Response to anonymous referee #2

We would like to thank referee #2 for their thorough and very constructive comments. Below follows a point-by-point response to the comments and changes that will be enacted in the revised manuscript. Our answers are indented for differentiation from the original text by referee #2.

In the manuscript entitled "Biotic Response of Plankton Communities to Middle to Late Miocene Monsoon Wind and Nutrient Flux Changes in the Oman Margin Upwelling Zone" submitted to "Climate of the Past", G. Auer and co-authors retrace the evolution of the upwelling cell in the Western Arabian Sea over the Middle to Late Miocene interval ~15 to 8.5 Ma. The authors integrate counts of calcareous nannofossils and diatom frustules in 71 samples and counts of planktonic foraminifers in 28 samples (all converted to abundance %) with published geochemical data (XRF-scanning elemental data, carbonate, organic carbon and nitrogen isotope measurements) from Bialik et al. (2020). Statistical methods including cluster analysis are applied to investigate associations between microfossil abundances and environmental parameters derived from geochemical data.

The main findings of the research are: (1) the onset of upwelling at ~14 Ma along the Oman margin and development of full monsoonal conditions after ~13 Ma were closely linked to the evolution of regional tectonics and global climate; (2) a high-productivity regime was gradually established at ~12-11 Ma in tandem with high-latitude re-organization of intermediate-water formation (AAIW and SAMW); (3) peak upwelling productivity between ~12 and 9.6 Ma was driven by enhanced nutrient fluxes from increased AAIW and SAMW production; (4) upwelling productivity declined after ~9.6 Ma due to the waning of monsoonal winds.

The manuscript presents interesting, important results concerning a climate sensitive region within the Asian Monsoon system and it targets a period of the Middle to Late Miocene that has remained highly enigmatic. The multiproxy approach, combining records from calcareous and siliceous microfossil groups as well as geochemical data, provides valuable insight into the biotic response to long-term changes in upwelling-driven productivity along the Oman margin. The manuscript is well-suited to the scope of "Climate of the Past", in particular to an issue dedicated to Dick Kroon, who pioneered paleo-monsoon research in the Arabian Sea. Despite these positive aspects, I feel, however, that the manuscript requires some substantial revision. Please find below some major and minor issues that should be addressed before the manuscript can be considered for publication in "Climate of the Past".

> **Reply:** We thank reviewer for their thorough assessment of our manuscript. A detailed list of enacted changes an responses has been attached below. The original comments are presented for reference.

Major issues

This work extends previous research published by Bialik et al. (2020) in "Paleoceanography and Paleoclimatology". However, the amount of overlap between the two contributions is at times equivocal and will need to be clarified during revision. Clarification is needed, in particular, concerning the originality of the data and interpretations. Some reiteration of background information and reference to previous results from Bialik et al. (2020) appear in various parts of the manuscript, but relevant information is not always provided or easy to locate. For instance, Line 144 mentions that

portions of the nannofossil data set was already published, but does not indicate how many samples were previously analysed. Overall, the novelty of the findings in the current manuscript needs to be more clearly highlighted.

Reply: Thank you for this recommendation, we have revised manuscript accordingly.

The manuscript is relatively long and I feel that the discussion on Lines 253-514 (Sections 5.1-5.3 of Discussion) could be streamlined to avoid some internal redundancy. In addition, the authors might consider summarizing the temporal progression of environmental changes outlined in Section 5.2 into a table for greater clarity. It would also be useful to include this information into one of the figures or into an additional summary figure. In the current version, the temporal evolution of upwelling productivity is not indicated on any of the figures and one has to search through the dense text to find this key information. The color coding in Figs. 2-3 and 5 only refers to the cluster assignment, based on the nannofossil assemblages.

Reply: Thank you for this suggestion, we follow it closely during the revision of the manuscript. However definition of TG and Intervals should always be separate to avoid confusion about assemblage interpretation versus the application of changes in assemblage occurrence within a stratigraphic context. These are strongly separate aspects of interpreting the data, both of which should not be neglected or overlooked when working with fossil assemblage data, especially when applying multivariate statistics.

We also agree that visualizing the complex aspects of the progression is an excellent suggestion. As a result, with have changed figure 3 and 5, to show the progression of interpreted upwelling intensity in conjunction with the intervals we defined based on our nannofossil taphocoenosis.

The manuscript contains abundant references to the recent literature to support the interpretation of the results and the discussion. To strengthen the interpretations and to highlight the key findings presented on Lines 515-691, it would be useful to add a synthesis figure that provides a direct comparison of results with some of the cited published records. At present, only the temperature data from Zhuang et al. (2017) are shown in Fig. 3. Adding a synthesis figure would be especially important to demonstrate, for instance, that major changes in global climate and ocean circulation are synchronous with changes in regional upwelling-driven productivity, as proposed in the discussion. Overall, such a figure would considerably help to bolster the interpretations.

Reply: Thank you for this suggestion. We had hoped that our Figure 6 may serve this purpose, but it appears to have been less successful in doing so than anticipated. We have therefore included an additional figure (now figure 6), which summarizes a limited amount of relevant datasets in both the Indian Ocean region, but also two global compilations: a) the CENOGRID d18O data of Westerhold et al. (2020), and b) the sea level data of Miller et al. (2020). Figure 1 was also adjusted to show the Sites where the data in the Indian Ocean originates from.

The paper contains little information on present day circulation patterns in the Indian Ocean and on the origin of the water masses that upwell today in the Arabian Sea. As the authors put a great deal of emphasis on the role of distant circulation changes in controlling nutrient availability and ultimately productivity in the upwelling cell along the Oman margin, it would be useful to relate their reconstructions of past circulation in Fig. 6 to the modern scenario. I find the expansion of SAMW and AAIW to water depths of 1000 and 1500 m north of the equator during the Miocene somewhat surprising. However, I accept that very little is known about Miocene Indian Ocean circulation and that it may have markedly differed. Nevertheless, I still feel that other potential influences should be considered, such as the role of the Indonesian Throughflow, when the Indo-Pacific gateway was fully

open. I am also puzzled that the water depth of Site 722 is not taken into consideration (see comment below for Lines 121-124), when assessing the intensity of upwelling.

Reply: This is a comment that has also been raised by referee#1. We note that there is clear modern-day evidence for the contribution of mode and intermediate waters forming in the ACC to low latitude upwelling cells (see Böning et al., 2009; Toggweiler et al., 2019; as well as Laufkötter und Gruber, 2018). As this is a critical aspect of our present study, we intend to add another panel to Figure 1 and be more specific in our introduction and discussion to give these aspects of our interpretation the necessary scientific basis.

Minor issues

Abstract

Lines 25-26: the sentence starting with "We combine…." is unclear. Please revise and clarify.

Reply: Thank you, this has been revised.

Line 30: the duration of the MCO, based on distinct isotopic events, is considered to be 16.9 to 14.7 Ma. A global d18O decrease at 16.9 Ma signals the onset of the MCO and a global d18O increase at 14.7 Ma marks the first step in ice sheet expansion and global cooling during the MMCT (cf. Holbourn et al., 2014, 2015).

Reply: This was revised as requested.

Lines 32-34: please specify time interval. Do you mean after 12 Ma?

Reply: Thank you, we clarified that it happened after 12 Ma and persisted thereafter, at least based on our current data basis and interpretation.

Lines 35-36: please break up into two shorter sentences.

Reply: Done, thank you for the suggestion.

Line 36: replace "beginning" by "the onset".

Reply: Done, thank you.

Line 39: unclear what "SAM" refers to here. Acronym not previously explained.

Reply: We apologize for this oversight, SAM is now spelled out at South Asian Monsoon. Thank you for pointing this out.

Line 40: "The absence of full correspondence…". Not really clear what is meant here.

Reply: Has been revised to: „The absence of a clear correlation with (…)"

Line 43: omit "fossil" here.

Reply: done

Introduction

Line 48: “a” missing before “biomass”

Reply: Thank you, we fix this typo.

Lines 54-60; upwelling areas can also be sources of CO2. Please revise.

Reply: While this is indeed is true on a short term basis, as CO2 degassing indeed releases ocean bound CO2 from the DIC system, we however have not come across any evidence that this short term release into the atmosphere can overcome the net CO2 sink based on productivity on geological timescales. Generally net C fluxes in upwelling zones remain skewed towards sequestration into the sediment (see Krapivin and Varotsos, 2016; DOI: 10.1016/j.jastp.2016.10.015). We admit however that ocean atmospheric CO2 exchange should not be omitted in the introduction, hence why we have revised this section accordingly.

Line 68: on glacial-interglacial timescales rather than “in”.

Reply: Revised.

Line 80: becomes established rather than “establishes.

Reply: changed

Line 93: sentence starting with “To date…” needs attention (seems incomplete).

Reply: Thank you, this sentence was indeed incomplete, which must have happened during editing of the final draft. We have now added the complete version of the sentence, which reads: To date, manganese redirection – i.e., the depletion of Mn in the sedimentary record due to Mn-reduction in the water column and subsequent advective transport to the edges of the OMZ – is one of the most used proxies to define OMZs and their past extent within the ocean (Dickens and Owen, 1994).

Line 102: see comment for Line 30 about duration of MCO.

Reply: Thank you, we added the more precise dates.

Line 104: verb should be plural (were established).

Reply: Thank you for catching this error. This portion, however, has changed due to revisions.

Lines 106-107: the MMCT usually refers to the Middle Miocene interval 14.7-13.8 Ma, and does not correspond to the Middle to Late Miocene, as implied here.

Reply: Thank you, we did not intend for this apparent imprecision. We only refert to cooling during the MMCT and subsequent upwelling intensification by 13 Ma (meaning after the MMCT). We have clarified this paragraph.

Section 2

Line 119: “location” more appropriate than “locale”?

Reply: Changed per the reviewers suggestion. Thank you.

Line 120: please add water depth of Site 722.

Reply: Done. This section was extended in the revised manuscript.

Lines 121-124: (a) Need to clarify relationship of Indian Ocean OMZ and Arabian Sea OMZ.

Reply: Done. This section was expended and also has been better described in the introduction.

(b) Present-day water depth of Site 772 is 2028 m, which is well below the Arabian Sea OMZ (given as between 200 and 1000 m on Line 123). Please check references on the OMZ vertical extent at site location.

Reply: Yes, this is correct. We are sorry it was not made clear we are fully aware of the fact the Site 722 lies below the OMZ in generally well oxygenated deep waters.

Line 125: according to ODP/IODP convention, site needs to be capitalized only when referring to a specific site (e.g., Site 722).

Reply: We are aware, and apologize for not being consistent with formatting through the manuscript. We again went through the MS the make sure all issues with Site vs site and erroneous reference to Site 722B (see comment on Line 127 below) are not correct.

Line 127: should be Hole 722B (one of the holes drilled at Site 722) and not Site 722B.

Reply: See above

Line 128: I guess you refer to Bialik et al., 2020a, when you mentioned “data used in this study”. This is a bit confusing, so please give reference here.

Reply: Done. We have extended this section to alleviate any potential imprecisions regarding this crucial detail.

Section 3

Line 147: Fig. 2 does not really show how the correction factor was derived and applied. Relevant information is required in Methods.

Reply: This was revised to the full application of MARs according to the request of rev#1. The section was also extended to better detail all performed calculations

Line 173: replace “less than” by “fewer than”.

Reply: Thank you, other changes to this text changed the wording.

Line 190: data usually plural.

Reply: True, thank you for pointing out this error.

Section 4

Lines 191-193: verb appears to be missing.

Reply: We added the missing verb ‚calculated'

Lines 197-199: verb tense should be consistent (either past or present).

Reply: Thank you, we have fixed this error

Line 237: please provide brief information on preservation, as you did for calcareous nannofossils.

Reply: Done, thank you for pointing out this oversight.

Section 5

Line 317: should be "delineate".

Reply: Thank you.

Lines 353, 376, 443, 451, 486: please use either "foraminifer" or "foraminifera" consistently throughout the ms.

Reply: done

Line 384: verb should be plural (are).

Reply: done

Line 387: AABW and NADW usually referred to as Antarctic Bottom Water and North Atlantic Deep Water (not Waters).

Reply: Thank you, we have fix this error.

Line 388: Did Woodruff and Savin (1989) specifically referred to this time interval? Precise dating of NADW expansion and AAWB intensification in this part of the Late Miocene remains controversial.

Reply: To quote from Woodruff and Savin (1989): *„At the sametime, NADW beganto formwith greatenoughintensityto influenceSouthAtlanticbenthicforaminifera. At approximately11 Ma, NADW formation became more intense, and AABW in a form more similarto today'sbeganto flow into the Atlantic and Pacific. Thelatest Miocene thermohaline circulation was inmostrespectssimilarto that of the modern ocean*".

Line 412: why refer to Fig. 1 here?

Reply: Since Site U1443 should be shown in figure one (which it isn't due to an error on our part). This was fixed in the revised version. We apologize for the confusion.

Line 461: should be “foraminifera”t to be consistent with remainder of text.

Reply: Done. Thank you

Lines 466-467: reference needed for this shift at 12 Ma.

Reply: Done

Line 515: there is a problem with the numbering of sections: duplication of headers (sections 5.1 and 5.2).

Reply: Thank you, we have fixed this formatting issue.

Lines 521-523: last part of sentence “paired with an expanded OMZ” appears disconnected from the first part of the sentence.

Reply: Indeed, we apologize. This issue was fixed.

Line 634: Taucher et al., 2022 is not an appropriate reference here.

Reply: Agreed, we removed the reference.

Line 711: these references are not appropriate here.

Reply: Agreed, they have been removed.

Line 731: ODP/IODP needs to be acknowledged for providing samples.

Reply: Done, we apologize for the oversight

Line 1234: Kuhnt et al. 2015 misspelt.

Reply: Thank you

Figures

Fig. 3: please specify calibration applied for TEX86 SST data from Zhuang et al. (2017).

Reply: Done.

Fig. 5: (a) Not really clear what is meant by “(note the abundance scaling of N*109/g)”, which also appears in the plot of % diatom frustules. (b) The label “Planktonic foraminifera” should be indicated on the last plot. One has to read the caption to find out what is plotted there. (c) please provide reference(s) in figure caption for previously published data, where appropriate.

Reply: Revised as requested

References:

Holbourn, A.E., Kuhnt, W., Lyle, M., Schneider, L., Romero, O., and Andersen. N., 2014. Middle Miocene climate cooling linked to intensification of eastern equatorial Pacific upwelling. Geology, 42, 19–22, doi:10.1130/G34890.1.

Holbourn, A.E., Kuhnt, W., Kochhann, K.G.D., Andersen. N., and Meier, K.J.S., 2015. Global perturbation of the carbon cycle at the onset of the Miocene climatic optimum. Geology, 43, 123–126, doi:10.1130/G36317.1.