

We thank the reviewer for the invested time in evaluating our study and the thoughtful comments that have helped to substantially improve the manuscript.

Below are our detailed point-by-point replies and suggested manuscript improvements (blue) for each comment (black).

Main comments:

Mechanisms by which the reduction of radiative forcing weakens the AMOC: Other reviewers have pointed out many points, so I'll just list potential ways to improve the manuscript.

1. Separate the paragraph explaining the effect of the Southern Ocean and North Atlantic. Section 3.2 goes back and forth between the role of NA and Southern Ocean. This makes it hard to follow the discussion. Related to this, Buizert and Schmittner (2015) provides a nice summary on the role of Southern Ocean. Ando and Oka (2021, GRL) also gives useful insight on the role of sea ice and heat transport on the stability of the AMOC. These two studies further performed hysteresis experiments with freshwater forcing. While the way of hysteresis experiment is not the same as in this study, I feel these studies should be cited and included in the discussion of the mechanism.

We rewrite the description of the processes at play in simulation B.slow, and follow the reviewer's advice to discuss changes in the North Atlantic and Southern Ocean separately. We will also refer to Buizert and Schmittner (2015) and Ando and Oka (2021) in the discussion of our results. The revised paragraphs read as follows:

In section 3.2:

"In our simulations, the primary processes controlling the AMOC strength under changing radiative forcing are density changes due to heat and salinity redistributions. We investigate these in more detail in experiment B.slow (Fig. 4 and 5). This experiment is characterised by a slow linear decrease in radiative forcing over 50 kyr, before it is increased again to the pre-industrial value with the same rate of change (Fig. 4a). Fig. 5 shows that AMOC weakens gradually over the first 24 kyr, then weakens abruptly by 1 Sv at 24 kyr into the simulation and by ~3 Sv at 27 kyr, and then continues to weaken gradually until the forcing is reversed (Fig. 5a). In addition to the abrupt transition in AMOC strength, we found several additional rapid changes in AMOC variability, heat and salt fluxes (Fig. 5) and regional density profiles (Fig. SI.7-9), which are not associated with abrupt changes in AMOC strength. In fact, experiment B.slow shows that a cascade of changes with little effect on the mean AMOC strength occur before the first abrupt AMOC weakening after 24 kyr. Since these changes might partially be artefacts of our coarse model resolution, we here only focus on the larger scale changes instead. Initially, the whole Atlantic surface ocean cools and freshens, leaving the temperature and salinity differences between the Irminger and Caribbean Seas almost unchanged (Fig 5e). However, NADW becomes less salty and colder in consequence (not shown) and the vertical density profiles in the subpolar North Atlantic change due to the temperature and salinity changes (Fig. SI.7-8).

After about 6 kyr, the changes in the North Atlantic density profile shift the location of NADW formation. NADW formation moves south as vertical density profiles in the subpolar east North Atlantic stabilise under a freshening of the surface and density profiles further south steepen due to surface cooling combined with subsurface warming (Fig. SI.7-9). Apart from temporary volatility, the mean AMOC strength is not affected by these changes, but freshwater and heat advection into the North Atlantic is reduced, sea ice expansion increases in the eastern North Atlantic and AMOC variance (calculated over a moving 50-year window) is increased (Fig. 5). Transport of heat and salinity into the North Atlantic decreases (Fig. 5f, g) and North Atlantic SST and SSS decrease (Fig. 5e). Reduced influx of subtropical surface waters also cause abrupt cooling and freshening in

the Irminger Sea (Fig. SI.8). At 24 kyr, the AMOC has weakened to ~14.5 Sv and sea ice cover extends south of the Irminger Sea (Fig SI.10). At this point, the AMOC strength drops abruptly by 1 Sv, and then by an additional 2.5 Sv ~3 kyr later, as the reduced salinity advection into the North Atlantic and precipitation and evaporation changes lead to a strong surface freshening. As a result of the North Atlantic density changes, the main North Atlantic convection site shifts southwards (determined by changes in the vertical density profiles, Fig SI.10). Sea ice also increasingly covers former areas of deep water formation in the North Atlantic. In the weakest circulation mode, the location of the maximum AMOC streamfunction shifts southwards by approximately 10 degrees and up in the water column by 400 m initially (28.5 kyr) and eventually almost 800 m (47 kyr) This shift allows cold, less dense water masses to extend further south into the North Atlantic.

In the Southern Ocean, the cooling enhances Southern Ocean deep water formation early on in the experiment and leads to a continuous expansion of sea ice in the Southern Hemisphere. The biggest AMOC weakening at ~27 kyr is also accompanied by a weak bipolar seesaw effect, which causes a temporary decline in sea ice coverage in the Atlantic sector of the Southern Ocean (Fig. 5). It is, however, too small to reduce the radiation-driven sea ice increase in the longer term. Both shifts in AMOC strength are accompanied by an increased spread of AABW into the North Atlantic (Fig. 5d)."

"The simulated step changes in AMOC strength in our simulations are thus the response to gradual surface cooling and freshening, and occur when NADW formation shifts southwards. The resulting redistributions of heat and salinity cause sudden shifts in the vertical density profiles and sea ice expansion which consolidate the new circulation state (Ando and Oka, 2021). In particular, reduced advection of heat and salinity into former locations of deep water formation result in a more stable local water column (Fig. SI.7-9). The downwelling zones are sensitive to heat and salt flux changes, because any reduction in sea surface temperatures (SST) increases surface density but simultaneously reduces evaporation in ice-free areas, thus effectively creating a small freshwater forcing and a negative feedback to the buoyancy changes caused by the initial SST decrease. Sea ice covering the downwelling areas stabilises the water column by preventing surface ocean cooling and evaporation. The progressive influx of AABW into the North Atlantic is a further process stabilising new circulation states by stratifying the water column from below (Buizert and Schmittner, 2015)."

In section 3.3:

"The primary importance of salinity and heat redistributions as well as sea ice extent in the North Atlantic for the simulated AMOC shifts resembles the findings from Ando and Oka (2021)'s hosing experiments under LGM conditions and Zhang et al. (2017)'s simulations of AMOC shifts in response to CO₂ changes under intermediate glacial conditions. While our experiments were run with pre-industrial topography, sea level and wind fields, the initial location of convection sites between Greenland and the British Islands (areas with lowest density differences over upper 1000 m in Fig. SI.8) resembles the LGM and intermediate glacial circulation states in Ando and Oka (2021) and Zhang et al. (2017)."

2. Use Fig. 3 to help explain the mechanism. For example, it would be more convincing for me if the authors explain the mechanism in the following manner "reduction of radiative forcing first weakens the convection in the Labrador Sea (Fig. 3) by increasing transport of sea ice from the arctic and by reducing the northward heat transport (Fig. 4). However, intensified surface cooling initiates the deepwater formation close to UK (Fig. 3), causing a shift of the AMOC into the second phase. Further reduction in radiative forcing" Obviously this is not a perfect example but please consider modifying the manuscript in this way.

When revising the manuscript we refer more to the figures, as suggested. We also clarify our description of processes (see new text in the answer to the previous comment).

3. Relation of heat transport and the AMOC is always tricky. They vary together and also the heat transport can either weaken or strengthen the AMOC depending on the background condition (e.g. Paul and Schulz 2002, https://doi.org/10.1007/978-3-662-04965-5_5, Ando and Oka 2021, GRL). Please cite these papers when discussing the effect of heat transport on AMOC and explain why it should work in that sense.

We add to the discussion of processes changing AMOC strength in our simulations, and cite Ando and Oka, 2021. The revised text in section 3.2 reads:

“The simulated step changes in AMOC strength in our simulations are thus the response to gradual surface cooling and freshening, and occur when NADW formation shifts southwards. The resulting redistributions of heat and salinity cause sudden shifts in the vertical density profiles and sea ice expansion which consolidate the new circulation state (Ando and Oka, 2021). In particular, reduced advection of heat and salinity into former locations of deep water formation result in a more stable local water column (Fig. SI.7-9).”

Experimental setup: I think the authors need to explain why they decide to vary the magnitude of the dust related radiative forcing but not others in their sensitivity experiments (I'm not saying that's bad!). I don't fully understand how this model works, but isn't there another way to do similar experiments, e.g. changing the magnitude of the emissivity of the atmosphere or the magnitude of the ice sheet related radiative forcing? Effect of dust forcing is of course uncertain, but so are others (Tierney et al. 2020).

Related to 2, another question I have is that “Does the radiative forcing by dust affect the global and local temperatures in the same way as the GHG do in this model?” Looking at results from GCMs (e.g. Kawamura et al. 2017 Science Advances, Ohgaito et al. 2018 CP), it is shown that GHG and dust affect the local temperatures in a different way. This information is important especially when we want to use the insight from this study to better understand results of AOGCMs.

We clarify our methods and specifically note that our applied forcing of radiation reductions are spatially uniform. As such, the pattern of the additional radiative forcing that we prescribe is slightly different to that of GHG. GCM simulations showed that spatially different forcings lead to a very similar temperature pattern due to feedbacks (Boer, G. and Yu, B., 2003. Climate sensitivity and response. Climate Dynamics, 20, pp.415-429.). In either case, our simulations contain the radiative effect of GHG and the additional, uniform ‘dust’ forcing. Hence, we do not specifically test the temperature effect of dust load changes specifically, but more generically of changes of the atmospheric radiation balance. There might be other ways of implementing this but in our model the effect would be virtually the same. We add the following sentences to our Methods for clarification:

“In our experiments, we applied spatially-uniform radiative forcings, to account for uncertain atmospheric optical depth changes due to changes in aerosols and dust, in addition to the better constrained temperature changes due to orbital changes and greenhouse gases, hence termed dust forcing. The scaling of this forcing varies between the simulations and transiently within each simulation.”

"It is important to note that we only consider the radiative effect of an assumed uniform distribution of aerosols in our simulations. In reality, this distribution would be non-uniform and aerosols would have additional effects on atmospheric freshwater fluxes, two factors which are both relevant for AMOC stability (Menary et al., 2013) but are poorly constrained for the last 780 kyr."

NADW formation in Norwegian/Greenland sea: This might be related to comments from other reviewers, but some previous studies have suggested the importance of cessation/resumption of convection over the Norwegian Sea when considering the thermal threshold of the AMOC (Oka et al. 2012). Please describe this feature in the Introduction and add some discussion wherever appropriate.

In the pre-industrial model state of Bern3D deep water formation does not occur north of the Irminger Sea. In the revised manuscript, we discuss the importance of the location of deep water formation sites at the beginning of the experiment for the existence of thermal thresholds. Specifically, we will add the following paragraph to section 3.3:

"The primary importance of salinity and heat redistributions as well as sea ice extent in the North Atlantic for the simulated AMOC shifts resembles the findings from Ando and Oka (2021)'s hosing experiments under LGM conditions and Zhang et al. (2017)'s simulations of AMOC shifts in response to CO₂ changes in intermediate glacial conditions. While our experiments are run with pre-industrial boundary conditions, the initial location of convection sites between Greenland and the British Islands (areas with lowest density differences over upper 1000m in Fig. SI.8) resembles the LGM and intermediate glacial circulation states in Ando and Oka (2021) and Zhang et al. (2017). Ganopolski and Rahmstorf (2001) found that the possibility of a southward shift of deep convection depends on the latitude of prior deep convection and the density field further south, and Oka et al. (2012) showed that the location of deep convection and its distance from the winter sea ice edge shape thermal thresholds in AMOC strength."

Specific comments:

P1L25-26: Given the limitations in the model, I think it would be safe to add "in this model" at the end of the sentence.

We specify that these results are only valid for our model in the revised manuscript.

P1L31-33: Isn't this the other way round; relatively salty water gets cooled by the atmosphere, the vertical density gradient weakens, and the water sinks and forms the NADW.

The reviewer is correct. We amend the sentence so that it reads:

"The Atlantic Meridional Overturning Circulation (AMOC) transports warm waters from the Southern Hemisphere and the Mexican Gulf towards the Nordic Seas, until the gradually cooled salty water sinks after losing enough buoyancy and forms North Atlantic Deep Water (NADW)."

P2L34: Perhaps "sensitive" -> "dependent"?

We change the wording as suggested.

P3L13-25: So many references are missing in this paragraph. Please add the appropriate reference for each sentence. (e.g. references for Bern3D model, references for freshwater flux corrections)

We will add the references describing the details of the Bern3D model and its setup as suggested.

P4L11-13: How did you define the maximum ice extent? Is it from the LGM?

We clarify our definition of the maximum forcing. Specifically, we change our description in the Methods section to the following:

“The maximum radiative dust forcing, defined via the peak LGM value in the smoothed $\delta^{18}O$ stack, is a free parameter, ranging from 0 to -8 W/m^2 relative to PI (Simulations A.0 to A.8)”

P5L23-24: Better to say “stable”->“monostable”, “unstable”->“bistable” here.

With our stability tests, we assessed how resilient the circulation is to a small perturbation, i.e. whether it is close to a potential bifurcation point. However, we did not test each circulation state for mono- or bistability and the existence of bifurcation points. Hence, we do not think that the suggested terminology is appropriate at this point in the manuscript. Instead, we will improve our terminology for our stability tests to clarify as follows:

“Our stability experiments demonstrate that the circulation modes before and after the shifts recover from small freshwater perturbations, and can thus be considered as stable, i.e. sufficiently far from bifurcation points to recover from the small perturbation”

P11L11-15: I could not understand this sentence. Can you further elaborate on this, please?

We rewrite the description of simulation B.slow with a clearer discussion of the relevant processes. We describe changes at the beginning of the simulation as follows:

“Initially, the whole Atlantic surface ocean cools and freshens, leaving the meridional temperature and salinity gradients almost unchanged (Fig 5e). However, NADW becomes less salty and colder in consequence (not shown) and the vertical density profiles in the subpolar North Atlantic change due to the temperature and salinity changes (Fig. SI.7-8).”

P13L4-5: Not quite sure what this positive feedback means here. In general, a surface cooling will reduce the SST and hence increase the surface density while the cooler SST reduces evaporation and causes a reduction in surface salinity and surface density. So isn't it a negative feedback?

We apologise for the confusion and the poorly formulated paragraph. We rewrite the paragraph for a clearer discussion of the relevant processes. Instead of feedbacks, we write of stabilising processes, which is a clearer terminology. The new paragraph is:

“The resulting redistributions of heat and salinity cause sudden shifts in the vertical density profiles and sea ice expansion which consolidate the new circulation state. The downwelling zones are sensitive to heat and salt flux changes, because any reduction in sea surface temperatures (SST) increases surface density but simultaneously reduces evaporation in ice-free areas, thus effectively creating a small freshwater forcing and a negative feedback to the buoyancy changes caused by the initial SST decrease. Sea ice covering the downwelling areas stabilise the water column by

preventing surface ocean cooling and evaporation. The progressive influx of AABW into the North Atlantic is a further process stabilising new circulation states by stratifying the water column from below (Buizert and Schmittner, 2015).. The difference between freshwater transport into the South Atlantic at 32°S and into the Arctic at 62.5°N in Fig. 5f can be used as a measure for the basin-wide salinity feedback (Rahmstorf, 1996, de Vries and Weber, 2005). In our simulation, changes in this metric are predominantly caused by changes in the transport across the northern edge, since transport into the South Atlantic remains almost unchanged throughout the cooling phase of B.slow. North Atlantic salinity is instead governed by changing transport from the subtropics into the North Atlantic and between the North Atlantic and Arctic. As such, the processes involved in the sudden AMOC strength changes, namely density changes in the upper water column, and those that stabilise new circulation states (salinity and heat redistributions, sea ice expansion) mostly operate in the North Atlantic region.”

P13L6: Isn't the sea ice feedback a positive feedback?

This is again an unclear description which we revise. In the new version, we mention sea ice expansion as a stabilising process.

Figs.2 and 9: Very nice figures.

Thank you!

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