Carbon isotopes and Pa/Th response to forced circulation changes: a model perspective

Note to the Editor and referees

We have requested a long deadline extension since a bug was found in the iLOVECLIM model code that could affect the carbon cycle part. To ensure scientific reproducibility, we first wanted to assess whether the bug found could have a significant impact on our results. This has required to run several multi-millennial long simulations. After analysis of the results of the newer version, we however found that our conclusions are unaffected by this error. We thank the Editor and the referees for their patience in this necessary process.

Response to the referees' comments

We thank both reviewers for their constructive comments that helped to improve and clarify the manuscript. We have addressed the comments in detail below.

Anonymous Referee #1

The authors implement Pa/Th in the intermediate complexity model LOVECLIM. With the carbon isotopes, which are already in the model, the authors evaluate the responses of different proxies to the freshwater fluxes in the North Atlantic in a classical hosing experiment. They find that the Pa/Th leads the carbon isotopes by a few hundred years in the deep Atlantic. Pa/Th has been implemented in different GCMS and the authors follow the approach in Rempfer et al. (2017). Also, modeled Pa/Th response to fresh water fluxes added to the North Atlantic is carried out in previous studies (Gu and Liu, 2017; Rempfer et al., 2017). However, the comparison between Pa/Th and carbon isotopes helps to distinguish this study with previous modeling studies. Revisions are needed before this could be acceptable for publication.

Major Comments:

1. I find the separation of the single response and the dual response quite confusing. First, is it really to identify the responses this way? It seems that for the dual response, the first response is associated with the AMOC reduction and the second response is associated with the AMOC overshoot (as pointed out in page 6 line 30). I think it is easier for people to follow if you state this as a response to decreased AMOC or increased AMOC instead of first or late response. Secondly, why some grids (for example 40S, 4000m, Figure 3 a, d and g) show both single response and dual response?

We thank the reviewer for highlighting the importance of the chosen terminology. We agree with the reviewer, in numerous locations, the "first response" seems to be associated with the AMOC reduction and the "the second response" with the AMOC overshoot. However, this is **not always true**. For instance, as pointed out in the manuscript, some locations display more than 2 responses, highlighting the complexity of identifying the proxy response to the AMOC slowdown or overshoot. Furthermore, for grid cells displaying strictly two responses, the first response does not necessarily correspond to the expected response to the AMOC slowdown. For instance, Figure 2B actually shows a δ_{13}C time series that displays a δ_{13}C increase as first response and a δ_{13}C decrease as a “second” or late response. In this case the first response likely corresponds to an accumulation of nutrients due to the cessation of NADW export as suggested in (Menviel et al., 2015) while the second or late response corresponds to the expected δ_{13}C decrease subsequent of an AMOC slowdown. Therefore, we kept the terminology of “first” and “second” response throughout the manuscript.

The second point of this comment on Figure 3 has also been raised by the reviewer #2 (see response to reviewer #2 comments). We agree with both reviewers; single and dual responses are clearly **mutually exclusive**. However, Figure 3 shows **zonally averaged** proxy responses over the western Atlantic. Consequently, for one grid cell to appear blank on Figure 3 A. (resp. 3.B.) it is required that the zonal average is empty and consequently that there is no grid cell in the full longitude range considered displaying a single response (resp. dual response). Therefore, it is possible to have overlaps on Figure 3. We added a sentence to Figure 3’s caption in order to clarify this point:

“Single and dual responses are mutually exclusive on a per location basis. Since panels A and B are showing zonal averages, overlaps may arise from different locations with the same latitude but different longitudes.”

2. Responses of Pa/Th and carbon isotopes in the Atlantic in a hosing experiment are not new and have been examined in other studies already. Since this paper focuses on Pa/Th, their modeled Pa/Th response should be compared to previous studies (Gu and Liu, 2017; Rempfer et al., 2017). Spatial and temporal similarities and differences with these previous studies should be compared and discussed.

We thank the reviewer for highlighting that the study from (Gu and Liu, 2017) dealing with Pa and Th in CESM was not cited in the original manuscript. We have now included a citation to this study in the revised manuscript.

It is true that the Pa/Th response to AMOC slowdown in hosing experiments has already been examined in different versions of Bern 3D (Rempfer et al., 2017; Siddall et al., 2007) and in CESM (Gu and Liu, 2017). We agree with the reviewer that it would be of great interest to evaluate the spatial and temporal similarities of the Pa/Th responses in those different models. This is however not an easy task and would require new coordinated modeling experiments with the different models. Indeed, the parameters of the hosing experiments performed (flux, input location and duration) are quite different in our study and in (Gu and Liu, 2017; Rempfer et al., 2017; Siddall et al., 2007). On the novelty of our study, we would like to point out that the Pa/Th response to the AMOC slowdown has not been assessed in a consistent way in the different above cited publications, most of them only displaying the Pa/Th response at selected locations of the North-Atlantic. Likewise, it is worth to point out that our study is the only one to consider spatial and temporal variability of the Pa/Th response to AMOC changes. Therefore, a detailed evaluation of spatial and temporal similarities as requested by the reviewer is i) not achievable given the existing publications and ii) out of the scope of this manuscript which focuses on the spatial and temporal similarities and differences between 2 carbon isotopes proxies and the Pa/Th in a single model. Given the interest of the topic, we have added a paragraph in the discussion section to acknowledge that Pa/Th response to AMOC slowdown has already been studied in other models and highlight that the Pa/Th response obtained in the present study is quite consistent with what has been observed in previous studies (see revised manuscript).

3. At the end of the introduction, three questions are raised. The first two questions are discussed in section 3 and 4, but the third question “How can the modelled multi-proxy response help to interpret the paleoproxy records” is not clearly answered. The implication for interpreting the paleoproxy records is not clearly state. This is a very important question for modeling proxies in GGMS. Authors need to add some discussion about this kind of implications in the discussion.

We thank the reviewer for this point. One of the main motivations for multi-proxy modelling is to achieve a more efficient model-data comparison by bringing model output closer to the observables (the proxy records). This study is the first one considering $\delta_{13}C$, $_{14}C$ and Pa/Th in a consistent modelling frame and it shows 1) strong spatial variability in the proxy response (according to the main water mass bathing the considered locations) and 2) the possibility for a time delay between proxy responses at a given location (200 year lag of the carbon isotopes response relative to the Pa/Th response in the deep Northwest Atlantic). Therefore, our results show that the interpretation of the proxy data might be complicated because a given circulation change event does not necessarily produce a single and consistent proxy response in the entire Atlantic basin, nor a synchronous multi-proxy response at a given core location. We have now revised the entire discussion and conclusions sections of the manuscript to account for the comments that we received, and we hope the implication of our study for the interpretation of the proxy records is now clearer regarding this topic.

4. More differences between Pa/Th and carbon isotopes in reconstructing past AMOC could be discussed and highlighted. As mentioned above, the novelty of this paper is studying the Pa/Th together with carbon isotopes since the Pa/Th and carbon isotopes in a hosing experiment have been presented in previous studies. However, I feel this multi-proxy comparison is not fully developed in the current manuscript. A more in-depth comparison between Pa/Th and carbon isotopes and their implications for paleoceanography (back to comment 3) are needed.

As already mentioned previously, and further explained below in this response to the reviewers, the discussion section of the manuscript has undergone very substantial revisions. It now includes a more in depth comparison of Pa/Th and carbon isotopes as requested by the reviewer. See for example lines 27 to 40 p8.

5. Pa/Th leads carbon isotopes, but lead by how many years? From Figure 5 a and c, it seems that the 300 years hosing is too short for carbon isotopes to fully adjust to the reduction of AMOC. If hosing is kept longer than 300 years, carbon isotopes may lag Pa/Th response even longer. Therefore, from this 300-years hosing experiment, we cannot determine the exact lead time. This should be pointed out.

As shown on Figure 4, the actual response times and therefore the lag time between Pa/Th and carbon isotopes responses has a strong spatial variability (with locations showing actually no lag, as shown on Figure 5). We agree that 300 years of freshwater addition is likely too short for the carbon isotopes to fully adjust. The revised discussion section now highlights these 2 points.

6. The modeled Pa/Th is compared to observations in Dutay et al., 2009 and Henderson et al., 1999 (Page 5, line 14). However, in recent years, many new observations are now available. GEOTRACES offers a lot of relevant new data (also used in Rempfer et al., 2017). More core top Pa/Th are also available. A more complete compilation of the observations should be used to tune the model parameters. Also, if comparing to the same compilation of observations as in previous studies (Gu and Liu, 2017; Rempfer et al., 2017; Van Hulten et al., 2018), model performance in simulating Pa/Th can be estimated quantitatively.

We agree with the reviewer that the GEOTRACES intermediate data product 2017 (Schlitzer et al., 2018) offers relevant new data. In fact, the core-top data used in Figure 1 is actually the same that was compiled in (van Hulten et al., 2018). We have corrected the citations in the manuscript accordingly. Besides, we have updated the supplementary figures for the sake of a better model performance evaluation. The main and supplementary figures now display: i) the zonally averaged Atlantic dissolved and particulate Pa, Th and Pa/Th (as suggested by the reviewer #2), ii) the model-data comparison along GEOTRACES transect GA03 and GA02S as shown in (Gu and Liu, 2017; van Hulten et al., 2018; Rempfer et al., 2017). The question of assessing the model performance using the GEOTRACES data and comparison with previous studies is developed in the response to reviewer #2- major comment n°1 below.

Minor Comments: 1. Page 3, Line 27, Gu et al. (2017) simulating Pa/Th in CESM should be mentioned here (higher resolution then Rempfer et al. (2017) and longer integration than van Hulten et al. (2018)). Gu, S., Liu, Z., 2017. 231Pa and 230Th in the ocean model of the Community Earth System Model (CESM1.3). Geosci. Model Dev. 10, 4723–4742. https://doi.org/10.5194/gmd-10-4723-2017

We thank the reviewer for highlighting this relevant reference, which has been added to the text as suggested (see revised manuscript).

2. Page 4, Authors follow Rempfer et al. (2017) to implement Pa/Th. One advance in Rempfer et al. (2017) in simulating Pa/Th is that bottom scavenging and boundary scavenging are included, which improves the simulation of water column Pa and Th activity. In page 8, line 37, authors state that the bottom and boundary scavenging

are not modeled in LOVECLIM. This should be mentioned earlier in section 2.1 (model description and developments). Also, the modeling scheme (similarities and differences) comparing with previous modeling efforts should be discussed explicitly in section 2.1.

We agree with the reviewer, among the models able to simulate the evolution of the Pa and the Th, Bern 3D is the only one having an explicit parametrization for bottom and boundary scavenging. As stated by the authors, this parametrization is rather crude and consists in scaling (increasing) the Pa scavenging coefficients in the coastal grid-cells in order to achieve enhanced Pa removal at the ocean boundaries (Rempfer et al., 2017).

We would like to point out that all models actually represent the so-called boundary scavenging effect. Indeed, the particles fluxes produced by the GCM NEMO-PISCES and used in iLOVECLIM show greater fluxes at the continental margins compared to the ocean interior. Therefore, the higher particle fluxes induce a greater Pa removal in the regions of high particle fluxes, even in the absence of additional parametrization of the boundary scavenging. Therefore, the need for an additional parametrization of the boundary scavenging does not appear to be fundamental.

The scavenging scheme and modelling choices are fully described in the method section. To date, the Pa and Th have been implemented in at least 5 models of intermediate complexity or GCMs. Therefore, a full discussion of the similarities and differences between these models would represent a model intercomparison project, which is out of the scope of this paper. Nevertheless, we have followed the reviewer's recommendations and modified the method description to i) mention that no explicit parametrization of boundary and bottom scavenging have been included in iLOVECLIM and ii) add information about how the modelling scheme used in this study compares with previous Pa/Th modelling work (see the method section of the revised manuscript).

3. Page 5, Line 20 Details about the PI forcing should be provided. From Figure 5, there is interannual variability. Is the PI forcing looping in the first 300 years?

The meaning of the question from the reviewer is unclear to us. Is the question related to interannual variability in the climate model itself? The setup we are using is a fully coupled atmosphere – ocean – vegetation climate model. Within that climate model system there is some interannual variability simulated in the climate by itself. Regarding the boundary conditions of the climate model, these are fixed to pre-industrial conditions and as such, there is no looping condition. The interannual variability in the model is not a product of the boundary conditions imposed but of the interactions within the atmosphere – ocean – vegetation climate numerical system used.

4. Section 3.1 Vertical structures of Pa/Th could also be provided and compared to observations (GEOTRACES transects), such as Figure 2 and Figure 3 in Rempfer et al. 2017. Figure S1 only have particulate and dissolved Pa and Th.

We would like to highlight that (Gu and Liu, 2017; Rempfer et al., 2017) only provide dissolved Pa and Th as well as particulate Pa/Th (i.e. no particulate Pa and Th) along the GEOTRACES transects GA03 and GA02S. As detailed above, we have included new supplementary figures showing dissolved, particulate Pa, Th and Pa/Th on a N-S Atlantic section as well as along GEOTRACES transect GA03 and GA02S (see response to previous comments and response to reviewer's 2 major comment n°1).

5. Page 6, section 3.2, first paragraph, Figure 5 can be referred here. Then people can see exactly how the fresh water is added and how the AMOC evolves.

Done

6. Page 6, line 14-16, this sentence can be rewritten for easier understanding.

We have split this sentence into two and added a coma (as suggested by the reviewer #2). We hope this technical information is now clearer.

7. Page 7, line 15, Any explanations for the 14C response time difference between the eastern and western basin?

The NADW is stronger in the western basin (western boundary current). The circulation pathways are hence different in the western and eastern Atlantic, both in real life and in the models. The NADW is less active in the eastern basin, which can explain the $_{14}$C response pattern (see revised manuscript p7 L33).

8. Figure 2 gives two examples of the single response and dual response. What is the proxy exactly? Pa/Th? 13C? or 14C? And where is the grid, location and depth? Also, it would be good to add AMOC in this plot for people to follow.

We thank the reviewer for his/her comment. However, we think that the purpose of Figure 2 has been misinterpreted.

Figure 2 has for only purpose to display the theoretical definition of "proxy response" and "proxy response time" as defined in the text whatever the grid cell, actual location and water depth. What is represented is δ_{13}C but the figure would be valid for any time series for any proxy. We have included the AMOC time series in Figure 2 as suggested by the reviewer.

9. Authors use fixed particle fluxes in their hosing experiment. After adding fresh water to the North Atlantic, the particle fluxes will change. Will this particle flux change affect the results of this paper should be discussed.

We agree with the reviewer that any change of the ocean surface conditions (adding freshwater, temperature…) will likely induce particle fluxes changes (i.e. flux intensity and/or composition). In its current version, with fixed particles, iLOVECLIM does not simulate the impact of primary productivity changes on the Pa/Th. Instead, we only simulate the impact of circulation changes, which is of interest in itself. As stated above, we have revised the discussion section of the manuscript and ensured to clearly state and discuss the implication of the use of fixed and prescribed particle fluxes.

10. The conclusions and perspectives can be improved to highlight the major findings. Currently, it is too broad and descriptive.

We have rewritten the conclusion in order to highlight the major findings.

References:

Gu, S. and Liu, Z.: 231 Pa and 230 Th in the ocean model of the Community Earth System Model (CESM1. 3)., Geosci. Model Dev., 10(12), 2017.
van Hulten, M., Dutay, J. C. and Roy-Barman, M.: A global scavenging and circulation ocean model of thorium-230 and protactinium-231 with realistic particle dynamics (NEMO–ProThorP 0.1), Geosci Model Dev Discuss, 2017, 1–32, doi:10.5194/gmd-2017-274, 2018.
Menviel, L., Mouchet, A., Meissner, K. J., Joos, F. and England, M. H.: Impact of oceanic circulation changes on atmospheric δ13CO2, Glob. Biogeochem. Cycles, 29(11), 1944–1961, doi:10.1002/2015GB005207, 2015.
Rempfer, J., Stocker, T. F., Joos, F., Lippold, J. and Jaccard, S. L.: New insights into cycling of 231Pa and 230Th in the Atlantic Ocean, Earth Planet. Sci. Lett., 468, 27–37, doi:https://doi.org/10.1016/j.epsl.2017.03.027, 2017.
Schlitzer, R., Anderson, R. F., Dodas, E. M., Lohan, M., Geibert, W., Tagliabue, A., Bowie, A., Jeandel, C., Maldonado, M. T. and Landing, W. M.: The GEOTRACES intermediate data product 2017, Chem. Geol., 493, 210–223, 2018.
Siddall, M., Stocker, T. F., Henderson, G. M., Joos, F., Frank, M., Edwards, N. R., Ritz, S. P. and Müller, S. A.: Modeling the relationship between 231Pa/230Th distribution in North Atlantic sediment and Atlantic meridional overturning circulation, Paleoceanography, 22(2), doi:10.1029/2006PA001358, 2007.