ANNUAL REPORT ON GEOTRACES ACTIVITIES IN INDIA

May 1st, 2024 to April 30th, 2025

New GEOTRACES or GEOTRACES relevant scientific results

- Understanding the sources and internal cycling of dissolved Iron (dFe) in the Indian Ocean.

Understanding the distribution and sources of dissolved iron (dFe) in the ocean is critical, as it is a key micronutrient that regulates primary productivity and carbon cycling in marine ecosystems. Thus, it becomes important to understand the source of dissolved iron in the ocean. Working with this premise, the distribution of dissolved iron (dFe) was analyzed along the GI10 and GI09 cruise transects, covering the Arabian Sea, Bay of Bengal, Central Indian Ocean Basin, and extending southward to 30ºS in the Indian Ocean. Dissolved iron concentrations in the Arabian Sea range from 0.02 to 3.5 nM, while slightly higher values are observed in the Bay of Bengal, varying between 0.02 and 4.6 nM. These variations are shaped by distinct biogeochemical processes, including coastal-to-open-ocean advection, atmospheric deposition, and the influence of regional Oxygen Minimum Zones (OMZs). In the Arabian Sea, lateral advection from the west coast of India is a major source of dFe to offshore waters. Conversely, in the Bay of Bengal, atmospheric dust deposition—enhanced by higher solubility—emerges as a dominant contributor, particularly in regions influenced by mesoscale eddies and downwelling systems. The OMZs in the Arabian Sea and Bay of Bengal show contrasting dFe behaviors. In the Arabian Sea, low-oxygen conditions facilitate dFe release through the remineralization of sinking organic matter. In contrast, in the Bay of Bengal, dFe is initially scavenged in the upper OMZ before being released at greater depths, possibly influenced by ballast effects and shifts in remineralization efficiency. Tectonic features such as the Carlsberg Ridge, Central Indian Ridge, and Southeast Indian Ridge also act as significant sources of dFe to deep waters, with concentrations typically ranging between 2 and 3 nM, and reaching up to ~20 nM near the Rodrigues Triple Junction. Similarly, the Java-Sumatra Subduction Zone contributes approximately 2.5 nM of dFe to the deep ocean. Looking ahead, global warming and rising sea surface temperatures are expected to intensify and expand the OMZs of the northern Indian Ocean. This expansion could enhance dFe release into the water column, potentially boosting surface productivity through upwelling or eddy-driven transport of subsurface dFe-enriched waters.

- Understanding the water mass mixing and terrestrial input to the Arabian Sea using radiogenic Nd isotopic composition (ε_{Nd})

Understanding the sources and mixing of water masses in the Arabian Sea is crucial for tracing the ocean circulation in the region and assessing the influence of continental inputs on the marine environment. This study provides new constraints on water mass structure and exchange processes through the analysis of dissolved neodymium (dNd) concentrations and isotopic compositions (ε_{Nd}) in the Arabian Sea. The present work is based on samples collected along the GEOTRACES India GI10 transect. The vertical distribution of dNd displays a characteristic profile: elevated concentrations in surface waters, a pronounced minimum at intermediate depths (200–300 m), followed by increasing concentrations with depth. This pattern reflects the influence of multiple processes, including surface contributions from atmospheric deposition, riverine discharge, and sediment dissolution; removal through scavenging onto biogenic and lithogenic particles in subsurface waters; and regeneration from particulate matter in deeper layers. In the southeastern Arabian Sea, surface waters during the winter monsoon exhibit relatively high dNd concentrations (18.2–21.9 pmol kg^{-1}) and less radiogenic εNd values (−10.9 to −12.0). These signatures point to the advection of Nd-rich, isotopically less radiogenic Bay of Bengal waters into the Arabian Sea, driven by seasonal reversal of coastal currents. In contrast, surface waters in the north-central Arabian Sea are characterized by lower dNd concentrations (9.4–14.5 pmol kg^{-1}) and more radiogenic εNd values (~−6), attributed to the dissolution of aeolian dust derived from the Arabian Peninsula. At subsurface depths (75–150 m), the Arabian Sea High Saline Water (ASHSW) is distinguished by a relatively radiogenic εNd signature (−6.5 to −7.5) in the north-central Arabian Sea, which becomes less radiogenic toward the southeast. This shift is likely caused by the mixing with less radiogenic particulate matter transported from the Bay of Bengal. Below the ASHSW, the presence of Persian Gulf Water (PGW) and Red Sea Water (RSW) is evident in the northern Arabian Sea by their εNd values ranging from −8 to −9. At greater depths, the Arabian Sea is filled by Antarctic Bottom Water (AABW), identified by a distinct and consistent εNd signal of −8.5 ± 0.4. These findings highlight the complex interplay of regional circulation, external inputs, and vertical biogeochemical processes that govern the Nd cycle in the Arabian Sea. The study enhances our understanding of past and present oceanographic conditions in the northern Indian Ocean and provides a baseline for detecting future changes under ongoing climate variability.

- Distribution and Sources of Dissolved Lead (dPb) in the Indian Ocean

Dissolved lead concentrations in the mixed layer ranged from 23 to 114 pM across the various basins of the Indian Ocean, with the maxima in the northern Indian Ocean. Notably, dPb concentrations reached up to 162 pM in the eastern Arabian Sea. A clear latitudinal gradient was evident, with concentrations decreasing from north to south. This pattern is primarily attributed to atmospheric deposition, which remains the dominant source of dPb in the open ocean. Emissions from coal combustion and industrial activity in densely populated, rapidly developing countries surrounding the Indian Ocean constitute major anthropogenic contributors. Estimated atmospheric lead fluxes, based on aluminum flux as a proxy, varied regionally: 7–292 μmol m^{-2} y^{-1} over the Arabian Sea, 10–128 μmol m^{-2} y^{-1} over the Bay of Bengal, 3.5–18.9 μmol m^{-2} y^{-1} in the equatorial Indian Ocean, and 4.5–30.5 μmol m^{-2} y^{-1} in the southern Indian Ocean. In comparison, lead fluxes from the continental shelf were notably higher in the Bay of Bengal (82.6–151 μmol m^{-2} y^{-1}) than in the Arabian Sea (14.1–15.9 μmol m^{-2} y^{-1}), underscoring the significance of sedimentary inputs from the shelf in the Bay of Bengal. This contrasts with the Arabian Sea, where atmospheric deposition overwhelmingly dominates lead input. Beyond industrial emissions, climatic phenomena such as the Indian Ocean Dipole (IOD) also play a key role in modulating lead deposition in the southern Indian Ocean by enhancing the occurrence of Australian bushfires and dust storms, which contribute additional dPb through long-range atmospheric transport. These results highlight the complex interplay of anthropogenic emissions, natural processes, and climate-driven events in governing the distribution of trace metal pollutants in the Indian Ocean. They provide a regional baseline for assessing future changes in marine Pb cycles under shifting climate and emission scenarios.

- Biogeochemical cycling of dissolved Nickel in the Arabian Sea

The distribution of dissolved nickel (dNi) was determined by sampling and analyzing seawater in the Arabian Sea to understand the various biogeochemical processes impacting the distribution of dNi. The distribution of dNi in the Arabian Sea is modulated by sources such as dust, riverine and submarine groundwater discharge, sinks such as biological uptake and adsorption processes, as well as internal cycling such as remineralization, reversible scavenging, and consumption in intense oxygen deficient zone in the water column influence the distribution of dNi in the Arabian Sea. A significantly higher concentration of dissolved nickel in the surface waters of the Arabian Sea is observed, potentially due to its unavailability for biological uptake. A considerable fraction of dissolved Ni (30%–50%) in the intermediate and deeper waters of the Arabian Sea is derived from the remineralization of organic matter, and the reversible scavenging process, which is confirmed by the presence of additional dNi in excess of the preformed Ni supplied by water mass mixing in the Arabian Sea. Large-scale depletion of dissolved Ni over Phosphate in the oxygen minimum zone of the Arabian Sea suggests its loss as sulphides or Fe oxides or POC and due to varying ecosystem composition.

GEOTRACES or GEOTRACES relevant cruises

- There was no new sample collection done throughout the last year. However, various water and sediment/particulate samples are being analyzed currently for their trace element and isotopic composition and other key parameters.

New projects and/or funding

- NA

GEOTRACES workshops and meetings organised

- NA

Outreach activities conducted (please list any outreach/educational material available that could be shared through the GEOTRACES web site) *(We are particularly interested in recordings from webinars from GEOTRACES research)*

- NA

Other GEOTRACES activities

- NA

New GEOTRACES or GEOTRACES-relevant publications (published or in press) *(If possible, please identify those publications acknowledging SCOR funding)*

1. Shukla Arvind, **Singh S.K.,** Singh D.P., Sharma A. and Dimri A.P., Strong climate control on the millennial-scale dust variability and sediment provenance in the Equatorial Indian Ocean inferred from Sr-Nd isotopes, ***Paleoceanography and Paleoclimatology***, 39 (3), 2024, e2023PA004808.
2. Malla N. and **Singh S.K.,** Spatial variability of dissolved cobalt in the Indian Ocean waters: Contrasting behavior in the Arabian Sea, the Bay of Bengal and the southern sector of the Indian Ocean, Accepted, ***Global Biogeochemical Cycles*** 38, e2024GB008291, https://doi.org/10.1029/2024GB008291.

3. Shukla A., Mishra T.K., **Singh S.K.** and Singh A.D., Substantial Invasion of Antarctic Intermediate Water into the Arabian Sea during Younger Dryas and Heinrich Stadials, ***Quaternary Science Research*** 349, 2025, 109115.
4. Tiwari R.K., Dalai T.K. Samadder R., Rahaman W. and **Singh S.K.**, Non-conservative behaviour of molybdenum in the Ganga (Hooghly) River estuary, India: Role of solute-particle interaction and sediment diagenesis, ***Chemical Geology*** 673, 2025, 122526; https://doi.org/10.1016/j.chemgeo.2024.122526.
5. Yadav C., **Singh S.K.** and Chinni V., Persistent elevated levels of dissolved lead in the Indian Ocean post-leaded gasoline ban: The impact of anthropogenic activities, sediment desorption, and dust storms, ***Marine Pollution Bulletin*** 215, 2025: 117874; DOI: 10.1016/j.marpolbul.2025.117874.
6. Malla N., **Singh S.K.**, Singh N. D., Shukla A., Chinni V., Goswami V., and John R. (). The role of water masses, biological processes, remineralization and reversible scavenging in controlling the distribution of dissolved Nickel in the Arabian Sea. ***Global Biogeochemical Cycles***, 39, e2024GB00844, 2025. https://doi.org/10.1029/2024GB008441.

Please indicate if there is any forthcoming or planned GEOTRACES special issue publication

- NA

***Completed GEOTRACES PhD or Master's these**s (please include the URL link to the pdf file of the thesis, if available)*

1. Arvind Shukla

Thesis title: Tracing Sediment Provenances and Paleo-circulation in the Northernand Equatorial Indian Ocean.

Affiliation: CSIR-National Institute of Oceanography, Goa University, India. Submission date: 8th July, 2024, Awarded on 4th Feb 2025.

2. Nirmalya Malla

Thesis title: Biogeochemical Cycling of Micro-Nutrients in the Indian Ocean

Affiliation: CSIR-National Institute of Oceanography, Academy of Scientific & Innovative Research, India. Submission date: December 2024.

GEOTRACES presentations in international conferences

- NA

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