Review 2 of Antarctic sensitivity to oceanic melting parameterizations

Juarez-Martinez et al. investigated the impacts of emission scenarios, the climate forcings and the heat exchange velocity in the basal melt parameterisation on the projected Antarctic mass loss before 2500 They found that the Antarctic ice sheet contributions to sea level rise highly depend on the heat exchange velocity at the ice-ocean interface and also the climate forcing chosen at high emission scenario. Separate atmospheric-only and oceanic-only experiments show that oceanic forcing plays a dominant role for the West Antarctic while atmospheric forcing is more important for the eastern sector and the interior. Overall, the manuscript is well written. However, the model setup section and some of the descriptions on results need improvements. I'm happy to support the publication of this study after major revisions.

We are thankful to the referee for their helpful feedback. We will take special care in improving the model setup section and the description of the results, and in implementing all the suggestions in the new version of the manuscript. Note that our comments are in blue.

Here are some general comments:

In the model description, some information is missing, including how the ice front position is updated, how the basal drag is treated for partially-floating cells, the reference SMB dataset. About the moving ice front positions, how the ice front position is updated is not described at all. Is a calving included? Could you please show the difference between the ice front position after spin-up and the present- day? How would the difference affect your results?

Yes, calving is computed following a von Mises calving law following the approach in Lipscomb et al. (2019). This gives a calving-retreat rate which is included in the ice shelf front. If the ice front velocity is larger than the calving rate, the ice front advances; if it is lower, the ice front retreats. The parameters related to this law are similar to those used in Lipscomb et al. (2019). The scaling calving parameters are k_t=0.0025 m/(yr Pa), w_2=25 for the calving eigenvalue weighting coefficient, and there is a calving limit in ice thickness set to 200 m. Regarding the grounding-line melt parameterization, we have used the PMP parametrization, where melting is scaled with the floating fraction (Leguy et al., 2021). Therefore we are reducing the basal dragging in the grounding line in accordance with the effective pressure. Finally, for Surface Mass Balance (SMB) and air (2 m) temperature we have used monthly values from the Regional Atmospheric Climate Model (RACMO v2.3) forced by the ERA-Interim reanalysis mean climatology from 1981-2010. For the oceanic fields, we have used the dataset from Jourdain et al. (2020). They first combine two known ocean climatologies: a prerelease from September 2018 of the NOAA World Ocean Atlas 2018 dataset and the Met Office EN4 subsurface ocean profiles with the complementary MEOP data. After that, they extrapolate the oceanic data to calculate the data under the ice shelves for each sector of the 16 in which Antarctica is divided (see Section 3 in Jourdain et al., 2020 for more details). We will include a more complete explanation of our setup as discussed here in the updated manuscript version.

We include below an updated figure (Figure 4) showing the AIS configuration after the spin-up (at the initial year, 2015) compared with observations. Following a request by another referee we zoom into the WAIS sector.

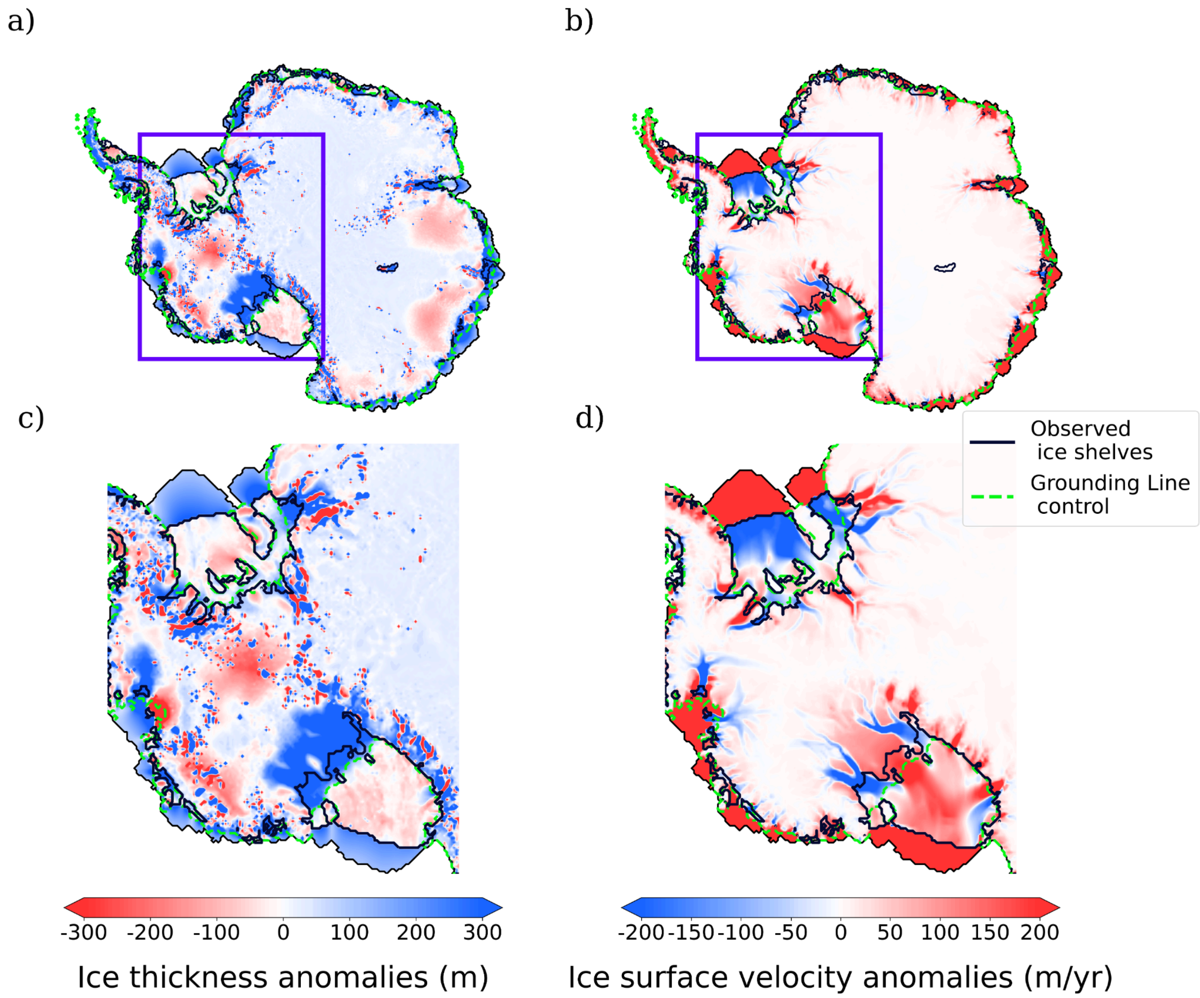

Figure 4. Ice thickness (a, in m) and surface velocity anomalies (b, in m/yr) in 2015 for the medium value of γ_0, with respect to observations from the BedMachine Antarctica V2 dataset and Rignot et al. (2011) respectively. c and d show insets of a and b, respectively, zoomed over the WAIS region.

After the spin-up, our model shows extended ice shelves compared with observations. The extension of the shelves is found to be dependent on the value of γ_0, increasing with decreasing γ_0 values. The highest γ_0 value yields the closest distribution to observations. This can also be seen from the RMSE values shown on Figure 3 on the manuscript.We note that we do not impose a cutoff at the ice-shelf front as other models do since we use exactly the same model setup for paleo simulations of colder climates (e.g. Blasco et al. 2019; 2021).

To test the impact of the overestimated ice-shelf extension on the ice-sheet response we have carried out additional simulations with limited ice-shelf extension masked with observations from the BedMachine dataset. In terms of sea-level contribution, results and spreads are very similar for higher-emission scenarios (Fig. B1) with differences ranging between 0.4 and 23.5% in absolute value, but generally being less than 10% (Table B1). In the case of the low-emission simulation this difference is much greater. In general we can say that our extended simulations have a stronger effect on sea level, but less than 141 mm SLE at 2500. Furthermore, the spread differences between the lower and higher values of γ_0 are not too big (Fig. B1c).

	CCSM4	HadGEM2-ES	CESM2-WACCM	UKESM1-0-LL	UKESM1-0-LL (low)
γ_0=9620 m/yr	23.5	-10	0.4	1.2	38
γ_0=14500 m/yr	13.5	4.3	1.9	4.7	-48
γ_0=21000 m/yr	7.9	3.1	0.9	2.7	-4.9

Table B1. Differences (in percentage) in sea level contribution at 2500 for the experiments carried out, between the runs with extended ice shelves and the ones with limited ice shelves.

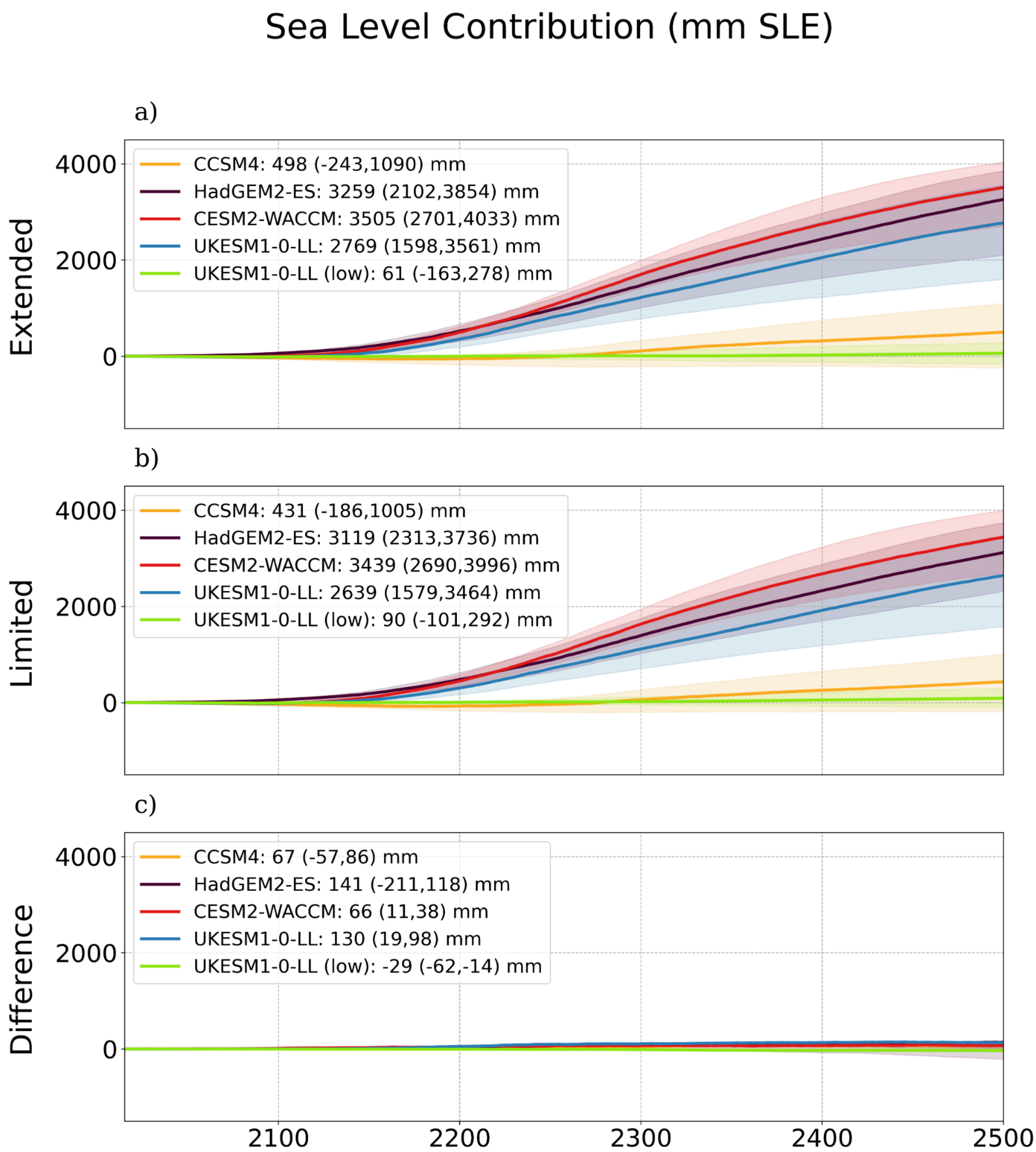

Figure B1. Evolution of the sea level contribution until 2500 for the different experiments carried out, together with the spread produced by the different values of γ_0. In a) with the extended ice shelves, in b) with the ice shelves limited by a mask from observations in the BedMachine dataset and in c) difference between a) and b).

We will include this discussion in the new version of the manuscript.

Coarse resolution like 16 km would largely affect the estimation of mass loss and also the movement of grounding line, which would influence the basal drag and basal melting applied at the grounding line. However, nothing related with this has been discussed, which I think is important.

Although we did not include a discussion on this issue, we did test the sensitivity of our results to the horizontal resolution, albeit with a coarser 32 km resolution. For 32 km, the results in terms of the global sea level evolution are very similar, increasing by 7-10% in high-emission scenarios for the medium value of γ_0 (Fig. B2). Yet, the spread at 2500 (Table B2) is very similar. Sensitivity to horizontal resolution has also been found in other studies, at different resolutions. Using CISM and extending until 2500, Lipscomb et al. (2021) showed sensitivities of up to ~20% with respect to horizontal resolution, although they used higher horizontal resolution values between 2-8 km using the CISM model. Same model with a resolution of 4 km was used by Berdhal et al. (2023), who made a similar study to ours but not only varying γ_0 but also the parameter p from Leguy's parametrization, which in our case is constant (p=0.5) in all experiments. Sutter et al. (2023) also found a sensitivity of their results with respect to horizontal resolution using PISM with 4-16 km. Although they argued that their 8 km ice-sheet configuration is close to their 16 km runs, the grounding-line retreat started earlier with increasing resolution, especially in the Thwaites Glacier.

In our case, we do not have a parallelized procedure to proceed with 8 km and it would be computationally unaffordable. Therefore we haven't been able to test the simulations on these shorter timescales for 8 km. In the revised text, we will nevertheless include this discussion with the possible influence of horizontal resolution in our results and consider comparisons with the aforementioned studies. Variations of the specific values from Lipscomb et al. (2021) and Berdhal et al. (2023) are susceptible to have much difference to ours quantitatively based not only in the resolution used but also in the parameters and the way in which they extend towards 2500 (using the ISMIP6-2100 dataset), but nonetheless results in terms of sensitivity for the γ_0 parameter are still well founded.

	CCSM4	**HadGEM2-ES**	**CESM2-WACCM**	**UKESM1-0-LL**	**UKESM1-0-LL (low)**
16 km	1333	1752	1332	1963	441
32 km	1199	1458	1357	1810	356

Table B2. Comparison of the spread (mm SLE) at 2500 between the low and high value of γ_0 for the experiments carried out for model resolutions of 16 and 32 km.

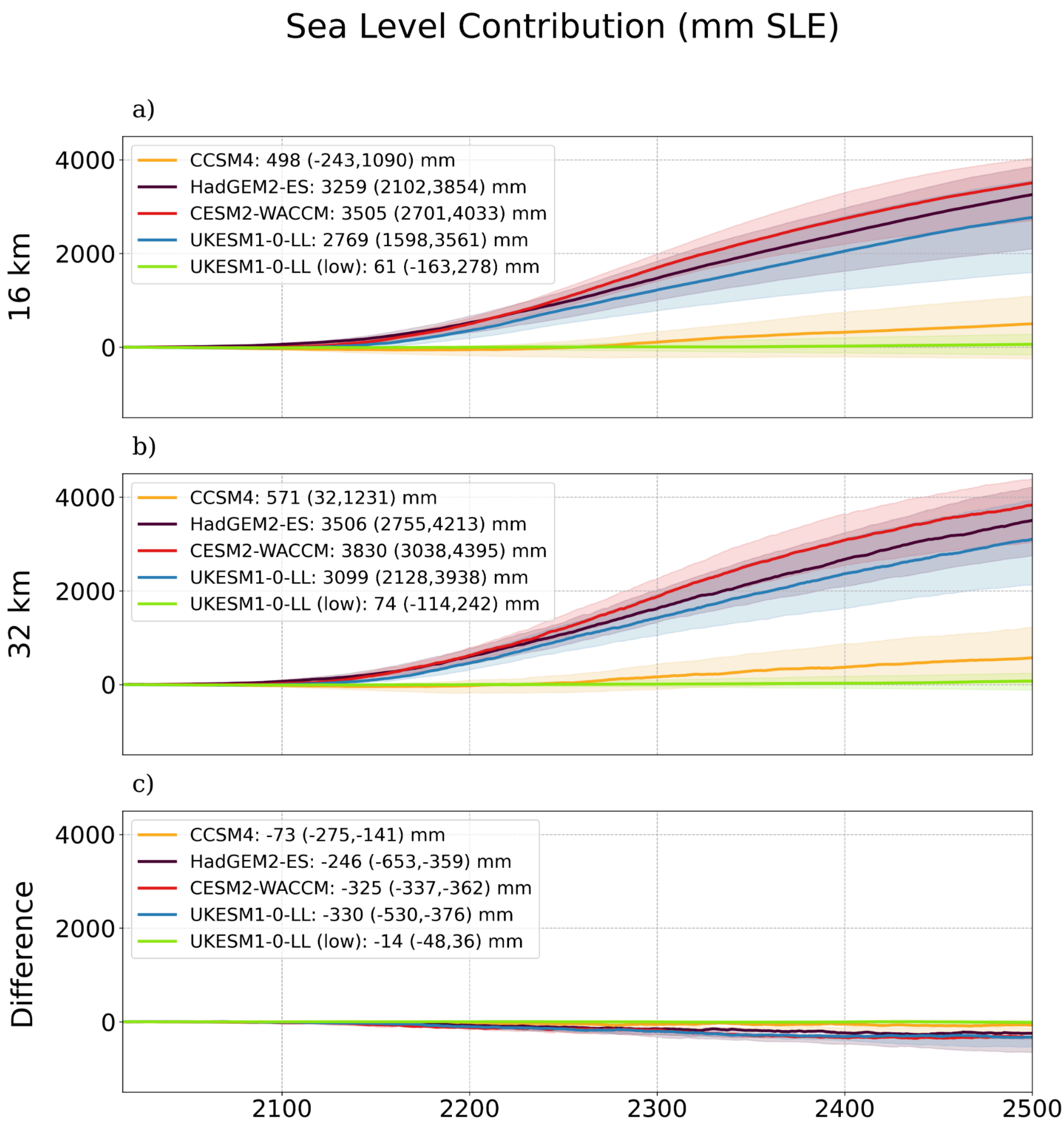

Figure B2. Sea level contribution for the different experiments carried out and spread of the values of γ_0 using resolutions of 16 km (a) and 32 km (b). In c, differences between a and b.

The section 3.1 needs to be restructured. You discuss the sensitivity to γ_0 in 1st paragraph and then discuss the sensitivity to different forcings under a medium value of γ_0 for the rest of the section. However, about the sensitivity to different forcings, you jump between different regions, different GCM forcings, low and high emissions, which is quite chaotic. The focus of each paragraph is not clear to me. About the summary paragraph in Line 245-246, it's a repeat of caption rather than a summary. I think Fig 9 is a good plot which can help you explain things earlier, which should be combined in your result description earlier.

Thank you for your comment. We will take everything into consideration in the revised manuscript version. Taking into account another comment from another referee, we will move the beginning of section 3.1 (results in the initialization proceeding) to a new section 2.5 at the end of the Methodology section.

We will add subsections for each part to make it more clear. Regarding Figure 9, we will refer to it before, when talking about sensitivity.

The Sec. 3.3 describes the individual effect of the atmosphere and the ocean on the projected ice mass loss from west and east Antarctica. However, it is not enough evidence to say that atmosphere is the dominant factor to margin of East Antarctic Ice Sheet, especially for Cook Ice shelf region, Toten Glacier region and Amery Ice Shelf region. These regions are losing ice clearly and show rounding line retreat in Fig 13b. Although it is not as obvious as west antarctica, it should be discussed at least.

In Figure 13, we wanted to make the argument that the atmosphere-only forced simulations (Fig. 13a) produce increases in ice thickness mainly in the AIS interior, while ice margins and shelves generally decrease.

Meanwhile, Figure 13b shows the disappearance of the ice shelves not only in the WAIS but also in the EAIS, with barely any increase in ice thickness. In this case, Pine Island, Ross and Ronne-Filchner retreated in a great amount towards the interior. For the atmosphere-only case, the ice-shelf retreat is much more limited. Looking at the numbers included in the figures for each experiment, we can see that the contribution of the ocean separately is between 2 and 3 metres for the highest emissions scenarios, mainly due to the WAIS retreat. Nevertheless, the total ice mass loss when both atmospheric and oceanic forcings are considered is not simply the sum of the two contributions, because nonlinear processes exist and play a role in the flow of ice.

In the revised manuscript, we will add this discussion and clarify in a better way the differences between these cases for both the EAIS and WAIS.

There are 13 figures and 4 tables in this manuscript, some of the figures are not very crucial to be included in the main manuscript, which can be moved to the supplementary material.

We agree with the reviewer. We have therefore decided to move Figures 8 and 11 to the supplementary material in the new version.

The resolution of some figures (Fig. 7, 8, 9, 11) is pretty low and needs to be improved. Some of the text labels on the figures appears. due to the low resolution of figures.

Yes, we have significantly improved the quality of the figures in the new version of the manuscript.

Specific Comments:

We will take special care to address each of the specific comments in the next version.

L21-22: citation please

Figure 1 in Rignot et al. (2013).

L28: What is 'ejecting circa'?

"ejecting circa 3331 Gt of ice to the Amundsen Sea". We meant that the Amundsen Sea has received approximately 3331 Gt of ice.

L45-46: need to add citation Edwards et al., (2021). We will include it in the next version.

L50: ice sheet stability? Instability could also be considered, but we referred to stability as a general concept, including both stability and instability.

L68: ISMIP6 is short for The Ice Sheet Model Intercomparison Project for CMIP6. We will clarify this in the next version.

L115: citation for this regularized Coulomb sliding law please. Schoof, C.: The effect of cavitation on glacier sliding, P. Roy. Soc. A-Math. Phy., 461, 609–627, https://doi.org/10.1098/rspa.2004.1350, 2005.

L130: you should explain specifically what $\gamma 0$ is here. $\gamma 0$ is the heat exchange velocity between ice and ocean, a parameter relating the rate at which the ocean and the ice in the shelves transfer their heat. We will clarify this in the updated version.

L163: is → are We will change it, thank you.

L169: which GCM forcing is chosen here for period 1995-2014? For the atmospheric fields, Surface Mass Balance (SMB) and 2m-air temperature, we have used monthly values from the Regional Atmospheric Climate Model (RACMO v2.3) together forced by ERA-Interim reanalysis mean climatology dataset from 1981-2010. Regarding the oceanic fields, the reference is Jourdain et al. (2020). We will clarify this in the final version.

L181: (Lipscomb et al., 2021) → Lipscomb et al., (2021) We will change it in the new version.

L190: imposed → kept constant? Yes, this is what we meant.

L198-199: refer to Fig. 4a here. Done.

L205: ocean forcing from CESM2 is not the maximum here compared with UKESM and HadGEM2. In this figure (Figure 1b), the grounding line is fixed, not evolving. Therefore we were referring to Figure 1c where we take the Yelmo outputs and the grounding line evolves.

L208: ‘the low-emission case’ with UKESM. No, it is rather the high-emission case. When referring to the low case we always add low at some point to distinguish.

L213: suggest ‘we can see the sea level contributions slows down in the last two centuries.’ Thank you for your suggestion. We will incorporate it in the revised manuscript.

L215: I think they are all nearly above 5 mm SLE/yr while HadGEM2 is close to 10 mm SLET/yr. Yes, we will change this to clarify (at 2500).

L219: for the medium value of γ_0, no experiments reach 3 m at 2500. Indeed, it was 2 m, not 3 m. The 3 metres were for the general case of the AIS. We will change that.

L221-222: 75% + 20% is not 100%. These were general numbers trying to summarize roughly for all the models, but only taking CESM2-WACCM and HadGEM2-ES in consideration. We will correct this in the new version.

L227: Fig 1 did not show anything related with Amundsen and Bellingshausen sea sectors. It indeed was Figure 2, we will correct this.

L228: for Amery, you need to cite Fig 7 rather than Fig 6. Indeed, we will change it.

L230: why do you only mention Ronne-Filchner here? Amery also shows loss of ice only for CSEM2 and CCSM4. Yes, we will correct this in the new manuscript. .

L233: it is not obvious to me in 2200. 2300 is more obvious. We will change the description in the revised text.

L235: not for CCSM4 Indeed, we will clarify that.

L236: what do you mean “reaching well above 300m”? the thickness? Yes, ice thickness. We will clarify this.

L237: why do you exclude the PIG and Thwaites here? We will include them.

L240: what do you mean “Ronne-Filchner ice shelf is larger”? If you are talking about readvance of GL (which I can’t tell it well from current resolution of figure) in these regions, the ice shelf area is smaller.

No, we meant that for the low-emission case, the Ronne-Filchner ice-shelf is gaining ice (thickness) with respect to the start of the simulation. We will make that sentence more clear.

L242: The ice flow is decelerating in ROSS under low emission scenario. Yes, the ice is decelerating in Ross in that case. See next answer here.

L253: this confused me a lot. If the ice shelf disappears from 2300 onward, why we still see floating regions in Figure 7 after 2300. From Figure 7, the ice shelf is always there.

Yes, we admit this can be a little bit confusing. In Fig. 7, we decided to plot the anomalies w.r.t the start of the forcing but without masking the ice as it evolves, that is, keeping the original size of the ice sheet. In this way, it is more apparent where the loss of ice takes place (mainly in the WAIS), identified by red colors. Masking the ice as it evolves instead is done on Fig. 8 for ice surface velocity.

L263: I can not tell mass loss from WAIS changes its tendency from Fig 11.

Yes, this was a mistake from our side, we meant Fig. 10.

L279: When you say ‘The EAIS ice shelves also have their ice mass reduced’, which plot are you talking about? Or you mean the margin of EAIS? We are talking about Figure 13. We meant both that ice shelves have a negative anomaly compared with 2015 and in some cases like CESM2-WACCM the margins also retreat towards the interior. We will clarify this issue in the new version.

L280: ‘in the interior and eastern areas’ → ‘in the eastern interior’? We will change this.

L297: the forcing is stopped? I thought it was just kept constant. Yes, it is kept constant from 2300 to 2500. We will clarify this, “stop” is not the right word.

L312: in more than 3 meters → by more than 3 meters; ‘affecting predominantly to the WAIS’ → ‘affecting the WAIS predominantly’ Thank you for revising the language, we will change those sentences.

L314: I don’t understand this sentence. Do you mean through enhanced surface melting?

No, we meant enhanced accumulation of ice. Figure 13a shows that the eastern region is gaining ice and therefore it is an opposed phenomenon compared with the ocean effects. We will make this more clear.

L319: There is also a clear mismatch between your result and Greve et al. 2022 in Table 4. Yes, we will mention that.

L321: Then what about the mismatch in CCSM4?

CCSM4 shows a mid-range air temperature evolution compared to the other GCM forcings, but it shows much lower ocean temperatures and therefore thermal forcing (Figure 1). The average anomaly in thermal forcing on the shelves in 1995-2300 with respect to the reference climatology for Greve et al. (2022) (see Table 1 in their article) is 1.652 ºC for both CCSM4 and 1.613 ºC for CESM2(-CAM), indicating very similar oceanic forcings for these two models in the extension towards 2300. Their results for sea level contribution are accordingly very similar for these models. In our case, these numbers are 1.586 ºC for CCSM4 and 2.373 ºC for CESM2-WACCM, calculated as the average thermal forcing under the shelves with respect to the reference given by Jourdain et al. (2020). Therefore, the ISMIP6-2300 extension of CCSM4 has a smaller thermal forcing than the extension made by Greve et al. (2022).

L346: unfished sentence. It is unclear to us what the reviewer meant here.

L366: on Eq (3). Or you don’t need to mention it here. We will revise that for the next version of the manuscript.

L372: I think you mean a position contribution to SLR. But by saying 'negative effect' can be confusing. Yes, we meant that. We will rephrase it for the next version.

Figures

Figures have been redone trying to make them larger while keeping the resolution and some extra features have been added following the advice of both referees. In the rewritten text these new figures will appear and we have thought about including some of them as an Appendix or Supplementary Material.

Figure 2: Caption: the differences in thermal forcing for b). We will change it, thank you.

Figure 7 & 8: I did not see the coastlines at all, which is a very important feature to be shown clearly in the figure. Yes, we have changed it. Nonetheless, we consider that only representing the grounding line improves the visualisation of the plot.

Figure 8: what do you mean the cells where there is ice? I think you mean grounded ice? If yes, why the floating ice is included in UKESM LOW emission case?

No, we mean both grounded and floating ice. For higher emissions experiments, the floating ice starts to disappear in 2200. That is why some ice shelves turn white (ocean has made its path here) but in the low-emission scenario there is still ice on the shelves. We only wanted to show the retreat towards the interior and the ice accelerates near the grounding lines (and of course where there is ice).

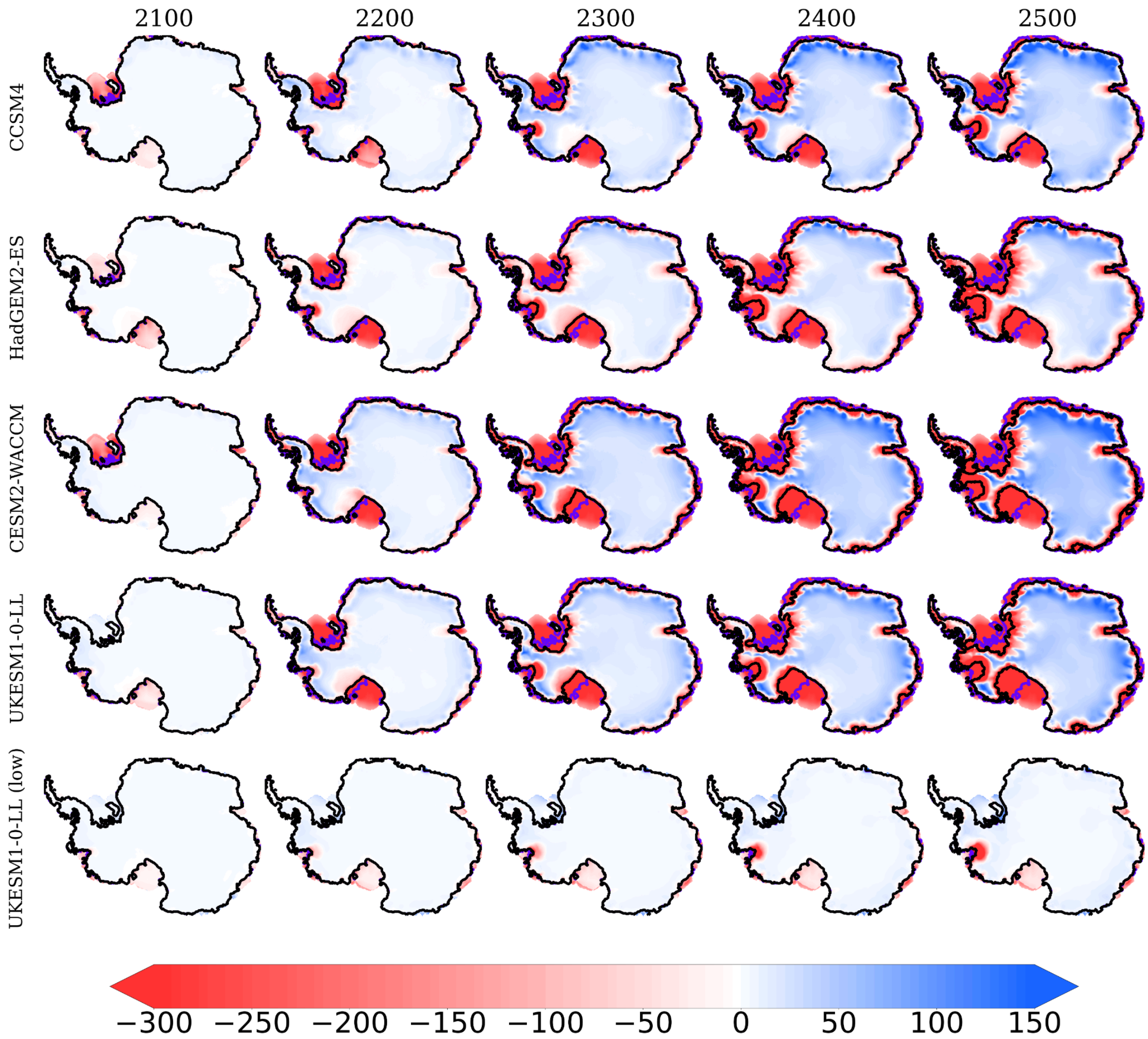

Figure 7. Ice thickness anomalies (in m) for years 2100, 2200, 2300, 2400 and 2500 with respect to the start of the simulations for the set of five experiments carried out with the median value of γ_0. The grounding line is represented by black and violet colors for 2500 and 2015 respectively. To show negative anomalies in the WAIS, no masking has been implemented as time evolves, keeping the original coastlines.

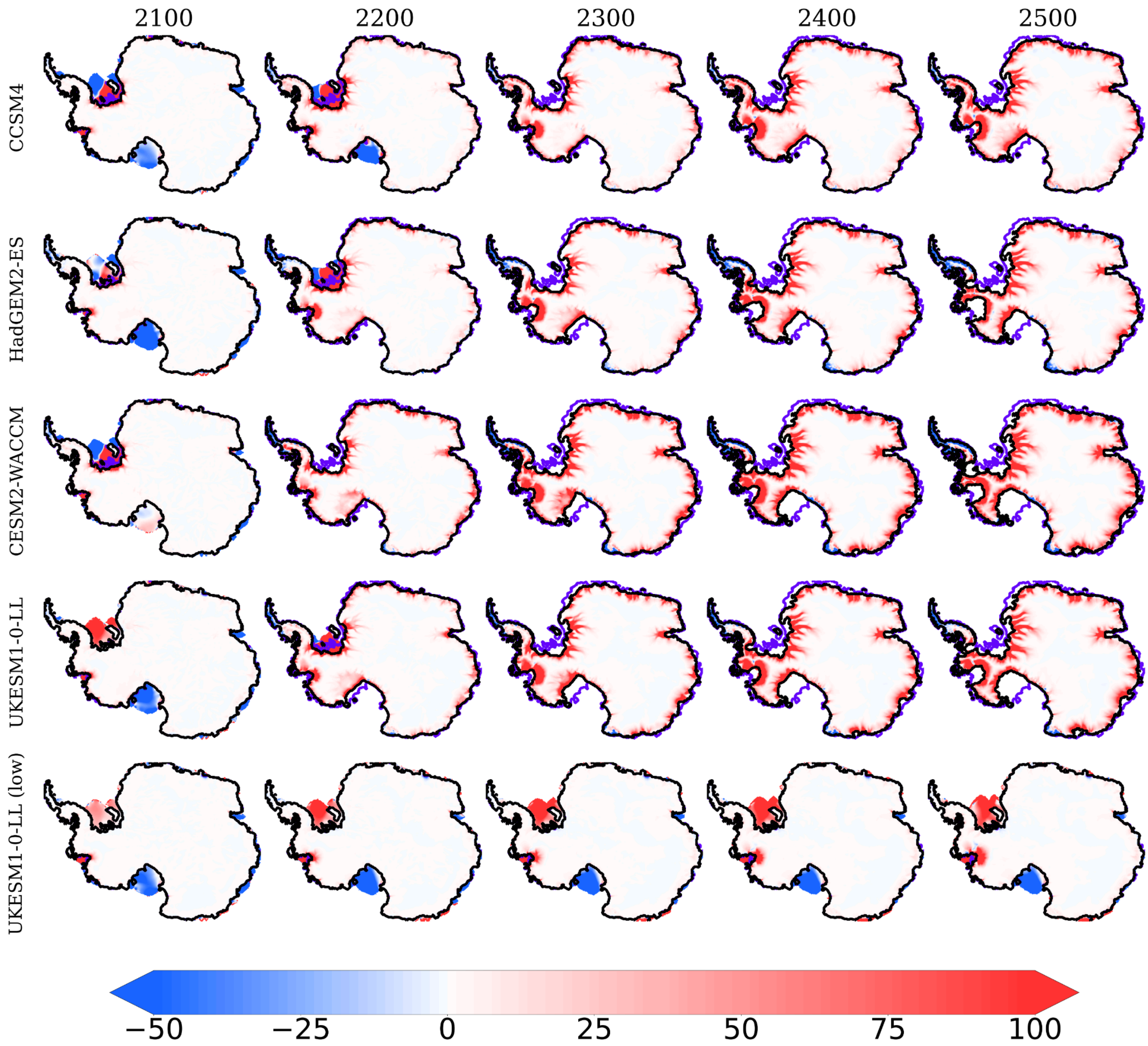

Figure 8. As Figure 7 but for ice surface velocity anomalies (in m/yr). Note that only the cells where there is ice (floating and grounded) at the specific times are represented.

Figure 12: in the AIS → from the AIS We will change it.

References

Thank you, we will include your given reference in the new version and refer to it at the lines you have said. Note that there are some others (in blue) cited by us in our reply.

Berdahl, M., Leguy, G., Lipscomb, W. H., Urban, N. M., & Hoffman, M. J. (2023). Exploring ice sheet model sensitivity to ocean thermal forcing and basal sliding using the Community Ice Sheet Model (CISM). *The Cryosphere*, *17*(4), 1513-1543.

Blasco, J., Tabone, I., Alvarez-Solas, J., Robinson, A., and Montoya, M.: The Antarctic Ice Sheet response to glacial millennial-scale variability, Clim. Past, 15, 121–133, https://doi.org/10.5194/cp-15-121-2019, 2019.

Blasco, J., Alvarez-Solas, J., Robinson, A., and Montoya, M.: Exploring the impact of atmospheric forcing and basal drag on the Antarctic Ice Sheet under Last Glacial Maximum conditions, The Cryosphere, 15, 215–231, https://doi.org/10.5194/tc-15-215-2021, 2021.

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