Comments on Ando & Oka 2026

Ando and Oka conduct stand-alone ocean model simulations to explore the impacts of various forcings on the strength of the AMOC. Using anomalous surface fluxes obtained from Paleoclimate Modelling Intercomparison Project (PMIP) models, they investigate the individual and combined impacts of thermal, freshwater, and momentum (wind stress) forcing on AMOC strength. Their findings suggest that thermal forcing weakens the AMOC, with its effects varying spatially. Specifically, LGM thermal forcing over the Southern Ocean weakens the AMOC by increasing the density of Antarctic Bottom Water. Cooling over the North Atlantic, however, has two competing effects. The expansion of sea ice reduces oceanic heat loss to the atmosphere, thereby weakening the AMOC, while enhanced heat loss in the open ocean strengthens it. Moreover, momentum forcing via anomalous wind stress enhances the LGM AMOC by affecting sea-ice transport and wind-driven ocean circulation. The influence of momentum forcing exhibits a clear dependence on the background thermal state. Freshwater forcing, however, has a negligible influence.

The study provides valuable insights into the impacts of various forcings on the simulated glacial AMOC and contributes to the interpretation of the large inter-model spread in AMOC strength across PMIP models. Nonetheless, multiple statements in the manuscript would benefit from the presentation of additional variables. Correlation coefficients are presented without accompanying p-values, which makes it challenging to evaluate the statistical significance and reliability of the results. Furthermore, the manuscript does not provide a comprehensive discussion regarding the specific mechanisms through which wind stress forcing affects LGM AMOC strength. As such, the manuscript requires substantial revisions. My detailed comments are provided below.

Major points:

1. Present additional variables to strengthen the discussion

I recommend that the authors include additional variables to support their statements.

Lines 144–145: The manuscript states, “Nevertheless, COCO reproduced the overall structure of the AMOC and the deep-water formation regions in the Labrador and Irminger Seas.” It would be beneficial to show the simulated winter mixed-layer depth in the COCO model.

Line 200: The text mentions, “while increased sea-ice formation under colder conditions further increases the salinity of newly formed AABW through brine rejection.” It is important to show the simulated changes in sea ice.

Lines 208–210: The manuscript states, “The evolution of the mixed-layer depth indicates that this reduction is associated with the cessation of deep-water formation south of Greenland. The expansion of sea ice into this region reduces air–sea heat exchange and suppresses deep-water formation.” Supporting data should be provided for this claim.

Lines 215–216: The authors note, “In these cases, further cooling over the North Atlantic deepens the winter mixed layer south of the sea-ice edge, around 40°N. This region corresponds approximately to the northern rim of the NADW cell.” Additional variables should also be included to support this statement.

Lines 257–258: The statement “Under the LGM thermal conditions, deep convection in the GIN Seas is largely absent, and deep-water formation in the subpolar gyre becomes dominant” should be supported.

Line 275: To support the statement regarding enhanced surface buoyancy loss in this region and the promotion of stronger deep-water formation, please provide figures illustrating the changes in surface buoyancy flux. This would help to establish the link between increased buoyancy loss and the conditions that lead to deep-water formation.

Lines 290–293: Please add a spatial pattern of evaporation (E), precipitation (P), and river runoff (R) over the North Atlantic. This helps to clarify how E–P–R fluxes affect the salinity in this region.

2. Provide the statistical significance for the correlation coefficients.

Lines 170–172: “The AMOC shows only a weak relationship with the mean Northern Hemisphere SAT ($r = -0.32$; Fig. 5a), and no robust relationship is found when the mean SAT is calculated over the North Atlantic instead of the entire Northern Hemisphere. In contrast, the AMOC tends to weaken as the Southern Hemisphere becomes colder ($r = 0.59$; Fig. 5b).” Please evaluate the significance of the correlation.

Lines 231–232: “The AMOC strength in EXP_T shows little correlation with the maximum westerly wind stress over the North Atlantic ($r = 0.16$).” Again, the authors should provide a p-value to assess its significance.

Line 255: “a moderately positive correlation ($r = 0.45$) is found between the maximum westerly wind stress over the North Atlantic and the AMOC strength.” To classify this correlation as “moderate,” the authors should provide supporting statistical evidence, such as p-values or confidence intervals, which would clarify the strength and reliability of this correlation.

3. On the naming of experiments

The experimental names are somewhat confusing and difficult to distinguish, and I suggest renaming the experiments to improve readability. The prefix “EXP” does not help distinguish among experiments, and some combinations, such as “onl” are quite confusing. I therefore suggest removing “EXP” from the names and renaming all experiments. For example, the authors could:

a. Forcing indicators: Use “H” for thermal forcing, “T” for momentum forcing, and “W” for freshwater forcing.

b. Region indicators: Subscripts “N” for Northern Hemisphere and “S” for Southern Hemisphere can clearly define the regions where thermal forcing is applied.

c. Latitudinal indicators: Superscripts “L” and “H” could be used to indicate the latitudinal range.

d. Sea-ice indicators: Similarly, superscripts “O” and “I” could indicate the ice-covered region and the open ocean, respectively.

The structured naming makes it easier for readers to follow and understand the specific conditions of each experiment.

4. The mechanism of how LGM wind stress affects the AMOC

The discussion of how LGM wind stress affects the AMOC is somewhat vague. The authors state that "Our sensitivity experiments indicate that this effect arises from both changes in sea-ice distribution and wind-driven ocean circulation," but it is unclear what is meant by "wind-driven ocean circulation." Do the authors mean oceanic salinity transport or the subpolar gyre? If wind-driven ocean circulation is indeed a crucial factor, it may be worth examining the wind stress curl rather than only the maximum zonal wind stress. Clarifying these specific mechanisms and citing relevant studies that explore this relationship would be highly beneficial. A deeper understanding of the interaction between wind stress and ocean circulation during the Last Glacial Maximum could provide valuable insights into past climate dynamics and inform contemporary climate models.

5. On the discussion of bathymetry

The authors attribute the differences between their simulated LGM AMOC and that in the PMIP simulations to the use of preindustrial bathymetry, particularly an open Bering Strait. I believe this perspective is somewhat limited. There are several other significant differences in bathymetry between the LGM and the preindustrial period, such as the closed Indonesian Passages, a closed Baffin Bay, and the Canadian Archipelago, among others. Therefore, concentrating solely on the Bering Strait could lead to misleading conclusions.

Furthermore, the authors performed stand-alone ocean-only simulations without interactive atmosphere–ocean coupling, which likely accounts for a considerable part of the observed differences. Last but not least, the mixing scheme in the PMIP models may be quite different from that in the COCO ocean model. Similar surface forcing can result in different responses in deep water. The authors should properly discuss the impacts of these factors on the different responses in the simulated LGM AMOC.

6. On the figures

The figures and figure captions should be improved.

Figure 2: As I understand it, the authors conducted stand-alone ocean model simulations. However, Figure 2 shows values of air temperature and wind stress forcing over land, which seems inconsistent with the context. Moreover, the land fill pattern/colour appears strange. Please check whether the variables are properly illustrated. The figure caption could use some revisions. I would recommend changing "Average LGM anomalies of surface" to "Multi-model mean LGM anomalies" or "Ensemble-mean LGM anomalies." The authors should clarify what the solid and dashed contours represent.

Figure 3 caption: Please clarify the corresponding integration periods for each of the simulations.

Figure 4: Please add more minor ticks and tick labels to the maximum ticks on the y-axis to improve readability.

Figure 4 caption: The AMOC index is actually defined as the maximum overturning streamfunction at 25°N, not 45°N. Please correct this in the text. Additionally, I would like to point out that the black lines represent the ensemble mean, while the gray boxes illustrate the ensemble standard deviation.

Figure 5: Please add tick labels to the maximum/minimum ticks on the x-axis to improve readability.

Figure 6: Please add more minor ticks and tick labels to the maximum ticks on the y-axis to improve readability.

Figure 7: Please adjust the ranges of the x- and y-axes to minimize white space. This adjustment would help highlight the information presented in the figure.

Figure 8: The authors may consider adding correlation coefficients and corresponding p-values in Figures 8a–b.

Figure 9: Please add tick labels for the maximum and minimum values on both the y- and x-axes. The sizes of the solid points in the legend should be modified to prevent any overlap.

Figure 10: Please consider a colour-filled pattern over land. For Figure 10a, it may be beneficial to represent the ice-covered area using colour shading. Revise the titles for Figures 10b, 10d, and 10f to provide more informative descriptions, such as “Differences between EXP A and B.”

Figure 10 caption: Please clarify which months are used to present winter.

Minor points

Line 10: “Thermal conditions of the LGM weakened the AMOC, while wind stress changes strengthened it, whereas freshwater flux had a relatively minor effect.”

Line 33: “... while the strength of the AMOC is influenced by ...” Would it be better to use “and” rather than “while”?

Line 34: “... a thermal threshold of the AMOC ...” It is better to use “for” rather than “of.”

Line 45: “... to reproduce the LGM AMOC consistent with proxy evidence ...” Reformulate to “reproduce an LGM AMOC consistent with proxy.”

Line 69: “as part of CMIP4.” I do not think there is a CMIP phase 4. Please check.

Line 100: “... All other experiments were initialized from the final state of the CTL experiment and integrated for 3000 years ...” The authors should explain which period of each simulation is analysed here.