Authors Replies to RC2: 'Comment on egusphere-2025-5136', Anonymous Referee #2, 23 Feb 2026
Today: 05 Mar 2026

We copy the comments of RC2 below and add our authors replies (AR) in italics.

General comments

In the paper the authors present a model intercomparison of radiocarbon-based marine reservoir ages (MRAs) over the last 55 kyr BP. The previous estimate of the global averaged MRA for the non-polar regions (Marine20) was obtained with the box model BICYCLE. However, in this previous estimate abrupt AMOC changes that occurred during the last glacial period were not considered. Here, the authors make use of two models of intermediate complexity (Bern3D and LOVECLIM) that can represent abrupt AMOC changes when forced with freshwater flux anomalies. They compare simulated MRA changes to published results obtained with the box model BICYCLE-SE and to outputs from an OGCM (LSG), and to reconstructions. The study aims to explore the robustness of model-based MRA estimates, in particular the sensitivity to AMOC abrupt changes. A second objective is to underline the regional variations of the MRA changes, in particular the authors present MRA changes in polar regions (that are not covered by Marine20).

The author found that (a) including AMOC changes produce non-polar MRA changes with magnitudes of the order of 100 and 200 14C yr (LOVECLIM and Bern3D, respectively) (Figure 3). (b) The multi model mean (of the two EMICS) of the non-polar MRA is close to that of Marine20 throughout the last 55 kyr BP, with less than 100 14C yr difference (Figure 7). Regarding polar regions, (c) the polar MRA north of 50°N is larger than Marine20 during the simulated Greenland stadials, the polar MRA south of 50°S is larger for most of the time period in comparison with Marine20 (Figure 7). This underlines the limits of using a global calibration curve for specific regions and time periods. (d) During the simulated Greenland stadials, the MRA changes in the polar regions depict a bipolar seesaw behavior (Figures 5, 7).
I find the study of high-interest and relevance for the community. It is well written and well organized. The motivations of the study are well justified and the results are clearly presented. The figures are also very clear, especially given the relatively large amount of information that is presented. Please note that I am not an expert in biogeochemistry or MRA. My research focuses more on climate modelling and the abrupt events of the last glacial period.

AR: We thank the reviewer for the overall positive evaluation of our study.

I have only a few comments/remarks that could be addressed before the paper is published. I hope that these are helpful. First, I think that the introduction could be improved by adding some basic information and background knowledge about marine reservoir age. For example, the term is never defined in the introduction. Then, regarding the experimental setup, I think providing more information on the simulations involving additional FWF as well as on the glacial simulations for the LSG would make the paper more self-contained (in the sense that readers would not need to read other articles to understand the setup). To finish, I find that the mechanisms described to account for the ΔMRA changes could be more detailed. In particular, more emphasis could be put on the mechanisms responsible for ΔMRA decrease and increase in sections 3.2 and 3.3 (around lines 261 and 293). I think that clarifying the

causal pathways underlying these changes would substantially improve the readability and interpretation of the model results.

AR: We will add the suggested improvements. See detailed comments/responses below.

Specific comments

Abstract:

- line 16: “in agreement with their reconstructed rises by about 1200-1300 14C yr”. I find this sentence a bit confusing. While Bern3D and LOVECLIM show MRA rises in the surface North Atlantic and in the deep Atlantic, Figure 6 suggests that the reconstructed MRAs do not exhibit such rises during HS1. For example, in Figure 6a, the reconstructed MRA appears relatively high between ~27 and 16 kyr BP and then it decreases. I therefore suggest rephrasing this sentence.

AR: The whole sentence reads: "Simulations with abrupt AMOC reductions during stadials display a rise in MRA in the surface northern Atlantic (>50°N) and the deep Atlantic, for example during Heinrich stadial 1 of 300-1250 and 500-1300 ^{14}C yr, respectively, roughly in agreement with their reconstructed rises by about 1200--1300 ^{14}C yr."
To express the whole complexity of the differences to the reconstructions is probably too much for one sentence in the abstract, we therefore suggest to shorten the sentence here: "Simulations with abrupt AMOC reductions during stadials display a rise in MRA in the surface northern Atlantic (>50°N) and the deep Atlantic, for example reaching 300-1250 and 500-1300 ^{14}C yr, respectively, during Heinrich stadial 1."

- lines 22-23: “but with model-specific details in the non-polar Atlantic”. I find this sentence a bit vague. I suggest removing it or precising the details within a few words.

AR: The whole sentence reads: "Spatially resolved results of the models show that changes in surface MRA during stadials depict the general pattern of a radiocarbon bipolar seesaw (older surface water in the high north, younger in the high south and in the Indo-Pacific), in agreement with previously published reconstructions, but with model-specific details in the non-polar Atlantic."
We suggest to revise the latter part: "Spatially resolved results of the models show that changes in surface MRA during stadials depict the general pattern of a radiocarbon bipolar seesaw (older surface water in the high north, younger in the high south and in the Indo-Pacific), in agreement with previously published reconstructions. However, some model-dependent differences remain in the non-polar Atlantic."

We believe this information is important (and should therefore be part of the abstract) but more details cannot be given here.

Introduction:

- I find the introduction very clear, but I think it could benefit from background information on MRA. I suggest adding a few lines to define and provide the reader with basic knowledge

about MRA. Maybe between lines 32-33?

AR: We will add a sentence (bold) after MRA has been introduced (after line 38): "From $\Delta^{14}C$ in both the atmosphere and the surface ocean the marine reservoir age (MRA) of the non-polar surface ocean, also called the Marine20 calibration curve (Heaton et al., 2020), has been constructed (Figure 1c). ***In general, the MRA is a measure for the level of the oceanic ^{14}C depletion with respect to the contemporaneous atmosphere, which is depending on time, geographic location, and when addressing not only the ocean surface, also on the water depth.***

- line 40: Please define piston velocity within brackets.

AR: Piston velocity is a common measure for the air-sea gas exchange velocity. We prefer to change the whole term accordingly, and not to include a definition within brackets.

Methods:

- line 93: "since this agrees best with 14C reconstructions in the deep Atlantic ocean". Is there a reference for this? Otherwise, the phrasing can sound speculative. I suggest adding the reference of a previous study or rephrasing the sentence.

AR: The reference for this is Köhler et al. (2024a), given in line 89. For clarity we will repeat it at the end of this sentence.

- line 111: "meltwater of up to 0.3 Sv is added into the North Atlantic". I wonder where exactly the freshwater flux is added. Can you indicate the latitudinal and longitudinal extent of the corresponding area? Also, I suggest adding "flux" after "meltwater".

AR: We will add the requested details. The sentence will be revised into: "To simulate the millennial-scale variability of the last glacial period and the impact of deglacial ice-sheet disintegration (scenario fwf), a meltwater flux of up to 0.3 Sv is added into the North Atlantic (50-60°N, 10-60°W).

- Regarding Figures S1, S2, S3 and Figure 3: How is the AMOC strength defined exactly? Is it the same definition for all models? If yes, I suggest adding the definition to the caption of Figure 3.

AR: AMOC strength in BICYCLE-SE is the prescribed strength of the overturning cell in the Atlantic. It is also the size of the North Atlantic Deep Water formation in the model. For LOVECLIM, it is the maximum of the meridional overturning streamfunction in the North Atlantic. For Bern3D it is the same, but only at depths greater 400 m to exclude the wind driven (sub)surface part. This information will be added to the captions of the figures.

- line 128: Same as for LOVECLIM, where are the freshwater fluxes added?

AR: The sentence will be revised into " In scenario PallSTD, additional freshwater fluxes are applied ***into a box in the North Atlantic (45-70°N, 66°W-14°E)*** *during all stadials, with a maximum freshwater flux of 0.4 Sv during Heinrich stadials (HS) and 0.2 Sv during non-Heinrich stadials."*

- line 142: What does 'constant ocean circulation' mean? Does it mean that all oceanic parameters are identical in the nine simulations? I suggest adding some lines to explain how the glacial scenarios are achieved and how a weaker AMOC is obtained. Also, would it be possible to have the equivalent figure of Figure S1 to S3 but for LSG?

AR: The simulations with LSG do not consider temporally changing boundary conditions in the physics (only changes in atmospheric CO_2 and $\Delta^{14}C$ as prescribed from data). Therefore, within one run the ocean circulation was constant, but it was different between the 3 different climate setups. For the two glacial climate scenarios the surface ocean conditions were taken from an atmospheric model, that itself was driven by SST reconstructions of either modified CLIMAP or GLAMAP data with some modified freshwater balances in the Southern Ocean - all as described in detail in Butzin et al., (2005). We will clarify these details.
An SI Figure for LSG was not produced since we do not have access to data from which we could calculate the MRA for the deep Atlantic and the AMOC would be a flat line.

- line 177: Do you have ideas for a particular effect?

AR: This comment refers to our discussion of Figure S4: "Independent of which version of the data-based ΔR we take we find in general a good agreement between them and natural GLODAP (differences of typically up to 100 ^{14}C years) with the exception of single data points and the entire the west coast of North America, where values in the data base are more than 100 ^{14}C years older than in GLODAP, ***potentially caused by coastal effects****."*
Apart from the already mentioned coastal effect we do not have any further insights on this bias on the North American west coast. However, if the dR values are based on beach sub-fossils, then this might have to do with strong seasonality of upwelling on the west coast, which may bias biota to old if they are profilerating in such periods. As is we have no proof for this speculative interpretation, and therefore would like not to go too much into details in the draft.

- line 180-185 (Figures S1 to S3 and Figure 6): How many cores are included to produce the time series for the North Atlantic surface and Atlantic depths for the data? It may be interesting to know?

AR: The surface North Atlantic MRA spline is based on data from 25 different sites; the deep Atlantic (>2000m) is based on data from 34 sites. These details will be included in the revised draft.

Results and Discussion:

3.1 Pre-industrial MRA compared to GLODAP

- line 201: Regarding Figure S5, why is it only the JFMJAS months that are used in Bern3D to display the mean MLD?

AR: These are summer (July, August, September) and winter (Jan, Feb, March) MLD means within one plot. There is no specific reason for using only these months apart from the fact, that they have been directly available from the existing model output, while a MLD on annual mean values has not.

- line 203: of the “mixed layer” depth range?

AR: Correct, "mixed layer" will be added before "depth range" here and in line 205, where a similar formulation appears.

- line 217: Is 500 14C yr a multi-model mean? If not, could you be more specific and provide the values for each model? I think that this could be relevant here, see my following comment.

AR: The mentioned 500 ^{14}C yr was approximated from Figure 2. The calculated values of surface MRA (<50°) are 461, 401, 344 and 443 ^{14}C yr for BICYCLE-SE, LOVECLIM, Bern3D and LSG, respectively. We will add these numbers. Note, that some more details on this comparison to GLODAP will also be added due to comments from reviewer #1.

- line 218: ”with BICYCLE-SE and LSG showing predominantly larger values, …”. It does not seem to be the case looking at Figure 2. For instance, LOVECLIM presents larger values than LSG in the Atlantic at 2 kyr BP.

AR: It is in detail correct that LOVECLIM presents larger values than LSG in part of the North Atlantic at 2 kyr BP, but we here write about the dominant pattern, and in the dominant parts of the ocean <50° our sentence is correct. We nevertheless will add the following for clarity: "The surface MRA in LOVECLIM in the North Atlantic seemed be an exception here showing a difference of more than 200 ^{14}C yr, a larger offset to GLODAP than the other models."

- line 222: “a similar offset to GLODAP is missing in the also 1000 m deep northern high latitudinal boxes, pointing to an alternative explanation”. I am not really convinced because almost all the BICYCLE-SE boxes seem to have the same surface MRA value at 2 kyr BP, so it could still be a box effect?

AR: The reviewer is probably correct. We therefore suggest to switch arguments from "Although it is tempting to suggest that this offset might be caused by the 1000~m deep surface ocean boxes in the polar regions, a similar offset to GLODAP is missing in the also 1000~m deep northern high latitudinal boxes, pointing to an alternative explanation." to "This offset might be caused by BICYCLE-SE’s 1000~m deep surface ocean boxes in the polar regions. However, since a similar offset to GLODAP is missing in the northern high latitudinal boxes, which are also 1000~m deep, some counteracting processes might be at work here."

3.2 MRA variations across the last glacial period

- line 234 (and 236): What is meant by adjusted? Were the applied freshwater fluxes adjusted beyond what is described in section 2.3 (and 2.2)? If yes, maybe the freshwater flux scenarios could be added to the Supplement Information.

AR: What was meant here was what has been described in the method section. However, we realized that details for LOVECLIM have been missing so far. They will be added to in section 2.2: "In LOVECLIM 0.3 Sv was added to the North Atlantic to achieve a collapsed AMOC during Heinrich stadials 1-4, while only 0.2 Sv was added during HS5. A triangular pulse of up to 0.3 Sv was also added between 13 and 12 ka to simulate a reduced AMOC during the Younger Dryas."
Since the focus of the paper is on the resulting impacts of AMOC reduction on MRA, we do not think plotted time series in the applied freshwater fluxes are of interest for most readers and prefer not to add another figure with them in the SI.

- line 244: Could you please specify the flux corrections that are mentioned here? Maybe between brackets?

AR: The following details on flux corrections will be added: "...since flux corrections from the North Atlantic to the North Pacific (45-70°N) applied in the other study have been neglected here." However, we believe the better place for these details will be in the methods, section 2.3, where these corrections are also mentioned.

- line 253: “show no consistent pattern”. I suggest to precise the sentence because Figure 3f shows that the differences between Bern3D (PallSTD) and Marine20 with respect to 2 kyr BP, as well as the differences from BiCYCLE-SE (A3), decrease during stadials.

AR: We will revise the sentence into "The differences to Marine20 — when plotted with respect to PI — show to a large degree model-specific responses which nearly all fall in their sizes within the 95% CI of Marine20 (Figure 3f). One more general pattern is the decrease of this difference in results from BICYCLE-SE and Bern3D during Greenland stadials not similarly seen in LOVECLIM."

- lines 260-261: Can you add a few lines to precise the mechanisms explaining why the global average surface MRA and the mean deep ocean 14C would vary in opposite directions, following AMOC weakening and eddy diffusivity reduction?

AR: Due to a comment from reviewer #1 this part will already change slightly. Following this comment, we will furthermore add some more details revising this paragraph into the following: "The main point outlined by Bard (1988) is that the global average surface MRA and mean deep ocean ^{14}C age vary in opposite directions when eddy diffusivity changes, mimicking global overturning variations (all else being equal). Interestingly, scaling the eddy diffusivity to our AMOC proxy curve (SST record by Davtian and Bard, 2023) leads to a similar ΔMRA pattern in the box-diffusion model as in the other models when they are averaged in the low and mid-latitudes (Figure 3g). The linear scaling of the eddy diffusivity assumes a modern value of 4000 m^2/yr and a minimum value of 500 m^2/yr at ca. 40 kyr BP

during the coldest interval of HS4 (ΔSST of -10 K, Fig. 1d). Instantaneous steady state MRA values are then calculated with the analytical equation 4 derived by Bard (1988). In the box-diffusion model, the ^{14}C production is mainly balanced by radioactive decay in the deep ocean reservoir. Reducing or stopping the exchange with the mixed layer implies that ^{14}C remains confined to the atmosphere and the mixed layer. These two boxes, which contain comparable total carbon inventories, would tend to homogenize, thus reducing the MRA."

- line 279: What are the radiocarbon distributions in the models? Are they similar? Can they be easily compared to observations? I feel that this could be worth exploring in future studies or that this could be a perspective (?).

AR: We think this point is beyond the scope of the present paper, but indeed a good starting point for future projects. We will therefore add the following sentence at the end of section 3.2: "Going here into more detail, e.g. by an extended deep ocean ^{14}C model-data comparison is beyond the scope of the present study, but a potential promising avenue for future studies."

3.3 Details of the impact of AMOC weakening on MRA

- line 293: Could you please briefly describe how the MRA increases in the North Atlantic are connected with reduced MLDs at this location. Also, the acronym MLD was not defined in the main text.

AR: We will write out MLD as "mixed layer depth" since the acronym appears only 3 times. Furthermore, looking in more detail on the changes in MLD and MRA we see that both vary (HS1-LGM) in phase in the North Atlantic but in anti-phase in the Southern Ocean (Figures S5 right, Figure 5), especially in Bern3D. We therefore have to conclude that changes in the MLD is not the dominant process that determines MRA in connection with AMOC weakening. These details will be added to the draft.

- line 308 (Figure 6): From what I have understood, the LOVECLIM and Bern3D outputs for the entire northern surface Atlantic (+Arctic) and deep Atlantic are compared to the reconstructed time series. I wonder how the comparison would be improved (or not), if the colocated-to-the-data model outputs were compared to the reconstructed time series.

AR: Location-specific data-model comparisons would be a time-consuming extra effort, which goes beyond the scope of the current paper. It would fit into a future project which might have the ^{14}C distribution within the ocean in focus (see reply to comment on line 279 above).

Conclusion:

- line 361: in LOVECLIM “in the surface northern Atlantic”? I suggest specifying the location because it seems that Bern3D is closer to the reconstructions elsewhere (Figure 5; PallSTD) and in the deep Atlantic (Figure 6; Pnofwf), during HS1.

AR: That is correct, we will therefore revise the sentence into "Directly observed information on MRAs over Heinrich stadials is relatively sparse which limits independent evaluation of

model behaviour. The direct data that do exist during HS1 (e.g. Skinner et al, 2019, 2023) suggest that no one model provides simulations with uniformly greater model-to-data accuracy. The simulated ΔMRA in LOVECLIM may be more accurate when compared to data-based reconstructions in the surface northern Atlantic; however Bern3D may be more accurate in other locations."

- lines 361 to 366: I would suggest inverting the last two sentences of this paragraph.

AR: Ok, will be changed accordingly.

- line 371: I would suggest removing "mini"? I feel that "mini" minimizes the impact of the study.

AR: Ok, agreed, it will be called MRA-MIP, not mini-MRA-MIP.

Technical corrections

- line 14: There are two "in".

AR: Corrected.

- line 38: There is a coma instead of a point at the end of the line.

AR: Corrected.

- line 135 and 301: Isn't there a syntax issue with these sentences? Please note that I am not a native english speaker.

AR: The sentence in line 135 reads: "The simulations shown here are due to the different spinup (and missing flux corrections) different to the run published in Pöppelmeier et al. (2023a), which has been compared to multi-proxies during Termination I." We will revise it into: "Note that the simulations shown here have different spin-ups (and contain no flux corrections) and so provide different results to the runs published in Pöppelmeier et al. (2023a) which considered multi-proxies during Termination 1."

AR: The sentences around line 301 read: "For some areas where the models disagree reconstruction-based evidence exist, especially from the Iberian Margin. However, for most of the equatorial Atlantic, where both models show the opposite change in MRA a data-based evaluation of the simulations is due to a lack of data still missing." We will revise this into: " In some of the regions where the two EMICs disagree, reconstruction-based evidence also exists – in particular for the Iberian Margin. However, in the equatorial Atlantic, where the models show opposite changes in MRA, such direct measurements are not available. This prevents a data-based evaluation of the two diverging simulations."

- I also find that some phrases are a bit long, and maybe the paper would benefit from splitting some of the sentences into two? e.g., lines 25, 45, 71.

AR: The sentence in line 25 reads: " Furthermore, changes in the MRA of the high latitude Southern Ocean (> 50°S) are extremely model-dependent and for most times between 18 and 43 kyr BP the changes in the multi-model mean MRA are larger than the 95% confidence interval of the non-polar MRA depicted in Marine20, making the construction of a similarly numerical model-based calibration curve for this region a challenging task."
We will revise this into: "Furthermore, changes in the MRA of the high latitude Southern Ocean (> 50°S) are extremely model-dependent and, for much of the period between 18 and 43 kyr BP, the changes in the multi-model mean MRA are larger than the 95% confidence interval of the non-polar MRA depicted in Marine20. These differences make the construction of a numerical model-based calibration curve for the high latitude Southern Ocean challenging.""

AR: The sentence in line 45 reads: "Although this is within the 2σ uncertainty of Marine20, reconstructions of past MRA variability demonstrate the occurrence of larger changes across the last deglaciation in association with millennial-scale climate anomalies (Skinner et al., 2019), which points to not yet fully considered errors in obtained simulations and larger uncertainties in marine radiocarbon calibrations around abrupt changes in AMOC strength."
We will revise this into: "Although this is within the 2σ uncertainty of Marine20, reconstructions of past MRA variability demonstrate the occurrence of larger changes across the last deglaciation in association with millennial-scale climate anomalies (Skinner et al., 2019). Taken together, this points to not yet fully considered errors in obtained simulations and larger uncertainties in marine radiocarbon calibrations around abrupt changes in AMOC strength."

AR: The sentence in line 71 reads: "This equation is identical to what is used for Marine20, when the sample is the non-polar surface ocean (Heaton et al., 2020) and as summarized in Skinner and Bard (2022) is equivalent to the radiocarbon age difference between two contemporary marine and atmospheric signal carriers, e.g. as for B-Atm radiocarbon age offsets (e.g. Skinner et al., 2023) for which benthic values are compared to the atmosphere."
We will revise this sentence into: "This equation is identical to what is used for Marine20, where the sample corresponds to the non-polar surface ocean (Heaton et al., 2020). As summarized in Skinner and Bard (2022) it is equivalent to the radiocarbon age difference between two contemporary marine and atmospheric signal carriers, e.g. as for B-Atm radiocarbon age offsets (e.g. Skinner et al., 2023) for which benthic values are compared to the atmosphere"