a sample to investigate past seasonal to interannual signals within a given interval of time. But how do we know how many tests are needed for robust statistics? Considering that the planktic foraminiferal lifespan is sub-annual and that the sediment sample may represent centuries to millennia, statistical testing of IFA at a location is very important for robust interpretation of such types of data. The ratio of the seasonality to interannual (and longer forms) of upper-ocean variability, in addition to the phenology of the selected planktic foraminiferal taxa is very important in interpretation and comparison of IFA datasets from different sedimentary intervals (Thirumalai et al. 2013). Indeed, IFA was first applied by Killingley et al. (1981) to precisely test the sampling uncertainty associated with multi-test foraminiferal analysis—after which, Schiffelbein and Hills (1984) formalized how bootstrap and jackknife resampling statistics may be used on observed and forward-modeled datasets to determine how many measurements are needed to reconstruct a robust signal. Nowadays, there are plenty of published (parametric and nonparametric) algorithms available to query how many IFA measurements are required to obtain robustly interpretable signals at a given site (Thirumalai et al. 2013; Glaubke et al. 2021; Bienzobas Montavez et al. 2024).

Individual foraminiferal analyses as a proxy for upper-ocean stratification

Here I will discuss an alternative to the multi-test $\delta^{18}\text{O}$ approach to constrain past stratification: multi-species individual foraminiferal analyses (IFA) of specimens from the same sedimentary sample. In this approach, numerous measurements of single-test $\delta^{18}\text{O}$ across multiple depth-stratified taxa provide statistical (per-species) $\delta^{18}\text{O}$ populations that can be compared across time intervals (Thirumalai et al., 2013; Fehrenbacher et al., 2024). Unlike the multi-test approach, IFA distributions provide windows into the variability of $\delta^{18}\text{O}$ between specimens that lived within the time interval—a signal that explicitly includes changes in seasonality and depth migration among species and individuals. Additionally, because the $\delta^{18}\text{O}$ of each specimen is influenced by seawater $\delta^{18}\text{O}$ (an indicator of salinity) and temperature, the distributions across taxa indirectly reflect distributions of seawater density—a metric of stratification. When IFA is applied to several depth-stratified planktic species from one sample, the overlap (or separation) between their distributions measures how sharply the upper water column was layered. Accordingly, in the Bay of Bengal, separation between surface and subsurface $\delta^{18}\text{O}$ populations implies freshwater-driven stratification from monsoon outflow, whereas in the coastal Arabian Sea it implies a breakdown of wind-driven mixing and upwelling (Fig. 2).

Two recent studies I was a part of applied this on either side of the subcontinent to focus on early versus late Holocene hydrography: 1) Thirumalai et al. (2025) worked on International Ocean Discovery Program Site U1446 (19.08°N, 85.73°E; 1,430 m) in the coastal northwestern Bay of Bengal, beneath the East India Coastal Current that carries Ganges–Brahmaputra–Meghna outflow southward each autumn; 2) Saravanan et al. (2026) worked on core SK240/496 (21.27°N, 68.57°E; 174 m) offshore Saurashtra in the northeastern Arabian Sea, near the upper edge of its oxygen minimum zone.

Both built radiocarbon age models and used depth-stratified species—*Globigerinoides ruber* (surface dweller), *Trilobatus sacculifer* (intermediate dweller), and, in every slice but the late Holocene Arabian Sea, *Neogloboquadrina dutertrei* (subsurface dweller)—with well-known relative calcification depths (Lakhani et al., 2022).

Earlier IFA work in the Oman margin by Ganssen et al. (2011) and Naidu et al. (2019) had already shown that inter-shell spread there responds to deglacial and Holocene change; what is new here is the multi-species, stratification-focused design. Here I consider only the IFA- $\delta^{18}\text{O}$ data, whose interpretation depends on the basin: in the Arabian Sea, forward modelling indicates that temperature drives most of the calcite $\delta^{18}\text{O}$ spread, since local seawater $\delta^{18}\text{O}$ varies little; in the coastal Bay of Bengal, the enormous freshwater runoff signal (Fig. 1) means that seawater $\delta^{18}\text{O}$ changes control foraminiferal $\delta^{18}\text{O}$ (Thirumalai and Clemens 2020). Either way, the quantity that matters is seawater density, so the hypothesis is simple: if the upper ocean was well mixed, surface- and subsurface-dwelling species experienced similar water properties, and their IFA- $\delta^{18}\text{O}$ distributions should overlap; if it was stratified, they should be separated.

Methods: from seafloor to mass spectrometer

The journey from seafloor to mass spectrometer for isotopic measurement of planktic foraminifera is long but now routine. Cores are retrieved by research vessel or drillship, split, and sampled downcore at ~1–5 cm intervals, each representing decades to centuries depending on location. Samples are disaggregated in water, wet-sieved over a 63 μm mesh to remove clay, then dried and dry-sieved into size fractions. Working within one narrow fraction matters for IFA, because shell size covaries with ontogeny and therefore with depth habitat; both studies picked from coarse fractions (400–500 μm at Site U1446; >355 μm at SK240/496). Specimens are then picked by hand under a microscope and identified from test morphology—chamber arrangement, aperture position, wall texture—with dissolved or overgrown shells rejected. Stable isotopes are measured by reacting the calcite with phosphoric acid and admitting the liberated CO_2 to an isotope ratio mass spectrometer (IRMS), which compares it against a reference gas to yield $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ on the Vienna Pee Dee Belemnite (VPDB) scale. A single foraminifer weighs only ~10–70 μg , so this demands an instrument tuned for small samples: both studies' IFA measurements were made at the Paleo² Laboratory, University of Arizona, on a Kiel IV Carbonate Device coupled to a Thermo Scientific MAT 253+ IRMS, with precision better than $\pm 0.08\text{‰}$ for $\delta^{18}\text{O}$ (Thirumalai et al., 2023; Prabhakar et al., 2024).

Multi-species IFA distributions: overlap as a signal of mixing at depth

Across both cores from each basin, we sampled early Holocene (~9.4 kyr BP in the Arabian Sea and ~9.8 kyr BP in the Bay of Bengal) and late Holocene (~3.8 kyr BP in the Arabian Sea and ~0.5 kyr BP in the Bay of Bengal) sediments for IFA using the following depth-stratified species (Fig. 2): ~0–50 m—*G. ruber*, ~60–100 m—*N. dutertrei* (where available), and *T. sacculifer* with depth habitat intermediate to the other two (Lakhani et al., 2022). Note that these comparisons represent site-specific early- and late-Holocene end members; the late-Holocene intervals are not synchronous.

In the Bay of Bengal (Fig. 2d), the early Holocene sample at 9.8 kyr BP shows the two mixed-layer species (*G. ruber* & *T. sacculifer*) with wide distributions containing a pronounced tail toward low $\delta^{18}\text{O}$ values—indicative of episodic, strongly-freshened surface water during peak monsoon outflow. On the other hand, *N. dutertrei* sits about a permil higher (equivalent to ~4 °C in purely thermal terms) and barely overlaps them. Freshening was capped above the subsurface species, indicative of a thick barrier layer (Thirumalai et al., 2025). By 0.5 kyr BP, the surface populations have contracted and shifted toward the subsurface ones (which do not change by much), and the separation narrows. This shows that stratification in the coastal Bay of Bengal relaxed as ISM runoff fell from its early Holocene peak.

The Arabian Sea (Fig. 2c) core shows the opposite trend in stratification over time. At 9.4 kyr BP, all three species overlap substantially among themselves, and the surface distributions are broad—an upper ocean repeatedly churned by monsoon winds that also drive upwelling, so shells sampled a wide range of conditions. By 3.8 kyr BP, the distributions become narrow, unimodal, and pulled apart: $\delta^{18}\text{O}$ offsets between *G. ruber* and *T. sacculifer* rise from 0.33 to 0.86 ‰, as the basin warmed by $1.4 \pm 0.4\text{ °C}$, according to independent proxies (Saravanan et al., 2026).

In summary, surface and subsurface $\delta^{18}\text{O}$ values overlap more in the eastern Arabian Sea during the early Holocene, whereas they overlap more in the coastal Bay of Bengal during the late Holocene.

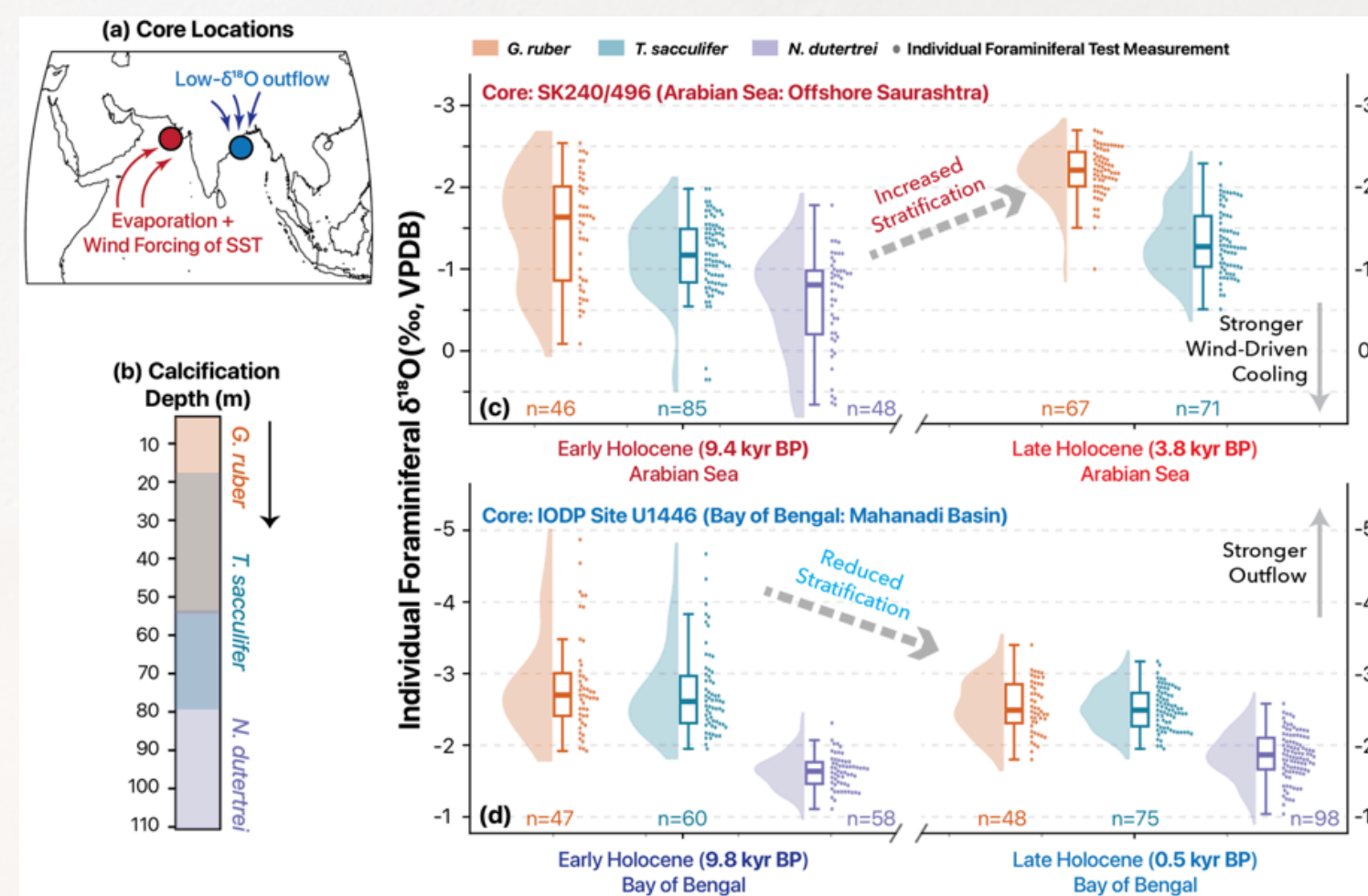


Fig. 2. Contrasting Holocene upper-ocean stratification in the Arabian Sea and Bay of Bengal. (a) Locations of core SK240/496 in the northeastern Arabian Sea (red) and IODP Site U1446 in the Bay of Bengal (blue), highlighting dominant surface-ocean forcing by evaporation and monsoon winds in the Arabian Sea and low- $\delta^{18}\text{O}$ freshwater input in the Bay of Bengal. (b) Approximate calcification-depth ranges of *G. ruber*, *T. sacculifer*, and *N. dutertrei*, representing progressively deeper upper-ocean habitats. (c) Individual foraminiferal $\delta^{18}\text{O}$ (IFA- $\delta^{18}\text{O}$; ‰ VPDB) distributions from early- (~9.4 kyr BP) and late-Holocene (~3.8 kyr BP) intervals at SK240/496, where the axis is inverted because warmer and fresher waters generate lower foraminiferal $\delta^{18}\text{O}$. Increased interspecific $\delta^{18}\text{O}$ separation during the late Holocene indicates enhanced stratification associated with weaker monsoon winds and reduced wind-driven cooling (Saravanan et al., 2026). (d) IFA- $\delta^{18}\text{O}$ distributions from early- (~9.8 kyr BP) and late-Holocene (~0.5 kyr BP) intervals at Site U1446. Reduced interspecific $\delta^{18}\text{O}$ separation during the late Holocene indicates weakened stratification as monsoon-driven freshwater input declined (Thirumalai et al., 2025). Points denote individual analyses; shaded distributions show data density, boxes show the interquartile range with median, whiskers indicate the data spread, and n denotes the number of individual tests analyzed. More positively skewed tails in the Arabian Sea surface-ocean IFA indicate a tendency for stronger mixed layer conditions to skew the distributions to cooler temperatures (i.e., more wind-driven mixing and less stratification), whereas the Bay of Bengal surface-ocean IFA tails during the early Holocene are negatively skewed owing to more negative freshwater $\delta^{18}\text{O}$ outflow (i.e., more stratification). Together, the records illustrate opposing Holocene stratification responses to weakening monsoon forcing over the Holocene in the two northern Indian Ocean basins.

Early Holocene paleoceanography informs future outlook on stratification

The IFA datasets point to contrasting stratification histories in the coastal Arabian Sea and Bay of Bengal during the early versus late Holocene. Under a stronger early Holocene monsoon wind regime, coastal Arabian Sea waters experienced larger seasonality and wind-driven mixing (Saravanan et al., 2026). However, this strengthened ISM wind regime was unable to ease stratification in the coastal Bay of Bengal during the early Holocene, where voluminous monsoon freshwater outflow—year after year—induced a thick, quasi-permanent barrier layer and restricted primary production (Thirumalai et al., 2025). During the late Holocene, as ISM outflow and winds weakened relative to the early Holocene, stratification strengthened in the Arabian Sea but reduced in the Bay of Bengal.

How can these results be reconciled with future projections? Models robustly project and largely agree that greenhouse forcing will induce stronger stratification across the global oceans (Kwiatkowski et al., 2020) and that ISM rains will intensify (Katzenberger et al., 2021)—although there is large uncertainty around the specific regional patterns (Varikoden et al. 2025). At face value, this would suggest a more “early Holocene”-like regime where monsoon outflow increases in the Bay of Bengal lead to more stratified and less productive conditions (Thirumalai et al., 2025).

But what about in the Arabian Sea? Unfortunately, projections of increases in ISM rainfall point to mechanisms of “thermodynamic” (how much moisture is available in the atmosphere) versus “dynamic” (how strong are moisture-bearing winds) intensification. In other words, monsoon rainfall and runoff are projected to increase without strong increases in wind strength.

The Holocene comparison highlights the importance of wind-driven mixing; future surface warming and freshening could strengthen stratification if wind-driven mixing does not increase sufficiently to offset them. Such a scenario clashes with the early Holocene interval, where ISM winds and circulation were presumably more vigorous than present-day conditions (Thirumalai et al. 2025). Accordingly, the early Holocene results support the expectation of weakened ISM circulation leading to poorer wind-driven mixing in the Arabian Sea. These are, however, two cores and a few hundred unicellular foraminiferal measurements that are spinning this tale of stratification. The climatic importance of the early Holocene interval for future changes deserves replication: runoff, currents, eddy activity, and barrier-layer thickness vary strongly along the Indian margin, and stratification itself shows intra-basin spatial variability. Extending multi-species IFA across the northern, eastern, and southern Bay—and along Arabian Sea transects spanning the upwelling gradient—are next steps. Overall, as a community, we have come an impressively long way in better listening to the sand-grain-sized unicellular remains of planktic foraminifera and the hemisphere-scale stories locked into their calcite shells. The answers are already in the sediment; they simply have to be measured shell by shell.

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Concrete 3D Printing for Coral Reef Restoration and Biodiversity Enhancement in the Andaman Islands



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Abstract

Coral reefs are among the most productive and biologically diverse ecosystems on Earth, providing critical habitat for marine organisms while protecting coastlines from erosion and wave action. However, increasing environmental pressures, including climate change, ocean warming, and anthropogenic disturbances, have led to widespread reef degradation worldwide. To address this challenge, the Atal Centre of Ocean Science and Technology (ACOSTI), Sri Vijaya Puram, a field Centre of the National Institute of Ocean Technology (NIOT), Chennai, in collaboration with the Technology Innovation Hub at IIT Guwahati (IITG TIDF) and Stratify 3D Pvt. Ltd., initiated a pioneering project utilising concrete 3D printing technology to develop artificial reef structures. The project combines bio-inspired design principles, advanced additive manufacturing, and marine-compatible materials to create artificial habitats that support biodiversity and facilitate ecosystem recovery. A total of 59 modular reef units were designed initially, fabricated, transported, and successfully deployed at multiple locations across the Andaman Islands. The initiative demonstrates the potential of digital manufacturing technologies to advance marine restoration and to establish scalable solutions for future blue economy applications.

1. Introduction

Coral reefs occupy less than one percent of the ocean floor but support nearly one-quarter of all known marine species. These ecosystems serve as breeding grounds, nurseries, and feeding habitats for a wide variety of marine organisms while providing substantial ecological and socio-economic benefits. Despite their importance, coral reef ecosystems worldwide are facing unprecedented decline due to increasing sea surface temperatures, ocean acidification, destructive fishing practices, coastal development, and pollution. Conventional reef restoration approaches often face limitations related to scalability, design flexibility, and deployment efficiency. Recent advancements in digital manufacturing technologies offer new opportunities to develop engineered reef systems that mimic the complexity of natural coral habitats. Recognizing this potential, NIOT and IIT Guwahati initiated a collaborative effort to explore the application of concrete 3D printing technology for marine ecosystem restoration. The project further benefited from the participation of Stratify 3D Pvt. Ltd supported by the IIT, Guwahati, which contributed to the large-scale fabrication of the reef structures, while NIOT-ACOSTI provided support for their deployment and subsequent ecosystem monitoring and assessment. The initiative aimed to demonstrate how bio-inspired design, sustainable construction materials, and advanced manufacturing technologies can contribute toward restoring degraded marine habitats and supporting biodiversity conservation.

2. Project Development and Deployment

2.1 Bio-Inspired Artificial Reef Design and Bio-Receptive Material Development

The artificial reef initiative was conceived to develop engineered underwater habitats that support marine biodiversity through advanced concrete 3D printing technology.

The reef designs were finalised after multiple iterations and refinements, considering ecological functionality, printability, transportation, deployment feasibility, and long-term marine performance. Based on expert inputs from IIT Guwahati and the NIOT-ACOSTI, Sri Vijaya Puram, bio-inspired reef geometries were selected. The first design was inspired by the natural morphology of brain corals, featuring interconnected cavities and complex curved surfaces suitable for a wide range of marine organisms. The second design was developed based on the habitat requirements of grouper fish species found in the Andaman and Nicobar (A&N) Islands, providing refuge spaces and breeding habitats. The engineered structures replicate the complexity of natural coral ecosystems and are expected to promote coral larvae settlement, provide shelter for marine organisms, and support the development of diverse underwater communities. A key innovation of the project was the development of a bio-receptive, low-pH cementitious material by IIT Guwahati. Unlike conventional cement-based materials, the low-pH formulation was designed to minimise alkaline leaching into seawater, thereby creating a more environmentally compatible interface for marine colonisation. Extensive laboratory studies were conducted to optimise printability, durability, dimensional stability, and surface characteristics, resulting in a material system well-suited for long-term marine habitat restoration applications.

2.2 Large-Scale Fabrication

Following successful laboratory validation, the Stratify 3D Pvt. Ltd., a deep-tech startup co-founded by three PhD graduates of IIT Guwahati, undertook large-scale manufacturing of the reef modules. Established with the vision of translating indigenous research into impactful real-world technologies, the startup played a key role in advancing the technology from laboratory-scale development to field deployment. Under the Startup Grant TIH/STARTUP/35 and a Memorandum of Understanding (MoU) with the IIT Guwahati Technology Innovation and Development Foundation (IITG TIDF), Stratify 3D undertook pilot-scale implementation and product-readiness activities for 3D-printed artificial reefs. Based on technical guidance from IITG TIDF and the NIOT-ACOSTI, the company successfully designed and fabricated three artificial reef clusters comprising 59 modular reef units. The reef modules were manufactured using a large-scale concrete 3D printing system at IIT Guwahati (Fig 1). The layer-by-layer additive manufacturing process enabled the creation of highly complex geometries without the need for molds, while providing more than 50% additional surface area compared with equivalent conventionally cast structures. Furthermore, the process generated virtually no material waste and allowed rapid production of modular reef units suitable for transportation and large-scale deployment.

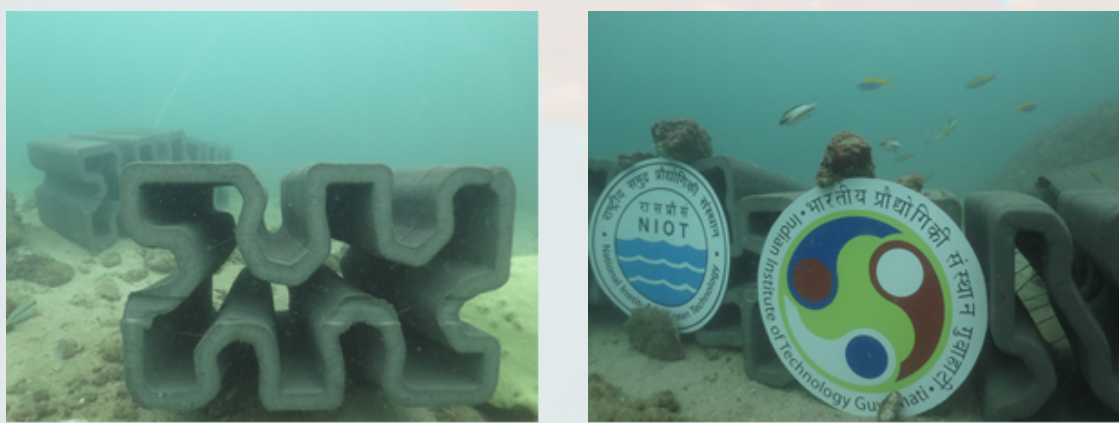
2.3 Deployment in the Andaman Islands

Upon completion of fabrication, the reef modules underwent controlled curing for approximately 30 to 45 days to achieve the desired mechanical and durability characteristics required for marine exposure.

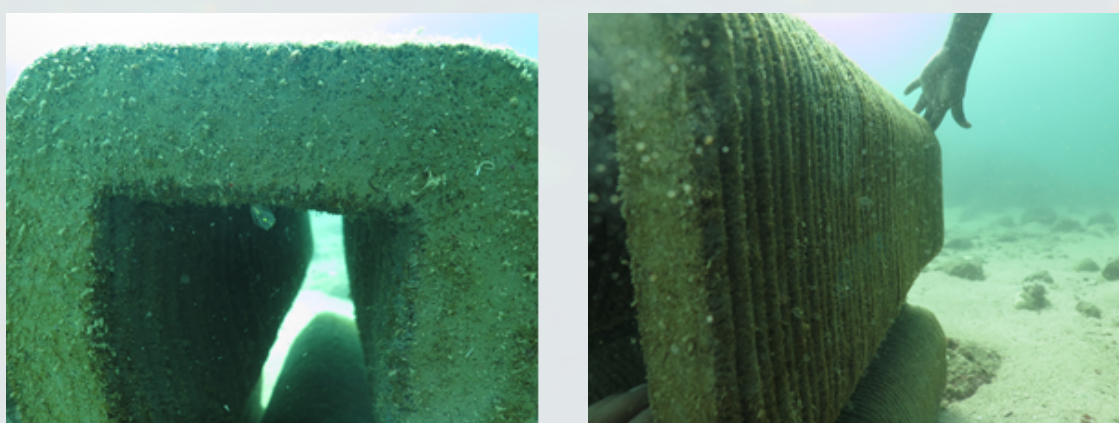


Fig. 1 Fabrication of 3D-printed artificial reef modules at IIT Guwahati

Subsequently, the modules were transported from IIT Guwahati to Sri Vijaya Puram (Port Blair) through a combination of road and sea logistics. Five deployment locations were identified across the Andaman Islands, namely Chidiyatappu, North Bay, Neil Island, Havelock Island, and Long Island. These locations were selected based on ecological suitability and restoration objectives identified by NIOT-ACOSTI scientists and marine experts. Professional diving teams, along with NIOT-ACOSTI scientists and members of the Stratify 3D team, deployed the reef modules at Chidiyatappu, approximately 200 metres from the shoreline at depths ranging from 10 to 15 meters below sea level (Fig. 2). The deployment operation provided invaluable field-scale insights into handling procedures, underwater positioning, seabed interactions, hydrodynamic effects, and installation methodologies.



Underwater condition of the 3D printed artificial reef during the deployment



Underwater condition of the 3D printed artificial reef after 22 days

Fig. 2 3D printed artificial reef modules at Chidiyatappu, South Andaman

2.4 Post-Deployment Assessment

Following deployment on 30.05.2026, preliminary underwater surveys were conducted by scientists of NIOT-ACOSTI. The assessment focused on evaluating structural placement, reef orientation, seabed stability, and the accessibility of habitat cavities, as well as initial settlement, without disturbing the 3D reef structure. The 22 days of observations yielded important information on initial colonisation, including tunicates, serpulidae, bryozoans, and barnacles. The study will provide a good insight about long-term restoration and conservation management in the coastal and marine environment. These findings are expected to guide future design optimization efforts, including stability, modular assembly strategies, and habitat performance.

2.5 Technology Demonstration on World Environment Day 2026

Coral reefs are among the most valuable marine ecosystems on Earth. They support a vast diversity of marine life, protect coastlines from erosion and storms, support fisheries, and contribute to local economies. However, climate change, ocean warming, pollution, and habitat destruction are threatening coral reefs worldwide. Therefore, efforts such as coral reef conservation and the deployment of artificial or 3D-printed reefs were planned on World Environment Day to create awareness for biodiversity, ecosystem restoration, and environmental sustainability. The successful deployment of the 3D-printed artificial reef modules was formally showcased during the World Environment Day celebrations held on 5 June 2026 in the NIOT-ACOSTI campus. The event was attended by several distinguished dignitaries, policymakers, researchers, and government officials, including the Chief Secretary, A&N Administration, the Director, NIOT, Secretary, Fisheries, A&N Administration, other dignitaries and senior representatives from the Fisheries Department, Forest Department, JNRM, Pondicherry University, central government departments, press and media.



Fig. 3 3D-printed artificial reef deployment on World Environment Day 2026 at Chidiyatappu

As part of the celebrations, a prototype artificial reef module was exhibited (Fig. 3), enabling stakeholders and policymakers to directly observe the innovative design, material technology, and manufacturing approach developed under the project. An official video documentary showcasing the complete journey from reef design and material development to large-scale fabrication, transportation, and underwater deployment was also released during the event. The event significantly enhanced the technology's visibility and demonstrated how indigenous research, startup-led innovation, and interdisciplinary collaboration can contribute to marine habitat restoration, biodiversity conservation, and the advancement of India's Blue Economy aspirations. The successful showcase established the project as a pioneering example of the application of concrete 3D printing technology for ocean sustainability and ecosystem restoration.

3. The Way Forward

The successful deployment of 3D-printed artificial reefs in the Andaman Islands marks an important milestone in the application of digital manufacturing technologies for marine ecosystem restoration and sustainable Blue Economy development in India. The initiative demonstrates how marine engineering, ecological science, and advanced concrete 3D printing can be integrated to address environmental challenges while creating long-term socio-economic benefits. Beyond promoting coral settlement and marine biodiversity, the artificial reef systems have the potential to enhance fisheries resources, strengthen coastal resilience, support marine ecotourism, and create platforms for ocean observation and scientific research. These benefits align closely with national priorities related to ocean sustainability, climate adaptation, and Blue Economy growth. Moving forward, long-term monitoring will be undertaken to assess coral settlement, biological colonization, fish aggregation, and overall ecosystem development around the deployed reef structures. Future work will focus on optimizing reef designs, improving field performance, and scaling up deployment for larger habitat restoration programmes. The collaboration among NIOT-ACOSTI and IIT Guwahati highlights the power of interdisciplinary partnerships and indigenous innovation in developing practical solutions for ocean conservation. The project provides a promising pathway for leveraging technology-driven restoration approaches to build healthier marine ecosystems and a more resilient Blue Economy for the future.

Sensitivity of Upper Ocean Response to the KPP Shape Function during cyclone Hudhud

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Abstract

Tropical cyclones strongly modify the upper-ocean thermal structure through enhanced wind- and wave-driven mixing. Ocean general circulation models using the K-profile parameterization (KPP) can overestimate this mixing, producing surface cold and subsurface warm biases. This study examines the sensitivity of the Bay of Bengal upper-ocean response to the KPP shape function during Tropical Cyclone Hudhud (October 2014). The MOM5 model was integrated with 50 years of spin-up and forced by JRA55-do for 2009–2023. A control experiment (CTRL) used the default cubic KPP shape function, whereas EXP used a sixth-order polynomial shape function. Model results were evaluated against daily RAMA observations at 15°N, 90°E over ± 10 days around 10 October 2014. EXP better represented cyclone-induced sea surface temperature (SST) cooling, oceanic heat content (OHC), thermocline depth (D20) and mixed layer depth (MLD) than CTRL and substantially reduced the subsurface warm bias, particularly at 90–110 m. Heat-budget analysis showed that vertical advection dominated the subsurface temperature tendency, while CTRL also exhibited larger variance in vertical turbulent heat flux, indicating excessive turbulence. The results demonstrate that modifying the KPP diffusivity profile improves the simulation of cyclone-induced upper-ocean thermohaline structure.

1. Introduction

Tropical cyclones generate intense upper-ocean turbulence through strong winds, waves and currents, leading to mixed-layer deepening, SST cooling and subsurface temperature changes. Accurate representation of this response is important for air–sea interaction and cyclone intensity prediction. The North Indian Ocean contributes a relatively small fraction of global cyclones but experiences several highly damaging storms; the warm Bay of Bengal is particularly favourable for cyclone development. A common problem in tropical ocean models is that they simulate too much vertical mixing. This often causes the simulated ocean surface to be colder than observed, while the water below the surface becomes warmer than observed. KPP represents vertical diffusivity using a vertical velocity scale, boundary-layer depth and shape function. LES results indicate that the conventional cubic shape may not be optimal under wavy conditions. Therefore, this study tests a sixth-order shape function in MOM5 using Hudhud as a cyclone case study.

- Objective: assess whether the modified sixth-order KPP shape function improves the simulated upper-ocean response to a tropical cyclone.
- Focus: SST, OHC, D20, MLD, vertical temperature structure and the processes responsible for subsurface bias reduction.

2. Model, Experiments and Observations

To explore how the tropical Indian Ocean responds to storms and climate shifts, scientists used a powerful ocean model called MOM5. Before diving into the main experiments, they let the model “settle in” with a 50-year warm-up run, so the simulated ocean could reach a stable state.

From 2009 to 2023, they ran two parallel experiments with the same setup and real-world weather data (from JRA55-do). The difference lay in how the model handled vertical mixing in the ocean:

- CTRL used the standard approach, where mixing is shaped by a simple cubic curve.
- EXP tested a new idea, replacing that curve with a more flexible sixth-order polynomial, to better capture how turbulence stirs heat and salt between surface and deeper waters.

The Hudhud case was evaluated using RAMA daily observations at 15°N, 90°E, where the cyclone was closest to the buoy on 9–10 October 2014. A 21-day window from 10 days before to 10 days after 10 October was used.

- CTRL: default cubic KPP shape function.
- EXP: modified sixth-order KPP shape function.
- Observations: RAMA buoy at 15°N, 90°E.
- Forcing: JRA55-do; cyclone track: JTWC (<https://www.metoc.navy.mil/jtwc/jtwc.html?best-tracks>).
- Diagnostics: wind speed, SST, OHC, D20, MLD, temperature, temperature gradient, temperature tendency and heat-budget terms.

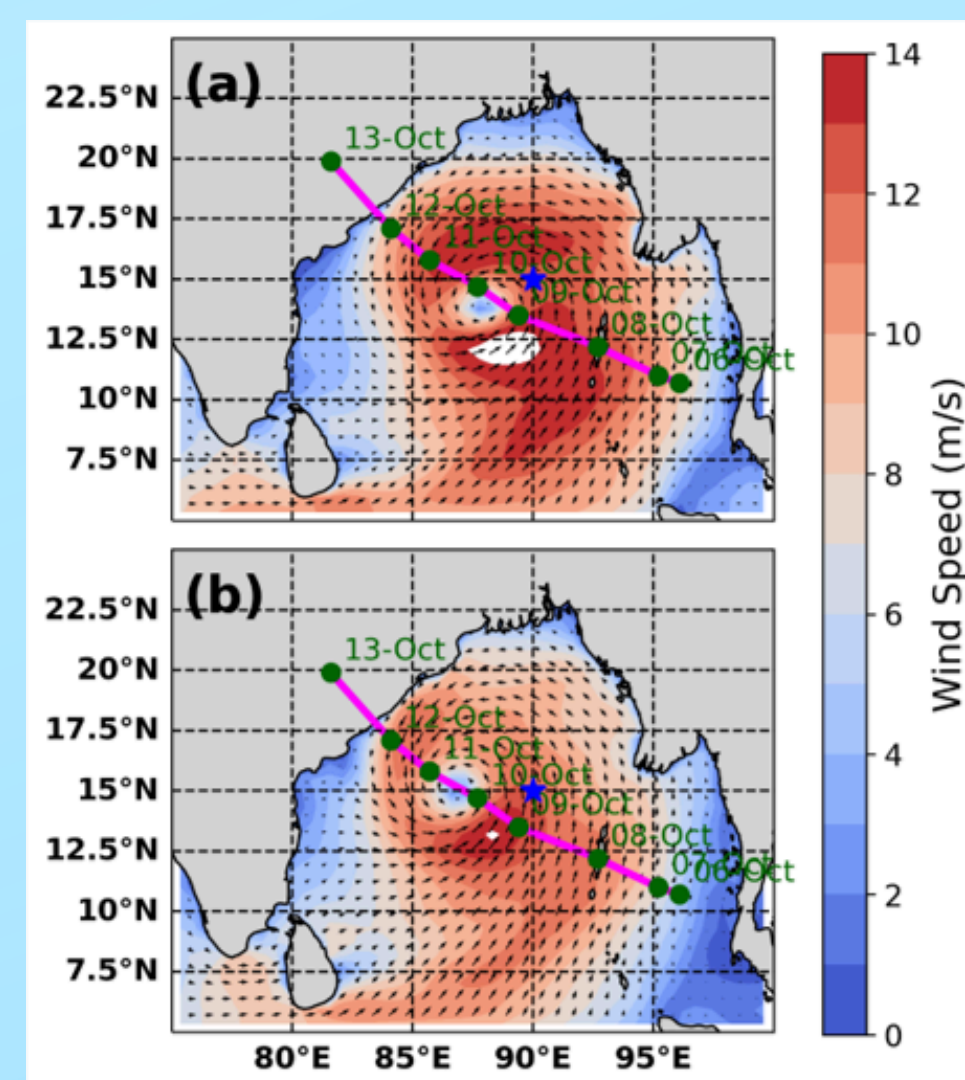


Fig. 1: Hudhud cyclone track displayed by pink line and green dots for particular day position with the cyclone wind (arrows). Shading denotes the wind speed (m/s). (a) and (b) are consecutively denoting for 9th Oct and 10th Oct which are cyclone closest location to the RAMA buoy (the blue star) 15°N 90°E.

3. Cyclone Evolution and Basic Ocean Response

JRA55-do and RAMA show a rapid increase in wind speed from about 3 to 12 m s⁻¹ during the approach to the cyclone peak, followed by a rapid decline. JRA55-do winds are 1–2 m s⁻¹ stronger than RAMA. RAMA SST decreases from >29.6°C before the cyclone to about 28.4°C afterwards. EXP reproduces the cyclone-induced SST cooling more realistically than CTRL. Both experiments overestimate OHC, D20 and MLD, but EXP is closer to RAMA. The D20 bias is reduced from about 20 m in CTRL to about 10 m in EXP, while the MLD bias is reduced by roughly 10–15 m.

Key results

The modified KPP formulation consistently reduces the magnitude of cyclone-related upper ocean biases. The improvement is most evident in SST cooling and the simulated evolution of OHC, D20 and MLD.

4. Vertical Thermal Structure and Stratification

CTRL exhibits a pronounced warm bias between approximately 50 and 120 m, reaching 2–5°C. EXP reduces this bias throughout the water column, with the largest improvement (>2.5°C) around 80–120 m. A residual warm bias remains in the upper 120 m, while a weaker cold bias occurs below. On the cyclone peak day, EXP agrees more closely with RAMA in temperature down to about 110 m and in vertical temperature gradient down to about 130 m. The temperature bias difference reaches approximately –2.8°C near 110 m, demonstrating a substantial reduction of the CTRL subsurface warm bias.

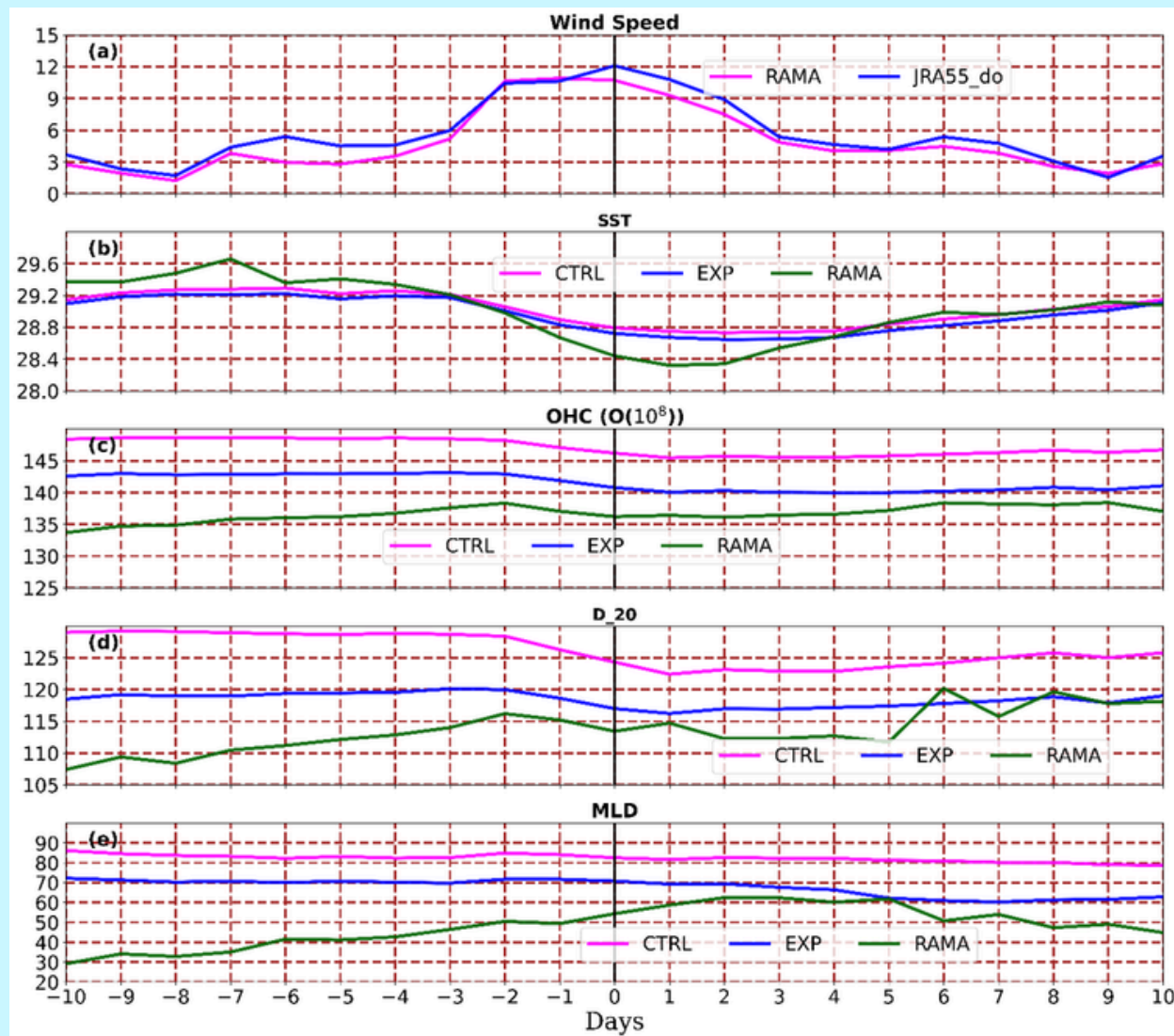


Fig. 2: Time series of (a) wind speed(m/s) from RAMA (magenta) and JRA55_do(blue). (b), (c), (d) and (e) are respectively the SST(°C), Oceanic Heat Content (J/m^2), thermocline depth, D20(m) and mixed layer depth, MLD(m) from CTRL (magenta), EXP (blue) experiments and RAMA observation(green).

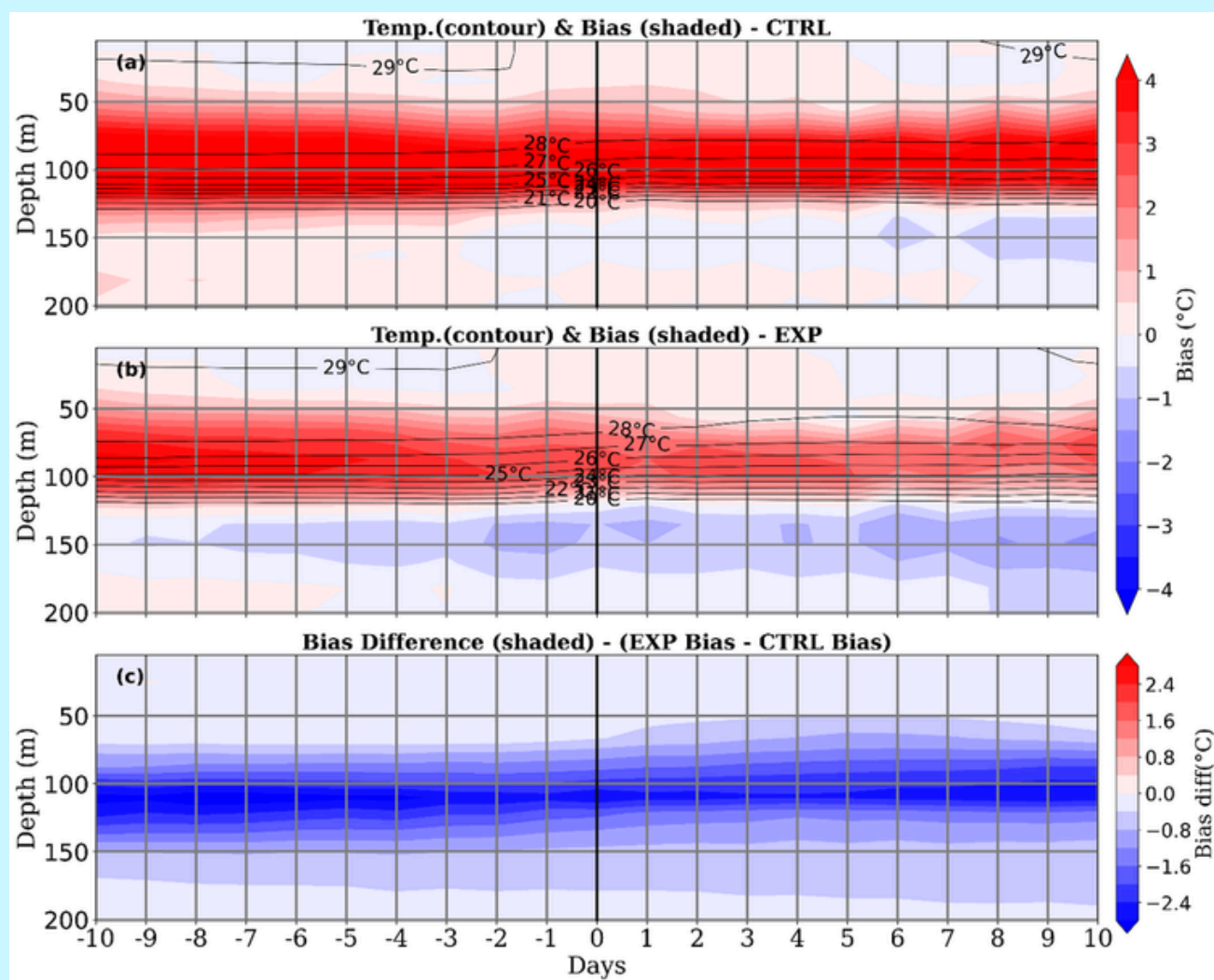


Fig. 3: Temperature (°C) depth section over the RAMA buoy location 15N90E from CTRL(a) and EXP(b) in contour and, CTRL bias(°C) and EXP bias (°C) with RAMA buoy is in shaded in (a) and (b). (c) the bias difference (°C). The x axis is from prior 10 days to post 10 days taking 10th Oct as 0th day.

5. Subsurface Bias and Responsible Processes

The largest improvement occurs in the 90–110 m layer. CTRL shows a larger subsurface warm bias, whereas EXP substantially reduces this bias. However, both simulations still cool the 90–110 m layer during the cyclone, while RAMA indicates subsurface warming, suggesting that cyclone-induced mixing remains somewhat excessive even in EXP.

- Temperature tendency analysis indicates that advection is the dominant contributor to subsurface temperature changes.
- Among advective components, vertical advection is dominant at 90–110 m, with correlations of 0.98 (CTRL) and 1.0 (EXP).
- CTRL is associated with stronger downward heat transport, favouring subsurface warming; EXP shows relatively more upward transport, reducing the warm bias.

6. Turbulent Heat Flux and Physical Interpretation

The vertical advective heat flux dominates the total temperature advection at 90–110 m. CTRL is characterized mainly by positive (downward) vertical heat transport, whereas EXP shifts toward negative (upward) transport. This change helps explain the reduction of the subsurface warm bias in EXP.

CTRL has a broader, flatter distribution and therefore larger variance in vertical turbulent heat flux than EXP. The higher variance indicates stronger turbulence and excessive mixing in CTRL, consistent with its larger surface cold and subsurface warm biases. EXP produces a narrower distribution and a more restrained turbulent response.

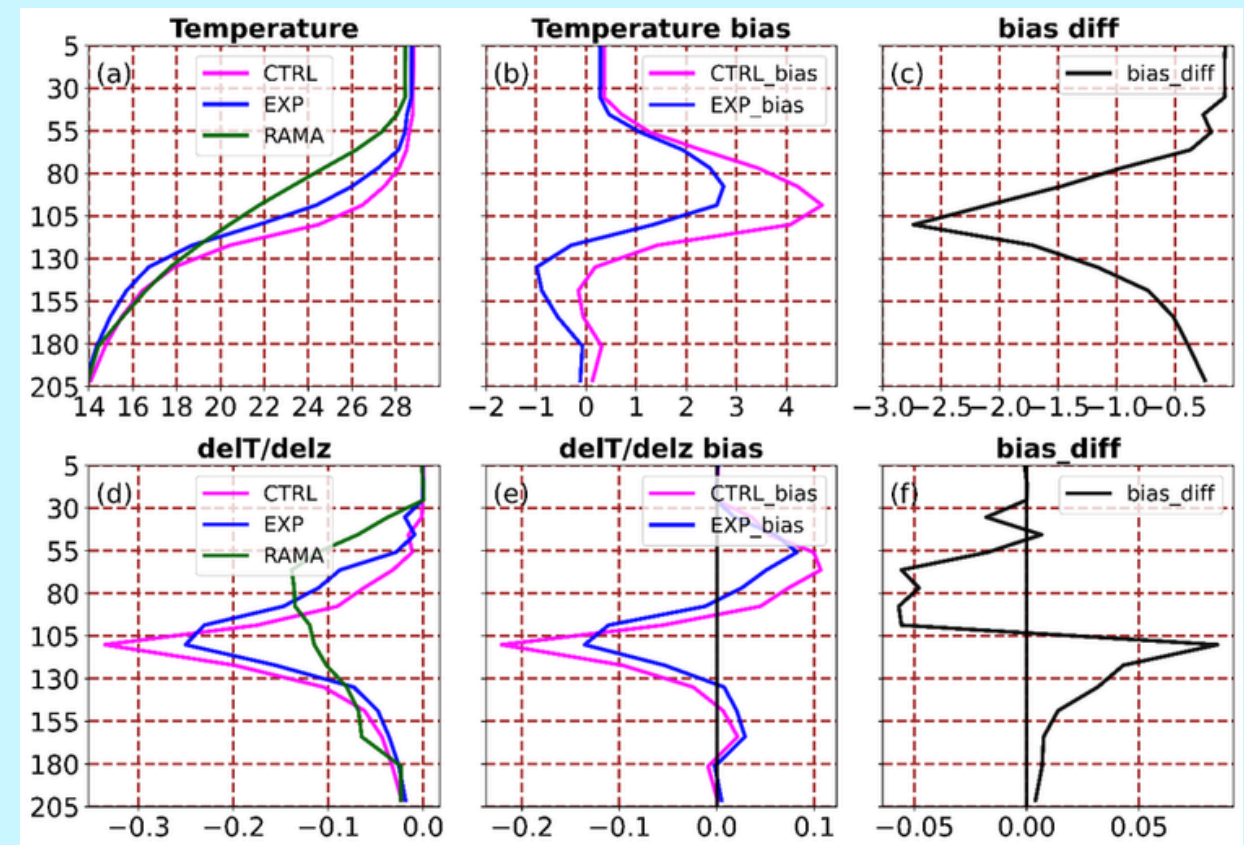


Fig. 4: Temperature (upper panel), $\Delta T/\Delta z$ (lower panel) with their bias with RAMA buoy data and bias difference. (a), (d) temperature, $\Delta T/\Delta z$ respectively for CTRL (magenta), EXP (blue) and RAMA (green). (b), (e) temperature, $\Delta T/\Delta z$ biases respectively with RAMA buoy data. (c), (f) the corresponding bias differences for temperature, $\Delta T/\Delta z$ profiles. This diagram is made for 10th October.

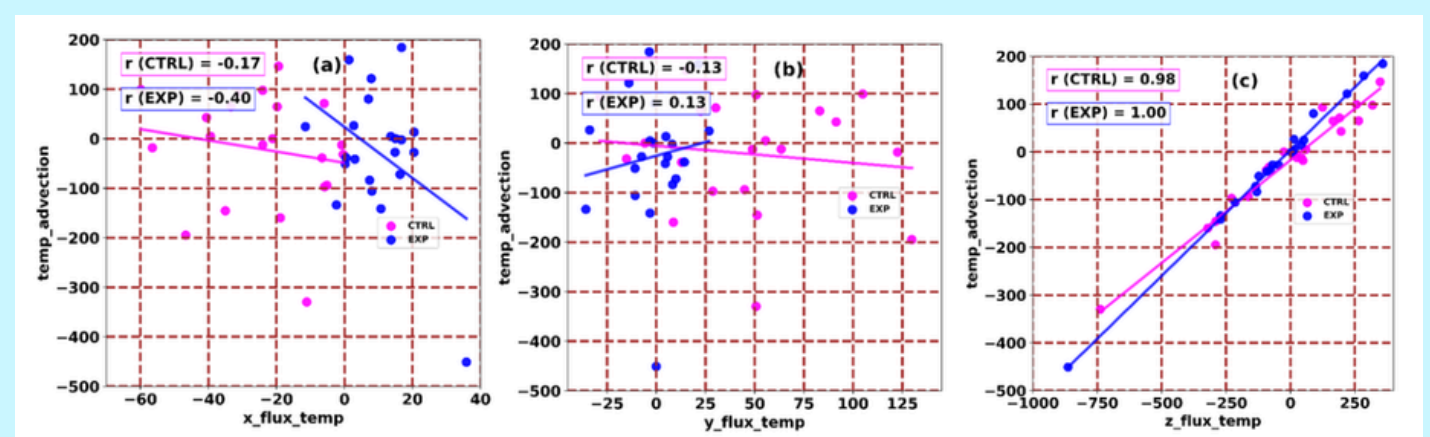


Fig. 5: Scatter diagram of temperature advection with respect to x-zonal (a), y- meridional (b), z-vertical (c) advective flux(W/m^2) in EXP(blue) to CTRL(magenta) averaged over 90m to 110m. Correlation is displayed in the respective box.

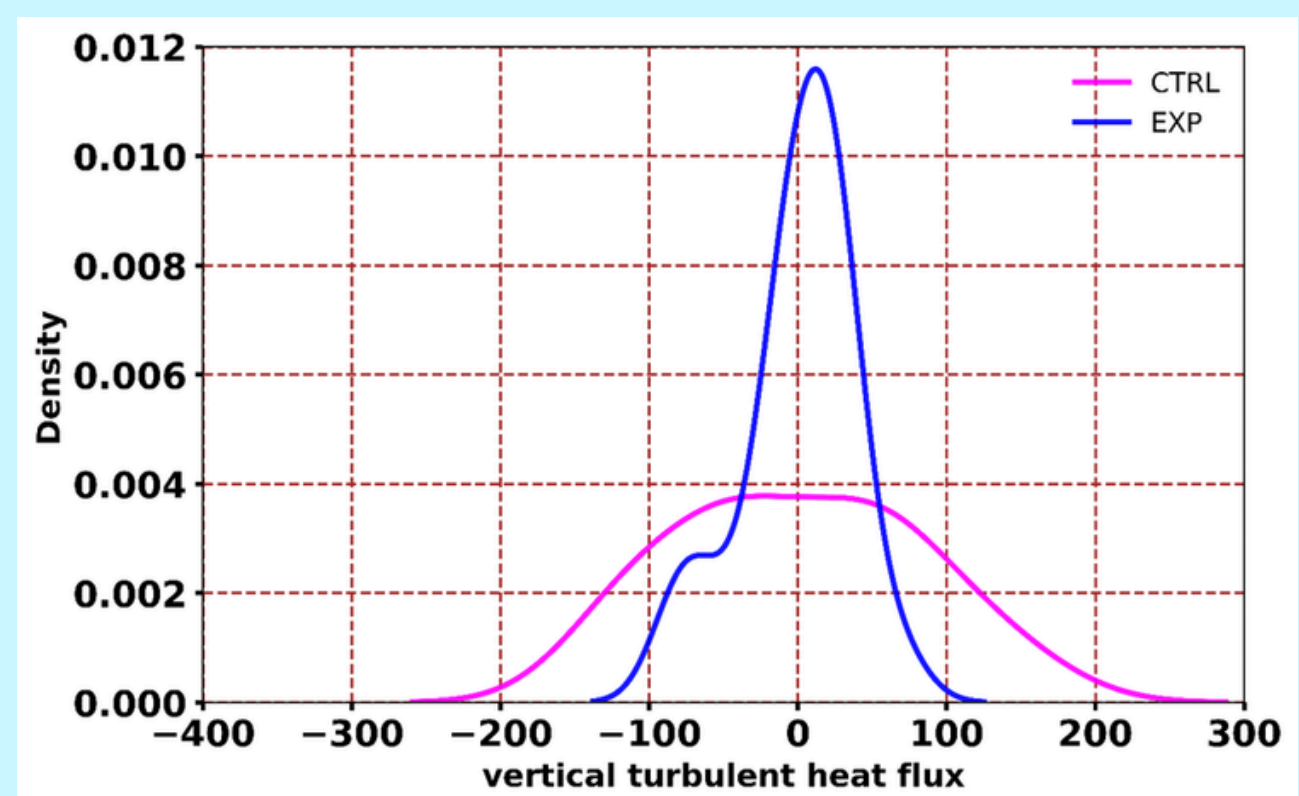


Fig. 6: The probability distribution of vertical turbulent heat flux(W/m^2) from CTRL (magenta) and EXP (blue).

7. Conclusions

- Hudhud generated strong wind-driven upper-ocean mixing, producing substantial SST cooling and changes in the subsurface thermal structure.
- The default cubic KPP formulation produces excessive mixing and larger biases in SST, OHC, D20, MLD and subsurface temperature.
- The sixth-order KPP shape function in EXP improves the simulated cyclone response and generally brings the model closer to RAMA observations.

- The strongest reduction in subsurface warm bias occurs around 90–110 m, with temperature-bias improvement exceeding 2.5°C around 80–120 m in the depth–time analysis.
- Vertical advection is the dominant contributor to the subsurface temperature tendency, while CTRL's larger turbulent heat-flux variance indicates excessive turbulence.
- Modifying the KPP diffusivity profile is therefore an effective approach for reducing excessive mixing and improving cyclone-induced upper-ocean thermohaline structure.

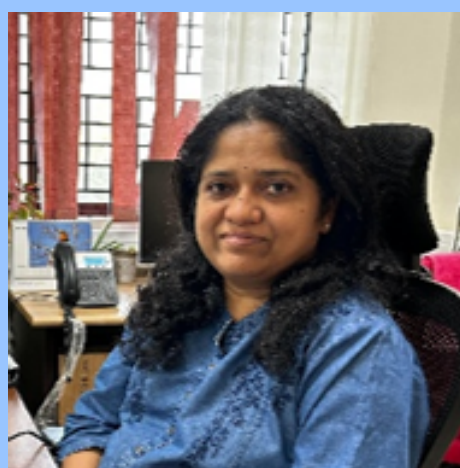
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Workshop report

Acoustic Techniques for Ecology Mapping and Assessment (ATLAS)



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A one-day workshop cum brainstorming meeting was conducted on Fisheries Acoustics, titled Acoustic Techniques for Ecology Mapping and Assessment (ATLAS), at the Centre for Marine Living Resources and Ecology, Ministry of Earth Sciences, Kochi, on 21st August 2026. The workshop was participated by nearly 50 scientists from almost 10 research institutes across the country, who have contributed in the field of ocean observations, fisheries acoustics, ocean & ecosystem modelling, fisheries, and resource assessment. Fisheries acoustics has emerged globally as a powerful, non-invasive tool for assessing marine living resources, enabling continuous, large-scale observations of fish and plankton distributions. By utilizing sound waves to detect and quantify biological targets in the water column, acoustic techniques provide high-resolution insights into biomass, behavior, and spatial dynamics of marine organisms.

In India, despite significant advancements in marine science and fisheries research, the operational use of fisheries acoustics remains limited. Present focus on deep and distant water fisheries for identifying potential resources for commercial exploitation, demands for regular biomass assessment, towards sustainable management of these resources. Also, the policies are to be strengthened to practice ecosystem-based fisheries management strategies. This creates a critical gap in our ability to generate sustained observations necessary for biomass, climate-resilient assessments, and operational oceanography, the use of acoustics-based techniques is to be strengthened in this regard. CMLRE holds the capacity for observation, synthesis and capacity building in these aspects, majorly utilizing the underwater acoustics systems onboard FORV Sagar Sampada. Leveraging the large data generated through these and linking all such facilities offers a transformative opportunity to create a distributed observation network, significantly enhancing data availability across the Indian Exclusive Economic Zone (EEZ). Also, the Careful and effective utilization of backscatter data from Acoustic Doppler Current Profilers (ADCP) installed onboard different RVs and the mooring systems, can extract information^S on the spatio-temporal variation in the plankton, even at deeper layers.

The participants discussed what can realistically be achieved using fisheries acoustics, with case studies at different parts of the world, what limitations currently exist, and how acoustic observations can be better connected with biological, physical, and ecosystem studies. The discussions moved across several themes, including fish biomass estimation, target strength, zooplankton, mesopelagic organisms, deep scattering layers (DSLs), oceanographic processes, modeling, spatial and temporal variability, data integration, possible technological advancements and the need for a coordinated national data & observation framework. A major outcome of the workshop was a shared understanding that fisheries acoustics should not be treated as an isolated technique solely for estimating fish biomass. Instead, it has the potential to become an important component of an integrated marine ecosystem observation system.

Overall, the ATLAS workshop highlighted the need to strengthen fisheries acoustics in India through sustained and coordinated observations, improved calibration and standardization, and integration of acoustic data with biological, physical oceanographic and ecosystem modelling approaches. The discussions emphasized applications in fish and zooplankton assessment, mesopelagic and deep-scattering-layer studies, biomass and standing-stock estimation, potential fishing zone advisories, seabed and demersal habitat mapping, and marine mammal studies. The workshop identified the need for species-specific Target Strength information, biological validation, improved noise correction, georeferenced and long-term observations, and a national platform for acoustic data management and sharing. Emerging approaches including ADCP backscatter, multi-frequency and multibeam acoustics, eDNA, optical sensors and AI/ML were recognized as important for improved species identification and ecosystem assessment. The workshop recommended establishing a national fisheries acoustics working group, strengthening inter-institutional collaboration and capacity building, developing low-cost and real-time observation capabilities, and translating acoustic research into operational products for sustainable fisheries management.



Announcement



Ocean Society of India and Indian Institute of Tropical Meteorology Organize

Tenth Conference (First International Conference) of the Ocean Society of India (OSICON-27)

With Special Focus on
From Science to Impact: Transforming Ocean Climate Science for Society

 : 20 -22 January 2027

 : Indian Institute of Tropical Meteorology, Pune, India

Preamble

The Ocean Society of India (OSI) was launched on 19th March 2006 at Kochi with an aim to provide a forum for sharing the knowledge and experience of individuals, scientific institutions and industrial organizations in science, technology, engineering and allied fields of the Ocean. The OSI with registered office at Kochi functions from the Centre for Marine Living Resources & Ecology (CMLRE). With eight chapters in several cities and a life membership of 960 as on August 2026, the Society has been organising the Ocean Society of India Conference (OSICON) every two years since 2009. These conferences hosted by leading academic/research institutes were very successful in bringing together researchers, students and professionals working in the area of ocean sciences, technology and allied fields to share their knowledge. The OSICON-27 will mark the 10th national and the first international conference, to be held at Indian Institute of Tropical Meteorology (IITM), Pune during 20-22 January 2027. Centered on the theme 'From Science to Impact: Transforming Ocean Climate Science for Society', the event will include keynote and invited talks on Indian Ocean climate by eminent international and national experts. The conference is designed to nurture the next generation of ocean scientists by offering students and early-career researchers opportunities to present their work and interact with global leaders in the field.

Objectives

- Provide a platform for oceanographers from across the country and abroad to share their expertise
- Enable researchers to connect with the international oceanography community
- Facilitate national and international collaborations

Themes:

- Physical Oceanography
- Chemical Oceanography
- Marine Geophysics & Geological Oceanography
- Biological Oceanography
- Oceans and Atmosphere
- Ocean Engineering
- Marine Microbiology and Biotechnology
- Blue Economy
- Bioinformatics
- Remote Sensing and In-situ Observations
- Ocean Modeling
- Monsoon in a Changing Climate
- Polar and Cryospheric Studies
- Coastal Estuary and Open Ocean Processes

Special Sessions

- ECOP -ECR Session
- WCRP Side Meeting
- IOC/ IODP Session
- IMS Session
- IGU Session
- Industry-Research Networking Session
- Interdisciplinary + Citizen science session

Abstract submission closes: 30 October 2026

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We'd love to hear from you! Please feel free to send your comments, criticism, feedback, and contributions to: osioceandigest@gmail.com.