Reviewer #2

Summary

This paper describes the performance of the CESM2 model in simulating factors relevant to the surface mass balance of the Antarctic ice sheet in the recent past and the next century. It is a useful exercise, providing documentation and detail for people who use CESM2 or its output to force ice sheet models, for other ESM groups as an example of good evaluation practice and context, and for cryosphere scientists who might not know what to expect of a global ESM simulation of AIS climate. As primarily a descriptive paper it doesn't contain revolutionary science conclusions, but it is still a very worthwhile contribution and I would consider it a TC paper rather than model development that might be more suited to e.g. Geoscientific Model Development. It is well written and organized with a good level of detail. I would recommend publishing it with minor revisions.

> We thank the reviewer for their positive and encouraging comments regarding our manuscript.

General comments

Some suggestions to consider for those minor revisions that would improve the utility of the paper:

Obviously, this paper focuses mainly on factors local to the AIS surface, but would also be nice to see a little more assessment of the regional climate away from AIS (confer the metrics used in assessing GCM climate plausibility for AIS SMB in section 2.2 of Barthel et al. 2020, https://doi.org/10.5194/tc-14-855-2020) that will have a significant influence on e.g. the amount of precip that gets tracked in from the ocean, or warm air advection. It would be good to have an attempt at attributing improvements wrt CESM1 to either the large-scale CESM2 climate or the changes in surface modelling.

> We agree with the reviewer that it is important to relate our findings to other climate processes in and around the AIS. There are several studies that provide an assessment of the regional climate away from the AIS and the large-scale CESM2 climate (Simpson et al 2020, Singh et al 2021, Raphael et al 2020, Dalaiden et al 2020). We argue that these studies provide sufficient analysis of CESM2's performance in reproducing the high-latitude climate system above and around Antarctica. To better link our results to this existing body of literature, we will add the following paragraph to the discussion section:
>
> "In the context of the larger Southern Hemisphere (SH), Delaiden et al (2020) show that the CESM2 Antarctic moisture budget due to synoptic and large-scale atmospheric circulation is realistic compared to reanalysis (ERA-Interim). This indicates that unrealistic CESM2 mean-state precipitation may be attributed to

cloud microphysics, not SH moisture budget. While CESM2 performs well regarding the mean-state SAM and the location of the SH jet, its representation of stationary waves and the speed of the SH jet have degraded from CESM1 (Simspon et al. 2020). Zonal circulation appears overall too strong in CESM2, which may enhance or reduce precipitation in various regions across the AIS. Analogous to the unrealistic precipitation trend in CESM2, there is also a decrease in CESM2 SH sea ice throughout the historical period that cannot be reconciled with observations (Duvivier et al. 2020, Raphael et al. 2020). The unrealistic SH sea ice and AIS precipitation trends may arise from similar factors (i.e. high CESM2 climate sensitivity); and/or, a decrease in sea ice may contribute to increasing AIS precipitation."

Whatever the cause, the improvements in match to the reference products at the end of the 20th century wrt CESM1 are very encouraging, and that - along with the potential for improving the sea-level projection capabilities in CMIP that are mentioned - should definitely be highlighted. The flipside though, whose impact I think could be discussed more and might carry as much importance, is what appears to be a very significant discrepancy in the sensitivity of the simulated precipitation to changes in 20th century climate. What credence should users of this model/simulation data put in the projections of future SMB on that evidence? I'm not criticizing the simulation, just asking for a more prominent discussion of the implications. I've just read the paper on the PaleoCalibr version of CESM2 (Zhu et al 2021, https://doi.org/10.1029/2021MS002776) which claims to have a better/more physical tuning of nucleation around ice in clouds and affects high latitude cloud and general climate sensitivity significantly. Since these cloud microphysics are mentioned as important in this text, it might be nice to have a comment on what, if any, impact they think that tuning might have on their SMB simulation and sensitivity?

We will add the following (after line 296) to our discussion to address unrealistic CESM2 climate sensitivity as noted by the reviewer:

"Zhu et al. (2021) find that the CESM2 climate is very sensitive to treatments of cloud microphysical processes and that tuning these processes results in a modeled climate sensitivity that more realistically matches present-day observations. CESM2's unrealistically high climate sensitivity likely implies that modeled future precipitation and runoff trends are also overestimated, something that should be taken into consideration when discussing AIS SMB under different future emissions scenarios in CESM2."

The title promises 1850-2100 but I think this is a little misleading:

1) The focus is mostly on evaluation against various high resolution or observationally-based products, so for understandable reasons there's virtually nothing about the situation before the 1970s. The only exception is figure B2, used to establish the change in precipitation trend in the model at the end of the 20th century, but that's a fairly scant use for 120+ years of

simulation. There is presumably little that can be said other than presenting the differences with CESM1 for the earlier period - that might be interesting in itself, or it might be better to change the title.

We agree with the reviewer that the focus is mostly on evaluating the model following 1979 when satellite-based products and observations were available. We will change the manuscript title to: "Antarctic surface climate and surface mass balance in the Community Earth System Model 2 during the satellite era and into the future (1979-2100)" to be more in-line with the topics of this paper.

2) Everything after 2014, for all climate and surface variables across several different scenarios, is condensed into 1 side of text and 2 figures - the future feels pretty shortchanged as well. What is there is good but it would be nice to see much more detail. For instance, does the pattern of increase in precipitation just match surface temperatures and scale with Clausius-Clapeyron humidity arguments, or is there evidence of something dynamic eg more frequent/vigorous storm incursions. How do the areas of increased shelf melt compare to estimates of which shelves will be vulnerable to hydrofracture from surface melting in the future. eg Kuipers Munneke et al. 2017 (https://doi.org/10.3189/2014JoG13J183).

An analysis of increased precipitation based on thermodynamical vs dynamical impacts has been done by Delaiden et al (2020) (see Figure 3) and a more thorough investigation of dynamics-induced precipitation changes is beyond the scope of this paper. We agree that Section 3.5 on future model trends should be expanded and will add the following paragraph and corresponding supplemental figure:

"At the end of the historical simulation (2005-2015), solid precipitation contributes to 91.7% of the total grounded SMB signal in CESM2, while rainfall, evaporation/sublimation, and runoff contribute 0.7%, 6.1%, and 1.5% respectively (Fig. A8). By the end of the future period (2090-2100), the contribution of both rainfall and runoff to the modeled SMB signal increases slightly in all scenarios (3.1% and 7.1%, respectively in SSP5-8.5), with a corresponding decrease in the contribution of precipitation (83.1% in SSP5-8.5). Over ice shelves, we see a much greater change in the contribution of these different components to the total CESM2 SMB signal at the end of the future period (Fig. A8). From 2005 to 2015, snowfall accounts for 77.6% of the modeled ice shelf SMB signal, rainfall accounts for 5.4%, evaporation/sublimation accounts for 7.0%, and runoff accounts for 10.0%. By the end of the SSP5-8.5 scenario, snowfall accounts for less than half of the ice shelf SMB signal (41.8%), with rainfall, evaporation/sublimation, and runoff accounting for 14.8%, 3.9%, and 39.5%, respectively."

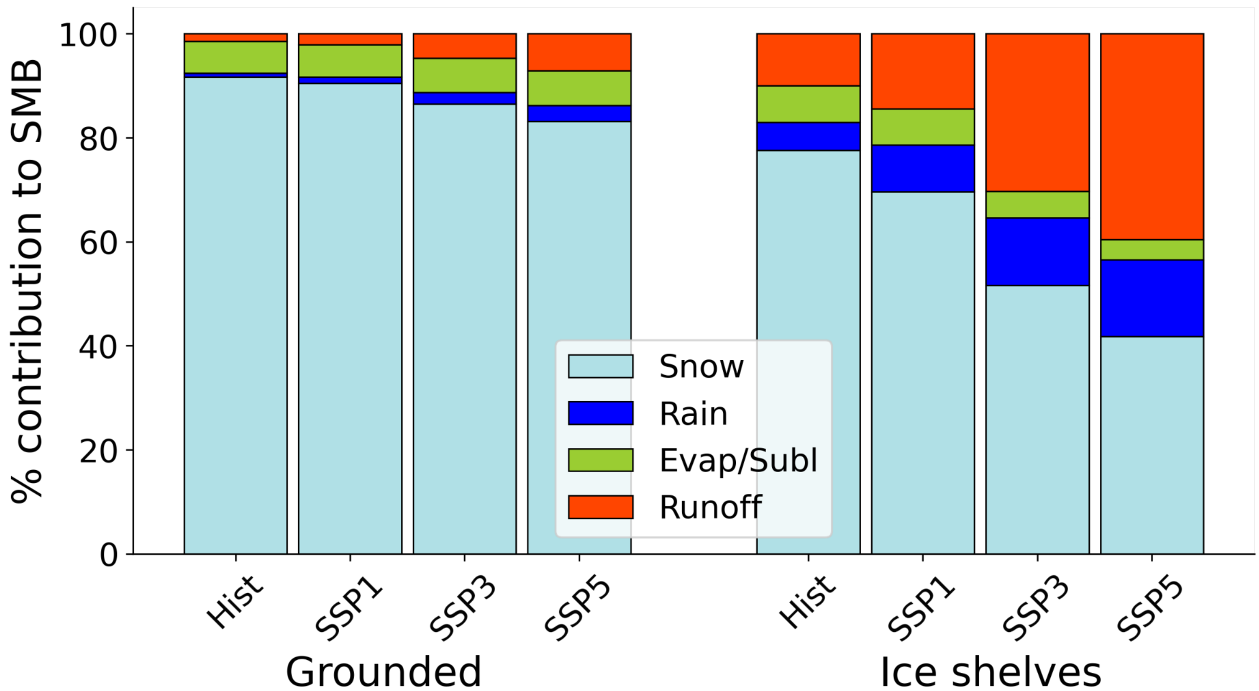

Fig. A8. The contribution of snowfall, rainfall, evaporation/sublimation, and runoff to the total CESM2 SMB signal over the grounded ice sheet (left) and ice shelves (right) at the end of the historical period (2005-2015) and at the end of future scenarios SSP1-2.6, SSP3-7.0, and SSP5-8.5 (2090-2100).

Given the limitations in CESM2's ability to simulate meltwater processes, we would like to refrain from making substantial claims on future ice shelf vulnerability to hydrofracture, and stick with the analysis of SMB and components. Surface melt and processes related to surface melt (ie refreezing, liquid water storage at the surface) are still not well captured by CESM2. Additionally, there are lots of other factors that contribute to meltwater ponding and the potential for hydrofracture (i.e. the availability of near-surface firn, the formation of impermeable ice lenses) that are likely not captured by CESM2. We propose that atmospheric forcing from CESM2 would need to be used as input for a more sophisticated firn model to analyze the impacts on ice shelf surface hydrology.

Specific Comments:

Line 1, abstract: could be more concise and to the point. I'm not sure the first or last 3 sentences are really needed here at all, since they provide general information and broad justification that could live in the Introduction. Some more numbers - integrated SMB, precipitation, runoff, percentage discrepancy from the reference products in the present, projections for the future - would be more useful. I would note the issue with the historical trends in CESM2 here too, as well as the marked improvement in the mean state wrt CESM1.

We will trim the first and last 3 sentences of the abstract to be more concise. We will also add a sentence regarding the issue with the historical trends in CESM2. Our modified abstract will read:

"Earth System Models (ESMs) allow us to explore minimally-observed components of the Antarctic Ice Sheet (AIS) climate system, both historically and under future climate change scenarios. Here, we present and analyze surface climate output from the most recent version of the National Center for Atmospheric Research's ESM: the Community Earth System Model version 2 (CESM2). We compare AIS surface climate and surface mass balance (SMB) trends as simulated by CESM2 with reanalysis and regional climate models and observations. We find that CESM2 substantially better represents the mean state of AIS near-surface temperature, wind speed, and surface melt compared with its predecessor, CESM1. This improvement is likely a result of the inclusion of new cloud microphysical parameterizations and changes made to the snow model component. However, we also find that grounded CESM2 SMB (2269 +\- 100 Gt/yr) is significantly higher than all other products used in this study and that both temperature and precipitation are increasing across the AIS during the historical period, a trend that cannot be reconciled with observations. This study provides a comprehensive analysis of the strengths and weaknesses of CESM2 representation of AIS surface climate, which will be especially useful in preparation for CESM3, which plans to incorporate a coupled ice sheet model that interacts with the ocean and atmosphere. "

Line 23: "attributing to" - should be "accounting for", perhaps?

We will change "attributing to" to "accounting for" in line 23 of the manuscript.

Line 40: the word "limit..." gets used a lot in these two sentences

We will update these sentences in lines 40-42 to read "Because of Antarctica's remoteness, in-situ observations are spatially and temporally sparse, limiting our understanding of how the surface climate and SMB are changing. Accordingly, we use additional products to assess the AIS surface climate, each with its own set of advantages and disadvantages."

Line 79, section2.1.2: are the CESM2 mec subgridscale ice elevation classes used for the AIS in either version? I think there were particular parameterisation tunings that were done for the calculation of Greenland SMB in CESM2, at least for the version of the model with interactive ice - eg adjustments to the phase of precipitation for certain land surface type (van Kampenhout et al, 2020 https://doi.org/10.1029/2019JF005318) - are they active here?

Yes, CESM has MECs active over Antarctica. Since the downscaling does not change the grid cell integrated mass or energy fluxes, CESM2 is not coupled to an ice sheet model over the AIS, and most atmospheric variables are not downscaled, we decided to present our results on the native CESM2 grid. We will make this clear in the Methods section in the manuscript.

Line 106: I may have missed something, but is this approximation for SMB used consistently in the analysis of all the model simulations and evaluation products, or does it only apply to ERA? If this is the formal definition to be used in the paper, it then needs amending for the future results where runoff becomes very significant.

Runoff is included in SMB calculations from all model simulations except for ERA5. We will update the ERA5 SMB calculation to include runoff and will clarify this by changing line 106 to "(approximated by precipitation - evaporation/sublimation - runoff)"

Figure 1: Does panel(d) impart useful information that can't be got from panel(e)?

We agree that panel d from Figures 1 and 4 are not necessary and will remove them from the Figures.

Line 137: can the CESM radiation components shown (and other surface energy fluxes) be compared with the RCMs/reanalysis?

We will add a comparison of incoming short and longwave radiation from CESM2 with ERA5 to Figure 2 (below) and the following paragraph to the results section:

"Compared with ERA5 (Fig. 2c,f), CESM2 has a spatially-averaged -7.3 W m^{-2} bias in incoming shortwave radiation (an improvement from the +20.8 W m^{-2} CESM1 bias) and a -1.8 W m^{-2} bias in incoming longwave radiation (improved from -12.2 W m^{-2} in CESM1). ERA5 suggests that CESM2 incoming shortwave radiation is negatively biased at the AIS coast and positively biased in the interior (Fig. 2c), a spatial pattern that is consistent with CESM2 near-surface temperature biases whereby modeled temperatures are largely too cold along the coast and too warm in the interior (Fig. 1c)."

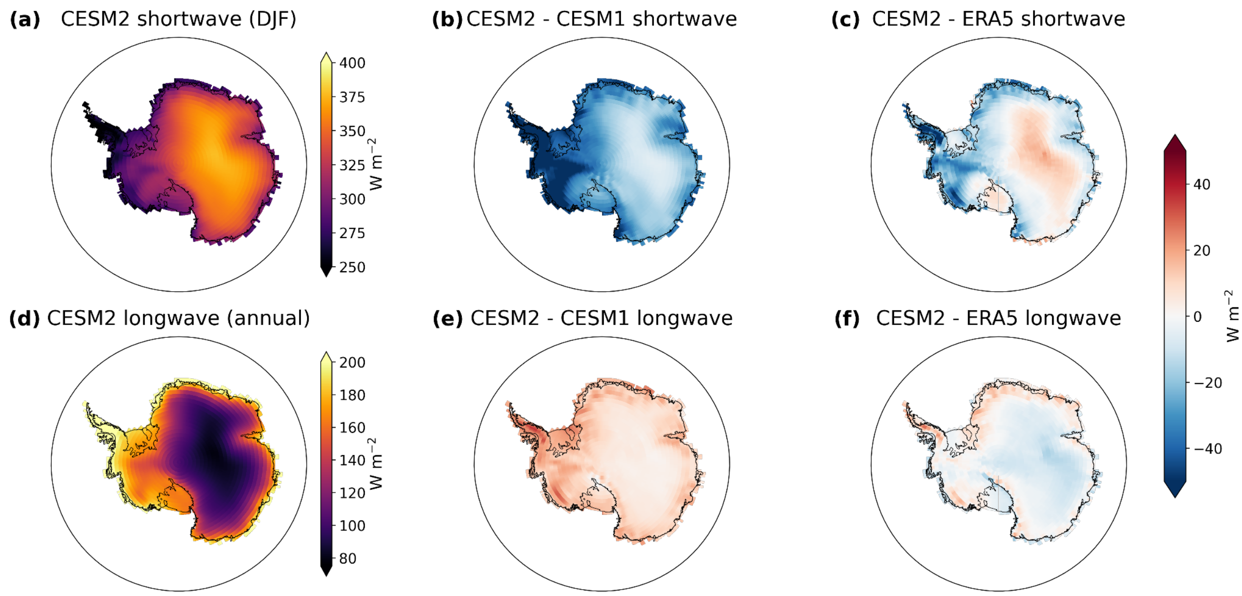

Figure 2. Comparison of incoming radiation components between CESM2 (1979-2015), CESM1 (1979-2005) and ERA5 (1979-2015). (a) CESM2 average austral summer incoming shortwave radiation. (b) CESM2 - CESM1 average austral summer incoming shortwave radiation. (c) CESM - ERA5 average austral summer incoming shortwave radiation. (d) CESM2 average annual incoming longwave radiation. (e) CESM2 - CESM1 average annual incoming longwave radiation. (f) CESM2 - ERA5 average annual incoming longwave radiation.

We will also update appendix Figure B1 to include a comparison of the sensible and latent heat flux between CESM2 and ERA5:

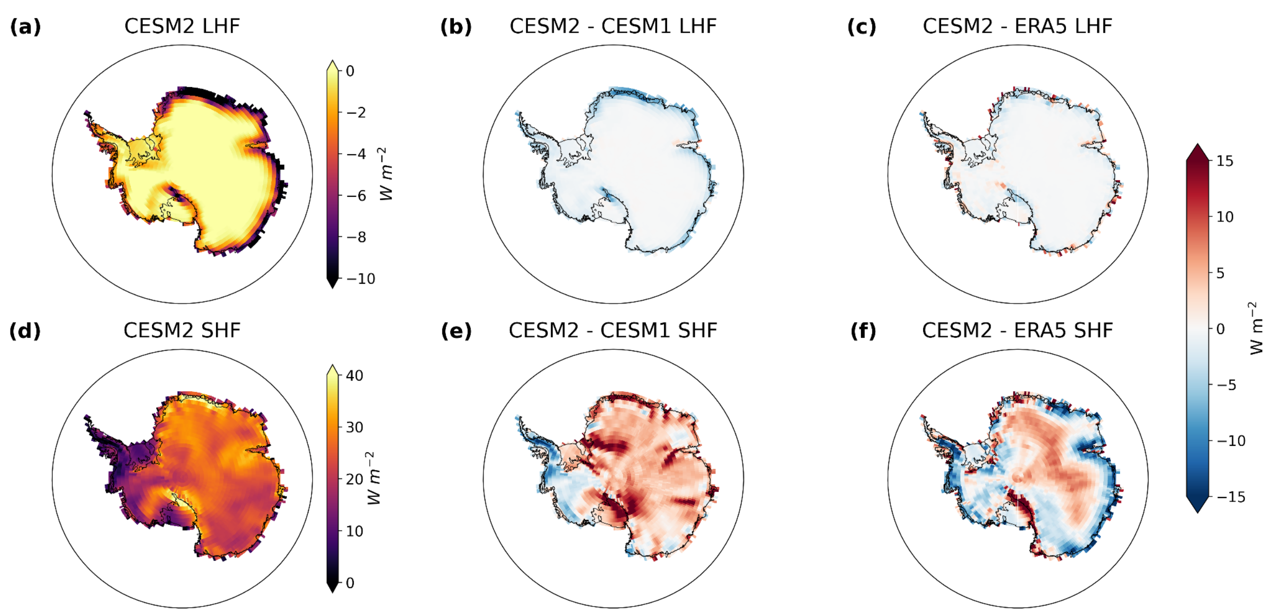

Figure B1. Comparison of turbulent fluxes between CESM2 (1979-2015), CESM1 (1979-2005) and ERA5 (1979-2015). (a) CESM2 average annual latent heat flux (LHF). (b) CESM2 - CESM1 average annual LHF. (c) CESM - ERA5 average annual LHF. (d) CESM2 average annual sensible heat flux (SHF) (e) CESM2 - CESM1 average annual SHF. (f) CESM2 - ERA5 average annual SHF. Positive values indicate a downward net energy flux (into the ice sheet).

Line 152: are the katabatic winds really well-resolved in a 1degree model?

> Our results show that CESM2 well-represents these strong down-slope winds in East Antarctica, so yes, these katabatic, or downslope winds appear to be resolved in a 1 degree model.

Line 169: these are the first of the area-integrated quantities, I think. It would be worth saying what the size of the AIS is in each of these different models/products. It's not obvious that a 1degree GCM will represent the AIS with exactly the same extent as a more detailed regional model, a factor which might bias results systematically high or low.

> We are using the Zwally mask which has been regridded for all of the modeling products used in this study. We will specify this and note the AIS grounded and ice shelf areas for each products in a new methods section 2.6 AIS Model masks:
>
> "For area-integrated quantities we use the Zwally et al. (2012) AIS mask which has been re-gridded for all of the modeling products used in this study. The resulting grounded AIS areas from these models are as follows: 12043565 km^2 for CESM1 and CESM2, 12059084 km^2 for ERA5, 12063497 km^2 for RACMO2.3, 12154338 km^2 for MAR, and 12028208 km^2 for the MT2019 reconstruction. The resulting ice shelf areas from these models are: 1738581 km^2 for CESM1 and CESM2, 1755916 km^2 for ERA5, 1734991 km^2 for RACMO2.3, and 1749205 km^2 for MAR. Ice shelves are not included in the MT2019 reconstruction."

Line 182: "to too melt" - too /much/ melt?

> We will change the phrase "to too melt" to "too much melt" on line 182.

Line 202, section 3.4: I know accumulation vastly outweighs other things in the current SMB balance, but we're not actually told a split between accumulation and ablation (whether or not that includes runoff) at any point here? Could something be shown on sublimation? Section 3.3 talks about surface melt, but no note of whether any of that runs off - the runoff and refreeze proportion becomes important in the future section later, so I think it should be mentioned for the present-day too, even if only briefly.

> We will add the following paragraph in Section 3.4.1 to briefly quantify the contribution of accumulation and ablation terms in the total SMB signal:

"For the full ice sheet, accumulation from both solid and liquid precipitation accounts for 91.7% of the total SMB signal in CESM2, with ablation terms accounting for 8.3% of the signal (6.5% from sublimation/evaporation and 1.8% from runoff). This breakdown is comparable to that from ERA5, where 92.1% of the total SMB signal comes from precipitation, 6.9% from sublimation/evaporation, and 1.0% from runoff. In comparison, only 2.0% of the total SMB signal from CESM1 comes from sublimation/evaporation (with 96.6% from precipitation and 1.4% from runoff). This increase in the sublimation/evaporation contribution to the SMB signal from CESM1 to CESM2 is likely due to the increase in near-surface wind speed (discussed in Section 3.2) which drives a corresponding increase in latent heat flux between the model versions."

Line 231: it could be clearer whether these two sentences are talking about CESM2 or reality.

We will update the two sentences in line 231 to read: "AIS historical precipitation trends in CESM2 appear to be largely driven by the increasing SAM and intensifying Antarctic ozone depletion, with spatial patterns similar to that shown in Lenaerts et al. (2018)."

Figure 6(b,c,d): it's not clear what's going on with the ice shelves. Are they excluded from the SMB analysis, and we're only talking about grounded ice here? Is it an issue with just this figure, or throughout the paper? Figure 5 shows melt on the shelves, so they're not excluded from all the analysis

Thank you for pointing out this confusion. Figure 6 and lines 204-208 only include SMB over the grounded ice sheet because the reconstruction only covers the grounded ice sheet. We will clarify this in the text by changing line 204 to "In CESM2, the annual average **grounded** surface mass balance (SMB) between 1979 and 2015 is…". We will also specify in the caption for Figure 6 that the timeseries (panel a) only includes the grounded ice sheet. To satisfy complaints from both reviewers we will expand our analysis in section 3.4.1 to include a comparison of ice shelf SMB from CESM2 with CESM1, ERA5, RACMO2.3, and MAR by adding the following paragraph:

"Over ice shelves, CESM2 has an average SMB of 559 +/- 27 Gt yr^{-1} between 1979 and 2015, significantly greater ($p < 0.05$) than the average SMB over ice shelves from CESM1 (520 +/- 26 Gt yr^{-1}), ERA5 (506 +/- 26 Gt yr^{-1}), RACMO2.3 (523 +/- 24 Gt yr^{-1}), and MAR (459 +/- 23 Gt yr^{-1}). The reconstruction only covers the grounded ice sheet and thus ice shelf SMB cannot be calculated from this product."

We will also included ice shelf SMB from CESM2 in Figure 6 panel b to indicate that our analysis does include ice shelves in this manuscript.

Line 242, section 3.5: is there a general "future simulations with CESM2" paper that could be cited for more context (eg Meehl et al., https://doi.org/10.1029/2020EA001296)?

Thanks for the suggestion, we will add the Meehl et al (2020) citation to the sentence in line 242.

Line 246: "SSPx" is an incomplete reference to which emissions scenario is being talked about - eg SSP5-8.5

We will update all references of SSP5 to SSP5-8.5, SSP3 to SSP3-7.0, and SSP1 to SSP1-2.6.

Line 247: "1990" is probably a typo

Thanks for catching this, we will update this typo to: (2090 – 2100) in line 247.

Line 257: is there any evidence from the 20th century simulation that the available pore space and refreezing in CESM2 are realistic to start with?

No, unfortunately there is no evidence that the available pore space and refreezing in CESM2 are realistic during the historical simulation. We discuss this limitation in lines 310-314 of the manuscript: “While CESM2's firn model has improved substantially (van Kampenhout et al., 2017), it still only allows for a ~20-30 meters deep firn column, which likely results in an underestimation of meltwater storage capacity in the firn across much of the AIS. In a future warming climate with non-linearly increasing meltwater production on Antarctic ice shelves, CESM2 may exaggerate runoff as a result of this shallow firn column, highlighting the need for a continued development of the snow model to better understand future SMB changes.

Line 315: "in the latest iteration of CMIP", perhaps - various EMICS, simpler models and even a CMIP6 ESM (Siahaan et al. 2021, https://doi.org/10.5194/tc-2021-371) have produced "coupled" estimates of future AIS contributions to sea level rise, for whatever they're worth.

We will update line 315 to read: “Even in the latest iteration of estimating future AIS contribution to sea level rise, few attempts have been made to couple ice sheet and ESMs (Siahaan et al., 2021). Antarctic ice sheet models are largely simulated as a stand-alone, meaning they require climate forcing (Seroussi et al., 2020).“

Line 316: "will be used" - it already has been (Payne et al. https://doi.org/10.1029/2020GL091741)!

We will change “will be used” in line 316 to “**will be more extensively used** as this forcing for ice sheet models (Payne et al. 2021)”.

Line 324: I don't think the repeat of the factors in parentheses is required.

We will delete the text in parentheses in line 324.

References

Dalaiden, Q., Goosse, H., Lenaerts, J., et al. Future Antarctic snow accumulation trend is dominated by atmospheric synoptic-scale events, Communications Earth & Environment, 1, 1-9, 2020.

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Payne, A., Nowicki, S., Abe-Ouchi, A., et al. Future Sea Level Change Under Coupled Model Intercomparison Project Phase 5 and Phase 6 Scenarios From the Greenland and Antarctic Ice Sheets, Geophysical Research Letters, 48, 1-8, 2021.

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Simpson, I., Bacmeister, J., Neale, R., et al. An Evaluation of the Large-Scale Atmospheric Circulation and Its Variability in CESM2 and Other CMIP Models, Journal of Geophysical Research: Atmospheres, 125, 1-42, 2020.

Singh, H., Landrum, L., Holland, M., et al. An Overview of Antarctic Sea Ice in the Community Earth System Model Version 2, Part 1: Analysis of the Seasonal Cycle in the Context of Sea Ice Thermodynamics and Coupled Atmosphere-Ocean-Ice Processes, Journal of Advances in Modeling Earth Systems, 3, 2021.

Zhu, J., Otto-Bliesner, B., Brady, E., et al. LGM Paleoclimate Constraints Inform Cloud Parameterizations and Equilibrium Climate Sensitivity in CESM2, Journal of Advances in Modeling Earth Systems, 14, 2022.