Response to Reviewer #2:

We respond to the referee's comments in blue font below.

This is a study that aims to improve the understanding of the climate of Marine Isotope Stage 3 (MIS3) when the millennial-time scale climate variability occurred most frequently during the last glacial period. The authors perform simulations of MIS3 with a comprehensive state-of-the-art climate model and compare the climate and the oceanic circulation, especially the Atlantic Meridional Overturning Circulation (AMOC) with those of the Preindustrial (PI) and the Last Glacial Maximum (LGM). The authors further show the sensitivity of the MIS3 climate and the AMOC to modifications in the boundary conditions, such as the Laurentide ice sheet and CO2. The model does not exhibit a threshold-type behaviour of the AMOC under low Laurentide ice sheet and low CO2 level. This is interesting, and it offers the community a chance to improve our understanding of the AMOC and discrepancies among models. This paper should be published because of two reasons. First, it produces important information of the climate of MIS3, which is still rare compared to that of the LGM. Second, it assesses the sensitivity of the MIS3 climate to modifications in the boundary conditions, which is unique compared to previous studies assessing the sensitivity under the PI and the LGM conditions. Nevertheless, I also feel that the important points of this study are still unclear and the manuscript is too long. Below are some suggestions to improve the manuscript.

We thank the reviewer for his/her thorough assessment and constructive comments on our manuscript. We respond to the reviewer's general and specific comments below point by point.

—General comments—

1. The author should focus more on the results of the sensitivity experiments and perform more analysis in these experiments, since they are the most important and interesting point of this study. In particular, what happens to surface salinity and density over the North Atlantic Deep Water (NADW) formation region and Antarctic bottom water

formation (AABW) region when the Laurentide ice sheet and CO2 are modified? Since previous studies have shown that changes in surface salinity and density are very important in understanding the changes in the strength and the threshold of the AMOC (e.g. Montoya and Levermann 2008, Oka et al. 2012, Sun et al. 2016, Buizert and Schmittner 2015, Sherriff-Tadano et al. 2018, Klockmann et al. 2018, Galbraith and de Lavergne 2018), analysis on this point is very important. This analysis will also give very useful information in comparing the results of your model with other climate models. Further analysis on the depth of the AMOC, as well as sea ice cover over the North Atlantic and Southern Ocean should be conducted (e.g. Klockmann et al. 2016, Kawamura et. 2017, Galbraith and de Lavergne 2018).

> We agree with the reviewer that the sensitivity experiments related to external forcing should be of high interest to many. However, in this work, we would prefer not to weigh the sensitivity experiments over the results of the MIS3 control simulation. There is a rich literature on LGM simulations, whereas there are few MIS3 simulations with a state-of-the-art climate model. Besides, most of the previous studies on AMOC bi-stability/abrupt climate change in the last glacial are configured with boundary conditions of either LGM or PI, thereby with a deviation/bias already in the control experiment. We therefore believe that a comprehensive assessment of the simulated MIS3 climate would be necessary and could serve as a useful reference and basis for dedicated, future MIS3 simulation studies with the same model that focus on climate sensitivity. However, we agree with the reviewer that the original manuscript can be more compact, and we have accordingly moved certain results to the supplementary material (see our response to the next comment).

In addition, in response to the reviewer's suggestion on more detailed analysis of the sensitivity experiments, we have added a section in the supplementary material showing the response of SSS, winter sea ice, and AMOC in depth-latitude space. As we have mentioned in the first draft of manuscript, NorESM is in a relatively stable state and stays far away from the threshold for state transitions; as a consequence, the

response of the climate system in the sensitivity experiments are relatively small, as reflected in the changes of metrics mentioned above. Specifically, as the changes in e.g. SSS, sea ice, and AMOC geometry are highly related to the strength of AMOC, which is only weakly reduced in the sensitivity experiments; therefore, significant changes in SSS, sea ice, and AMOC geometry etc. would not be expected. We have also added some discussions in the manuscript.

2. The manuscript is too descriptive and long, which makes the reader difficult to understand the important message of this study. In particular, sections 3.1, 3.2, and 4 are too descriptive. I do understand that these sections show important results, however, they do not give new results and rather follows several previous studies. Unless you compare these simulation results with proxies and other climate models in detail, you should move some part of this section to the Supplementary section. This will help shorten the manuscript.

> As also mentioned in our response to the previous comment, we have moved quite a bit of results in sections 3.1, 3.2, and 4 to the supplementary material; these include the time series of sea ice, several atmospheric diagnosis, the whole section of "Modes of variability", and the discussion on the "stadial" experiment. We believe that the results are presented in a more succinct manner in the updated manuscript.

—Specific comments—
1 Introduction
The authors should state the significance of this study compared to previous studies more clearly in the last three paragraphs. These points are vague in the manuscript. I understand that the simulation of MIS3 is important since most previous studies conducted simulations of the LGM when they explore the glacial climate. However, in the manuscript, the significance of this study compared to previous MIS3 modelling studies is vague. This point should be clarified.

> Following the reviewer' comment, we have rephrased the text in Introduction to highlight the significance of our study.

2 Methods
P4 L30-32: I couldn't quite understand this sentence. Do you just mean that the shape of the ice sheet is prescribed in the model?

> Yes, exactly; we have clarified this in the updated manuscript: "NorESM1-F does not have a dynamic land ice component, and the assumed ice sheet extent and elevation during MIS3 compared to present day are prescribed."

P5 L10: MSI3 → MIS3 3 Results

> corrected.

3.1 Model spin-up
I agree that the model has almost reached a quasi-equilibrium state. However, I feel that this section is too long, which makes the reader tired. Please consider reducing the amount of this section. (See also Comment 2).

> Following the reviewer' suggestion, we have moved the text/discussion on sea ice to the supplementary material. We think that the rest of metrics are important for the evaluation of model drift, and therefore would prefer to keep them.

P7 L11: Where is the location of the open ocean convection over the Southern Ocean in the MIS3 experiment?

> In the Weddell Sea region and the Pacific and Indian sectors of the Southern Ocean. We have included a figure of austral winter mixed layer depth in the supplementary material.

3.2 Simulated MIS3 climate
This section is too descriptive and long. Please consider reducing the amount of this section by moving some part of it to the Supplementary. (See also Comment 2).

> We have done so. Please see our response to the reviewer's general comment 2.

P7 L33-P8 L1: The strengthening of the surface easterly wind stress over the Irminger Sea is also caused by the expansion of the Laurentide ice sheet (Sherriff-Tadano et al. 2018).

> yes, good point; reference cited.

P8 L30-P9 L3: Please mention that the lowering of CO2 is important in causing the expansion of sea ice and in decreasing the sea surface temperature.

> We have added the following to the beginning of the subsection: "The reduced level of CO_2 during MIS3 is important in lowering SST and in causing the expansion of sea ice."

P9 L27: You may remove the first sentence, which is already mentioned in the Introduction.

> sentence removed.

P9L30-L31: Did you try to say 'The deeper overturning stream function is associated with contracted and weakened AABW'?

> The original statement is a bit misleading; we have rephrased it as "The lower overturning cell associated with AABW is contracted and weakened."

P10L21-L25: Kobayashi et al. (2015) also report similar response in their LGM simulation. The decrease in ideal age of the water is attributed to enhanced open ocean convections over the Southern Ocean. You may cite this paper as well.

> We thank the reviewer for the suggestion of this study. We have referred to this paper in the revised manuscript: "Kobayashi et al. (2015)

reported similar response of LGM water mass age in the Southern Ocean owing to enhanced open ocean convections."

P11L18-L20: Merkal et al. (2010) also shows similar results in their MIS3 insterstiadial simulation. You may cite this study as well.
P11L32-L33: Is this difference statistically significant?
P12L2-L3: Is this difference statistically significant?

> The study by Merkel et al. (2010) is very relevant and has been cited. Following the reviewer's second general comment, we have moved the section of ENSO/NAM to the supplementary material.

4 MIS3 simulation forced by stadial conditions Please consider reducing the amount of this section by moving some part of it to the Supplementary. (See also Comment 2).

> We have done so. Please see our response to the reviewer's general comment 2.

5 Discussion
5.1 Simulated AMOC in MIS3
P13L13: I rather use 'bottom water formation' than 'open ocean convection'.

> modified.

P13L26-L30: As far as I know, Montoya and Levermann (2008) first showed the potential role of surface winds over the North Atlantic in intensifying the AMOC, Oka et al. (2012) showed that the LGM surface wind enhanced the AMOC with one model, Muglia and Schmittner (2015) confirmed the study of Oka et al. (2012) by performing analysis with PMIP3 climate models, and Sherriff-Tadano et al. (2018) investigated the processes by which surface winds anomaly induced by the ice sheets enhanced the AMOC. These studies should also be cited in this sentence.

> We thank the reviewer for pointing to a detailed list of very relevant references. We have cited them in the updated manuscript.

P13L31: Hu et al. (2015) investigated the impact of the closure of Bering Strait on the AMOC. This study should also be cited in this sentence.

> added; this reference is indeed very relevant.

5.2 MIS3 sensitivity to CO2 and ice sheet size
Results presented in this section are really interesting! As mentioned in Comment 1, I strongly encourage the authors to perform more analysis on these sensitivity experiments (surface salinity, density and sea ice cover over the NADW and AABW formation region, and the depth of the AMOC). Based on these analysis, you may further discuss the possible cause of differences among previous modelling studies. (Also, if possible, it may be interesting to discuss changes in surface air temperature and precipitation in the half-size Laurentide ice sheet. This analysis can provide an uncertainty of the simulated temperature and precipitation anomalies arising from the uncertainty in the shape of the MIS3 ice sheet. Just a suggestion.)

> Please see our response to the reviewer' general comment 1 regarding further analysis on the sensitivity experiments.

Discussion on the changes in temperature/precipitation in the modified ice sheet experiments would definitely be interesting to certain readership, as the reviewer suggested. Meanwhile, we would prefer to keep our focus on the AMOC bi-stability in this section and illustrate the relative insensitivity of NorESM MIS3 climate to external forcing. We would therefore not include this discussion in the manuscript, but rather leave it for future studies or for model intercomparison activities.

P15L13: What do you mean by ‘ice inhibiting convection’?

> We mean "... Norwegian Sea are covered by sea ice that inhibits convection through its insulating effect."

Figures

Fig.2: Can you put labels on the contours?

> Yes, we have put labels on the contour lines 1000 m and 2000 m.

Fig.11: Can you add a figure showing the anomaly? It's difficult to understand the difference between MIS3 and PI from these figures.

> We tried to plot an anomaly map on the stream function, e.g. see the figure below. Comparing the two different ways of presenting, we think the original figure is relatively more straightforward and intuitive in comparing the stream functions during the two periods.

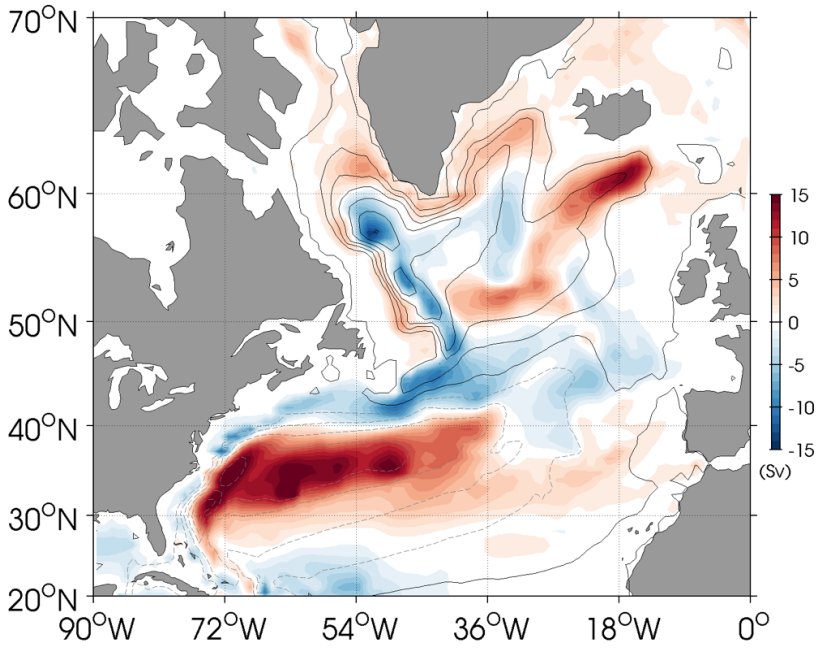

Figure above: MIS3 subtropical and subpolar gyre stream functions (Sv; contours) and difference with PI (Sv; shading)

References

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