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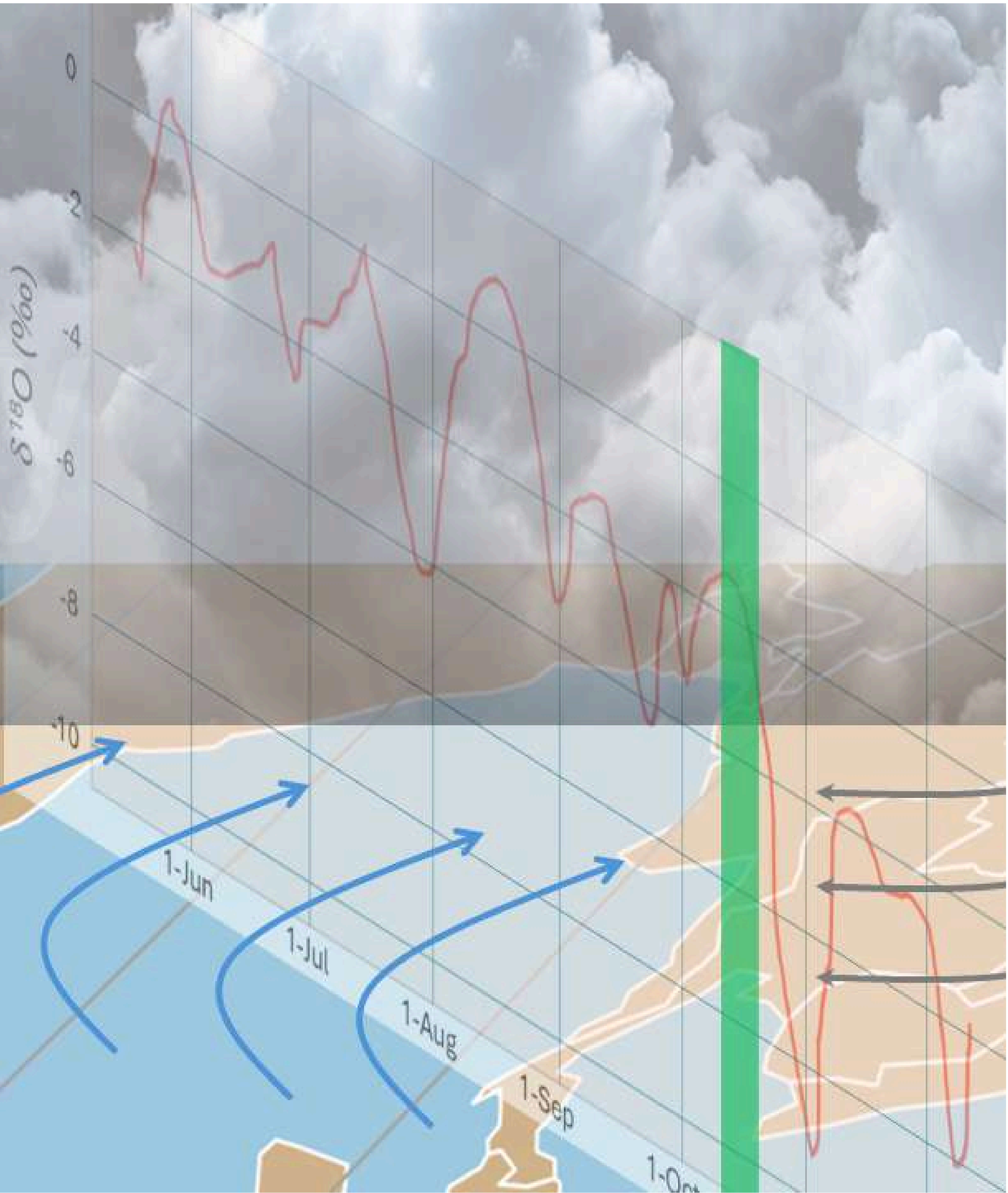

Ocean Digest

Volume 12, Issue 3, July 2025

From the Editors' Desk

As we present the third issue of Ocean Digest for 2025, we find ourselves reflecting on the remarkable diversity of processes that shape the oceans, the atmosphere, and the climate systems that bind them. This issue brings together three distinct yet interconnected scientific narratives- each illuminating a different facet of the Indian Ocean realm, from the deep seafloor to the monsoon-laden skies above.

Our invited article for this issue explores one of the most intriguing and dynamic environments of the deep sea: methane cold seeps. These systems, often hidden along continental margins, are windows into the Earth's subsurface plumbing. Cold seeps form where methane-rich fluids migrate upward through faults, fractures, and sedimentary conduits, escaping at the seabed under near-ambient temperatures. Their presence is marked by gas flares, chemosynthetic communities, and the precipitation of authigenic carbonates—features that reveal a delicate interplay between geology, geochemistry, and biology. In the Indian Ocean, particularly along the Krishna–Godavari and Cauvery–Mannar basins, cold seeps host thriving ecosystems of tubeworms, clams, mussels, and microbial consortia that rely not on sunlight, but on chemical energy derived from methane and hydrogen sulfide. The invited article in this issue synthesizes recent discoveries from these regions, underscoring India's emergence as a significant contributor to global cold-seep research.

From the deep ocean, we shift our attention to the atmosphere and its long-term rhythms. The second article in this issue examines past monsoon variability using marine and terrestrial proxies, including foraminiferal Mg/Ca ratios and speleothem oxygen isotopes. These archives allow us to peer into monsoon behavior across millennial timescales, revealing how sea surface temperatures, atmospheric gradients, and hemispheric climate modes have shaped rainfall patterns over thousands of years. Such reconstructions are essential for understanding the sensitivity of the Indian Summer Monsoon to natural climate variability—knowledge that becomes increasingly relevant in a warming world.

The monsoon theme continues with a third contribution that brings the discussion closer to home: precipitation isotopes from the Andaman Islands. This article demonstrates how high-frequency rainfall isotope measurements can capture the seasonal transition from the southwest monsoon to the post-monsoon northeasterlies. The isotopic shift associated with this withdrawal phase provides a powerful diagnostic tool for identifying the end of the monsoon season, an aspect of monsoon dynamics that remains less well defined than its onset. By integrating atmospheric circulation patterns with isotopic signatures, the study offers a fresh perspective on how regional moisture sources evolve through the monsoon cycle.

Together, these articles highlight the breadth of scientific inquiry within the Ocean Society of India—from deep-sea ecosystems shaped by methane fluxes to atmospheric processes recorded in corals, foraminifera, and rainfall. They also remind us that the ocean and monsoon are not separate domains but deeply intertwined systems whose interactions influence climate, ecosystems, and human livelihoods across the subcontinent.

We hope this issue inspires curiosity, sparks new conversations, and encourages continued exploration of the ocean–monsoon continuum.

Yours faithfully,
The Editorial Team

Cover page: Monsoon Circulation and Isotopic Signatures at Port Blair The visual integrates atmospheric circulation patterns with isotopic data from Port Blair to highlight the seasonal dynamics of the Indian monsoon. The red line graph traces precipitation isotopic ($\delta^{18}O$) variations in precipitation, showing enriched values during the southwest monsoon (June–September) and a distinct decline during the post-monsoon period (October–December), marked by a green vertical bar. Blue curved arrows represent the southwesterly monsoon winds, while light grey arrows depict the northeasterly circulation. These contrasting airflows transport moisture with differing isotopic compositions, reflected in the observed shift in rainfall isotopes following the seasonal transition.

Cover design: Supriyo Chakraborty

Ocean Digest

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Methane cold seep ecosystem: A seabed expression of deep gas sources and subsurface fault fracture networks.

Invited Article

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Abstract

Methane cold seeps are dynamic seafloor systems that form where methane-rich fluids ascend from deep reservoirs and seep at the seabed along structurally controlled pathways. Fault-fracture networks, gas chimneys, and shale diapirs provide the plumbing that links deep thermogenic and/or biogenic gas sources to the sediment-water interface. Methane cold seeps along the eastern Indian margin host vigorous, fault-controlled fluid discharges linking deep, over-pressured thermogenic-biogenic methane reservoirs to the seabed. Integrated geophysical, geochemical, and ecological investigations in the Krishna-Godavari and Cauvery-Mannar basins reveal persistent gas flares, shallow methane hydrates, and diverse chemosynthetic communities sustained by sulfate-driven anaerobic oxidation of methane (SD-AOM). Authigenic carbonates, elevated H_2S, and seep-endemic fauna including Lamellibrachia tubeworms, Calyptogena clams, mussels, gastropods, and squat lobsters indicate long-term seepage and focused fluid migration through faults and fractures. These findings establish the Indian EEZ as a major cold-seep province and highlight its significance for deep-sea carbon cycling and hydrate system dynamics.

Introduction

Methane cold seeps are sites of focused fluid discharge where methane-rich, reduced fluids escape at the seabed under near-ambient temperature conditions (Fig. 1). Globally, cold seeps have been identified along passive and active continental margins (Fig. 2: Pillutla et al., 2024; Suess, 2020). Their distribution is strongly controlled by subsurface basin architecture and the efficiency of fluid-migration pathways (Dewangan et al., 2010; Suess, 2020). Methane at seep sites originates from either thermogenic process, which involve the breakdown of kerogen at elevated temperatures and pressures, or from microbial methanogenesis in anoxic sediments, where CO_2 reduction and acetate fermentation occur (Whiticar et al., 1986). Accumulation of methane in stratigraphic traps is a necessary but not sufficient condition for seep development; vertical or subvertical conduits must breach seal layers and connect deep reservoirs to near-surface sediments. Faults, fractures, gas chimneys, shale diapirs, toe-thrusts, and mass-transport deposits are all known to provide such pathways (Dewangan et al., 2021; Mazumdar et al., 2009).

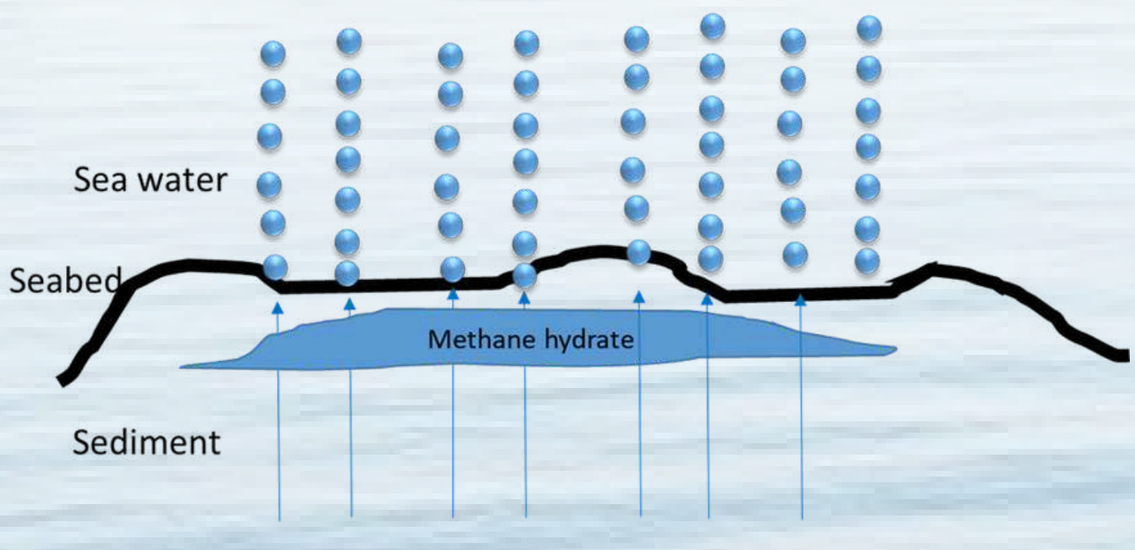

Fig. 1. Schematic illustration of methane seepage across the sediment-water interface at cold seeps

When methane-rich fluids rise into the uppermost sediment column, they intersect with downward-diffusing sulfate from seawater. This interaction establishes a sulfate-methane transition zone (SMTZ), a narrow but highly reactive interface where anaerobic oxidation of methane (AOM) converts methane and sulfate into bicarbonate and hydrogen sulfide. This process modifies porewater chemistry, drives the formation of authigenic minerals, and fuels chemosynthetic ecosystems (Levin et al., 2016). Chemosynthesis is the microbial use of chemical energy from reduced compounds such as hydrogen sulfide or methane, fueling ecosystem development in dark ocean environments. Methanotrophs oxidize methane (CH_4), while thiotrophs oxidize hydrogen sulfide (H_2S), forming the metabolic foundation of these communities. The presence of diverse fauna at such depths underscores the fundamental distinction between surface ecosystems and deep-sea communities.

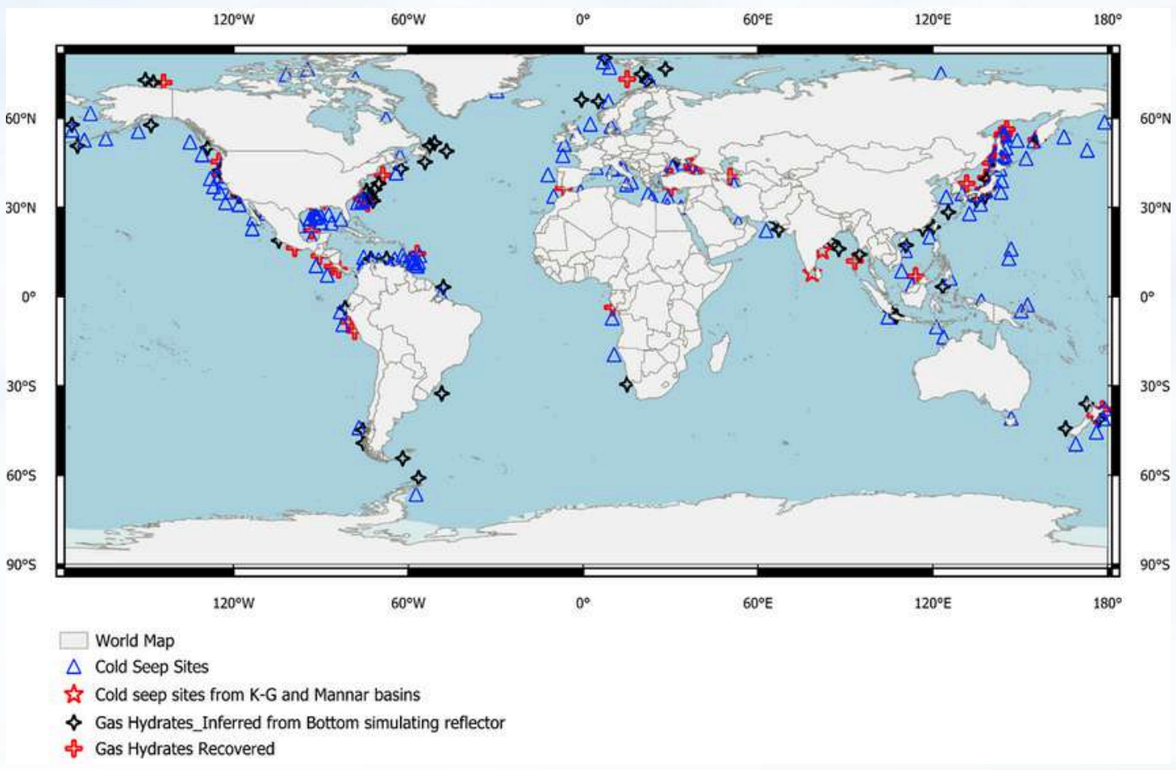

Fig. 2. Global distribution of methane cold seeps and gas hydrates across the globe modified after Pillutla et al. (2024)

The eastern Indian margin particularly the Krishna-Godavari (K-G) Basin and the Cauvery-Mannar Basin has emerged as a key natural laboratory for investigating cold seep processes in detail, encompassing their geological, geochemical, and ecological dimensions. Over the last decade and a half, methane hydrate research group at the CSIR-National Institute of Oceanography (CSIR-NIO) has documented paleo-and active seepage activities, gas hydrate systems, authigenic carbonates, and seep faunas in these basins, offering a coherent example of how structural geology, fluid flow, and biogeochemistry interact at cold seeps (Dewangan et al., 2010; Dewangan et al., 2021; Joshi, 2011; Joshi et al., 2014; Mazumdar et al., 2009; Mazumdar et al., 2021; Mazumdar et al., 2019; Mazumdar et al., 2012; Peketi et al., 2022; Pillutla et al., 2024; Ramprasad et al., 2013)

Method

Methane cold seep investigations involve multiple experimental protocols, including geophysical and geological studies. The geophysical studies include bathymetry, sub-bottom profiling, and water-column profiling to detect gas signatures. The geochemical protocol involves collecting a sediment core, extracting porewaters and gases, and subsampling the sediments. The composition of gases and porewater is measured at the onshore laboratory.

Results and Discussion

The study by Mazumdar et al. (2019) documents the first discovery of an active methane-seep ecosystem in the Krishna-Godavari (K-G) basin at water depths of 900-1800 m. High-resolution multibeam water-column imaging revealed gas flares rising up to ~700 m above the seabed, indicating vigorous methane ebullition. These seep sites occur along toe-thrust fault systems and diapiric shale ridges, confirming the role of fault-controlled fluid migration in focusing methane-rich advective flow. Seafloor sampling revealed a diverse chemosynthetic fauna, including Bathymodiolus mussels, Calyptogena clams, Acharax, Conchocele, (Fig. 4) Provannid gastropods, limpets, siboglinid tubeworms (Sclerolinum), serpulid worms, brittle stars, squat lobsters, and goose barnacles. Many of these fauna host thiotrophic and methanotrophic symbionts, that rely on elevated fluxes of hydrogen sulfide and methane at seep sites. A significant outcome of the study is the recovery of shallow methane hydrates about 2 to 3 meters below seafloor (mbsf) directly beneath seep fauna. These hydrates occur as fracture-filling, cavity-filling, and tubular forms, (Fig. 3) with $\delta^{13}C\text{-}CH_4$ values (~ -74‰) indicating a methane is derived from biogenic sources. Their occurrence at unusually shallow depths is attributed to intense methane flux, rapid upward migration through fracture networks, and favourable pressure-temperature conditions within the gas hydrate stability zone. This work places India on the global cold-seep map and demonstrates that the K-G basin hosts a previously unknown, highly productive seep ecosystem.

Fig. 3. (a) Methane hydrate observed within sediment core collected from the K-G basin cold seep site; (b) Methane hydrate containing gas cavities; (c) Fracture-filling methane hydrate (indicated by arrow mark); and (d) tubular forms of methane hydrate (indicated by arrows) as documented by Mazumdar et al. (2019)

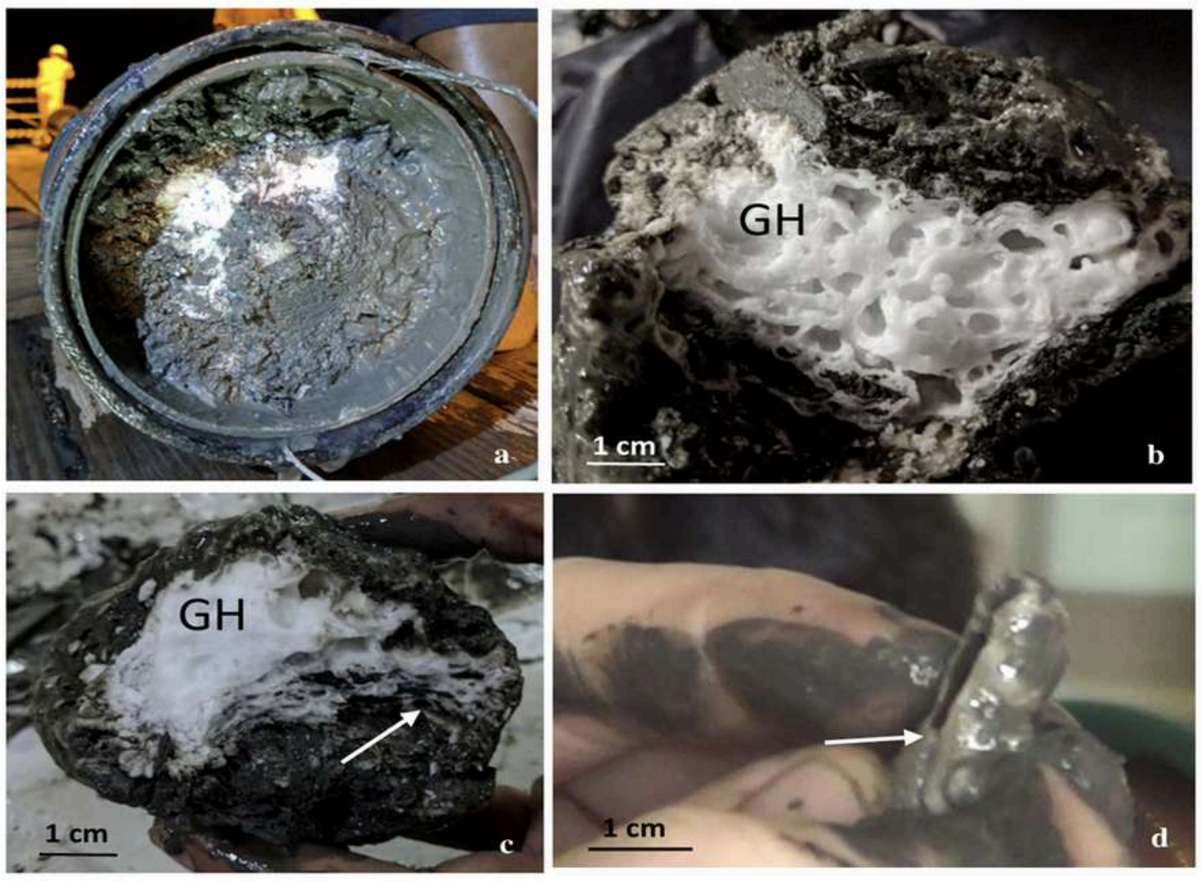

Fig. 4. Chemosynthetic bivalves recovered from cold seep sites in the K-G Basin a) Calyptogena sp., b) Conchocele sp., c) Acharax sp., and d) Bathymodiolus clusters as reported by Mazumdar et al. (2019).

A subsequent study by Mazumdar et al. (2021) in the Mannar basin revealed the persistence of methane gas flares at depths of 900 to 1200 meters, coinciding with the discovery of chemosynthetic fauna in the basin. The first publication reports the discovery of Lamellibrachia (Siboglinidae) tubeworms (Fig. 5), a globally distributed but previously unrecorded taxon in the Indian Ocean from a methane cold-seep site at 1644 m water depth in the Cauvery-Mannar Basin. This seep system consists of authigenic carbonate crusts (chemoherms) enriched with large relict Calyptogena shells, indicating long-term seepage. The Lamellibrachia tubes were firmly anchored into these carbonate substrates, with individuals reaching up to 93 cm in length, suggesting longevity (potentially >100 years based on known growth rates of vestimentiferans). The publication describes a diverse associated fauna, including two morphotypes of the Munidopsis squat lobster, Buccinidae gastropods, and abundant Calyptogena bivalve shells. The living community structure reflects typical seep assemblages fueled by sulfide-methane-rich pore fluids. Sediment geochemistry revealed exceptionally high pore-water H_2S concentrations (3800-12900 µM) at ~30-40 cm depth, sufficient to sustain sulfide-oxidizing symbionts within Lamellibrachia trophosome tissues. The sulfide originates from SD-AOM, which simultaneously promotes carbonate precipitation, forming the chemoherm. Methane hydrates were recovered from fractures within sediments, with gas composition (presence of ethane and propane) and $\delta^{13}C\text{-}CH_4$ values (-28.4 to -79.5 ‰) indicating mixed thermogenic and biogenic methane sources, channelized through fault-fracture networks.

Fig. 5. Lamellibrachia tubes recovered from the methane seep site in the Cauvery-Mannar Basin as reported by Mazumdar et al. (2021).

Conclusion

India's eastern continental margin hosts vigorous methane cold-seep systems sustained by deep, over-pressured gas reservoirs and fault-fracture networks that focus fluid migration toward the seafloor. Integrated discoveries from the Krishna-Godavari and Cauvery-Mannar basins reveal active methane discharge, shallow gas hydrates, and long-lived chemosynthetic communities dominated by Lamellibrachia tubeworms, Calyptogena clams, mussels, gastropods, and squat lobsters. Elevated fluxes of methane and the hydrogen sulfide generated through SD-AOM sustain these ecosystems and drive extensive authigenic carbonate formation. The combined geological, geochemical, and ecological evidence firmly positions the Indian EEZ as a major global cold-seep province. These findings underscore the importance of deep thermogenic-biogenic methane sources and tectonic control in shaping seep dynamics, carbon cycling, and deep-sea habitability.

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Student Article

Indian Ocean SST Variability from Proxies and Its Impact on the Indian Summer Monsoon

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Abstract
The Indian summer monsoon (ISM) is traditionally explained by land–sea temperature contrast. However, uncertainties remain regarding how circulation sustains after onset, when this gradient weakens. Xavier et al. (2007) proposed that the tropospheric temperature gradient (ΔTT) drives ISM variability. This study examines proxy-derived sea surface temperature (SST) and monsoon rainfall records across paleo and modern timescales. Results suggest that warming of the Indian Ocean weakens monsoon intensity, though discrepancies highlight the complexity of monsoon dynamics.

Introduction

The Indian Summer Monsoon (ISM) circulation has long been attributed to the land–sea temperature contrast. While this theory is well established, it suffers from certain limitations. Following the onset of the monsoon, land temperatures decline, weakening the land–ocean gradient. Despite this reduction, monsoon circulation persists, delivering substantial rainfall to the Indian subcontinent for nearly four months.

Xavier et al. (2007) revisited the temperature gradient theory and proposed an alternative hypothesis: it is not the surface land–ocean gradient but rather the tropospheric temperature gradient that drives monsoon circulation. To test this, they calculated tropospheric temperatures within two vertical boxes—one spanning 5°N–35°N, 40°E–100°E (Northern box) and the other 15°S–5°N, 40°E–100°E (Southern box)—extending vertically from 600 hPa to 200 hPa. Their analysis demonstrated that the difference between the Northern and Southern box temperatures (ΔTT) is strongly proportional to ISM intensity. Years with relatively high ΔTT correspond to normal or above-normal rainfall, whereas El Niño years, typically associated with below-normal rainfall, are characterized by low ΔTT values.

Using data from 1950 to 2003, Xavier et al. (2007) provided empirical support for this hypothesis. They argued that a warmer Indian Ocean enhances convective activity, transporting heat anomalies aloft, thereby weakening ΔTT and reducing monsoon intensity. Indeed, the ISM has shown a progressive decline over the past five to six decades, coinciding with rapid warming of the equatorial Indian Ocean (Roxy et al., 2015; Roxy et al., 2020). This suggests that the hypothesis holds on modern timescales.

However, its applicability to paleo-timescales remains less explored. Limited evidence exists to support the hypothesis in deeper geological contexts. Kumar et al. (2021) investigated the relationship during the last glacial period and found a strong correlation between tropospheric temperature differences and monsoon circulation during deglaciation (approximately 16–14 kyr BP). Building on such studies, the present work seeks to further examine the hypothesis across different temporal horizons.

Data and Methods

Our approach combines sea surface temperature (SST) reconstructions with speleothem oxygen isotope ($\delta^{18}O$) records to explore monsoon–ocean linkages across geological timescales. The guiding principle is simple: SST reflects the thermal state of the ocean, while speleothem $\delta^{18}O$ serves as a well-established proxy for monsoon rainfall intensity (Wang et al., 2001; Berkelhammer et al., 2012; Sinha et al., 2007; Sinha et al., 2018). By examining these two archives side by side, we can trace how precipitation and ocean conditions co-varied through time.

Long-term SST reconstructions.

Dekens et al. (2002) demonstrated that Mg/Ca ratios in foraminifera can be calibrated into SST estimates. Building on this technique, Saraswat et al. (2008) analyzed Globigerinoides ruber from a sediment core in the equatorial Indian Ocean, producing an SST record that spans ~137 kyr. This dataset provides the backbone for our long-term SST analysis.

Recent SST reconstructions.

For shorter, more recent intervals, corals offer high-resolution insights. Coral $\delta^{18}O$ records not only capture SST but also seasonal variability. We used coral data from the Maldives (Storz et al., 2021), which cover the period 1917–2007, offering a century-scale window into SST fluctuations in the northern Indian Ocean.

Precipitation variability from speleothems.

To reconstruct monsoon rainfall, we relied on speleothem $\delta^{18}O$ records from multiple caves across South Asia:

- Bitto Cave (30.79°N, 77.77°E, northern India): spanning the last 280 kyr (Kathayat et al., 2016).
- Dandak Cave (19°N, 82°E, eastern India): covering the past 1,400 years (Sinha et al., 2007).

These records provide complementary perspectives on monsoon variability across vastly different timescales.

Regional coherence with Chinese caves.

Because the Indian Summer Monsoon and Asian Summer Monsoon often display coherent behavior (Berkelhammer et al., 2012), we also incorporated speleothem records from China:

- Yamen Cave (Southwestern China): $\delta^{18}O$ record from deglaciation (~16,200 yr BP) to the early–mid Holocene (~7,300 yr BP), with ~9-year resolution (Yang et al., 2010).
- Hulu Cave (Eastern China): $\delta^{18}O$ record spanning 178–128 kyr BP (Cheng et al., 2006).
- Xinya Cave: $\delta^{18}O$ record from the late Holocene (Li et al., 2017).

Together, these datasets allow us to compare monsoon dynamics across regions and timescales, highlighting both local variability and broader hemispheric coherence.

Results and Discussion

The equatorial Indian Ocean SST record, reconstructed from Globigerinoides ruber Mg/Ca ratios (Saraswat et al., 2008), spans approximately 135–30 kyr BP. Owing to differences in sampling resolution, the dataset was divided into two intervals: Time Slice 1 (70–50 kyr BP; Figure 1) and Time Slice 2 (105–135 kyr BP; Fig. 2).

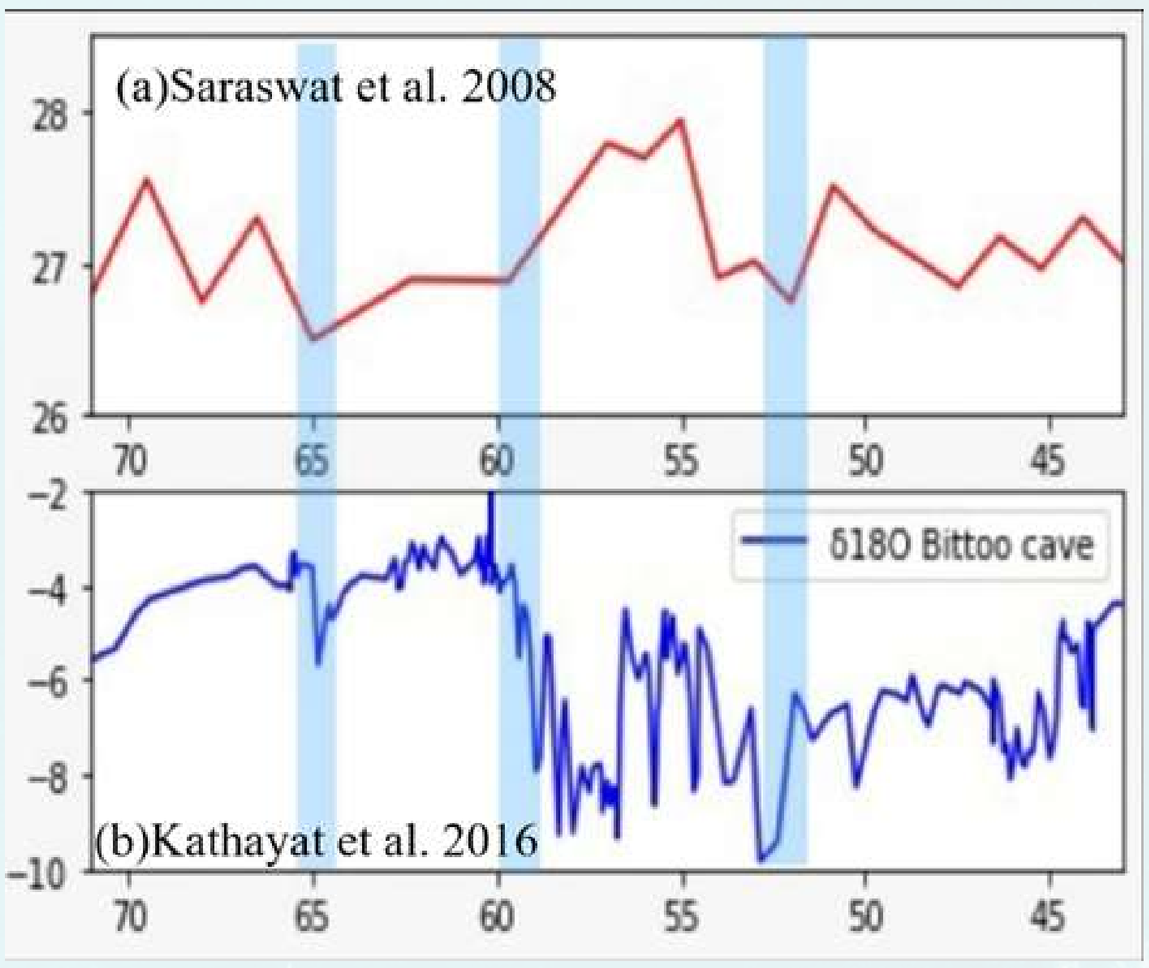

Figure 1 (a) Equatorial Indian Ocean SST variability from 75 to 44 Kyr BP (b) Oxygen isotopic variability of a speleothem sample retrieved from the Bitto cave of northern India (75-44 Kyr BP)

For Time Slice 1 (Fig. 1; 75–44 kyr BP), SST variability was compared with speleothem $\delta^{18}O$ records from Bitto Cave, northern India (Kathayat et al., 2016). Between 58-40 Kyr BP, $\delta^{18}O$ values remained relatively low (–4 to –10 ‰) relative to the 70-60 Kyr BP period, suggesting a strong monsoon, though fluctuations of 2–4 ‰ were evident. Around 55–52 kyr BP, SST decreased significantly. The later portion of this interval (71-58 kyr BP) showed fairly constant $\delta^{18}O$ values, indicative of a stable monsoon. Notably, at ~65 kyr BP, speleothem $\delta^{18}O$ declined sharply by ~2‰, coinciding with an SST minimum of ~26.5 °C (Fig. 1a, 1b).

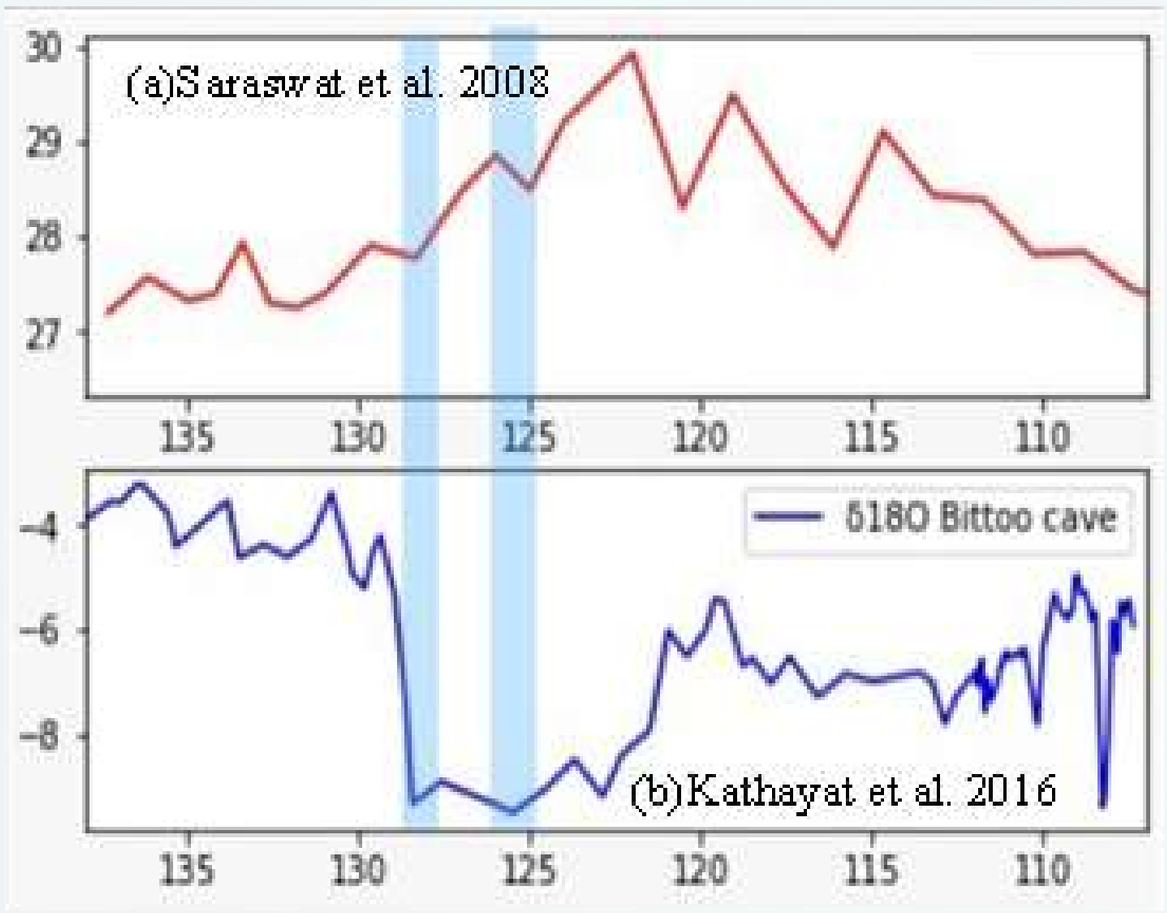

Fig. 2 (a) SST variability from 137-107 Kyr BP representing the Equatorial Indian Ocean. (b) Oxygen isotopic variability of a speleothem sample retrieved from the Bitto cave of northern India (137-107 Kyr BP)

Fig. 2a and b show the SST and d18O variability for the Time Slice 2, 137–107 kyr BP time window. Around ~128.5 kyr BP, one of the lowest $\delta^{18}O$ values was observed, coinciding with a slight drop in SST. A similar association was evident at ~125.5 kyr BP, reinforcing the linkage between cooler SSTs and stronger monsoon activity.

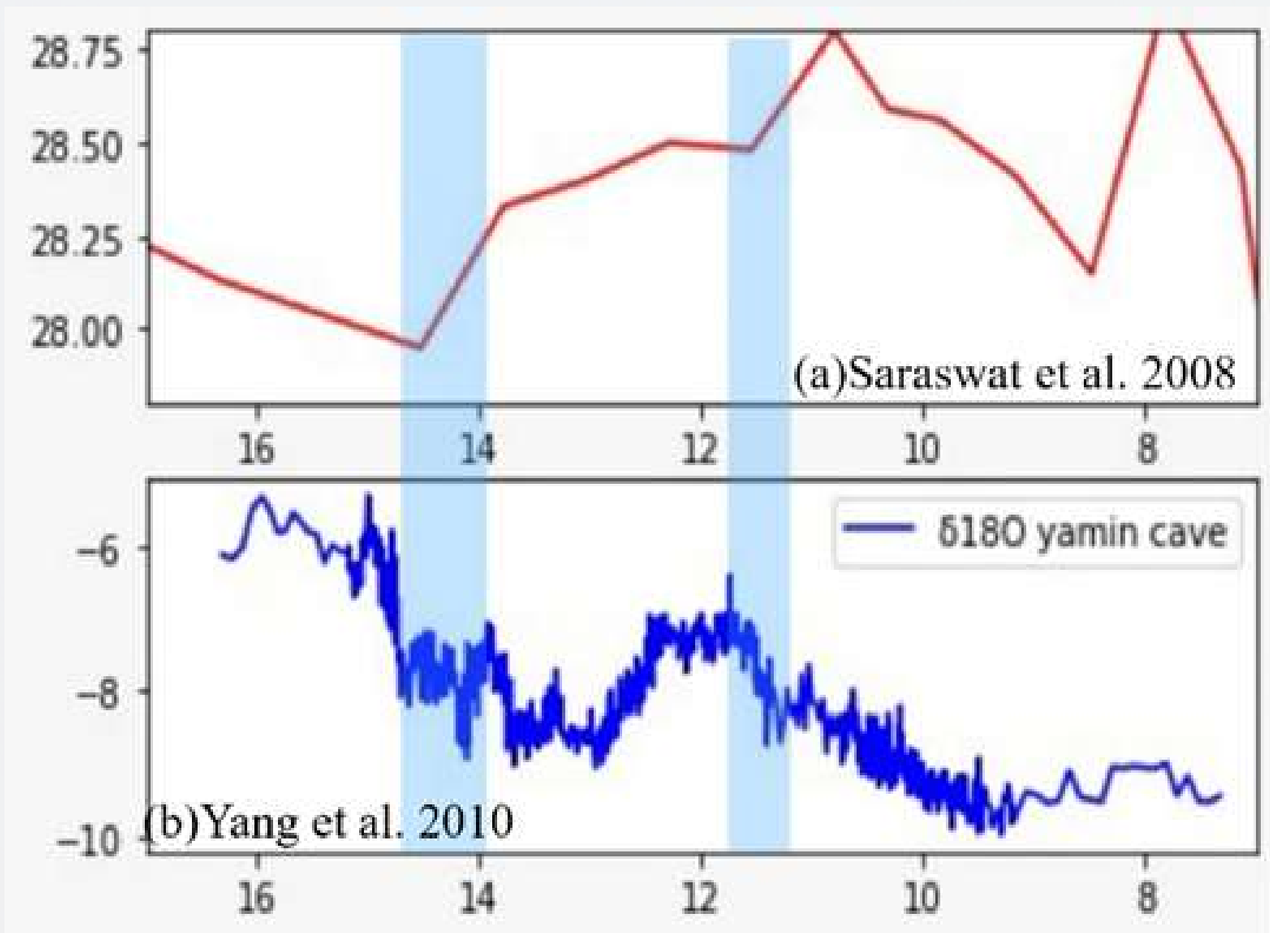

Fig. 3 (a) SST variability from 15.5-8.5 Kyr BP representing the Equatorial Indian Ocean. (b) Oxygen isotopic variability of a speleothem sample retrieved from the Yamin cave of China. (15.5-8.5 Kyr BP)

To assess broader monsoon coherence, sea surface temperature (SST) records were compared with speleothem $\delta^{18}O$ data from Chinese caves. Fig. 3b presents the $\delta^{18}O$ record from Yamen Cave, spanning 15.5–8.5 Kyr BP (Yang et al., 2010), while Indian Ocean SST variability for the same interval was obtained from Saraswat et al. (2008). The first phase (16.2–7.3 Kyr BP) corresponds to the deglaciation and early Holocene. Around 14.5 Kyr BP, SST dropped to ~27.8 °C (Fig. 3a), accompanied by a sharp decline in $\delta^{18}O$ to –9‰ (Fig. 3b), signalling intensified monsoon rainfall. Some divergence was noted, however: $\delta^{18}O$ continued to decrease, reaching its minimum near 13 Kyr BP, even as SST progressively increased. Between 13–12 Kyr BP, both SST and $\delta^{18}O$ rose, indicating weaker monsoon activity. At ~11.5 Kyr BP, SST fell again (~28.35 °C), coinciding with another sharp $\delta^{18}O$ decline, consistent with strengthened monsoon precipitation.

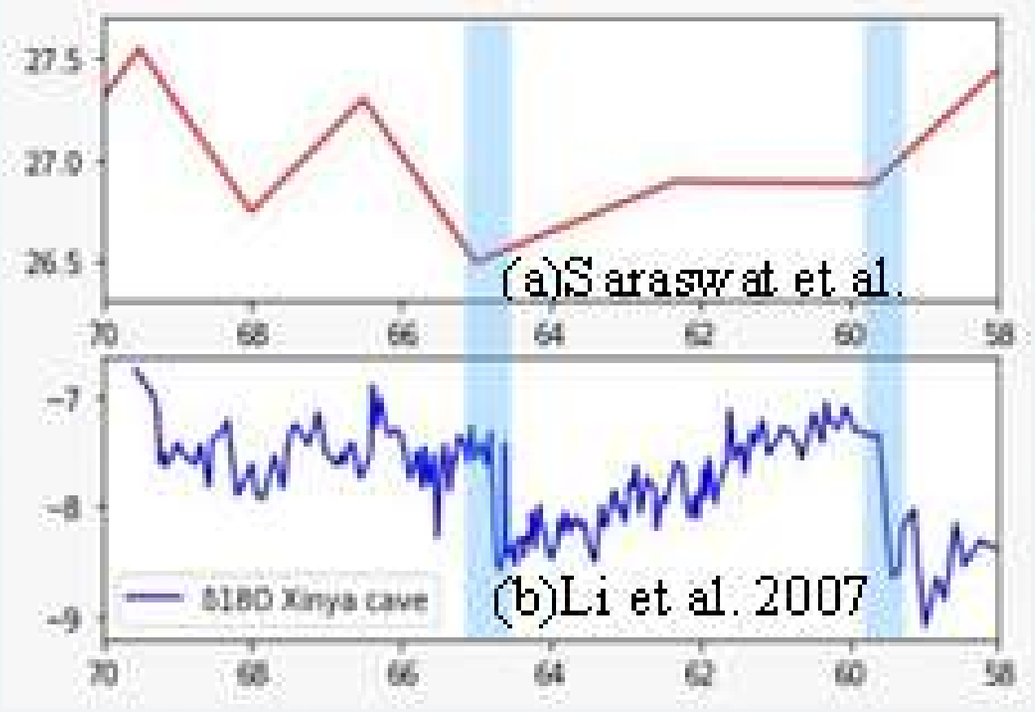

Fig. 4 (a) SST variability from 15.5-8.5 Kyr BP representing the Equatorial Indian Ocean. (b) Oxygen isotopic variability of a speleothem sample retrieved from the Yamin cave of China. (15.5-8.5 Kyr BP).

The second interval (70–58 Kyr BP) was compared with $\delta^{18}O$ data from Xinya Cave, northeastern China (Li et al., 2007). At ~65 Kyr BP, SST reached ~26.6 °C (Fig. 4a), coinciding with a $\delta^{18}O$ decline to –8.9 ‰ (Figure 4b). Another SST minimum (~26.8 °C) at ~59.8 Kyr BP was accompanied by $\delta^{18}O$ values near –9‰, again reflecting intensified monsoon rainfall.

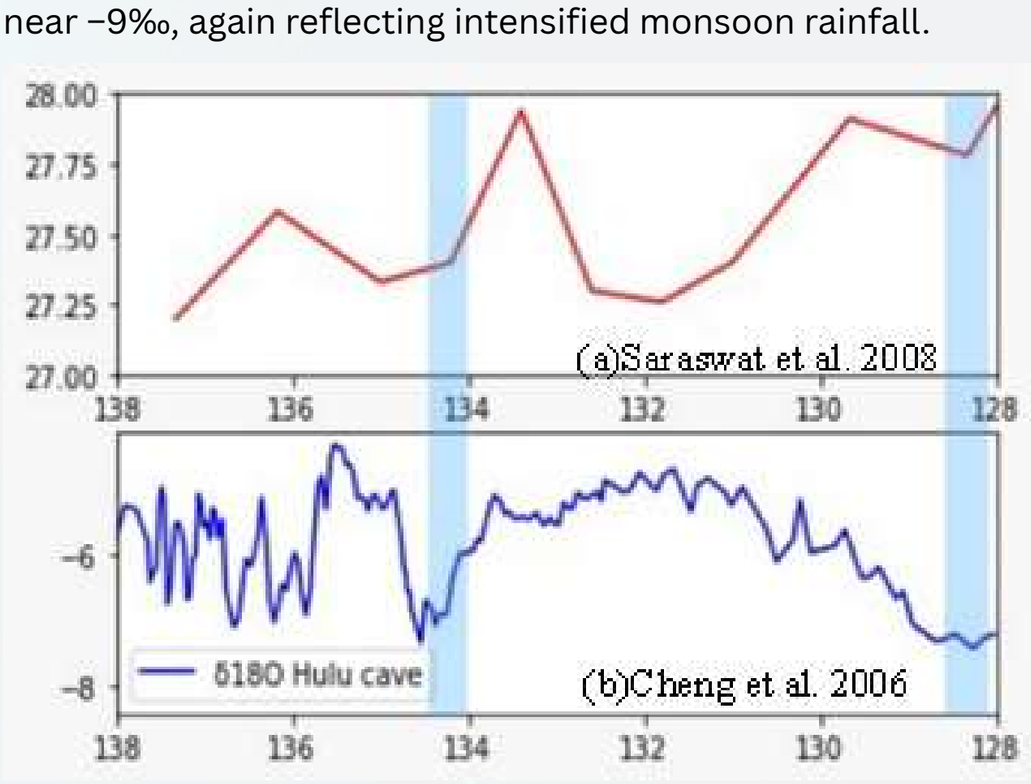

Fig. 5(a) SST variability from 138-128 Kyr BP representing the Equatorial Indian Ocean. (b) Oxygen isotopic variability of a speleothem sample retrieved from the Hulu cave of China (138-128 Kyr BP).

The third interval (138–128 Kyr BP) was examined using Hulu Cave $\delta^{18}O$ records (Cheng et al., 2006). At ~134 Kyr BP, SST decreased and $\delta^{18}O$ fell to –7.8‰ (Figure 5a, 5b). Subsequently, SST rose until ~133 Kyr BP before declining again at ~132 Kyr BP. Near 128 Kyr BP, SST peaked (~27.75 °C), while $\delta^{18}O$ reached its lowest value (~–8‰), indicating strong monsoon activity. rn timescale variability was assessed using coral $\delta^{18}O$ records from the Maldives (Storz et al., 2013) and speleothem $\delta^{18}O$ from Dandak Cave, India (Sinha et al., 2007). The coral dataset

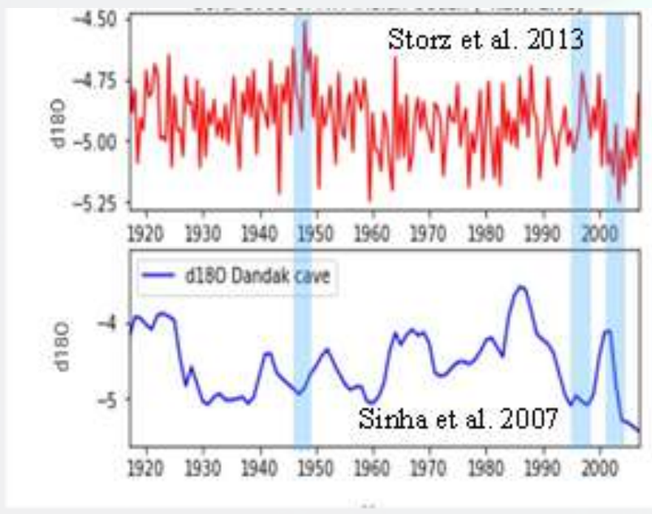

Fig. 6(a) Oxygen isotope variability of corals found in Northern Indian Ocean (1920-2005). (b) Oxygen isotope variability of Dandak Cave speleothem, India from 1920-2005.

spans 1917–2007, overlapping with the speleothem record from 1920–2007. Coral $\delta^{18}O$ values around 1948 (~–4.6 ‰) suggest cooler SSTs, coinciding with low speleothem $\delta^{18}O$ (~–4.9 ‰ ; Figure 6a, 6b) and intensified monsoon rainfall. In 1997–1998, coral $\delta^{18}O$ shifted from –4.75‰ to –4.9‰, reflecting ENSO-related variability. Post-2000, coral $\delta^{18}O$ reached ~–5.24 ‰ (higher SST), while speleothem $\delta^{18}O$ rose (~–4.2‰), consistent with weaker monsoon intensity.

Taken together, these results demonstrate that across multiple timescales, SST minima generally coincide with sharp declines in speleothem $\delta^{18}O$, indicating stronger monsoon rainfall. Conversely, higher SSTs are often associated with weaker monsoon signals. While this relationship holds in many intervals, discrepancies remain, underscoring the complexity of ocean–monsoon interactions and the need for further investigation.

Conclusions

This study examined the association between Indian Ocean SST and ISM intensity using marine and speleothem proxies. Results in general, support the hypothesis that warming SST reduces tropospheric temperature gradients, weakening monsoon circulation. While correlations are evident across several time slices, discrepancies remain, suggesting additional mechanisms influence monsoon variability. Further high-resolution studies are required to resolve these complexities.

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Monsoon Mysteries Unveiled: How Water Isotopes Help Decode India's Seasonal Rhythms

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The Indian monsoon is one of nature's most dramatic performances—a seasonal wind reversal that brings life-giving rains to nearly a quarter of the world's population. While monsoons occur in various parts of the globe, their intensity and complexity are unmatched in the Indian subcontinent. This annual phenomenon is not just a meteorological event; it's a lifeline for agriculture, water resources, and the economy. Understanding its behavior is crucial—and scientists are now turning to an unexpected ally: the isotopes in raindrops.

The Pulse of the Planet: What Drives the Monsoon?

Monsoon winds arise from intricate interactions among the ocean, atmosphere, land, vegetation, and even ice sheets. These interactions span vast spatial and temporal scales—from daily fluctuations to millennia-long cycles. To study such variability, scientists rely on both instrumental data (like rain gauges and satellites) and proxy records (such as cave deposits or tree rings). Among these, isotopic analysis of precipitation has emerged as a powerful tool, offering insights into both short-term dynamics and long-term climate patterns.

Isotopes: Nature's Hidden Signatures

Every raindrop carries a chemical fingerprint. The ratios of oxygen ($^{18}O/^{16}O$) and hydrogen ($^{2}H/^{1}H$) isotopes in precipitation are shaped by processes like evaporation, condensation, and moisture transport. These isotopes respond to both thermodynamic properties (like moisture content and phase changes) and dynamic features (such as wind circulation). This dual sensitivity makes them ideal for studying the monsoon's behavior. (Chakraborty, 2017).

For instance, studies over the Andaman Islands and Bay of Bengal show that precipitation isotopes are closely linked to moisture flux convergence and the evaporation-to-precipitation ratio. They also reflect the influence of westerly and easterly winds, which bring moisture from different sources. In essence, isotopes act as tracers—revealing where the moisture came from and how it evolved.

Beyond Rainfall: Rethinking Monsoon Indices

Traditionally, meteorologists have used parameters like rainfall, temperature, and wind to define monsoon onset and withdrawal. One notable attempt is the Xavier et al. (2007) index, which uses upper-tropospheric temperature gradients. However, this index is more sensitive to planetary waves than to surface moisture dynamics. What's missing is an index that captures the integrated moisture characteristics—the very essence of monsoon thermodynamics.

This is where isotopic tools shine. Since isotope fractionation is governed by phase changes (evaporation, condensation), it directly reflects moisture processes. Moreover, isotopes respond to atmospheric circulation, carrying both thermodynamic and dynamic signatures. This dual capability makes them promising candidates for developing new monsoon indices.

Active and Break Phases: A New Lens

One of the monsoon's defining features is its alternating phases of heavy rainfall (active) and dry spells (break). These phases are typically identified using meteorological data. But recent research suggests that isotopic records of transpired water—the water released by plants—can also delineate these phases (Chakraborty et al. 2018). This opens up exciting possibilities for studying monsoon variability through eco-hydrological pathways.

Port Blair Insights: Isotopes and Monsoon Withdrawal

A breakthrough study by Fousiya et al. (2022) focused on Port Blair, a key location in the Bay of Bengal. The researchers analyzed the isotopic composition of rainfall and found a distinct pattern that correlates with the monsoon withdrawal date. Specifically, they observed that:

$\delta^{18}O$ values in precipitation showed a sharp transition during the withdrawal phase. Fig. 1 shows how the precipitation isotopic records at Port Blair in the Andaman Islands respond to seasonal shift in the monsoon circulation. The red line shows the precipitation isotopic variability showing relatively high values during the monsoon season (June to September) and slightly lower values during the post-monsoon season (October to December). A green vertical bar approximately marks this transition. This transition was linked to changes in moisture source regions and circulation patterns.

By plotting $\delta^{18}O$ against the Webster-Yang circulation index, the team identified two well-defined clusters—one representing the active monsoon and the other the post-monsoon phase. This clustering suggests that isotopes can serve as reliable markers for monsoon phase transitions.

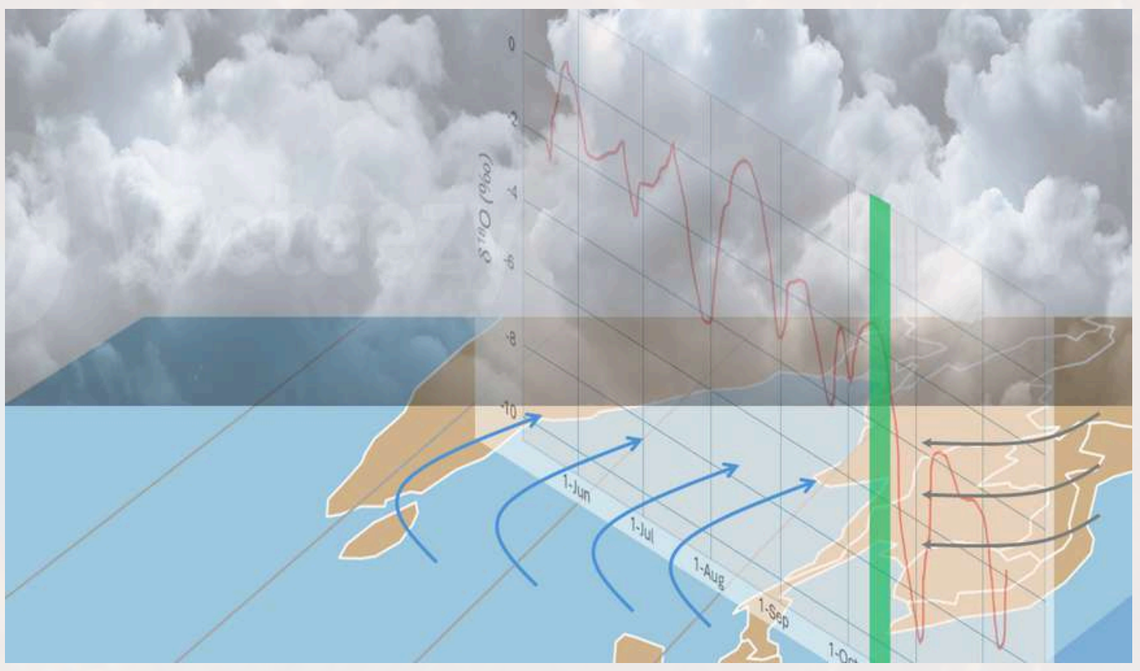

Fig. 1. Seasonal evolution of precipitation isotopes at Port Blair in response to monsoon circulation shifts. The red line depicts $\delta^{18}O$ variability in rainfall, with enriched values during the southwest monsoon (June–September) and a marked decline during the post-monsoon transition (October–December), indicated by the green vertical bar. Blue curved arrows represent the southwesterly monsoon winds, while light grey arrows denote the northeasterly circulation. These contrasting air masses carry moisture with distinct isotopic signatures, reflected in the observed isotopic shift following the seasonal transition.

Implications

The ability to pinpoint monsoon onset and withdrawal using isotopic technique has profound implications. It can improve seasonal forecasting, guide agricultural planning, and enhance climate models. Isotopic tools offer a fresh perspective—one that integrates moisture dynamics, circulation patterns, and phase transitions in a single framework.

Moreover, as satellite-based remote sensing and ground-based isotope monitoring become more accessible, these methods can be scaled across regions. From the Andaman Islands to the Western Ghats, isotopic studies could revolutionize our understanding of India's monsoon.

In the end, every raindrop tells a story—not just of where it fell, but of the journey it took through clouds, winds, and oceans. By decoding these stories through isotopes, scientists are uncovering the hidden rhythms of the monsoon. As climate change adds new layers of complexity, such tools will be vital in safeguarding the subcontinent's water future.

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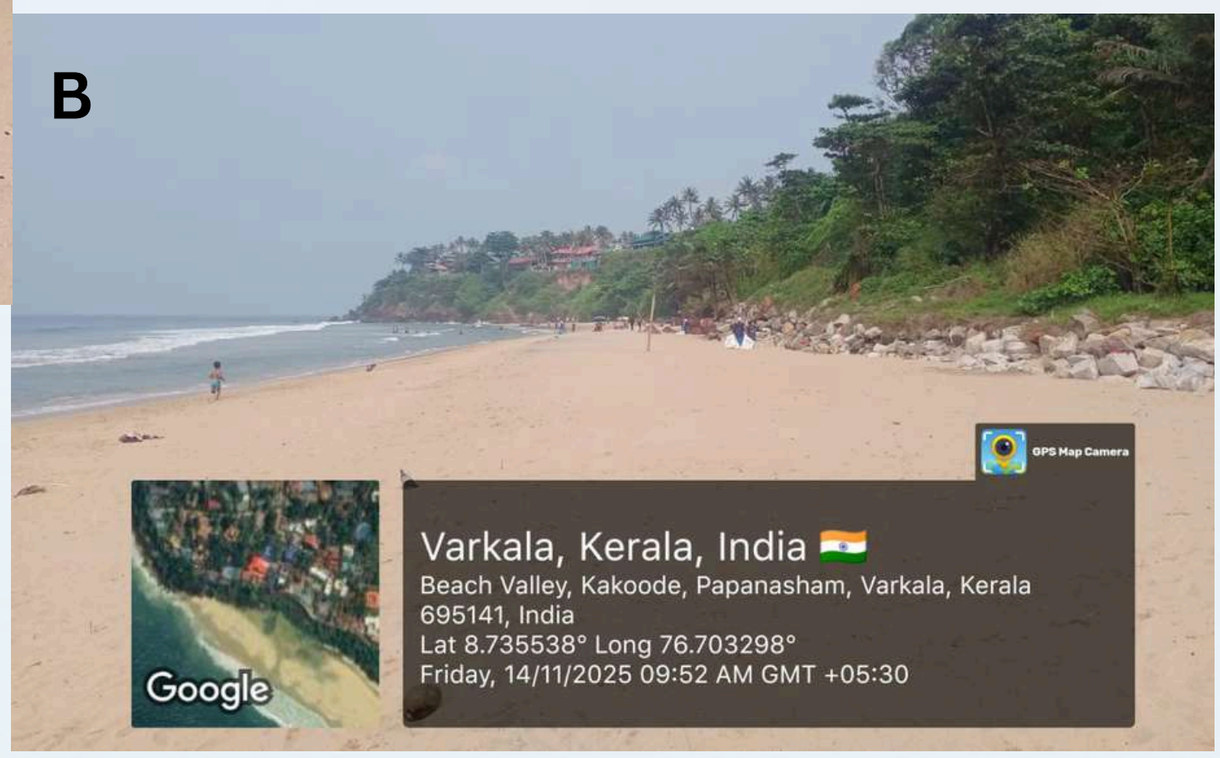
Success story of Varkala beach of Kerala

OSI initiated cleaning of Varkala beach with the support of Zoology Dept. of S N College, Varkala. This activity led by OSI prompted the Municipality to implement regular cleaning of the beach engaging the Haritha Karma Sena which is a community-based waste management initiative. It is a success story of OSI.

A. Cleaning activity by Haritha Karma Sena (arranged by the Tourism Department) at Varkala beach



B. Cleaned beach

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