

Reply to Editor

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

L. 329-330: The meaning of that sentence is unclear to me.

Following the comment, we modified the corresponding sentence in the revised manuscript as follows (L347-349),

“For example, if glacial ice sheets cause a very small cooling over the Southern Ocean in other models, this will reduce the weakening effect of the AMOC through the Southern Ocean (Fig. 12). As a result, the overall weakening effect by the glacial ice sheet induced-cooling on the AMOC should be reduced.”

L. 337 (and elsewhere): Please consider changing “strengthening of surface cooling” into “a stronger surface cooling” or “a decrease in surface temperature”.

We changed it to “a stronger surface cooling” (L357).

This modification is also applied in L258, L342, L419.

Please remove the bullet points from the Conclusion

Following the editor’s suggestion, we removed the bullet points.

L. 419-420: Please slightly amend the sentence so that it is clear that some climate model outputs are available for MIS3 (even if less so than for the LGM), and consider also adding the MIS3 simulation performed with LOVECLIM.

Thank you for pointing out. Indeed, we should include results from LOVECLIM, which also offer very useful dataset of MIS3. We modified the sentence as follows (L431-433),

“The results of the present study also offer a global dataset of climate during MIS3 and MIS5a, which has been also provide by previous studies (e.g. Van Meerbeek et al. 2009, Gong et al. 2013, Menviel et al. 2014, Guo et al. 2019), though still lacking compared with the LGM”

Figure 9a: Consider changing the colours of some lines (e.g. the 2 green and 2 purple lines can be confusing).

We modified the colors in the revised figure 10a. We hope the revised figure is easier to see.

Schematic (Fig. 11): The impact of Southern Ocean sea-ice on AMOC is unclear to me

We added a following sentence in the caption of revised figure 12 to make clearer the effect of Southern Ocean sea-ice on AMOC.

“A stronger surface wind induced by the glacial ice sheets enhances wind-driven transport of salt into the deepwater formation region and causes a strengthening of the AMOC. In contrast, a stronger surface cooling by the glacial ice sheets causes a weakening of the AMOC by increasing the sea ice at the North Atlantic, which insulates the atmosphere-ocean heat exchange (Oka et al. 2012). A stronger surface cooling by the northern glacial ice sheets also causes a cooling and an increase in sea ice over the Southern Ocean by increasing the oceanic heat transport. This change in the Southern Ocean then weakens the AMOC by increasing the density of the AABW and bottom ocean stratification (Weber et al. 2007, Klockmann et al. 2018).”

Answer to Reviewer 2 (point 11): You state that stronger wind, strengthen the wind driven circulation and meridional oceanic heat transport (as seen in Fig. 6). However, you also suggest that this leads to further cooling in the North Atlantic. I agree that stronger wind will enhance ocean heat release in the North Atlantic, acting to cool the ocean and warm the atmosphere. However the stronger wind-driven circulation and enhanced meridional oceanic heat transport should lead to a warming of the North Atlantic.

Thank you for the constructive comment. We agree to the editor’s point. In the reply to Reviewer 2, we mainly considered the changes in the atmosphere-ocean heat flux. However, as mentioned by the editor, the increase in the oceanic heat transport by the surface wind does increase the surface temperature at high latitude. Based on a previous study (Oka et al. 2012), showing the importance of surface temperature on the glacial AMOC through its effect on the sea ice, we reconsider that the changes in the surface temperature is more important than the atmosphere-ocean heat flux itself. Following this reconsideration, we modified the corresponding paragraph as follows in L316-322.

“Considering the fact that most climate models show a strengthening of the AMOC in response to the glacial ice sheet expansion, the effect of surface wind seems to dominate in most models. The reason behind this still remains elusive, though we speculate that two processes play a role. The first process is associated with the change in wind-driven transport of heat over the subpolar region. For example, the strengthening of the surface wind can increase the strength of the northward oceanic heat transport at high latitude by enhancing the wind-driven ocean circulation. This causes an increase in the surface air temperature and a decrease in sea ice at high latitudes and can reduce the effect of a stronger surface cooling by the glacial ice sheets. ”

Figure S1 (In the answer to Reviewer 2), c) should be MIS3-5aice
Thank you for pointing out. We corrected this mistake.

Reply to Reviewer1

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

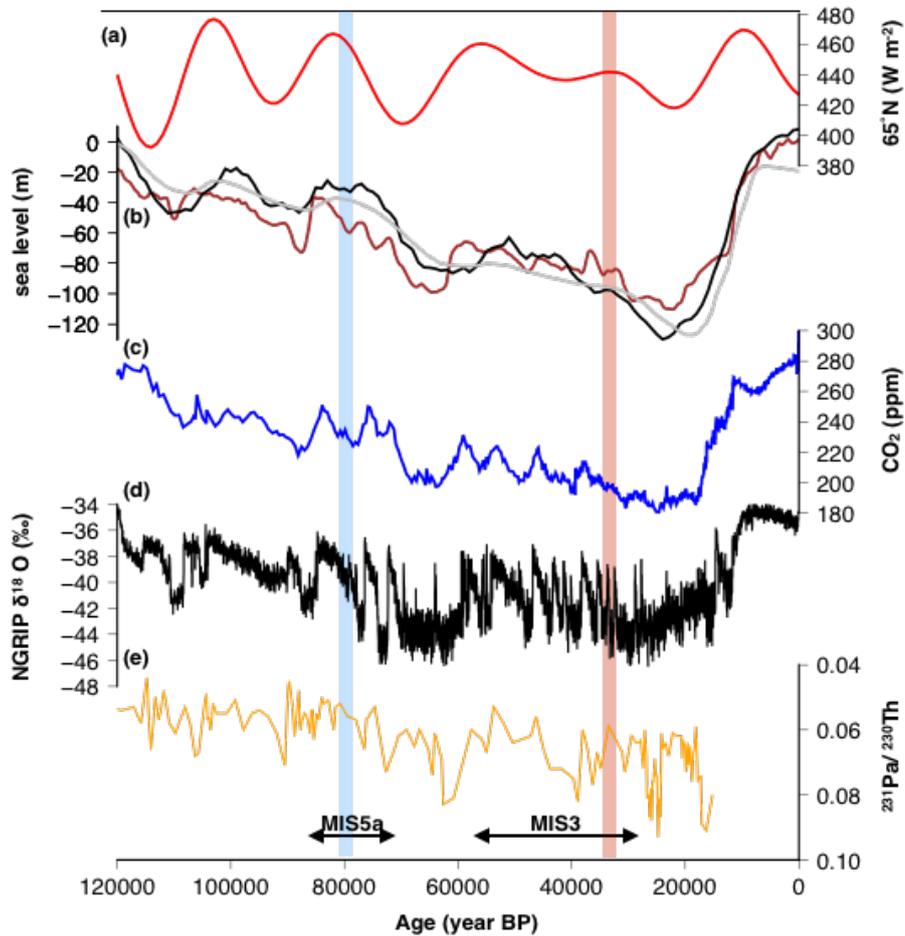


Figure 1: Time series of climate records of the last glacial period. (a) 65°N July insolation ($W m^{-2}$), (b) black: sea level data from Spratt and Lisiecki (2016), brown: sea level data from Grant et al. (2012), gray: simulated time evolution of ice sheet by Abe-Ouchi et al. 2013, (c) CO₂ (Bereiter et al. 2015), (d) Greenland ice core delta 18 O from North Greenland Ice Core Project (NGRIP) core (Rasmussen 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 target 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 add a following paragraph in the method section in the revised manuscript (L111-L118).

“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 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 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 (L127-L129).

“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 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 (L362-L365).

“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 density of AABW. These processes may contribute to re-strengthen the AMOC (Weber et al. 2007, Buizert and Schmittner 2015, Jansen 2017, Klockmann et al. 2018). “

>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 (L365-L372);

“With respect to the lack of atmospheric feedback, previous studies show that the expansion of sea ice due to a reduction of the AMOC 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). In the partially coupled experiments described above (PC-MIS3heat), the sea ice covers the large area of northern high latitude (Fig. S1e), and should activate this positive feedback, which will stabilize the weak AMOC. However, these atmospheric feedbacks are removed in PC-MIS3heat and hence may contributed to the destabilization of the weak AMOC.”

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. 10a). 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 (L360-L375 in the revised manuscript), 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 12.

>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 now adequately refer to the schematic figure (Fig. 12 in the revised manuscript) in 4.2, 5, and 6. We also increased the explanation of each effect in the caption so that the reader can understand the figure more easily. In addition, 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, which is increased as described above.

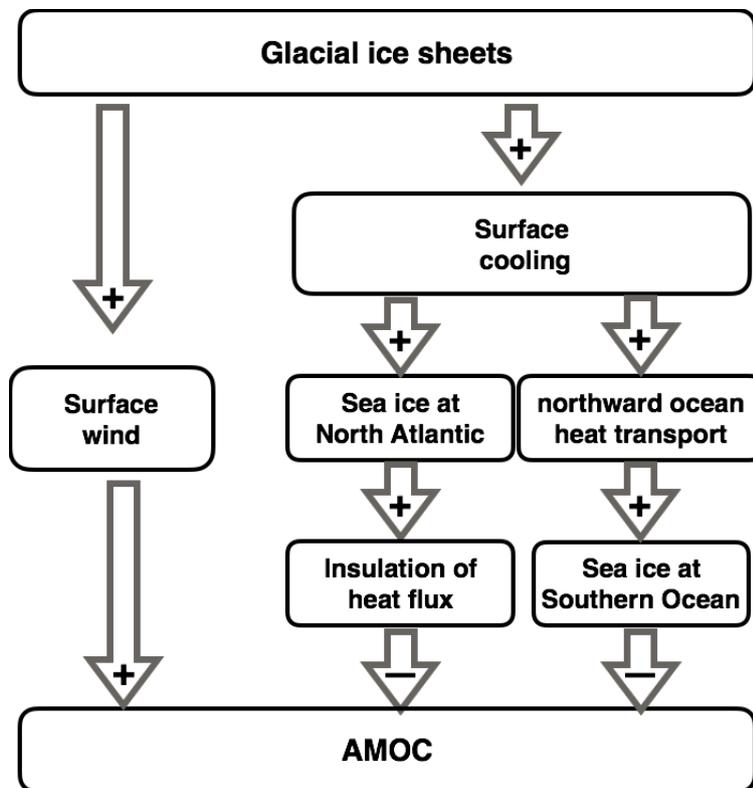


Figure 12: Simple schematic of the processes by which changes in the glacial ice sheet affect the AMOC. A stronger surface wind induced by the glacial ice sheets enhances wind-driven transport of salt into the deepwater formation region and causes a strengthening of the AMOC. In contrast, a stronger surface cooling by the glacial ice sheets causes a weakening of the AMOC by increasing the sea ice at the North Atlantic, which insulates the atmosphere-ocean heat exchange (Oka et al. 2012). A stronger surface cooling by the northern glacial ice sheets also causes a cooling and an increase in sea ice over the Southern Ocean by increasing the oceanic heat transport. This change in the Southern Ocean then weakens the AMOC by increasing the density of the AABW and bottom ocean stratification (Weber et al. 2007, Klockmann et al. 2018). 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 (L9).

>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 add the time slice in the revised manuscript (L11) 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 (L57-L60 and L259).

>L65: you mean “For” these two periods?

We meant that the ice sheet of MIS3 is considered to be slightly larger compared with that of MI5a (L67).

>L71: “: : , whose effect of surface cooling is prominent.” This reads a bit ambiguous to me; please consider rephrasing it.

We modified this sentence in the revised manuscript as follows (L72-L73);

“Hence, by comparing the early-glacial and mid-glacial ice sheets, one may obtain different responses in the AMOC and global climate and quantify the effect of changes in ice sheet extent and the surface cooling”

>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 (L110-L111).

>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 (L153-L156),

“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 change. We added a following sentence on this point in the revised manuscript (L179-L181).

“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 (L195).

>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 (L197).

>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. 5c in the revised manuscript, which shows the effect of ice sheet on ocean temperature. We have modified this sentence as follows (L231-L232),

“This is associated with a cooling of the NADW (Fig. 5c), which is induced by the stronger surface cooling by the glacial ice sheets. ”

In Fig.5c, you can find a cooling of NADW, which is associated with the ice sheet expansion and 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 (L233-L235).

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

Corrected (L246).

>L261: change “are replaced with” to “replace with”?

As pointed out by the reviewer, this sentence was strange. We modified the sentence as follows (L273-L274).

“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 (Table 2)”

>L265: “compensates”

Corrected (L278).

>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 modify this sentence as follows (L282-L285);

“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 (Born et al. 2010). “

>L272: again, the more stable ocean column is not clear to me from Fig. 4c.

We 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.

Vertical profile of water mass at the deep water formation region (60°W-0°, 55°N-65°N)

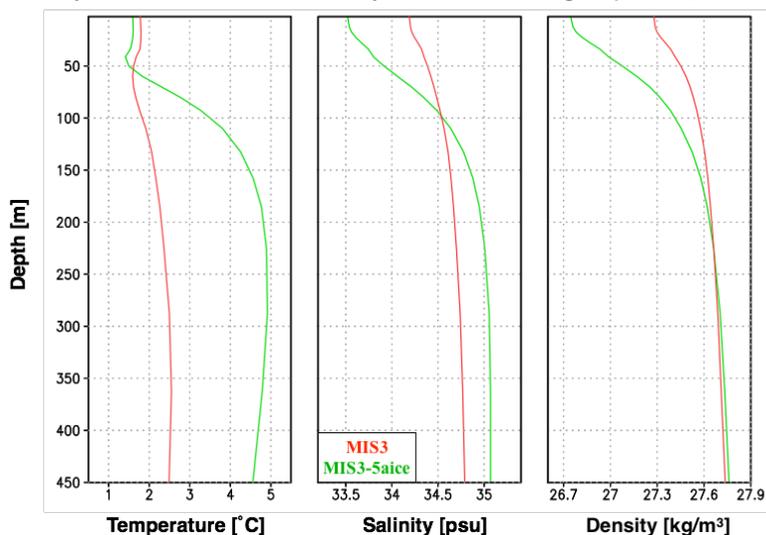


Figure S2: Vertical profile of oceanic properties at the North Atlantic Deep Water formation region (60°W-0°, 55°N-65°N). Red: MIS3 and Green: MIS3-5aice. Cold water occupies the subsurface ocean in MIS3 compared with MIS3-5aice. The climatology of the last 100 years is used to create these figures.

>L273: suggest to tone down “overcomes” to “tends to overcome”.
Corrected (L287).

>L283: “The results above demonstrate: : :”?
Corrected (L297).

>L303: there are two full stops.
Corrected (L317). 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 add a figure supporting this sentence in the supplementary file and keep this discussion in the revised manuscript (L324).

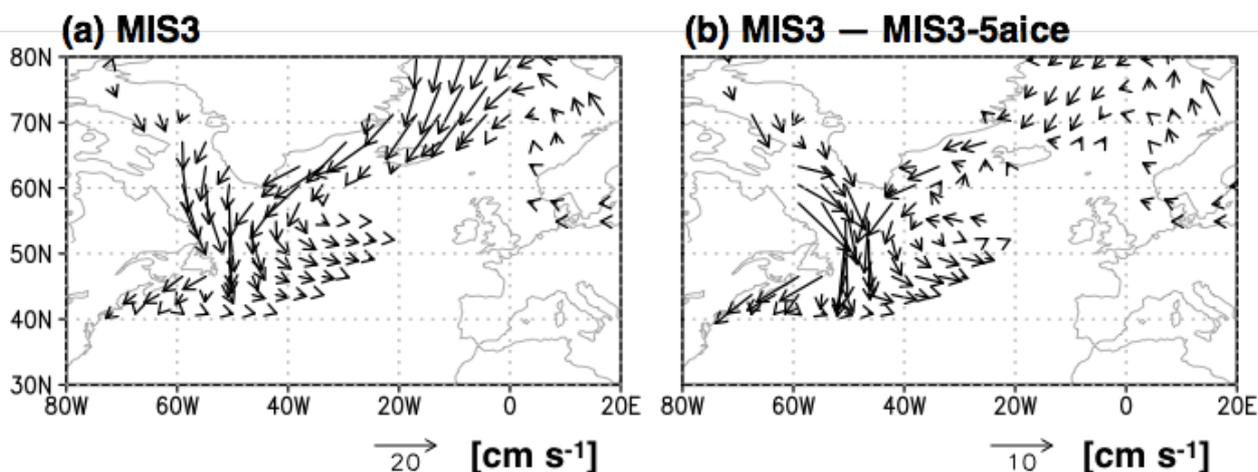


Figure S4: Spatial maps of annual mean sea ice velocity (arrow, cm s^{-1}) from AOGCM experiments. (a) MIS3 and (b) differences between MIS3 and MIS3-5aice. The results of the last 100 years are used.

>L329: ice sheet“-induced” cooling?
Corrected (L349).

>L335: replace “deny” with “exclude”?
Corrected (L356).

>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 fix the legend and also modify the color of “PC-MIS3-5aice” as follows. Note that the figure has been modified slightly from that submitted in the previous reply letter following editor’s suggestion.

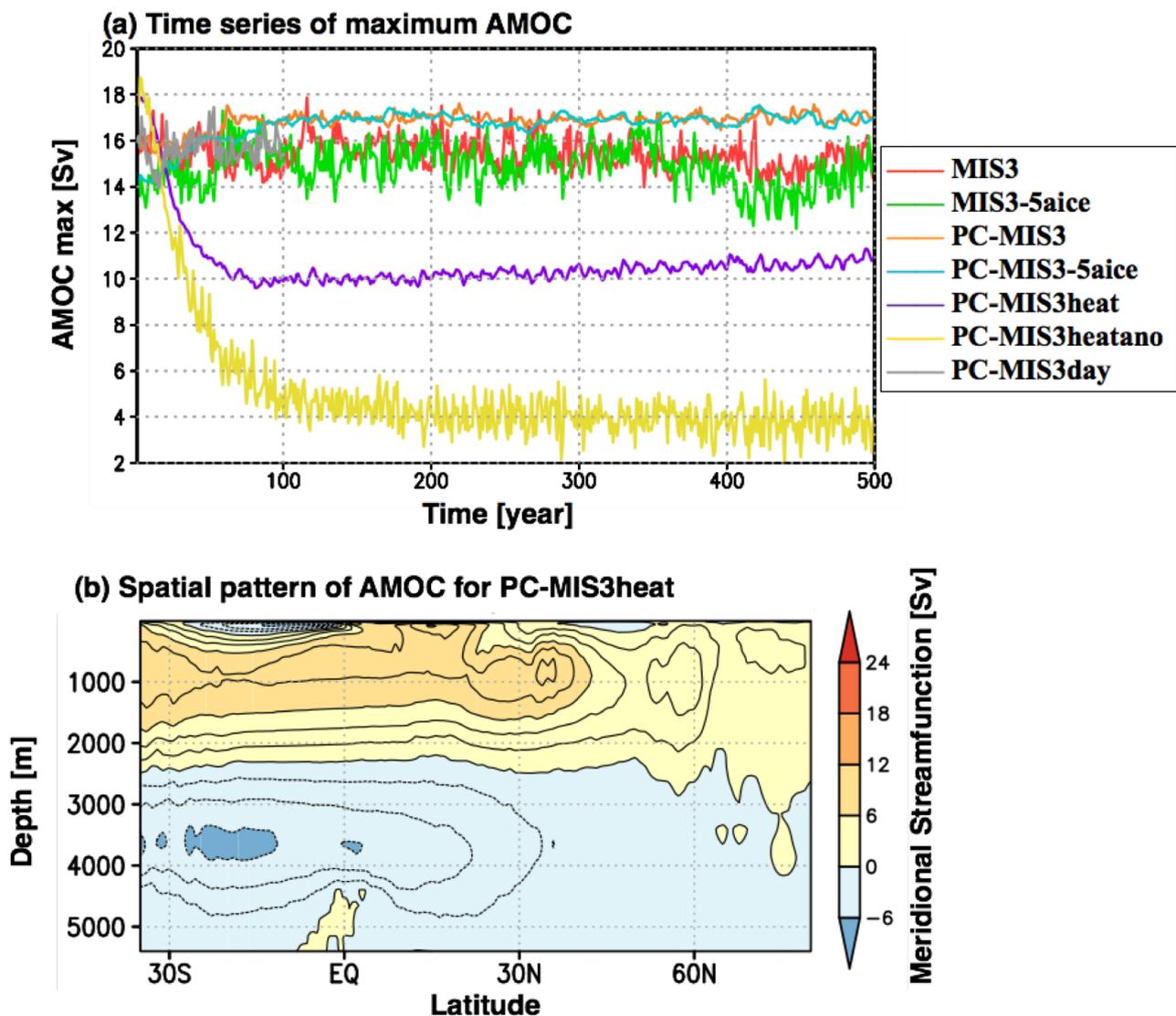


Figure 10: Results of partially coupled experiment conducted with the AOGCM. (a) Time series of the maximum strength of the AMOC. (b) Spatial pattern of the Atlantic meridional streamfunction calculated from PC-MIS3heat. The climatology of the last 100 years is used to create this figure.

New Reference

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- Hu, A. X., Meehl, G. A., Han, W. Q., Otto-Blietner, 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-Blietner, 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.
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- Weber, S. L., Drijfhout, S. S., Abe-Ouchi, A., Crucifix, M., Eby, M., Ganopolski, A., Murakami, S., Otto-Blietner, 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.

Reply to Reviewer2

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

Major comments:

1. In Figure 1, please add a panel for the ice-sheet anomalies between 36ka and 80ka, since it is a key to interpolate the modelling results.

We agree on this point. We add the following figure in the revised manuscript as Fig. 2.

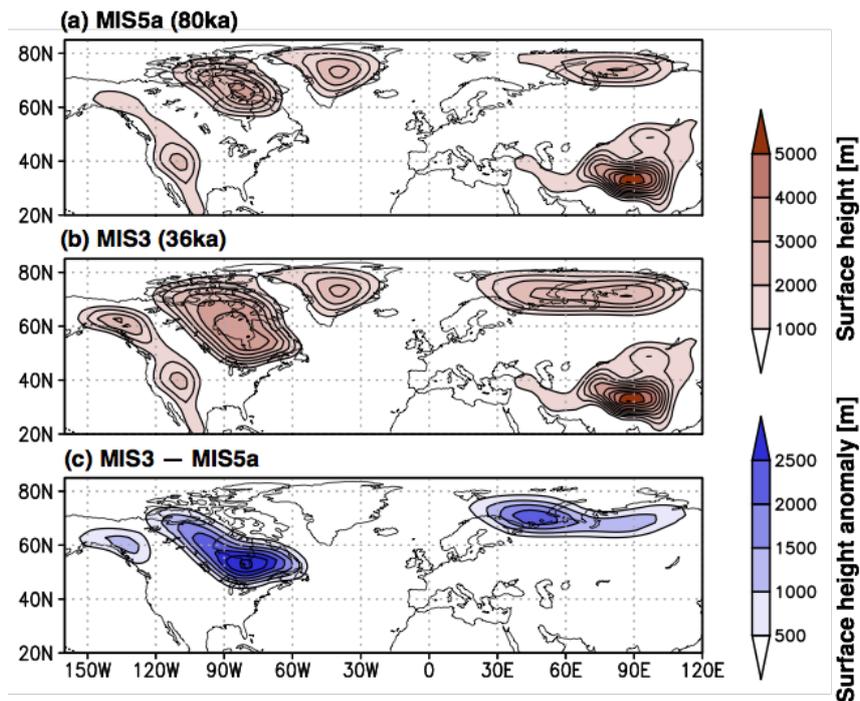


Figure 2: Surface Topography of (a) MIS5a (80 ka), (b) MIS3 (36 ka), and their difference (c) MIS3 - MIS5a. Results from an ice sheet model are presented (Abe-Ouchi et al. 2013). These ice sheet configurations are used for climate model simulations.

2. Line 116: why to use the CO₂ concentration and insolation at 35ka, instead of 36ka? A linguistic error? Or specific reason?

To be honest, there is no special reason. At the time we started the experiment, we had the data of the ice sheet of 36ka in our server, hence we used it. Nevertheless, there is very little difference in the simulated ice sheet between 36ka and 35ka. Therefore, we don't think this slight difference in the ice sheet will affect our result.

3. Line 170: Please add a reference for the LGM experiment.

We add the reference of LGM experiment (Sherriff-Tadano and Abe-Ouchi 2020) in the revised manuscript (L179).

4. Line 195-196: Please give the value of AMOC strength in PI experiment.

We include the value (16.1 Sv) in the revised Table 1.

Table 1: Forcing and boundary conditions of climate simulations. Results of global mean temperature (GMT) and Atlantic meridional overturning circulation (AMOC) are also shown.

Name	CO ₂	Ice sheet	Obliquity	Precession	Ecc	GMT	AMOC
MIS5a	240 ppm	80 ka	23.175	312.25	0.0288	10.58°C	18.7 Sv
MIS3	200 ppm	36 ka	22.754	251.28	0.0154	7.85°C	15.6 Sv
MIS3-5aice	200 ppm	80 ka	22.754	251.28	0.0154	8.91°C	15.1 Sv
PI	285 ppm	0 ka	23.45	102.04	0.0167	12.83°C	16.1 Sv

5. Line 219 and Figure 6: Please add the curve for the modelled PI state.
 We add the result of PI in the revised Fig. 7.

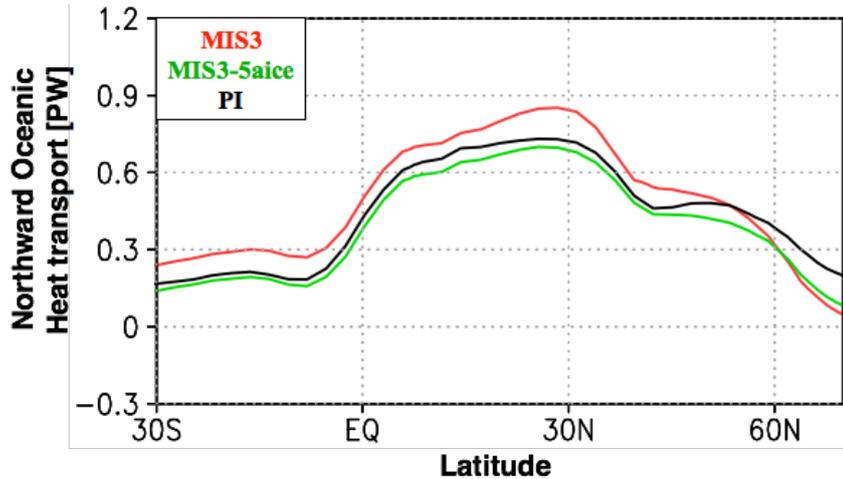


Figure 7: Northward oceanic heat transport over the Atlantic basin simulated from the AOGCM. Red: MIS3, Green: MIS3-5aice, and Black: PI. The climatology of the last 100 years is used to create these figures.

6. In what area are the NADW formed? Are they consistent among experiments? Any response of the NADW formation in the NORDIC Sea?

The deepwater mainly forms at the Nordic Sea and Irminger Sea. They are similar among the experiments, but there is a slight southward shift in the convection site at the Nordic Seas in MIS3 compared with MIS5a. We add a figure of deepwater formation region in the supplementary figure.

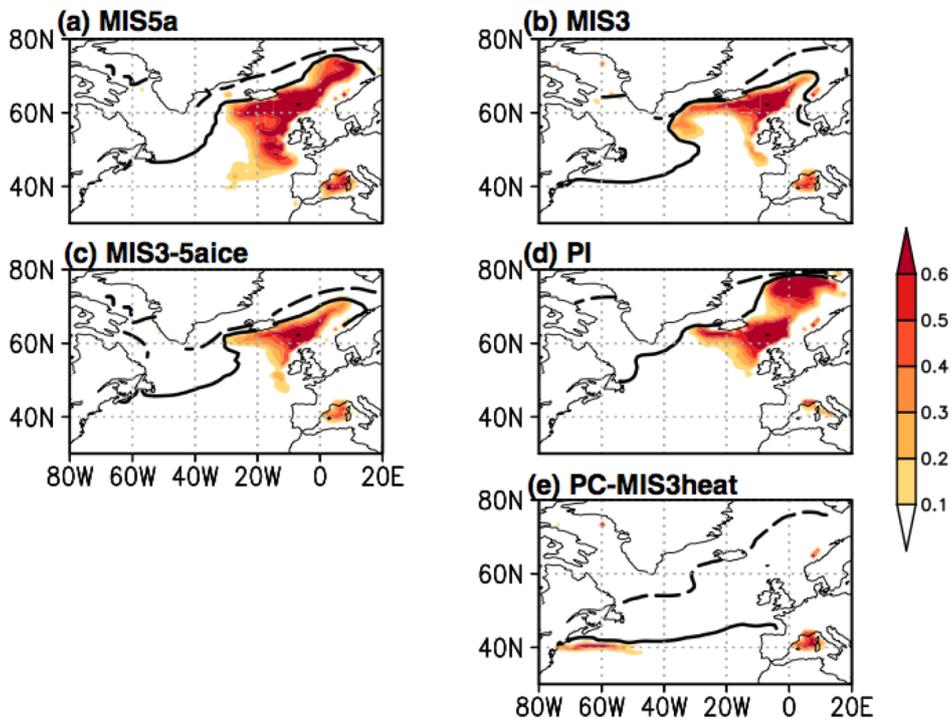


Figure S1: Spatial maps of sea ice edge (contour) and deepwater formation region (color) at the North Atlantic. For sea ice, climatology of 15% sea ice concentration at February (solid) and August (dashed) are shown. For deepwater formation region, frequency of convective adjustment at 600 meter depth is shown. The climatology of the last 100 years is used to create these figures

7. Line 249: bottom ocean stratification with respect to density? If so, please add the information for density in Figure 4.

Yes, in deed. We add a figure of density in the revised figure 5. Also, we noticed that the previous figure was showing the zonal average of the global ocean. We fixed this mistake in the revised manuscript.

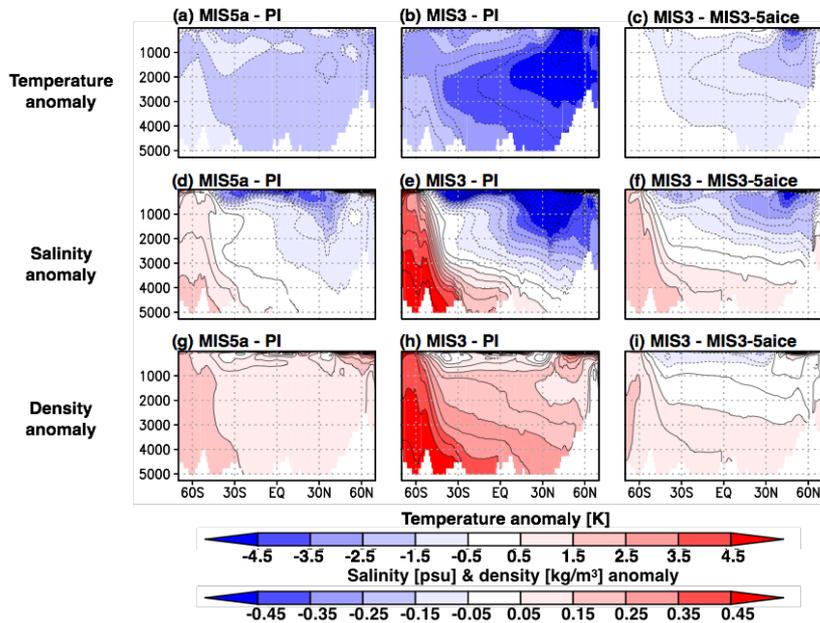


Figure 5: Anomalies of zonally averaged oceanic properties over the Atlantic simulated from the AOGCM. The top panels show temperature anomalies, the middle panels show salinity anomalies, and the bottom panels show density anomalies. (a, d, g) MIS5a minus PI, (b, e, h) MIS3 minus PI, (c, f, i) MIS3 minus MIS3-5aice. The climatology of the last 100 years is used to create these figures.

8. Line 271: In addition to Figure 10, please show the convection map as that in Fig.7c. We add a figure of the convection map in the revised figure S1 as shown above.

9. Also in Line 271: please add a figure for the statement ‘colder water occupies the subsurface ocean in MIS3 compared with MIS3-5aice.’, in either Main text or SI.

We add a figure of the vertical profile of ocean temperature in the supplementary figure.

Vertical profile of water mass at the deep water formation region (60°W-0°, 55°N-65°N)

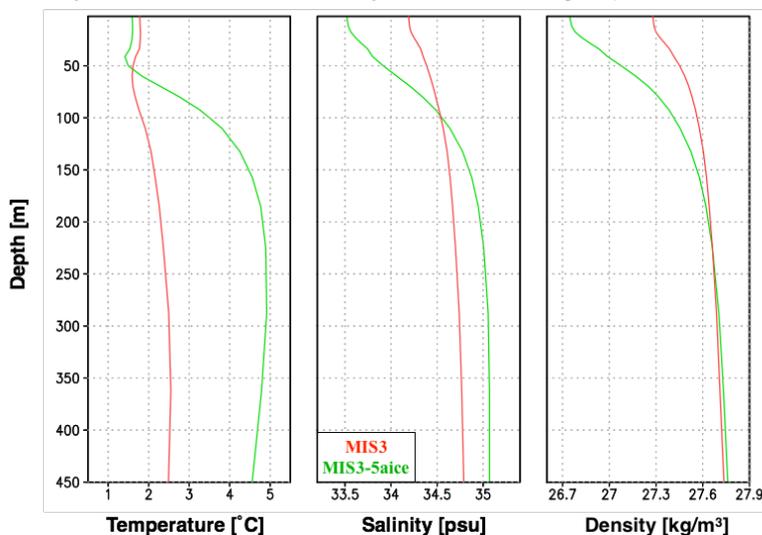


Figure S2: Vertical profile of oceanic properties at the North Atlantic Deep Water formation region (60°W-0°, 55°N-65°N). Red: MIS3 and Green: MIS3-5aice. Cold water occupies the subsurface ocean in MIS3 compared with MIS3-5aice. The climatology of the last 100 years is used to create these figures.

10. In Table 1: please add the information also for the PI and LGM experiments together with their references.

We add the information of PI in the revised Table 1 since the results of PI appear in several figures (please see the revised Table 1 shown above). For LGM, we decided not to add in the table, as the results do not appear in other figures, and it is discussed only for once. Nevertheless, we add a reference of LGM in the revised manuscript (L179).

11. In Figure 11, how to address the impact of stronger surface winds on the northward ocean heat transport and surface cooling in the northern North Atlantic? Any indications based on the experiments in this study? Thank you for the constructive comment. We reconsidered our previous response to Reviewer 2 after receiving editor's comment. In the previous reply, we mainly considered the changes in the atmosphere-ocean heat flux associated with the surface wind anomaly. In this case, the stronger oceanic wind-driven heat transport will increase the temperature difference between the atmosphere and ocean, and causes an increase in the atmosphere-ocean heat flux. However, as mentioned by the editor, the increase in the oceanic heat transport induced by the surface wind anomaly does try to increase the surface temperature at high latitude. Based on a previous study (Oka et al. 2012), showing the importance of surface temperature on the glacial AMOC through its effect on the sea ice, we reconsider that the changes in the surface temperature is more important than the atmosphere-ocean heat flux itself. Following this reconsideration, we reconsidered that the strong surface wind tries to reduce the weakening effect of the stronger surface cooling on the AMOC by increasing the surface temperature and reducing the sea ice, which is the opposite to what we have mentioned in the previous reply. The modified paragraph can be found in L316-322.

“Considering the fact that most climate models show a strengthening of the AMOC in response to the glacial ice sheet expansion, the effect of surface wind seems to dominate in most models. The reason behind this still remains elusive, though we speculate that two processes play a role. The first process is associated with the change in wind-driven transport of heat over the subpolar region. For example, the strengthening of the surface wind can increase the strength of the northward oceanic heat transport at high latitude by enhancing the wind-driven ocean circulation. This causes an increase in the surface air temperature and a decrease in sea ice at high latitudes and can reduce the effect of a stronger surface cooling by the glacial ice sheets. ”

Also, we decided to remove the information of internal feedback in the schematic figure to make the figure simple and to focus on the main topic of this paper, which is to show that the impact of the ice sheet is determined by the two competing effects, surface wind and surface cooling. Nevertheless, we keep the discussion on the internal feedback in the revised manuscript.

Minor comments:

Line 37: 'Project' to 'Projects'
Corrected (L39).

Line 210: please refer to Figure 2d, for the warmer surface around Alaska
Corrected (L222).

Line 303: ‘.’ has been double used.
Corrected (L317). Thank you for pointing out.

Impact of mid-glacial ice sheets on deep ocean circulation and global climate: Role of surface cooling on the ~~AMOC~~Atlantic Meridional Overturning Circulation

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Abstract. This study explores the effect of southward expansion of Northern Hemisphere (American) mid-glacial ice sheets on the global climate and the Atlantic meridional overturning circulation (AMOC), as well as the processes by which the ice sheets modify the AMOC. For this purpose, simulations of Marine Isotope Stage (MIS) 3 (36ka) and 5a (80ka) are performed with an atmosphere-ocean general circulation model. In the MIS3 and MIS5a simulations, the global average temperature decreases by 5.0 °C and 2.2 °C, respectively, compared with the preindustrial climate simulation. The AMOC weakens by 3% in MIS3, whereas it ~~is enhanced~~strengthens by 16% in MIS5a, both of which are consistent with a reconstruction. Sensitivity experiments extracting the effect of the southward expansion of glacial ice sheets from MIS5a to MIS3 show a global cooling of 1.1 °C, contributing to about 40% of the total surface cooling from MIS5a to MIS3. These experiments also demonstrate that the ice sheet expansion leads to a surface cooling of 2 °C over the Southern Ocean as a result of colder North Atlantic deep water. We find that the southward expansion of the mid-glacial ice sheet exerts a small impact on the AMOC. Partially coupled experiments reveal that the global surface cooling by the glacial ice sheet tends to reduce the AMOC by increasing the sea ice at both poles, and hence compensates for the strengthening effect of the enhanced surface wind over the North Atlantic. Our results show that the total effect of glacial ice sheets on the AMOC is determined by the two competing effects, surface wind and surface cooling. The relative strength of surface wind and surface cooling effects depends on the ice sheet configuration, and the strength of the surface cooling can be comparable to that of surface wind when changes in the extent of ice sheet are prominent.

25 1 Introduction

During the last glacial period, ice sheets evolved drastically over the Northern continent (Lisiecki and Raymo 2005, Clark et al. 2009, Grant et al. 2012, Spratt and Lisiecki 2016, Fig. 1). After the initiation of the ~~northern~~Northern Hemisphere glacial ice sheets at the end of the Last Interglacial, the ice sheets expanded over northern North America and northern Europe during

the early glacial period, Marine Isotope Stage (MIS) 5d-a, and further expanded during MIS4 associated with weakening of summer insolation. Then, the glacial ice sheets once shrank during the mid-glacial period (MIS3), when the summer insolation and the concentration of CO₂ were relatively large (Abe-Ouchi et al. 2007, Grant et al. 2012, Spratt and Lisiecki 2016, Pico et al. 2017, Fig. 1). Subsequently, the ice sheets further expanded during MIS2, when the summer insolation and the concentration of CO₂ were low, and reached their maximum volume at the Last Glacial Maximum (LGM, Peltier 2004, Clark et al. 2009, Tarasov et al. 2012, Ishiwa et al. 2016). Because of these drastic differences in the ice sheet and climate compared with modern times, the last glacial period is considered as important to improve the understanding of the effect of ice sheets on climate.

Previous studies investigated the impact of glacial ice sheets on the climate under the LGM, which is set as the target period in the Paleoclimate Model Intercomparison ~~Project~~Projects (PMIP, Braconnot et al. 2007, Braconnot et al. 2012, Abe-Ouchi et al. 2015, Kageyama et al. 2017). Based on reconstructions, the climate of the LGM is known to be the coldest and most stable period of the last glacial (Kindler et al. 2014, Kawamura et al. 2017). Furthermore, the Atlantic meridional overturning circulation (AMOC) is considered to have been shallower and perhaps weaker compared with the preindustrial era (McManus et al. 2004, Bohm et al. 2015, Muglia et al. 2018, Menviel et al. 2020). Modelling studies show that the expansion of the glacial ice sheet cause a large cooling, a strengthening of atmospheric circulation, and a southward shift of the rain belt over the North Atlantic (Cook and Held 1988, Kageyama et al. 2000, Abe-Ouchi et al. 2007, Laine et al. 2009, Pausata et al. 2011, Hofer et al. 2012, Lofverstorm et al. 2014, Merz et al. 2015). These studies also show that the response of the atmospheric circulation is largely affected by the height of the ice sheet (Gong et al. 2015, Merz et al. 2015), while the strength of the surface cooling is ~~largely affected~~mainly controlled by the extent of the ice sheet (Abe-Ouchi et al. 2007).

Several studies using an atmosphere ocean coupled general circulation model (AOGCM) also show that the glacial ice sheets exert a large impact on the AMOC. Many of these studies show a strengthening of the AMOC in response to the expansion of the northern glacial ice sheet (Eisenman et al. 2009, Brady et al. 2013, Zhang et al. 2014a, Gong et al. 2015, Klockmann et al. 2016, Brown and Galbraith 2016, Kawamura et al. 2017), while one study shows a reduction of the AMOC (Kim 2004). From sensitivity experiments, it is shown clearly that the higher glacial ice sheets enhance the surface wind as well as the wind-driven oceanic transport of salt into the deep-water formation region over the North Atlantic, which increases the surface salinity and causes a strengthening of the AMOC (Oka et al. 2012, Muglia and Schmittner 2015, Sherriff-Tadano et al. 2018). Other studies also suggest the importance of changes in surface cooling (Smith and Gregory 2012), which can cause either a strengthening ~~or weakening~~ of the AMOC by enhancing deep-water formation over the North Atlantic (Schmittner et al. 2002, Oka et al. 2012, Smith and Gregory 2012) or a **weakening of the AMOC** by increasing the amount of sea ice over the northern North Atlantic and Southern Ocean (Kawamura et al. 2017). Nevertheless, due to the complicated coupling between the atmosphere and ocean in climate systems, the role of surface cooling by the glacial ice sheets on the AMOC still remains elusive.

While the effects of glacial ice sheets on the LGM climate gain large attention, the effect of pre-LGM glacial ice sheet on the global climate and AMOC is less explored. Reconstructions of the ice sheets prior to the LGM still have large uncertainties, though recent studies suggest ~~some~~ notable differences in ice sheets between the early glacial (MIS5a) and mid-glacial (MIS3). Between these two periods, the volume of ice sheets is slightly larger in MIS3 than in MIS5a (Lisiecki and Raymo 2005, Grant et al. 2012, Abe-Ouchi et al. 2013, Spratt and Lisiecki 2016, Pico et al. 2017, Willeit and Ganopolski 2018). In addition, studies with ice sheet modelling suggest a larger extent of the North American ice sheet in MIS3 compared with MIS5a, despite small differences in the maximum height of the ice sheet (Fig. 1a2, Abe-Ouchi et al. 2007, 2013, Niu et al. 2019). This is different from what is revealed with explorations using the LGM ice sheet, whose changes are large in both the height and extent. Hence, by comparing the early-glacial and mid-glacial ice sheets, one may obtain different responses in the AMOC and global climate, whose and quantify the effect of changes in ice sheet extent and the surface cooling is prominent.

Furthermore, recent reconstructions show some discrepancies between the MIS3 and MIS5a climates. For example, it is shown that the AMOC is slightly weaker in MIS3 compared with that of MIS5a (Bohm et al. 2015). Ice core data also show that the duration of the millennial time-scale climate variability is shorter in MIS3 compared with MIS5 (Capron et al. 2010, Buizert and Shemittner 2015, Lohmann and Ditlevsen 2019). Hence, by exploring the impact of the mid-glacial ice sheets on the global climate and AMOC, one can also assess the potential role of differences in ice sheets between MIS3 and MIS5a in causing the differences in climate and AMOC between MIS3 and MIS5a.

In this study, we investigate the impact of the expansion of the mid-glacial ice sheets on the global climate and the AMOC. Specifically, we explore how the differences in the ice sheets between MIS3 and MIS5a have an impact on global climate and AMOC. For this purpose, we perform climate simulations of MIS3 and MIS5a with a comprehensive climate model. Furthermore, we explore the processes by which the changes in the ice sheet modify the AMOC. Particularly, we focus on the role of changes in surface cooling by the glacial ice sheets on the AMOC, which is also considered important in driving the AMOC changes (Loving and Vallis 2005, Arzel et al. 2010, Oka et al. 2012, Sun et al. 2016, Jansen 2017), but still remains elusive in previous LGM studies. For this purpose, partially coupled experiments are conducted (Mikolajewicz and Voss 2000, Schmittner et al. 2002, Gregory et al. 2005, Sherriff-Tadano and Abe-Ouchi 2020). In this experiment, the atmospheric forcing that drives the oceanic component is switched one by one to a different forcing. For example, Gregory et al. (2005) apply this method to interpret the cause of the weakening of the AMOC in the CO₂ doubling simulations in the CMIP3 models. They find that the changes in the surface heating play a large role in causing the weakening of the AMOC through reducing the heat exchange between the atmosphere and the ocean. Hence, the use of partially coupled experiments enables us to extract the effect of changes in surface cooling by the mid-glacial ice sheets on the AMOC.

This study is organized as follows. In section 2, we describe the model and the experimental design. In sections 3 and 4, we show the results of MIS3 and MIS5a simulations, and then investigate the role of mid-glacial ice sheets on the global climate

and the AMOC. The effect of surface cooling by the mid-glacial ice sheet is also explored by means of ~~a~~ partially coupled ~~experiment~~ experiments. Sections 5 and 6 discuss and summarise the results, respectively.

2. Methodology

100 2.1 Model

We perform numerical experiments with the Model for Interdisciplinary Research on Climate 4m (MIROC4m; Hasumi and Emori 2004, Chan et al. 2011) AOGCM. This model consists of an atmospheric general circulation model (AGCM) and an oceanic general circulation model (OGCM). The AGCM solves the primitive equations on a sphere using a spectral method. The horizontal resolution of the atmospheric model is $\sim 2.8^\circ$ and there are 20 vertical layers. The AGCM is coupled to a land-
105 surface model. The OGCM solves the primitive equation on a sphere, where the Boussinesq and hydrostatic approximations are adopted. The horizontal resolution is $\sim 1.4^\circ$ in longitude and 0.56° – 1.4° in latitude (latitudinal resolution is finer near the equator). There are 43 vertical layers. It is coupled to a dynamic-thermodynamic sea-ice model. Note that the coefficient of ~~horizontal diffusion of~~ the isopycnal layer thickness ~~diffusion~~ in the OGCM is slightly increased to $700 \text{ m}^2 \text{ s}^{-1}$ ~~compared with~~ ~~from~~ $300 \text{ m}^2 \text{ s}^{-1}$ in the original model version (~~$300 \text{ m}^2 \text{ s}^{-1}$~~) that was submitted to PMIP2 [these two model versions are
110 referred to as Model B and Model A, respectively, in Sherriff-Tadano and Abe-Ouchi (2020)]. The model version used in this study ~~is~~ 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
115 previous version (Fig. 4). This model version has been used extensively for paleoclimate (Obase and Abe-Ouchi 2019) and future climate studies (Yamamoto et al. 2015). It ~~also~~ has a climate sensitivity of 4.1 K and reproduces the AMOC of the LGM reasonably well (Sherriff-Tadano and Abe-Ouchi 2020).

2.2 Model simulations

Three experiments are conducted with MIROC4m AOGCM (Table 1). The first experiment is named MIS5a, which aims at a
120 period of approximately 80 ka- (Fig. 1, blue shade). In this experiment, we apply a CO_2 level of 240 ppm, insolation of 80 ka, and an ice sheet boundary configuration of 80 ka taken from an ice sheet model (see next paragraph for detailed information). The second and third experiments are performed under MIS3 boundary conditions, CO_2 of 200 ppm and insolation of 35 ka- (Fig. 1, red shade). In these two experiments, the configurations of the ice sheets differ (Fig. 1b2). In the second experiment, we apply an ice sheet of 36 ka (Fig. 1b2b). In the third experiment, we apply an ice sheet of 80 ka (Fig. 1a2a). These
125 experiments are named MIS3 and MIS3-5aice, respectively (Table 1). Note that the Antarctic ice sheet is fixed to the modern configuration. 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)).

For methane and other greenhouse gases, the concentration of the LGM is used (Dallenbach et al. 2000). Hence, by comparing MIS3 and MIS3-5aice, one can assess the impact of mid-glacial ice sheets on the global climate and AMOC. The difference between MIS3-5aice and MIS5a shows the effect of changes in CO₂ and insolation.

For the ice sheet forcing, we use the output from the Ice sheet model for Integrated Earth system Studies (IceS, Saito and Abe-Ouchi 2005) driven with the climatic parameterization derived from MIROC (IceS-MIROC, Abe-Ouchi et al. 2007, 2013). This model reproduces the evolution of the Northern Hemisphere ice sheet over the past 400,000 years (Abe-Ouchi et al. 2013), and it is used as a boundary condition for the simulations of the Penultimate Glacial Termination (Meniel et al. 2019). The model also reproduces the general pattern of the evolution of the global ice sheet volume (or equivalent sea level change) over the last glacial period reasonably well (Abe-Ouchi et al. 2013, Fig. 1a, 2), that is, larger ice sheets during MIS3 compared with MIS5a (Grant et al. 2012, Spratt and Lisiecki 2016, Pico et al. 2017). These volumes are the 40-meter sea level equivalent for MIS5a (approximately 33% of the LGM) and 96-meter sea level equivalent for MIS3 (approximately 80% of the LGM, Abe-Ouchi et al. 2013). The volume of the MIS3 ice sheet slightly exceeds the estimated range of sea level reconstructions (approximately 40- to 90-meter sea level equivalent during the mid-glacial, Grant et al. 2012, Spratt and Lisiecki 2016, Pico et al. 2017). This is further discussed in section 4.

The three simulations are initiated from the previous LGM experiment of Kawamura et al. (2017), which has a weak and shallow AMOC. MIS5a is integrated for 2,000 years and MIS3 and MIS3-5aice are integrated for 3,000 years. After the integration, the AMOC settles into a vigorous mode (interstadial mode) in all experiments. Decreasing trends of deep ocean temperature of the last 100 years are 0.002 °C in MIS5a, 0.011 °C in MIS3, and 0.007 °C in MIS3-5aice. Hence, these simulations have settled to quasi-equilibrium states (Zhang et al. 2013).

2.3 Partially coupled experiments

To assess the processes by which the mid-glacial ice sheets modify the AMOC, partially coupled experiments are conducted (Table 2). In these experiments, the atmospheric forcing – wind stress and atmospheric freshwater flux (precipitation, evaporation, and river runoff) – that drives the ocean is replaced with a monthly climatology. 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). Four partially coupled experiments are conducted based on the MIS3 and MIS3-5aice experiments (Table 2). These experiments are initiated from the last year (year 3000) of MIS3 or MIS3-5aice. The first experiment (PC-MIS3) is intended as a validation of the method. In this experiment, the atmospheric forcing is replaced with the monthly climatology of the last 100 years of the same MIS3 experiment. Hence, the climatological atmospheric forcing is identical to that of the original experiment. The second experiment (PC-MIS3-5aice) is also conducted in a similar manner under MIS3-5aice, using the monthly climatology of MIS3-5aice. The third experiment is conducted under the MIS3 condition (PC-

MIS3heat), where the wind forcing and atmospheric freshwater forcing are replaced with the monthly climatology of MIS3-5aice. Hence, the oceanic component of the model is forced by wind and atmospheric freshwater fluxes of MIS3-5aice and the surface heat flux of MIS3- (Table 2). By comparing the results between PC-MIS3heat and PC-MIS3-5aice, one can evaluate the effect of surface cooling on the oceanic circulation (Gregory et al. 2005). Note that the effect of surface cooling includes changes in freshwater flux from the sea ice in addition to changes in an atmosphere-ocean heat exchange. In the fourth experiment (PC-MIS3heatano), the effect of surface cooling is evaluated in a slightly different way. In this experiment, we apply the anomalies of monthly climatology of surface wind and atmospheric freshwater flux between MIS3 and MIS3-5aice to MIS3. Hence, this experiment is also forced by winds and atmospheric freshwater fluxes of MIS3-5aice and the surface heat flux of MIS3- (Table 2). By comparing the MIS3-5aice experiment with PC-MIS3heatano, we can estimate the effect of surface cooling on the oceanic circulation. The advantage of this experiment is that it retains high-frequency variabilities in the atmospheric forcing, which are removed in other partially coupled experiments. In addition, this experiment retains the effect of atmospheric feedback after a modification in the AMOC, which affects the stability of the AMOC (Sherriff-Tadano and Abe-Ouchi 2020), see also the Discussion). Note that the final results are independent of the choice of the applied atmospheric forcing.

175 3 Overall characteristics of MIS3 and MIS5a climates

The simulated global cooling for MIS3 and MIS5a compared with the Pre-industrial climate (PI) are 5.0 °C and 2.2 °C, respectively (Fig. 23). The strengths of these global surface cooling are smaller compared with that obtained from the LGM simulation (5.2 °C) with the same model. The (Sherriff-Tadano and Abe-Ouchi 2020). 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). Nevertheless, the simulated MIS3 cooling falls within the range of simulations obtained from previous modelling studies: Guo et al. (2019) simulate the MIS3 climate with the boundary conditions of 38 ka and show a global cooling of 2.9 °C, Merkel et al. (2010) show a cooling of 3.4 °C under 35-ka boundary conditions, Zhang et al. (2014b) show a cooling of 3.5 °C under 38-ka boundary conditions, and Brandefelt et al. (2011) show a global cooling of 5.5 °C under 44-ka boundary conditions. The spatial maps of the surface cooling show a well-known polar amplification pattern (Fig. 23). In MIS3 and MIS5a, the largest cooling takes place over the North American and Northern Europe as the ice sheets expand southward. In these regions, the surface air temperature drops by more than 10 °C, and is associated with the high albedo and elevation of the ice sheets. The surface cooling is also large over the Southern Ocean, where the local surface cooling exceeds 10 °C and 3 °C for MIS3 and MIS5a, respectively. The surface cooling is relatively mild over the tropics compared with the polar regions, and the areal average cooling over 30°S and 30°N is 3.5 °C and 1.7 °C for MIS3 and MIS5a, respectively.

The amplified cooling over the polar regions is associated with the expansion of sea ice (Fig. 34). Over the North Atlantic, the Labrador Sea is covered by sea ice in all experiments. Sea ice also expands southward over the Norwegian Sea, though the

southern part of the Norwegian Sea still remains ice-free- (Dokken et al. 2013, Sadazki et al. 2019). These expansions in sea
195 ice are consistent with a large surface cooling simulated in the northern North Atlantic. Over the Southern Ocean, sea ice
expands northwards in both experiments compared with the PI. In MIS3, sea ice largely expands northward in the ~~western~~
~~part~~ Pacific sector of the Southern Ocean and contributes to the large surface cooling observed in that region. In association
with the increase in the amount of sea ice, the deep ocean salinity increases and deep ocean temperature decreases in MIS3
compared with PI (Fig. 45b, e). A similar feature is also observed in MIS5a, but with a smaller magnitude- (Fig. 5a, d). Note
200 that the decrease in ocean temperature is also attributed to the cooling of the North Atlantic Deep Water (NADW, Fig. 5b).

Both the MIS3 and MIS5a experiments simulate an ~~interglacial~~ interstadial mode of the AMOC (Fig. 56a, b). This is in line
with an ice-free condition over the Norwegian Sea and Irminger Sea, where deep water forms due to intense surface cooling
(Dokken et al. 2013, Sadazki et al. 2019). Nevertheless, the strength of the AMOC responds differently to MIS3 and MIS5a
205 boundary forcing (ice sheet, CO₂, and insolation). In MIS3, the maximum strength of the AMOC decreases by 3% (−0.5 Sv,
Table 1) and the AMOC shoals compared with the PI (Fig. 5b6b, d). In contrast, the AMOC strengthens in MIS5a by 16%
(+2.6 Sv) and shows small changes in depth compared with the PI (16.1 Sv, Fig. 5a6a, d, Table 1). These simulated
characteristic of MIS3 and MIS5a are consistent with a reconstruction showing a slightly stronger AMOC in MIS5a and a
slightly weaker AMOC in MIS3 (Bohm et al. 2015, Fig. 1). Therefore, the simulations of MIS3 and MIS5a capture the large-
210 scale features of climate and deep ocean circulation reasonably well.

4 Effect of mid-glacial ice sheet

4.1 Global climate and deep ocean circulation

The results of MIS3-5a ice are used to extract the effect of the southward expansion of mid-glacial ice sheets from MIS5a to
MIS3 on the global climate as well as the AMOC. The simulated global cooling in MIS3-5a ice is 3.9 °C. This gives a global
215 surface cooling of 1.1 °C by the expansion of mid-glacial ice sheets (difference between MIS3 and MIS3-5a ice) and a global
cooling of 1.7 °C by the lowering of CO₂ and changes in insolation (difference between MIS3-5a ice and MIS5a). The
southward expansion of the northern glacial ice sheets induces a large surface cooling over the North America, Northern
Europe, and the northern North Atlantic (Fig. 2d3d). The latter is induced by a vigorous advection of cold air from the North
American ice sheet, which expands near the Labrador Sea (Fig. 7b8b). A slight warming is observed in the Irminger Sea, which
220 is associated with a slight shift in the deep-water formation region and sea ice. A surface warming is also observed around
Alaska- (Fig. 3d). This is associated with the strengthening of the southerly wind over the eastern North Pacific, which is
related to the high surface pressure anomaly over North America induced by the expansion of the glacial ice sheet (Yanase
and Abe-Ouchi 2010).

225 Interestingly, the expansion of the mid-glacial ice sheet exerts an impact on the Southern Ocean by causing a surface cooling
of 2 °C (Fig. 23d). This surface cooling is solely induced by the northern mid-glacial ice sheets, because the configuration of
the Antarctic ice sheet is fixed to that of the PI. Similar results are reported in Ganopolski and Roche (2009) and Roberts and
Valdes (2017). These studies show that the stronger northward oceanic heat transport is responsible for causing the decrease
230 larger in MIS3 compared with MIS3-5aice in our simulations (Fig. 67). This is associated with a cooling of the NADW; (Fig.
5c), which is induced by the stronger surface cooling by the glacial ice sheets (Fig. 4). As a result, colder deep water outcrops
in the Southern Hemisphere and cools the Southern Ocean. Furthermore, associated with the stronger surface cooling over the
Southern Ocean, the amount of sea ice ~~also~~ increases in this region (Fig. 3) and 4), which increases the deep ocean salinity;
~~which~~ via brine rejection (Fig. 5f), and enhances the bottom ocean stratification (Fig. 45i).

235

Unlike the oceanic heat transport, the expansion of mid-glacial ice sheets exerts a very small impact on the AMOC. The
maximum strength of the AMOC increases by only 0.5 Sv between MIS3 and MIS3-5aice. These results show that the changes
in the AMOC from MIS5a to MIS3 are mostly explained by the modifications to the CO₂ levels and insolation. The small
response in the AMOC to ice sheet forcing differs from what is shown by previous studies, which show a strengthening and
240 deepening of the AMOC (Eisenman et al. 2009, Brady et al. 2013, Zhang et al. 2014a, Gong et al. 2015, Brown and Galbraith
2016, Klockmann et al. 2016, 2018, Kawamura et al. 2017). Analysis of the surface wind stress curl shows an enhancement in
response to the mid-glacial ice sheet expansion (Fig. 8a, b). This strengthening of surface wind stress curl is mostly explained
by the strong northwesterly wind stress anomaly over the Labrador Sea, which is induced by the southward expansion of ice
sheets in this region (Fig. 7a, b 8b). As a result of the increased wind stress curl, the wind-driven ocean circulation and the
245 northward transport of salt increases; (Fig. 8c, d), which tend to intensify the AMOC, as shown by previous studies (Fig. 7e,
d; Montoya and Levermann 2008, Oka et al. 2012, Muglia and Schmittner 2015, Sherriff-Tadano et al. 2018). Nevertheless,
the AMOC retains a similar strength in our simulations. This result suggests that other processes are playing a role in
compensating for the strengthening effect of the surface wind.

4.2 Roles of surface cooling by mid-glacial ice sheets on the AMOC

250 In addition to surface wind, changes in atmospheric freshwater flux and surface cooling modify the AMOC (Eisenman et al.
2009, Smith and Gregory 2012). The atmospheric freshwater flux can affect the AMOC by modifying the surface salinity field
(Eisenman et al. 2009). Figure 89 shows the difference in atmospheric freshwater fluxes between MIS3 and MIS3-5aice. It is
found that the expansion of the mid-glacial ice sheet reduces the input of atmospheric freshwater flux over the northern North
Atlantic, which is associated with a southward displacement of the westerlies (Hofer et al. 2012), as well as a decrease in
255 specific humidity due to the intense cooling (Laine et al. 2009). This tends to enhance the AMOC by increasing the surface
salinity in the deep-water formation region (Eisenman et al. 2009), which is qualitatively opposite to what we observe now.
The ~~strengthening of the~~ stronger surface cooling (Fig. 2d 3d) can cause either a strengthening ~~or weakening~~ of the AMOC by

enhancing deep-water formation in the North Atlantic (Oka et al. 2012, Smith and Gregory 2012) or a [weakening of the AMOC](#) by increasing the amount of sea ice over the northern North Atlantic and Southern Ocean (Oka et al. 2012, Kawamura et al. 2017). Considering the increase in sea ice over both poles (Fig. 34) and the increase in the bottom ocean stratification (Fig. 45i), changes in surface cooling seem to play a role in reducing the AMOC, which is the opposite of the effects of surface wind.

To clarify the effect of surface cooling by the mid-glacial ice sheets on the AMOC, partially coupled (PC) experiments are conducted (Table 2, Fig. 910). In the first two experiments (PC-MIS3 and PC-MIS3-5aice), the surface wind stress and atmospheric freshwater flux are replaced with the climatological forcing of MIS3 and MIS3-5aice, respectively. In both experiments, ~~while~~ the AMOC becomes stronger than in the corresponding original experiments, [though](#) it remains in a similar state as simulated in MIS3 and MIS3-5aice. Therefore, the PC experiments reproduce the general pattern of the original experiments. The slight strengthening [of the AMOC](#) is associated with an initiation of deep-water formation over the Irminger Sea, which is related to the removal of daily variations in the surface wind (see further discussion in [section 4, Figs. 9 and 10](#)~~the supplementary file, Fig. S3~~).

In the third experiment (PC-MIS3heat), in which the monthly climatology of surface wind stress and atmospheric freshwater flux ~~from~~ [MIS3-5aice](#) are replaced with those of MIS3-5aice (Table 2), the AMOC changes drastically. The maximum strength of the AMOC decreases to 11 Sv (Fig. 910) and the sea ice covers the deep-water formation region (Fig. 1011, Fig. S1e). Similar weakening is also observed in PC-MIS3heatano (Fig. 910). Because the surface wind and atmospheric freshwater flux are identical to those of MIS3-5aice, this result shows that the intense surface cooling by the MIS3 ice sheets reduces the AMOC. These simulations show that the weakening effect of the surface cooling ~~compensate~~ [compensates](#) the strengthening effect of the surface wind, and hence induces a small change in the AMOC between MIS3 and MIS3-5aice.

How does the intense surface cooling reduce the AMOC? Two processes play a role- (Fig. 12). The first process is associated with the intense surface cooling over the northern North Atlantic. Due to this surface cooling, the sea ice increases over the northern North Atlantic, ~~and it melts over the deep-water formation region and~~ (Fig. 11b). The increase in sea ice tends to weaken the oceanic convection and the AMOC (~~Fig. 10b~~ [by insulating the atmosphere-ocean heat flux](#) (Oka et al. 2012) [and by increasing the meltwater flux over the deep-water formation region](#) (Born et al. 2010). In addition, colder water occupies the subsurface ocean in MIS3 compared with MIS3-5aice. As a result, the oceanic column is more stable with respect to temperature (Fig. 4eS2). When the mid-glacial ice sheet generates strong winds, the large surface salinity ~~overcome~~ [tends to overcome](#) the thermally stratified oceanic condition and hence maintains the deep-water formation- (Fig. S2). However, when only strong surface cooling is applied, the deep-water formation is interrupted and the AMOC weakens. The second process involves the Southern Ocean cooling- (Fig. 3d). Due to the intense surface cooling in the northern North Atlantic, the temperature of the NADW decreases, which is transported to the South and outcrops at the sea surface. This cooling anomaly

is further amplified by the atmosphere and sea ice feedback. As a result, the formation of sea ice near the Antarctic coastal regions increases and enhances the formation of the Antarctic bottom water (AABW). This causes an increase of density of AABW as well as bottom ocean stratification and reduces the AMOC (Fig. 5i, Weber et al. 2007, Buizert and Schmittner 2015, Sun et al. 2016, Klockmann et al. 2016, 2018). Due to these processes, the AMOC weakens in response to the intense surface cooling by the mid-glacial ice sheet.

5 Discussion

The results above demonstrate a substantial impact of the mid-glacial ice sheets on the global climate. They contribute to a global cooling of 1.1 °C from MIS5a to MIS3, which is about 40% of the total surface cooling from MIS5a to MIS3. As shown by previous studies, the expansion of northern glacial ice sheets causes an intense cooling over northern North America and Europe. Interestingly, the expansion of the mid-glacial ice sheet also causes a surface cooling of 2 °C over the Southern Ocean. It has been thought that the changes in Northern Hemisphere ice sheet have a small impact on the climate over the Southern Hemisphere. For example, Manabe and Broccoli (1985) show with an AGCM coupled with a slab ocean model that the glacial ice sheets have a small impact on the climate over the Southern Hemisphere. The present study shows that the Northern Hemisphere glacial ice sheets can modify the climate over the Southern Hemisphere and deep ocean via oceanic heat transport, whose effect is not included in their study. These results hence show the importance of the ocean dynamics and long integrations in assessing the effect of glacial ice sheet on the global climate. Similar results are also reported for other AOGCMs, which use ice sheet reconstructions of the LGM (Galbraith and de LangenLavergne 2019) and deglaciation (Roberts and Valdes 2017). This study further confirms that this effect is applicable in the mid-glacial period as well.

The changes in ice sheet from MIS5a to MIS3 exert a small impact on the AMOC, unlike the results of previous studies using LGM ice sheets. Partially coupled experiments show that the intense surface cooling by the glacial ice sheets compensates for the strengthening effect of the surface wind by increasing the amount of sea ice over the North Atlantic and the Southern Ocean (Fig. 4). As a result, the induced changes in the AMOC are small. Hence, it is found that the total impact of the expansion of the glacial ice sheet is determined by the balance between the wind effect and the surface cooling effect (Fig. 12). Considering the fact that most climate models show a strengthening of the AMOC in response to the glacial ice sheet expansion, the effect of surface wind dominates seems to dominate in most models. The reason behind this still remains elusive, though we speculate that two processes play a role. The first process is associated with the change in wind-driven ocean transport of heat over the subpolar region. For example, the strengthening of the surface wind can increase the strength of the northward oceanic heat transport at high latitude by enhancing the wind-driven ocean circulation. This causes an increase in the surface air temperature and a decrease in sea ice at high latitudes and can reduce the effect of a stronger surface cooling by the glacial ice sheets. The second process is associated with a strong northerly wind east of the North American ice sheet (Fig. 8b). Due to this strong northerly wind anomaly, a large amount of sea ice is transported to the south in MIS3 compared

with MIS3-5a ice (Fig. S4). Thus, the sea ice is transported inefficiently to the deep-water formation region in MIS3. As a result, the cooling effect of the glacial ice sheet may be reduced and thus the wind effect becomes stronger. In contrast, Kim (2004) show a weakening of the AMOC in response to the expansion of the glacial ice sheet. In these simulations, the effect of surface cooling may be stronger than the wind effect. Hence, further analysis on these model outputs would contribute to a better understanding on the relative importance of wind effect and cooling effect on the AMOC.

330 Why is the strength of the cooling effect comparable to the wind effect in this study? In the present study, the main difference in the ice sheet between MIS3 and MIS5a appears in the extent of the ice sheet, while the differences in the height is relatively small (Fig. 1). According to previous studies, it has been shown that the strength of the wind is largely sensitive to the height of the ice sheet (Gong et al. 2015, Sherriff-Tadano et al. 2018), while the surface cooling is sensitive to the extent of the ice sheet (Abe-Ouchi et al. 2007). Hence, the changes in surface wind may be ~~smaller~~small compared with those obtained from other studies using the LGM ice sheet, whereas the change in surface cooling is large in this study. As a result, the AMOC changes only modestly. These results show that the relative strength of the surface wind and surface cooling can depend on the ice sheet configurations, which may cause different responses in the AMOC (Ullman et al. 2014). Furthermore, this result implies that the history of the shape of the ice sheets (changes in the extent and height) is an important factor when interpreting climate change during the glacial period.

340 The effect of surface cooling on the AMOC seen here is qualitatively different from some previous studies. For example, Schmittner et al. (2002) show that ~~the strengthening of a~~ stronger surface cooling over the North Atlantic enhances the AMOC in their glacial simulation by conducting partially coupled experiments with an earth system model of intermediate complexity. In addition, Smith and Gregory (2012) suggest that the glacial ice sheets enhance the AMOC through strengthening the atmosphere-ocean heat exchange over the deep-water formation region based on their AOGCM experiments. The discrepancy among models may be attributed to two aspects. The first aspect is associated with the ~~strength~~magnitude of surface cooling over the Southern Ocean. ~~If the surface~~For example, if glacial ice sheets cause a very small cooling over the Southern Ocean ~~is weak,~~in other models, this will reduce the weakening effect ~~on the AMOC~~of the AMOC through the Southern Ocean (Fig. 12). As a result, the overall weakening effect by the glacial ice sheet ~~induced-cooling~~ may on the AMOC should be reduced.

350 The second aspect is related to the thermal threshold of the AMOC. As shown in Oka et al. (2012, 2020), the effect of enhanced surface cooling on the AMOC can depend on the distance from the thermal threshold; when the system is far from the threshold in the parameter space, the surface cooling strengthens the AMOC by enhancing deep-water formation. In contrast, when the system is close to the thermal threshold, a stronger surface cooling can cause a drastic weakening of the AMOC by covering the deepwater formation region with sea ice. Based on this result, in the present study, the AMOC may be close to the thermal threshold; hence, stronger surface cooling triggers a drastic weakening of the AMOC, whereas the AMOC may be far from the thermal threshold in other studies. Hence, we do not ~~deny~~exclude the possibility that the stronger surface cooling can

intensify the AMOC when the system is far from the threshold. The important point shown in this study is that ~~the strengthening of a stronger~~ surface cooling by glacial ice sheets can affect the thermal threshold of the AMOC and weaken it.

360 ~~The PC experiments show a slight strengthening of the AMOC compared with the corresponding original experiments. This overestimation is induced by an initiation of deep water formation over the Irminger Sea, in association with the change in sea ice transport. In the PC experiments, the sea ice becomes thicker near the south-eastern Greenland shore and thinner in the centre of the subpolar region, which increases the gradient of sea ice thickness from the shore to the open ocean (Fig. 10e). Because the climatological surface wind stress applied to the oceanic component is identical between the PC experiments and~~
365 ~~original experiments, the only difference in the surface wind stress is the removal of the sub-monthly variations in the surface wind stress in the PC experiments. In fact, in another sensitivity experiment, in which we cyclically apply the raw daily winds of the last 100 years of MIS3 to the oceanic component (PC-MIS3day), the strength of the AMOC and the sea ice thickness resembles that of MIS3 (Figs. 9 and 10d). Hence, the slight increase in the PC experiments are associated with the removal of sub-monthly variations in the surface wind stress, which transport the sea ice from the shore to the open ocean and reduce the~~
370 ~~gradient of sea ice thickness. This result implies that the variability in the surface wind on a sub-monthly time-scale plays a role in homogenizing the ice thickness distribution.~~

The time series of the maximum AMOC shows an increasing trend in PC-MIS3heat (Fig. 910). This trend ~~is~~may be associated with two factors: oceanic feedback and the lack of atmospheric feedback in response to a drastic weakening of the AMOC.
375 With respect to the oceanic feedback, the weakening of the AMOC causes a warming ~~of the subsurface ocean. Furthermore, the warming~~ over the Southern Ocean due to ~~a bipolar see-saw affects~~the reduction in the northward heat transport, and hence ~~reduces~~ the deep ocean stratification (Fig. 11) ~~and the density of AABW~~. These processes ~~tend~~may contribute to re-strengthen the AMOC (Brown and Galbraith 2016, Vettoreti and Peltier 2016 Weber et al. 2007, Buizert and Schmittner 2015, Jansen 2017, Klockmann et al. 2018). With respect to the lack of atmospheric feedback, previous studies show that the expansion of
380 sea ice ~~due to a reduction of the AMOC~~ causes a weakening of the surface wind over the North Atlantic by ~~increasing the static stability of the lower troposphere (Byrkedal et al. 2006), which,~~ Sherriff-Tadano and Abe-Ouchi 2020). They further show that this weakening of the surface wind plays a role in maintaining a weak AMOC ~~and extensive sea ice (Figs. 10~~ by ~~reducing the wind-driven transport of salt to the deepwater formation region (Zhang et al. 2014a, Sherriff-Tadano and~~ ~~11,~~ ~~Sherriff-Tadano and~~ Abe-Ouchi 2020). In the partially coupled experiments described above (PC-MIS3heat), the sea ice covers
385 ~~the large area of northern high latitude (Fig. S1e), and should activate this positive feedback, which will stabilize the weak AMOC. However,~~ these atmospheric feedbacks are removed in PC-MIS3heat and hence ~~contribute~~may contributed to the destabilization of the weak AMOC. In fact, in PC-MIS3heatano, in which anomalies of the atmospheric forcing are applied, and hence the atmospheric feedback in response to the AMOC weakening is retained, the increasing trend of the AMOC after the weakening is very small (Fig. 910). Therefore, these two processes ~~cause~~may play a role in causing the increasing trend in
390 PC-MIS3heat.

We should note that the volume of the ice sheets used in this study (40-meter sea level equivalent for 80 ka and 96-meter sea level equivalent for 36 ka) are overestimated compared with reconstructions. For example, sea level reconstruction suggests an ice sheet volume of approximately 40- to 90-meter sea level equivalent during MIS3 (Grant et al. 2012, Spratt and Lisiecki 2016, Pico et al. 2017), which is smaller than that used in this study. Furthermore, recent studies even show a much smaller ice sheet during a portion of MIS3 (Pico et al. 2017, Batchelor et al. 2019). Nevertheless, these reconstructions still show that the ice sheets are slightly larger in MIS3 compared with those in MIS5a (Pico et al. 2017). Hence, while the quantitative effect of the mid-glacial ice sheet might be overestimated in the present study, the qualitative impact of the expansion of MIS3 ice sheet relative to MIS5a is unlikely to change.

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The present study has implications for the understanding of climate variability during the glacial period. Ice core studies have shown that the stability and duration of the interstadial climate are strongly related to surface cooling over the North Atlantic (Shultz 2002, Lohmann and Ditlevsen 2019) and Southern Ocean (Buizert and Schmittner 2015). For example, Shultz (2002) shows that the enhanced surface cooling by the expansion of the glacial ice sheet may explain the shortening of the duration of the interstadial during the mid-glacial period. However, modelling studies have been showing a strengthening of the AMOC in response to the ice sheet expansion, which stabilizes a vigorous AMOC and the interstadial climate. In contrast, this study shows a possibility that the expansion of glacial ice sheet can in fact cause the weakening of the AMOC and hence destabilization of the vigorous AMOC, which contributes to shorter interstadial duration. This is the case when the effect of surface cooling dominates the effect of surface wind. In this case, both the ~~enhanced~~ stronger surface cooling over the North Atlantic and the Southern Ocean can play a role, which are consistent with ice core studies (Buizert and Schmittner 2015, Lohmann and Ditlevsen 2019). This result suggests that the changes in the relative strength of surface wind and surface cooling can affect the AMOC and climate drastically and may be important in interpreting the millennial time-scale climate variability of the glacial periods.

410

6 Conclusions

In this study, the role of mid-glacial ice sheets on the global climate and the AMOC is explored. For this purpose, simulations of MIS3 and MIS5a are conducted with the comprehensive climate model MIROC4m. The ice sheet configurations are taken from an ice sheet model, which reproduces the ice sheet evolution over the past 400,000 years (Abe-Ouchi et al. 2013). Furthermore, to assess the processes by which the mid-glacial ice sheets affect the AMOC, ~~PC~~ partially coupled experiments are conducted with MIROC4m. The main results of the present study can be summarised as follows:

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In the MIS3 and MIS5a simulations, the global average temperature decreases by 5.0 °C and 2.2 °C, respectively, compared with the PI climate simulation. Comparison of the MIS3 and MIS5a results show that the expansion of mid-

glacial ice sheets contributes to a global cooling of 1.1 °C, which is about 40% of the total surface cooling from MIS5a to MIS3 of about 2.8 °C.

425 The southward expansion of northern mid-glacial ice sheets not only causes a drastic cooling over the northern North Atlantic, but also causes a 2 °C of surface cooling over the Southern Ocean. The cooling over the Southern Ocean is associated with the cooling of the NADW.

The AMOC is enhanced by 16% in MIS5a, whereas it weakens by 3% in MIS3 compared with the preindustrial climate simulation. The weaker AMOC in MIS3 compared with MIS5a is consistent with a previous proxy study (Bohm et al. 2015).

430 A sensitivity experiment that modifies the glacial ice sheets showed that the southward ice sheet expansion [from MIS5a to MIS3](#) exerts a very small impact on the AMOC (0.5 Sv), despite the strengthening of surface wind and wind-driven ocean circulation over the North Atlantic, which tends to intensify the AMOC (Oka et al. 2012, Klockmann et al. 2016, Sherriff-Tadano et al. 2018).

435 Partially coupled experiments reveal that the ~~intense~~[stronger](#) surface cooling by the glacial ice sheet weakens the AMOC and counteracts the strengthening effect of surface wind. The surface cooling increases the sea ice over the northern North Atlantic, which ~~melts over the deep-water formation region~~[insulates the atmosphere-ocean heat exchange](#) and weakens oceanic convection. Also, the northern surface cooling causes a cooling over the Southern Ocean, which strengthens [and increases the density of](#) the AABW, increases the stratification of the bottom ocean, and weakens the AMOC.

440 It is found that the total impact of glacial ice sheets on the AMOC is determined by the relative strength of two factors, surface wind and surface cooling- ([Fig. 12](#)). In most models, the effect of surface wind is stronger; hence, the AMOC strengthens in response to the ice sheet expansion. In the present study, the main difference in the ice sheets appears in their extent, rather than their height. As a result, the strength of the cooling effect become comparable to that of the wind effect, and it causes small changes in the AMOC. Our result suggests that the relative strength of the wind effect and cooling effect depends on the shape of the ice sheet reconstructions.

445 The results of the present study also offer a global dataset of climate during MIS3 and MIS5a, which ~~is~~[has been also provide](#) by previous studies (e.g. Van Meerbeek et al. 2009, Gong et al. 2013, Menviel et al. 2014, Guo et al. 2019), though still lacking compared with the LGM (~~Gong et al. 2013, Guo et al. 2019~~). Recently, the amount of reconstruction of mid-glacial period is increasing (Jensen et al. 2018), and hence more detailed comparisons with these reconstructions need to be conducted in future. Furthermore, the present results provide a reference climate state for investigating the millennial time-scale climate variability that occurred during the mid and early glacial period (Henry et al. 2016, Mitsui and Crucifix 2017, Guo et al. 2019). In a forthcoming study, we will perform freshwater hosing experiments with these simulations and investigate how the changes in boundary conditions affect climate variability and the recovery time of the AMOC. This can contribute to a better understanding of millennial time-scale climate variability, which is still not fully understood and remains as one of the largest questions in the study of paleoclimate.

Code and data availability

The code of MIROC associated with this study is available to those who conduct collaborative research with the model users under license from copyright holders. The code of partial couple experiments is available from corresponding author (S. S.-T.) upon reasonable request. The simulation data will be available from <https://ccsr.aori.u-tokyo.ac.jp/~tadano/>.

460 Author contribution

All authors conceived the study. S. S.-T. performed the climate model simulation and analyzed the results with the assistance of A. A.-O., and A. O.. S. S.-T. performed the partially coupled experiments with the assistance of A. O.. Manuscript written by S. S.-T. with contributions from all authors.

Competing interest

465 The authors declare no competing interests.

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710 **Table 1: Forcing and boundary conditions of climate simulations. Results of global mean temperature (GMT) and Atlantic meridional overturning circulation (AMOC) are also shown. For reference, results of Preindustrial climate simulation is shown.**

Name	CO ₂	Ice sheet	Obliquity	Precession	Ecc	GMT	AMOC
MIS5a	240 ppm	80 ka	23.175	312.25	0.0288	10.58°C	18.7 Sv
MIS3	200 ppm	36 ka	22.754	251.28	0.0154	7.85°C	15.6 Sv
MIS3-5aice	200 ppm	80 ka	22.754	251.28	0.0154	8.91°C	15.1 Sv

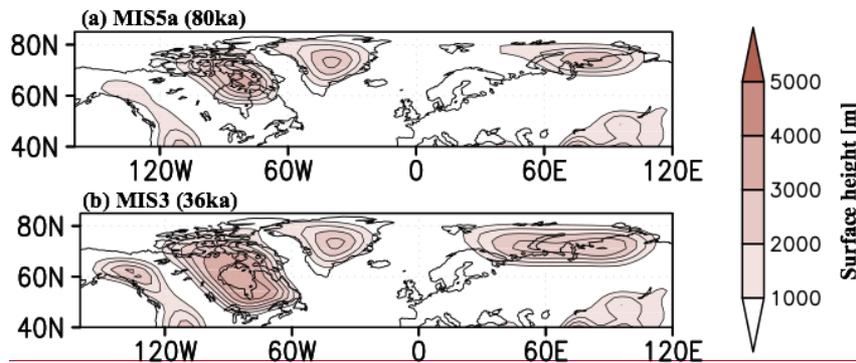
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MIS3-5aice	200 ppm	80 ka	22.754	251.28	0.0154	8.91°C	15.1 Sv
PI	285 ppm	0 ka	23.45	102.04	0.0167	12.83°C	16.1 Sv

Table 2: Partially coupled experiments. In PC-MIS3heatano, climate anomalies in surface wind and atmospheric freshwater (FW) flux between MIS3-5aice and MIS3 are added to MIS3.

Name	Surface wind	Atmos. Fw flux	Surface cooling
PC-MIS3	MIS3	MIS3	MIS3
PC-MIS3-5aice	MIS3-5aice	MIS3-5aice	MIS3-5aice
PC-MIS3heat	MIS3-5aice	MIS3-5aice	MIS3
PC-MIS3heatano	MIS3-5aice	MIS3-5aice	MIS3

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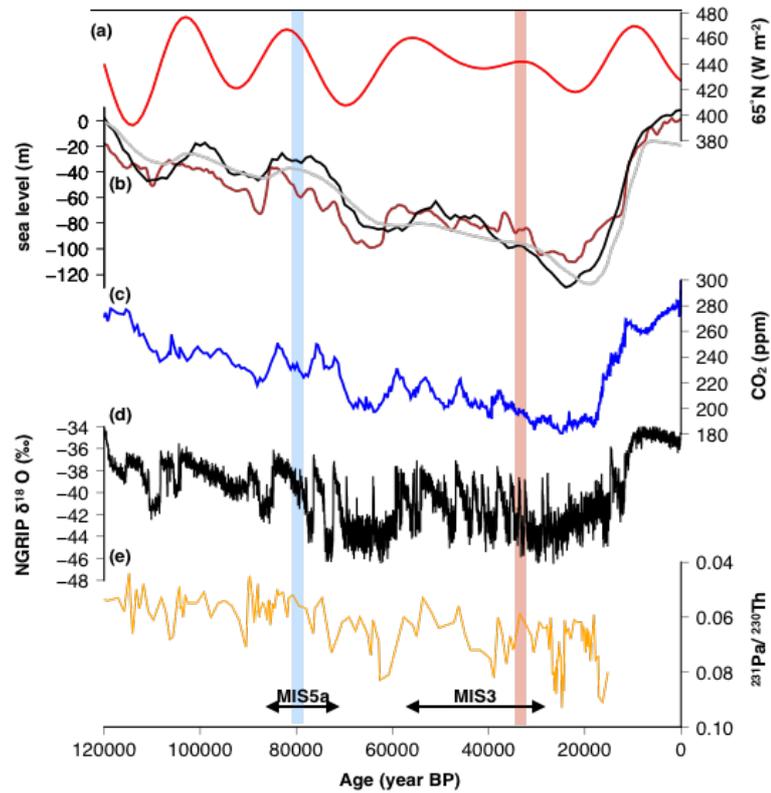


Figure 1

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 by 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 (Rasmussen et al. 2013). (e) Bermuda Rise $^{231}\text{Pa}/^{230}\text{Th}$ (Bohm et al. 2015), which is a proxy of the strength of the AMOC. Red and Blue shades correspond to the target period of MIS3 and MIS5a in our climate model simulations, respectively.

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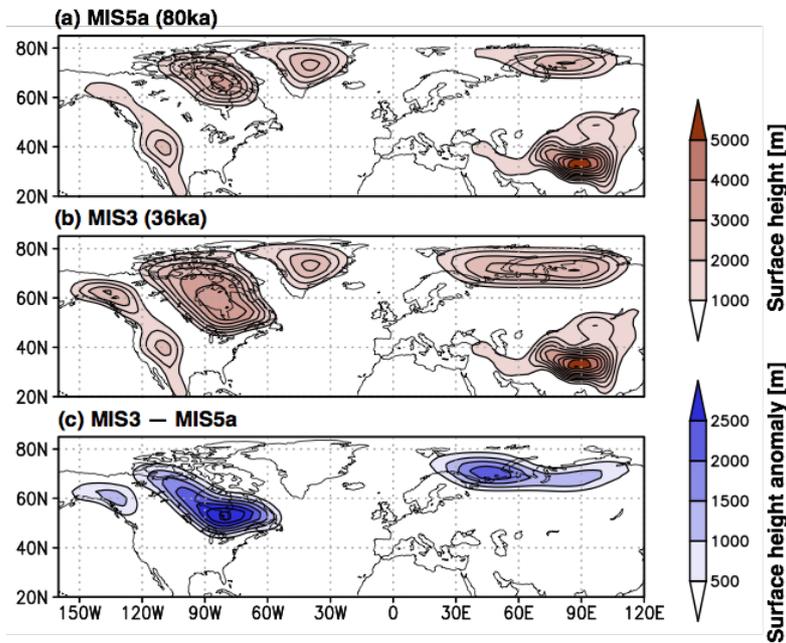
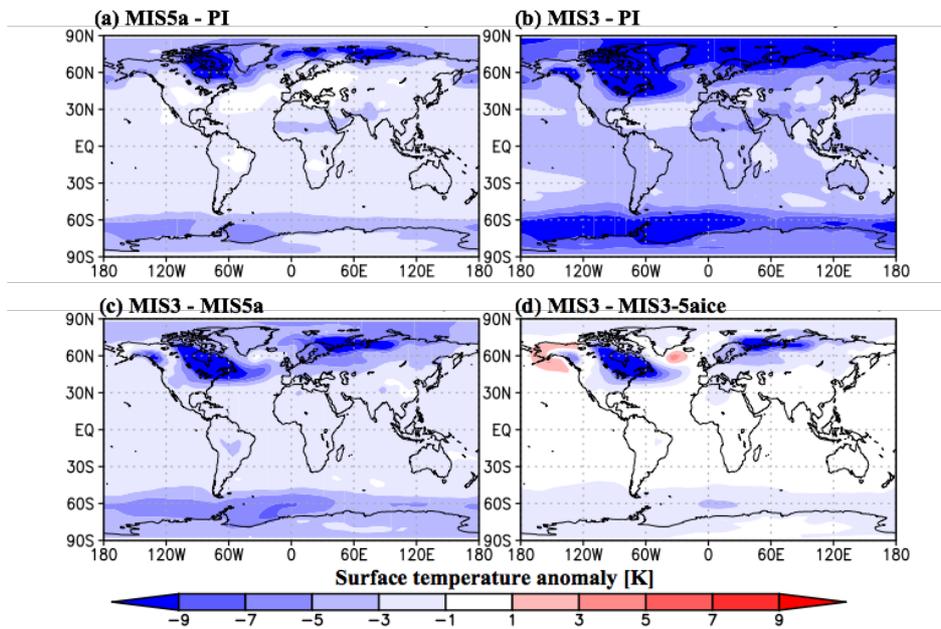
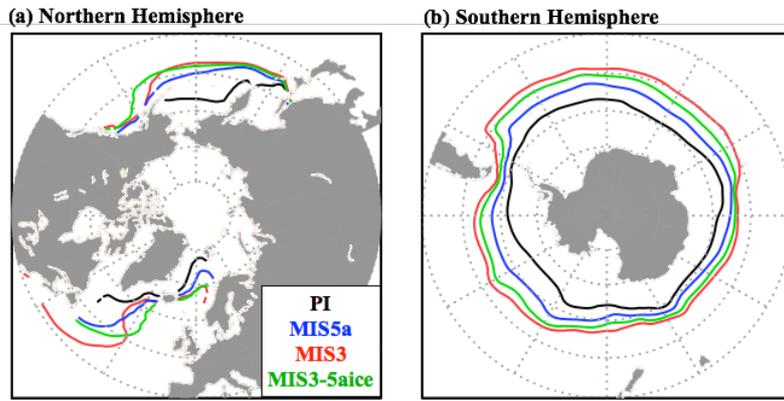


Figure 2: Topography of (a) MIS5a (80 ka) and (b) MIS3 (36 ka). Results from an ice sheet model are presented (Abe-Ouchi et al. 2013). These ice sheet configurations are used for climate model simulations.

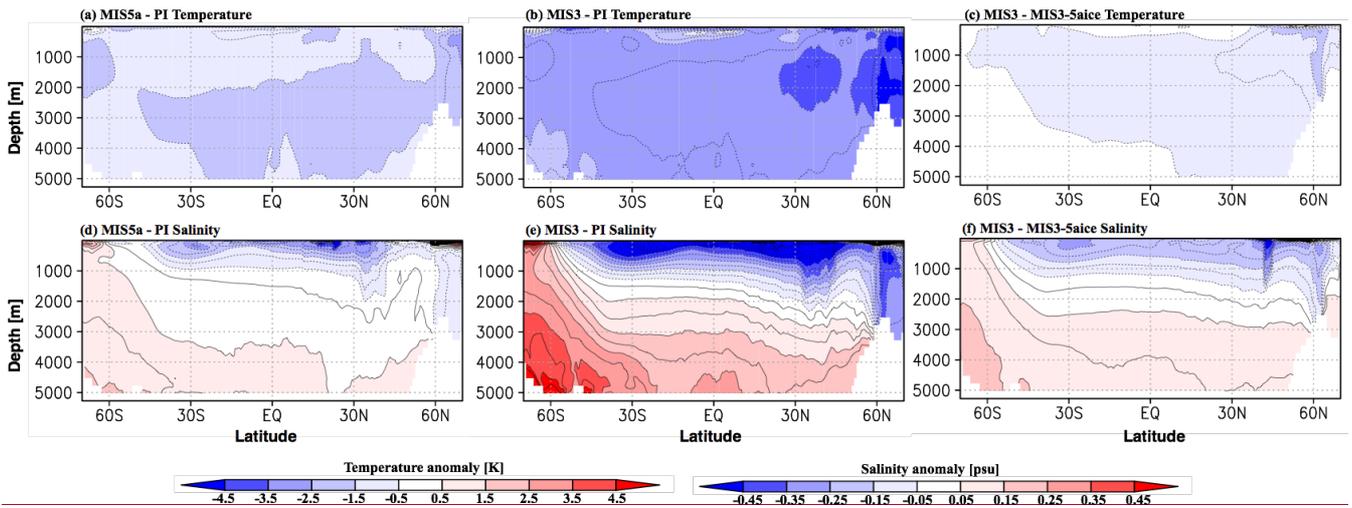


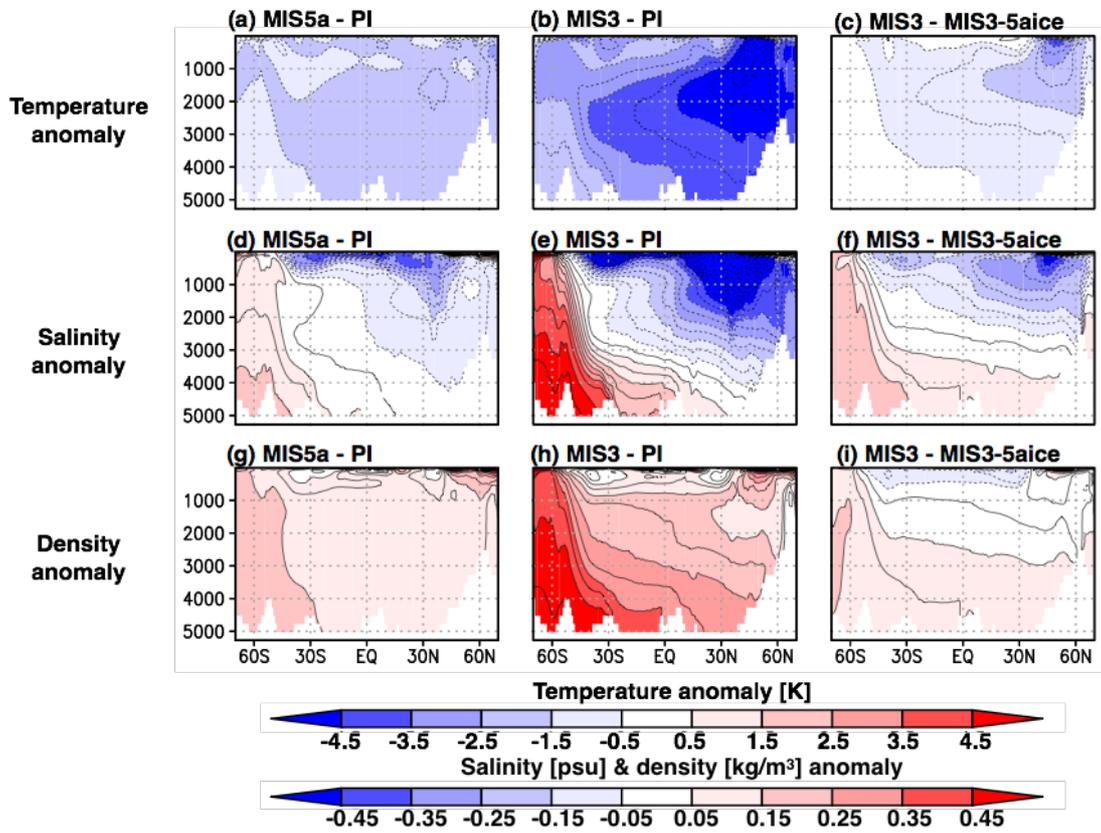
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Figure 23: Surface air temperature anomalies calculated from the AOGCM. The 100-year climatology is used to calculate the anomalies. (a) MIS5a minus PI and (b) MIS3 minus PI. In (c), differences between MIS3 and MIS5a are shown. In (d), the effect of ice sheet expansion from MIS5a to MIS3 is shown (MIS3 minus MIS3-5aice).

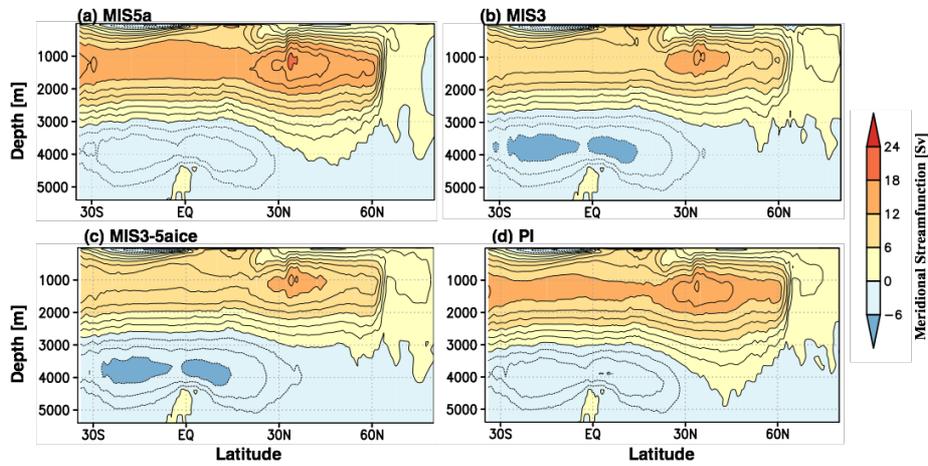


735 **Figure 34:** Annual mean sea ice coverage simulated from the AOGCM. The coverage is defined by 15% sea ice concentration. A 100-year average is used. (a) Northern Hemisphere, (b) Southern Hemisphere. Black: PI, Blue: MIS5a, Red: MIS3, and Green: MIS3-5aice.



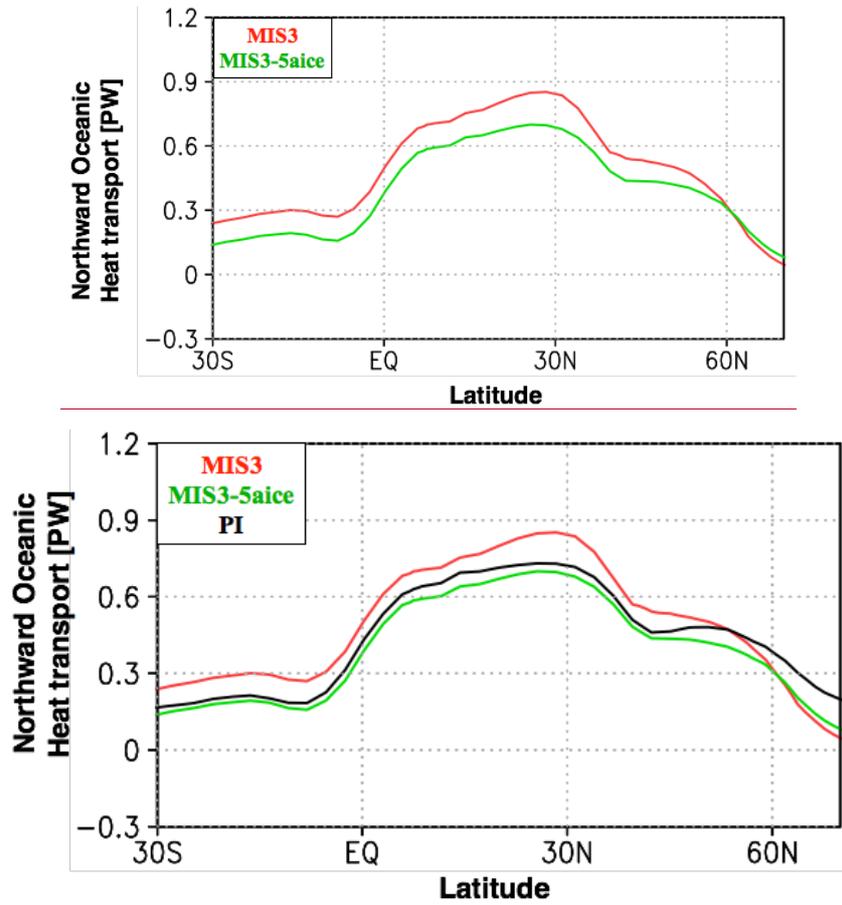


740 Figure 45: Anomalies of zonally averaged oceanic properties over the Atlantic simulated from the AOGCM. The top panels show temperature anomalies, the middle panels show salinity anomalies, and the bottom panels show salinity density anomalies. (a, d, g) MIS5a minus PI, (b, e, h) MIS3 minus PI, (c, f, i) MIS3 minus MIS3-5aice. The climatology of the last 100 years is used to create these figures.

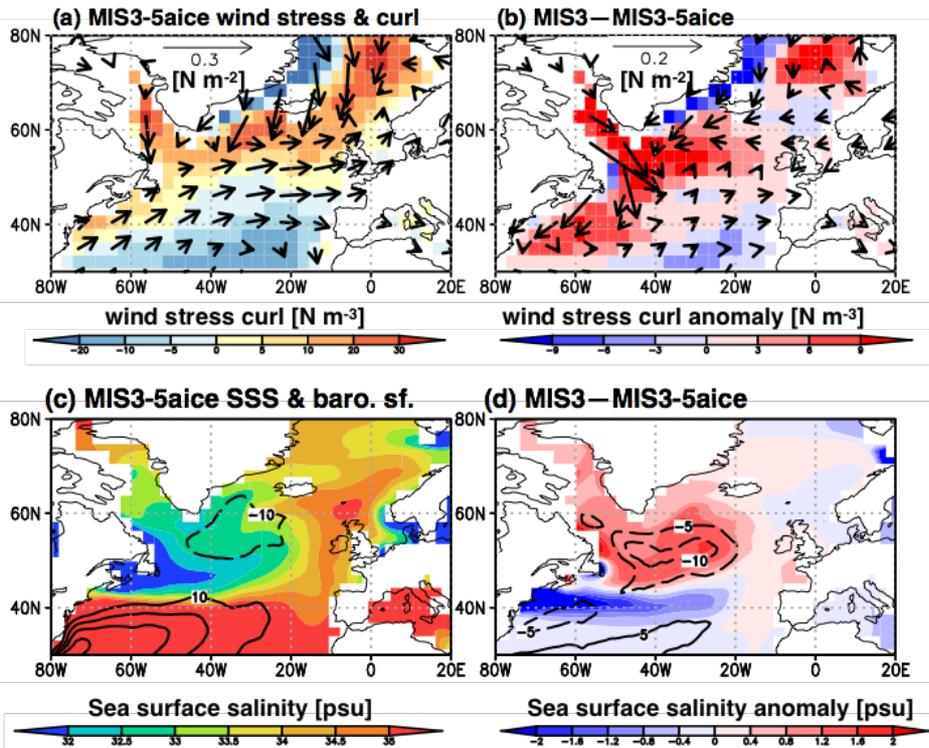


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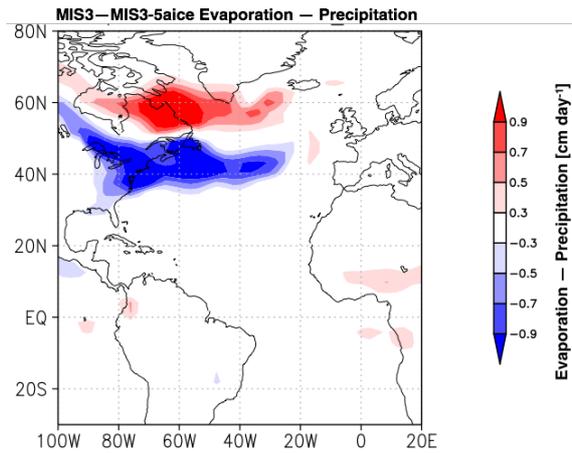
Figure 56: Meridional streamfunction ($Sv=10^6 \text{ m}^3 \text{ s}^{-1}$) over the Atlantic simulated from the AOGCM. (a) MIS5a, (b) MIS3, (c) MIS3-5aice, and (d) PI. The climatology of the last 100 years is used to create these figures.



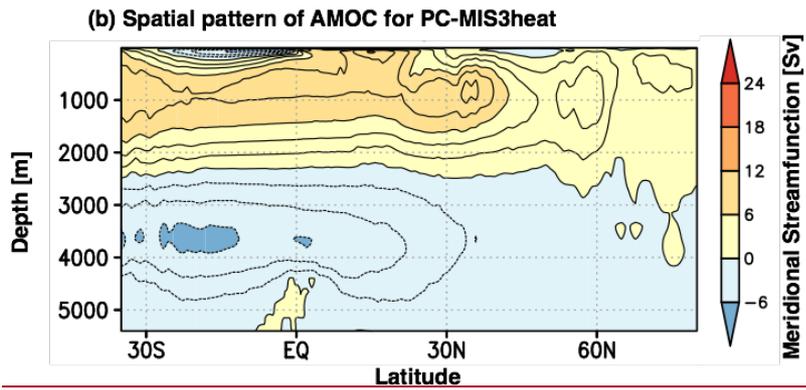
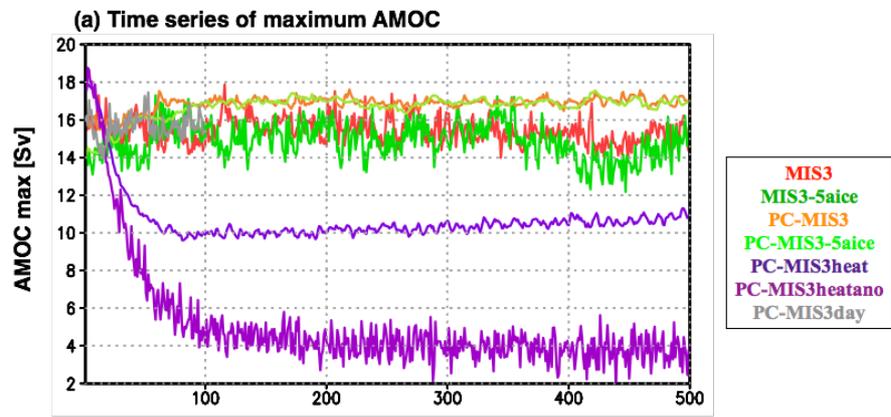
750 Figure 67: Northward oceanic heat transport over the Atlantic basin simulated from the AOGCM. Red: MIS3-and, Green: MIS3-5aice-, and Black: PI. The climatology of the last 100 years is used to create these figures.

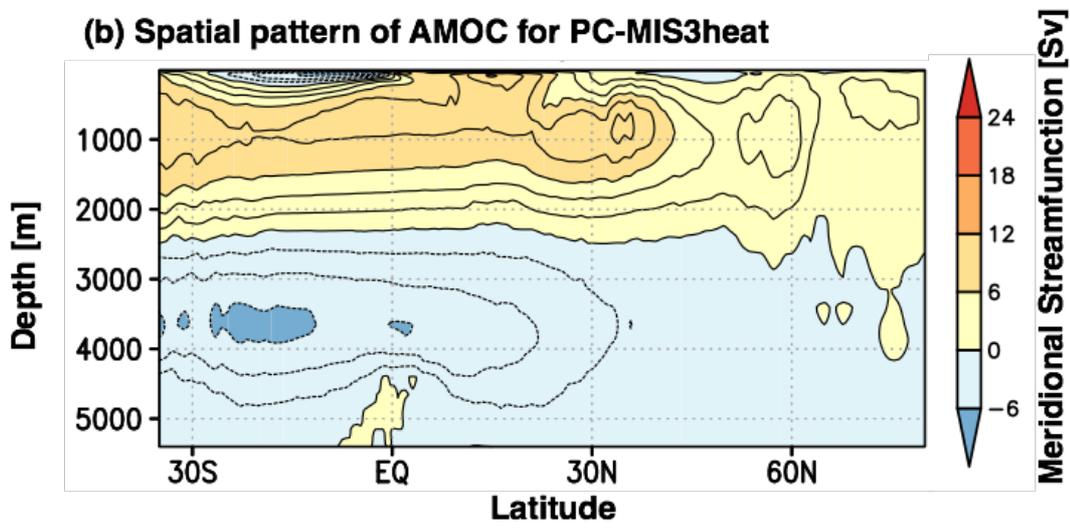
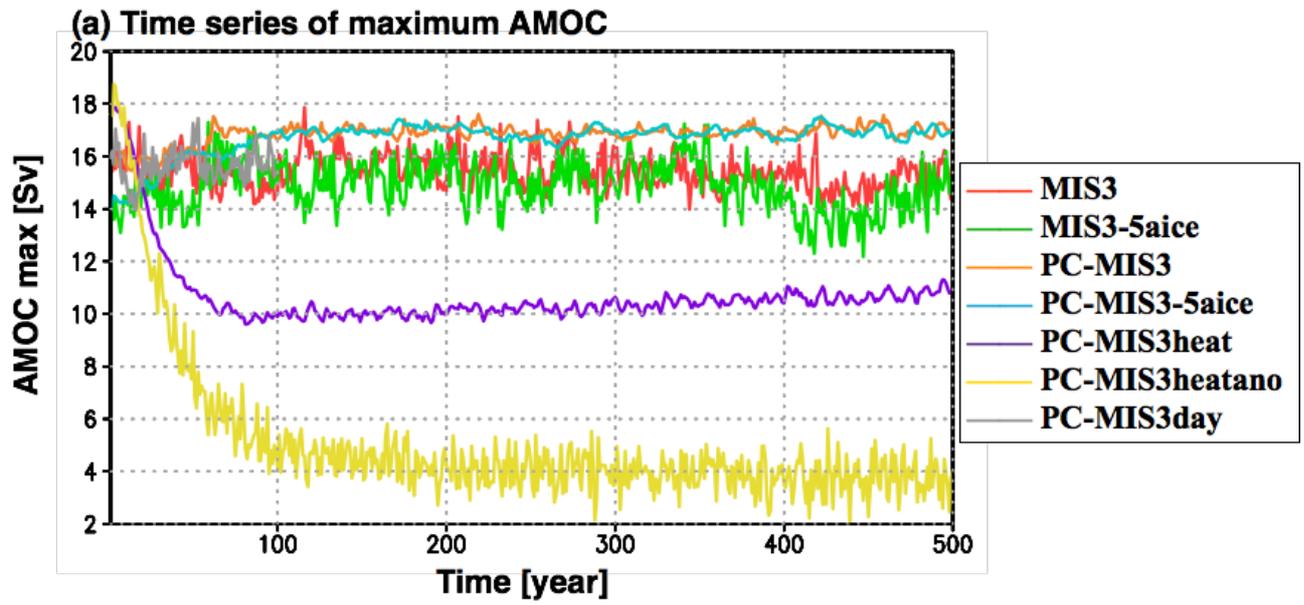


755 **Figure 78:** Changes in surface wind stress and wind-driven ocean circulation associated with expansion of the northern glacial ice sheet from MIS5a to MIS3. Top figures show the surface wind stress (arrow, N m^{-2}) and wind stress curl (colour, N m^{-3}), and bottom figures show the barotropic streamfunction (contour, Sv) and sea surface salinity (colour, psu). (a, c) MIS3-5aice and (b, d) MIS3 minus MIS3-5aice (ice sheet effect). The climatology of the last 100 years is used to create these figures.

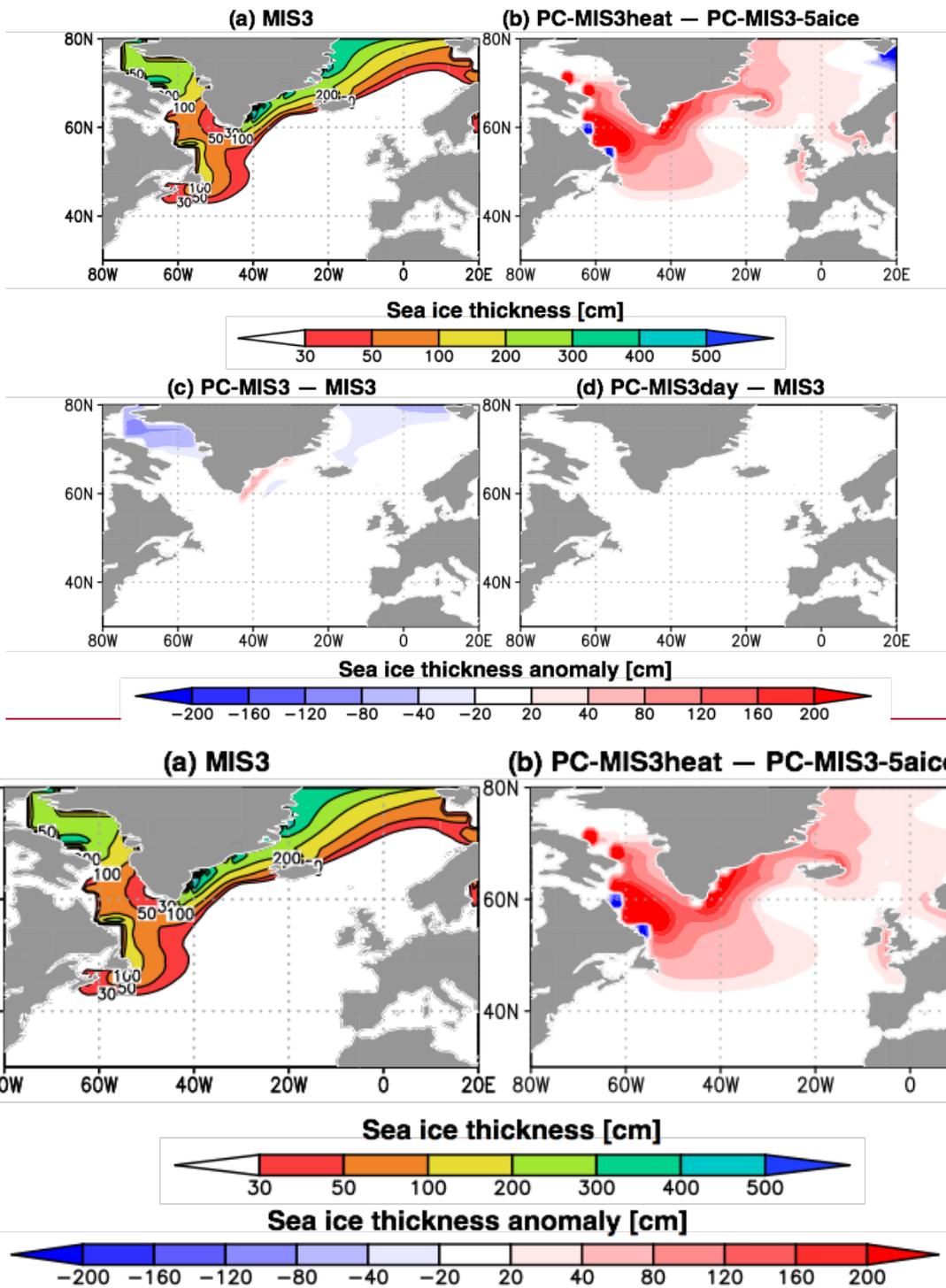


760 **Figure 89:** Anomalies of atmospheric freshwater flux (E-P , cm day^{-1}) out of the ocean between MIS3 and MIS3-5aice. Red colour shows freshwater flux out of the ocean and blue colour shows freshwater flux into the ocean. The climatology of the last 100 years is used to create these figures.



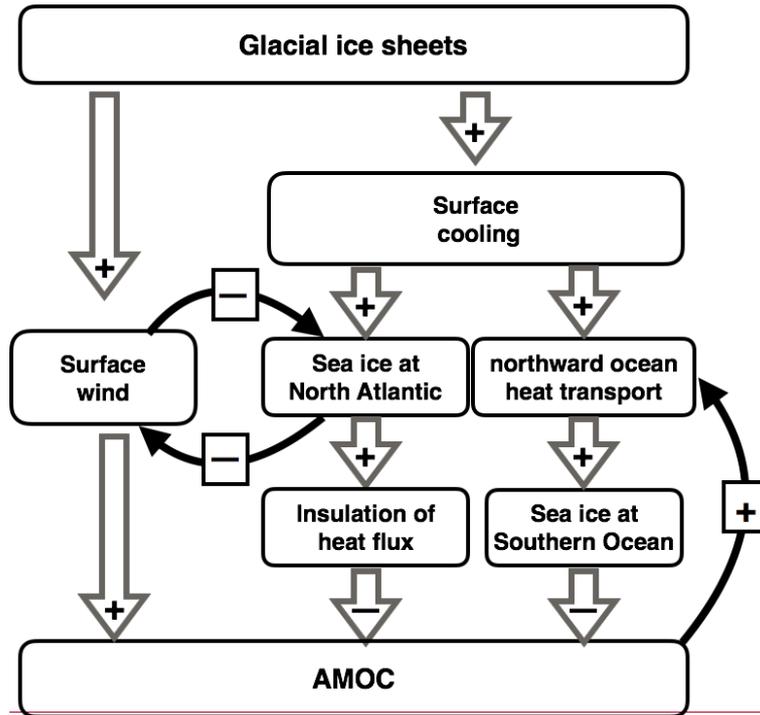


765 **Figure 910:** Results of partially coupled experiment conducted with the AOGCM. (a) Time series of the maximum strength of the AMOC. (b) Spatial pattern of the Atlantic meridional streamfunction calculated from PC-MIS3heat. The climatology of the last 100 years is used to create this figure.

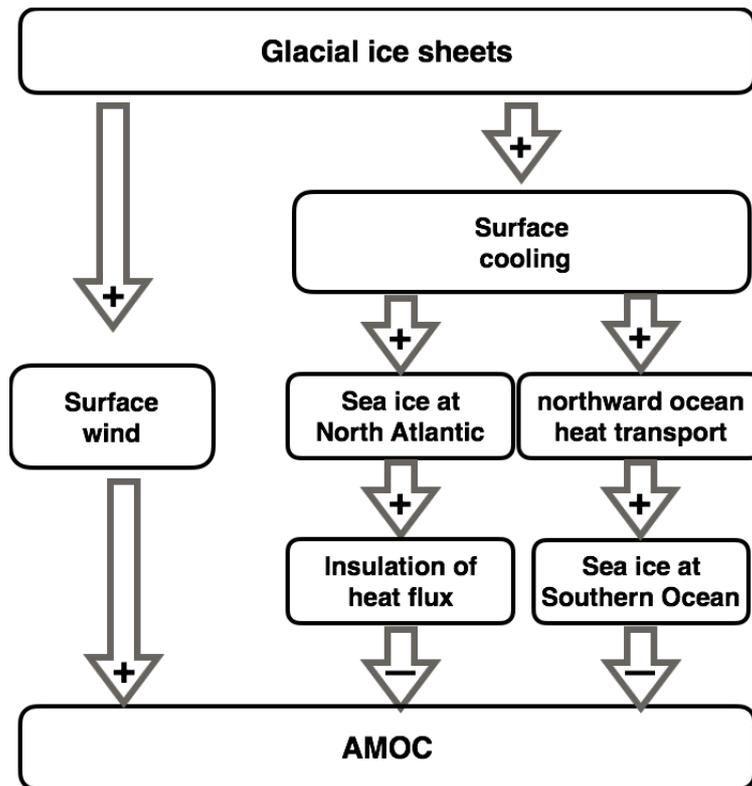


770 **Figure 1011:** Annual mean sea ice thickness (cm, colour) over the North Atlantic simulated from the AOGCM and partially coupled experiments. (a) MIS3. (b) Effect of surface cooling by mid-glacial ice sheet (PC-MIS3heat minus PC-MIS3-5aice). (c) and (d) show

the reproducibility of sea ice thickness by the partially-coupled experiment: (c) PC-MIS3 minus MIS3 and (d) PC-MIS3day minus MIS3. In (a), (b), and (c), the results of the last 100 years are used. In (d), the results of the last 50 years are used for PC-MIS3day. The results of the last 100 years are used.



775 **Figure 11: Schematic of the processes by which changes in the glacial ice sheet affect the AMOC. The black solid arrows indicate a feedback within the atmosphere-sea ice-ocean system (Kawamura et al. 2017, Sherriff-Tadano and Abe-Ouchi 2020).**



780 **Figure 12: Simple schematic of the processes by which changes in the glacial ice sheet affect the AMOC. A stronger surface wind induced by the glacial ice sheets enhances wind-driven transport of salt into the deepwater formation region and causes a strengthening of the AMOC. In contrast, a stronger surface cooling by the glacial ice sheets causes a weakening of the AMOC by increasing the sea ice at the North Atlantic, which insulates the atmosphere-ocean heat exchange (Oka et al. 2012). A stronger surface cooling by the northern glacial ice sheets also causes a cooling and an increase in sea ice over the Southern Ocean by increasing the oceanic heat transport. This change in the Southern Ocean then weakens the AMOC by increasing the density of the AABW and bottom ocean stratification (Weber et al. 2007, Klockmann et al. 2018). Possible internal feedbacks within the atmosphere-sea ice-**

785 **ocean system are discussed in the Discussion section.**