Review of manuscript by Adloff et al. “Multiple thermal AMOC thresholds in the intermediate complexity model Bern 3D”

In this manuscript, the authors performing several sets of transient experiments in Bern3D investigate thermally induced AMOC stability across glacial cycles. The results are new and complementary to our current theoretical understanding of glacial abrupt climate change. I believe this is a nice contribution to the community and suitable to Clim Past, but I reserve my recommendation for publication of this version since there remains room to improve its robustness and significance. In general, the authors shall 1) provide a more comprehensive introduction/discussion by considering at least most relevant literatures regarding AMOC stability during glacial cycles, 2) improve the clarity for mechanisms and feedback involved before, during and after AMOC transitions and 3) substantiate conclusions/statements by specifying the corresponding plots or adding direct modeling results/literatures. In addition, I would also recommend adding the 800-kyr results at least in the supplementary to provide an overview of the results, which would be of great interest for colleagues who are working on earlier glacial cycles as well.

Detailed comments are as follows:

P2L15-18: Freshwater input might be positive feedback to AMOC weakening as well. please refer to Barker et al 2015 and rephrase the sentences accordingly here as well as in L23-24.

P2L25-29: other key relevant paper should be cited, for instance, Zhang et al., 2014, 2017.

P2L33: also consider citing Zhang et al 2021; Vettoretti et al 2022 here.

P2L45-47: Please add relevant papers after the first sentence (e.g. Knorr and Lohmann 2007, Zhang et al 2017; Galbraith and de Lavergne 2018, etc.)

P4 L5: one predominant feature of glacial cycle is the development and demise of northern hemisphere ice sheet, involving both area and height, of which impacts on climate system are not the same. The former, as discussed in this study, via its albedo feedback is a thermal impact, while the latter, via its impacts on winds, is a kinetic impact (Zhang et al., 2014). In addition, there is no change in Bering Strait considered as well (Hu et al., 2011) (P5L4, a typo there). I was wondering how far these additional setups can alter the key messages of the thermal thresholds in this study. As seeing in my following comments, at least a comprehensive discussion around this is required.

P6 3.1: it would be good to present the 800kyr long transient simulation results. In Figure 1, it is of great help to add the radiative forcing curves to enable a comparison with B.slow experiment.

P7L15-17: As alluded, lacking feedback from topo changes might overestimate the LGM cooling caused by radiative forcing decrease because higher NHIS can cause a stronger AMOC which promotes heat release from the ocean and hence North Atlantic warming. This might stimulate some discussion perhaps in data-model comparison or model limitation sections.

P8. Fig3: given the North Atlantic and Nordic Sea are the key regions for AMOC state shift, it would be better to provide a zoom-in plot for this region, especially for the sea ice fraction plot. Please also revise the color scheme for "sea ice cover fraction" to highlight change in the low values (<0.5) or just provide anomalous field as delta Density. Please also include lat-lon info in the plots. In addition, as you are discussing AMOC states, AMOC plots are highly recommended in this figure.

P8L18-20: in the state (II), deep water formation is enhanced in west and south of Greenland. In general, it is more reddish in State (II) than in State (I), but why the AMOC is weakened in the former. Is this due to that convection in the western North Atlantic is not the key to the strength of the AMOC?

P8L25: "south-flowing fresh Arctic waters further stratify …". This is a key process to stabilize the glacial AMOC state, but in this version, there is not direct evidence to support it. Note that freshwater convergence in Fig5e cannot provide such support to this statement because it is a sum of freshwater flux across both 40N and 70N in the North Atlantic.

P9L10: what is Kolmogrov-Smirnov test? Add details and reference.

P10 Fig 5: Panel e, it would be good to interpret meanings of positive/negative values of freshwater convergence to help readers understand this plot (e.g. positive values indicate freshwater import and hence a stable AMOC). In addition, the definition of freshwater convergence should be added to the Method section. It is worth noting that this AMOC stability indicator (Liu et al., 2014 Clim Dyn) predict a mono-stable AMOC regime in B.slow., in contrast to the hysteresis feature shown in Fig 4b. In addition, comparing the panel a) with Fig 4b, it appears that B.slow.b is initialized from a AMOC state that is bistable with respect to radiative forcing. If so, why the AMOC recovers to its initial strong mode after removing the freshwater input? Typo in y-axis labels of panel c). it is also good to add radiative forcing panel on the top of it, with a vertical shaded bar to highlight periods when AMOC is bistable.

P11L31: how do you identify the reduced heat convergence "off the British Isles" based on the time series in Fig5?

P11L33: It is also not logically clear why this is the cause to the northward spread of AABW. In Fig5, the northward intrusion of AABW is starting from the beginning of the experiment, not lagging the reduction of heat convergence in North Atlantic.

P11L35: why "heat advection to >55N stops entirely"? could the authors present the evidence?

P11L37-39: Again, no direct lines of evidence to support this statement. Does the contemporary sea ice expansion and its seasonality contribute to the freshening in the eastern Nordic Sea? As well as in P11L42-43. Please clarify.

Is there a bipolar thermal seesaw during abrupt AMOC reduction in B.slow? The results appear to show that bipolar sea ice change out of phase with AMOC/NADW change – sea ice expansion with NADW weakening. The subdued thermal seesaw in B.slow indicates the dominant role of decreasing radiative forcing in controlling bipolar change.

P12L27: what's the statement "… increased heat advection into the North Atlantic" based on?

P12L29: weakened north ward transport of what? Upper cell of the AMOC?

P13L1: please show the weakened the meridional salinity gradient in the North Atlantic.

P13L3-5: how does the increased surface density promote SST decrease? This is not clear at all here.

P13L5-7: the authors proposed that sea ice expansion over convection sites acts as negative feedback in response to SST cooling, which is not convincing. This process, as demonstrated in this sentence, can avoid further cooling of sea surface, which in turn reduced sea surface heat loss to increase surface density, and thus stratifying the water column. This seems to exert rather positive feedback to stabilizing the cooling-induced AMOC slowdown. Please clarify. In general, positive/negative feedback discussed in this paragraph is hard to follow. Please clarify with more direct evidence/references.

P13L11-13: As mentioned in previous comments, providing supportive evidence is of crucial importance since this is important positive feedback to the AMOC slow-down.

P13L15: please clarity and specify the positive and negative feedback mentioned here.

P13L22-23: given the gradual decreasing radiative forcing, it is not clear whether it is the self oscillation or just an increased variability (small magnitude, 0.5Sv) as the system approaches the threshold. It appears that AMOC variance is of comparable or even larger magnitude during 6-11kyr (Fig 5b). Is this also corresponding to self-oscillation?

P13P26-33: as discussed, results from B.slow.b seem not to support the hysteresis behavior with respect to radiative forcing change. What about stability/sensitivity of the AMOC at ~6kyr in B.slow?

P13L36: Orbital configuration consists of three orbital parameters. Their combinations in the chosen time slices are different but this does not mean the associated climatic impacts are significantly distinct, for instance, 21ka versus 0ka. It is thus better to show values of obliquity, precession, eccentricity and boreal summer insolation for the chosen time slices here, which would be helpful to clarify whether orbital forcing matters the transient behavior of the AMOC. A better approach to test roles of orbital configurations is to re-conduct such transient experiments based on orbital sensitivity, for example, high versus low obliquity experiments (e.g. experiments in Extended Data Table 1 of Zhang et al 2021).

P14L5-7: not a full list of key relevant papers. Please add Knorr & Lohmann 2007, Banderas et al 2012 and Zhang et al 2017. Re multiple stable AMOC states, the difference in the strength of the AMOC is significantly different with a magnitude of >5Sv. In this context, it appears that the metastable AMOC states proposed here are perhaps sub-states of the interglacial/glacial AMOC state. Given the low AMOC variability in Bern3D, I assume this might not be reproducible by full GCMs nor perhaps in proxies.

P14L12-16: what's the exact role of 'heat advection" in AMOC mode transition? A positive feedback, a trigger or else? It would be good to have a clearer description here to specify the importance of heat advection.

P14L26-27: it is not true. For instance, Zhang et al 2017 applying a fully coupled AOGCM proposes that atmospheric CO2 levels are of control for glacial AMOC bi-stability.

P14L28-30: this may be true if comparing with other EMICs or simple models but not for GCM. Please clarify.

P14L35: please provide modeling results or relevant literatures to support this statement especially regarding poleward moisture transport. It appears to me Fig 5e would be the right panel to refer to given the different trends between Atlantic and North Atlantic freshwater convergence. Sentences in P11L13-14 seem already touch this point, but it requires future clarification to link them to moisture transport and so on.

P15: it is good to see the discussion about potential impacts of other parameters, especially ice sheet topography and associated wind, on the simulated AMOC change in different transient runs. In a glacial cycle, both changes in radiative forcing (e.g. CO2) and wind circulation/gateway caused by ice volume changes play a role in the strength/stability of the AMOC (Hu et al., 2011; Zhang et al 2014, 2017, 2021). Of most relevance here is their opposite impacts on the strength of the AMOC through glacial cycles in comparison to the thermal forcing (Barker and Knorr 2021). In this study, the authors investigated the roles of changes in radiative forcing in AMOC stability, which is the half story of AMOC multi-equilibria in glacial cycles. How do changes in those key parameters influence the results of A experiments? I would be happy to see more comprehensive discussion around this here as well as in Section 3.4 and 3.5. Perhaps, Section 3.3-3.5 can be integrated to one section to highlight and discuss the current understanding of AMOC stability, impacts of current model limitation on the current results and data-model comparison, and their implications and future perspectives.

P15 L14-15: Please add relevant reference to "different representations of processes affecting AABW density changes".

P17 Figure 9: it would be good to flip y-axis of d18O curve upside down, given the tradition of plotting LR04/sea level curves.