Response to Reviewer #2

We would like to thank again the reviewer for his second round of comments on our paper and provide a response to the comments in blue below.

Summary

This is my second review of the paper by Willeit and others. In the revised manuscript, the authors have expanded the Introduction by adding relevant previous studies exploring the potential causes of the occurrence of DO cycles at mid glacial period. The authors have also included the theoretical background of the new index M in the appendix and added a new discussion on the potential role of the noise in causing different shapes of DO-like variabilities simulated by different coupled models.

I think the authors have done a nice work in addressing my concerns that I raised in the first review. While I have some small comments and suggestions, I think that the M can be a good index to inform the possibility of the AMOC instability for other models, which are trying to simulate intrinsic variations in the AMOC similar to DO cycles. I would like to thank the authors for their effort in the revision and would be happy to recommend the manuscript for publication after minor corrections.

Minor comments

1. Implication of the areal integration of the buoyancy flux
The impact of sea ice transport and the related salinity changes within the North Atlantic-Arctic domain on the M and the stability of AMOC is still a bit vague to me. For example, Born et al. (2010) showed that a decrease in net radiative forcing over the Arctic modified the transports of sea ice and salinity within the domain and caused a weakening of the ocean convection and AMOC. In this case, although the net Fw within the domain is zero, AMOC weakened and approached destabilization. Of course, I know the authors do not focus on the strength of AMOC, but as shown in Figure 10, there is a strong relationship between AMOC strength and M, making it difficult to separate the two. Therefore, I am concerned that sea ice transport within the domain may alter the relationship between M and AMOC (for example, even if M is non-zero and has a negative value, AMOC could still destabilize depending on the sea ice and salt transport within the domain). Obviously, the magnitude of this effect should largely depend on models, and as the authors suggest, in the case of the 35m sea ice simulated in Vettoretti's model, the impact could be quite substantial, while in other models, the impact might be smaller. However, I feel that this is a good point to make in the discussion. Just adding some words or a sentence on L286-287 or wherever appropriate would be sufficient.

In our paper we discuss extensively the strong interaction between AMOC and sea ice, although the most important aspect of this interaction is the control of sea ice extent by the northward heat transport of the AMOC. We do not fully understand why the reviewer thinks that sea ice transport (which is of course included in our model) could invalidate the relationship between the integrated buoyancy flux *M* and the stability of deep water formation in the North Atlantic. Actually, one of the main strengths of our "theory" is that we suggest that redistributions of freshwater within the domain north of 55°N are

irrelevant, and this includes sea ice transport.
The reviewer cites the work of Born et al. (2010) as an example. However, what Born et al. found is that under the Eemian (126 ka) orbital configuration, a new deep convection site (in addition to two others) appeared south of Greenland (and south of 55°N, i.e. outside our domain) that does not exist under pre-industrial and 116 ka conditions. Born et al. explained the appearance of this convection site by a reduction in sea ice transport through the Denmark Strait at 126 ka compared to 116 ka. However, the changes in convection locations in their study occurred for changes in orbital configuration, that probably have significant effects on buoyancy through changes in surface temperature, AMOC heat transport and possibly also the precipitation-evaporation balance, in addition to sea ice transport changes.
In any case, we have clearly outlined the assumptions entering the derivation of our stability criterion in the main text and in the Appendix, and our "theory" can only be challenged by explicitly calculating *M* with other models and demonstrating that in other models this criterion does not explain the convective (in)stability of the AMOC.

To make this clearer we added the following sentence to the discussion section:
'Ultimately, estimations of M and its relation with convection and AMOC in other models will be needed to assess the robustness of our instability criterion.'

L185: I had a difficulty understanding this sentence. Could you rephrase it?

We have rephrased it to:
'Under some conditions, e.g. for present day ice sheets and CO2 between 220 and 240 ppm, two modes of the AMOC corresponding to different convective patterns are stable for the same CO2 (Fig. 10a), but this is not a pre-requisite for the occurrence of internal oscillations.'

L377-385: Could you add a bit more explanation of why $\Psi 2$ ($S* - S2$) could be small and neglected? In the same paragraph, it says S2 is significantly lower than S*, which means that (S*-S2) could be quite large.

The value S2 in our conceptual model is indeed "significantly lower" than 35 psu (it is at present about 33 psu). However, what is crucial for our theory is whether the following assumption is valid under glacial conditions: "2) Most of the net freshwater flux entering the North Atlantic/Arctic domain is mixed downward in the deep convection areas and then transported away by oceanic currents below the surface layer". Since under glacial conditions both the Bering Strait and the passage between Canada and Greenland were closed, and the only escape route was through the Denmark Strait, we believe that this assumption is a reasonable one and this is confirmed by the results of our model simulations.
We have added the following to make this clearer:
' In our model this flux is small (generally <0.01 Sv) and can be neglected'.

Fig. 12: Love this figure!