Goldschmidt 2025 Abstract
https://doi.org/10.7185/gold2025.26004

Glacial expansion and deglacial retreat of the Arabian Sea Oxygen Deficient Zone

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Ongoing anthropogenically forced warming has reduced oceanic oxygen levels, raising concerns about the expansion of Oxygen Deficient Zones (ODZs) and their effects on marine habitats. The Arabian Sea, a perennial ODZ, exhibits extremely low oxygen concentrations at intermediate depths, which promotes anaerobic processes like denitrification and anaerobic ammonium oxidation (anammox), resulting in the loss of bioavailable nitrogen and the production of nitrous oxide. The mechanisms beyond climate warming that influence the Arabian Sea ODZ variability remain uncertain due to limited observations. Therefore, understanding the long-term variations of ODZs under diverse climatic conditions through geological history is essential. Here, we present a multi-proxy reconstruction of dissolved oxygen levels across the past glacial-interglacial cycle. For this reconstruction, we have used iodine-to-calcium (I/Ca) ratios in planktic foraminifera and nitrogen isotopic composition of bulk sediments from two sediment cores: one from the northern Arabian Sea and the other from the southeastern Arabian Sea over the last ~35 ka.

We find that the Arabian Sea ODZ expanded during the Last Glacial Maximum (LGM), extending southward to the southeastern Arabian Sea. This ODZ expansion was likely driven by enhanced primary productivity due to strengthened winter monsoonal winds and reduced influx of Antarctic Intermediate Water (AAIW). However, during the deglaciation (~18-12 ka), oxygen-depleted waters remained largely restricted to the north, primarily due to the enhanced intrusion of AAIW into the eastern Arabian Sea, particularly during the Younger Dryas. The glacial expansion of the Arabian Sea ODZ resulted in relatively heightened denitrification compared to the deglaciation, alongside pronounced nitrogen fixation likely due to the increased aeolian dust deposition and excess phosphorus released through denitrification. In contrast, the shrinking of the ODZ during the deglaciation led to weakened denitrification. Furthermore, during the early Holocene, renewed expansion of the oxygen-depleted waters probably induced intense denitrification in the Arabian Sea. Our findings underscore the susceptibility of the Arabian Sea ODZ to climate-driven changes in monsoonal winds and intermediate water ventilation. They suggest ongoing anthropogenic warming could further exacerbate oxygen loss and intensify nitrogen cycle disruptions.