Dear editor,

Thank you for your consideration and all the helpful comments. We have carefully revised the manuscript according to the comments from you and all reviewers. The answers and explanations are in blue color, the corresponding change in the revision-marked version was tracked in red color. The point-to-point responses to the editor and reviewers are listed as following:

Response to the Editor:

1. There need to be more a consistent interpretation of changes in the Cd_w values (as the reviewer already mention in the first review).

Answer: We fully agree with editor and reviewer #1 that the interpretation of Cd_w records should be more consistent. We have enhanced the discussion by the evaluation of all possible factors on intermediate Cd_w records at different time scales. Please see the revised lines 421-444 (section 5.2):

From the last deglaciation to the late Holocene, the Cd_w record displays a significant shift from ~0.7 nmol/kg to about twice values of ~1.59 nmol/kg. The intermediate Cd_w values are thus extremely high during the late Holocene and synchronous with the higher values of C_{org} and *G. bulloides* percentage records. These observed similar trends suggest that the increased surface productivity at the core site during the late Holocene is associated to higher intermediate Cd_w values. Besides, previous studies have suggested that increased Cd_w values (>1 nmol/kg) could correspond to elevated surface productivity (Bostock et al., 2010; Olsen et al., 2016). However, at millennial time scale, we also observed several decreases in intermediate Cd_w values (~0.81 nmol/kg) during the late Holocene, reaching nearly similar values during the last deglaciation (Fig. 5). Thus, the variations in the Cd_w values cannot be fully associated to variations in the surface productivity.

As mentioned before, during the Holocene, an increased influence of NADW in IDW was observed in the northern Indian Ocean (Yu et al., 2018; Ma et al., 2019; 2020). NADW is characterized by a depleted nutrient content (modern Cd_w, ~0.2 nmol/kg; Poggemann et al., 2017), and its contribution to IDW may affect the intermediate Cd_w by deep-water masses upwelling when flowing northward. However, during the late Holocene, benthic foraminiferal assemblage 1 is associated to lower oxygen concentrations, which seem to be inconsistent with an enhanced influence of better ventilated NADW in IDW in the northern Indian Ocean. Therefore, this appearing discrepancy seems to indicate that deep-intermediate water masses variations is not an important control during the Holocene in this area, although we could not fully exclude the influence of NADW in IDW at millennial time scale. Moreover, there is no clear evidence for such a millennial-scale variability in the IDW and/or NADW circulation in the studied area. Thus, we suggest the intermediate Cd_w at core MD77-191 site may be mainly influenced by surface productivity, especially during the Holocene.

2. I consent with reviewer that the depth of NADW and IDW in the Indian Ocean needs to be clarified be clarified according to the reviewers comment and the literature. In order to verify the water mass interpretation, a) the hydrography section still needs further improvement and b) there needs to be a more in-depth explanation how of a deep-water mass, currently occurring below ~2km, affect sediment cores at true intermediate water depth.

Answer: We fully agree with the reviewer that the discussion about the NADW has to be improved.

We have added a short paragraph to introduce the detailed information on modern hydrological setting at the studied site. Please see the revised lines 130-137 (section 2):

Due to the land-sea configuration in the north by Asia, the deep waters of the northern Indian Ocean originate from the south, including the Circumpolar Deep Water (CDW) and North Atlantic Deep Water (NADW) (You, 2000; Tomczak and Godfrey, 2003; Talley et al., 2011). Thus, between 1500 and 3800m, the dominant deep water in the North Indian Ocean is Indian Deep Water (IDW), originating from the CDW admixed with NADW (You, 2000; Tomczak and Godfrey, 2003; Talley et al., 2011). Then, during their pathway, the bottom water upwells when it expands northward in northern Indian Ocean, returning to shallower depths (You, 2000, Figure 1c). Therefore, variations of deep water masses can also influence the intermediate-depth waters in the northern Indian Ocean.

Besides, to be more precise, we also revised the use of “NADW” as “enhanced contribution of NADW in IDW” in the discussion. Please see lines 361, 363, 380, 391, 432, 437 and 440.

Reply to reviewer #1 comments:

Review of manuscript “Changes in productivity and intermediate circulation in the northern Indian Ocean since the last deglaciation: new insights from benthic foraminiferal Cd/Ca records and benthic assemblage analyses” by Ma et al.. This is a revised version of a manuscript that presents data from a sediment cores from the northern Indian Ocean (Arabian Sea and Bay of Bengal), comprising geochemical time series generated on benthic foraminifera as well as census data for planktic and benthic foraminifera. Based on these data, the authors deduce monsoon driven changes in productivity mainly dominating the various records during the Holocene and changes in intermediate water chemistry during the deglaciation. Whilst the revised version of the manuscript has improved by addressing some of the issues raised, there are still a number of problems hampering wholehearted support at this stage.

These are some of the issues (line references are based on the "...ACT1" version of the manuscript that highlights changes in the document):

a) One issue still relates to the consistency of interpreting the Cdw records (a part of this section is unchanged text from the previous review). In chapter 5.4 the authors claim that the Cdw values during the deglaciation are lower than during the Holocene. First, this statement is only correct if longer term averages are considered. On short time scales (which need to be considered, given that this is a chapter on millennial scale change), the youngest Cdw data in core MD77-191 (2-1.5 KaBP) are comparable to the low YD and HS1 values. Up to this point a big effort has gone into establishing Cdw as reflecting productivity variations at the sea surface and the related flux of organic carbon. Now the focus shifts to bottom water ventilation changes being recorded. If general water ventilation would play are role in setting the recorded Cdw values, this has to apply to the Holocene too and would therefore need to be considered there. The revised version of the text does contain some extra lines, but the arguments made are rather unconvincing. First, the discrepancies between the Cdw and the *G. bulloides*/Corg data in figure 5 during the Holocene are not “little” as stated in line 400. There seems to be some covariation at times, but there are also significant offsets during other periods, in particular in the youngest part of the record. Both, *G. bulloides* records in figure 5 as well as the Corg record suggest that the there is high productivity in the latest part of the Holocene. Yet, the Cdw values in core MD77-191 drop back to very low values. Taking this observation as face value, the long-terms trends between the records do show differences too. The authors then argue that the Cdw values in the late Holocene are too high (quoting a value of 1.59 nmol/kg which is difficult to reconcile with figures 4 and 5) to be explained by water mass related changes (here discussed as NADW influence). This refers back to the Cdw record of core MD77-191, however, which does show very low values in the top section, which would be in line with a low Cdw water mass incursion and are not consistent with the high productivity values indicated in the other data in figure 5 for the latest Holocene. This part of the discussion should contain a more in-depth evaluation of all possible factors explaining the Cdw record. In addition, ignoring (too a large extend) the millennial scale change in the Holocene in Cdw records may turn out to be a missed chance.

Answer: To take into account the comments from reviewer #1, first, we rephrase each time necessary in the manuscript the "little millennial timescale variations" (See, for instance, Lines 420, 428, 440 and 475). Then, the reviewer indicates that the interpretation of Cd_w records should be more consistent, and need to contain the evaluation of all possible factors, especially on a millennial time-scale during the late Holocene (2-1.5 cal kyr BP). In order to clarify this point, we developed the discussion in section 5.2 (lines 421-444) about the detailed discussion of all the possible factors on the intermediate Cd_w at different time scales. Briefly, at a long-time scale, a significant increased trend was observed for MD77-191 Cd_w records from the last deglaciation to the late Holocene. These extremely high values during the late Holocene are consistent with the increased C_{org} and *G. bulloides* percentage records, as well as changes in the benthic assemblages, associated with the increased surface productivity at the core site during the late Holocene. Besides, previous studies have suggested that increased Cd_w values (>1 nmol/kg) could correspond to elevated surface productivity (Bostock et al., 2010; Olsen et al., 2016). All these records seem to indicate the important influence of surface productivity on intermediate Cd_w during the late Holocene.

However, at millennial time scale during the late Holocene, we could also observe quite low intermediate Cd_w values (～0.81 nmol/kg) in 2-1.4 cal kyr BP, which are similar with the values during the last deglaciation. Based on previous studies, increased influence of NADW in IDW was observed during the Holocene in the northern Indian Ocean (Yu et al., 2018; Ma et al., 2019; 2020). NADW is characterized by the depleted nutrient content (modern Cdw, ～0.2 nmol/kg; Poggemann et al., 2017), may affect the intermediate Cd_w by deep-water masses upwelling when flowing northward. However, during the late Holocene, benthic foraminiferal assemblage 1 indicates the lower oxygen concentrations, that seem to be inconsistent with previous studies suggesting an enhanced influence of better ventilated NADW in IDW in the northern Indian Ocean. Therefore, although we could not exclude the influence of NADW in IDW at millennial time scale during the late Holocene, this appearing discrepancy cannot insure that deep-intermediate water masses variations played an important role during the Holocene in this area. Thus, we suggest that our initial interpretation could be also maintained for the Holocene, even if we developed the discussion as suggested by Reviewer #1.

b) Usage of term NADW: In response to my previous comment on the referral to NADW, the authors did change the manuscript. It has improved to some degree but contains a misleading use of NADW. Initially NADW is introduced as a contributing water mass to IDW. The first problem is that usage thereafter only mentions NADW, whilst, at most, I guess, it would reflect an added contribution to IDW (?). Also, it is claimed that IDW would occur in the northern Indian Ocean between 1500 and 3800m (according to Talley 2011). Based on the usage of NADW in latter parts of the manuscript the reader is led to believe that NADW would also be occurring at water depths as shallow as 1500m. Yet, using the salinity maximum, referred to in Talley (2011, chapter 11, figure 11.16), as an indicator, NADW occurs below roughly 2000m, in line with the text in that chapter. In addition, the only region original (largely unmixed) NADW occurs is off the southeast coast of Africa, with the northward propagation blocked by the Davie Ridge (although there is some discussion in relation to a potential northward spillover occurring). In order to substantiate their argument, a) the hydrography section still needs further improvement and b) there needs to be a more in-depth explanation how (even contributions) of a deepwater mass, currently occurring below ~2km, affect sediment cores at true intermediate water depth. The changes in the revised version are not entirely convincing. This affects large parts of the discussion.

Answer: The reviewer suggests that the hydrography section should be improved, especially the explanation about the influence of deep waters at intermediate water depth in the northern Indian Ocean. In order to reinforce the interpretation, we have added a paragraph in the revised manuscript (section 2, lines 130-137), greatly improving the quality of the description of modern hydrological setting at the studied site. To do that, we especially based our description on a new reference: You, Y.: Implications of the deep circulation and ventilation of the Indian Ocean on the renewal mechanism of North Atlantic Deep Water, Journal of Geophysical Research: Oceans, 105, 23895–23926, 2000. Briefly, in the northern Indian Ocean, IDW lies between 1500 and 3800 m, originated from Circumpolar Deep Water admixed with NADW (You, 2000; Tomczak and Godfrey, 2003; Talley et al., 2011). As the deep water upwells when it moves northward, the deep waters can eventually return to shallower depths (You, 2000). Thus, changes in the deep waters can also affect shallower-depth water masses in the northern Indian Ocean.

Besides, we would also like to thank the reviewer for the comment, pointing out that the use of NADW in the discussion is not precise. We have replaced that with "enhanced contribution of NADW in IDW". Please see lines 361, 363, 380, 391, 432, 437 and 440.

c) The usage of PCA's, assemblages and/or individual species concentrations is rather confusing, and pieces of information are missing. In lines 238-239, e.g. the authors state that the PCA analysis yielded 3 factors, referring to table 1. Yet table 1 only shows 2. In lines 246-248, referral is made to assemblage 3 (PC3) without figures 3 and S2 actually showing PC3 scores. This should be clarified. In addition, the usage of assemblage and individual species concentrations is rather confusing. Given that the factor analysis did produce groupings of species, it would help to add plots showing change in the grouped assemblages. It would help the flow of the text and may add robustness to the results. This requires changes across the manuscript.

Answer: The confusion seems to come from the number of assemblages (3) compared to the use of 2 PCs. Thus, as indicated in section 4.2 (lines 250-279), we clearly clarified that we only use PC1 (positive and negative loadings) and PC2 (positive loadings) in the manuscript to recognize three assemblages. These two PCs could represent about 61% of the total variance, and these three assemblages are dominated during the last deglaciation, early and late Holocene, respectively.

For PC3, as is shown in the following figure, compared with the total variance of PC1 (42%) and PC2 (19%), PC3 is the largest one and only explains 8% of the total variance for the rest PCs. The species composition consists of *Hoeglundina elegans* (0.66), *Globobulimina* spp. (0.22) (Positive loadings), *Uvigerina peregrina* (-0.59), *Cibicidoides pachyderma* (-0.21) (Negative loadings). It seems that the main composition of assemblages (PC3) is quite similar to PC1 and does not show more information about the bottom conditions. Therefore, we only focus on the PC1 and PC2 in the manuscript for the interpretation and do not present other PCs in the discussion. We added these explanations in section 4.2 (lines 255 to 260) and also put PC3 loadings in Table 1.

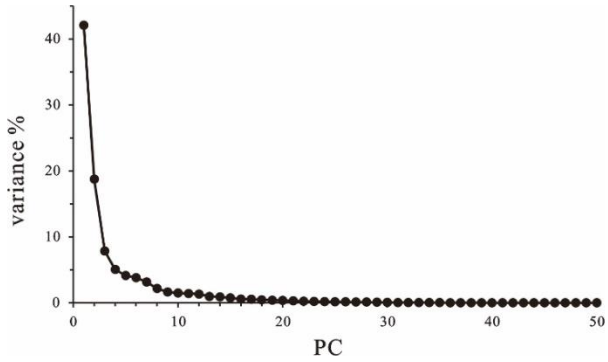

Figure: the variance of total PCs for core MD77-191

d) (somewhat minor point) Lines 543/4 Figure 7 needs a much better embedding in manuscript. This is first and only time it is mentioned. There is no real stipulation of the main findings. The reader to left to deduce this alone.

Answer: We used this comment to improve the discussion of Figure 7 by adding one sentence to detailed describe this figure in the revised version (Please see lines 571-574).

Detailed comments:

Lines 35-36 the ages in Monnin are not in line with this statement

Answer: We have corrected this mistake in the revised manuscript. Please see lines 42-43.

line 93 this statement is not true. The figures reach back 17-18 ka BP in most cases, which includes the deglaciation

Answer: We understand that the use of “since” appears confusing of Reviewer #1 to indicate the time period covered by our study. However, as the time interval of core MD77-191 (Arabian Sea) is from 17 to about 1 cal kyr BP, and the data obtained from MD77-176 (northeast BoB) range between 18 and 1 cal kyr BP, all of these data cover the interval of the last deglaciation to the Holocene. Thus, we prefer to keep the expression “since the last deglaciation” in the manuscript, which means these continuous records include both the last deglaciation and Holocene periods.

chapter 4.1: This chapter is not placed correctly. It would be better placed in the methods section.

Answer: In the literature about elemental ratios in foraminifera, it is classical to begin the description of the results by discarding the influence of contaminants thanks to Al/Ca, Mn/Ca and Fe/Ca ratios, so we just apply this common use from previous studies. Moreover, as these ratios are measured at the same time than the other elemental ratios, they can be described in the results part. However, in order to take into account this comment, we added some sentences to interpret the reason for performing Mn/Ca, Fe/Ca and Al/Ca analyses in the method (Section 3.1, see lines 166-169).

Line 248-250 This statement is inconsistent with figure 3. The figure clearly shows that the statement only applies to parts of the Holocene and is not valid for the entire period. Also, the description of the counts is focused on the Holocene whilst earlier description cover the entire 18ka. This leaves the reader very confused as to the main thrust of the manuscript.

Answer: As we have detailed interpreted the benthic foraminiferal assemblage analyses in section 4.2, three assemblages were recognized based on the positive loadings (assemblage 1, during the late Holocene), negative loadings (assemblage 2, during the early Holocene) of PC1, as well as positive loadings of PC2 (assemblage 3, during the last deglaciation). Therefore, these three assemblages have covered the entire record from the last deglaciation to Holocene. In order to easy compare these three assemblages, we prefer to show the percentages of major species for three assemblages in figure 3, and put the rest associated species in the supplementary figure S2.

Besides, *Bulimina aculeate* and *C. pachyderma* dominate assemblage 1, which corresponds to the benthic foraminiferal fauna during the late Holocene. By contrast, *H. elegans* dominate assemblage 2, which is more important during the early Holocene. Besides, in figure 3, we can also observed high percentages of these species in late and early Holocene, respectively. Thus, we described in the manuscript that "However, the main species from negative loadings consist of *Bulimina aculeata*, *H. elegans* and *C. pachyderma*, which dominated the Holocene." It seems that the main composition of PC2 negative loadings is quite similar to assemblages 1 and 2, and then does not show more information. Therefore, we do not use the negative loadings of PC2 in the manuscript to recognize more assemblages.

Lines 337-338 this does not make sense. There is confusion in the use of "since". This includes the title.

Answer: Please refer to the reply for question "line 93 this statement is not true. The figures reach back 17-18 ka BP in most cases, which includes the deglaciation". As already detailed answer to the upper comment, the meaning of phrase "since the last deglaciation" is the interval of last deglaciation and Holocene, which has been widely used in multiple works (e.g., Dommain et al., 2014; Billy et al., 2018; Ma et al., 2019, 2020; Hudson et al., 2021).

Figure 4: The application of a 5 point running average has led to offsets between the timing of the actual peak and those shown in the smoothed record. A time-controlled box car filter should be applied.

Answer: Indeed, for figure 4b, the red line was calculated by the time-controlled "simple" moving average (boxcar) filter, and this point has been clarified in the revised manuscript (please see line 977). Besides, we agree that the offsets between the actual peaks and the smoothing curve. We have corrected that using a two-point moving average. Please see new figure 4.

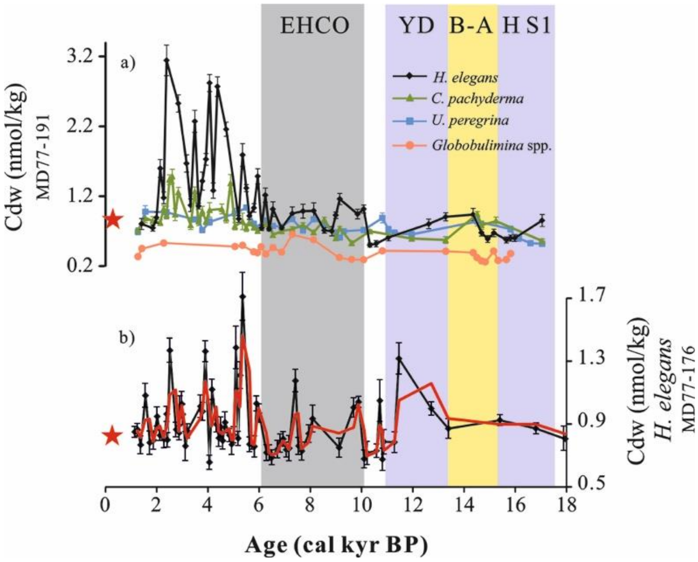

Fig. 4. (a) Cd_w records calculated based on the Cd/Ca of benthic foraminifera *Hoeglundina elegans* (black), *Cibicidoides pachyderma* (green), *Uvigerina peregrina* (blue), and *Globobulimina* spp. (orange) obtained from core MD77-191, (b) Cd_w record from core MD77-176 reconstructed using *H. elegans* Cd/Ca, the red line is the smoothed curves using a two-point moving average. The red stars represent the modern Cd_w (~0.83 nmol/kg) in the northern Indian Ocean (Boyle et al., 1995). The color shaded intervals and abbreviations are the same as in Figure 2.

Overall, the manuscript has improved a little. There are, however, issues remaining that require a further rewrite.

<u>Reply to reviewer #2 comments:</u>

Review of Ma et al. (revised version)

In my view the authors did a great job to address the concerns raised by both Reviewers. In particular they now more clearly discuss the uncertainties of their Cdw record on the potentially varying influence of primary surface productivity and intermediate water properties. Hence, I suggest acceptance of the manuscript pending very minor revisions, which basically regard typos and ambiguous wording.

In particular the abstract would benefit from more explicitly writing which factors are driving the Cdw record during which time period. The authors all state this is the abstract but it reads rather indirect. Below a recommendation for rephrasing (lines 22-29), please feel free to adopt or dismiss these suggestion.

"These results suggest that during the last deglaciation Cdw variability was primarily driven changes in intermediate water properties, indicating an enhanced ventilation of intermediate-bottom water masses during both Heinrich Stadial 1 and Younger Dryas (HS1 and YD, respectively). During the Holocene, however, surface primary productivity appeared to have influenced Cdw more than intermediate water mass properties. This is evident during the early Holocene (from 10 to 6 cal kyr BP) when benthic foraminiferal assemblages indicate that surface primary productivity was low, resulting in low intermediate water Cdw at both sites. Then, from ~

5.2 to 2.4 cal kyr BP, surface productivity increased markedly, causing a significant increase in the intermediate water Cdw in the southeastern Arabian Sea and the northeastern BoB.

Answer: We would like to thank the reviewer for this comment, providing us a more clearly way to interpreter our results in the abstract. We have corrected in the revised version, please see lines 22-36.

L. 48: “contribute to up to..:”

Answer: Corrected. Please see line 55.

L. 86: “only few works indicate the” – do you mean “investigate”?

Answer: We have corrected this sentence in the revised manuscript. Please see line 93.

L. 114: avoid using “.” as multiplier

Answer: Corrected. Please see line 121.

L. 142: “linked to increased primary productivity”

Answer: Corrected. Please see line 155.

L. 148: what do you mean by “species level differences”? Inter-species offsets?

Answer: We have corrected this sentence in the revised manuscript. Please see line 161.

L. 335: “which is characterized by the well-ventilated and depleted nutrient” – something is missing here

Answer: Corrected. Please see lines 364.

L. 340: “Benthic foraminifera” - no capital

Answer: Corrected. Please see line 378.

L 357: “in the bottom water”

Answer: Corrected. Please see lines 397-398.

L. 359: “Assemblage 1” – no capital

Answer: We have corrected this sentence in the revised version. Please see lines 398-403.

L. 361: Globigerina can be abbreviated

Answer: Corrected. Please see line 399.

L. 375: “little discrepancies” – better use “small-scale” instead of little. However, I think the discrepancies are not so small, although I agree that the long-term trend is similar.

Answer: We have corrected in the revised manuscript. Please see line 420.

L. 423: “from the deep layer” – please also specify which deep layer you mean. Intermediate waters? Thermocline waters?

Answer: Corrected. Please see line 486.

L. 480-481: “another evidence for the influence of changes in water masses and/or ventilation during the HS1 and YD, as already demonstrated by” – this sentence might be rephrased as it undersells the results; especially “another evidence” and “as already” sounds like the data adds nothing new to the existing records which is not the case). I would suggest to write “… another evidence for the influence of changes in water masses and/or ventilation during the HS1 and YD, in line with…”

Answer: We have corrected in the revised manuscript. Please see line 546.

L. 498-499: “enhanced northward flow of southern sourced intermediate water mass AAIW” – there is something missing here

Answer: We have corrected this sentence in the revised manuscript. Please see line 564.

We sincerely thank the editor and reviewers for your kind considerations of our work and inspiring suggestions for the improvement our manuscript. With your kind help, we have improved our manuscript and hope that our work meets the criteria of *Climate of the Past*.

With regards,

Sincerely,

Dr. Ruifang Ma (on behalf of all authors)