Hamburg, November 2, 2023

Dear Editor,

thank you for your comments, the comments of the two reviewers, and for granting us sufficient time to complete a revised version of the manuscript. We gratefully acknowledge the referees' efforts and thoughtful suggestions for improving our manuscript. Generally, we have followed most of their suggestions. We have added three new figures and enhanced the associated text in order to provide better and more convincing information on our age model establishment and on the northern hemisphere climate impact on deep-water formation in the northern Red Sea. The modified passages of the manuscript are marked in the "track changes" mode. Below, please find a point-by-point account (in "red") of how we have dealt with the comments.

Reviewer #1:

> Hubert-Huard et al presented high-resolution composite carbon and oxygen isotope records in epifaunal benthic foraminifera in the central Red Sea during the MIS3. The authors attempted to use these records to infer changes in the Red Sea Overturning Circulation (ROC). The data presented seems to be of high quality. However, the authors did not convincingly explain how their data can be used to infer ROC changes, which is fundamental to the presented discussion. For this reason, the manuscript would need to be significantly expanded and improved for further consideration. Below, I will explain the main point I raised in detail and raise a few other minor issues. I hope these can be helpful for the authors to improve the manuscript.

Thank you for acknowledging our efforts and for your helpful review! We have enhanced the comparison and discussion of the available stable isotope records and hope that the discussion and presentation of our data are more convincing in the revised version of the manuscript.

> **C-O isotopes and ROC**
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> The authors did not explain how the oxygen isotope is linked to the ROC. I agree with the authors that oxygen isotope is linked to temperature and, with some caveat, salinity. However, the authors did not lay out how the salinity/temperature changes at Site KL11 are linked to the circulation change before they used the resemblance of their record with the Greenland ice core record to argue for the link between the NH climate and ROC changes.

We have generated new figures and enhanced the associated discussion in order to clarify the link between high northern latitude climate variability and deep-water formation in the northern Red Sea. Figure 4 shows the comparison of the benthic δ^{18}O records from the northern and central Red Sea. This comparison not only illustrates our strategy for the establishment of the age model for KL11 (see below) but also strikingly shows the homogenous deep-water oxygen isotopic composition of the Red Sea basin and the presence of concomitant basin-wide changes.

In the new figure 7, we compare the planktic $\delta^{18}O$ record from the northernmost Red Sea with our epibenthic $\delta^{18}O$ record from the central Red Sea. As previously demonstrated in various studies, the Red Sea planktic $\delta^{18}O$ record is closely associated with sea level and thus the exchange of water masses with the Arabian Sea, which ultimately controls the salinity in the Red Sea surface water. The planktic $\delta^{18}O$ record was interpreted to contain a combination of both southern and northern hemisphere signatures (Siddall et al., 2003; Rohling et al., 2004) and, thus, lacks the typical succession of D/O and Heinrich events seen in Greenland ice cores. Although the deep-water $\delta^{18}O$ record should reflect the preconditioning of $\delta^{18}O$ in the surface water, it displays a different signal which is nicely illustrated by the difference between the epibenthic (deep-water) $\delta^{18}O$ record of KL11 and the planktic (surface-water in the vicinity of deep-water formation sites) $\delta^{18}O$ record of GeoB5844 (Fig. 7). The $\Delta\delta^{18}O$ record reveals maximum values for cold intervals (stadials and Heinrich events), highlighting the formation of significantly colder and/or more saline water masses at deep-water formation sites during northern hemisphere cold events. This provides evidence for a high northern hemisphere climate control of Red Sea deep-water formation, which is of central importance for the ROC.

There are clearly alternative ways to explain the oxygen isotope data. A plausible one would be the sea-level control, mentioned in the introduction by the authors, and can be further supported by the similar oxygen isotope record at Site KL11 to the relative sea level at an upstream site (GEOB5844-2), which is also based on the benthic oxygen isotope data. Overall, it appears to me that it is difficult to use salinity/temperature changes at a single site to deduce circulation changes.

As previously shown and addressed above, the oxygen isotopic composition of the surface water in the Red Sea is closely associated with sea level. The salinity also preconditions the formation of deep-water masses in the northern Red Sea. Consequently, the base level of the deep-water $\delta^{18}O$ signal is related to the exchange of water masses with the Arabian Sea and thus contains a sea level signal (Arz et al., 2007). The homogeneity of deep-water masses in the Red Sea is nicely reflected by the close resemblance of the benthic $\delta^{18}O$ records from the central and northern Red Sea, which we used for constraining our age model (see new Fig. 4). Since $\delta^{18}O$ is a conservative tracer, in the deep-sea it will only change if it mixes with other water masses. Accordingly, any changes in temperature and/or salinity of surface waters at the deep-water formation sites are readily transferred to the deep sea in the entire Red Sea.
As already stated above, the deep-water $\delta^{18}O$ record differs from the planktic $\delta^{18}O$ record of the northern Red Sea, which is nicely illustrated by the $\Delta\delta^{18}O$ signal. The observed changes in the $\Delta\delta^{18}O$ record suggest a close link to northern hemisphere climate variability with more dense water formation during cold intervals (stadials and Heinrich event) and less dense water formation during warmer intervals. We have modified the discussion accordingly and hope that this together with our improved illustration resulted in a more convincing discussion and interpretation.

For the carbon isotope record, it is also difficult to use the single site record to infer circulation changes. Benthic carbon isotopes at Site KL11 may help reveal ROC changes, only when combined with other records from sites either shallower/deeper than KL11 or upstream/downstream of KL11.

We agree that it would be better to compare epibenthic $\delta^{13}C$ records from different sites along a north south gradient to monitor potential changes in the residence time of deep waters and to infer changes in the intensity of the ROC. Unfortunately, we do not have such a data set. This is mainly due to the fact that epibenthic foraminifera are virtually absent during MIS3 in the northern Red Sea, and benthic $\delta^{13}C$ data are only available for the infaunal species *Bulimina marginata* for this time interval (Arz et al., 2007). Infaunal $\delta^{13}C$ signals bear a strong microhabitat effect and do not provide confident information on the $\delta^{13}C$ composition of the deep water DIC. We are also aware that potential north-south gradients in deep-water $\delta^{13}C$ of a marginal basin such as the Red Sea are also shaped by gradients in surface-water productivity and related organic matter fluxes to the deep sea. We have addressed this process in our manuscript.
Nevertheless, the close resemblance of changes in the epibenthic $\delta^{13}C$ record of KL11 and the NGRIP isotope record suggests a link to deep-water formation processes in the northern Red Sea. This interpretation is supported by the $\Delta\delta^{18}O$ record (see above).

As no strong link was established between the C and O isotopes and ROC by the author, lots of effort is made to interpret the C and O isotopes (e.g., Lines 210-230, Section 4.2), which appears to be off the topic of ROC change set by the title and introduction of the manuscript.

We agree that different processes have to be considered in the interpretation of the available isotope records and disentangling of it is challenging. Despite this complexity, we are convinced that by including the $\Delta\delta^{18}O$ signal we are now able to present strong evidence for a close relation of Red Sea deep-water formation to high northern latitude climate. We agree that this is not the only process which drives the ROC but at least an important component. Nevertheless, we regard the discussion of other processes, in particular the potential influence of sea-level on the preconditioning of surface water salinity and productivity, the latter process leading to the addition of ^{12}C to the deep-sea.

Minor points

Figure 2. I highly recommend the authors comprehensively show wind fields, salinity, density, dissolved oxygen concentrations, etc., during two monsoon seasons to aid readers with the seasonal circulation changes in the Red Sea. Not every reader of the journal would be familiar with the Red Sea hydrography.

We have created a new figure (Fig. 2) with information on the seasonal patterns of salinity, temperature, and surface currents for better illustration of the Red Sea hydrography. The surface currents also reflect the average seasonal wind field.

Age model. Better to show the alignment between cores KL11 and GEOB5844-2, and show the age tuning points in Figures 4 and 5.

We have created a new figure (Fig. 4) showing the alignment of the benthic δ^{18}O records of core KL11 and GeoB5844-2, also indicating the position of radiocarbon dates, paleomagnetic dates and graphical tie points.

Line 157: Carbon isotope fluctuation is not linked to the carbon inventory.

We agree and refrained from using the term carbon inventory with respect to stable carbon isotope composition.

Reviewer #2:

The study present new high-resolution benthic d13C and d18O records from the central red Sea, a region that captures several modes of palaeoclimate variability (glacial-interglacial sea-level changes, orbital monsoon variability, millennial variability). This study focusses on millennial variability in MIS 2-4. It is well written and presented and suitable for publication in Climate of the Past, in light of the following comments/suggestions.

Thanks for the acknowledgment of our efforts and for your helpful review!

First, the authors need to show synchronization of KL11 d18Obenthic to GeoB5844 d18Obenthic. A table of depth-age points is given, but I'd like to see the d18O tuning, and more details of the Arz et al chronology, as the timing of orbital and millennial variability in the new records presented here largely hinges on the Arz et al 2007 chronology for core GeoB5844.

We have created a new figure (Fig. 4) showing the alignment of the benthic δ^{18}O records of core KL11 and GeoB5844-2, also indicating the position of all available radiocarbon and paleomagnetic dates (Schmelzer, 1998; Arz et al., 2007), and additional graphical tie points (this study). In Table 1, we do not list the radiocarbon ages for core GeoB5844-2 since all dates and further information is given already in Arz et al. (2007).

What are the black lines in Fig. 4a and 4b? Looks like a moving average, but caption doesn't state. Given the data spread and the rather large standard deviation for each species, and the fact that different species were used and corrected for their offsets, it would be nice to see an attempt to quantify these uncertainties.

> The box & whisker plots demonstrate the wide SD of the data. The large millennial-scale variability in d18O is appears robust however, regardless of the above, due to the high-amplitude shifts in isotopic values.
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> For d13C, amplitude of millennial variability is within the range of the calculated standard deviations, so initially I'm a bit more cautious about the black line in Fig. 4b and its interpretation. For instance, the older part of the d13C plot (>50 ka) is very consistent among species, hence the trend appears robust, but the younger part shows quite a bit of divergence among species, despite their being corrected for inter-specific isotopic offsets. However, the younger portion of the d13C record shows strong correlation with d18O, which suggests that the described millennial variability in d13C is robust.

The black lines in former Fig. 4a, b (now Fig. 6a, b) correspond to the composites, representing the averages from the up to three analysed benthic foraminiferal species per sample. Before calculating the averages, the isotope signals of *D. bertheloti* s.l. and *H. boueana* s.l. were corrected by their mean species-specific offsets from the signal of *C. mabahethi*, as shown in Fig. 5. The caption of Fig. 6 has been updated in the manuscript.

We agree that the standard deviations shown in the box and whisker plots of Fig. 5 are relatively high. Nevertheless, the standard deviations of the calculated averages in the composite records are quite low (±0.16‰ for $\delta^{18}O$ and ±0.13‰ for $\delta^{13}C$) suggesting a robust signal. Given the high amplitudes of the $\delta^{18}O$ record and the good correlation between $\delta^{13}C$ and $\delta^{18}O$ (in the younger part of the studied interval), we consider the observed millennial-scale changes as robust and confident.

We have extended the text of the discussion in the revised manuscript accordingly.

> Is the observed synchroneity of the KL11 d18Obenthic millennial variability with NGRIP biased to some extent by tuning to the Arz et al 07 chronology?
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> (in the same way that millennial variability in the Siddall/Rohling sea-level record -using KL11- shown in Fig. 5d may be biased by their tuning to Antarctica).
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> I agree with the authors' observation that the offsets in inferred relationships to sea level may relate to age model strategies and uncertainties. I also wonder if this offset is real, ie, in KL11 the planktics are recording global sea level variations (which ~ follow Antarctic temperature) while the benthics are recording millennial ROC (which ~follows Greenland millennial variability). This can be explored with same-sample d18O on benthics and planktics.

The age model of KL11 in Siddall et al. (2003) was established by tuning to the Byrd ice core record from Antarctica. Instead, the age model of core GeoB5844-2 (Arz et al., 2007) is based on absolute dating of the record using radiocarbon and paleomagnetic dates. The homogeneity of the Red Sea deep-water in terms of salinity and temperature and, thus, close correspondence of the benthic $\delta^{18}O$ records of KL11 and GeoB5844-2 allows the alignment of the two records (see new Fig. 4). We are aware that also the radiocarbon dating can be biased by uncertainties of reservoir ages. Although preservation of the used planktic foraminiferal tests and pteropod shells for radiocarbon dating appeared excellent, we also cannot fully exclude potential diagenetic effects. Despite these potential biases, we decided to base our age model on the absolute dating and intercorrelation of the cores from the Red Sea in order to avoid tuning of the records to external data series.

In order to explore the question of the reviewer concerning the sea-level control of the planktic δ^{18}O and the northern hemisphere climate control of the benthic δ^{18}O, we have created a new figure (Fig. 7) and extended the associated discussion in the text. The $\Delta\delta^{18}$O signal (difference between planktic δ^{18}O of core GeoB5844-2 and epibenthic δ^{18}O record of KL11) reveals high values during stadials and Heinrich events. This suggests a strong control of deep-water formation in the northern Red Sea by high northern latitude climate variability. Instead, the planktic δ^{18}O record seems to primarily reflect changes in sea-level, lacking the typical sequence of D/O and Heinrich events, confirming earlier evidence.

> The discussion of the short-term sea-level variability from line 190 is rather brief and may benefit from further reference to Siddall et al 2008 Rev. Geophys.

Thanks for this comment. We have extended the discussion, referring to the suggested paper.

> In the paragraph from line 196, the inferred max ROC during HEs is attributed to restricted exchange with the Indian Ocean and consequent SSS increases. But the sea level signal is not like that of NGRIP or KL11 d18Obenthic (which are more asymmetric with a sharp stadial-interstadial transition, as the authors describe); sea level variations are more symmetrical, like Antarctic climate. So, isn't it more likely that the strong ROC during HEs is instead related to extreme cooling of the Northern Red Sea due to an expanded Siberian High and attendant northerly winds? (line 203 in the next paragraph suggests cooling & enhanced evap in HEs, but doesn't describe mechanisms of cooling & enhanced evap, only the SSS-Indian Ocean exchange mechanism).

We agree with this comment and changed our discussion accordingly. The close resemblance of the epibenthic δ^{18}O record with the NGRIP ice core records suggests a dominant role of processes at the formation sites, which is best explained by phases of strong cooling. We have added reference to the Siberian High. We are also convinced that the preconditioning of the salinity of surface water masses (which is linked to sea-level) also plays a role. This may explain the appearance of maximum $\Delta\delta^{18}$O values (see new Fig. 7) at the end of Heinrich events. However, our temporal resolution is probably too low and potential dating errors too high to fully resolve the combination of the different signals in full detail.

> Good discussion of comparison to different monsoon indices and integration with evidence from the literature.

Thanks for the appreciation of our work!

Minor points

Line 29: mass or masses, not masse

It has been corrected.

Line 161: do you mean '…and also exhibits…'?

It has been corrected.

Editor:

After studying the Reviewers' comments and your answers, I am happy to invite you to submit a revised version of your manuscript. Please make sure your revised manuscript include all the changes highlighted in your responses. In particular, please provide more detailed information about the processes that could lead to changes in ROC and d18O. This can be based on both proxy records and climate modelling.

It has been corrected.

Please carefully assess how the inclusion of H Boueana affects your d13C composite. Please consider showing a d13C composite with and without H Boueana (at least in the Appendix).

The inclusion of *H. boueana* allows us to complete our isotopic record along the MIS 3, especially with two samples where the two other species were absent. The composite record without *H. boueana* follows the same patterns and closely resembles to the composite record with *H. boueana*. Therefore, including *H. boueana* allows us to complete and improve our data set (see new Supplement B).

Please also be clearer in your interpretation of the d13C record: i.e. how the climatic and circulation changes affect your record as well as how you estimate and explain the multi-millennial time lag.

The observed long-term decrease in our benthic δ^{13}C record in the lower part of the studied section clearly reflects the intrusion of nutrients from the Arabian Sea during winter, fuelling surface water productivity and related organic matter fluxes in the southern to central Red Sea. Our observation is confirmed by the appearance of planktic foraminiferal high-productivity indicators (Trommer et al., 2011). This proxy evidence implies the impact of a more or less pure East Asian summer monsoon signal, which is known to lag summer insolation by ca. 3 kyr (as inferred from Asian speleothem records; see review of Clemens et al., 2010). Instead, the stacked summer monsoon proxy record from the Arabian Sea lags summer insolation by ca. 8 kyr. This strong lag has been attributed to the influence of northern hemisphere ice volume and southern Indian Ocean SST (Clemens et al., 2010) but this discussion is still ongoing. More recently, the model study of Jalihal et al. (2022) was able to reconcile the conflicting evidence. Their model results suggested that upwelling in the Arabian Sea occurred in phase with summer monsoon strength only in a narrow region along the coast of the Arabian Peninsula, while it became weaker or out of phase further away from the coast. The rather immediate Red Sea response demonstrates that nutrient intrusions are linked to inflowing nutrient-rich surface water from near-coastal waters of the northern Arabian Sea.