

Comments Anonymous Referee #2

The paper by Burdanowitz et al. aims to reconstruct oxygen conditions in the Gulf of Oman over the last 45,000 years using a multiproxy approach (bulk sediment $\delta^{15}\text{N}$, lipid biomarker analysis, and a benthic foraminifera index). The authors propose two distinct modes of oxygenation during this time, with the Holocene reflecting stable conditions, and other periods (e.g., MIS 3) displaying a high degree of fluctuations between oxygenated and deoxygenated conditions. The research contributes to our understanding of the connections between bottom water oxygenation in the region and global climate events.

The authors employ established methodology to produce a robust, high resolution record, and they present their findings in a cohesive manner. Overall, the manuscript is well-written, engaging, and well-organized, and is within the scope of the journal. I present some minor suggestions where additions may help clarify some ideas.

Major points:

Point 1: the $\delta^{15}\text{N}$ sedimentary record is good, but the caveats of the method should at least be mentioned. Robinson et al. (2012) addresses when it is appropriate to use this method, versus when degradation of material becomes an important factor. The shallow water depth of the core used in this study is one factor that argues against alteration of the signal, but a time period of low accumulation could account for some changes in $\delta^{15}\text{N}$ and should be addressed. Other useful references are Tesdal et al., (2012) and Junium et al., (2015).

Response: First, we thank the referee for her/his comments and suggestions, which helps us to improve the manuscript.

We agree that we initially did not address the limitations using sedimentary $\delta^{15}\text{N}$ in a proper way. We therefore will add following paragraph to the introduction: "Denitrification occurs in oxygen-depleted oceanic zones, serving as oxygen source for heterotrophic bacteria reducing nitrate via nitrite to N_2 (Devol, 2008; Rixen et al., 2020 and references therein). For these heterotrophic bacteria it is energetically more efficient to use the lighter ^{14}N from the nitrate source (Devol, 2008). Because of this isotopic fractionation, the remaining nitrate, which is used by phytoplankton, becomes more enriched in ^{15}N (Montoya, 2008 and references therein). The global average $\delta^{15}\text{N}$ of deep water nitrate is about 4.8 ± 0.2 ‰ (Sigman et al., 2000) but denitrification processes lead to more enriched $\delta^{15}\text{N}$ in nitrate with values above 18 ‰ in the Arabian Sea OMZ (Rixen et al., 2014). During the nitrate consumption, phytoplankton also uses the lighter ^{14}N and have an isotope discrimination factor of about 5 ‰ and incorporate the denitrification signal into the biomass (Montoya, 2008). Sinking of this biomass to the ocean floor transports the denitrification signal to the sediments (e.g. Altabet et al., 1995; Gaye-Haake et al., 2005). Therefore, $\delta^{15}\text{N}$ values can be used as a proxy for the OMZ strength in the water column (e.g. Altabet et al., 1995; Reichart et al., 1997). However, diagenetic processes can alter sedimentary $\delta^{15}\text{N}$ values especially under low sedimentation rates (Gaye-Haake et al., 2005; Jung et al., 1997; Junium et al., 2015; Möbius et al., 2011; Tesdal et al., 2013). Nevertheless, it was found that in the Arabian Sea, especially under high sedimentation rates, sedimentary $\delta^{15}\text{N}$ values are a reliable indicator for past denitrification processes (Möbius et al., 2011)."

Sedimentation rates in SL167 are high, ranging between 9.7 and 49 cm/kyr. From other studies (e.g. Möbius et al., 2011 and Jung et al., 1997) we know, that with this high sedimentation rates it is

unlikely that $\delta^{15}\text{N}$ is altered by diagenesis. We will add this to the discussion. Further, we will add cross plot of TN- $\delta^{15}\text{N}$ and sedimentation rates – $\delta^{15}\text{N}$ to the appendix.

Point 2: the use of acronyms in the manuscript was confusing. Some acronyms were introduced (e.g., EBFOI) only for them to be written in full several paragraphs later. Other acronyms were only introduced in the last paragraph of the discussion (LTG and LIG, lines 322 and 323) and were not necessary. Some acronyms were not written out in full at all (ISM, line 265; AS, line 245). My suggestion would be to limit acronym use to terms that are frequently used throughout the paper, and to write out the full names of indices/events that are referred to only once or twice.

Response: We agree that some of the acronyms can be avoided due to their limited usage and we will check this. Further, we realized that we made a mistake regarding LTG and LIG. LTG is the latitudinal temperature gradient and not “latitudinal insolation gradient” as written in the manuscript and we will correct this.

Minor points and typos:

Line 9: “Climatic conditions and its change” -> “Climatic conditions can change”

Response: We will rewrite this sentence to “Changing climatic conditions can shape the strength and extent of the oxygen minimum zone (OMZ).”.

Line 10: “for their ecosystem” -> “for its ecosystem”

Response: We will change it to “for its ecosystem”.

Line 17: “Contrary -> “In contrast”

Response: We will change it to “In contrast”.

Line 28: What is the largest sink? OMZs are the largest sink for nitrogen?

Response: The denitrification is the largest sink for nitrogen in the ocean. We will clarify this by adding following part to the sentence: “...and denitrification also acts as the largest sink...”.

Line 29: N2O not N20

Response: We will change the typo.

Line 59: Why is the isoprenoid hydrocarbon lycopene rarely used? Any reasons you can point to?

Response: We will add “...which is mainly limited to sediments from OMZs or oceanic anoxic events in the past..” as well as the references Farrington et al. (1988), Dumann et al. (2021) and Sabino et al. (2021) to this sentence. A further explanation for its rarely usage is the fast degradation under oxic conditions as stated in lines 67-69 of the manuscript. Lycopane is also not found in every sediment core within the OMZ. For instance, in a core from the NE Arabian Sea (SO90-63KA) within the OMZ we could not find lycopane in the samples, but a “normal” terrestrial plant-wax derived *n*-alkane distribution (see Burdanowitz et al. 2021).

Section 2: RSW is also important in the southern Indian Ocean and has been detected in the Agulhas Current region (see Marshall et al., 2023); not necessarily relevant to your paper, but if you want to emphasize the importance of RSW, a sentence or two could be added here.

Response: The referee is correct, that RSW is also quite important for the southern Indian Ocean and Agulhas region. However, as we focus on the northern Arabian Sea we think this is beyond the scope of our manuscript.

Line 111: “The age-depth model (Figure 3)”

Response: Figure 3 (figure 4 in the new version of the manuscript) shows the results of the age-depth model. As we are describing the methods in this part, we will refer to the figure in the results section.

Section 3.2 and 3.3: Any references used for $\delta^{15}\text{N}$ and column chromatography methods would be good here.

Response: We will add a reference (Menzel et al., 2014) describing the procedure for the $\delta^{15}\text{N}$ measurements. For the column chromatography of the lipids, we will add the reference Herrmann et al. (2016) and some further detailed description of the procedure as follows: “Therefore, a combusted Pasteur pipette was packed with cleaned cotton wool and about 2 cm NaSO_4 . The column was then first cleaned with about 8 ml hexane. Then TLE was transferred with about 1 ml hexane to the column and the remaining 4 ml vial was cleaned 3 times with about 1 ml hexane, which was also transferred to the column. For the hexane-insoluble fraction, about 1 ml of DCM was added for 4 times on the column. The hexane-soluble was saponified (85°C, 2 h) in a 5 % potassium hydroxide (KOH) in MeOH solution and the neutral fraction was extracted with hexane.”.

Line 130: “were” -> “was”

Response: We will change “were” to “was”.

Line 150: “were counted at each depth from representative splits”

Response: We will add “at each depth” to the sentence.

Line 155: Could you explain the Shannon Index here briefly in one sentence?

Response: We will add “For benthic foraminiferal diversity, the Shannon Index $H(S)$ was calculated according to Buzas and Gibson (1969). The $H(S)$ considers the number of species and their relative proportion in the sample. The $H(S)$ value is at a maximum, when all species have equal proportions, while species with low abundances contribute little to it. In eutrophic to mesotrophic ecosystems, the diversity and microhabitat structure is oxygen-controlled, as predicted by the TROX (Trophic-Oxygen) model (Goody, 2003; Jorissen et al., 1995) (Figure 3).” for a brief explanation.

Line 157: A table showing the species and their habitat preference (oxic, suboxic, dysoxic) would be very helpful, even if for the supplemental.

Response: We will add a supplementary table showing the species names, preference to certain oxygen conditions (oxic, suboxic, dysoxic), and relative abundances in all studied samples.

Line 130: “were” -> “was”

Response: We will change this.

Line 233: “led” -> “lead”

Response: We will change this.

Line 235: This could use a reference: “the sea level was in general lower during MIS 3 than during the Holocene.”

Response: We will add the references Rohling et al. (2008) and Siddall et al. (2003). As we refer to the Red Sea sea level curve shown in Figure 6f the sentence before, we will add the references only.

Line 240: “In total, the interplay and the bipolar seesaw structure of the northern and southern hemispheric climate signals may lead to the feature that some of the D/O events as well as Heinrich events are not represented in the record.” This isn’t very clear to me - do you mean the interplay between northern and southern signals? What specific combination of climate factors could result in the dampened signal in the region?

Response: The referee raises here an important question. It is not easy to answer it because local, regional and global factors have an impact on oxygenation in the water column and bottom water. We have tried so summarize these points in this section (lines 228 – 239). First, D/O events are different in their durations and strength (e.g. Buizert & Schmittner, 2015) and thus their impact on the Indian and Asian Monsoon systems. Second, fluctuations of Red Sea sea level results in variations of RSW influence at the core site. Third, the northward extension of the AAIW is linked North Atlantic climate. In line 240 we mean the interplay of all these mentioned points, this includes the bipolar seesaw pattern between northern and southern hemispheric climate but also the climate and oceanic patterns on regional scale. We will rewrite this sentence for better understanding.

Line 245: You could reference your figure after mentioning the triple peak for the first time, as well as writing which proxies show the triple peak most clearly.

Response: We will add “ $\delta^{15}\text{N}$ ” to the sentence and refer to Figure 5b, where the $\delta^{15}\text{N}$ record is shown.

Lines 228 – 277: This paragraph is quite long and puts forward several ideas. Maybe it could be broken up into two or three paragraphs (e.g., break at line 246 or 263).

Response: We agree with the referee and we will restructure this section. We will split this part into two main sections. The first one for the time period Pleistocene until Younger Dryas, with own paragraphs for the LGM and B/A and the other main section for the Holocene.

Line 276: To what does “this” refer to? The fact that no lycopanes were preserved? Why does the presence of this species aid the interpretation (because of its habitat preference)?

Response: In general, high ratios of $(\text{Lycopane} + \text{C}_{35})/\text{C}_{31}$ indicate a good preservation of lycopane under oxygen depleted conditions. In this case also fast burial of organic matter, indicated by high total organic carbon mass accumulations rates (Fig A1a), plays an important role of the high lycopane content. “This” refers to the assumption that high total organic carbon mass accumulation rates are responsible for the good preservation of lycopane. Further, the dominant species *Uvigerina peregrina* favors high supply/quantity of organic matter (Koho et al., 2008; Schmiedl et al., 2010). We will add this information.

Line 289: “environmental” -> “environmentally”

Response: We will change this.

Line 299: Periods just before this were written to one decimal point, and the ones here are written with two; it might be clearer to round these to one point.

Response: We agree with the referee and will round it to one decimal point.

Line 308: What does an interstadial AMOC mode mean in this context? A weaker circulation?

Response: Buizert & Schmittner (2015) use the term “interstadial AMOC mode” to a strong AMOC/warm North Atlantic Ocean. In contrast, a “stadial AMOC mode” would mean a weak AMOC/cold North Atlantic. They also describe a “glacial AMOC mode” associated with the cold Heinrich events and weakest AMOC as well as strongly reduced Glacial North Atlantic Intermediate Water formation. We will add this information to make it clear as follows “...inhibited an interstadial AMOC mode (strong AMOC/warm North Atlantic), which is required to initiate D/O events (Buizert and Schmittner, 2015).”.

Line 310: This phrase sounds odd, as it is not explored further. Perhaps a better way to phrase it would be “this pattern may or may not be the reason for the absence of a strong D/O 6 signal...”

Response: We used “might not be” in the wrong context. We will change it.

Line 334: the phrasing could be changed - “the very well ventilated conditions” -> “the well-mixed/the strong ventilation/the oxygenated conditions”

Response: We will change it to “The well oxygenated conditions...”.

Line 344: the phrasing could be changed – “with swinging back and forth oxygen conditions” -> “with fluctuating high and low oxygen conditions.”

Response: We will change it as suggested.

References mentioned in the reply:

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