

**Author response to interactive comment on
“Role of CO₂ and Southern Ocean winds in glacial abrupt climate change”
by R. Banderas, J. Álvarez-Solas and M. Montoya**

Anonymous Referee #2

The authors thank the referee for the time devoted to review the manuscript and for his/her useful and constructive comments. All the points cited by the referee were carefully considered and the article has substantially benefited from the changes proposed. Each point arisen by the referee has been highlighted in blue and precedes the corresponding response of the authors. Changes in the manuscript have been highlighted here in italics below each point.

If I understand this paper correctly, it uses a coupled model simulation to argue that gradual (millennial-scale) increases in CO₂ concentration or wind strength during glacial conditions can lead to an abrupt (centennial scale) climate change. In this climate change, the Nordic Sea became warmer and saltier and the deep Atlantic overturning (AMOC) becomes much stronger. This is a very interesting result, but there are several puzzling aspects which I believe the authors must clarify before publication. I list these in “Specific Comments” below. I expect that once these clarifications are made, the paper should be a good contribution to CP.

Specific Comments

1. Roughly doubling of CO₂ from current conditions is predicted to make the high latitude North Atlantic warmer and fresher, with a moderate decrease in AMOC strength (see AR4 IPCC report Working Group I). It seems strange that under glacial conditions, a 10% increase CO₂ would make northern North Atlantic saltier and make a big increase in AMOC. Why the opposite behavior during current and glacial conditions?

We understand that our response to CO₂ might seem puzzling given the results of future projections which suggest warmer and fresher conditions in the North Atlantic leading to a moderate decrease in the AMOC strength. This apparent contradiction was already assessed by Knorr and Lohmann (2007) who found that, starting from glacial conditions, slowly varying background climate conditions in the Southern Ocean, as well as globally, are able to trigger rapid climate change. In our case a reduction in freshwater fluxes is found in response to enhanced CO₂ mainly through sea-ice changes at its margins. Because the CO₂ change is small, the response of atmospheric freshwater fluxes is minor. However, the reduction in sea-ice allows for a non-linear response of the system. Thus, we think background climatic conditions play a vital role in leading the system to critical stability properties which eventually govern its behaviour in agreement with Weaver et al. (2007). We have tried to clarify this in the Conclusions as follows:

Our results support those of Knorr and Lohmann (2003, 2007), who found that, starting from glacial conditions, slowly varying background climate conditions in the Southern Ocean, as well as globally, are able to trigger rapid climate change. Note that in our case global warming was achieved by incorporating increasing atmospheric CO₂ levels rather than prescribing gradually warmer conditions as in Knorr and Lohmann (2007). This result might seem contradictory with future projections, which suggest an increase in atmospheric CO₂ levels leads to North Atlantic warming and freshening, both of which weaken NADW formation. The question as to how abrupt climate change can be promoted in a context of global warming was investigated by Knorr and Lohmann (2007), who specifically assessed this issue in the context of deglaciation, which involves surface warming and freshening associated to melting ice sheets. In that case the mechanism responsible for the transition was found to be the preconditioning by an increase in ventilation of the warm subsurface water in the northern North Atlantic which resulted in an increase in the meridional transport of salt to the northern high latitudes leading to a resumption of convection and a rapid intensification of the AMOC. In our case a reduction in freshwater fluxes is found in response to enhanced CO₂ mainly through sea-ice changes at its margins. Because the CO₂ change is small, the response of atmospheric freshwater fluxes is minor. However, the reduction in sea-ice allows for a non-linear response of the system. Thus, in our view, the background climate, and particularly the North Atlantic sea-ice configuration, plays an important role in setting the climate sensitivity and its stability properties. This view is supported by Weaver et al. (2007) who found that the North Atlantic sea-ice distribution of the initial mean climate determines the amplitude of the thermal response as well as the sign of the freshwater flux forcing associated with increasing greenhouse gases. For cold climates, freshwater flux forcing acted to reduce the transient AMOC decrease whereas for warmer climates it reinforced the transient AMOC decrease.

2. There is not a clear discussion of the mechanism for the AMOC to strengthen (more than double). If a previously ice-covered Nordic Sea becomes ice free, doesn't this just change the location of the deep water formation (DWF)? That doesn't necessarily change the density of the DWF site or the AMOC strength. If the density in the DWF region increases relative to the density in the Southern Ocean, that might have a major effect in strengthening the flow. But then the density comparison should be between the previous DWF location (further south) and the new DWF location. In today's climate, high latitudes have large freshwater sources and lower latitudes are closer to subtropical evaporation, so higher latitudes typically are saltier than lower latitudes. I don't know what it was like during the ice ages but I would expect the new higher latitude DWF site should be fresher than the old lower latitude DWF. Apparently it isn't...why? This should be addressed by the paper.

The referee is right about the fact that changing the location of DWF does not necessarily translate into an AMOC intensification. However, in all three experiments, following the onset of convection in the Nordic seas an important density increase takes place in this region. In contrast, no significant density changes are observed in southern latitudes in the CO₂-only experiment. This leads to an intensification in the meridional density gradient which translates into an AMOC strengthening (Fig. R1). This is mentioned in Section 3, (*Stadial to interstadial transition*):

The onset of convection in the Nordic seas is also accompanied by a significant increase in the meridional density gradient which eventually leads to a strong AMOC strengthening.

Under wind-only forcing conditions, both the meridional density gradient and the AMOC are enhanced once the forcing is switched on. As discussed in the manuscript (Section 3, *Stadial to interstadial transition*), this is partly due to a reduction of density of Antarctic Intermediate Water (AAIW) in response to increased Southern Ocean winds:

This results in stronger outcropping of isopycnals in the Southern Ocean, and thereby a reduction of the density of Antarctic Intermediate Water (AAIW, not shown) which translates into an increase of the Atlantic outflow (Schewe and Levermann, 2010) by nearly 2 Sv (Fig. 6a).

[...]

The resulting salinity anomalies and the enhanced density gradient between both hemispheres are considered to be the precursors of NADW formation recovery and the AMOC reactivation, respectively, leading to the interstadial state.

The reason why the increase in density in the North Atlantic takes place despite the fact that the new convection sites are located further north, thus possibly in a fresher location, is related to the second point addressed by the referee. Surface salinity in the Nordic seas increases due to a reduction in sea-ice export into this region. This progressively favours vertical mixing in the area (Fig. R2) which eventually translates into bringing deep saltier water upwards sustaining convection and contributing to cool down the water column (Fig. R3). Together with the contribution of a more vigorous overturning to northward salinity transport this translates into a denser DWF site relative to the previous one located further south. We have decided not to include this in the paper because the prevalent paradigm of stadial to interstadial transitions during the last glacial period consists of a prominent AMOC intensification together with a northward shift of DWF sites which are successfully captured in our results.

3. I found the discussion of the Nordic Sea salt budget hard to follow.

We have rewritten this paragraph in order to clarify these issues in section 3, *Stadial to interstadial transition*:

The ultimate causes of the northern summer surface freshwater flux change have been unravelled through a detailed analysis of its balance (precipitation, evaporation and sea-ice changes) over the Nordic Seas region (Fig. 3a, black box) at the transition and stadial states (Table 1). The net northern summer surface freshwater flux in the area is found to be reduced by 0.59 m yr⁻¹ (25%) relative to the stadial state. This is partly due to a reduction in precipitation minus evaporation by 0.06 Sv, but mostly due to a reduction in sea ice melting by 0.53 m yr⁻¹. Although rising temperatures due to increased CO₂ levels result in local widespread freshening, a northward shift of the northern summer polar front takes place north of the Fennoscandian coast (Fig. 5a). As a consequence, sea-ice export into this region, and thus melting there, is strongly reduced, counteracting the effect of sea-ice melting, and resulting in local net negative freshwater flux anomalies.

[...]

Increased North Atlantic SATs related to enhanced northward heat transport driven by the AMOC result in melting of the Nordic sea-ice cover. The summer sea-ice polar front retreats to the north, which translates into reduced freshwater fluxes and thereby increased surface salinity in critical convective areas in the North Atlantic. Again, sea-ice changes related to surface salinity increase dominate freshwater flux balance over this area (Table 1). In this case the reduction in freshwater flux over the Fennoscandian coast is of 0.53 m yr^{-1} , of which 0.47 m yr^{-1} ($\sim 90\%$) are due to the sea-ice reduction and, again, only 0.06 Sv to a reduction in precipitation minus evaporation. The resulting salinity anomalies and the enhanced density gradient between both hemispheres are considered to be the precursors of NADW formation recovery and the AMOC reactivation, respectively, leading to the interstadial state.

4. The Conclusions refer to the model being configured "so that the system resides close to a threshold associated with drastic changes". How was this chosen? Do the authors have any more information about the characteristics or location in parameter space of this threshold?

Montoya and Levermann (2008) investigated the sensitivity of the glacial AMOC to wind-stress strength by integrating the CLIMBER-3 α model to equilibrium with the Trenberth et al. (1989) surface wind-stress climatology multiplied globally by varying factors $\alpha \in [0.5, 2]$. At $\alpha = \alpha_c \equiv 1.7$ a threshold, associated with a drastic AMOC increase of more than 10 Sv and a northward shift of NADW formation north of the Greenland-Iceland Scotland (GIS) ridge, was found. We hypothesise herein that the glacial AMOC is close to this threshold. This issue is explained in the experimental setup.

Technical Corrections

- a. Abstract and/or Introduction should briefly define what is meant by "abrupt".

Here, abrupt means "large and rapid", as exemplified by D/O events. We have explicitly mentioned this in the Introduction:

These are considered to be the most abrupt, i.e., large and rapid, climate changes of the past 110 kyr, repeatedly manifested as warming in Greenland by more than 10 K on decadal timescales (e.g., Lang et al., 1999) with widespread global climatic effects.

- b. Ocean model is rather coarse resolution for the complex topography of the Nordic Sea, Greenland-Iceland-Scotland Ridge, etc., and the atmospheric model is even more coarse and does not contain complete dynamics. It would be helpful to comment on how this might influence the model results.

The dynamic scheme included in the atmospheric component of the model is relatively simplified and its resolution even in the ocean too coarse to fully capture the complex topography of the Nordic Seas, which is involved in DWF processes relevant to the mechanism described. Nevertheless, we note that, up to now, abrupt climate change studies have been generally carried out with even more simplified EMICs. Interestingly, our results could be reassessed with more comprehensive models in the future when these are computationally affordable. We have included these caveats in the Conclusions:

Yet, up to now glacial abrupt climate change has almost exclusively been investigated from a modelling perspective using intermediate or simpler complexity models. Interestingly, it would be desirable to reassess our results with more comprehensive models in the future when these are computationally affordable.

- c. In graphs (especially Figs 1, 4 and 6), it would be helpful to extend a grid throughout the graph (based on tick marks) to make it easier to read quantitative information from the graph.

A grid has been included in Figs. 1, 4 and 6.

Finally, we would like to mention that we have received a comment by Dr. Gregor Knorr suggesting some clarifications. Knorr and Lohmann (2007) does not restrict slowly varying background climate changes to the Southern Ocean. In the deglacial scenarios of Knorr and Lohmann (2007) they applied gradual background climate changes from glacial to interglacial conditions at a global scale, e.g. including global temperature changes (therein CO₂) and wind stress changes. The Introduction has been modified to properly take into account this previous study.

Enhanced surface freshwater fluxes (Weaver et al., 2003) and slowly varying background climate conditions in the Southern Ocean (Knorr and Lohmann, 2003) have been shown to be able to trigger an AMOC intensification leading to an abrupt warming in the North Atlantic. The same result was found when applying gradual background climate changes from glacial to interglacial climate conditions on a global scale, including temperature and wind-stress (Knorr and Lohmann, 2007). [...] Taken together, these results led Knorr and Lohmann (2007) to suggest CO₂ increases could have contributed to rapid AMOC intensification after Heinrich events, corresponding with the largest DO events.

References

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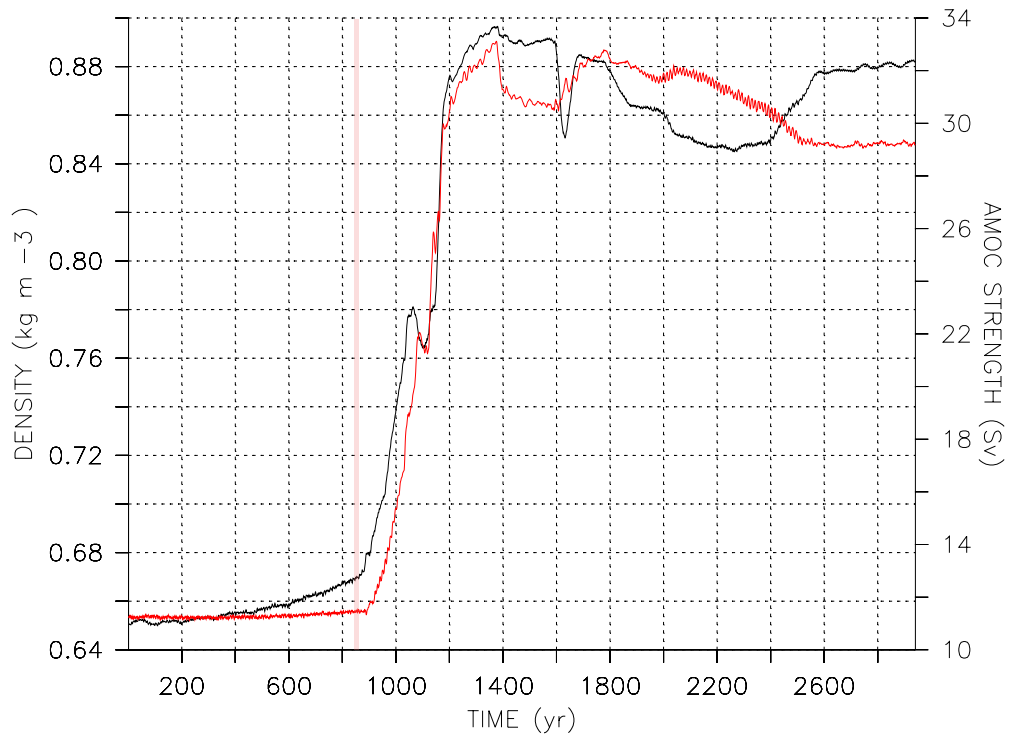


Fig. R. 1: Estimation of the meridional density gradient in Kg m^{-3} calculated as the density difference between the North Atlantic ($35^{\circ}\text{N}-80^{\circ}\text{N}$, $60^{\circ}\text{W}-10^{\circ}\text{E}$) and the South Atlantic (40°S , $60^{\circ}\text{W}-10^{\circ}\text{E}$) at 750 m depth (black line) and AMOC strength in Sv (red line), for the CO_2 -only experiment. The red shaded bar indicates the CO_2 -only transition stage.

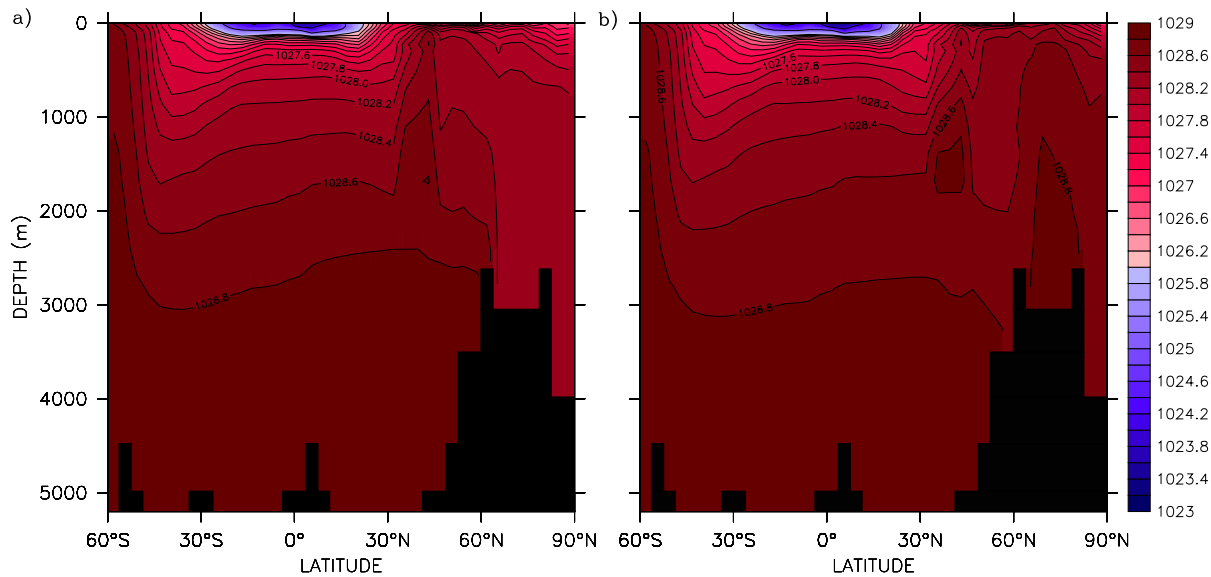


Fig. R. 2: Zonally average density in the Atlantic basin within the CO_2 -only forcing scenario in Kg m^{-3} for: a) the stadal state and b) the post-transition state.

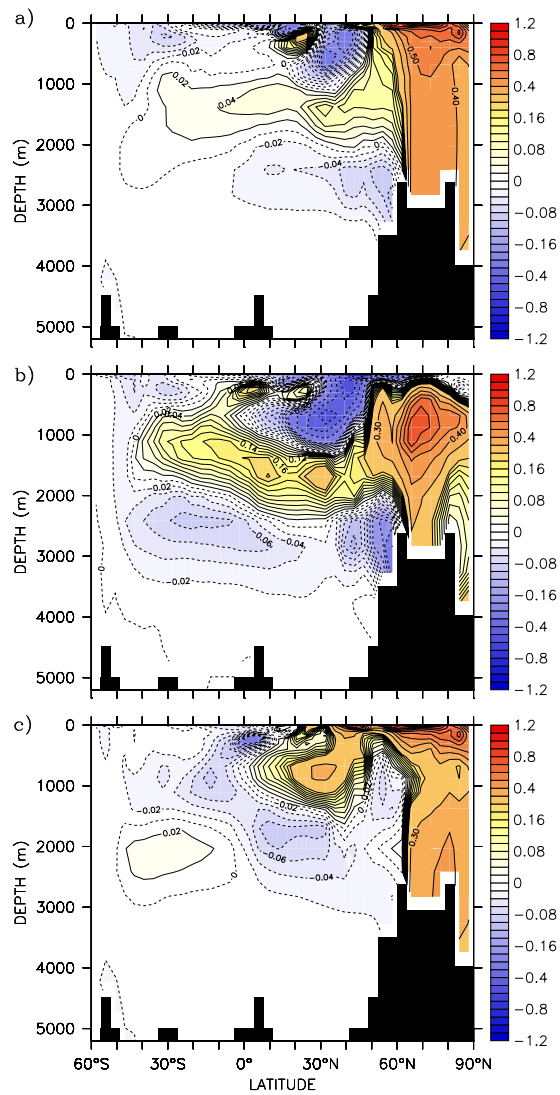


Fig. R. 3: a) Zonally averaged Atlantic density anomalies following the onset of convection in the Nordic Seas relative to the stadial regime for the CO₂-only experiment and contribution to the latter by b) temperature and c) salinity in Kg m⁻³ assuming a linear equation of state.