Author's response to "Interactive comment on ***Climate and vegetation changes around the Atlantic Ocean resulting from changes in the meridional overturning circulation during deglaciation*** by D. Handiani et al."

By Handiani et al.

We thank the anonymous referee #1 for the constructive and helpful comments as well as suggestions to improve the manuscript.

We thank the editor for proposed suggestions how to handle the reviewer comments and how to prepare the revised manuscript.

We considered and implemented almost all the comments and suggestions into the revised manuscript. We think that this change largely improved our manuscript.

In the following we refer to the referee #1 comments.

Response to Anonymous Referee #1

General comments

This paper focuses on both, changes in vegetation and changes in the ocean circulation, without really connecting these two subjects. I would therefore recommend to re-write the paper in a way to tie the ends together and make a more consistent story.

Answer: We changed and improved the manuscript. We analyzed and discussed the interaction between ocean and atmospheric circulation, which then corresponds to changes in precipitation pattern and vegetation cover. The mechanism of this interaction is one possibility to connect the abrupt climate warming of the Bølling-Allerød (BA) period to changes in vegetation cover.

In addition I have several major concerns as listed below.

1. *Vegetation: I find the vegetation part of the paper a little too light. The vegetation model used in this study is quite simple; it is therefore not surprising that the model-reconstruction comparison under BA boundary conditions is far from being perfect. This deficiency could be overcome by analyzing changes in vegetation cover under different boundary conditions and compare those to changes seen in the reconstructed vegetation during abrupt climate change. The authors go only half way, (a) comparing simulated equilibrium vegetation with reconstructions for the BA and (b) comparing changes in simulated vegetation due to changes in the AMOC. Therefore, one of my first suggestions/ideas after a first read was to analyze biome reconstructions for both H1 and BA and then compare the main differences in these reconstructions with modeled vegetation shifts (namely between T2 and T0; I do not think that the vegetation had enough time to recover in T1 to show an equilibrium response). I then went on to read Handiani et al. (2012) and realized that most of the H1 comparison has been done. I therefore wonder if there is enough new science in this paper? I would also like to point out that the same model has been used in the past to analyze vegetation changes during Heinrich Events in Africa (Carto et al. 2009).*

Answer: We added a new analysis to understand the difference in vegetation cover and climate conditions between T2 (BA-like climate) and T0 (HE1-like climate). We also added new Figures (Figs. 6 and 7, subsection 3.1 and 3.2) to support the analysis. Another new figure (Fig. 8) was added with the results of the two BA experiments that show an abrupt warming due to a recovery of the AMOC. These experiments show two different mechanisms for AMOC recovery. The first mechanism is by adding freshwater to the Southern Ocean under present-day climate conditions and the second mechanism is by extracting freshwater from the North Atlantic Ocean under HE1 climate conditions. We compared the vegetation cover of both experiments between time T2 and T0. A detailed comparison is made for four regions around the Atlantic Ocean: North America, tropical South America, Europe and North Africa, and tropical Africa (Fig. 1b). The regions are chosen to allow comparison with available pollen records (Fig. 1a). The analysis aims to understand the response of the vegetation cover in each experiment and leads to the conclusion that both experiments show an increase of vegetation cover over northern and equatorial northern Africa.

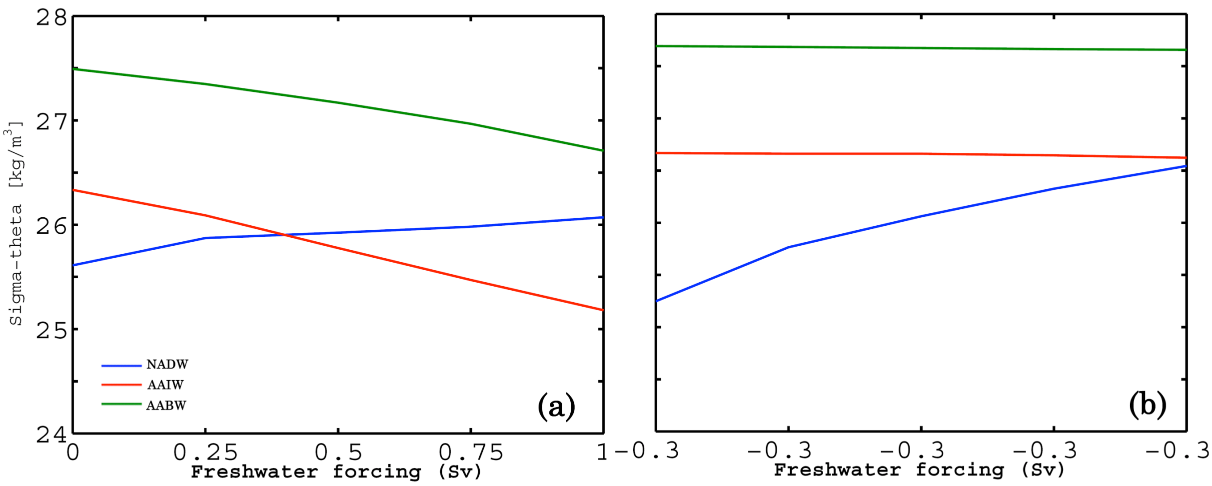
2. *Ocean: This paper lacks a concise literature review about well-known stable equilibria in coupled models and how one can switch between two or more of those (including discussions of box models, etc). There is a confusion in this paper between the: *NADW/AABW see-saw (which is also the best known and best covered in the literature) *NADW/AAIW seesaw (e.g., for the UVic model, Saenko et al. 2003) and the *NADW/NPDW seesaw (e.g., for the UVic model, Saenko et al. 2004; or for LOVECLIM, Okasaki et al. 2010) In addition to expanding the literature review, I think that the simulations need to be analyzed further. According to the figures, it looks like the simulations presented here are displaying the NADW/AABW seesaw, although the authors claim at least at one point that the NADW/AAIW seesaw plays a role too. This needs to be analyzed and rectified. I would also like to encourage the authors to double-check that none of their simulations is forming North Pacific Deep Water, especially when hosing the North Atlantic. One of the most interesting results in this study is the fact that adding freshwater to region B has different results on NADW formation depending on the boundary conditions. This should be further explored. Is it maybe the sea ice cover in the Southern Ocean that plays a major role here? On page 2833 the authors mention the freshwater transport into the Atlantic Basin – maybe they should show these time series in the paper? On the other hand, adding salt to the Atlantic Ocean would rejuvenate any AMOC, so I do not think that there is need to dwell on this mechanism too long. Finally, I find it puzzling that some simulations show a warming in the North Atlantic Ocean, although the AMOC does not recover. What is causing this warming? Are there changes in the North Pacific circulation? An analysis of heat fluxes and budgets in the ocean might shed light to this question.*

<u>Answer:</u>

- Since we are focusing in the study of vegetation cover changes, we did not dwell on the details of the AMOC stability analysis. Nevertheless, we extended our literature review and added several references to the concept of stable equilibria in coupled models to the Introduction section (p. 4, lines 20-32 and p.5, lines 1-7). This concept is the bases of AMOC stability analysis.
- We added a new figure to explain the role of potential density in the formation of deep and intermediate water masses in the Atlantic Ocean (Fig. 5). The figure shows the surface potential density in the source region of each water mass as a function of the freshwater perturbation (similar to Fig. 3 in Weaver et al., 2003). The source regions are the North Atlantic for NADW, the southeast Pacific and southwest Atlantic for AAIW, and the Weddell and Ross Seas for AABW. The surface density at the end of the experiments in which the AMOC does not recover show the relationship $\rho_{AABW} > \rho_{AAIW} > \rho_{NADW}$, while in the experiment in which the AMOC recovers the relationship $\rho_{AABW} > \rho_{NADW} > \rho_{AAIW}$ holds (Fig. 5). The latter experiment shows a decline of surface density over the region of AAIW formation and a slight increase of surface density in the source region of NADW. Noticeably, the reduction of surface density over the region of AAIW formation is closely related to the reduction of surface density over the region of AABW formation. This pattern is also shown by Weaver et al. (2003) in similar freshwater perturbation experiments. The recovery in this experiment was triggered by adding freshwater to the Southern Ocean under present-day climate conditions (see below Fig. a). The transition from

an 'off' state of the AMOC to an 'on' state under Heinrich event climate conditions can be triggered by extracting freshwater from the North Atlantic Ocean. This experiment results in similar climate conditions as the one that involved adding freshwater to the Southern Ocean. However, the relationships between the surface densities in the regions of deep and intermediate water formation in both experiments differ. The relationship at the end of the recovery experiment using freshwater extraction is $\rho_{AABW} > \rho_{AAIW} > \rho_{NADW}$, with only a slight difference in density between the NADW and AAIW source regions (see below Fig. b). The surface density over the region of NADW formation increases with only little contributions from the reduction of surface density over the regions AAIW and NADW formation. We conclude that the AMOC transition from 'off' to 'on' by adding freshwater to the Southern Hemisphere is more difficult to obtain under glacial climate conditions than under modern ones. A detailed discussion was added to the Discussion section (p. 15, lines 6-31 and p. 16, lines 1-20).

- We withdrew the statement on page 2833 regarding the possibility of freshwater transport into the Atlantic Basin.
- We withdrew the former Fig. 5 and added a new figure, Fig. 6 in the revised manuscript. The North Atlantic Ocean is only warmer than the South Atlantic Ocean after the AMOC recovered (Figs. 6e and 6h).



Surface potential density (σ_0=ρ_0-1000) in the source regions of NADW formation, AAIW formation, and AABW formation as a function of freshwater perturbation by adding freshwater to the Southern Ocean (a) and by extracting freshwater from the North Atlantic Ocean (b). The locations of water mass formations refer to Weaver et al. (2003) and figure (a) is the same with Figure 5d in the revised manuscript.

3. *Winds: Most of the vegetation changes, which are a crucial component of the paper, are due to changes in precipitation. The authors explain that these changes are due to "a northward shift of the Intertropical Convergence Zone" without any further analysis. The UVic ESCM has a very simple atmospheric component, which does not calculate winds diagnostically. As the authors did not specify which wind fields they used to force the model, I suspect that the model is integrated with present-day winds and a superimposed wind anomaly due to geostropic adjustment calculated based on temperature changes. Am I right? In that case it might be interesting to at least discuss this simple parameterization and how it might be successful (or not) to simulate a shift in convection zones. Given that this paper is centered on vegetation shift, one might even want to go a step further and reintegrate the simulations with wind fields diagnosed from an atmospheric GCM. Figures 3 and 4 tell the same story, I would suggest to only show (and describe) one of them.*

<u>Answer:</u>

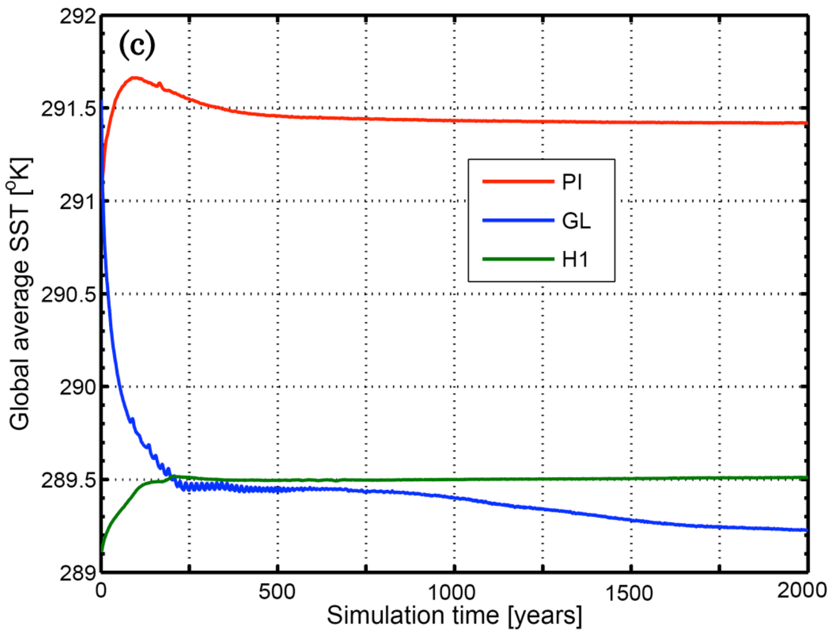
- We are aware of the fact that the UVic ESCM has only a simple atmospheric component, which compromises the precipitation results in our study. For that matter we mentioned the wind and wind-stress fields that were used in our experiments (Sect. 2 model description and experimental designs, p.6, lines 5-7). We also briefly discussed the parameterization of the dynamic wind feedback in the UVic ESCM, which might partly compensate the deficiency in the atmospheric model. This can be found in Sect. 4, Discussion (p. 18, lines 13-29).

- Further investigations to compare the vegetation response in two models differing in complexity of the atmospheric component were carried out in another study (Handiani et al., in press). This study compares the response of the vegetation cover to changes in climate due to AMOC slowdown of the UVic ESCM with that of the Community Climate System Model (CCSM3), a coupled general circulation model with a complex atmospheric component.
- We withdrew both Figs. 3 and 4.

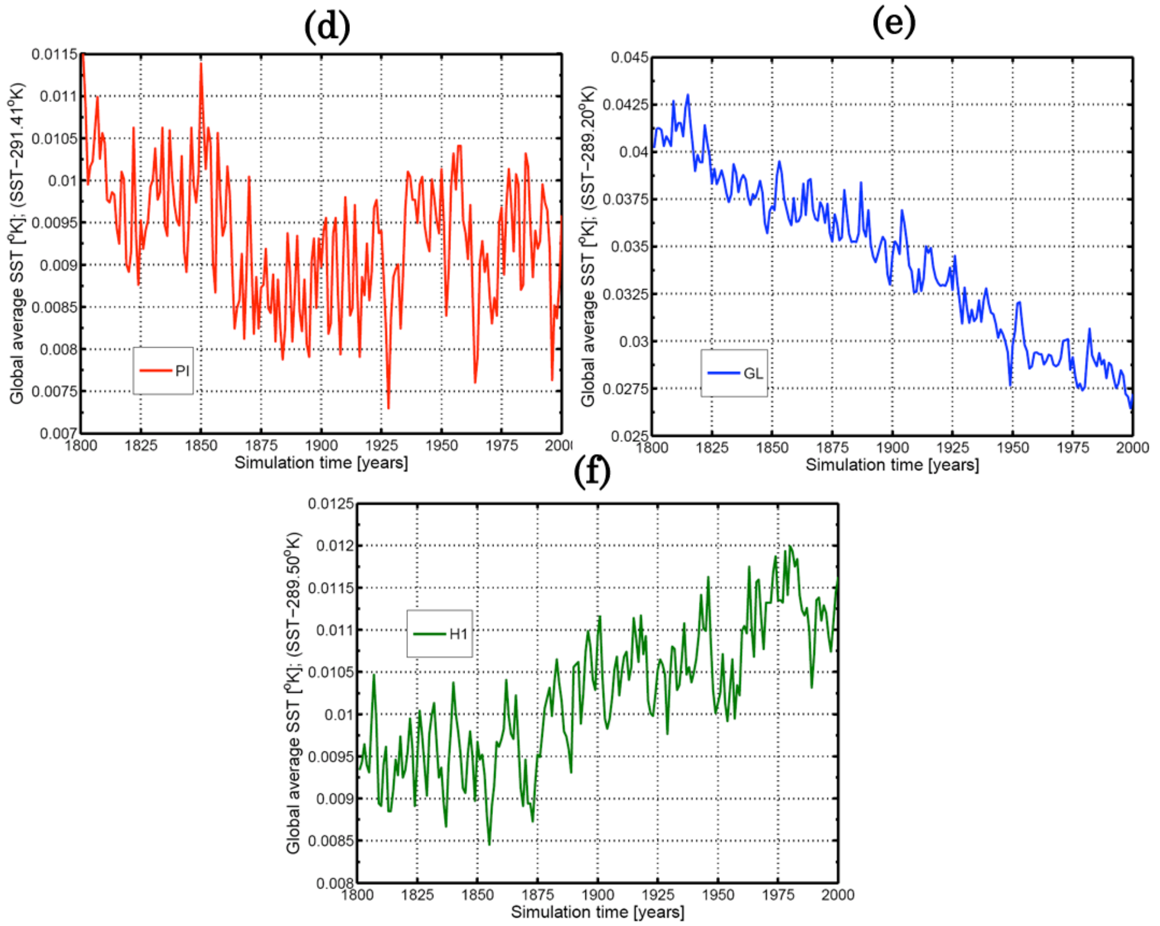
Specific comments

Page 2824, line 7: 2000 years is quite short for an equilibrium simulation. What is the drift in ocean temperature at the end of our equilibrium simulations?

Answer: In the case of our equilibrium simulations, the drift of the annual global average sea-surface temperature at the end of 2000 years of integration is around 10^{-3} ºC or less in all sequences (Figs. c-f). Furthermore, earlier studies (Weaver et al., 2001) suggested that 2000 years of integration is enough to bring the UVic ESCM close to equilibrium, and at that time the annually-averaged surface fluxes are nearly zero.



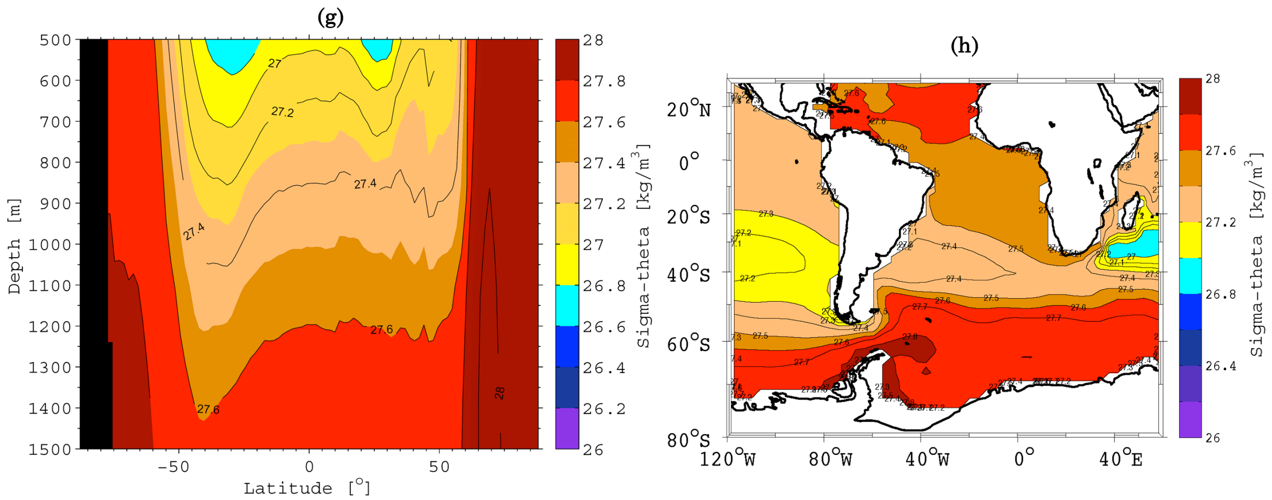
Annually-averaged of sea surface temperature of 2000 years equilibrium integration for PI, GL, and H1 sequence.



Annually-averaged of sea surface temperature of the last 200 years equilibrium integration for PI (d), GL (e), and H1 (f) sequence.

Page 2824, line 17: Before making this statement, please double-check where AAIW is formed in your simulations. I doubt that this is in region B.

<u>Answer:</u> We rewrote the statement. The location of freshwater discharge in our study is similar to the one in Weaver et al. (2003), which is located in the Southern Ocean (to the west of the Antarctic Peninsula). Weaver et al. (2003) demonstrate that adding freshwater in this location can influence the formation of AAIW and lead to a recovery of the AMOC; they also state that this location is an important place of AAIW formation in the UVic ESCM. The AAIW in our study is found at around a 600 to 1200 m depth and has a range in density of 27-27.5 kg m^{-3}. These results refer to the equilibrium simulation under a present-day climate background (Fig. g). The location of AAIW formation in this simulation is around the tip of South America, which is between the latitude of 45ºN-50ºN (Fig. h). However, our results show that the AMOC could recover by adding freshwater to the Southern Ocean only under present-day climate conditions (Fig. 2b in our revised manuscript).



Averaged depth-integrated potential density profile (g) and Southern Hemisphere potential density at 850 m depth (h) for PI sequence at the end of equilibrium simulation (T-1)

Page 2828, line 15: As already mentioned above, I would compare the vegetation at T2 with vegetation at T0. At T1 the vegetation won't be in equilibrium yet.

Page 2830, line 6: I do not agree that the reconstructed biomes are similar to proxy reconstructions; they only get one or two locations right, mainly in Southeast Africa? Maybe a slight rewording here?

Answer: We implemented the suggestion and rewrote the statement.

Page 2831, line 22: you probably mean "less dense AAIW" and not "denser AAIW"? Also, I am not convinced that it is the NADW/AAIW seesaw that plays the major role in your simulations. Please double-check and change discussion accordingly.

Page 2831, line 11-13: isn't it the difference in densities between AAIW and NADW that is crucial? I am not sure if one needs to increase NADW densities?

Page 2831, lines 24-26: please do not draw conclusions on a potential mechanism without proving that this mechanism is at play.

Page 2832: lines 23-25: Again, please do not draw conclusions without proving them. You need to calculate freshwater budgets to prove this point (or, even better, introduce a colour tracer with the freshwater added to region B, so that you can track it).

Page 2834, lines 18-19: Did Weaver et al analyze this change in behaviour depending on CO_2 concentrations, and if so, does the same mechanism apply here?

Page 2834, line 25: Are the changes in Peru just one grid box? If this is the case, is that a solid result worth discussing?

Page 2836, line 16-18: this is a conclusion you cannot draw. By construction there are "seeds" of each PFT in every grid box. Nothing can therefore go "extinct". Nothing can "migrate" either, as vegetation will just pop up whenever the climatic conditions are right. This model is therefore ill-suited to test if plant species went extinct or migrated (in the sense to allow for slow propagation).

Answer: Since we changed the discussion section substantially (Sect. 4), many statements were withdrawn and rewritten. A few conclusions from our discussion section:

- The model shows that under glacial climate conditions the AMOC is less susceptible to recovery by adding freshwater in the Southern Ocean than under interglacial conditions. Under these conditions, NADW is less dense, AAIW is denser and the density difference between NADW and AAIW is larger than under interglacial climate conditions (all densities refer to the surface potential densities in the source regions).

- After recovery of the AMOC, the climate of the North Atlantic Ocean is warmer and wetter than that of the South Atlantic Ocean.
- The model shows that the regions of sub-tropical and equatorial North Africa are most sensitive to climate changes in the North Atlantic Ocean. The vegetation cover in those regions mostly increased due to increased precipitation over northern Africa.
- The results show that both locality and intensity of the vegetation response in northern Africa are different in the two recovery experiments.
- Biome reconstructions from our results indicate agreement with pollen records from western tropical Africa, southwest Europe and the Mediterranean.

Page 2837, line 7: Adding salt to the North Atlantic is not mimicking a reduction of iceberg calving. A reduction of iceberg calving would be the weakening of the positive freshwater perturbation.

Page 2837: lines 20-23: see above. You cannot draw this conclusion. The model is constructed to react that way.

Answer: We rewrote and withdrew the statement, see p. 20, lines 31-32 and p.21, lines 1-2.

Page 2849: Figure 5: Why is the Atlantic Ocean uniformly colder? I do not understand this? Did the atmospheric CO_2 change? Also why is the warming for the other plots concentrated along the African and European Coast? Where are your deepwater formation sites?

Answer: We withdrew and changed Fig. 5. The new figure (Fig. 6) shows differences between T2 and T0 for SST, SSS and precipitation. The withdrawn figure showed the differences between T1 and T0, which turned out to be confusing.

Page 2850: Figure 6: Can you please include western North America in these plots as these regions are discussed in the text?

Page 2852: Figure 8: it would be very helpful to add the symbols from Figure 1b into all the panels of this picture (smaller symbols than in 1b so that one can still see the model result). Also, I find it surprising that there is no change in vegetation between H1 and H1-EXT, the two plots look almost identical. If true, it means that the strength of the NADW has no effect on vegetation under BA boundary conditions? And if that is true, the main conclusion/focus of this paper should probably be re-written.

Answer:

- We put symbols in panel d of Fig. 9, in which we compare the model results and the pollen records. Similarity between model results and data is denoted by blue circles, while any discrepancy is denoted by red circles (see Fig. 9).
- Our results showed that the effect of the abrupt warming leading up to a BA-like climate is indeed quite small. Nonetheless, there are differences in biomes between H1 and H1_EXT, mainly in the coverage over northern Africa; the forests in H1_EXT have a slightly wider extension than in H1, probably due to wetter climate conditions in the H1_EXT sequence.

Technical comments

Page 2821, line 22: Ganopolsky and Rahmstorf do not reduce the meltwater flux, they add salt (negative meltwater flux in their Fig 5).

Page 2824, line 5: the PI simulation should be called "preindustrial" and not "present day" simulation throughout the text. (E.g. 2825, 7 etc)

Page 2824, line 10: HE1 was probably closer to 500 years long. Although I agree that this does not really matter, as these are sensitivity studies.

Page 2825, line 17: Please do not call the increase of 1Sv (from 1Sv to 2Sv) an "increase" in AMOC. In both cases the AMOC is collapsed.

Page 2827, line 2: "a small change of" should read "a small change in"

Page 2829, line 18: Wording: "before and after the AMOC recovery"; would mean "AMOC off and AMOC recovered" although I think you mean "before H1 and after the AMOC recovery".

Page 2831, line 16: see above – I would not call the increase of 1 Sv "intensifies".

Page 2832: line 14: "atmosphere-ocean general circulation": please add the word "model".

Page 2833, line 11: Atlantic with only one "l".

Page 2833, line 24: one of the first publications with a coupled model that analyzed feedbacks between ice sheet mass balance and overturning is probably Meissner and Gerdes (2003).

Page 2834, lines 12-15: Where did Weaver et al add this freshwater flux?

Page 2834, line 22: How can the warm climate be caused by changes in tropical precipitation and vegetation?

Page 2845, Figure Caption 1 a: please change "discharge" to "forcing". Discharge is usually used in the context of river discharge.

Page 2847, Figure Caption 3: please add that these are Atlantic only plots (same for Figure 4).

Answer: We included the technical corrections, rephrased the sentences and figure captions where necessary, and updated the figures accordingly.