

Response to the editor and reviewer 1

We thank the editor and the reviewer for their careful assessment and constructive comments. Below we respond point by point and describe the changes made for the manuscript.

In this paper the authors investigate the climate and carbon cycle impacts of an AMOC collapse under climate change in an Earth System Model. Where most studies use pre-industrial conditions and don't use an interactive carbon cycle, this study does both which adds to the existing literature. I find the paper well written and the analysis of the results robust. It is already a very nice paper that was nice to read. I have some minor comments that can help clarify parts of the paper, and one larger concern that I'd like to see addressed in the authors' response.

We thank the reviewer for the positive assessment and constructive suggestions.

Major concern:

The paper does not address whether carbon and alkalinity are conserved in the model, and to what extent the total carbon content of each model simulation differs. I would like the authors to comment on the issue. I think it's very unlikely that it will change the results and the conclusion in a major way, but I think it is important to mention this, and discuss the differences between the model setups. Specifically, between the 2C-ref and the 2C-hos-Eref simulations.

We thank the reviewer for raising this important point. Carbon and alkalinity are not strictly conserved in the model because external inputs through river runoff are not exactly balanced by removal through sedimentation at the seafloor and, in the case of alkalinity, by the effects of atmospheric nitrate deposition. However, the resulting imbalances are small. In our 500-year preindustrial control simulation with an interactive carbon cycle, total ocean alkalinity increases slightly by $0.04 \text{ Pmol century}^{-1}$, indicating that riverine alkalinity inputs marginally exceed removal. Over the same period, the combined carbon inventory of the ocean, land, and atmosphere decreases by $0.29 \text{ Pmol C century}^{-1}$ ($3.50 \text{ Pg C century}^{-1}$), reflecting a small excess of carbon removal through sedimentation over riverine inputs. Consequently, the ocean carbon inventory gradually decreases, while atmospheric carbon increases slightly by $0.50 \text{ Pg C century}^{-1}$ ($0.23 \text{ ppm century}^{-1}$) due to oceanic CO_2 outgassing.

In examining these budgets, we also identified an implementation error in the hosing experiments. The imposed freshwater flux was inadvertently treated as an additional riverine input, thereby introducing artificial inputs of dissolved inorganic carbon and alkalinity. We have now corrected the implementation to ensure that the imposed freshwater flux does not introduce additional carbon or alkalinity, and have rerun the affected simulations (i.e. 2°C-hos-Eref, 2°C-hos-Eadapt and 2°C-r100-Eref). The correction results in generally small quantitative changes in the simulated responses, including very minor differences in the climate response arising from different phasing of internal variability in the new ensembles. The most notable change concerns the carbon response to AMOC collapse in the North Atlantic north of 20°N , which now represents a carbon source to the atmosphere of 3.4 Pg C , rather than a sink of 1.8 Pg C as previously reported. While this changes the sign of the

regional carbon response (Fig. 9a), the broader patterns of carbon redistribution and the main conclusions of the study remain unchanged.

We have updated all figures and numerical values throughout the manuscript to reflect the corrected simulations and revised the corresponding results sections and discussion where necessary.

In addition, we have clarified the mechanisms underlying the relatively large changes in carbon exchange with organic carbon reservoirs following AMOC collapse: *“Riverine carbon input in the Northern Hemisphere is decreased under AMOC collapse (Fig.9a) as a result of the reduced precipitation over land (Fig.8f). Changes in internal sources and sinks of dissolved inorganic carbon under AMOC collapse drive a decrease in dissolved inorganic carbon in the Northern Hemisphere north of 20°N (Fig.9a), mainly resulting from decreased remineralization of dissolved organic carbon (DOC) associated with decreased northward DOC transport from the low latitudes. Likewise, the increase in dissolved inorganic carbon from internal sources and sinks in the low latitudes and Southern Hemisphere is mainly associated with increased DOC storage and remineralization.”*

Minor comments:

1. Line 59/60: I think it would be good to cite Boot et al. (2024) also in line 59 and/or line 60.

We have added the important paper by Boot et al. (2024) to the discussion of previous carbon cycle studies.

2. Line 77: ‘However, their analysis ...’ How I think I should understand the sentence here, I think that’s correct. The sentence is a bit confusing since Boot et al. (2024) did use emission-driven simulations. I think the sentence can also be read as if they didn’t. I suggest to clarify the sentence.

We agree. Also in light of comments by reviewer 2 and 3, we changed the sentence to: *“Boot et al. (2024) examined carbon cycle responses to strong AMOC weakening under low- and high-emission scenarios using a comprehensive Earth system model, finding modest increases in atmospheric CO₂ driven by changes in oceanic and terrestrial carbon fluxes.”*

3. Section 2.1: I suggest extending the model description with respect to TOPAZv2.0 and LM3.0 to include a short description of processes relevant for section 3.5.

Also in response to reviewer 3 comment, we have extended the descriptions of TOPAZv2.0 and LM3.0 to clarify the processes relevant to the carbon cycle response to AMOC collapse. The revised text describes ocean biological production, carbon export and remineralization, carbonate chemistry, and air–sea CO₂ exchange, together with terrestrial productivity, vegetation dynamics, and temperature- and moisture-dependent soil carbon decomposition. It reads:

“We use the comprehensive global coupled carbon–climate model GFDL ESM2M (Dunne et al. 2012,2013), developed by NOAA’s Geophysical Fluid Dynamics

Laboratory (GFDL). Based on CM2.1 (Delworth et al. 2006), ESM2M couples the ocean (MOM4p1), atmosphere (AM2), land (LM3.0), and sea ice (including iceberg dynamics) components. MOM4p1 (Griffies 2009) simulates ocean physics on a 1° horizontal grid, refined to 1/3° near the equator, with 50 vertical levels and a tripolar grid north of 65°N. Ocean biogeochemistry is represented by TOPAZv2.0, which simulates the cycles of key elements (C, P, Si, N, Fe, O₂, alkalinity and lithogenic material) using 30 prognostic tracers. TOPAZv2.0 represents phytoplankton production regulated by temperature, light, and nutrient availability, together with organic matter export and remineralization, carbonate chemistry, and air–sea CO₂ exchange (Dunne et al. 2013). Coupling these processes to ocean transport and mixing allows the ocean carbon cycle to respond to AMOC collapse through changes in carbon and nutrient redistribution, ocean ventilation, biological production, surface CO₂ exchange and other processes. AM2 (Anderson et al. 2004) resolves atmospheric processes at 2°×2.5° with 24 vertical levels. LM3.0 (Shevliakova et al. 2009) simulates water, energy, and carbon cycles, multi-layer soil and snow dynamics, and vegetation processes. Vegetation is dynamic and represented by five plant functional types (C3 and C4 grasses, temperate deciduous trees, tropical trees, and cold evergreen trees). Vegetation type is reevaluated annually based on simulated biomass and climatic conditions, allowing vegetation distribution and biomass to respond to changes in climate. However, the model does not represent evolutionary adaptation of plant functional traits. Net primary production (NPP) does not have a prescribed temperature dependence but emerges from temperature- and moisture-dependent physiological processes, including photosynthesis and plant respiration. Carbon is allocated among vegetation pools and transferred to soil pools through turnover and mortality. Soil carbon is represented by two pools with different turnover times, whose decomposition and associated heterotrophic respiration depend on soil temperature and moisture (Shevliakova et al. 2009, Dunne et al. 2013). These processes, together with dynamic vegetation, allow AMOC-induced changes in temperature and precipitation to affect terrestrial carbon storage through changes in productivity, vegetation distribution, and soil carbon turnover. The sea ice model (Winton 2000) runs on the same grid as MOM4p1. GFDL ESM2M does not include a dynamic ice sheet component.”

4. Line 129: I suggest adding what the (approximate) absolute threshold values for an AMOC collapse are in this model.

We have added the numbers: 4.5 Sv at 26.5°N and 4.7 Sv at 48°N

5. Line 130: ‘With the 2C-ref experiment ...’ I suggest making clearer that the AMOC collapse signal becomes apparent from comparing the two simulations (2C-ref and 2C-hos-Eref).

Thank you for the suggestion. We change the sentence to “*By comparing the 2°C-hos-Eref and 2°C-ref experiments, ...*”

6. Line 145: I’m not sure what is meant with ‘... or global salinity drifts.’

We delete 'global salinity drifts' as the sentence is clear without it.

7. Line 159: I suggest adding references here for the model biases (they are already somewhere else in the manuscript).

Added.

8. Line 253: What is the reason for the shift into regime 3? From the feedbacks it appears changes in cloud cover. Do you know why this happens? I think it would make for a nice addition to the paper if this could be explained in more detail.

We have included figures showing low-level cloud cover change for the period 2071-2100 to compare it with the changes in 2171-2200 (see new extended Figure B5). This additional analysis shows that the ongoing cooling after 2100 is again caused by the increase in low-level cloud cover. We have added the following sentence to the manuscript: "*The continued cooling after 2100 is also caused by clouds feedback as the low-level cloud cover over the north Atlantic continues to increase after 2100 (Fig. B5).*"

9. Line 302: Is the cloud feedback different in other ESMs? And if so, would you expect different qualitative results for those models?

We thank the reviewer for this question. Cloud feedback differs substantially among Earth system models and is also a major cause of the spread of climate sensitivity among models (Zelinka et al., 2020, <https://doi.org/10.1029/2019GL085782>). We therefore expect the magnitude and spatial pattern of the cloud radiative response, as well as its contribution to the temperature response, to vary across models. Whether these would alter the qualitative conclusions of our study cannot be established from the available cloud-feedback estimates alone and requires coordinated AMOC-collapse experiments across multiple models. We have added to the end to the second paragraph of the discussion: "*However, it is well-known that the cloud radiative response depends on the model considered (Sherwood et al. 2014, <https://www.nature.com/articles/nature12829>). For instance, ESM2M exhibits a weaker global net cloud feedback under CO₂-driven warming than the CMIP5 ensemble mean (Zelinka et al., 2020). Therefore, to gain confidence in the magnitude, and potentially even the sign of the cloud feedback change in response to AMOC substantial weakening requires assessment across multiple models. This would allow us to evaluate the robustness of our results, which is the first time to our knowledge that such a quantification has been performed. In this respect, the TIPMIP-OCEAN multi-model ensemble (Swingedouw et al. 2026; https://editor.copernicus.org/EGUsphere/ms_records/egusphere-2026-6311) will constitute a dataset to perform such an analysis.*"

10. Line 319: I suggest referencing to Fig. 5 here.

Done.

11. Figure 5: I think it would be insightful to add the absolute numbers of the two simulations as well in the figure. And for clarity, I suggest adding a '+' sign in front of the positive differences to highlight it's a number representing a difference.

We have added an additional figure to the appendix showing the heat budget changes from 2026 to 2171-2200 in the 2°C-ref simulation for comparison. We have added a few sentences about this comparison:

"The zonally and depth-integrated heat budget (Fig. 5) reveals that the ocean north of 20°N stores 237 ZJ less heat than in the 2°C-ref, where ocean heat storage increases by 560 ZJ (Fig. B7) over the same period. "

and

"In contrast, south of 20°N, excess heat accumulates in the tropical and Southern Hemisphere oceans, consistent with reduced meridional heat redistribution. The net OHC increase of 498 ZJ between 20°S and 20°N corresponds to an additional 46% increase in ocean heat content relative to the 2°C-ref simulation. South 20°S the ocean stores an addition of 251 ZJ (+ 26%) relative to 2°C-ref simulation."

We did not include '+' and '-' signs in the figure because we considered it sufficiently clear from the caption that the values represent differences.

12. Figure 8: the land response in southern Finland is quite different from the response in the surrounding area. It is also qualitatively different compared to the results in Boot et al. (2024) in the same region. From the air temperature and precipitation I do not see a clear reason why this region would behave differently. Why does this region show this response?

We thank the reviewer for highlighting the distinct response in southern Finland and its difference from the results of Boot et al. (2024). Similar local departures from the surrounding land carbon uptake response occur in northeastern China and southeastern Canada. In our simulations, these features coincide with distinct responses in net primary production, but the temperature and precipitation changes alone do not provide a clear explanation.

We therefore cannot confidently attribute the response in southern Finland to a specific mechanism or explain its difference from Boot et al. (2024). Doing so would require a more detailed analysis of local vegetation and soil conditions and the processes controlling NPP. Such an analysis is beyond the scope of this study, which focuses on global and broad regional climate-carbon cycle responses. These local features should consequently be interpreted with caution and warrant further investigation.

13. Figure 9: Similar as for Figure 5.

We have added an additional figure to the appendix showing the carbon budget changes from 2026 to 2171-2200 in the 2°C-ref simulation for comparison. We have

also added to the text: *“The excess carbon inventory in the 2°C-hos-Eref simulation is reduced by -44% relative to the 2°C-ref simulation.”*

14. Figure 9: For clarity it might be nice to add the word atmosphere above the ocean boxes so that we know the fluxes up there are air-sea exchanges without having to read the caption.

Thank you for the suggestion. We keep the figure as is as we think it is clear enough given that we indicate the ocean boxes.

15. I suggest discussing Lerner and Romanou (2026), even though it’s still a preprint.

We thank the reviewer for drawing our attention to Lerner and Romanou (2026). We acknowledge its relevance but have chosen not to include a detailed comparison at this stage because the study remains under review and its findings may be revised. We will reconsider its inclusion if a peer-reviewed version becomes available before our manuscript is finalized.

16. Figure A1: I suggest adding to the caption that the y-axis differs per subpanel.

We have added: *“The y-axis scales differ among panels.”*

17. Equations A5-A7: I suggest keeping the order of the feedbacks consistent.

Done.

18. Figure B2: I suggest adding a contour line at 0 Sv.

Thank you for this suggestion. We have retained the existing contours, which distinguish positive and negative streamfunction values. We prefer to keep the current figure to avoid additional visual clutter, as we consider the circulation structure sufficiently clear without an explicit 0 Sv contour.

References:

Paul Lerner, Anastasia Romanou. Cascading Impacts of AMOC weakening and collapse on Marine Biogeochemistry, 08 May 2026, PREPRINT (Version 1) available at Research Square [<https://doi.org/10.21203/rs.3.rs-9044876/v1>]