Review of manuscript egusphere-2024-128
'***Uncertainty in the projected Antarctic contribution to sea level due to internal climate variability***' by J. Caillet et al.

Summary

The study by Caillet et al. quantifies the uncertainties in the projected Antarctic contribution to sea-level change by 2100 related to internal climate variability in a subset of CMIP6 models. Three CMIP6 models are selected based on a summary of previous evaluations (Purich and England, 2021; Beadling et al., 2020; Heuzé, 2021; Sect. 2.1). The Antarctic sea-level contribution is projected with the stand-alone ice-sheet model Elmer/Ice; the respective experimental setup is presented in Sect. 2.2 and Sect. 2.3.

First, internal climate variability in the selected CMIP6 models is explored (Sect. 3.1 and Sect. 3.2). Then, the Antarctic contribution to sea-level change projected by Elmer/Ice based on different ensembles members for the selected CMIP6 models is presented (Sect. 3.3).

The authors quantify the effect of internal climate variability on the Antarctic sea-level contribution by the end of this century with 45% to 93%, with a higher impact from atmospheric variability compared to ocean variability, and modulated by the CMIP6 model. Results are discussed in terms of the robust representation of internal climate variability in CMIP models (Sect. 4.1), the internal climate variability as a source of uncertainty in Antarctic sea-level projections (Sect. 4.2), and identifying best ensemble members as an alternative approach to account for internal climate variability in sea-level projections (Sect. 4.3). The authors conclude with general recommendations for future assessments of the Antarctic contribution to sea-level change (Sect. 5).

General comments

By bringing together internal climate variability and the future evolution of the Antarctic Ice Sheet, the paper addresses a relevant and scientific interesting question, that has rarely been explored in previous assessments of the future trajectory of the Antarctic Ice Sheet. The presented results and related discussion may be valuable for future assessments of the Antarctic contribution to sea-level rise.
The title clearly reflects the contents of the paper. The abstract provides a concise and complete summary. Overall, the study has a sound methodology and experimental setup. In some cases, the description of the methods could be more precise, and the clarity of language improved. While the results span a wide range from exploring the representation of internal climate variability in selected CMIP6 models to the modelled response of the Antarctic Ice Sheet, the manuscript may benefit from linking both in greater depth (e.g. explaining the climate model - dependence of the impact of climate variability on the projected sea-level contribution, ranging between 45% and 93%, if possible). Here, additional figures, e.g. in a Supplementary Material, may be helpful for the reader. In addition, the discussion on a possible selection of best ensemble members from CMIP models could be better integrated in the manuscript. Finally, some additional explanations may be needed to directly derive and support some of the recommendations given in the conclusion based on the results presented in this study.

I have included more specific comments, questions and suggestions below.

Specific comments

L12-14: In the abstract, the results of the sea-level projections are summarized before describing the internal climate variability in the CMIP6 models. Maybe it would be more intuitive to follow the same order as in the main text (that is, internal climate variability in CMIP6 models followed by sea-level projections)?

L12-14: Maybe a brief remark on the upper end of the amplitude of oceanic internal variability covered by different climate models could be added, in addition to the mentioned and explained weak mid-depth ocean variability?

L15: Please specify 'use of several members in the run and its initialisation'. I think I understand what is meant here after reading the manuscript but this phrase may be unclear for the reader when starting with the abstract.

L24: Maybe add 'estimates of' or 'projections of', e.g. 'Estimates of the AIS contribution to future sea level rise are currently based...'

L25: I think CMIP stands for Coupled Model Intercomparison Project. Please check.

L31-35: In this paragraph climate variability is introduced as consisting of two components (1) variability from natural and anthropogenic external forcings and (2) internal variability, and explanations for these components are given, after having referred to internal climate variability in the previous paragraph. Maybe some restructuring is possible to define internal climate variability with its first use?

L49/50: Maybe 'the *Antarctic* Sea Level Contribution'?

L50: Why did you chose the SSP2-4.5 emission pathway? Please add a short explanation either here or in Sect. 2.3.

L56: 'drivers' instead of 'driver'?

L58-64: Please specify the properties that are used to evaluate the CMIP6 models. Some of them are given in Figure 1 or its caption, but it may be helpful to also include them in the main text.

- What properties of ASBW and CDW are evaluated? Please add this information also in the main text.
- Many dynamical features for the Southern Ocean are listed in the legend of Figure 1b. It might be helpful for the reader to better link the legend and caption of Figure 1 to the description in the main text. This applies to e.g. the ocean properties that are evaluated in terms of their meridional gradients.
- What bottom properties of the Southern Ocean are evaluated? Maybe add this information also in the main text.

L58-64: To facilitate readability, bold or italic fonts for some phrases in this list could be used (e.g. for the evaluated water masses). As an alternative, these properties could be given in a table rather than in a list.

L65: Is the assessment presented in Figure 1 based on one ensemble member of the respective CMIP6 models or an average over all available ensemble members? As different

ensemble members are used later in the manuscript, maybe add this information here (or in the figure caption) to avoid confusion.

L66: How is 'best' defined? Does UKESM-1-0-LL have one of the lowest RMSE in all three studies? Maybe state this more explicitly here.

L68: If I understand Figure 1 correctly, MPI-ESM1.2-HR was evaluated in two of three studies (red triangles in Figure 1a and c). Please check.

L70-73: This is a very general sentence, in particular for readers not familiar with the representation of ice-shelf melting in CMIP models. What is meant by '*some kind of* prescribed ice-shelf melting at depth'? Does this impact the assessment / ranking of CMIP6 models in Figure 1? I think it may be helpful to briefly discuss the link between the treatment of ice-shelf melting and the CMIP6 model assessment, if this information is mentioned here.

L74-77: Please add more detail on the assessment of atmospheric properties for the CMIP5/6 models in the manuscript, also given that Agosta et al. (2022) refers to a conference abstract. For example, which atmospheric properties have been evaluated and which method is used for the assessment?

Figure 1: Please consider marking the selected CMIP6 models in a different way, e.g. by colouring the model name or adding a box around the model name. The red triangles can be easily confused with the other markers (or appear within the legend, compare Figure 1b).

Figure 1: Please briefly introduce the abbreviations used in the legend, e.g. in panel b in the figure caption and / or in the main text (L58-64).

L82: Please add a reference for the friction law.

L84: What do you mean by '*preferentially* refined'? Please specify.

L85: What do you mean by 'high *curvatures*'? Please clarify.

L100-103: Are the ocean temperature corrections to match observed melt rates also based on Reese et al. (2023)? I assume that these may differ from the corrections presented in Reese et al. (2023) given the use of a different ocean climatology here. Please describe how the temperature corrections applied here are derived. It may also be helpful for the reader to briefly mention why temperature corrections are applied (instead of e.g. changing the PICO parameters to match present-day observed melt rates).

L106-107: Why is a *10 %* reduction of the inverted friction coefficients applied? Is this based on testing, a 'best fit' or some other methodology? Does the reduction of the friction coefficients change the modelled velocities (as this quantify has been the target of the inversion)?

L107-108: The ice-sheet model configuration slightly overestimates mass loss in West Antarctica (when compared to the uncertainty ranges of the observations) if I understand Table 1 correctly.

L108-109: Can you maybe add a brief remark (or a figure) on how large the trend bias in the ice-sheet model setup is?

L109-110: Please specify the reference that your results (in terms of the Antarctic sea-level contribution) are compared to. Are the projections in response to the CMIP6 climate models

analysed relative to each other? Do you substract from a control experiment to remove the drift? After reading the discussion, I think the trend is not removed.

L112-114: This formulation might be confusing for some readers.

Figure 2: It may be helpful to indicate the most relevant ice shelves in a map (as already done for the Antarctic basins in Figure 7).

L115-116: I got confused by the focus on the ocean here. Do you also run projections with ocean forcing only?

L116: I am not sure if I understand what is meant by 'constrained'. Maybe consider replacing by e.g. 'driven' or 'forced', if applicable.

L118-122: Please add more details on the selection of the CMIP6 ensembles members. I am not sure which section you are referring to for additional information on the selection, based on covering a wide spread in (1) possible ocean temperatures in the Amundsen Sea Embayment and (2) surface mass balance. Is the focus on the Amundsen Sea Embayment motivated by observed present-day mass loss in this region? Why is a different number of ensemble members chosen for each CMIP6 model? I appreciate the assessment of CMIP6 models in Figure 1, but, if I understand correctly, this evaluation justifies the choice of the CMIP6 model rather than the individual ensemble members for driving Elmer/Ice. It might be helpful for the reader to stress the link between the CMIP6 model evaluation, the assessment of the internal climate variability for these CMIP6 models and the selection of a subset of ensemble members for driving Elmer/Ice.

L120-122: I am not sure how familiar readers are with the CMIP variant labelling. While it may not be necessary to explain it in full detail, it may be helpful to briefly state that these lists describe different ensemble members for each of the CMIP6 models.

L129-135: This paragraph could be shortened. Maybe detailed information on the SMB in ISMIP6-Antarctic (L129-130) is not needed here.

L135: Maybe 'constrain' could be replaced by 'drive' or something similar, if applicable.

L136-144: I would like to mention that my comments are limited to this manuscript, and I have not assessed the approach for emulating MAR and thus for obtaining the estimates of SMB used in this study. From my point of view, no detailed evaluation is needed here and it is fine to refer to the approach described in Jourdain et al. (2024, in discussion) as done. Please make sure that respective inputs and outputs of this approach become clear (see some of the following comments / questions).

L137: '*surface* melting' instead of 'melting'?

L140-141: I am not sure if I understand correctly how the SMB for a given member is estimated. What is meant by '*perturbed* as a function of the annual temperature difference'?

L150: Maybe replace '*a* subset' by '*the* subset'?

L150: 'two first subsections' could be replaced by directly stating the subsections that you would like to refer to here to improve readability.

L153-155: It might be helpful for the reader to explicitly state the ocean properties that reflect the oceanic internal climate variability in the beginning of this section (that is, salinity and

temperature, as shown in Fig. 3, and as eventually described in the beginning of the following paragraph starting in L159).

L155: What is meant by '*typical*' standard deviation across model members? Does this mean that in most regions values are around 0.017 g kg-1 and 0.07°C for MPI-ESM1.1-HR? Or are these typical values for CMIP6 models?

L159: 'continental shelf' instead of 'shelf'?

L161: Maybe replace '*largest* variability' by '*large* variability' to avoid confusion? If I understand correctly, for example, the highest variability in mid-depth salinity for UKESM1-0-LL is found around Prydz Bay.

L171: Is 'deep ocean' considered as same ocean depth as 'mid-depth'?

L173: I would like to suggest to replace 'ice-sheet mass loss' by '*present-day* ice-sheet mass loss' or something similar.

L184-190: I think it may be helpful to add figures on the assessment of oceanic internal climate variability based on 60-year averages, at least in form of a Supplementary Material, given that the discussion and recommendations reflect on the time period of averaging.

L197: Please specify that the increased water vapour saturation in warmer air then results in enhanced precipitation.

L200: Is the SMB that you refer to here emulated or directly derived from the CMIP6 models? According to the caption of Figure 5 it is based on the MAR emulation. Maybe this could be specified again also in the main text.

L202: 'consistent' instead of 'consistently'?

L202 - 205: This section also refers to the absolute SMB. Since the atmosphere is suggested as an important factor for the (spread in the) projected Antarctic sea-level contribution in the following section, and the choice of the CMIP6 model at the same time also modulates the projected sea-level change, I would like to suggest to add a related figure of SMB and atmospheric temperatures (e.g. in the Supplementary Material) for interested readers.

L204: 'which is both due to' instead of 'which is due both'?

L205: MPI-ESM1.2-HR also shows a relatively high standard deviation in atmospheric temperature in the Siple Coast region, compared to the other selected CMIP6 models. Is this relevant for the projected future evolution of the Antarctic Ice Sheet? In Figure 7, the ice-sheet response in basin 9 (Siple Coast) to atmospheric changes in MPI-ESM1.2-HR (showing mass loss) differs from the other CMIP6 models (showing mass gain).

L205-208: What are the typical characteristics of the two Pacific-South American modes? Maybe add a short summary here for readers that are not familiar with Wang et al. (2022) and Marshall and Thompson (2016).

L210-227: Maybe the link between the analysis of internal climate variability in CMIP6 models and the projected Antarctic sea-level contribution could be stressed here, in particular, for explaining some of the key results related to the uncertainties in the projected contribution of the Antarctic Ice Sheet to sea-level change. This includes, for example, the results that (1) atmospheric internal climate variability has a larger effect on the spread in the projected sea-

level change with Elmer/Ice than oceanic internal climate variability, (2) the impact of the choice of the CMIP6 model on the sea-level contribution from Antarctica, and (3) the similarity of atmospheric internal climate variability for the selected CMIP6 models.

L213: For MPI-ESM1.2-HR there is a mean (?) mass loss related to the atmosphere in West Antarctica (Fig. 6i).

L215-217: Do you meant to refer to 'Pine Island and Thwaites *ice shelves*' / 'Getz ice *shelf*' here or rather the respective basins?

L217-218: Is this drift of the unforced Elmer/Ice experiment removed or is the absolute Antarctic sea-level contribution given in the respective figures? I think I got confused by the statement in L109-110 (please also see my related previous comment). And can the influence of the drift on the trends in East Antarctica be quantified?

L217: I would like to suggest to replace 'contaminated' by 'influenced' (or something similar).

L218: What can be learned on the sensitivity of East Antarctica and the Antarctic Peninsula to internal climate variability based on the simulations presented here? Maybe you can make use of Figure 7 and add some details in this section.

L220-222: I would like to suggest to give the full name of the CMIP6 models throughout the whole manuscript (consistent with e.g. Sect. 3.1).

L223: Basin 5 (including Totten glacier) shows a relatively large spread in the dynamical sea-level contribution (Fig. 7b). Can this be related to the assessment of oceanic internal climate variability in Sect. 3.2?

L226-227: Please add more information on this finding. How is the number determined? Can it be seen in a figure (likely Figure 6)?

Figure 6: I assume that the number in brackets in the legend refers to the number of ensemble members for each CMIP6 model. Why do the numbers differ between panel a/b and panel c? Please check.

Figure 6: Does the solid line indicate the mean? Maybe I have missed this.

L232-233: Maybe specify which paleoclimate proxies are used in Parsons et al. (2020) (similar to stating that Casado et al. 2023 base their analysis on ice core reconstructions in the following paragraph), for readers that are not familiar with this study?

L232: 'global mean surface air temperature' or its variability?

L233: Maybe you could add the observational plausible range for the temperature variability for comparison with the values for the CMIP6 models?

L243: If possible, maybe a conclusion on the representation of atmospheric variability in CMIP models could be added, bringing together the results of this study (Sect. 3.1) with the previous literature?

L245: Maybe add a reference for these observations?

L258-259: As the choice of the CMIP6 model is suggested to have a similar impact on the Antarctic sea-level contribution as the internal climate variability, it may be helpful to add a short paragraph on this finding also in Sect. 3.3 (in addition to this statement in the discussion).

L265-266: This sentence can maybe be reformulated. As already indicated, given the limited impact of the emission pathway on the Antarctic sea-level contribution to 2100, SSP2.4.5 may not be the main explanation for the Elmer/Ice projections presented here being at the lower end of previous projections.

L269: I would like to suggest 'ocean-*induced* melting' (or something similar).

L270: I am not sure if I understand the meaning of 'high variability of 20-year means' correctly. Maybe it is possible to rephrase?

L278-283: This paragraph seems to contain much information that is also given in the beginning of the following Sect. 4.3. I would like to suggest to move L278-283 to Sect. 4.3 and merge with the first part of this section.

L284-354: This is an interesting analysis and discussion. If I understand correctly, it supports to include multiple CMIP ensemble members in Antarctic sea-level projections as done in the work presented here. At the same time, it seems slightly detached from the previous parts of the manuscript. I would like to suggest two options that may help to add focus to this section:

> A) This section may be shortened, summarizing the main analysis and the conclusion. The major part of the analysis may be moved to the Supplementary Material.
>
> B) Parts of this section (e.g., the metrics and justification for these metrics) may be included in the Methods, and the outcomes could be highlighted and discussed with the main results. If applicable, the Antarctic sea-level contribution for the 'best' ensemble members could be added separately to e.g. Figure 6.

L290: I am not sure if I understand this phrase. Maybe replace 'assess' by e.g. 'demonstrate'?

L368-384: This paragraph contains many valid and helpful recommendations for future assessments of the Antarctic contribution to sea-level change. However, some of these recommendations do not seem to be directly justified by the presented results, or a better link to and additional information in Sect. 3 may be needed. For example, a fully-coupled assessment would be ideal to include feedbacks of the ice sheet with the ocean and the atmosphere, but some additional discussion how this would e.g. improve the representation of or remove biases in the internal climate variability in the selected CMIP6 models presented in Sect. 3.1 and Sect. 3.2 may be needed to directly relate to this study.

L379-380 / L382: Do the 'various members' / 'multiple members' refer to the CMIP6 model ensemble members or to ice-sheet initial states?