Review cp-2023-86-version2 Obase et al.

Summary

In this paper, Obase and co-authors compare transient deglacial simulations that have been run as part of the Palaeo Modelling Intercomparison Project (PMIP), and assess the climate evolution in Antarctica and the Southern Ocean. The paper covers the general comparison of important climate metrics like ocean overturning circulation, surface air and ocean temperatures, etc. and link changes in those metrics to each other. They use two simplified models, a multiple linear regression (MLR) model and a bipolar seesaw model, to assess the response of Southern Ocean SST to changes in Atlantic meridional overturning circulation (AMOC) and atmospheric CO_2.

This is version 2 of the manuscript, which has been revised based on the comments of two other reviewers (not me). The introduction of the paper reads well and covers relevant literature. The methods have been clarified, but I suggest some additional edits. While the results and discussion of the paper are useful and generally presented in a reasonable way, these parts of the manuscript still require substantial polishing to make the material more easily accessible to the reader. At the moment, some concepts are not carefully defined, acronyms are introduced without definition and/or to describe essentially the same thing as another (e.g. WDC/EDC becomes WAIS/EAIS), figures and captions are missing some details, and some phrasings are not clear. This makes the manuscript a lot more difficult to follow than it needs to be. I therefore suggest major revisions of the paper before it is accepted for publication.

One useful outcome of the study is the comparison in deglacial Southern high latitude (SHL) climate response between the different FWF forcing strategies. As mentioned in the manuscript, PMIP models are, so far, incapable of reconciling FWF resulting from the reconstructed ice sheet retreat with the reconstructed AMOC behaviour in this time period (meltwater paradox, Ivanovic et al., 2018; Snoll et al. 2024). While this may have been discussed for the Northern Hemisphere (Snoll et al., 2024), and assessed in individual model papers, this paper allows us to compare the model behaviours that result from the different FWF strategies also for the SHL, and get an idea of the biases that can result from this lack in model skill. Therefore, I would have liked to see a clearer discussion of this. The first half of the final paragraph in Section 4-3 talks about this but does not pointedly link back to the two different FWF strategies. To me, not discussing this in a more concrete way seems like a missed opportunity.

General comments

- The definition of the reference period is not entirely clear. In some instances (e.g., Section 3-2-2), pre-industrial is mentioned but never defined in terms of what that means for these simulations. For the most part, 11ka seems to be the reference period but, in my experience, that would not be referred to as pre-industrial but rather Holocene.

- Bølling-Allerød (BA, 14.7 – 12.8 ka, or 13 ka depending on where in the manuscript you look) and Atlantic Cold Reversal (ACR, 15 – 13 ka) are used nearly interchangeably in the manuscript, which causes unnecessary confusion for the reader. While BA is used in the figures and earlier results sections, ACR starts being used from Section 3-6 and onwards through the Discussion, while still referring to figures with a shading gap that encompasses the BA (which is no longer mentioned). As the ACR is more relevant to this region and to the results of the paper, and even highlighted in the Abstract, it is not clear why it is not indicated earlier in the results section nor in the figures.
- Figure captions require some clarification
- Figure references are somewhat lacking in 3-2-1 and 3-2-2 (see specific comments). References to subpanels are very rare, even though they would be appropriate. In a paper that has so many figures, more substantial figure referencing could be very helpful to the reader.
- In the response to previous reviewers, the authors include a figure R.1. with results from the bipolar seesaw model, which nicely demonstrate that all models would have simulated the ACR if their AMOC changes looked as those in iTRACE. This is a useful result but it is not clearly mentioned in the updated version of the manuscript. I suggest adding the figure to Supplementary figures, and discuss the result in section 4-2.

Specific comments

L. 32: For clarity, consider adding "at this time" before the parenthesis.
L. 49-51: Ocean processes should also be mentioned among the feedbacks, e.g., with a reference to Kohfeld and Ridgwell (2009).
L. 58: Please define "early Holocene".
L. 150-151: "focus on the magnitude and rate of Antarctic [...] (SST) and [...] (SAT) changes" – This sentence would read better as "focus on the magnitude and rate of changes in Antarctic [...] (SST) and [...] (SAT)"
L. 151: "difference between the AMOCs" – This should be more specific, e.g. "difference between the AMOC's strength and temporal evolution".
L. 162: "These simulations are initiated with glacial conditions" – It would be helpful if the authors would add here what time period the simulations cover, or at least what part of these simulations is analysed. This is not entirely clear from the manuscript text in its current form.
L. 167-168: "which shows models simulate reasonable sea ice extent" - I somewhat disagree with this statement. Two models severely underestimate the sea ice extent (SIE), and most others underestimate but to a lesser degree. I suggest changing to something along the lines of "which shows most models underestimate pre-industrial SIE, but mostly to an acceptable level, with more severe underestimates by LOVECLIM and, in particular, iLOVECLIM."
L. 177-178: "elevation change since the LGM" – Make it clear that the elevation is lower in present-day climate by changing to "elevation reduction since the LGM".
L. 181-182: [a] and [b] – Consider changing to capital letters to avoid confusion with panel letters in the figures cited in the same sentence. These groups could be indicated with similar line styles in the figures where all models' time series are shown together. In the current version of the manuscripts, these groups are defined but never referred to with

these attributes a and b again. I feel like you could either rewrite the sentence and skip the attributes altogether "classified into two groups; the first group with FWF adjusted [...], and the second group with FWF consistent with [...]" or, preferably, actively refer back to the two defined groups later in the text.

L. 185-187: "In LOVECLIM and MIROC, the meltwater flux was uniformly applied [...] while other models [...] apply a spatially varying FWF (Table 2) – This particular difference in strategy is not clear from Table 2, and could be clarified in the table. The table mentions the freshwater schemes, but without explanations for what "TraCE-like" and "ICE-6G_C" mean, it is difficult to understand if this refers to the spatial distribution or something else.

L. 202: "maximum and minimum values" → "temporal maximum and minimum values" (if this is what is used in the normalisation?)

L. 204-206: "Every 100-years mean SST, AMOC and CO_2 [...], so each dataset has 90 time-slices." – Does the selection of these 100-year intervals matter? Would the results differ if intervals were spaced/centered differently?

L. 209: At the end of Section 2-2-2, you mention the results table of the bipolar seesaw model (Table 5). You do not mention Table 4 (results of MLR) at all before then. As the table numbering should follow the text, you should mention it here, at the end of Section 2-2-1, in a similar way as Table 5 is mentioned in the next section. That would lead to renumbering of Tables 3 and 4 (switch order) throughout the manuscript but would still allow for related tables to follow each other.

L. 217: The term *m(t)* represents the AMOC modes. That would be even clearer from a quick glance at the equation if you rename it as $AMOC_m(t)$.

L. 223-224: "Based on Figure 2, we assume that the AMOC is in a strong mode (m(t)=0) if the AMOC is greater than 14 Sv." – I assume that AMOC < 14 Sv means m(t)=1, but it should be phrased more clearly that the modes are binary.

L. 236-237: "weaker LGM AMOC if GLAC-1D ice sheet was used" – I suggest "weaker LGM AMOC in sensitivity studies where GLAC-1D ice sheet was used"

L. 238: "compared to pre-industrial (PI)" – When reading the paper, it is quite difficult to follow what the different reference periods are. Sometimes, PI is used (and thus a different control simulation), and sometimes results are compared to 11 ka (thus the transient simulation). The difference is not made sufficiently clear, and I got lost several times reading the parts that make these comparisons.

L. 248: "display an AMOC weakening due to" – It is not clear over what time interval the weakening is happening. Please clarify by changing to "display an AMOC weakening at <time> c.f. <reference time> due to"

L. 250: "simulate an AMOC decline" – This wording suggests a continuous decline throughout the time period. Changing to "a weakened AMOC state c.f. LGM and the BA" would make the wording less open to interpretation.

L. 252: "a gradual AMOC reduction" – Over what time period? Still YD? If so, I suggest changing to "a small but gradual AMOC reduction throughout the YD"

L. 257-260: Please improve figure referencing (specific panels)

L. 262-263: For the EDC warming, refer to Fig. 4a. Noting here that MPI-ESM overestimates the EDC warming c.f. the ice core estimate.

L. 268-269: What temperature is referenced when talking about larger/largest warming (+6-8 degC)? The SATs in Fig. 3? If so, refer to Fig 3 c-d, and clarify the text accordingly.

L. 276-278: Noting that iTRACE also has the largest sea ice area to start with, which may give it a larger potential for reduction compared to other models.

L. 280-282: Please improve figure referencing (specific panel for AMOC) and add reference to Fig. 3 with panels for SAT and SST.

L. 296: “The total deglacial (21-11 ka) warming” - I suggest changing to “The proxy-record based estimates of total deglacial (21-11 ka) warming”

L. 297-300: Please add figure references including specific panels.

L. 299-300: “The Southern Ocean sea ice edge retreats poleward by 10 deg latitude in most models” – This might not be realistic, as most models underestimate the PI sea ice area.

L. 300: “In this area” – Please, be more specific. I am not sure which area this refers to.

L. 309-311: “This indicates that [...] based on ice core reconstructions” – I am struggling to follow this sentence. Is it models that would require additional Holocene warming, or is it proxy record temperatures at 11 ka that are similar to pre-industrial? Also, the onset of the Holocene has not been clearly defined in the manuscript.

L. 319: “significant AMOC changes” - Throughout the manuscript, changes are several times referred to as significant (see e.g. in Section 3-6), though I do not get the impression that the actual statistical significance is tested. I suggest using a different wording, e.g. “substantial AMOC changes” in these cases, to make it clear that these types of statements do not refer to actual statistical significance.

L. 320: “an AMOC weakening” → Not every blue circle shows a weakening c.f. to the previous point. You need to specify that you are referring to a weaker AMOC with respect to the long-term mean.

L. 330-331: “has the potential to explain about half of the SST changes” – What is this estimate based on when the model range is so large? Is it just a mean of all coefficients? Also, I would recommend being more specific as to what SST changes you are referring to, e.g. rephrasing to “Southern Ocean SST anomaly”.

L. 337: It does not quite make sense to me to have the bipolar seesaw model as a separate subsection when the entire section talks about both MLR and bipolar seesaw models and compare them. This section seems more like a continuation of 3-4.

L. 353-374: This section lacks some motivation for why these additional metrics are valuable, and for why certain choices have been made (notably the focus on the onset of deglaciation (L. 354-355), and the subsurface temperatures south of 60ºS at depth of around 500 m.

L. 359-361: Models show different AABW behaviour but, meanwhile, they all show increased SSTs. This might be worth noting.

L. 361-365: These sentences address only the strength of the zonal winds. However, the peak strength latitude could also be of importance, e.g. for SST fields due to shifts in upwelling (add refs.)

L. 366: It would be nice to mention here, and possibly discuss further, that the behaviour of AABW formation, and other variables in this section, are decoupled from the AMOC behaviour. AABW formation behaviour is also not consistent within the two groups of FWF forcing strategies.

L. 369-370: “During the ACR (15-13 ka)” – In the rest of the results section, the focus is on the BA (14.7 – 13 ka), which almost overlaps completely with the ACR. Thus, it seems unnecessary to use two names for such closely overlapping time intervals. I suggest either choosing one of the two, or making it clearer how the two are related and why you want to highlight the ACR.

L. 376-389: This section lacks a few references to specific figure panels (L. 380-381, Fig. 11d; L. 384-385, Fig. 11h).

L. 376: Indicate here that MIROC and HadCM3 belong to different groups of the FWF forcing strategies.

L. 384: “significantly reduces the AMOC” – I suggest changing to “reduces the AMOC by ~15 Sv”. Also, the figure panel letter should be 11f, not b, I think.

L. 384-385: “induces an additional ~1 °C increase in Southern Ocean SST compared to the standard simulation.” – How does this compare to the MLR and bipolar seesaw model results?

L. 422: ~1 °C per 100m – I presume that this is a decrease with increasing altitude, but this should be made clearer.

L. 426: “contrast between EAIS and WAIS” – These acronyms have not been previously defined. Here, it also seems unnecessary to introduce further acronyms to refer to the same areas that have, so far, been known to the reader as WDC and EDC. I suggest either sticking to the same acronyms as before or writing out “contrast between the East and West Antarctic ice sheets”.

L. 427-428: “and the associated impact on the atmospheric circulation” – Here, I would like to see a reference that explains what these impacts may be.

L. 428-431: “In addition, the relatively coarse resolution [...] may impact the AMOC sensitivity [...] or parameterizations of mesoscale processes [...] – I think you need to phrase more clearly what you mean when saying that the resolution impacts the parameterizations. On the one hand, there is the effect of the use of an eddy parameterization, but I am not sure if that is what you are referring to, or if you also mean other effects. Adding some helpful references would also be advisable.

L. 433-434: “additional warming occurs after the onset of the Holocene” – As the onset of the Holocene has not been clearly defined, I struggle to find this warming in the figure.

L. 436-438. “The higher surface elevation [...] may contribute to the simulated Holocene warming” – This confuses me. Above, you say that lower elevation leads to warming. Please, clarify this!

L. 442-443: “HS1 [...] AMOC changes” – It could be useful to reiterate that these sensitivities are tested in the model.

L. 449: “weakly simulated” – I suggest changing to “not fully represented” .

L 449-450: “the largest global mean changes at the LGM (7.3 °C, compared to the six-model mean of 5.3 °C)” – This phrasing makes it sound like the models are warmer at the LGM. I suggest “the largest cooling of global mean SAT at the LGM c.f. PI”.

L. 452: “LGM global mean SAT changes” - Please be specific in what those changes are in reference to (PI?)

L. 463-466: “However, the simulation length [...] climate response at high southern latitudes” – The sentence is long and does not read well. I suggest splitting into three sentences, the first ending after “less than 420 years”. The second sentence can be rephrased as “In this study, we estimate the timescale for the bipolar seesaw to be 500-700 years (Table 5). Thus, longer simulations may be needed to evaluate the extent of the climate response at high southern latitudes.”

L. 469-471: “Other forcings [...] have positive correlations with the CO_2 forcing.” – The message of this sentence is not quite clear to me. Do you mean that other gradual forcings that have positive correlations with the CO_2 forcing could be included in the coefficients? I feel like there may be a word or two missing to make the meaning clear.

L. 471-472: “Antarctic and Northern Hemisphere ice sheet changes could impact Southern Ocean SST through deep-water formation” – How this happens should be briefly explained, adding appropriate references.

L. 477-494: I suggest making it clearer how this part of the discussion relates to the FWF strategies.

L. 506-511: Note that an “accurate” position of the SHW in PI simulations c.f. observations is difficult to achieve when using an atmospheric model of insufficient resolution (Guemas and Codron, 2011; Hourdin et al., 2012). If the position in the control state climate is biased, this affects the potential range for a latitudinal shift in the wind position.

Guemas and Codron, 2011: https://doi.org/10.1175/2011jcli4093.1
Hourdin et al., 2012: https://doi.org/10.1007/s00382-012-1411-3

L. 511-514: The message of the two sentences "In addition, no model [...] and decreasing surface salinity" is unclear. Is the second sentence talking about the models or the real world?

L. 516: (Marzocchi et al., 2020; Stein et al., 2020) – Please also add a reference to Ferrari et al., 2014: https://doi.org/10.1073/pnas.1323922111

L. 534-535: "smaller LGM sea ice extent" – It is not clear what you are referring to. The LGM sea ice extent is smaller compared to what?

L. 538: "a major warming occurs" – Please specify where the warming occurs, e.g. a major warming occurs in the high southern latitudes (HSL). Note that this acronym can also be used in several other places in the Conclusion.

L. 540: "a larger warming" – Specify where the warming takes place by saying "a larger HSL warming"

L. 544-546: "The simulations do not exhibit significant changes in [...] meridional circulation in the Southern Ocean" – Where in the paper was this shown? AABW formation changes substantially.

L. 546: "which could contribute to enhanced CO_2 outgassing from the Southern Ocean" – Does that outgassing really happen? If not, rephrase to "which could have contributed" and make it clear whether this is observed or not.

Table 1, L. 573-574: It is not clear to me what the difference is between "Name" and "Climate model name". References are missing for MPI-ESM and iLOVECLIM. If these simulations are not previously published, then please indicate this.

L. 574: "ECS" – The acronym has not yet been used in the text when the table is introduced, so please also write it out here as "Equilibrium Climate Sensitivity (ECS)".

Table 2, L 576-577: In the text, PMIP 4 is referred to as "Bereiter et al. (2015)". Given that Kohler et al. (2017) is given for the other choice in the table, I would prefer if Bereiter et al. were also listed instead of PMIP4.

Figure 1, L. 583: The caption is not entirely clear. Panel a) Does both insolation lines come from the same reference?, c) There is only one line per ice reconstruction in this panel, but it needs to be clarified that the same colours apply in the next panel, d-e) There is no panel e.

Figure 2: It would be helpful to indicate the groups of FWF in the figure.

L. 591-592: Use these two lines about the shading in all other figures that use this shading (Fig. 3, 6, 10). Each figure caption should be standalone.

Figure 3: Check if this figure is readable for people with colour vision impairment (e.g. using https://www.color-blindness.com/coblis-color-blindness-simulator/). If not, try and also distinguish lines that do not stand out enough by using different line types. Add description about shading (see L. 591-592) to caption.

L. 595: e) "Southern Ocean SST" – This should be more specific, i.e. "zonal mean SST in the latitude band 40-55 °S"

Figure 5: Colour bar title and unit are missing. This is nicely done in Figure 4, but missing here. I am also somewhat confused as to why SATs are not shown here as they are in Fig. 4.

Figure 6, L. 613: In general, the approach used in this figure is informative, but why did you choose the EDC of Parrenin et al. (2013) for the grey line in b? Noting that Buizert et al. (2013) provide both WDC and EDC and could thus also be used. Please, motivate this choice or use both references. Add description about shading (see L. 591-592) to caption.

Figure 7: I would choose to use other colours to indicate the AMOC strength, because blue is instinctively thought of as cold and red as warm, but here, the dots fall on the other end of the temperature spectrum.

Figure 8: Colour bar title and unit are missing.
L. 622: Please specify what you mean by LGM sea ice edges. In the text, you mention winter sea ice edge, and it looks like this is what you are showing, but this should also be clear in the caption.
Figure 10 caption: Add description about shading (see L. 591-592)

Supplementary Materials: Supplementary figure numbering is not consistent with the numbering and order in the main text

Minor comments

L. 147:"feedback" → feedbacks
L. 183: (Fig. 2a, black lines) → (Fig. 2a, upper panel, red and black lines, respectively)
L. 226: "bipolar seesaw models" → bipolar seesaw model
L. 259: Switch the order of LOVECLIM and iTRACE to follow the same order as in the figure.
L. 264: "is not simulated" → is not fully simulated
L. 265: "also" after MPI-ESM is not needed
L. 280, L. 290 and L. 292: Switch order of MIROC and LOVECLIM in text to follow order in figure.
L. 394, L. 408: Fig. S2 → Fig. S3
L. 446: "simulates" → simulate (talking about the five models)
L. 453: Fig. S3 → Fig. S4
L. 473: "from ECS value" → from the ECS value
L. 475 Fig. S4 → Fig. S2
L. 476 "separations" → separation
L. 511 "increase in AABW" → increase in AABW formation
L. 628: "850hPa winds" → 850 hPa eastward winds
L. 577, Table 1: Typo in MPI-ESM and iLOVECLIM Ice sheets "Ice-6G_c" → Ice-6g_C