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Evolution and dynamics of the Arabian Sea oxygen minimum zone: Understanding the paradoxes

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A B S T R A C T

The Arabian Sea hosts a perennial and intense oxygen minimum zone (OMZ) at 150–1200 m depths with O_2 concentrations <0.5 ml/l. It is generally believed that the oxygen-depleted conditions at mid-water depths result from high rate of O_2 consumption due to monsoon-driven productivity generating a high organic matter flux, combined with slow renewal of thermocline waters in the region. With global warming and increasing hypoxia, there is growing interest to better understand the various factors controlling oxygen conditions in the thermocline waters and the impact on the nutrient cycling and climate. In this contribution, we provide an overview of new advances in understanding the basin-wide changes of the OMZ, and highlight new perspectives on the relative roles of ocean and atmospheric circulations in modulating the OMZ intensity through the late glacial-Holocene period. Comprehension of the existing and new proxy records ($\delta^{15}N$, aragonite preservation, $\delta^{13}C$ of benthic foraminifera) from the productive western and oligotrophic eastern and north-eastern Arabian Sea provides insights into the regional heterogeneity in basin-wide changes of the OMZ, denitrification and carbonate (aragonite) lysocline, and their links to the seasonal monsoon variability and reorganisation of thermocline circulation. We also highlight the limitations of the existing proxy data to address the important questions of how circulation and chemical properties of intermediate/deep water masses contributing to the Arabian Sea thermocline waters changed in the past. Hence, more detailed proxy data are required to characterise sources of water masses, past changes in their pathways and vertical extents in the Arabian Sea, which are crucial to better constrain the temporal evolution of thermocline ventilation basin-wide.

1. Introduction

The current scenario of global warming and increasing hypoxia in the world ocean necessitates gaining a better understanding of various factors driving mid-water oxygen conditions, ocean deoxygenation and associated biogeochemical processes. The oxygen loss or deoxygenation in oceans modifies marine productivity, biodiversity and biogeochemical cycles (Breitburg et al., 2018). There is growing evidence suggesting that ocean and atmospheric circulation changes can potentially modulate oxygen conditions at mid-water depths (e.g. Stramma et al., 2008).

The Arabian Sea (AS) is one of the few areas in the world, where mid-water oxygen minima (<0.5 ml/l dissolved O_2) develop because of high surface productivity and a poorly ventilated thermocline. While, the monsoon induced changes in surface hydrography controls the productivity patterns across the basin (Fig. 1a–b), the thermocline waters are significantly influenced by changes in the global overturning circulations. Unlike other open-ocean hypoxic zones, the Arabian Sea is of particular interest, as it is developed in the oligotrophic central-eastern part, away from the region of intense upwelling in the western Arabian Sea (Naqvi, 1991; Morrison et al., 1999; Banse et al., 2014; Rixen et al., 2020). Paleoceanographic studies revealed major changes in the oxygen minimum zone (OMZ) intensity over orbital to millennial and decadal timescales, in concert with the global climate change (e.g. Reichart et al., 1997; Stramma et al., 2008; Jung et al., 2009). It has been demonstrated that the OMZ in the global oceans contracted during cold periods and expanded in the warm periods (Stramma et al., 2008; Lachkar et al., 2019). Nevertheless, the relative importance of atmospheric and deep-ocean circulations modulating the Arabian Sea OMZ through time and space is not well understood.

The intensification of the OMZ (or deoxygenation) in recent times is

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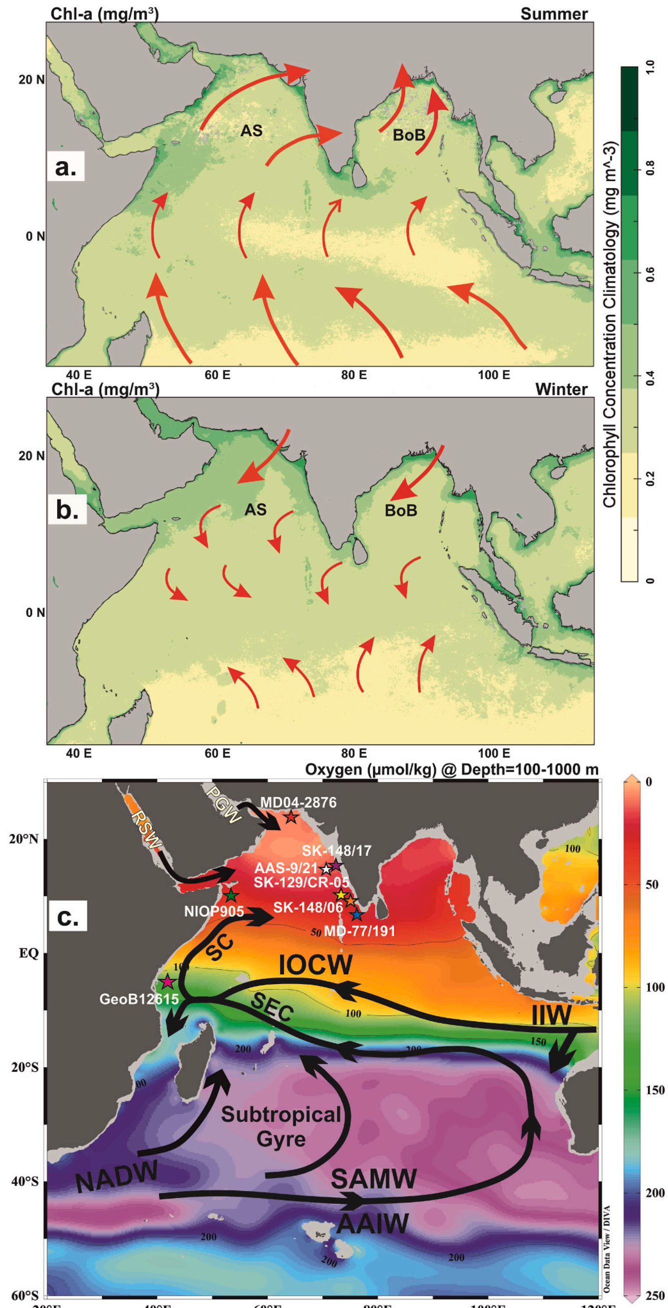

Fig. 1. Map showing the chlorophyll-a concentration (mg/m^3) with schematic wind directions (red arrows) during (a) the southwest (summer) monsoon and (b) the northeast (winter) monsoon. The seasonal chlorophyll-a concentration data is an average of the years 2002–2019 and is taken from https://oceancolor.gsfc.nasa.gov/. (c) Map showing the oxygen concentration (μmol/kg) at 100–1000 m water depths in the Indian Ocean (World Ocean Atlas, 2018; Garcia et al., 2018). The coloured stars are the location of cores discussed in the text. Schematic pathways of the intermediate water masses in the Indian Ocean are denoted by black arrows [modified after You (1998)]. Map source is Ocean Data View (ODV; Schlitzer, 2015). Acronyms are as follows: AS, Arabian Sea; BoB, Bay of Bengal; PGW, Persian Gulf Water; RSW, Red Sea Water; SC, Somali Current; SEC, South Equatorial Current; IIW, Indonesian Intermediate Water; NADW, North Atlantic Deep Water; IOCW, Indian Ocean Central Water; SAMW, Sub-Antarctic Mode Water; AAIW, Antarctic Intermediate Water.

generally explained by the reduction of oxygen solubility due to ocean warming combined with poor oxygen replenishment (Keeling and Garcia, 2002; Stramma et al., 2008). Observational data and model based studies indicated that the oxygen level in the AS waters declined over the last decades, due to ocean deoxygenation leading to expansion of the OMZ (Keeling and Garcia, 2002; Resplandy et al., 2012). The results of model projections for this region, however, point towards contrasting future O_2 conditions across the basin. In order to assess the potential expansion and magnitude of the intensification, it is essential to study basin-wide changes in the extent and intensity of the OMZ in response to the climate variability at different time scales. In this article, we compared and discussed the selected published proxy records of denitrification, productivity, thermocline ventilation and OMZ intensity from the western, north-eastern and the eastern Arabian Sea margins to evaluate the potential processes controlling the OMZ variability through the late glacial-Holocene period at millennial time-scale.

2. OMZ variability and controlling factors

The rate of monsoon driven production of organic matter, its respiration and the magnitude of thermocline ventilation control the oxygen levels at mid-depths of the OMZ in the AS. Thus, the intensity of the OMZ depends on the amount of O_2 supply and consumption in the intermediate waters of the region. A perennial and pronounced OMZ has developed in the AS today within the permanent thermocline (150–1200 m), which is maintained by a balance between enhanced oxygen consumption associated with high primary productivity and poorly ventilated intermediate waters (Swallow, 1984; Resplandy et al., 2012; Banse et al., 2014). The OMZ intensifies when oxygen demand due to high rate of organic matter respiration exceeds the oxygen supply through various physical processes. Hence, past changes in surface productivity is one of the dominant factors governing the mid-water oxygen condition. The organic matter (OM) flux in AS across the basin shows a large-scale seasonal bimodal pattern with its maximum (50 % of the annual flux) in the western Arabian Sea during summer (e.g. Haake et al., 1993), whereas a secondary maximum occurs in the north-eastern Arabian Sea during winter (Fig. 1a–b).

The OMZ ventilation is modulated by both the basin-wide thermocline circulation (Wyrtki, 1973) and the local vertical mixing (McCreary et al., 2013). The main water masses influencing the subsurface waters of the OMZ at 200–1000 m originate from the northwest [high density Red Sea Water (RSW) and Persian Gulf Water (PSW)] and from the south [the Indian Ocean Central Water (IOCW)] (Fig. 1c, You and Tomczak, 1993; You, 1998). The IOCW is the mixture of Sub-Antarctic Mode Water (SAMW), Antarctic Intermediate Water (AAIW) and Indonesian Throughflow (ITF) Water (e.g. You, 1998). The water mass below 2000 m contains a mixture of Circumpolar Deep Water (CDW) and the North Atlantic Deep Water (NADW). The southern water mass flows across the western boundary in summer monsoon season, resulting in O_2 replenishment in the western part of the AS. When it reaches to the north-eastern region, the water mass becomes oxygen-poor (You, 1998).

Paleoceanographic reconstructions based on a suite of proxy records from the AS showed millennial-scale variability in the OMZ intensity, which was attributed to the monsoon-related export flux of organic carbon and the thermocline ventilation changes (Reichart et al., 1997; Schulz et al., 2002; Tripathi et al., 2020; Nagoji and Tiwari, 2021). These studies have demonstrated that the OMZ intensity varied in the AS with respect to the changes in strengths of summer monsoon upwelling and winter monsoon cooling, indicating a dominant role of monsoon circulation in driving mid-water oxygenation (Pichevin et al., 2007; Böll et al., 2015; Gaye et al., 2018). Importantly, the lateral advection of the OM from the productive western Arabian Sea to the central and eastern part of the basin is also considered to be an important factor causing OMZ intensification in the oligotrophic region (Resplandy et al., 2012). Given the regional decoupling between monsoon induced productivity and the development of the OMZ, it is increasingly realised that a change in O_2 supply to the thermocline waters can significantly modulate the volume and intensity of the OMZ across the AS basin (Olson et al., 1993; Schulte et al., 1999; Schmittner et al., 2007).

3. Regional heterogeneity in the oxygen minimum zone and denitrification variability

A pronounced ocean hypoxia results in high N_2 production through denitrification and influences the oceanic nutrient inventory and global climate significantly. Paleo-reconstructions based on multi-proxy records from various locations in the AS indicate millennial-scale variability characterised by D-O oscillations and Heinrich stadials. The Arabian Sea OMZ intensified during D-O interstadials and weakened during the stadials (e.g. Deplazes et al., 2014). These studies provide compelling evidence of a strong coupling between the OMZ intensity and denitrification. The sedimentary $\delta^{15}N$ is a useful proxy of denitrification, hence a potential tracer to record changes in O_2 demand (OM flux) and O_2 supply (thermocline ventilation) within the OMZ. Previous studies revealed that the basin–wide millennial-scale changes in denitrification were coeval with the changes in summer monsoon induced productivity and associated OM flux variations, suggesting a dominant role for the summer monsoon in modulating O_2 condition at mid-water depths (Altabet et al., 2002; Kim et al., 2018). However, the influence of the winter monsoon on the OMZ variability is not yet fully understood. Recently, Singh et al. (2011) suggested a basin-wide decline in both summer and winter monsoon-related primary productivity during the Heinrich and D-O stadials. Intriguingly, the productivity maxima occurs today in the western AS, a region of strong upwelling in summer, but mid-water oxygen-depleted conditions develop in the relatively oligotrophic central and eastern AS. This decoupling between primary productivity, OMZ and denitrification has been suggested to be related to thermocline circulation and ventilation (e.g. Altabet et al., 2002; Pichevin et al., 2007). Several studies highlighted the roles of both the local mixing and basin-wide circulation in driving the thermocline oxygen conditions, hence the OMZ intensity. Previous studies pointed to SAMW-AAIW as the main source of thermocline ventilation within the OMZ. Other water mass sources (PGW, RSW, ITF) also contribute to the thermocline waters in the AS (Wyrtki, 1973; Rixen et al., 1996; Lachkar et al., 2018). Locally, the winter monsoon-induced convective mixing also ventilates upper thermocline waters in the northern AS (McCreary et al., 2013).

A comparison of $\delta^{15}N$ records from the productive western Arabian Sea (WAS) with the oligotrophic eastern Arabian Sea (EAS) and northeastern Arabian Sea (NEAS) reveals regional heterogeneity in terms of both the magnitude and pattern of variation across the basin (Fig. 2, Panel a). Although the overall structure of $\delta^{15}N$ variability on millennial-scale is similar across the basin with increased values during the interstadials [Bølling/Allerød (B/A)] and minima during the stadials (HS1 and YD), the amplitude and trends of variation in the EAS, WAS and NEAS differ conspicuously during the last glacial maximum (LGM) and the Holocene. In general higher $\delta^{15}N$ values in the EAS compared to the WAS indicates a progressive OMZ intensification from west to east, which can be attributed to the relatively sluggish eastern boundary circulation in the eastern basin (Morrison et al., 1999). Also, the lateral advection of OM from the productive WAS to the EAS would have increased the O_2 consumption rate due to enhanced remineralisation. Today, the dissolved O_2 concentration in the OMZ of the WAS is estimated to be much higher (0.48 ml/l, de Wilde and Helder, 1997) than in the EAS (~0 ml/l between 200 and 800 m), and the O_2 concentration in the NEAS (off Pakistan) is reported to be almost similar to that in the EAS (Schulte et al., 1999). This indicates the development of O_2 deficiency at mid-water depths in the oligotrophic EAS and NEAS rather than in the

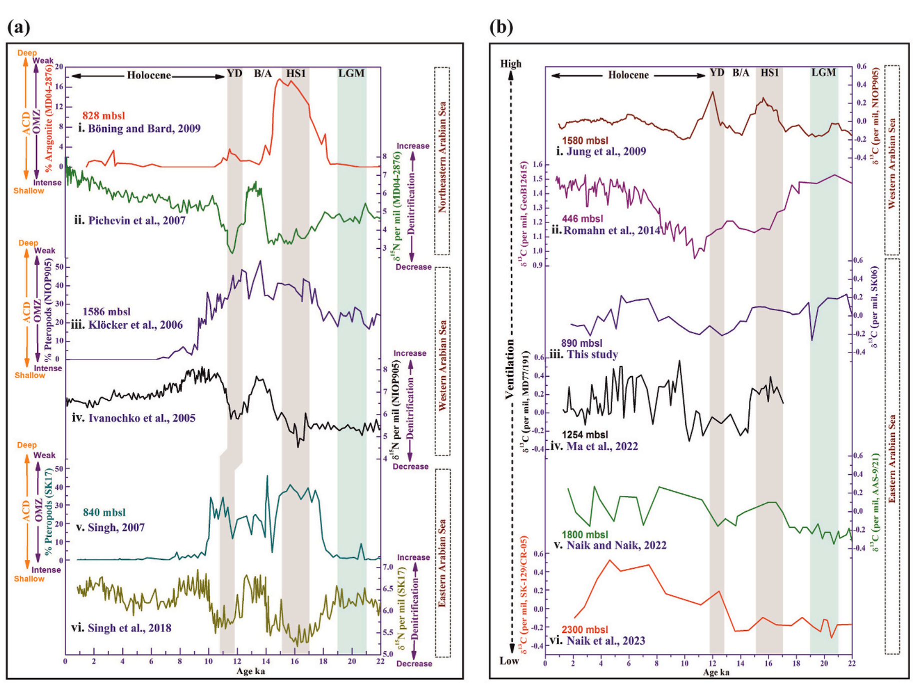

Fig. 2. Basin-wide comparison of proxy records ($\delta^{15}N$, aragonite preservation, $\delta^{13}C$ of benthic foraminifera) from the Arabian Sea.
Panel (a) shows a comparison of $\delta^{15}N$ (denitrification) and % aragonite/pteropod shells (aragonite preservation) records from the Arabian Sea: (i, ii) Northeastern Arabian Sea (core MD04-2876; 24°50′57 °N, 064°00′49 °E; Pichevin et al., 2007; Böning and Bard, 2009), (iii, iv) Western Arabian Sea (core NIOP905; 10°46.01°N, 51°57.04 °E; Ivanochko et al., 2005; Klöcker et al., 2006) and (v, vi) Eastern Arabian Sea (core SK148/17; 15°15′ °N, 72°58′ °E; Singh et al., 2018; Singh, 2007). Panel (b) shows a comparison of benthic stable carbon isotope ($\delta^{13}C$ ‰) records from the Arabian Sea: **(i, ii)** Western Arabian Sea (cores NIOP905 (Jung et al., 2009) & GeoB12615; 7°08.300′ °S, 39°50.45′ °W (Romahn et al., 2014)) and the (iii, iv, v, vi) Eastern Arabian Sea (cores SK06; 9° 20′ °N, 75° 33′ °E (*this study*, see supplementary file for isotope data), MD-77/191; 07°30′ °N, 76°43′ °E (Ma et al., 2022), AAS-9/21; 14°50′ °N, 72°65′ °E (Naik and Naik, 2022), SK-129/CR05; 9°35′ °N, 71°98′ °E (Naik et al., 2023)). Heinrich stadial 1 (HS1), and Younger Dryas (YD) are indicated by vertical grey bars while the last glacial maximum (LGM) is indicated by vertical blue bar.

productive WAS.

The $\delta^{15}N$ proxy records from different locations across the basin margins depict three broad maxima in the EAS (B/A, early and late Holocene), two each in the WAS (B/A and early Holocene) and the NEAS (B/A and late Holocene). The trend of variability in the NEAS within the Holocene showing a prominent and gradual increase from the early to late Holocene is opposite to the variation pattern in the WAS (Fig. 2, Panel a). The observed regional heterogeneity in denitrification intensity changes across the basin cannot be explained solely by the seasonal monsoon-related productivity variations. The millennial-scale changes in WAS, with intense denitrification during B/A interstadial and the early Holocene and declines during the stadials (YD and HS1) appear to be related to the variation in summer monsoon-induced productivity, which was low during the stadials and high during the interstadials and the early Holocene. An year-round low productivity in the AS during Heinrich and D-O stadials due to the weakening of both summer and winter monsoon circulations (e.g. Singh et al., 2011) might have caused weakening of the OMZ and low denitrification in the entire basin. The intensified winter wind-induced deep vertical mixing in the northern AS during the cold periods further increased O_2 supply from surface to the upper thermocline waters resulting in suppressed denitrification and a weak OMZ (Reichart et al., 1997; Pichevin et al., 2007). It has also been proposed that an enhanced inflow of SAMW-AAIW as a result of a reduction in NADW formation, during Heinrich and D-O stadials, increased the O_2 inventory causing OMZ weakening in the AS (e.g. Schmittner et al., 2007).

The denitrification in the WAS declined since 8 ka, whereas it increased gradually in the NEAS. Altogether, a different pattern of variation occurred in the EAS; with an intensification during the early Holocene (~10–8 ka), followed by a decline until ~4 ka and again strengthening since then (Fig. 2, Panel a). The pronounced heterogeneity between the NEAS and WAS with respect to denitrification and OMZ intensity variations has been explained by the reorganisation of upper thermocline circulation because of the post-glacial sea-level rise that facilitated the propagation of O_2 poor intermediate waters from the southwest to the NEAS combined with the reduced inflow of southern sourced O_2-rich waters due to the development of a strong frontal zone along the equator (Pichevin et al., 2007). Unlike the NEAS, a prominent increase in denitrification during the early Holocene in the EAS is intriguing, given that the hydrography of the region is influenced significantly by the winter monsoon. The reorganisation of subsurface water masses has been suggested as a major driving factor for the Holocene changes in OMZ and denitrification intensity in the EAS (Kessarkar et al., 2018). As the early Holocene productivity in the EAS is reported to be low (e.g. Singh et al., 2011), an alternate causal role for intense denitrification can be invoked. An intensified summer monsoon-related overhead precipitation and fluvial runoff from the Western Ghats during the early Holocene might have created a strong surface water stratification in the region, which inhibited surface mixing and upper thermocline ventilation. This together with advected OM from the productive area may account for an enhancement of denitrification.

4. Intermediate water circulation and thermocline ventilation changes

The intermediate circulation and thermocline ventilation changes coupled with the seasonal monsoon productivity variations account for changes in the O_2 inventory within the OMZ across the basin. It was suggested that the advection of water masses, their strengths, spatial extents and seasonal variability of advective pathways are the potential factors responsible for the eastward shift of the Arabian Sea OMZ and its perennial character (Schmidt et al., 2020). Hence, in order to better understand the OMZ dynamics, it is crucial to assess past changes in dissolved oxygen (DO) of thermocline waters and the underlying mechanisms, which controls the OMZ intensity and associated biogeochemical processes. Different geochemical (e.g. Anderson et al., 1989), isotopic (e.g. Kajiwara and Kaiho, 1992) and faunal proxies (Singh and Conan, 2008; Ohkushi et al., 2013; Singh et al., 2015; Kranner et al., 2022) can be used to track changes in DO concentration.

Past changes in DO conditions at intermediate depths that controls the OMZ intensity, can be reconstructed by analysing aragonite (a metastable polymorph of calcite) preservation in sediment cores collected from the OMZ regions (e.g. Klöcker et al., 2006; Singh, 2007). The aragonite preservation/dissolution depends on the pH of thermocline waters. An enhanced respiration of sinking OM raises CO_2 and dissolved inorganic carbon (DIC) concentrations in subsurface waters and lowers the pH leading to the OMZ intensification and shoaling of aragonite lysocline. The preservation condition of pelagic aragonite in sediment is related to the variation of aragonite lysocline/aragonite compensation depths. Today the average aragonite compensation depth (ACD) is shallower (~500–600 m) due to high consumption of O_2 and poorly ventilated thermocline waters (Millero et al., 1998). Pteropods are the main aragonite source to marine carbonates (Singh and Conan, 2008). The preservation record of pteropod shells/aragonite, particularly in highly productive region like the AS, is commonly used to reconstruct changes in ACD, which is intimately linked with the OMZ intensity and subsurface water mass chemistry. We compared the published records of aragonite preservation (pteropod shell abundances/aragonite content in sediment) from various locations of the AS margins in order to assess basin-wide changes in the thermocline oxygenation/ventilation within the OMZ (Fig. 2, Panel a, Klöcker et al., 2006; Böning and Bard, 2009; Naidu et al., 2014).

The temporal variation in the pteropod/aragonite preservation depicts millennial-scale events of abundance maxima occurring most prominently during the Heinrich stadials. Interestingly, all the major preservation spikes identified in different sediment cores across the basin (within the errors of the radiocarbon chronology) have an anti-phase relationship with the $\delta^{15}N$ values, which is primarily controlled by the OMZ intensity (Fig. 2, Panel a). This indicates an enhanced pteropod preservation owing to reduced oxygen consumption in the thermocline waters and/or enhanced supply of oxygenated water at intermediate depths. The pteropod/aragonite spikes correspond to the periods of significant reduction or even collapse of denitrification associated with a weakened OMZ and deep ACD. Conversely, the intervals featuring very low abundance or absence of pteropods are likely to be associated with an intensified OMZ and a shallow ACD. It can be argued that the overlying water at the core sites during these periods of pteropod/aragonite dissolution was under-saturated and aragonite saturation depth was considerably shoaled. While having a closer look at the chronology of the preservation events at each location, we observe some inconsistency in relation with the amplitude and timings except for the most pronounced event that occurred synchronously across the basin during Heinrich stadial 1 (HS1).

A marked difference in the magnitude of aragonite preservation between the EAS and NEAS is evident during the YD. Pteropod/aragonite preservation is favoured in the EAS, while it declined conspicuously in the NEAS (Fig. 2, Panel a). It is noteworthy that the OMZ in the NEAS during the YD was relatively much weaker than the EAS, as reflected by $\delta^{15}N$ records. Therefore, aragonite preservation in the NEAS is expected to be high. Probably, the differential influence of water masses with varying intensity (from the marginal seas and southern sourced) ventilating the thermocline waters in the NEAS and EAS caused this discrepancy in the two regions (e.g. Böning and Bard, 2009). Nevertheless, the limitations in comparing the preservational records based on different proxy approaches (pteropod shell abundance and % aragonite) cannot be ignored. The poor preservation or complete dissolution of pteropod shells during the Holocene and LGM is evident in all the preservation records across the basin, with an exception in the WAS where pteropods are moderately preserved during the LGM (Fig. 2, Panel a).

Several studies from the AS have emphasised that the oxygen depletion at mid-water depths is primarily driven by monsoon-induced surface productivity (e.g. Reichart et al., 1997; Schulte and Müller, 2001; Altabet et al., 2002) and subsurface ventilation by oxygen-rich waters either due to local or externally sourced water masses (Reichart et al., 1997; Naidu et al., 2014). The proxy data presented here clearly indicate that the monsoon production cannot solely explain the aragonite dissolution during the late Holocene and LGM, as annual primary production was low across the basin during these periods. Furthermore, the East–West heterogeneity in the preservation/dissolution events warrants other additional factors/mechanisms to be considered. It is plausible that the thermocline ventilation through basin-wide circulation and local mixing processes played a critical role in modulating the OMZ intensity, ACD and hence the aragonite preservation condition. A recent study has indicated changes in CO_3^{2-} concentration in the AS in response to the deep-water circulation change, which led to variation in the carbonate lysocline, causing fluctuations in carbonate preservation (Naik et al., 2023). Previous paleoceanographic studies have demonstrated links between pteropod preservation/dissolution, OMZ ventilation and intermediate water mass circulation (e.g. Klöcker et al., 2006; Böning and Bard, 2009; Naidu et al., 2014). However, the relative role of atmospheric and ocean circulation controlling sub-surface oxygen conditions and the contribution of different intermediate water masses to ventilate the thermocline across the basin remain elusive, due to a paucity of adequate proxy records.

5. Evolution of intermediate and deep-water mass circulation in the Arabian sea

Recent studies suggest the SAMW-AAIW is an important source for thermocline ventilation in the AS (e.g. Böning and Bard, 2009). These studies point to an enhanced production and northward penetration of SAMW-AAIW in the Indian Ocean during the stadials (Schulte et al., 1999; Pichevin et al., 2007; Schmittner et al., 2007), when NADW flow was reduced (e.g. Böhm et al., 2015). On the contrary, some studies from the Southern Ocean indicate increased production of AAIW during the LGM and deglaciation (e.g. Skinner et al., 2010). An intensified inflow of oxygen-rich SAMW-AAIW in the AS could increase thermocline oxygen in the basin and influence the OMZ intensity (e.g. Böning and Bard, 2009). It is believed that the northward penetration of southern sourced intermediate waters was accelerated during the late glacial because of reduced inflow of the denser RSW and PGW due to low sea-level (e.g. Kuhnt et al., 2013). The increase of O_2 supply to the thermocline led to the development of a weak OMZ, ACD deepening and shutting-down of denitrification. But the origin of the different water masses contributing to the O_2 supply in AS thermocline waters, and variations in their pathways and vertical extents through time, which is crucial to better understand the OMZ evolution, remains unclear. Although, attempts have been made in recent years to investigate the temporal evolution of the source and ventilation of the deep-water masses in the northern Indian Ocean, the proxy records pertaining to the intermediate circulation changes are very limited compared to the deep-water circulations (Jung et al., 2009; Bryan et al., 2010; Ma et al., 2020).

The $\delta^{13}C$ of epibenthic foraminifera is a common proxy for reconstructing past deep-water circulation and distribution of water masses. Today, the vertical distribution of deep-water masses in the AS is less distinguishable because of a progressive mixing (Ma et al., 2020). The circulation below 1500 m depth is dominated by the Indian Deep Water, which forms when CDW mixes with NADW (You and Tomczak, 1993). In the southern Indian Ocean, AAIW flows between 1000 and 1500 m depth above the CDW. The northward penetration of AAIW today is reported up to 10° S. As the deep-water masses move northwards, they upwell to shallower depths (Talley et al., 2011). Available $\delta^{13}C$ records of benthic foraminifera from intermediate water depths (800–2000 m) in the WAS and EAS show a broad similarity in their pattern of variation during the late glacial, deglacial and Holocene, although millennial-scale changes are often not marked clearly due to low sampling resolution (Fig. 2, Panel b). $\delta^{13}C$ increases during the deglacial have been attributed to northward propagation of AAIW into the AS (Jung et al., 2009; Ma et al., 2020). By contrast, $\delta^{13}C$ record from shallower locations in the WAS (Romahn et al., 2014, Fig. 2, Panel b) is not comparable with the intermediate record, which points towards the possibility of either two different sourced water masses with their flow paths at different depths bathing the sites and/or a change in the vertical extent of their pathways through time. The regional discrepancy in $\delta^{13}C$ values may also be related to the input of $\delta^{13}C$ depleted carbon from OM respiration to the water masses during their transport or a switch in the source and area of formation (Bostock et al., 2004). Furthermore, changes in $\delta^{13}C$ are likely to result from variations in deep-ocean nutrient generation, surface ocean productivity and air-sea gas exchange of CO_2 in the source area of water masses. The decrease in $\delta^{13}C$ values suggests that a CO_2 rich deep-water mass bathed the deeper site (>2000 m) during the late glacial and deglacial periods, as reflected by the decrease in $\delta^{13}C$ values (Fig. 2, Panel b). SAMW-AAIW is formed as a result of intense mixing in the Southern Ocean during winter, sub-duction at intermediate depths and eventually advected northward. The probable explanation for differences in $\delta^{13}C$ in AAIW could be (i) a greater mixing of AAIW with underlying CDW or (ii) a change in the $\delta^{13}C$ of source waters. A general increase of $\delta^{13}C$ during the Holocene can be explained by the enhanced contribution of $\delta^{13}C$ rich NADW water to the upwelled CDW (Duplessy et al., 1988).

This study demonstrates that the current knowledge of basin-wide changes in thermocline circulations modulating the Arabian Sea OMZ intensity through time is not yet complete, which is essential to assess the potential future evolution. Therefore, more detailed, multi-proxy reconstructions (ε_{Nd}, paired planktic-benthic ages ($\Delta^{14}C$), benthic foraminiferal oxygen index, $\delta^{18}O$, $\delta^{13}C$ and elemental composition, etc.) are required. It is also necessary to strategically select the study sites across the AS margins to record the basin-wide changes in the extent and intensity of the OMZ. Model based analysis incorporating the temporal as well as spatial variability of water mass circulation and ventilation in response to the climate variability at different time scales will enhance the ability to predict future OMZ changes in the AS.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.eve.2023.100028.

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