Reply to Reviewer1

We are grateful to the reviewer for his time in evaluating the manuscript and his constructive comments and suggestions. As listed below, we have taken all the comments into account by the reviewer in the revised manuscript. In the following, our responses will be written in blue, while the comments by the reviewer will be written in black.

>L24-34: I suggest that the authors add a schematic figure illustrating the time evolution of certain climate variables from paleo records (e.g. summer insolation, CO2, sea level, d18O etc.) from last interglacial to the present day. This can provide a more clear context and would be especially beneficial to a wider audience.

We agree to the suggestion. We will add a figure illustrating the time evolution of summer insolation, CO2, sea level, Greenland ice core data, and AMOC in Fig.1 of the revised manuscript.

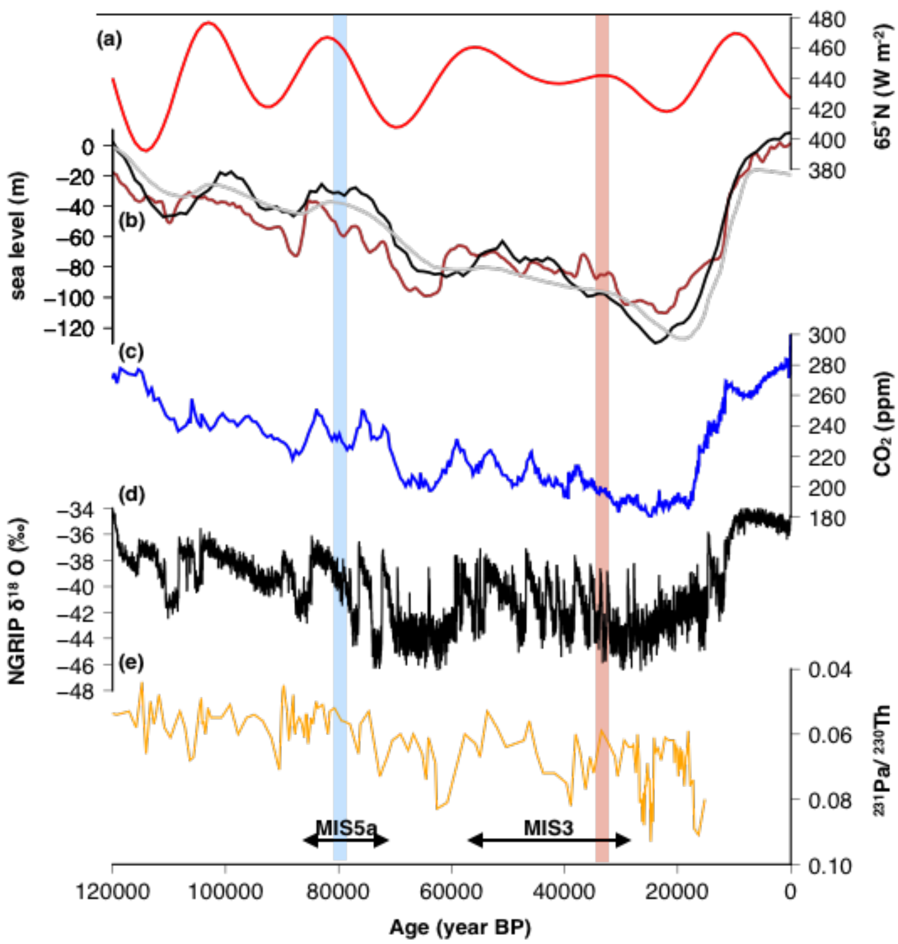

Figure 1: Time series of climate records of the last glacial period. (a) 65˚N July insolation (W m^{-2}), (b) black: sea level data from Spratt and Lisiecki (2016), brown: sea level data from Grant et al. (2012), gray: simulated time evolution of ice sheet (Abe-Ouchi et al. 2013), (c) CO_2 (Bereiter et al. 2015), (d) Greenland ice core delta 18 O from North Greenland Ice Core Project (NGRIP) core (Rasumussen et al. 2013). (e) Bermuda Rise $^{231}Pa/^{230}Th$ (Bohm et al. 2015), which is a proxy of the strength of the AMOC. Red and Blue shades correspond to the simulated period of MIS3 and MIS5a in our climate model simulations, respectively.

>section 2.1: Could the authors add a short paragraph briefly summarizing the performance of MIROC4m for the preindustrial and/or present day simulations, especially for the metrics that are relevant for the analysis later in the main text? Such metrics can include, but not limited to, sea ice concentration, mixed layer depth, ocean profiles/stratification in the North Atlantic. Climate sensitivity would be useful to mention as well. Any significant bias and therefore its implication for the conclusions drawn in this work should also be discussed where relevant.
Following the reviewer's suggestion, we will add a following paragraph in the method section in the revised manuscript.
"The model version used in this study reproduces the modern AMOC (Fig. 6d), the deepwater formation over the Nordic Seas (Fig. S1) and sea ice extent over the North Atlantic (Fig. 4) reasonably well as in the previous version (Otto-Bliesner et al. 2007, Weber et al. 2007, Kawamura et al. 2017). While the current model version overestimates sea ice extent and lacks deepwater formation over the Labrador Sea (Fig. S1, Fig. 4), the performance of the modern Southern Ocean sea ice extent has improved compared with the previous version (Fig. 4). This model version has also been used extensively for paleoclimate (Obase and Abe-Ouchi 2019) and future climate studies (Yamamoto et al. 2015). It has a climate sensitivity of 4.1 K and reproduces the AMOC of the LGM reasonably well (Sherriff-Tadano and Abe-Ouchi 2020)"

>L121: Did the authors perform any sensitivity experiment with regard to the opening/closing of the Bering Strait by any chance? If yes would be useful to briefly discuss it here. Some studies have shown how an opened/closed Bering Strait could have some significant impact on the North Atlantic ocean state.
As pointed out by the reviewer, the closure of the Bering Strait can have an impact on the AMOC. However, unfortunately, we have not performed sensitivity experiments closing the Bering Strait. Nevertheless, we will add a following sentence to the revised manuscript so that the readers can refer to the effect of Bering Strait on the AMOC in other studies.
"The global sea level is unchanged, and the land sea mask outside the northern glacial ice sheet region is same as the modern configuration (e.g., the Bering Strait remains open, which itself may impact on the AMOC (Hu et al. 2015))."

>L355-357: It is not immediately clear to me how do subsurface warming and southern ocean warming are able to re-strengthen the AMOC. The latter due to reduced production of AABW? How about subsurface warming? Please elaborate a bit more on the dynamic links here.
We removed the sentence associated with the subsurface warming since we agree that the accumulation of heat at the subsurface ocean over the North Atlantic does not cause a gradual recovery of the AMOC, but rather causes an abrupt strengthening by triggering a new deepwater formation. With respect to the Southern Ocean process, we will increase the explanation and also add some references, which show the effect of temperature changes over the Southern Ocean on the AMOC (Buizert and Schmittner 2015, Jansen 2017), to support our discussion. We also nuanced the paragraph since the original sentence looked too confident.
"With respect to the oceanic feedback, the weakening of the AMOC causes a warming over the Southern Ocean due to the reduction in the northward heat transport, and hence reduces the deep ocean stratification and the AABW (Fig. 11). These processes can contribute to re-strengthen the AMOC (Buizert and Schmittner 2015, Jansen 2017). "

>L358-359: Once again, it is not clear to me the link between the expanded sea ice and a weakening surface wind. My understanding is that a more extensive sea ice cover in the North Atlantic 'protects' the ocean surface from the wind stress above, which tends to spin down the ocean circulation, and is favorable for maintaining a weak AMOC.

As the reviewer says, the link between the expanded sea ice and a weakening of the surface wind was not clear in the original manuscript. In the revised manuscript, we increased the description on this topic as follows;

"With respect to the lack of atmospheric feedback, previous studies show that the expansion of sea ice causes a weakening of the surface wind over the North Atlantic by increasing the static stability of the lower troposphere (Byrkedal et al. 2006, Sherriff-Tadano and Abe-Ouchi 2020). They further show that this weakening of the surface wind plays a role in maintaining a weak AMOC by reducing the wind-driven transport of salt to the deepwater formation region (Zhang et al. 2014a, Sherriff-Tadano and Abe-Ouchi 2020)."

Also, as the reviewer pointed out, the extensive sea ice protects the ocean surface from the wind stress, and causes a weakening of the wind-driven ocean circulation. In fact, this feedback is taken into account in the model experiments (both the original and partially coupled) when the sea ice expands. However, if this feedback is dominant, one should expect a stable weak AMOC, rather than a gradual increase in the AMOC, which is observed in our partially coupled experiments (Fig. 10). This result suggests that other processes/feedback after the weakening of the AMOC is causing the gradual increase in the AMOC. From several previous studies presented above, we speculate that the lack of the sea ice-wind feedback can destabilize the weak AMOC and cause the gradual increase in the AMOC.

>L340-364: I appreciate the authors' efforts in explaining some of the interesting modelling results here. However, to me this part has a very limited contribution to the main points of the paper, and could be a distraction to the readers in this section. I think by removing it or moving it to supplementary material could help enhance the legibility of this section. It is up to the authors to decide though.

Following the reviewer's suggestion, we decided to move the first paragraph to the supplement to increase the eligibility of the section. Related to this, we moved Fig. 10c,d in the original manuscript to Fig. S3 in the revised manuscript because it is no longer discussed in the main manuscript. For the second paragraph, we decided to keep it in the main manuscript since we think this paragraph discusses important internal feedback within the atmosphere-ocean system, which can appear in the simple schematic figure.

>Fig. 11: this schematic is not adequately discussed/referred to in the main text. There are several places in the text (mainly in 'Discussion') where the relevant processes are described and should refer to this figure. In addition, the feedbacks indicated by the black solid arrows are not straightforward to me. Please consider elucidating it more explicitly in the main text or in the caption where appropriate.

In the revised manuscript, we will adequately refer to the schematic figure (Fig. 12 in the revised manuscript) in 4.2, 5, and 6. In addition, we increased the explanation of the feedbacks as described above. Also, in order to concentrate on our main finding, we decided to remove the black arrows of internal feedback from the revised Fig. 12. Nevertheless, we modified the caption so that the reader can refer to the main text for the discussion on the possible internal feedbacks.

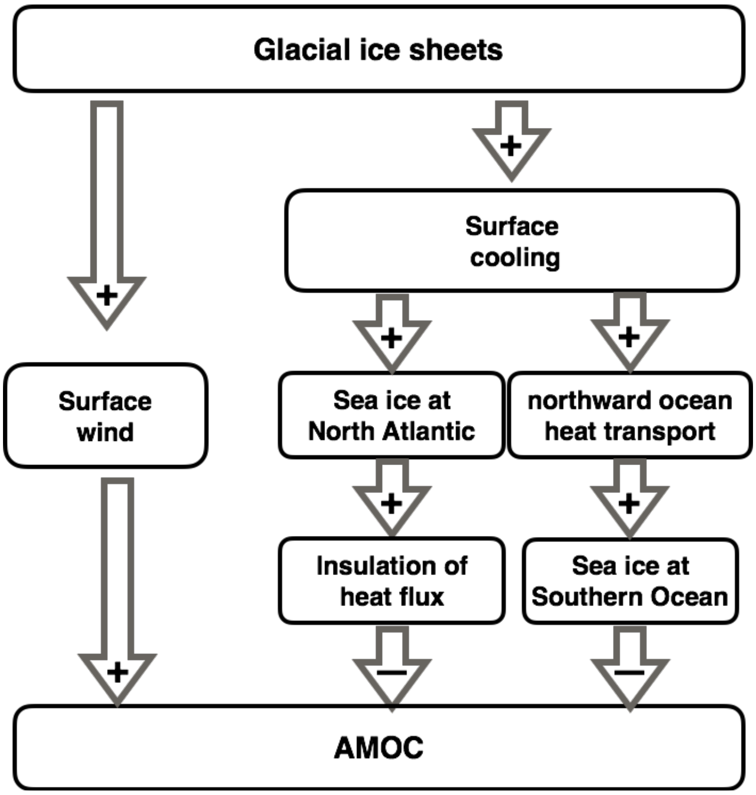

Figure 12: Simple schematic of the processes by which changes in the glacial ice sheet affect the AMOC. Possible internal feedbacks within the atmosphere-sea ice-ocean system are discussed in the Discussion section.

Minor and technical comments:
>title: I think that it is good practice to try to avoid abbreviations in the title (e.g. AMOC).
Corrected.

>L8: should spell out that it is about the expansion of ice sheet in North America.
Corrected.

>L10: it would be useful to mention the MIS3 and 5a time slices that the authors chose in this study, such that the readers can get a quick grasp by reading the abstract.
We will add the time slice in the revised manuscript as well as in the revised Fig. 1.

>L55-59: suggest to rephrase the sentence as ": : :, which can cause either a strengthening of the AMOC by : : :, or a weakening of the AMOC by: : :" This also applies to L246-248.
Corrected.

>L65: you mean "For" these two periods?
We meant that the ice sheet is considered to be slightly larger in MIS3 compared with MI5a.

>L71: ": : :, whose effect of surface cooling is prominent." This reads a bit ambiguous to me; please consider rephrasing it.
We will modify this sentence in the revised manuscript as follows;
":::, whose effect of the ice sheet extent and hence the surface cooling is prominent."

>L108-109: is it relevant to include the information in the square bracket? If not please consider removing it.
We think this sentence is important to avoid readers from getting confused when they look back to previous articles. Therefore, we will remain this sentence.

>L146-147: To my understanding, it should be stressed that surface heat flux cannot be imposed because it is strongly coupled to SST, whereas surface freshwater flux can because there is no direct SSS feedback to the flux.
As suggested by the reviewer, we modified the sentence as follows,
“Following previous studies (Schmittner et al. 2002, Gregory et al. 2005), the heat flux is unchanged in these experiments. This is because the heat flux is strongly coupled to the sea surface temperature and that fixing the surface heat condition has an unrealistic impact on the AMOC (Marozke 2012).”

>L168-170: I am a bit surprised the simulated LGM climate is only about 0.2 deg-C colder than the MIS3 climate, considering that there is a CO2 difference of 20 ppm plus some (supposedly moderate) difference in the distribution of ice sheet. Could the authors comment on this?
We were also surprised at the result when we saw it. One possible reason is the lower obliquity in this experiment compared with the LGM. Several previous studies have shown that the lower obliquity can cause an annual global cooling by increasing the sea ice in the Southern Ocean and Arctic regions, even though the global input of insolation does not differ. We added a following sentence on this point in the revised manuscript.
“The strong MIS3 cooling similar to that of LGM is possibly related to the low obliquity applied in MIS3, which increases the amount of sea ice in both hemispheres and causes a global cooling through feedbacks within the atmosphere-ocean coupled system (Galbraith and de Lavergne 2019).
“

>L184: perhaps the reference of Dokken et al. and Sadazki et al. in lines 193-194 can be moved here.
We added these reference in the sentence.

>L186: I find it a bit odd to say “the western part of the Southern Ocean”; suggest to change to, for example, Pacific/Indian/Atlantic Ocean sector of the Southern Ocean.
Corrected.

>L220: it is not clear from Fig. 4 that there is ‘stronger surface cooling’. I see a relatively homogenous distribution of ocean cooling in Fig 4(a,b). Is this the case or it has to do with the color bar?
As pointed out by the reviewer, the original sentence was misleading. We should have clearly mention that we are referring to Fig. 4c, which shows the effect of ice sheet on ocean temperature. We have modified this sentence as follows,
“This is associated with a cooling of the NADW (Fig. 4c), which is induced by the stronger surface cooling by the glacial ice sheets"
In Fig.4c, you can find a cooling of NADW, which is associated with the ice sheet expansion and hence the resulting stronger surface cooling.

>L222: “and increases the deep ocean salinity, : : :” error in grammar. Also, should spell out the increased deep ocean salinity is via brine rejection.
Corrected. Also added the explanation of brine rejection.

>L235: suggest to move “Fig. 7c,d” to the middle of L234.
Corrected.

>L261: change “are replaced with” to “replace with”?
As pointed out by the reviewer, this sentence was strange. We modified the sentence as follows. “In the third experiment (PC-MIS3heat), in which the monthly climatology of surface wind stress and atmospheric freshwater flux of MIS3 are replaced with those of MIS3-5aice"

>L265: “compensates”
Corrected.

>L269-271: “Due to : : : AMOC (Fig. 10b).” To me the main effect of sea ice in weakening the AMOC in the north Atlantic is because of its insulation that reduces air-sea flux and therefore ocean convection. The effect of melting of sea ice, if one can do a back-of-envelope calculation converting the melted sea ice into sverdrups, should be relatively small.
As the reviewer suggests, the expansion of sea ice weakens the AMOC by suppressing the atmosphere-ocean heat exchange (Oka et al. 2012). In addition, it has been shown that the increase in sea ice over the north North Atlantic can reduce the AMOC and the ocean convection via meltwater at the sea ice edge (Born et al. 2010). Following these previous studies, we will modify this sentence as follows;
“Due to this surface cooling, the sea ice increases over the northern North Atlantic (Fig. 11b). The increase in sea ice tends to weaken the oceanic convection and the AMOC by insulating the atmosphere-ocean heat flux (Oka et al. 2012) and by increasing the meltwater flux over the deep-water formation region and (Born et al. 2010). “

>L272: again, the more stable ocean column is not clear to me from Fig. 4c.
We will add a figure of vertical profile of ocean temperature in the Fig. S2, which shows that MIS3 exhibits more stable ocean column in terms of temperature compared with MIS3-5aice.

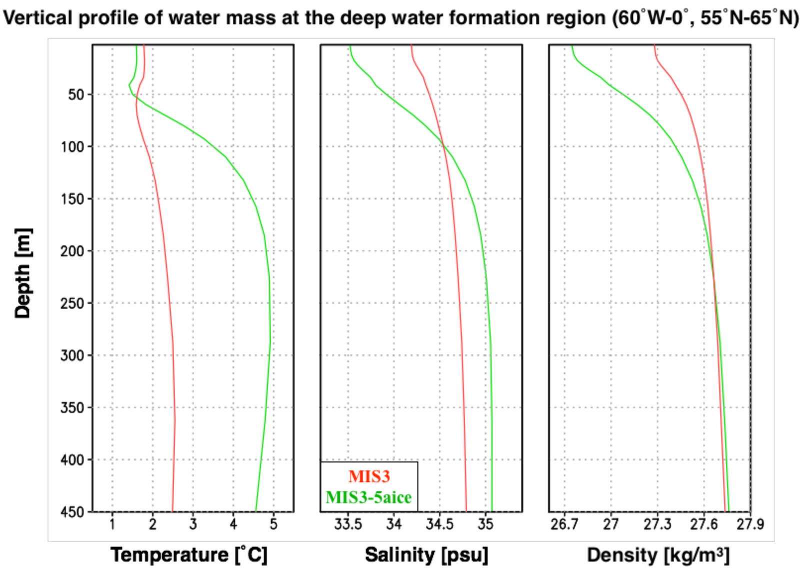

Figure S2: Vertical profile of oceanic properties at the North Atlantic Deep Water formation region (60˚W-0˚, 55˚N-65˚N). Red: MIS3 and Green: MIS3-5aice. Cold water occupies the subsurface ocean in MIS3 compared with MIS3-5aice. The climatology of the last 100 years is used to create these figures.

>L273: suggest to tone down “overcomes” to “tends to overcome”.
Corrected.

>L283: “The results above demonstrate: : :”?
Corrected.

>L303: there are two full stops.
Corrected. Thanks for pointing out.

>L303-307: this reads very speculative to me, if I understand the authors’ point correctly here. Please consider removing it or providing more evidence (it’s up to the authors to decide).
Indeed it is a speculative discussion, but we think this point is quite important, which the modelers should keep in mind. We will add a figure supporting this sentence in the supplementary file and keep this discussion in the revised manuscript.

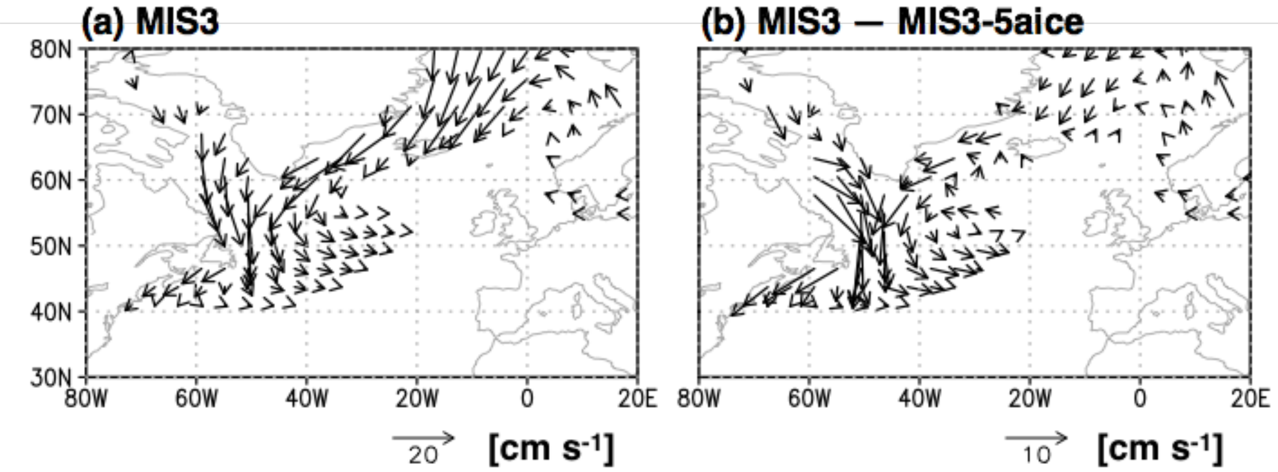

Figure S4: Spatial maps of annual mean sea ice velocity (arrow, cm s^{-1}) from AOGCM experiments. (a) MIS3 and (b) differences between MIS3 and MIS3-5aice. The results of the last 100 years are used.

>L329: ice sheet“-induced” cooling?
Corrected.

>L335: replace “deny” with “exclude”?
Corrected.

>L348: “resemble”?
Corrected. We moved this paragraph to the supplement to increase the eligibility of the section.

>Fig. 9: the color of “PC-MIS3-5aice” in the legend is not correct.
We will fix the legend and also modify the color of “PC-MIS3-5aice” as follows.

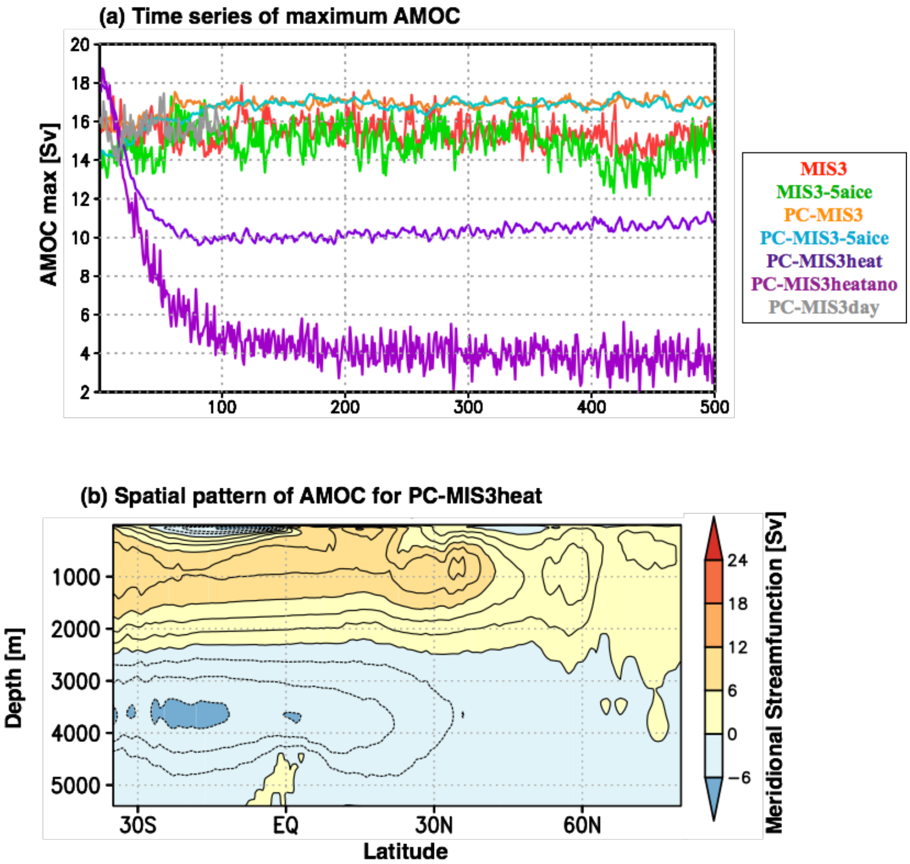

Figure 10: Results of partially coupled experiment conducted with the AOGCM. (a) Time series of the maximum strength of the AMOC. (b) Spatial pattern of the Atlantic meridional streamfunction calculated from PC-MIS3heat. The climatology of the last 100 years is used to create this figure.

New Reference

Born, A., Nisancioglu, K. H., and Braconnot, P.: Sea ice induced changes in ocean circulation during the Eemian, Climate Dynamics, 35, 1361-1371, 10.1007/s00382-009-0709-2, 2010.

Hu, A. X., Meehl, G. A., Han, W. Q., Otto-Bliestner, B., Abe-Ouchi, A., and Rosenbloom, N.: Effects of the Bering Strait closure on AMOC and global climate under different background climates, Progress in Oceanography, 132, 174-196, 10.1016/j.pocean.2014.02.004, 2015.

Otto-Bliesner, B. L., Hewitt, C. D., Marchitto, T. M., Brady, E., Abe-Ouchi, A., Crucifix, M., Murakami, S., and Weber, S. L.: Last Glacial Maximum ocean thermohaline circulation: PMIP2 model intercomparisons and data constraints, Geophysical Research Letters, 34, 6, 10.1029/2007gl029475, 2007.

Rasmussen, S. O., Abbott, P. M., Blunier, T., Bourne, A. J., Brook, E., Buchardt, S. L., Buizert, C., Chappellaz, J., Clausen, H. B., Cook, E., Dahl-Jensen, D., Davies, S. M., Guillevic, M., Kipfstuhl, S., Laepple, T., Seierstad, I. K., Severinghaus, J. P., Steffensen, J. P., Stowasser, C., Svensson, A., Vallelonga, P., Vinther, B. M., Wilhelms, F., and Winstrup, M.: A first chronology for the North Greenland Eemian Ice Drilling (NEEM) ice core, Climate of the Past, 9, 2713-2730, 10.5194/cp-9-2713-2013, 2013.

Weber, S. L., Drijfhout, S. S., Abe-Ouchi, A., Crucifix, M., Eby, M., Ganopolski, A., Murakami, S., Otto-Bliesner, B., and Peltier, W. R.: The modern and glacial overturning circulation in the Atlantic Ocean in PMIP coupled model simulations, Climate of the Past, 3, 51-64, 2007.