Response to the comments of the reviewers for the manuscript
'The long-term sea-level commitment from Antarctica'

by A. K. Klose, V. Coulon, F. Pattyn, and R. Winkelmann

We would like to thank the reviewers for carefully reading our manuscript and for their efforts in creating their review comments. We considered their suggestions thoroughly and adapted the manuscript accordingly.

In the revised version of the manuscript, we have particularly addressed the following points as raised by all reviewers:

- We have included a discussion of the applied **ice-sheet initialization approaches** as well as an **assessment of the resulting initial ice-sheet states** and the **historical ice-sheet trajectories** determined by Kori-ULB and PISM in comparison to observations.
- We have reformulated the **description of our results** to improve clarity and readability. Our results are presented in a more detailed context of the future Antarctic climates projected by the applied four CMIP6 GCMs. Ice-sheet model agreement in the short- and long-term Antarctic sea-level contribution is highlighted and uncertainties in the Antarctic sea-level commitment due to both diverging climate trajectories and model uncertainties (including uncertainties in ice-sheet processes, their parameterisation in ice-sheet models and distinct initialization approaches) are assessed.
- We have reorganized and added **figures** to allow a better understanding of the simulated ice-sheet response on different timescales, depending on the applied GCM forcing and ice-sheet models.

Note that PISM experiments have been rerun to ensure consistency of the till friction angle parameterization across possible restarts of the experiments (compare Section 2.1 in the original manuscript), with a negligible difference to the simulations presented in the original manuscript.

We provide a point-by-point response to all comments below. The reviewers' comments are given in bold font (with related sections from the original manuscript given in grey), the authors' reply in normal font and changes to the text in italic font. Line numbers mentioned in our responses refer to the manuscript version showing how these proposed changes would be implemented. It is attached at the end of this document.

We are grateful for the opportunity to further improve our manuscript and are looking forward to your feedback.

Sincerely yours,

Ann Kristin Klose, Violaine Coulon, Frank Pattyn, and Ricarda Winkelmann

Reviewer Comment 1

Klose et al. investigates the millennial-scale commitment of the Antarctic Ice Sheet to global sea level from 21st century emissions scenarios using an ensemble of two continental-scale ice sheet models. Their results demonstrate that a multi-meter sea level commitment of a low emissions scenario (SSP1-2.6) cannot be ruled out over millennial timescales, highlighting the difference between what they define as the transient "realised" sea level contribution from the long-term "committed" sea level contribution. Under high emissions (SSP5-8.5), the sea level contribution is as high as 40 m over 7000 years, with significant loss of the EAIS.
The study is a comprehensive and well-written and has potential to be a useful contribution to *The Cryosphere*. One of the main points of novelty of this study is that the millennial-scale projections are performed with two different ice sheet models in a consistent manner. However, the approaches used to initialise these ice sheet models are very different, resulting in quite substantial bias in one of the models. It does not seem clear to me that the authors have considered to what extent the inter-model uncertainties they describe are due to these large differences in the ice sheet initial state. I suggest that the authors address this aspect in particular to improve the work. This review is divided into general comments and specific comments.

We are grateful for the overall positive evaluation of our work. We thank the reviewer for carefully reading our manuscript and providing us with helpful comments to improve our manuscript, in particular, with regard to the discussion of the potential role of different initialization approaches for model differences in the Antarctic sea-level contribution on shorter (muli-centennial) and longer (multi-millennial) timescales.

General comments

Two different approaches are used to initialise the ice sheet models. For PISM, an ensemble of spin-up simulations were run and the model output were scored based on the fit of modelled floating and grounded ice area, ice thickness, and surface velocity to Bedmap2 and Rignot et al. (2011) velocities. Fig S1 indicates that the initial state of PISM for the projection is hundreds of meters too thick for most of WAIS, and hundreds of meters too thin for most of EAIS. For Kori-ULB, a nudging procedure is implemented to minimise model drift from Bedmachine-Antarctica. The authors should elaborate on why these two different methods are employed as well as the potential impacts on their results.
Differences in the input datasets, such as bed topography, could alone account for some of the ice sheet model differences (e.g. Wernecke et al., 2022), but this is generally not discussed other than with regard to present-day climatologies.
The results section jumps straight into the projection experiments, but I think it is worth commenting on the historical simulations. Notably, the two models show differences in the direction of SLE change over the course of the historical run, with one of the models showing a basal melt rate of nearly double the other (Fig S2). This is important context for the transient ice-sheet response.
As a specific example of the impact of the initial state, for SSP1-2.6, the two different ice sheet models display different short-term and long-term behaviour. In general, Kori-

ULB simulations show a higher centennial-scale sea level contribution than the PISM simulations, but this reverses for many of the simulations by the year 3000 (judging from Fig 2c). To what extent is this slower but eventually larger response of PISM due to its initial bias in ice thickness? One of the key findings highlighted in the abstract is this large sea level contribution under SSP1-2.6 of up to 6 m, but would a PISM model with a thinner initial WAIS produce the same result? This is worth exploring with a few sensitivity experiments.

We thank the reviewer for the detailed general comment that is very helpful for improving the presentation and discussion of our results, in particular with regard to the applied initialization approaches and potentially related model differences in the response of the Antarctic Ice Sheet. Our response to this general comment is structured along the following main points raised by the reviewer:

(1) Applied initialization approaches and resulting initial ice-sheet states compared to observations
(2) Historical ice-sheet trajectories simulated by Kori-ULB and PISM compared to observations
(3) Differences in ice-sheet model behaviour on shorter (multi-centennial) and longer (multi-millennial) timescales, in relation to the initial ice-sheet states

(1) **Applied initialization approaches and resulting initial ice-sheet states**

Two different initialization approaches are included in our work, based on the state-of-the-art ice-sheet models Kori-ULB and PISM. We do not consider the application of these different initialization approaches as inconsistency in our experimental setup, but rather as an advantage. Given that we include two common ways of initializing ice-sheet models (compare e.g., Seroussi et al., 2019, 2020), we sample uncertainties associated with the choice of the initialization approach.

In our view, this is important, as no single initialization approach available and applied to date can lead to an initial ice-sheet state that fully captures the characteristics of the (present-day) Antarctic Ice Sheet. While an inverse simulation allows to generate ice-sheet states that match (present-day) observations to a large degree (e.g., in terms of the ice-sheet geometry), the resulting parameter fields (e.g., basal sliding coefficients) may compensate for errors or uncertainties in other ice-sheet processes (Berends et al., 2023; Aschwanden et al., 2013). In addition, this approach assumes that the fields obtained in the inverse simulation to match (present-day) observations do not change in the future. In contrast, in the ice-sheet state resulting from a spin-up, the ice-sheet variables may be modelled in a consistent way, but its geometry might differ from the observed ice sheet. It is the result of the covered ice-sheet physics in the model for a set of uncertain parameters, without any nudging.

At present, each ice-sheet model tends to apply a preferred initialization approach for e.g. projections of the Antarctic sea-level contribution. While some assessments on the influence of the initialization approach exist (e.g., in the framework of initMIP, Seroussi et al., 2019), a direct comparison of different initialization approaches within a single ice-sheet model and their impacts on Antarctic sea-level projections is rare and should be part of future research. As such, there is no clear evidence that either of the initialization approaches is to be preferred.

In line with the editor comments, we have included a discussion of these initialization approaches and their advantages as well as a comparison of the initial ice-sheet states in our study to observations in Section 2.2.2 of the revised manuscript (lines 237-255):

> *Given that we include two common ways of initializing ice-sheet models (compare e.g., Seroussi et al., 2019, Seroussi et al., 2020), we sample uncertainties associated with the choice of the initialization approach. While an inverse simulation allows to reproduce the present–day ice sheet geometry well, the resulting parameter fields (such as basal sliding coefficients in Kori-ULB) may compensate for errors or uncertainties in other ice–sheet processes (Berends et al., 2023b; Aschwanden et al., 2013). In addition, it is assumed that the field obtained in the inverse simulation to match present–day observations does not change in the future. In contrast, in the simulated ice–sheet state resulting from a spin-up the ice–sheet variables may be modelled in a consistent way, but its geometry might differ from the observed ice sheet. It is the result of the covered ice–sheet physics in the ice–sheet model for a set of uncertain parameters, without any nudging.*
>
> *The simulated grounding–line position and ice thickness of the initial ice–sheet states are compared to present–day observations in Figure S1. As a result of the inverse simulation, the grounding–line position and ice thickness compare well to present–day observations in the initial ice–sheet states for Kori-ULB (Fig. S1a and c). With the spin–up approach applied in PISM, the initial ice–sheet states are characterized by larger ice thickness differences compared to present–day observations (Fig. S1b and d). Overall, ice in West Antarctica and in some coastal regions in East Antarctica (e.g,. in Dronning Maud Land, upstream of Amery Ice Shelf and in Wilkes Land) is thicker than observed at present (comparable to Reese et al., 2023), while the ice thickness in the interior of East Antarctica is underestimated. In addition, the grounding line in the Siple Coast area (and in the catchment draining Ronne–Filchner Ice Shelf for the MAR climatology) is located upstream of the observed grounding line in the present–day (Fig. S1 b and d), as previously seen in a model initialisation in a spin–up approach, e.g., Reese et al. (2023) and Sutter et al. (2023). These differences should be taken into account when interpreting the simulated long–term evolution of the Antarctic Ice Sheet.*

As an outcome related to these initialization approaches, basal friction deviates spatially between both ice-sheet models, in particular in the interior of West Antarctic marine basins. This can also be expected to influence the ice-sheet response and its timescales. In Section 2.2.2 of the revised manuscript, a paragraph describing the optimized field of basal sliding coefficients in Kori-ULB in comparison to the parameterized material properties of subglacial till in PISM is added (lines 225-230) as follows:

> *The optimized field of basal sliding coefficients in Kori-ULB is characterized by high basal sliding coefficients at the ice–sheet margins, turning into regions of low slipperiness (low basal sliding coefficients) towards the interior of West Antarctica. It thus differs from the basal friction experienced by the Antarctic Ice Sheet in experiments with PISM, where overall slippery bed conditions in the interior of marine subglacial basins are found, given the parameterized, bed–elevation dependent material properties of the subglacial till (in particular, the till friction angle; Sect. 2.1). These inter–model differences in basal friction linked to the applied initialization approaches are expected to influence the ice–sheet response.*

(2) **Historical ice-sheet trajectories simulated by Kori-ULB and PISM compared to observations**

Over the historical period and in response to the historical NorESM1-M climate trajectory, we find ice-sheet thinning in the Amundsen and Bellingshausen Sea regions and ice-sheet thickening in the interior of East Antarctica, overall matching the observed pattern of mass change in these regions (e.g., Smith et al., 2020) with both ice-sheet models.

In the PISM simulations presented in our study, the magnitude of mass loss from Thwaites and Pine Island glaciers in the Amundsen Sea sector is, however, underestimated compared to these observations. This ice loss in West Antarctica (and the Antarctic Peninsula) is dominating the overall observed ice-sheet mass changes to date (Otosaka et al., 2023). The lower sensitivity in the Amundsen Sea sector over the historical period in the PISM simulations shown here may thus explain the overall negative sea-level contribution to 2015. It may also contribute to the delayed response in this region on centennial timescales compared to ice-sheet changes projected by Kori-ULB, and should be taken into account when interpreting the projected Antarctic Ice Sheet evolution.

In the presented PISM simulations, we also find ice loss for Ross, Ronne-Filchner and Amery ice shelves, in contrast to observed ice thickening in these regions in present-day (Smith et al., 2020). This sensitivity in the Siple Coast region already during the historical period may also contribute to a larger long-term response in the PISM simulations presented here compared to the ice-sheet changes projected by Kori-ULB for low to intermediate warming levels.

Note that the hindcasting period of 65 years is relatively short (with an overlap of only about 35 years with available observations) compared to the typical response timescales of ice sheets of up to thousands of years, also given a lack of observational records. In addition, the hindcasts presented here are based on the historical climate trajectory from a single GCM (NorESM1-M; Bentsen et al., 2013) with potential biases in Antarctic climate, that could also cause some discrepancies in the simulated ice-sheet evolution compared to observations.
To date, many projections of future Antarctic Ice Sheet trajectories, also those presented in the recent IPCC assessment (Fox-Kemper et al., 2021), do not include any historical period. A multi-model community effort may be required to improve model hindcasts over the observational period for the Antarctic Ice Sheet (Aschwanden et al., 2021).

In line with the general editor comment, we have (1) added an assessment of the simulated ice-sheet trajectories in response to the NorESM1-M climate trajectory over the historical period as outlined above as Section 3.1, (2) included a related figure as Figure 2, and (3) linked the simulated historical ice-sheet response to the projected ice-sheet response to 2300 (Sect. 3.2) in the revised manuscript.

The main related paragraph in the revised manuscript (lines 314-338) reads as:

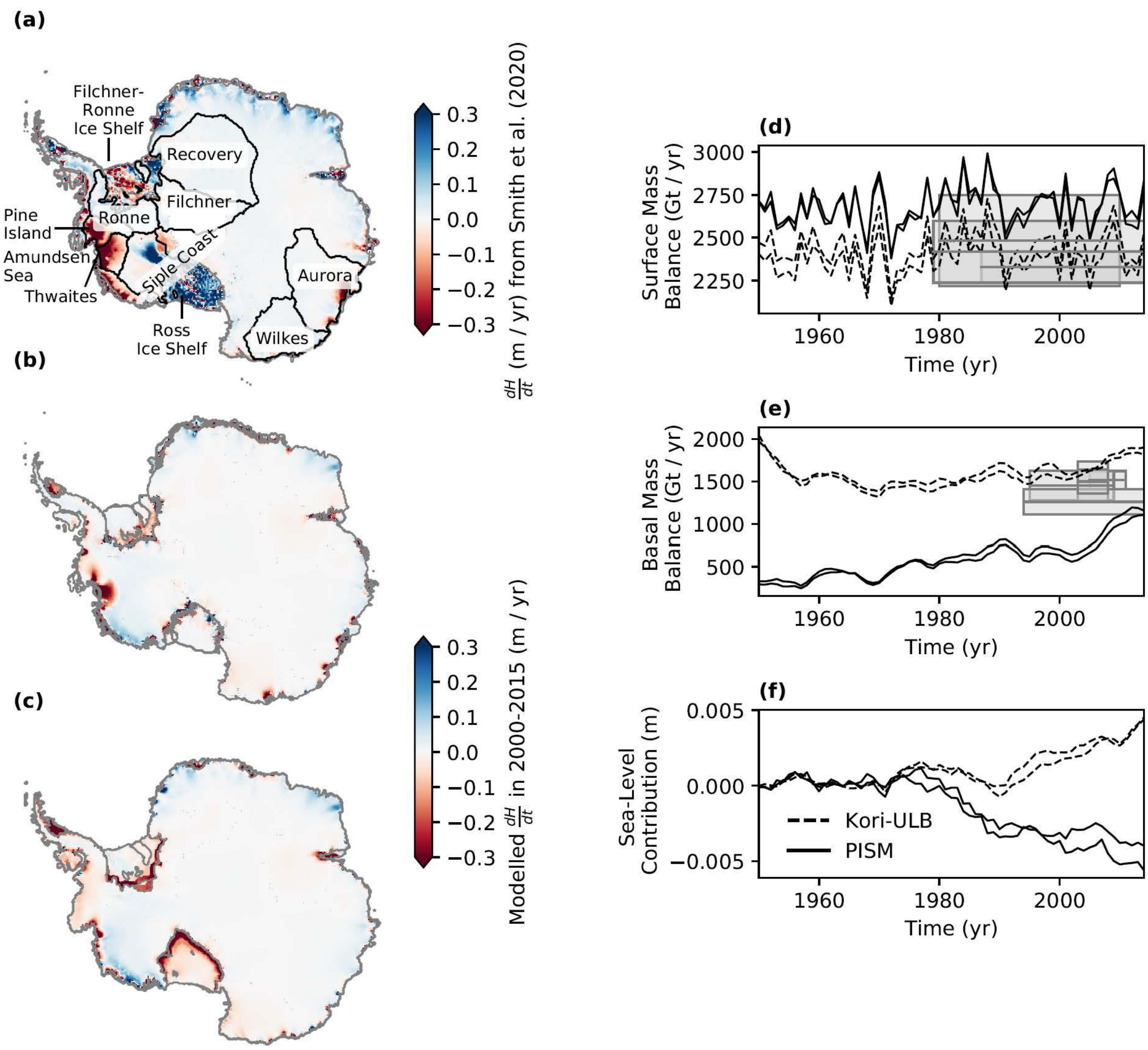
> *The pattern of observed present–day rates of ice–thickness change (e.g., Smith et al., 2020) is overall captured by both ice–sheet models in response to the historical NorESM1-M climate trajectory (Fig. 2a – c), with a thinning in the Amundsen and Bellingshausen Sea region and the Antarctic Peninsula and a thickening in the ice–sheet interior. The magnitude of ice–sheet thinning in the Amundsen Sea Embayment is, however, underestimated compared to present–day observations in the historical simulations with PISM presented here (Fig. 2a and c). In addition, we find ice loss for*

Ross, Ronne–Filchner and Amery ice shelves in PISM in contrast to observations (Fig. 2a and c).

The evolution of the continent–wide integrated surface mass balance is relatively similar for both ice–sheet models, but occurs on a higher, though still within RCM uncertainties, level in PISM than in Kori-ULB (Fig. 2d). While sub–shelf melt increases in PISM from about 300 Gt yr−1 in 1950 towards 1100 Gt yr−1 in 2015 at the lower end of present–day observations (Fig. 2e, solid lines), the basal mass balance is on the order of the observational record in Kori-ULB over the entire historical period, slightly exceeding its upper end in 2015 with about 1800 Gt yr−1 (Fig. 2e, dashed lines). The continent–wide aggregated sub–shelf melt rates observed in present–day are thus reproduced with both sets of PICO parameters (see Sect. 2.2.3), but they result in different sensitivities of sub–shelf melt rates to ocean temperature changes over the historical period (Fig. 2e; Reese et al., 2023).

Mass loss in the Amundsen Sea sector dominates the overall observed ice sheet mass changes in Antarctica to date (Otosaka et al., 2023). Given the lower magnitude of ice–sheet thinning of Pine Island and Thwaites glaciers in PISM, and stronger sub–shelf melt in Kori-ULB, we find diverging ice–sheet trajectories with both ice–sheet models in terms of the Antarctic sea–level contribution over the historical period from 1950 to 2015: Kori-ULB shows an integrated mass loss with a sea–level contribution of about +4 mm in 2015 (Fig. 2f, dashed lines), while the ice sheet overall gains mass equivalent to a sea–level change ranging between -4 mm and -6 mm in PISM (Fig. 2f, solid lines; within spread of recent ensemble of historical ice–sheet trajectories, Reese et al., 2023).

In the future evolution of the Antarctic Ice Sheet determined by PISM (Sect. 3.2 – 3.4), changes in the regions of Ross and Ronne–Filchner ice shelves could thus be overestimated, while the lower thinning rates over the historical period in the Amundsen Sea Embayment could suggest a reduced sensitivity of Thwaites and Pine Island glaciers to changes in climate conditions in these experiments.



(3) **Differences in ice-sheet model behaviour on shorter (multi-centennial) and longer (multi-millennial) timescales, in relation to the initial ice-sheet states**

In our experiments, we find differences in the ice-sheet model behaviour, in terms of the Antarctic sea-level contribution, on shorter (multi-centennial) and longer (multi-millennial) timescales that are most pronounced for low to intermediate levels of warming (corresponding to warming projected under SSP1-2.6, as outlined in the comment by Reviewer 1). For higher warming levels, the results from different ice-sheet models are in overall good agreement.

The higher short-term sensitivity under SSP1-2.6 in Kori-ULB compared to PISM is related to a stronger dynamical response, in particular in the Amundsen Sea sector, continuing the trends in this region over the historical period (see (2)). On multi-millennial timescales, both ice-sheet models eventually show a committed substantial grounding-line retreat in the Amundsen Sea Embayment under the lower-emission pathway SSP1-2.6.

The difference in the committed sea-level contribution (by year 7000) under SSP1-2.6 is explained by ice loss from the catchment draining Ross Ice Shelf in PISM experiments presented here with the loss of this ice shelf (resulting in a partial collapse of the West Antarctic Ice Sheet), opposed to a grounding-line advance and upstream thickening in the Siple Coast region in experiments with Kori-ULB.

We agree that the difference in the initial ice-sheet geometry could be a factor that contributes to the model difference in the Antarctic sea-level commitment under SSP1-2.6. As argued by the reviewer, the Antarctic sea-level contribution on multi-millennial timescales with substantial ice loss in some Antarctic regions could be higher in PISM than in Kori-ULB due to the over-estimation of the ice thickness in West Antarctica compared to observations (assuming a same pattern of mass loss; compare (1)). In our experiments the difference can be mainly explained by differences in the ice-sheet response in the Siple Coast described above leading to a higher Antarctic sea-level commitment in PISM than in Kori-ULB in the first place.

These model differences in the Siple Coast response can likely be linked to the initialization approaches and the simulated ice-sheet behaviour over the historical period, with (a) a drift in Kori-ULB, given lower sub-shelf melt rates obtained with PICO in this area compared to those that are obtained from the initialization approach to keep the ice sheet steady, and (b) the upstream location of the simulated grounding line compared to present-day observations (see (1), as previously seen in a model initialisation in a spin-up approach, e.g., Reese et al. (2023) and Sutter et al. (2023)) and the simulated thinning in Ross Ice Shelf over the historical period (compare (2)) in PISM. In addition, once grounding-line retreat is triggered, a collapse of the West Antarctic Ice Sheet may be more likely in PISM than in Kori-ULB, where low slipperiness towards the interior of West Antarctica (given low basal sliding coefficients retrieved in the inverse simulations, see (1)) slows down ice-sheet retreat. Stronger forcing (that is, warming levels reached by the end of this century under SSP5-8.5) is required in the Kori-ULB experiments presented here to overcome this low slipperiness towards the interior of West Antarctica and to induce a complete collapse of the West Antarctic Ice Sheet.

Beyond the low to intermediate warming levels covered by the lower emission pathway SSP1-2.6, the pattern of mass loss and the resulting sea-level contribution from Antarctica are robust across both ice-sheet models, irrespective of their initialization approach and structural differences. In particular, we find a stepwise long-term decline of the Antarctic Ice Sheet across two ice-sheet models: With increasing warming, our experiments suggest a committed partial collapse of the West Antarctic Ice Sheet, associated with substantial retreat in the Amundsen Sea Sector, up to its complete collapse, followed by enhanced mass loss from the East Antarctic marine Wilkes, Recovery and Aurora subglacial basins and an eventual decline of terrestrial parts of the ice sheet.

In the revised manuscript, we have reformulated the description of the projected multi-centennial Antarctic ice-sheet trajectories (Sect. 3.2; lines 339-393) as well as the multi-millennial committed Antarctic sea-level contribution (Sect. 3.3; lines 394-522), that now include explanations linking the ice-sheet response during the historical period, on shorter (multi-centennial) and longer (multi-millennial) timescales. In addition, Sect. 4 and, in particular, the discussion of model uncertainties (Sect. 4.2; lines 693-765) is reorganized and also elaborates on differences in ice-sheet model behaviour on shorter (multi-centennial) and longer (multi-millennial) timescales, in relation to ice-sheet modelling and initialization choices. Please see the attached manuscript for changes in the text.

Overall, we hope that by

- adding a detailed description of the outcomes of the initialization, compare (1),
- adding a paragraph outlining the simulated ice-sheet trajectories over the historical period, compare (2)

- and reformulating Section 3 (Results) and Section 4 (Discussion), relating ice-sheet modelling and initialization choices to the simulated ice-sheet behaviour during the historical period, on multi-centennial and multi-millennial timescales (see above),

the factors that may contribute to the differences in ice-sheet model behaviour on shorter (multi-centennial) and longer (multi-millennial) timescales become clearer in the revised manuscript.

Specific comments

Could you provide a table of experiments run, both in terms of forcings and ice sheet model parameter values?

We thank the reviewer for this suggestion, and agree that an overview table for the presented commitment experiments can support clarity on the experiments presented in our study. In addition to Table S1, showing the CMIP6 GCMs for deriving the changes in Antarctic climate in combination with the different branchoff points in time, we have added Table S2 in the revised Supplementary Material. Table S2 displays the ice-sheet model configurations used for assessing Antarctic sea-level commitment with Kori-ULB and PISM, see below.

Table S2. Ice-sheet model configurations. Ice-sheet model configurations used for assessing Antarctic sea-level commitment. While ice—sheet initial conditions with Kori-ULB are obtained in an inverse simulation for each of the atmospheric climatologies, it is derived from a spin–up ensemble for each atmospheric climatologies in PISM. The combinations of PISM parameters for the initial states selected from these ensembles are given as well.

	Atmospheric climatology	Sliding exponent	SIA enhancement factor	Tillwater decay rate	Till effective overburden fraction
Kori-ULB	MARv3.11	-	-	-	-
	RACMO2.3p2	-	-	-	-
PISM	MARv3.11	0.75	2.0	7 mm yr^{-1}	0.015
	RACMO2.3p2	0.5	1.5	7 mm yr^{-1}	0.015

Line 180: capitalise "Initialisation"

Thanks. We have corrected this typo in the revised manuscript.

Line 184-185: NorESM1-M is CMIP5? "ocean and atmosphere anomalies" refers to anomalies of this particular GCM?

Yes. We create the historical climatologies, roughly representing the year 1950, based on a historical simulation by NorESM1-M in CMIP5 (Bentsen et al., 2013). This follows recommendations in ISMIP6, where CMIP5 NorESM1-M was found to represent the Antarctic climate over the historical period reasonably well, compared to other CMIP5 GCMs (Barthel et al., 2020; Nowicki et al., 2020).

In the revised manuscript (lines 189-197), we have adjusted the corresponding section to avoid confusion about the origin of the ocean and atmosphere anomalies. It reads as follows:

> *The historical climatic boundary conditions for the year 1950 are constructed using the historical changes in ocean and atmosphere with respect to the reference period from 1995 to 2014 from the Norwegian Earth System Model (NorESM1-M; Bentsen et al.,*

2013) in CMIP5. The oceanic and atmospheric anomalies from NorESM1-M are averaged over the period 1945–1955 and subsequently added to present–day atmospheric temperatures and precipitation derived from Regional Climate Models (RCMs) as well as observed present–day ocean temperatures and salinities. Present–day atmospheric climatologies are derived from the RCMs Modèle Atmosphérique Régional (MARv3.11; Kittel et al., 2021) and the Regional Atmospheric Climate MOdel (RACMO2.3p2; Van Wessem et al., 2018) to take into account uncertainties in the representation of present–day Antarctic surface climate (compare Mottram et al., 2021).

Fig 1a: Should the top part of the curve have a steeper slope? (i.e. accelerated mass loss)

Figure 1a illustrates various factors that may contribute to the substantial difference between the transient realized and the long-term committed sea-level change, such as the potential of crossing critical temperature thresholds with progressing warming. While such critical temperature thresholds may already be crossed during the next decades or centuries, the corresponding ice loss could then unfold on multi-centennial to multi-millennial timescales.

The potential threshold behaviour of the ice sheet depending on the ice-sheet boundary conditions can be seen in its equilibrium response, indicated in black. It could be obtained by very slowly changing the environmental conditions (e.g., global mean temperature) at a rate which is much slower than the typical rates of changes in an ice sheet. Once a critical temperature is crossed, there is a stepwise change to a qualitatively different ice-sheet configuration, which is associated with a relatively higher sea-level contribution in Figure 1a. It corresponds to the loss of the lower stable equilibrium branch (solid black line) and the transition to the upper stable equilibrium branch (solid black line). In the transient ice-sheet response, for example following a warming trajectory under the higher-emission pathway, this stepwise change translates into an accelerated mass loss over time. That is, an accelerated mass loss, that is associated with the crossing of critical temperature thresholds, corresponds to the 'jump' from the lower to the higher sea-level contribution in Figure 1a.

In the revised manuscript, we have added the following sentences to the caption of Figure 1 for clarification:

For example, the crossing of critical thresholds with ongoing warming may result in accelerated mass loss. This is associated with the stepwise change (jump) towards a higher sea-level contribution indicated as (2).

Line 192: By atmospheric climatologies, do you mean from the RCMs or the CMIP forcing?

To build initial ice–sheet representations with PISM, a spin–up approach is applied for each of the atmospheric climatologies individually.

Atmospheric climatologies here refer to the climatologies representing the historical climate (around 1950). These are a combination of present-day atmospheric climatologies from the RCMs MAR and RACMO and historical changes in Antarctic climate derived from NorESM1-M. We thank the reviewer for pointing out this lack of clarity in the original manuscript, and have reformulated this paragraph as follows in the revised manuscript (lines 203-204):

> *To build initial ice–sheet states with PISM, a spin–up approach is applied for each of the historical atmospheric climatologies (around 1950, see above) individually:*

In addition, lines 189-197 have been reformulated in the revised manuscript to clarify the construction of the historical climatologies. We refer to the response to the related previous reviewer comment.

Line 204: So scoring for Bedmap2 for PISM, but Bedmachine for Kori-ULB?

Yes, this is correct. We use the observed Bedmap2 ice thickness for scoring of the PISM initial ice-sheet states, while the Bedmachine present-day ice thickness is used in the initialization of Kori-ULB. Using the Bedmachine ice thickness instead of the Bedmap2 ice thickness likely does not change the scoring substantially, given the overall magnitudes of differences between the simulated ice thickness compared to observations relative to the differences between both datasets.

Note that there is no scoring after the initialization with Kori-ULB, but a nudging is performed for a given (fixed) set of ice-sheet model parameters to match the observed ice-sheet thickness. That is, the difference to the present-day ice thickness is minimized by iteratively adjusting the basal sliding coefficients under grounded ice and sub-shelf melt rates under floating ice in an inverse simulation (following Pollard and DeConto, 2012) under historical (1950) atmospheric conditions. Here, the Bedmachine present-day ice thickness from Morlighem et al. (2020) was chosen as a target.

For PISM, different possible initial ice-sheet states are obtained in a full-physics spin-up ensemble. Here, starting from the observed Bedmap2 ice thickness (Fretwell et al., 2013), the ice sheet evolves freely under historical (1950) climate. The ice-sheet state that is used for assessing the Antarctic sea-level commitment is chosen by scoring the ensemble members based on the mean-square-error mismatch of grounded and floating ice area, ice thickness, grounding-line location and surface velocity compared to present-day observations (Fretwell et al., 2013; Rignot et al., 2011).

Please also see our response to the general reviewer comment for a more detailed discussion of the application of different initialization approaches for assessing the Antarctic sea-level commitment in our study and related adjustments in the revised manuscript.

Line 214: "balanced"

Thanks. We have corrected this typo in the revised manuscript.

Line 230: "GCMs"

Thanks. We have corrected this typo in the revised manuscript.

Line 240-243: Do you average at or over a particular depth?

> Missing values for the oceanic forcing on the continental shelf (arising due to the coarse resolution of CMIP6 GCMs) and in currently ice-covered regions are filled following Kreuzer et al. (2021), i.e., by averaging over all existing values in neighbouring cells.

We thank the reviewer for pointing us to missing information on the processing of ocean forcing in this part of the original manuscript. Filling of missing values is done for every available ocean layer of the different GCMs. In a next step, and to have forcing fields that are applicable to PICO, ocean properties derived from CMIP6 GCMs are linearly interpolated to the continental shelf depth (compare line 266 in the original manuscript).

In the revised manuscript, we have moved the remark on the linear interpolation to lines 276-277.

Line 270: Is the reason for the difference in parameter values that they produce better fit to observations for those particular ice sheet models?

The values of the PICO parameters are an individual choice for each ice-sheet model. They have been chosen such that for the respective ice-sheet model observed sub-shelf melt sensitivities and / or melt rates are matched, and are based on parameter optimizations for PICO (Reese et al., 2018; Reese et al., 2023).

In the revised manuscript (lines 301-302), a short explanation has been added as follows:

> *The values of the PICO overturning strength parameter C and the turbulent heat exchange coefficient γ_T* are an individual choice for each ice–sheet model to match sub–shelf melt sensitivities and / or observed melt rates.*

Line 278: Is the negative SLE change from a model that has positive SLE change over the historical period? It is worth specifying if the models that show modern ice mass loss have a negative or positive SL contribution.

> Following the lower–emission pathway SSP1-2.6 results in a sea–level change ranging from -5.0 cm to +8.0 cm by the end of this century and from -0.2 m to +0.5 m in 2300 (Fig. 2a; Tab. 1). Therein, Kori-ULB projects a positive sea–level contribution for this lower–emission scenario (dashed lines), while PISM projects a sea–level drop (solid lines).

We thank the reviewer for this important question. We agree that stressing the relation between the simulated historical ice-sheet trajectories in Kori-ULB and PISM and the projected sea-level contribution on multi-centennial to multi-millennial timescales in the revised manuscript would be helpful.

Over the historical period in response to NorESM1-M climate trajectories, Kori-ULB ice-sheet trajectories show an integrated mass loss, while the Antarctic Ice Sheet slightly gains mass in the PISM experiments presented here. The simulated trends of ice-sheet changes over the historical period are continued in future projections under SSP1-2.6 with both ice-sheet models. That is, PISM projects a sea-level drop by 2300 compared to present-day for the majority of lower-emission climate trajectories. Kori-ULB projects a positive sea-level contribution for this lower-emission scenario, related to a stronger dynamical response in the Amundsen sea sector. Ice-sheet trajectories under SSP1-2.6 are thus influenced by the simulated historical trends and differences in ice-sheet modelling choices. Under the higher-emission pathway SSP5-8.5, we find that climate drivers dominate the projected multi-centennial ice-sheet changes.

Please see our response to the general reviewer comment for a more detailed discussion of the simulated historical ice-sheet trajectories and the ice-sheet response on multi-centennial timescales as well as related adjustments in the revised manuscript.

Line 280: I would think the difference in initial state is a larger contributor to the differences between the two models than the dynamic response to the forcings.

> The overall sign of ice–sheet mass changes contributing to a change in sea–level depends on the balance between the dynamic response to sub–shelf melting and ice–shelf thinning and the surface mass balance. We find that the integrated surface mass balance remains positive for both ice–sheet models until 2300 under SSP1-2.6 (Fig. S3a). However, the response in dynamic discharge contributing to a sea–level increase on centennial timescales is higher in Kori-ULB (with ice–sheet thinning in the Amundsen Sea Embayment extending inland, Fig. S4–S5) than in PISM (see Fig. S6–S7 for comparison), explaining the diverging sea–level contribution under SSP1-2.6 until 2300.

We agree that the difference in the initial ice-sheet states may be one factor that contributes to the model difference in the projected Antarctic sea-level contribution. Please compare our response to the general reviewer comment for a more detailed discussion of the initial ice-sheet states that result from the different initialization approaches, their impact on the projected transient sea-level contribution from the Antarctic Ice Sheet to 2300 and related adjustments in the revised manuscript.

Line 284-286: PISM is too thick in the ASE to start with.

Given the spin-up approach applied in PISM, the initial ice-sheet states are characterized by larger ice-thickness differences compared to present-day observations. Please compare our response to the general reviewer comment for a more detailed discussion of the initial ice-sheet states that result from the different initialization approaches, their impact on the ice-sheet model behaviour on shorter (multi-centennial) and longer (multi-millennial) timescales and related adjustments in the revised manuscript.

Line 297-300: The models don't include hydrofracture parameterization, correct? Does surface temperature of ice shelves reach threshold for melt pond formation? e.g. van Wessem et al. (2023)

This is correct. In the experiments presented here, a hydrofracture parameterization is not applied.

The formation of melt ponds and subsequent hydrofracturing with future warming and increasing surface melt are discussed as precursors for ice-shelf loss or collapse (e.g., Lai et al., 2020; Pollard et al., 2015; Trusel et al., 2015). Van Wessem et al. (2023) identify temperature thresholds for melt pond formation in Antarctica. For mild and wet ice shelves such as in West Antarctica and the western Antarctic Peninsula, melt pond formation is suggested to occur for temperatures higher than -9°C. For cold and dry ice shelves, this threshold is estimated around -12 °C or even less than -15°C for Ronne-Filchner, Ross and Amery ice shelves (Van Wessem et al., 2023).

When comparing to future warming projected within CMIP6 by 2100, these thresholds for melt pond formation may be crossed for many ice shelves, in particular under SSP5-8.5 (as shown by Van Wessem et al., 2023). In our experiments, we follow the warming trajectories projected by four CMIP6 GCMs even beyond the end of the century until 2300. Consistent with Van Wessem et al. (2023), these GMCs project atmospheric temperature changes exceeding the melt pond formation thresholds under SSP5-8.5. Temperature changes due to an evolving ice-sheet geometry by means of the atmospheric lapse rate might add to the warming projected by the GCMs.

So far, hydrofracturing is poorly represented in ice-sheet models and the availability of parameterizations is limited. One parameterization for including this process in sea-level projections has been proposed by Pollard et al. (2015) and DeConto and Pollard (2016). In addition, ice-shelf collapse, that may be caused by, among others, hydrofracturing, is prescribed by a yearly mask defining regions and timing of collapse based on the presence of mean annual surface melting above 725mm over a decade in ISMIP6 (Trusel et al., 2015; Seroussi et al., 2020).

Coulon et al. (2024) tested the sensitivity of the Antarctic sea-level contribution by the end of the millennium to hydrofracturing based on the parameterization of Pollard et al. (2015) and DeConto and Pollard (2016): In their sea-level projections, the rate of the Antarctic contribution to global mean sea-level rise is increased compared to simulations that do not account for ice-shelf collapse through hydrofracturing. This is due to an acceleration of grounding-line retreat in West Antarctica as well as in the marine basins of the East Antarctic Ice Sheet as a consequence of accelerated ice-shelf breakup.

In the revised manuscript, we have added a paragraph that discusses the potential consequences of hydrofracture for Antarctic sea-level commitment in Section 4.3 (lines 785-792). It reads as:

> *Surface melt on Antarctic ice shelves facilitates hydrofracturing and may, thereby, trigger ice–shelf collapse (Van Wessem et al., 2023; Lai et al., 2020; Pollard et al., 2015; Trusel et al., 2015) and potentially the Marine Ice Cliff Instability (MICI; Bassis and Walker, 2012; Pollard et al., 2015). While temperature thresholds for melt pond formation as a precursor for such ice–shelf loss may be exceeded by the end of the century (Van Wessem et al., 2023), the availability of parameterizations to include these processes in ice–sheet models is still limited (Pollard et al., 2015; DeConto and Pollard, 2016; Seroussi et al., 2020). Considering hydrofracturing (following Pollard et al., 2015; DeConto and Pollard, 2016; Seroussi et al., 2020) may speed–up grounding-line retreat in marine Antarctic basins due to an earlier ice-shelf breakup (Coulon et al., 2024; Seroussi et al., 2020).*

Line 303: "(ISMIP6)"

In the revised manuscript, the abbreviation has been introduced as:

> *Ice Sheet Model Intercomparison Project for CMIP6 (ISMIP6)*

Line 315: But you have some simulations that show the opposite

> Our simulations confirm that sea level may keep rising for centuries to millennia to come even if warming is kept at a constant level (Fig. 2c and d, consistent with, e.g., Winkelmann et al., 2015; Van Breedam et al., 2020).

This is correct, thanks for pointing this out. While the bulk of our simulations show that sea level may keep rising for centuries to millennia to come even if warming is kept at a constant level, there are some ice-sheet trajectories showing a decline in the Antarctic sea-level contribution towards the year 7000 after an initial positive sea-level change. This is most pronounced in simulations when following MRI-ESM2-0 climate under SSP1-2.6, and may be attributed to a thickening trend upstream of Ross Ice Shelf (in Kori-ULB only) and in the ice-sheet interior towards the year 7000, outweighing the initial Antarctic mass loss. Note that despite the decline of sea-level rise for some ice-sheet trajectories, these are still characterised by an initial sharp increase in the Antarctic sea-level contribution.

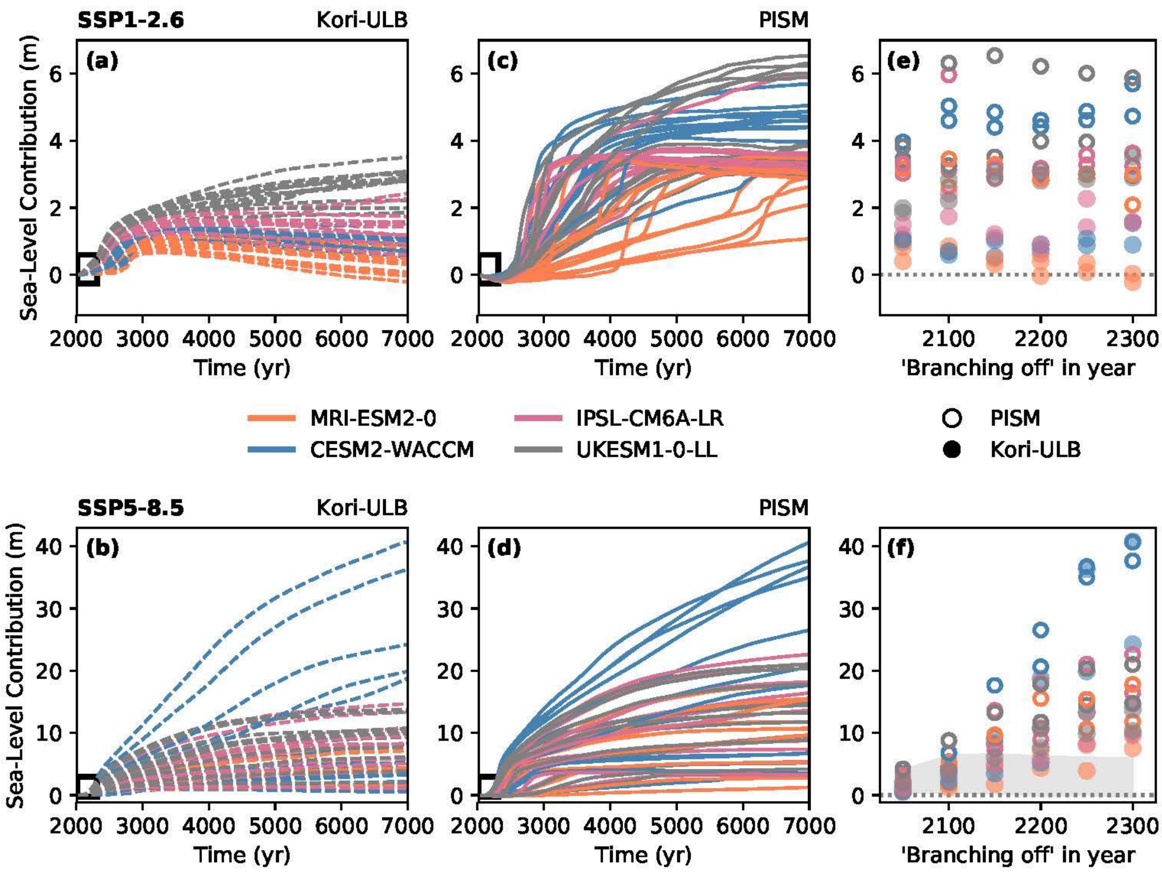
In the revised manuscript, we have reformulated the description of the committed Antarctic sea-level contribution under SSP1-2.6 (Sect. 3.3.1; lines 408-476). Please see the attached manuscript for changes in the text. In particular, the related paragraph (lines 401-402 and lines 410-413) now reads as:

> *The bulk of our simulations shows that sea level may keep rising for centuries to millennia to come even if warming is kept at a constant level (Fig. 5a – d; consistent with, e.g., Winkelmann et al., 2015; Van Breedam et al., 2020).*
> *[...]*
> *Some of the ice–sheet trajectories eventually show a decline in the Antarctic sea–level contribution on multi–millennial timescales (Fig. 5a and c; e.g., for MRI-ESM2-0 climate indicated in orange), with a thickening trend upstream of Ross Ice Shelf (in Kori-ULB only, see below) and in the ice–sheet interior towards the year 7000, outweighting the initial mass loss.*

In addition, we have added the following explanation for the decline in the Antarctic sea-level contribution in lines 442-449 of the revised manuscript:

> *In Kori-ULB, both large ice shelves are preserved to year 7000, and we find a grounding–line advance and upstream thickening in the Siple Coast region (Fig. 6a). This long–term ice–sheet response in the Siple Coast may, in parts, result from a drift of the initialisation procedure, given lower sub–shelf melt rates obtained with PICO in this area compared to those that are obtained from the initialization approach to keep the ice sheet steady (Sect. 2.2.2). A thickening signal upstream of Ross Ice Shelf has also been observed over the past decades (with the stagnation of Kamb Ice Stream; Smith et al., 2020). The simulated thickening upstream of Ross Ice Shelf contributes to the decay in the long–term Antarctic sea–level contribution over time after the year 3000 in some Kori-ULB experiments, which is most pronounced for sustained MRI-ESM2-0 climate (Fig. 5a, orange).*

The related Figure 2 in the original manuscript has also been changed following an editor comment. In particular, a figure focusing on the committed ice-sheet response has been introduced as Figure 5 in the revised manuscript. We here show the multi-millennial ice-sheet response in terms of the sea-level contribution under SSP1-2.6 and SSP5-8.5, separately for Kori-ULB and PISM, together with the sea-level commitment in the year 7000, depending on the branchoff point in time. We hope that, with this separation of the long-term ice-sheet trajectories by the ice-sheet models, simulations can be better distinguished.



Line 339-342: This sentence is confusing.

> In PISM, a substantial portion of the marine ice–sheet in West Antarctica is lost by year 7000 under most considered climate trajectories (compare Fig. S14–S15), determining (in combination with a potential grounding–line retreat in the Wilkes basin) the upper range of Antarctic sea–level commitment under SSP1-2.6 in our ensemble of simulations (Fig. 2e).

Lines 339-342 in the original manuscript refer to the committed ice-sheet response simulated by PISM under SSP1-2.6. Here, the combined ice loss from West Antarctica and the East Antarctic Wilkes basin (especially for UKESM1-0-LL climate) gives rise to the upper end of the long-term Antarctic sea-level commitment of up to 6.5 m under this lower-emission pathway in our ensemble of simulations.

In the revised manuscript, we have reformulated the description of the committed ice-sheet changes under SSP1-2.6 (Sect. 3.3.1, lines 408-476) and we hope that it is clearer in its revised form. Please see the attached manuscript for changes in the text. In particular, a related sentence (lines 463-466) now reads as:

> *The combined ice loss from West Antarctica and the East Antarctic Wilkes subglacial basin in PISM gives rise to the upper end of the long–term Antarctic sea–level commitment of up to +6.5 m found under the lower–emission pathway in our experiments (Fig. 5c and e, grey open markers).*

Figure 2: I suggest changing the colors because SSP1-2.6 is generally dark blue, and SSP5-8.5 is generally dark red, but here the colors refer to different GCMs.

Thanks for this suggestion. We have changed the colours indicating the GCMs in Figure 2 and elsewhere in the figures of the revised manuscript.

Fig 3: Clarify the time of commitment. Are these means of both models?

In the revised manuscript, we have made sure that the time of commitment is given in all figure captions where needed.

Line 391: "changes"

Thanks. We have corrected this typo in the revised manuscript.

Line 399: By regional warming, do you mean of air temperature?

Yes. Warming levels are given as regional Antarctic-averaged atmospheric temperature changes, compared to 1995-2014. Thanks for pointing out that this information is missing in line 399 of the original manuscript. In the revised manuscript, we have made sure that this information is clearly stated where needed.

Line 406: Is this realistic that the Ross Ice Shelf doesn't collapse under sustained SSP5 forcing? It could be an artifact of the basal melt parameterization, or the fact that there is no hydrofracture parameterization implemented.

> While Ross Ice Shelf is maintained in simulations with Kori-ULB, it is lost in most simulations with PISM (compare Fig. 4c and d, l).

In experiments with Kori-ULB, Ross Ice Shelf does not collapse when sustaining the warming that is reached by the year 2050 under the SSP5-8.5 emission pathway and for warming levels under the lower-emission pathway SSP1-2.6. Please note, however, that it may be lost on multi-millennial timescales for stronger warming levels that are reached later in time under SSP5-8.5 (compare Figures S16 and S17 of the original Supplementary Material).

These differences in the timing of ice-shelf collapse may be related to the calving schemes employed in the ice-sheet models or different sub-shelf melt sensitivities to changes in ocean temperature in PICO. The values of the PICO parameters are an individual choice for each ice-sheet model. They have been chosen such that for the respective ice-sheet model observed sub-shelf melt sensitivities and / or melt rates are matched, and are based on parameter optimizations for PICO (Reese et al., 2018; Reese et al., 2023).

In the revised manuscript (lines 301-302), we have added an explanation on the choice of PICO parameters, following a previous reviewer comment:

> *The values of the PICO overturning strength parameter C and the turbulent heat exchange coefficient γ_T* are an individual choice for each ice–sheet model to match sub–shelf melt sensitivities and / or observed melt rates.*

Note that overall the availability of projections of the evolution of the Antarctic Ice Sheet after 2100 is limited. In particular, substantial parametric uncertainty exists, some of which (e.g., basal melt parameterizations and related parametric uncertainty) is explored in more detail in Coulon et al. (2024) in terms of the Antarctic sea-level contribution by the end of this millennium. It thus remains an important next step for future research to assess the effects of this parametric uncertainty on the Antarctic Ice Sheet response (including the potential loss of ice shelves) also on multi-millennial timescales as discussed e.g. in lines 594-605 of the original manuscript / lines 744-758 in the revised manuscript.

While not including hydrofracturing as a process in our assessment of the Antarctic sea-level commitment, potential consequences, e.g. via an earlier ice-shelf collapse, are discussed in the revised manuscript, in an additional paragraph in Section 4.3 (lines 785-792). Please also see our response to the previous related reviewer comment for a more detailed discussion of hydrofracturing and related adjustments in the revised manuscript.

Line 409: For how much warming? And is this due to the initial condition (i.e. PISM has more of WAIS to lose…)?

> While 2% of the initial ice mass in Antarctica contributing to global mean sea–level rise is lost in Kori-ULB (raising global mean sea–level by up to approximately +2.0 m), a slightly higher fraction of 6% (equivalent to a global mean sea–level change between +3.0 m and +4.0 m) is found in simulations with PISM (Fig. 4b), due to the discharge of larger parts of the West Antarctic Ice Sheet as opposed to an advance of the grounding line in the Siple Coast area in Kori-ULB (compare Fig. 4c and d, l).

The given amount of ice is lost for a regional Antarctic-averaged atmospheric warming below 4°C in our experiments. Note that, in the revised manuscript, we have reformulated the description of the committed Antarctic sea-level contribution under SSP1-2.6 (Sect. 3.3.1; lines 408-476) to improve clarity. Please see the attached manuscript for changes in the text.

We agree that the difference in the initial ice-sheet state may be one factor that contributes to the model difference in Antarctic sea-level commitment. As argued by the reviewer, the sea-level contribution could be higher in PISM than in Kori-ULB due to the overestimation of the ice thickness in West Antarctica compared to observations (assuming a same pattern of mass loss).

We here, however, also find some difference in the pattern of mass loss, with ice loss from the catchment draining Ross Ice Shelf in PISM, opposed to grounding-line advance and upstream thickening in this region in experiments with Kori-ULB. In addition, the subglacial basin draining Ronne Ice Shelf shows more mass loss in the PISM experiments presented here than in Kori-ULB experiments. This may explain the differences in the long-term sea-level contribution under SSP1-2.6 as determined by PISM and Kori-ULB in the first place.

These differences can likely be linked to the different initialization approaches applied in the ice-sheet models. Please compare our response to the general reviewer comment for a more detailed discussion of the initial ice-sheet states that result from the different initialization approaches, their impact on the ice-sheet model behaviour on shorter (multi-centennial) and longer (multi-millennial) timescales and related adjustments in the revised manuscript.

Line 413: What do you mean by "uncertainty"?

> The uncertainty in the initial ice–sheet configurations of each model results in differences on the order of decimeters in sea–level contribution in this warming range and is thus less significant than the inter–model spread.

We here aimed to quantify the difference in the Antarctic sea-level contribution that is caused by using distinct initial ice-sheet states for each ice-sheet model. This is sometimes referred to as 'initial-state uncertainty'. In our experiments and related to the initialization approaches, differences in initial ice-sheet states are, however, not only related to different initial ice-sheet geometries, but at the same time basal sliding coefficients (in Kori-ULB, as obtained in the inverse simulation under historical climate) or ice-sheet model parameters (in PISM, as a result of the spin-up ensemble under historical climate) may be different across initial ice-sheet states and could influence the ice-sheet response to changes in climate.

In the revised manuscript, we have reformulated the description of the committed Antarctic sea-level contribution under SSP1-2.6 (Sect. 3.3.1; lines 408-476) to improve clarity. Please see the attached manuscript for changes in the text.

Line 477: The projection experiments are consistent, but the initialisations are not.

> Experiments were carried out systematically for stabilized climate at different points in time over the course of the next centuries and in a consistent way with the stand–alone ice–sheet models PISM and Kori-ULB accounting for some inter– and intra–model uncertainty*.*

Two different initialization approaches are included in our work, based on the state-of-the-art ice-sheet models Kori-ULB and PISM. We do not consider the application of these different initialization approaches as inconsistency in our experimental setup, but rather as an advantage. Given that we include two common ways of initializing ice-sheet models (compare e.g., Seroussi et al., 2019, 2020), we sample uncertainties associated with the choice of the initialization approach. Please compare our response to the general reviewer comment for a more detailed discussion of the application of different initialization approaches for assessing the Antarctic sea-level commitment and related adjustments in the revised manuscript.

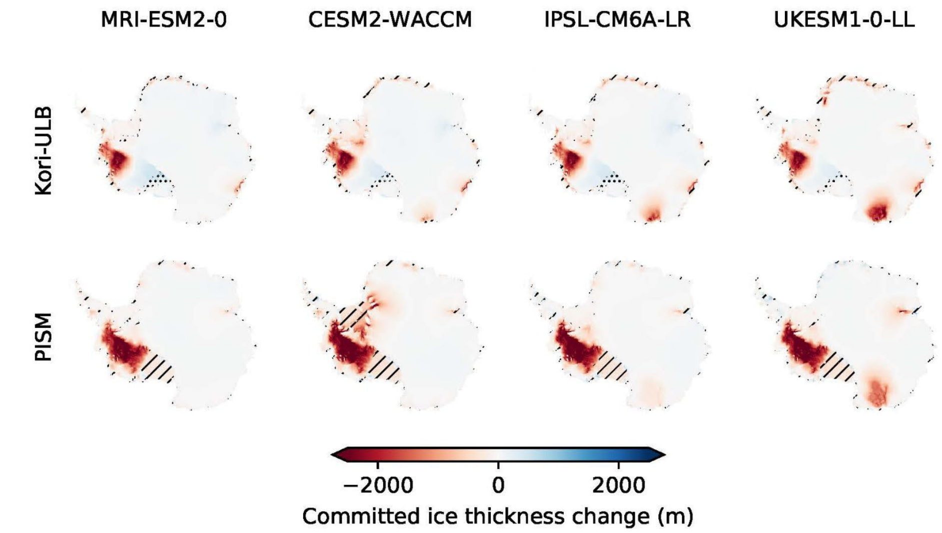
Line 567-593: Initial state discussion focuses on the choice of present atmospheric forcing, but what about the initialisation procedure, which seems to result in quite different ice thicknesses?

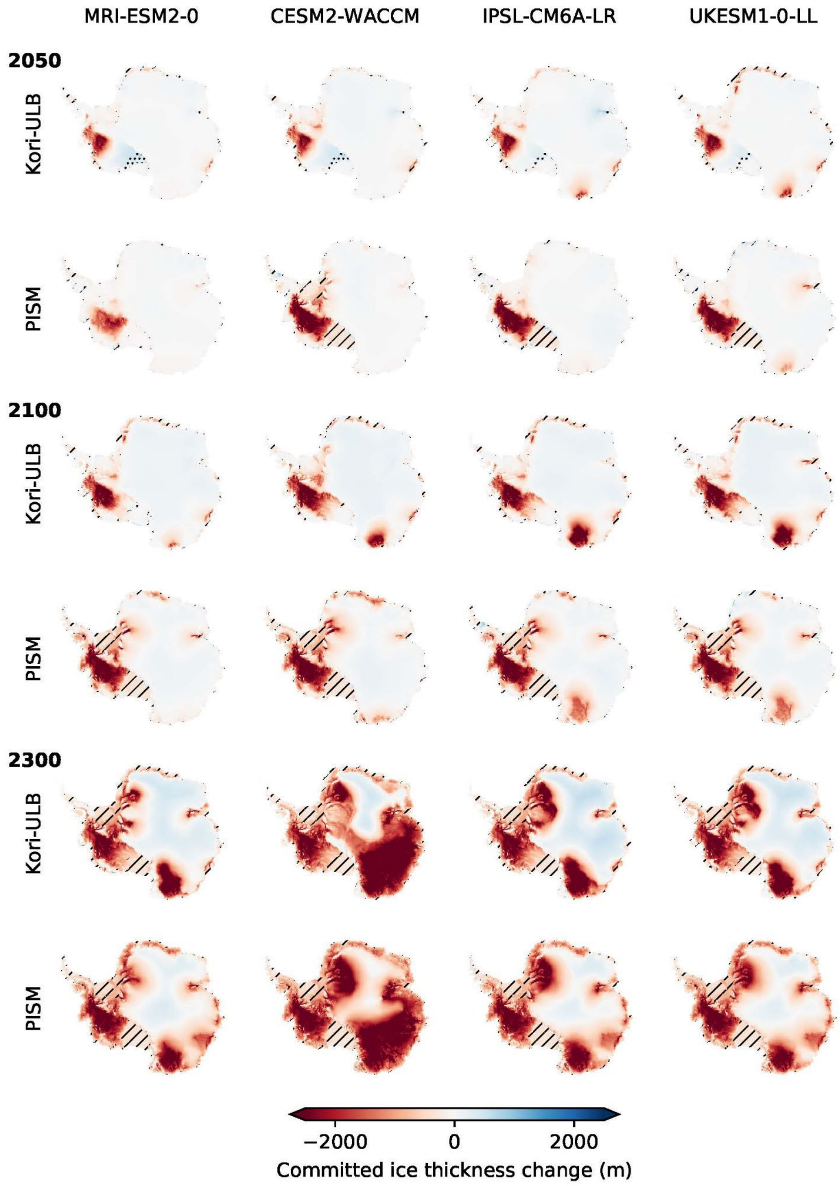
We agree that the difference in the initial ice-sheet geometry may be one factor that contributes to the model difference in Antarctic sea-level commitment. As argued by the reviewer, the sea-level contribution could be higher in PISM than in Kori-ULB despite the same pattern of mass loss due to the overestimation of the ice thickness in West Antarctica compared to observations. We here, however, also find some difference in the pattern of mass loss, with ice loss from the catchment draining Ross Ice Shelf in PISM, opposed to the grounding-line advance and upstream thickening in this region in experiments with Kori-ULB.

Please compare our response to the general reviewer comment for a more detailed discussion of the initial ice-sheet states that result from the different initialization approaches, their impact on the ice-sheet model behaviour on shorter (multi-centennial) and longer (multi-millennial) timescales and related adjustments in the revised manuscript.

I suggest that you reduce the number of supplemental figures by consolidating Fig S4 to Fig S19.

We thank the reviewer for this suggestion. In the revised version of the Supplementary Material, we have consolidated Figure S4 - Figure S19 of the original Supplementary Material as Figure S2 and Figure S3.


MRI-ESM2-0
CESM2-WACCM
IPSL-CM6A-LR
UKESM1-0-LL
Kori-ULB
PISM
−2000
0
2000
Committed ice thickness change (m)


MRI-ESM2-0
CESM2-WACCM
IPSL-CM6A-LR
UKESM1-0-LL
2050
Kori-ULB
PISM
2100
Kori-ULB
PISM
2300
Kori-ULB
PISM
−2000
0
2000
Committed ice thickness change (m)

References

Wernecke, A., Edwards, T. L., Holden, P. B., Edwards, N. R., & Cornford, S. L. (2022). Quantifying the impact of bedrock topography uncertainty in Pine Island Glacier projections for this century. *Geophysical Research Letters*, *49*(6), e2021GL096589.

van Wessem, J. M., van den Broeke, M. R., Wouters, B., & Lhermitte, S. (2023). Variable temperature thresholds of melt pond formation on Antarctic ice shelves. *Nature Climate Change*, 13(2), 161-166.

Editor comment

The paper by Klose et al. address the multi-millennial sea level commitment of the Antarctic ice sheet using two different ice sheet models forced by a set of four coupled climate simulations from the CMIP6 initiative. An anomaly method is used to create the climate forcing based on regional atmospheric models MAR and RACMO on which GCM future climate is added. To estimate the long-term sea level commitment corresponding to different level of global mean atmospheric warming, the simulations are branched off at different moments with the next two centuries and climatic conditions are maintained constant at their branching-off level.

The scientific content of the manuscript is good and very interesting. This is something that is needed for different reasons: testing the physics of ice sheet models and parameterizations, pushing to obtain ling-term multi-centennial climate forcing etc… I really liked the manuscript. However I can feel that this is perhaps the first or on of the first article written by the first author here: the writing of the manuscript needs some substantial work to be clear an readable. Information are some times provided in a very messy way, spread out in different sub sections etc…In addition I feel that the description of the results is sometimes approximative and also messy amongst the two ice sheet models. The authors should consider describing everything in depth with one model and then describing the discrepancies with the other model. The discussion (from Uncertainties to boundary conditions) is also chaotic and does not allow the reader to really appreciate the real advance of the work. I below provide some generic comments, but most of the specific comments can be found in the attached commented pdf version of the main manuscript.

We are grateful for the overall positive evaluation of this work. We thank the editor for carefully reading our manuscript and providing us with helpful comments, in particular, with regard to the description of our results and figures.

General comments

The description of the result is too "descriptive" and many times, no real explanation is provided for some observed behavior, or really little. Some of them are explained further int eh discussion, some others not at all. The results are sometimes described in a very approximative way. Sentences are sometime useless because not bringing any substantial info. In general try to group the info related to one topic or one model together. Right now, the reader needs to jump from one paragraph to another to synthesise all the info about one process or one model.

We would like to thank the editor for the effort of creating detailed comments on our manuscript. In the revised manuscript, we have reformulated the description of the results in Section 3, also following the specific and very helpful suggestions and/or questions of the editor in the commented version of the main manuscript (see below) and the reviewer comments (see above).

The changes in the revised manuscript include

- the addition of a section on the simulated historical ice-sheet evolution (Sect. 3.1, lines 313-338)
- a reformulation of the description of the transient ice-sheet response under SSP1-2.6 and SSP5-8.5 (Sect. 3.2, lines 339-393)
- a reformulation of the description of the committed ice-sheet changes under SSP1-2.6 (Sect. 3.3.1, lines 408-476) and SSP8-5.8 (Sect. 3.3.2, lines 477-522)

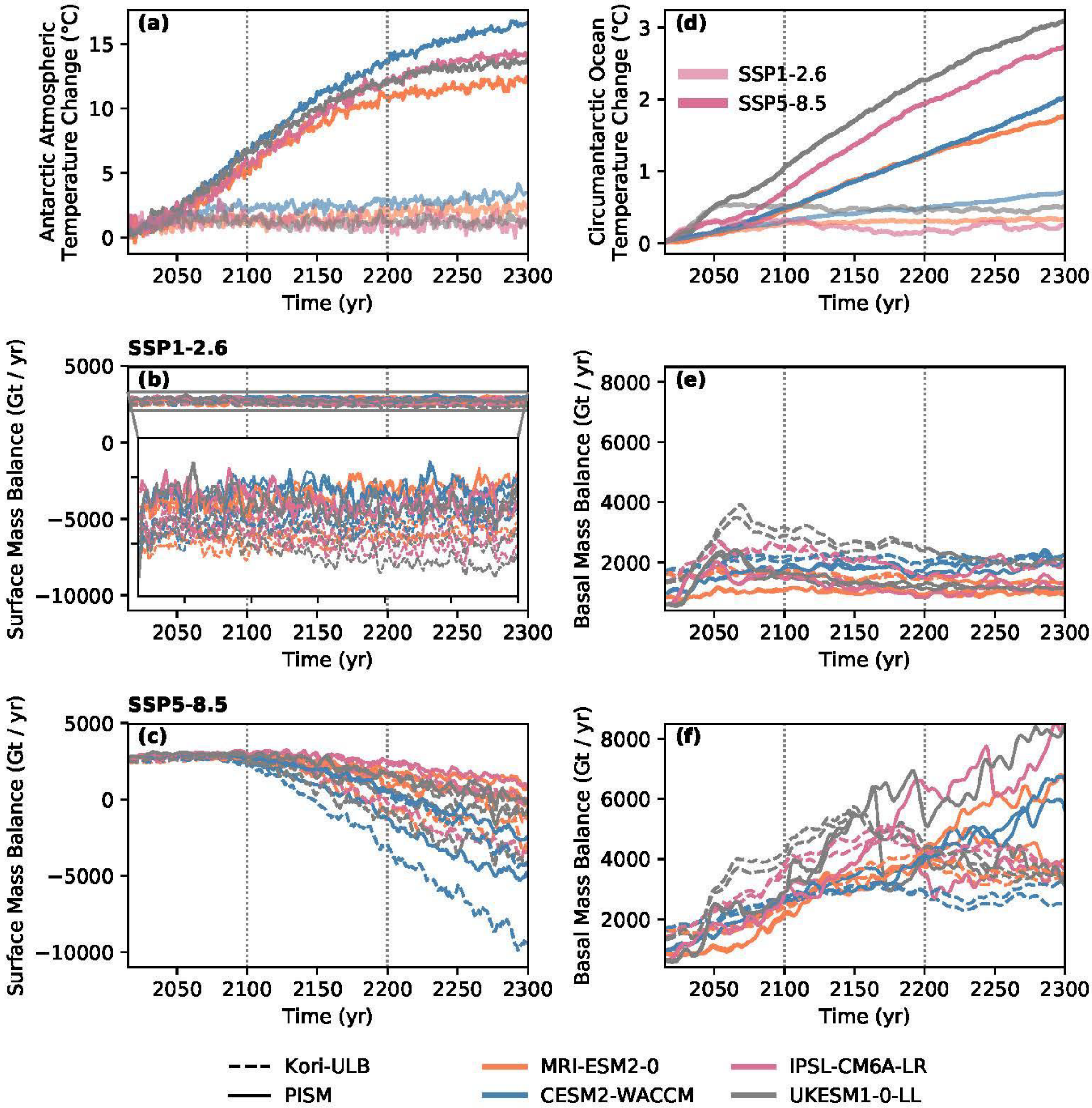
Overall, results are grouped as follows in the revised manuscript: In general, committed ice-sheet changes are assessed depending on the branchoff point in time for each emission pathway (Sect. 3.3) and summarized depending on the climatic boundary conditions, to overcome the dependency on the diverging climate trajectories (Sect. 3.4). Within each section, changes that are consistent across ice-sheet models are introduced. Uncertainties in the Antarctic Ice Sheet response related to ice-sheet modelling choices are outlined afterwards. Throughout the manuscript, we aimed for a good balance between giving possible explanations for the simulated ice-sheet response and relating to previous research directly with the description of the results or later in the discussion (to avoid repetition).

We would also like to refer to our responses to the specific comments by the editor below and to the attached manuscript for changes in the text.

I generally find the climate analysis a bit weak, given that the paper looks at sea level commitment. I would have expected a bit more climate analysis to really show the relationship between the different steps of the retreats and the competition between atmospheric warming induced melting and basal melting from oceanic warming. For example Figure S3 to my opinion should be inserted within the main manuscript and with two additional panels showing atmospheric warming and oceanic warming evolution through time. Although it is a bit complicated for the oceanic warming since it depends very much on the sector of Antarctica.

We never see one figure of climate forcing and this is instead very important since the climate forcing here plays a critical role in all the results. Thus I expect to see a bit more of climate in terms of figures and forcing description. That will allow the authors and the reader to better described and understand the results.

We thank the editor for this suggestion. In the revised manuscript, we have included an additional figure as Figure 4, based on Figure S3 in the original manuscript, showing (1) projected atmospheric and ocean warming as well as (2) projected Antarctic mass balance components, depending on the CMIP6 GMCs and emission pathways. Figure 4 and the related analysis of the projected Antarctic climate is integrated in the revised description of the results (see previous editor comment), in particular in the presentation of the projected transient ice-sheet response until 2300 (Sect. 3.2, lines 339-393). For example, we find that climate drivers dominate the projected multi-centennial ice-sheet changes under the higher-emission pathway SSP5-8.5. In line with Coulon et al. (2024), our projections indicate that the atmosphere becomes an amplifying driver of Antarctic mass loss beyond the end of this century, irrespective of the ice-sheet model. Please see the attached manuscript for changes in the text.



There is no real description of the outcomes of the initialization. There is only one sentence stating that ice sheet models reproduce correctly the AIS geometry- Which is not true, since PISM is far from having the GL in the right place, especially for the big ice shelves that are extensively then discussed in the rest of the manuscript. As stated in the discussion, PISM large sensitivity and large retreat of the WAIS is likely due to the already retreated grounding line. PISM performance is not very good in general because the final elevation differs quite a lot from the observed one and the discrepancies fall in the range of what is observed int terms of elevation changes by satellites. In addition there is no description of the historical run at all. This is also an important part to be added.

We thank the editor for this important comment and agree that the manuscript would benefit from a full description of the outcomes of the initialization and the simulated ice-sheet trajectories over the historical period. Please also see our response to the general reviewer comment for a more detailed discussion of the different initialization approaches, a comparison of the ice-sheet initial states in our study to observations, and the simulated ice-sheet trajectories over the historical period.

In line with the general reviewer comment, we have included a discussion of these initialization approaches and their advantages as well as a comparison of the initial ice-sheet states in our study to observations in Section 2.2.2 of the revised manuscript (lines 237-255):

> *Given that we include two common ways of initializing ice-sheet models (compare e.g., Seroussi et al., 2019, 2020), we sample uncertainties associated with the choice of the initialization approach. While an inverse simulation allows to reproduce the present–day ice sheet geometry well, the resulting parameter fields (such as basal sliding coefficients in Kori-ULB) may compensate for errors or uncertainties in other ice–sheet processes (Berends et al., 2023b; Aschwanden et al., 2013). In addition, it is assumed that the field obtained in the inverse simulation to match present–day observations does not change in the future. In contrast, in the simulated ice–sheet state resulting from a spin-up the ice–sheet variables may be modelled in a consistent way, but its geometry might differ from the observed ice sheet. It is the result of the covered ice–sheet physics in the ice–sheet model for a set of uncertain parameters, without any nudging.*
>
> *The simulated grounding–line position and ice thickness of the initial ice–sheet states are compared to present–day observations in Figure S1. As a result of the inverse simulation, the grounding–line position and ice thickness compare well to present–day observations in the initial ice–sheet states for Kori-ULB (Fig. S1a and c). With the spin–up approach applied in PISM, the initial ice–sheet states are characterized by larger ice thickness differences compared to present–day observations (Fig. S1b and d). Overall, ice in West Antarctica and in some coastal regions in East Antarctica (e.g,. in Dronning Maud Land, upstream of Amery Ice Shelf and in Wilkes Land) is thicker than observed at present (comparable to Reese et al., 2023), while the ice thickness in the interior of East Antarctica is underestimated. In addition, the grounding line in the Siple Coast area (and in the catchment draining Ronne–Filchner Ice Shelf for the MAR climatology) is located upstream of the observed grounding line in the present–day (Fig. S1 b and d), as previously seen in a model initialisation in a spin–up approach, e.g., Reese et al. (2023) and Sutter et al. (2023). These differences should be taken into account when interpreting the simulated long–term evolution of the Antarctic Ice Sheet.*

As an outcome related to these initialization approaches, basal friction deviates spatially between both ice-sheet models, in particular in the interior of West Antarctic marine basins. This can also be expected to influence the ice-sheet response and its timescales. In Section 2.2.2 of the revised manuscript, a paragraph describing the optimized field of basal sliding coefficients in Kori-ULB in comparison to the parameterized material properties of subglacial till in PISM has been added (lines 225-230) as follows:

> *The optimized field of basal sliding coefficients in Kori-ULB is characterized by high basal sliding coefficients at the ice–sheet margins, turning into regions of low slipperiness (low basal sliding coefficients) towards the interior of West Antarctica. It thus differs from the basal friction experienced by the Antarctic Ice Sheet in experiments with PISM, where overall slippery bed conditions in the interior of marine subglacial*

basins are found, given the parameterized, bed–elevation dependent material properties of the subglacial till (in particular, the till friction angle; Sect. 2.1). These inter–model differences in basal friction linked to the applied initialization approaches are expected to influence the ice–sheet response.

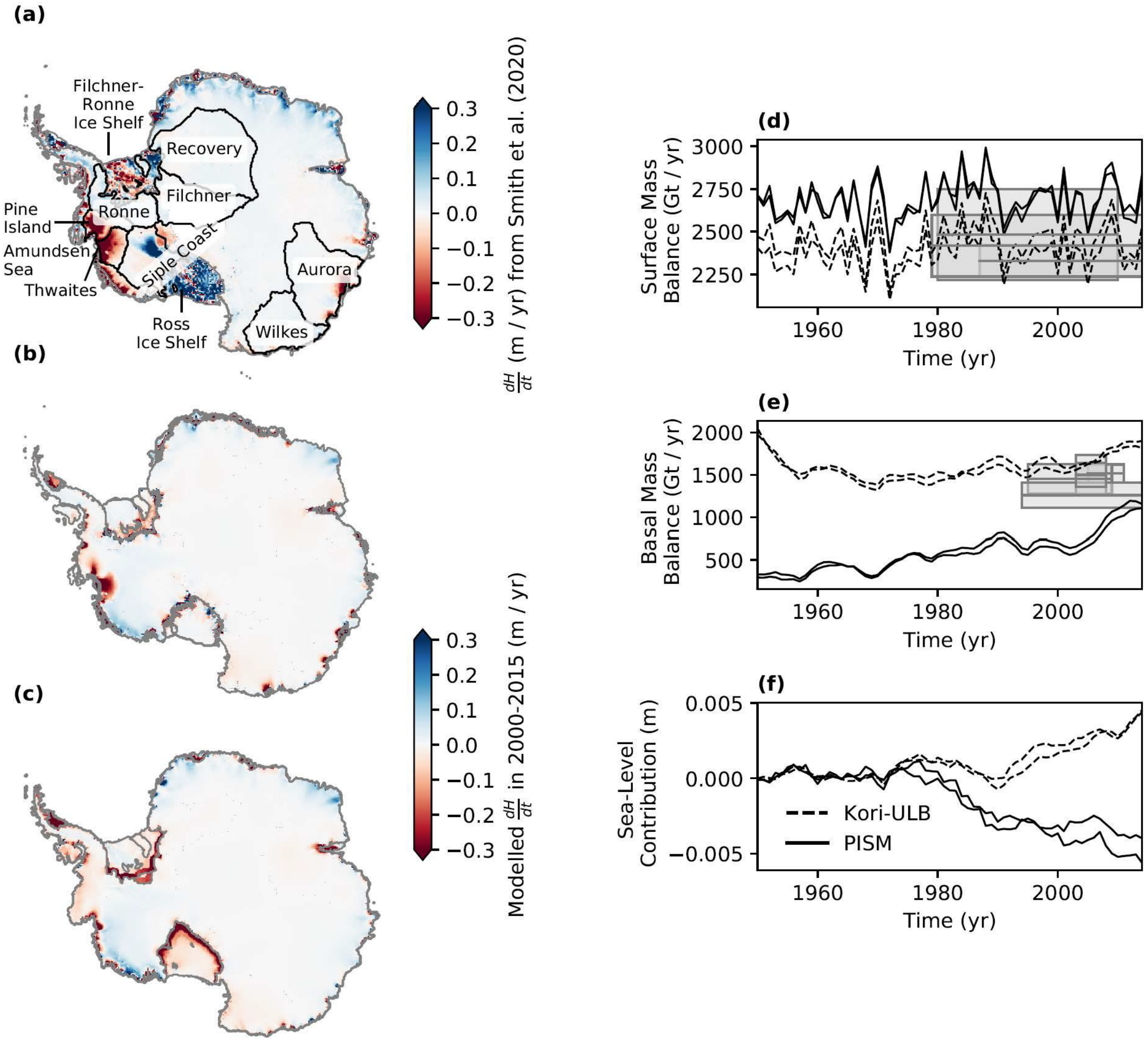
We have also (1) added an assessment of the simulated ice-sheet trajectories in response to the NorESM1-M climate trajectory over the historical period as Section 3.1, (2) included a related figure as Figure 2, and (3) linked the simulated historical ice-sheet response to the projected ice-sheet response to 2300 (Sect. 3.2) in the revised manuscript. The main related paragraph in the revised manuscript (lines 314-338) reads as:

The pattern of observed present–day rates of ice–thickness change (e.g., Smith et al., 2020) is overall captured by both ice–sheet models in response to the historical NorESM1-M climate trajectory (Fig. 2a – c), with a thinning in the Amundsen and Bellingshausen Sea region and the Antarctic Peninsula and a thickening in the ice–sheet interior. The magnitude of ice–sheet thinning in the Amundsen Sea Embayment is, however, underestimated compared to present–day observations in the historical simulations with PISM presented here (Fig. 2a and c). In addition, we find ice loss for Ross, Ronne–Filchner and Amery ice shelves in PISM in contrast to observations (Fig. 2a and c).

The evolution of the continent–wide integrated surface mass balance is relatively similar for both ice–sheet models, but occurs on a higher, though still within RCM uncertainties, level in PISM than in Kori-ULB (Fig. 2d). While sub–shelf melt increases in PISM from about 300 Gt yr−1 in 1950 towards 1100 Gt yr−1 in 2015 at the lower end of present–day observations (Fig. 2e, solid lines), the basal mass balance is on the order of the observational record in Kori-ULB over the entire historical period, slightly exceeding its upper end in 2015 with about 1800 Gt yr−1 (Fig. 2e, dashed lines). The continent–wide aggregated sub–shelf melt rates observed in present–day are thus reproduced with both sets of PICO parameters (see Sect. 2.2.3), but they result in different sensitivities of sub–shelf melt rates to ocean temperature changes over the historical period (Fig. 2e; Reese et al., 2023).

Mass loss in the Amundsen Sea sector dominates the overall observed ice sheet mass changes in Antarctica to date (Otosaka et al., 2023). Given the lower magnitude of ice–sheet thinning of Pine Island and Thwaites glaciers in PISM, and stronger sub–shelf melt in Kori-ULB, we find diverging ice–sheet trajectories with both ice–sheet models in terms of the Antarctic sea–level contribution over the historical period from 1950 to 2015: Kori-ULB shows an integrated mass loss with a sea–level contribution of about +4 mm in 2015 (Fig. 2f, dashed lines), while the ice sheet overall gains mass equivalent to a sea–level change ranging between -4 mm and -6 mm in PISM (Fig. 2f, solid lines; within spread of recent ensemble of historical ice–sheet trajectories, Reese et al., 2023).

In the future evolution of the Antarctic Ice Sheet determined by PISM (Sect. 3.2 – 3.4), changes in the regions of Ross and Ronne–Filchner ice shelves could thus be overestimated, while the lower thinning rates over the historical period in the Amundsen Sea Embayment could suggest a reduced sensitivity of Thwaites and Pine Island glaciers to changes in climate conditions in these experiments.



To really appreciate the full description of the results, you also need to introduce a map, as first Figure of the manuscript show the different drainage basins, ice shelves and related names. You only show this in Fig3a, and honestly, it is so hard to understand even when printed.

We agree that a more detailed figure showing the different drainage basins and ice shelves relevant for our study may be helpful for the reader and thank the editor for this suggestion.

In the revised manuscript, we have added such a figure as a panel in Figure 2 (compare panel a in previous editor comment).

The figures are too dense, e.g. Fig 2., it would benefit from separating each ice sheet model simulations in different frames to better appreciate the difference and understand them.

We thank the editor for the comments and suggestions for improving the figures in our manuscript. In the revised manuscript, we have made the following adjustments:

- Figure 2 has been reorganized, and an additional figure has been introduced. Figure 3 in the revised manuscript shows the transient ice-sheet response to 2300, in combination with the projected ice-sheet changes (in terms of the ice thickness) in the years 2050, 2100 and 2300. The committed ice-sheet response is the focus of Figure 5 in the revised manuscript. We here show the multi-millennial ice-sheet response in terms of the Antarctic sea-level contribution under SSP1-2.6 and SSP5-8.5, separately for Kori-ULB and PISM, together with the sea-level commitment in the year 7000, depending on the (branchoff) point in time.
- Figure 5 in the original manuscript has been modified as Figure 8 in the revised manuscript in terms of the numbers of displayed basins and the colouring. An additional Figure S4 in the Supplementary Material has been added to show the dependence of the committed ice loss from selected basins on changes in the ocean.

Please also see our response to the related specific editor comments below.

The section about "Intra and inter-models uncertainties" is not useful in its present form. It would be better to divide it in several sections. Eg: "Initialization" (actually once again, the info about the impact of initialization are spread out through the section and is thus a bit messy), "model physics", etc… it would help organising a bit this part.

In the revised manuscript, Section 4 and, in particular, the discussion of model uncertainties (including uncertainties in ice-sheet processes, their parameterization in ice-sheet models and distinct initialization approaches; Sect. 4.2; lines 693-765) has been reorganized and also elaborates on differences in ice-sheet model behaviour on shorter (multi-centennial) and longer (multi-millennial) timescales, in relation to ice-sheet modelling and initialization choices. Please see the attached manuscript for changes in the text.

Specific comments: see the attached pdf.

Line 25: "presumed inception". In the paleo-antarctic community, this is the terminology that we agreed to employ.

> The Antarctic Ice Sheet has experienced changing environmental conditions on various timescales from decadal to orbital-scale climate variability since its inception at the Eocene–Oligocene transition about 34 Mry ago (Zachos et al., 2001; DeConto and Pollard, 2003).

We thank the editor for this remark and have adjusted the revised manuscript (lines 24-26) accordingly.

Line 28: Not happy with this modeling ref here of Pollard and Deconto. It would be better to remove it and only let observation based ref.

We have removed this modelling reference in the revised manuscript.

Line 28: "terrestrial parts" is more correct in general for the meaning of the sentence.

> While large parts of the terrestrial East Antarctic Ice Sheet have persisted for millions of years (Sugden et al., 1995; Shakun et al., 2018), ice–sheet variability involved an occasional collapse of the West Antarctic Ice Sheet (Naish et al., 2009) and inward migration of ice–sheet margins in marine–based sectors of East Antarctica during Pliocene warm periods (Cook et al., 2013; Patterson et al., 2014; Aitken et al., 2016).

We have changed this formulation in the revised manuscript (lines 28-32), following the editor's suggestion.

Line 28: remove "terrestrial" and move it just before. see previous comment.

We have changed this formulation in the revised manuscript (lines 28-32), following the editor's suggestion.

Line 30: I think that is would be nice to define "marine-based sectors", because it is usefull further on in the text. Something like: (i.e., where the ice sheet grounds below sea level).

We thank the editor for suggesting this addition and have adjusted the revised manuscript (lines 28-32) accordingly.

Line 31: and also during some interglacials of the Pleistocene (e.g. Stokes et al., 2022 for a review or some of the references you cite in the next sentence.).

> While large parts of the terrestrial East Antarctic Ice Sheet have persisted for millions of years (Sugden et al., 1995; Shakun et al., 2018), ice–sheet variability involved an occasional collapse of the West Antarctic Ice Sheet (Naish et al., 2009) and inward migration of ice–sheet margins in marine–based sectors of East Antarctica during Pliocene warm periods (Cook et al., 2013; Patterson et al., 2014; Aitken et al., 2016).

In this sentence, we aim to outline the Antarctic Ice Sheet changes during Pliocene warm periods. As stated by the editor, an inward migration of ice-sheet margins in marine-based sectors of East Antarctica has also been suggested during some Pleistocene Interglacials (e.g., Wilson et al., 2018; Blackburn et al., 2020; Turney et al., 2020). This is addressed in the following sentence, and in line with the following editor comment, this sentence has been reformulated in the revised manuscript (lines 32-35) as:

> *During Pleistocene Interglacials, Antarctic ice loss from the East Antarctic Wilkes subglacial basin (Wilson et al., 2018; Blackburn et al., 2020) and across the Weddel Sea Embayment (Turney et al., 2020) contributed to sea–level high–stands of 6 to 9 m higher than present (including a contribution from thermal expansion and mass loss from the Greenland Ice Sheet; Dutton et al., 2015).*

Line 31: This sentence is too vague: to which parts does it refers? is it just to mention sea level high stands? if yes then provide some numbers (have a look at Colleoni et al., 2022 - it is a book chapter synthesis in which you can find some usefull refs, write me an email and I send you the pdf).

During Pleistocene Interglacials, Antarctic ice loss contributed to sea–level high–stands (Wilson et al., 2018; Blackburn et al., 2020; Turney et al., 2020).

In the revised manuscript (lines 32-35), we have reformulated this sentence and included the parts of the Antarctic Ice Sheet showing mass loss during Pleistocene Interglacials. It now reads as:

During Pleistocene Interglacials, Antarctic ice loss from the East AntarcticWilkes sub-glacial basin (Wilson et al., 2018; Blackburn et al., 2020) and across the Weddel Sea Embayment (Turney et al., 2020) contributed to sea–level high–stands of 6 to 9 m higher than present (including a contribution from thermal expansion and mass loss from the Greenland Ice Sheet; Dutton et al., 2015).

Line 34: why using brakets here? I would suggest: "knowledge and representation of", but not in brakets.

The future trajectory of the Antarctic Ice Sheet under progressing warming, however, is highly uncertain. This is due to uncertainties in the (representation of) ice-sheet processes and ice-climate interactions (Fox-Kemper et al., 2021) as well as the potentially high magnitudes and rates of recent and projected warming.

Thanks. We agree and have adjusted the formulation in the revised manuscript (lines 36-38).

Line 35: How much is this rate? Please provide some number.

The future trajectory of the Antarctic Ice Sheet under progressing warming, however, is highly uncertain. This is due to uncertainties in the (representation of) ice-sheet processes and ice-climate interactions (Fox-Kemper et al., 2021) as well as the potentially high magnitudes and rates of recent and projected warming.

We have added numbers on the rate of warming based on the latest assessment of the IPCC (Gulev et al., 2021) in the revised manuscript (lines 38-40). This sentence now reads as:

The present rate of warming is unprecedented in at least 2000 years, with an increase of 1.09 °C in the global mean surface temperature between 1850–1900 and 2011–2020 (Gulev et al., 2021).

Line 39: Please provide a time for the beginning of the Holocene

The amount of warming projected for the end of this century under the Shared Socio-economic Pathways (e.g., for the higher-emission scenario SSP5-8.5 with an increase in global annual mean surface air temperature of 3.6 °C to 6.5 °C relative to 1850-1900; Lee et al., 2021) is comparable to the transition from the Last Glacial Maximum to the beginning of the Holocene, but is expected to develop on much shorter time-scales.

We have added a time for the beginning of the Holocene in the revised manuscript (lines 40-43) as follows:

The amount of warming projected for the end of this century under the Shared Socio-economic Pathways (e.g., for the higher–emission scenario SSP5-8.5 with an increase in global annual mean surface air temperature of 3.6 °C to 6.5 °C relative to 1850 – 1900; Lee et al., 2021) is comparable to the transition from the Last Glacial Maximum to the beginning of the Holocene approximately 11,700 years before present, but is expected to develop on much shorter timescales.

Line 48: You could update with a ref of the last report on tipping points that was released early December.

We have added this recent reference in the revised manuscript (line 52).

Line 49: than what? You need some references here.

> This long-term sea-level response, that has already been triggered or may be triggered during the next decades (but unfolds over the following centuries and millennia), might be substantially higher than and is not represented in typical sea-level projections.

We agree that this formulation is misleading. We have adjusted the wording in the revised manuscript (lines 52-55), and the sentence now reads as:

This long–term sea–level response, that has already been triggered or may be triggered during the next decades or centuries (but unfolds thereafter over multiple centuries and millennia), might be substantially higher than the transient sea–level change, while it is not represented in typical sea–level projections (Seroussi et al., 2020; Edwards et al., 2021).

Line 52: "the gap", what do you mean? It is unclear, please reformulate.

> We furthermore identify the gap between the transient realized sea–level contribution from Antarctica at a particular point in time and the respective long–term committed sea–level contribution (Winkelmann et al., in review).

We here used the word 'gap' to describe the substantial difference between the transient realized sea-level contribution from Antarctica (for example, projected by the year 2100) and the corresponding long-term committed sea-level change (that may already be triggered or locked-in given the warming by e.g. 2100 but unfolds thereafter on timescales on the order of centuries to millennia). We have changed the wording in the revised manuscript (lines 57-58), and hope that it is clearer now:

We furthermore quantify the difference or offset between the transient realized sea–level contribution from Antarctica at a particular point in time and the respective long–term committed sea–level contribution.

Line 53: Why citing a paper in review? Is it not the purpose of this work?. O would suggest to remove this ref, unless this paper is going to be published before this one and properly citable here.

We have removed this reference in the revised manuscript.

Line 60: instead of using "self-reinforcing", "positive...feedback" would be enough. This is the definition of positive feedback.

Following the recently published Global Tipping Points Report (Lenton et al., 2023), we have changed the naming of feedbacks to 'amplifying' and 'dampening' feedback or 'positive' and 'negative' feedbacks, respectively, in the revised manuscript.

Line 62: Perhaps it is a bit too complicated...I think that if you remove the last part of the sentence from "owing...", it is better. Atmospheric lapse rate is a parameter in the ice sheet and atmospheric models. But it describes a elevation-T° relationship found in the troposphere. So no need here.

> With the lowering of the ice-sheet surface due to melting, it is exposed to higher air temperatures owing to the atmospheric lapse rate.

We have adjusted this sentence in the revised manuscript (lines 66-67), following the editor's remark.

Line 63: a critical threshold in what? T°, critical mass loss?

> Surface melting is, in turn, enhanced, promoting persistent ice loss upon crossing a critical threshold.

In the revised manuscript (lines 67-68), we have adjusted this sentence as:

> *Surface melting is, in turn, enhanced, promoting persistent ice loss upon crossing a critical temperature threshold.*

Line 66: Once again: "self-sustainable mechanism" or "positive feedback". Pleease carefully check throughout the manuscript.

Following the recently published Global Tipping Points Report (Lenton et al., 2023), we have changed the naming of feedbacks to 'amplifying' and 'dampening' feedback or 'positive' and 'negative' feedbacks, respectively, in the revised manuscript.

Line 68: Remove "grounding lines": just for writing style to avoid repeating "grounding"

> In a theoretical flowline setup, it was shown that, due to the ice flux being a nonlinear function of the ice thickness, grounding lines of ice sheets grounded below sea level on a retrograde, inland sloping bed are unstable (Marine Ice Sheet Instability; Weertman, 1974; Schoof, 2007).

We have removed 'grounding lines' in the revised manuscript.

Line 74: remove "to ice mass changes". This is not necessary here.

> Ice loss may be dampened, on the other hand, by negative feedbacks such as introduced by e.g., the isostatic rebound of the solid Earth underlying the ice sheet to ice mass changes, which could potentially stabilize West Antarctic grounding lines (Coulon et al., 2021; Barletta et al., 2018).

We have removed 'to ice mass changes' in the revised manuscript.

Line 79: which system?

> Due to the inertia in the system and the related delay in the ice–sheet response under realistic forcing, the ice sheet's trajectory likely deviates from the ice–sheet equilibrium response to warming (Garbe et al., 2020; Rosier et al., 2021).

We here refer to ice sheets, and have adjusted the wording in the revised manuscript (lines 83-85).

Line 79: "volume trajectory" would be more correct. And I am not sure to really understand what you mean here in this sentence. Please clarify in the text.

> Due to the inertia in the system and the related delay in the ice-sheet response under realistic forcing, the ice sheet's trajectory likely deviates from the ice-sheet equilibrium response to warming (Garbe et al., 2020; Rosier et al., 2021).

Various factors may contribute to the substantial difference between the transient realized and long-term committed sea-level change, as illustrated in Figure 1b, one of them being ice-sheet inertia (see also lines 54-58 in the original manuscript). This slow ice-sheet response to perturbations in its climatic boundary conditions manifests as a delay in the transient ice-sheet response, for example following a warming trajectory under the higher-emission pathway, when compared to the ice-sheet equilibrium response for a given warming level. Here, the ice-sheet equilibrium response (shown in black in Figure 1b) could be obtained by very slowly changing the environmental conditions (e.g., global mean temperature) at a rate which is much slower than the typical rates of changes in an ice sheet (e.g., Garbe et al., 2020; Rosier et al., 2021).

In the revised manuscript (lines 83-85), we have reformulated this sentence as follows, including the previous editor comment:

> *Due to the inertia of ice sheets and the related delay in their transient response following a realistic warming trajectory under e.g. a higher–emission pathway, the ice sheet's volume trajectory likely deviates from the ice–sheet equilibrium response to warming (Garbe et al., 2020; Rosier et al., 2021).*

Figure 1

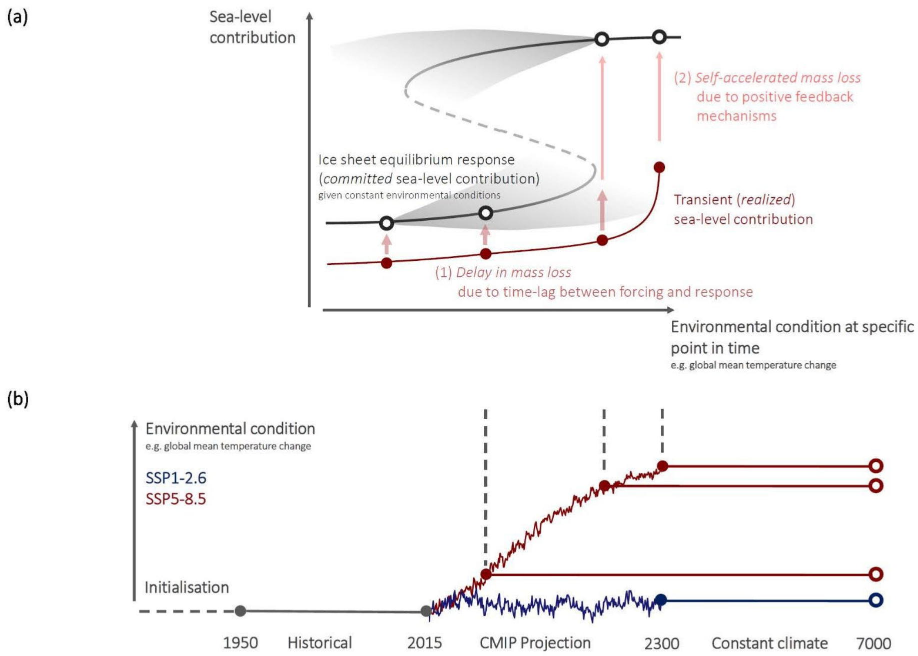
- **I still don't understand what you mean by a gap.**

  Please see our response to a previous related editor comment for an explanation. In the revised manuscript, we have adjusted the wording in the caption of Figure 1, and hope that it is clearer now:

Idealized and simplified stability diagram of the Antarctic Ice Sheet as possible tipping element, which illustrates some underlying factors potentially contributing to the substantial difference or offset between the transient realized and long-term committed ice-sheet response (in terms of sea-level contribution).

- **Please precise here that blue is SSP2.6 and red is SSP8.5...it took me a while to understand...also because it i sunclear which quantoity is represented here. Is it global mean temperature for each scenario? Please refine the caption here for panel b).**

  We thank the editor for pointing out the missing axis labels and legend for the emission pathways in Figure 1b. In the revised manuscript, we have modified Figure 1b by (1) adding a vertical axis and (2) providing a legend that relates the colours to the emission pathways.



Line 219: Well...This is not really the case for PISM experiments. Ok, they are in the range of ISMIP6 initialised geometry, but please specify here that Kori-ULB is way better. PISM grounding line position for big ice shelves is far from being close to the current one and thickness difference is really large, and exceeds or underestimates the range of observed elevation changes for most Antarctica.

We agree that the PISM initial ice-sheet states have larger deviations in their geometry from observations than the Kori-ULB initial ice-sheet states. This is a result of the different initialization approaches applied in our study.

In the revised manuscript, we have addressed and clarified differences of the initial ice-sheet states to observations in more detail, and here refer to our response to the general editor and reviewer comments for a more detailed discussion of the different initialization approaches, a comparison of the initial ice-sheet states in our study to observations and related adjustments in the revised manuscript.

Line 259: Do you also correct precipitation? for the desertification effect? If not, why not?

This is an important question. Changes in the ice-sheet surface elevation are accompanied by a 'local' change in the air temperatures given the atmospheric lapse rate and this is accounted for in our experiments with Kori-ULB and PISM. The change in air temperatures at the surface of the ice sheet also impacts the surface melt and runoff (thus ultimately the surface mass balance) by the use of the positive-degree-day model in our experiments.

In our experiments, we do not correct precipitation for changes in the ice-sheet surface elevation. The overall increase in precipitation with warmer regional temperatures (e.g., Frieler et al., 2015) is already accounted for in the GCM forcing that we apply. Further correcting precipitation based on a lapse-rate approach would artificially create changes in the amount of snowfall, but not necessarily for the correct reason. We believe that, at this stage, changes in the atmospheric circulation and respective precipitation patterns triggered by ice-sheet geometry changes may only be properly accounted for by a coupled simulation between an ice-sheet model and a climate model. Future research should explore changes in precipitation due to a changing ice-sheet geometry, to eventually include these processes in ice-sheet models.

Line 271: missing star here.

Thanks. We have added the missing star in the revised manuscript.

Line 280: Not true: red solid lines also project a sea level rise by 2300. I suggest to improve this sentence with a more rigorous description of Fig2a.

> Following the lower–emission pathway SSP1-2.6 results in a sea–level change ranging from -5.0 cm to +8.0 cm by the end of this century and from -0.2 m to +0.5 m in 2300 (Fig. 2a; Tab. 1). Therein, Kori-ULB projects a positive sea–level contribution for this lower–emission scenario (dashed lines), while PISM projects a sea–level drop (solid lines).

We thank the editor for pointing out the potential for improvement of the description of the multi-centennial Antarctic sea-level contribution under the lower-emission pathway SSP1-2.6 in the original manuscript.

It is correct that, under SSP1-2.6, some PISM ice-sheet trajectories show the onset of mass loss after an initial mass gain (e.g. for CESM2-WACCM climate, red solid lines in Figure 2a in the original manuscript). The Antarctic sea-level contribution projected by PISM in 2300, however, remains negative when compared to present-day (with -0.002 m and -0.038 m sea-level equivalent depending on the PISM initial ice-sheet state).

In the revised manuscript, we have included a more rigorous description of Figure 2a of the original manuscript, along with a reformulation of the description of the projected ice-sheet changes to 2300 (Sect. 3.2, lines 339-393). Please see the attached manuscript for changes in the text. In particular, a related sentence (lines 350-354) now reads as:

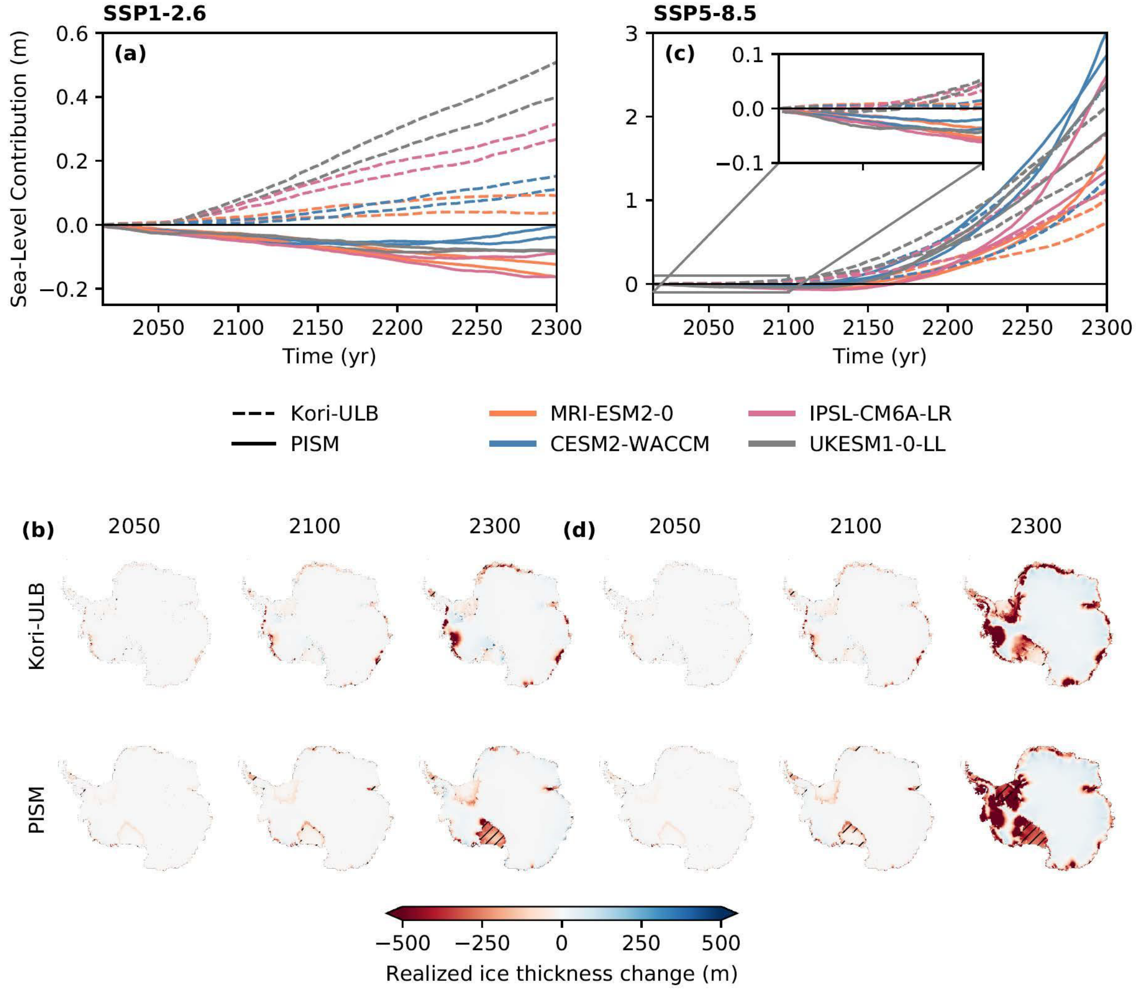
Following the lower–emission pathway SSP1-2.6 to 2300 results in a sea–level change ranging from -0.2 m to +0.5 m compared to present–day (Fig. 3a, Tab. 1). Therein, Kori-ULB projects a steadily increasing Antarctic contribution to sea–level rise (Fig. 3a, dashed lines). While some PISM ice–sheet trajectories show the onset of mass loss after an initial mass gain (e.g. for CESM2-WACCM climate, indicated in blue), the Antarctic sea–level contribution projected by PISM in 2300 compared to present–day remains negative (Fig. 3a, solid lines).

Line 285: I found a pity not to have those figures within the text. The way they are presented in the Suppl. does not allow for this. however I would suggest to integrate a separate figure of ensemble mean at 2300 with 8 pannels (4 for each scenario) 4 for Kori-ULB and 4 for PISMs, here in the many manuscript, summarizing Figure S4 to S11.

We find that the integrated surface mass balance remains positive for both ice–sheet models until 2300 under SSP1-2.6 (Fig. S3a). However, the response in dynamic discharge contributing to a sea–level increase on centennial timescales is higher in Kori-ULB (with ice–sheet thinning in the Amundsen Sea Embayment extending inland, Fig. S4–S5) 285 than in PISM (see Fig. S6–S7 for comparison), explaining the diverging sea–level contribution under SSP1-2.6 until 2300.

We thank the editor for this suggestion. We agree that such a figure is helpful in the main text to illustrate agreement and differences in the transient ice-sheet response between the ice-sheet models.

In the revised manuscript, we have followed the editor’s suggestion. In particular, we have added a figure that shows the projected ice-thickness change in the years 2050, 2100 and 2300, depending on the ice-sheet model and the emission pathway, as Figure 3 in the revised manuscript. The ice-thickness change compared to present-day is averaged across the GCMs used to derive changes in Antarctic climate and the respective ice-sheet model configurations. This is accompanied by a reorganisation of Figure 2 of the original manuscript: The projected ice-sheet response in terms of the sea-level contribution is also given in this Figure 3 in the revised manuscript, while Figure 5 in the revised manuscript focuses on the committed changes. Please also see our response to the editor comment on Figure 2 in the original manuscript.



Line 289: You never mentioned it in the previous paragraph about SSP1-2.6. Please provide a more detailed description also for SSP1-2.6 simus.

> The initial sea–level drop by 2100 is again found in simulations from PISM and can be attributed to increasing snowfall with warming, which dominates the ice–sheet mass balance until the end of this century.

We thank the editor for pointing out this misleading formulation of an 'initial' sea-level drop by 2100 projected by PISM under SSP5-8.5 in the original manuscript.

In the revised manuscript, we have reformulated the description of the projected Antarctic sea-level contribution to 2300 (Sect. 3.2, lines 339-393). Please see the attached manuscript for changes in the text.

Line 289: I find this explanation not convincing. Why is this not happening with Kori-ULB if this is only a matter of more precip? My guess is that the refreezing scheme influences a lot the SMB here. How much is the refreezing in Kori-ULB compared to PISM for this simulation?

> Under climate trajectories following the SSP5-8.5 emission pathway, the Antarctic ice loss varies between -6.0 cm and +6.0 cm sea–level equivalent by the end of this century, increasing to +0.7 – +3.1 m by 2300 (Fig. 2b; Tab. 1).The initial sea–level drop by 2100 is again found in simulations from PISM and can be attributed to increasing snowfall with warming, which dominates the ice–sheet mass balance until the end of this century.

We here respond to both editor comments that refer to the description of the projected ice-sheet response under the higher-emission pathway SSP5-8.5 (line 289 and the following comment on line 291 in the original manuscript).

Under SSP5-8.5, PISM and Kori-ULB project a sea-level contribution ranging between +0.7 - +3.1 m due to Antarctic mass loss by 2300. Until the end of this century, the Antarctic sea-level contribution compared to present-day projected by PISM is negative, while we find Antarctic mass loss with Kori-ULB. It is thus comparable to projected changes under SSP1-2.6, in line with Coulon et al. (2024), Lowry et al. (2021) and Edwards et al. (2021) and given a very similar evolution of Antarctic climate at least during the first half of the 21st century. In both ice-sheet models, the integrated surface mass balance remains positive until the end of the century under SSP5-8.5, with strong GCM-dependent variability. The magnitude of sub-shelf melt is higher for projections by Kori-ULB compared to PISM, following the respective levels reached at the end of the historical period. The dynamic ice-sheet response in the Amundsen Sea sector in 2100 in terms of its magnitude and inland extent is stronger in Kori-ULB than in PISM, explaining the difference in the overall ice-sheet mass balance by 2100.

In the revised manuscript, we have reformulated the description of the projected ice-sheet changes under SSP5-8.5 to 2300 (Sect. 3.2, lines 339-393) and hope that the explanation is better understandable now. Please see the attached manuscript for changes in the text.

Line 291: is this initial increase in SMB also observed in Kori-ULB? I find all this paragraph a bit confusing. It could be better described and organised. If you describe a feature (e.g. SMB), do it for both models in the same sentence or couple of sentences, do not spread the info about one single process in different sentences through out the paragraph. It is hard to follow the speach then.

> Simulations by Kori-ULB show an earlier grounding–line retreat in the Amundsen Sea Embayment, outweighing the initial increase in the integrated surface mass balance and resulting in a positive sea–level contribution already during the 21st century.

Please see our response to the previous related editor comment.

Line 298: Not sure of what Figure 3 shows: is it an average between Kori-ULB and PISM? This is not written in the caption. Why ice shelves do not retreat in Kori-ULB?

> The major ice shelves including the Ross Ice Shelf as well as the Filchner–Ronne Ice Shelf thin, in particular near the grounding line, and are (in PISM only) even lost sequentially by 2150 and 2300, respectively (Fig. 3b, realized; Fig. S10–S11).

Figure 3 in the original manuscript shows the mean ice thickness changes determined by both ice-sheet model and for all GMC forcings at the given point in time. We agree that this has not been clear in the original manuscript and have added an explanation to the caption where needed in the revised manuscript.

In our experiments, we find model differences in the timing of ice-shelf collapse: While Ross and Ronne-Filchner ice shelves are lost sequentially by 2150 and 2300, respectively, under the higher-emission pathway SSP5-8.5 in PISM, they are sustained longer in Kori-ULB. These major Antarctic ice shelves may be lost on multi-millennial timescales in Kori-ULB when sustaining warming that is projected by 2100 and thereafter under this higher-emission pathway.

The model differences in the timing of ice-shelf collapse may be related to the calving schemes employed in the ice-sheet models or different sub-shelf melt sensitivities to changes in ocean temperature in PICO. The values of the PICO parameters are an individual choice for each ice-sheet model. They have been chosen such that for the respective ice-sheet model observed sub-shelf melt sensitivities and / or melt rates are matched, and are based on parameter optimizations for PICO (Reese et al., 2018; Reese et al., 2023).

In the revised manuscript (lines 301-302), we have added an explanation on the choice of PICO parameters, following a previous reviewer comment:

> *The values of the PICO overturning strength parameter C and the turbulent heat exchange coefficient γ_T* are an individual choice for each ice–sheet model to match sub–shelf melt sensitivities and / or observed melt rates.*

Note that overall the availability of projections of the evolution of the Antarctic Ice Sheet after 2100 is limited. In particular, substantial parametric uncertainty exists, some of which (e.g., basal melt parameterizations and related parametric uncertainty) is explored in more detail in Coulon et al. (2024) in terms of the Antarctic sea-level contribution by the end of this millennium. It thus remains an important next step for future research to assess the effects of this parametric uncertainty on the Antarctic Ice Sheet response (including the potential loss of ice shelves) also on multi-millennial timescales as discussed e.g. in lines 594-605 of the original manuscript / lines 744-758 in the revised manuscript.

Line 305: "contribution"

Thanks. We have adjusted the wording in the revised manuscript.

Line 305: Ok, so what do those studies show?

> The forced response of the Antarctic Ice Sheet until 2300 is in line with the results of both Golledge et al. (2015) and Chambers et al. (2022) and is consistent with the range of -0.3 m - +3.2 m sea–level equivalent given as estimate for the Antarctic sea–level contribution in the latest IPCC assessment (Fox-Kemper et al., 2021).

We have added the sea-level change determined in Golledge et al. (2015) by the year 2300 under RCP2.6 and RCP8.5 in the revised manuscript. For consistency, we have removed the reference to Chambers et al. (2022) as the 21st-century climate is kept constant in the projections after the end of this century.

In the revised manuscript (lines 370-373), the sentence has been reformulated (also following the following comment of the editor) and integrated into the description of the projected ice-sheet changes under SSP5-8.5 (Sect. 3.2) as:

> *The forced contribution of the Antarctic Ice Sheet to sea–level change until 2300 is in line with the results of e.g. Golledge et al. (2015) (showing an ice loss of +1.6 m – +2.96 m under RCP8.5) and is consistent with the Antarctic contribution to sea–level rise reported in the latest IPCC assessment of -0.3 m – +3.2 m sea–level equivalent (Fox-Kemper et al., 2021).*

Line 306: perhaps it would be better this way "is consistent with Antarctic contribution to sea level rise reported in the last IPCC report AR6 (Fox Kemper et al., 2021) and ranging from -0.3m to +3.2 m".

> The forced response of the Antarctic Ice Sheet until 2300 is in line with the results of both Golledge et al. (2015) and Chambers et al. (2022) and is consistent with the range of -0.3 m - +3.2 m sea–level equivalent given as estimate for the Antarctic sea–level contribution in the latest IPCC assessment (Fox-Kemper et al., 2021).

Thanks for this suggestion. We have reformulated this sentence along the lines of the editor's suggestion and integrated it into the description of the projected ice-sheet changes under SSP5-8.5 (Sect. 3.2). In the revised manuscript (lines 370-373), this sentence now reads as:

> *The forced contribution of the Antarctic Ice Sheet to sea–level change until 2300 is in line with the results of e.g. Golledge et al. (2015) (showing an ice loss of +1.6 m – +2.96 m under RCP8.5) and is consistent with the Antarctic contribution to sea–level rise reported in the latest IPCC assessment of -0.3 m – +3.2 m sea–level equivalent (Fox-Kemper et al., 2021).*

Line 319: Please remove the parts related to this paper in review to which the reader to not have access. I suggest to repharse the sentence and remove this unpublished ref.

We have removed the reference in the revised manuscript. With the rephrasing of the corresponding section in the revised manuscript, the sentence has been removed as well.

Line 325: See, my previous comment on Fig2e and 2f and relative caption.

We refer to our response to the editor's comment on Figure 2 in the original manuscript.

Line 326: Why is this happening? What is the reason behind? Are all trajectories of PISM delayed? It is actually very hard to see on Fig2c. I suggest to separate in different frames the simulations from PISM from those of Kori-ULB. It would be much simpler to interpret the descripancies resulting from some feedbakc within each models, or amongst the two models.

> We find a sharp increase in the Antarctic sea–level contribution over the next millennium, irrespective of the emission scenario. When following the lower–emission pathway SSP1-2.6, the ice–sheet response levels off after a peak in the rate of Antarctic ice loss within this millennium or at latest by the beginning of the following millennium.
>
> In some cases, abrupt changes in the Antarctic sea–level contribution occur delayed (compared to other trajectories under the lower–emission pathway) in PISM, with a lag of multiple millennia to the onset of the perturbation in ice–sheet boundary conditions.

These are important questions and we thank the editor for pointing out the lack of explanation for the delay in some ice-sheet trajectories under the lower-emission pathway SSP1-2.6 in the original manuscript.

The delay in the Antarctic sea-level contribution is related to a later onset of substantial grounding-line retreat in the Amundsen Sea Embayment. Such a delay in the Antarctic sea-level contribution is most pronounced for MRI-ESM2-0 climate and may be explained by the comparably smaller projected changes in circumantarctic ocean warming compared to the other GCMs.

In the revised manuscript, we have reformulated the description of the committed Antarctic sea-level contribution under SSP1-2.6 (Sect. 3.3.1, lines 408-476). Please see the attached manuscript for changes in the text. In particular, we have added the following explanation for the delay in the Antarctic sea-level contribution in lines 413-418 of the revised manuscript:

> *Abrupt changes in the Antarctic sea–level contribution may also occur delayed for MRI-ESM2-0 climate (Fig. 5a and c, orange), with a lag of up to multiple millennia to the onset of the perturbation in climatic boundary conditions in PISM experiments. This delay is related to a later onset of substantial grounding–line retreat in the Amundsen Sea Embayment in these simulations with comparably smaller projected oceanic changes in Antarctic climate in MRI-ESM2-0 (compared to other climate trajectories under the lower–emission pathway; Fig. 4a and d).*

In addition, we have adjusted Figure 2 of the original manuscript. In Figure 5 of the revised manuscript, showing the committed ice-sheet changes, separate panels for Kori-ULB and PISM are introduced. We hope that the individual ice-sheet trajectories following the different GCM climates and determined by Kori-ULB and PISM can now be better distinguished.

Line 328: What to do you mean here? The fnal sea level contribution at 7000 years ranges from below 0 to 6 meters...Do you mean that the simulations carried out with the same cliamte forcing converge towards the same magnitude? If yes, please be more specific here. It is tto vague.

> These ice–sheet trajectories, however, eventually converge to the same magnitude of sea–level contribution on multi–millennial timescales.

We thank the editor for pointing out the potentially misleading formulation related to the sea-level commitment under SSP1-2.6 in the original manuscript.

In our simulations carried out with Kori-ULB and PISM, we find that under the lower-emission pathway SSP1-2.6 the magnitude of the committed Antarctic sea-level contribution is determined by the applied GCM forcing for each ice-sheet model and does not strongly depend on the point in time where climate is kept constant. In other words, the ice-sheet trajectories resulting from the climate projected by the same GCM are characterized by a very similar sea-level contribution on multi-millennial timescales, irrespective of the branchoff point in time.

In the revised manuscript, we have reformulated the description of the committed Antarctic sea-level contribution under SSP1-2.6 (Sect. 3.3.1, lines 408-476). Please see the attached manuscript for changes in the text. In particular, the related paragraph (lines 419-430) now reads as:

> *Irrespective of the timing of abrupt ice loss, the multi–millennial ice–sheet trajectories eventually are characterized by qualitatively different stages of ice–sheet decline with the same magnitude of the Antarctic sea–level contribution determined by the applied GCM forcing for each ice–sheet model (Fig. 5a and c). That is, in our simulations under the SSP1-2.6 pathway, we do not find a strong dependency of the long–term Antarctic sea–level commitment reached in year 7000 on the point in time after which climatic boundary conditions are kept constant (Fig. 5e, Fig. 6a). When sustaining the warming level potentially reached until year 2050, global mean sea–level may increase by +0.4 m to +4.0 m on the long–term (Fig. 5e, Tab. 1). For climatic boundary conditions representative of the end of this century and thereafter, Antarctic mass changes range between -0.2 m and +6.5 m of sea–level equivalent, which unfolds over the next millennia (Fig. 5e, Tab. 1).*
>
> *This strong modulation of the magnitude of the committed Antarctic sea–level contribution by the applied GCM forcing for each ice–sheet model (Fig. 5e, Fig. S2) is linked to substantial differences in the trajectories of atmospheric to oceanic warming between the applied GCMs under this lower–emission pathway (Fig. 4a and d). Their impact on the ice–sheet response plays out and becomes evident on longer timescales (on the order of millennia).*

Line 329: Please reformulate: "we don't find a strong dependency on ice sheet parameters on the long-term contribution reached at 7000 years" or similar. What about the dependency of the ice sheet model?

> In our simulations under SSP1-2.6, we do not find a strong dependency of the long–term ice–sheet configuration reached in year 7000 on the point in time after which climatic boundary conditions are kept constant (Fig. 2e; Fig. 3a, committed).

We here aim at describing the dependence of the long-term Antarctic sea-level contribution under SSP1-2.6 on the point in time after which climatic boundary conditions are kept constant (branchoff point in time). In our simulations, we find that the Antarctic sea-level commitment (in the year 7000) does not strongly depend on the branchoff point in time. We agree that the term 'long-term ice-sheet configuration reached in year 7000' in the original manuscript may be misleading.

In the revised manuscript, we have reformulated the description of the committed Antarctic sea-level contribution under SSP1-2.6 (Sect. 3.3.1, lines 408-476). Please see the attached manuscript for changes in the text. In particular, the paragraph in lines 419-430 (see also our response to the previous editor comment) refers to the editor comment.

Line 333: This could be reformulated inn a way to somehow linked with the previous sentences on non-dependency on ice sheet parameters: "We find a strong dependency on the magnitude of long-term contribution committment on the climate forcing used to force the ice sheet models".

> The applied GCM forcing determines the magnitude of the committed Antarctic sea–level contribution under SSP1-2.6 at a given (branchoff) point in time (Fig. 2e).

We thank the editor for the suggestion of linking (1) the non-dependency of Antarctic sea-level commitment on the branchoff point in time and (2) the dependence of Antarctic sea-level commitment on the applied GCM forcing.

In the revised manuscript, we have reformulated the description of the committed Antarctic sea-level contribution under SSP1-2.6 (Sect. 3.3.1, lines 408-476). Please see the attached manuscript for changes in the text. In particular, the paragraph in lines 419-430 (see also our response to the previous editor comment) refers to the editor comment.

Line 335: We can't appreciate this. It would be nice to have a figure showing the comparison of climate and ocean fields from each GCMs.

> For both ice–sheet models, stronger ocean warming in the Wilkes basin projected by UKESM1-0-LL and IPSLCM6A-LR compared to the other GCMs may promote grounding–line retreat in this region (compare Fig. S12–S15), giving rise to the upper limit of long–term ice loss found under the lower–emission pathway (Fig. 2e).

We agree and thank the reviewer for the suggestion of adding a separate figure on the changes in Antarctic climate that are projected by the different GCMs. We refer to the related general editor comment on the climate analysis for a more detailed response.

Line 336: "explaining" instead of "giving" would be better?

Thanks. We have changed the wording as suggested by the editor in the revised manuscript.

Line 337: Fig2e actually shows the committment. So here better ref to Fig2c. is you write about ice loss

> For both ice–sheet models, stronger ocean warming in the Wilkes basin projected by UKESM1-0-LL and IPSLCM6A-LR compared to the other GCMs may promote grounding–line retreat in this region (compare Fig. S12–S15), giving rise to the upper limit of long–term ice loss found under the lower–emission pathway (Fig. 2e).

We agree that the wording may be misleading here. This sentence (and the long-term ice loss) is supposed to refer to the Antarctic sea-level commitment under SSP1-2.6, as shown in Figure 2e of the original manuscript.

In the revised manuscript, we have reformulated the description of the committed Antarctic sea-level contribution under SSP1-2.6 (Sect. 3.3.1, lines 408-476). Please see the attached manuscript for changes in the text.

Line 342: It would be nice also to indicate here the symbols you are refering too, it would definitely helps.

We thank the editor for this suggestion. In the revised manuscript, we have made better use of the different symbols and colours in the figures and added references in the main text wherever applicable.

Line 345: Why is Kori-ULB less sensitive than PISM? No explaination is provided about it here. I guess later on in the paper, but then it is strange to not already discuss this here, at least mention the reason and saying that it is further developed in the discussion.

> This limits the long–term sea–level change from Antarctica to approximately +3.0 m in Kori-ULB (in combination with a retreating grounding line in Wilkes basin under UKESM1-0-LL and IPSL-CM6A-LR; Fig. 2e).

This is an important question. The uncertainty in the committed sea-level contribution under SSP1-2.6 determined by Kori-ULB and PISM is related to varying ice-sheet sensitivities to changes in climate in the Siple Coast catchment that drains Ross Ice Shelf. In particular, we find a grounding-line advance and thickening upstream of the grounding line in this region in simulations with Kori-ULB on multi-millennial timescales. Ross Ice Shelf is not lost in simulations with Kori-ULB under SSP1-2.6. In simulations with PISM, Ross Ice Shelf collapses and ice from the corresponding drainage basin is lost subsequently.

Both ice-sheet responses can likely be linked to the different initialization approaches applied in the ice-sheet models. Please see our response to the related general reviewer comment for a more detailed discussion.

In the revised manuscript, we have reformulated the description of the committed Antarctic sea-level contribution under SSP1-2.6 (Sect. 3.3.1, lines 408-476). Please see the attached manuscript for changes in the text. In particular, the related paragraph (lines 441-466), now also including possible explanations for the varying long-term ice-sheet response in the Siple Coast under SSP1-2.6, reads as:

> *The magnitude of Antarctic sea–level commitment under SSP1-2.6 is further modulated by the long–term consequences of a potential collapse of Ross and Ronne–Filchner ice shelves: In Kori-ULB, both large ice shelves are preserved to year 7000, and we find a grounding–line advance and upstream thickening in the Siple Coast region (Fig. 6a). This long–term ice–sheet response in the Siple Coast may, in parts, result from a drift of the initialisation procedure, given lower sub–shelf melt rates obtained*

with PICO in this area compared to those that are obtained from the initialization approach to keep the ice sheet steady (Sect. 2.2.2). A thickening signal upstream of Ross Ice Shelf has also been observed over the past decades (with the stagnation of Kamb Ice Stream; Smith et al., 2020). The simulated thickening upstream of Ross Ice Shelf contributes to the decay in the long–term Antarctic sea–level contribution over time after the year 3000 in some Kori-ULB experiments, which is most pronounced for sustained MRI-ESM2-0 climate (Fig. 5a, orange). The preservation of these buttressing ice shelves limits the long–term sea–level change from Antarctica under SSP1-2.6 to less than +3.5 m in the Kori-ULB experiments (with the upper bound reached under UKESM1-0-LL and IPSL-CM6A-LR climate due to a combined grounding–line retreat in Wilkes subglacial basin and the Amundsen Sea sector; Fig. 5a and e, grey and pink filled markers). In PISM, a substantial portion of the marine ice–sheet in West Antarctica is lost with the collapse of Ross Ice Shelf and the subsequent retreat of the Siple Coast grounding line by year 7000 under most considered climate trajectories (Fig. 6a, Fig. S2). The loss of Ross Ice Shelf and the stronger sensitivity of the Siple Coast grounding line under SSP1-2.6 climate in the PISM experiments may be related to the initialized upstream grounding–line location compared to observations at present–day (compare Sect. 2.2.2, Fig. S1; as previously seen in a model initialisation in a spin–up approach, e.g., Reese et al., 2023; Sutter et al., 2023), and the simulated thinning in Ross Ice Shelf over the historical period (compare Sect. 3.1, Fig. 2c; also when determining the historical ice–sheet evolution on higher horizontal resolution using PISM,e.g., Reese et al., 2020, 2023). In addition, the higher basal melt sensitivity (compare Sect. 2.2.3 and Sect. 3.1) also translates the projected ocean warming into pronounced ice–shelf thinning (Fig. 4f, Fig. 6a). Furthermore, once grounding–line retreat is triggered, a collapse of the West Antarctic Ice Sheet may be more likely in PISM than in Kori-ULB, where low slipperiness towards the interior of West Antarctica (given low basal sliding coefficients retrieved in the inverse simulations, Sect. 2.2.2) slows down ice–sheet retreat. The combined ice loss from West Antarctica and the East Antarctic Wilkes subglacial basin in PISM gives rise to the upper end of the long–term Antarctic sea–level commitment of up to +6.5 m found under the lower–emission pathway in our experiments (Fig. 5c and e, grey open markers).

Line 367: Please show it. plot some integrated curve over this area comparing surface melt, SMB, accumulation etc…

We also find a substantial ice thickness decrease in inner parts of East Antarctica grounded above sea level that is triggered under sustained high levels of warming and possibly exacerbated by the melt–elevation feedback (Fig. 3b, committed).

To disentangle the role of the melt-elevation feedback in the committed ice-sheet evolution, a comparison with experiments without the lapse-rate correction of atmospheric temperatures with changes in the ice-sheet surface elevation would be needed, as in Coulon et al. (2024). In their multi-centennial ensembles following similar CMIP6 warming trajectories, Coulon et al. (2024) find the ice-sheet collapse to be accelerated by the melt-elevation feedback over the next millennium, pointing towards similar mechanisms being at play in our experiments as well.

Note that, in the revised manuscript, we have reformulated the description of the committed Antarctic sea-level contribution under SSP5-8.5 (Sect. 3.3.2, lines 477-522). Please see the attached manuscript for changes in the text.

Line 386: also in the physics…

> Under equivalent warming, the long–term dynamical and topographical changes of the Antarctic Ice Sheet are largely consistent (for each ice–sheet model configuration) and uncertainty in Antarctic ice loss for a given warming level is due to inter– and intra–model uncertainty (e.g., arising in the ice–sheet model initialisation, compare Sect. 2.2.2, and by differences between applied atmospheric climatologies).

In the revised manuscript, we have reformulated the description of the committed Antarctic sea-level contribution depending on the changes in Antarctic climate (Sect. 3.4, lines 523-595). We have also added the aspect of model physics in the respective paragraph of the revised manuscript (lines 583-586):

> *Under equivalent warming, the long–term dynamical and topographical changes of the Antarctic Ice Sheet are largely con- sistent for each ice–sheet model configuration (compare Table S2). We find a spread in long–term mass loss at a given warming level due to model uncertainties (e.g., arising in the ice–sheet model initialisation and physics), which is pronounced for low to intermediate warming levels in Antarctica covered by the lower–emission pathway SSP1-2.6 (Fig. 7b).*

Figure 2

- **It would be nice to report the scale also in the Y axis in panels e and f.**

  We have added the scale of the vertical axis in the related figure of the revised manuscript.

- **"contribution" would be better than "response", as written on the Y axis of the frames**
- **"contribution" again.**

  We have changed the wording in the caption of the related figure in the revised manuscript from ‘response’ to ‘contribution’.

- **I think panel e and f X-axis title deserve a bit more description: You should insert something like "branching off" in the caption of the x-axis. Then in the caption, refer to Figure 1 with a sentence: "Committed Antarctic sea level contribution in the year 7000 for the simulations with constant climate conditions from 2100, 2200 and 2300, respectively."...It took me a while, once again to figure it out.**

  We agree and thank the editor for this suggestion to modify the label of the horizontal axis of this figure. In the revised manuscript, the label ‘branching off in the year’ has been added. In addition, the corresponding part of the caption now reads as:

Committed Antarctic sea-level contribution in the year 7000 when stabilizing Antarctic climate at different points in time (that is, 'branching off' in the years 2050, 2100, 2150, 2200, 2250 and 2300; compare Sect. 2.2.1 and Fig. 1)

- **This caption is so difficult to understand...Please write in a simple way, providing the info necessary to be understandable by the reader: "triangles corresponds to simulations initialied using MAR/RACMO, while circle corresponds to simulations initialised with MAR/RACMO".**

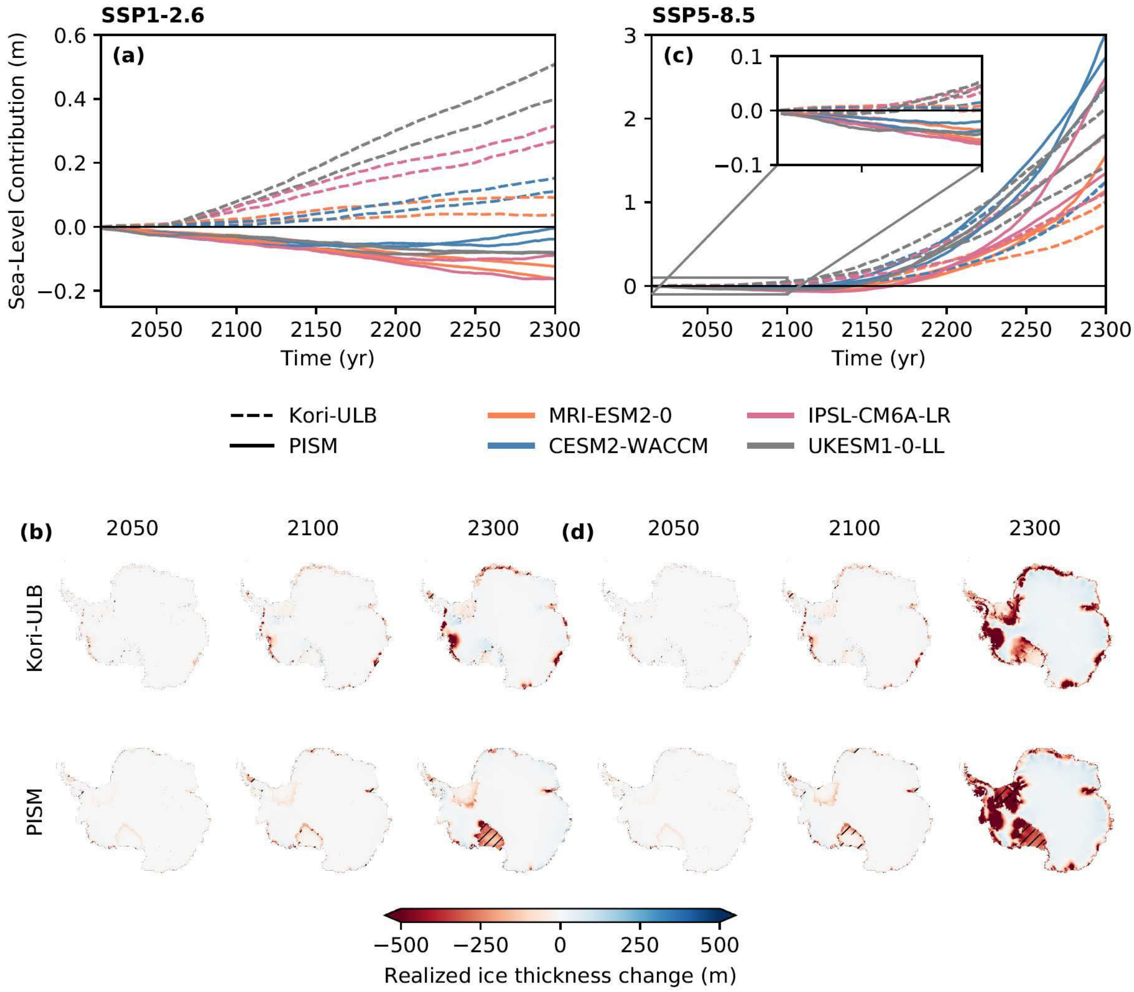
  Throughout the revised manuscript, we have removed the information on the different atmospheric climatologies involved in the ice-sheet model initialization. We hope that the focus on model agreement and differences in the Antarctic sea-level contribution between Kori-ULB and PISM improves the clarity in the revised manuscript.

- **"ice loss by 7000 under SSP1-2.6 (e) is reported by the gray shade in f)." or something like this.**
- **"the gray shade" woudl be better?**

  We have adjusted this part of the caption as suggested in the revised manuscript:

  For comparison of the committed sea-level rise under both emission pathways, the range of Antarctic ice loss by 7000 under SSP1-2.6 (e) is reported by the light grey shade in (f).

Please note that Figure 2 of the original manuscript has been reorganized, and an additional figure has been introduced in the revised manuscript as Figure 3. Figure 3 in the revised manuscript shows the transient ice-sheet response to 2300, in combination with the projected ice-sheet changes (in terms of the ice thickness) in the years 2050, 2100 and 2300. The committed ice-sheet response is the focus of Figure 5 in the revised manuscript. We here show the multi-millennial ice-sheet response in terms of the Antarctic sea-level contribution under SSP1-2.6 and SSP5-8.5, separately for PISM and Kori-ULB, together with the sea-level commitment in the year 7000, depending on the branchoff point in time.



SSP1-2.6
(a)
Sea-Level Contribution (m)
0.6
0.4
0.2
0.0
−0.2
2050
2100
2150
2200
2250
2300
Time (yr)
SSP5-8.5
(c)
3
2
1
0
0.1
0.0
−0.1
Kori-ULB
PISM
MRI-ESM2-0
CESM2-WACCM
IPSL-CM6A-LR
UKESM1-0-LL
(b)
(d)
Kori-ULB
PISM
−500
−250
0
250
500
Realized ice thickness change (m)

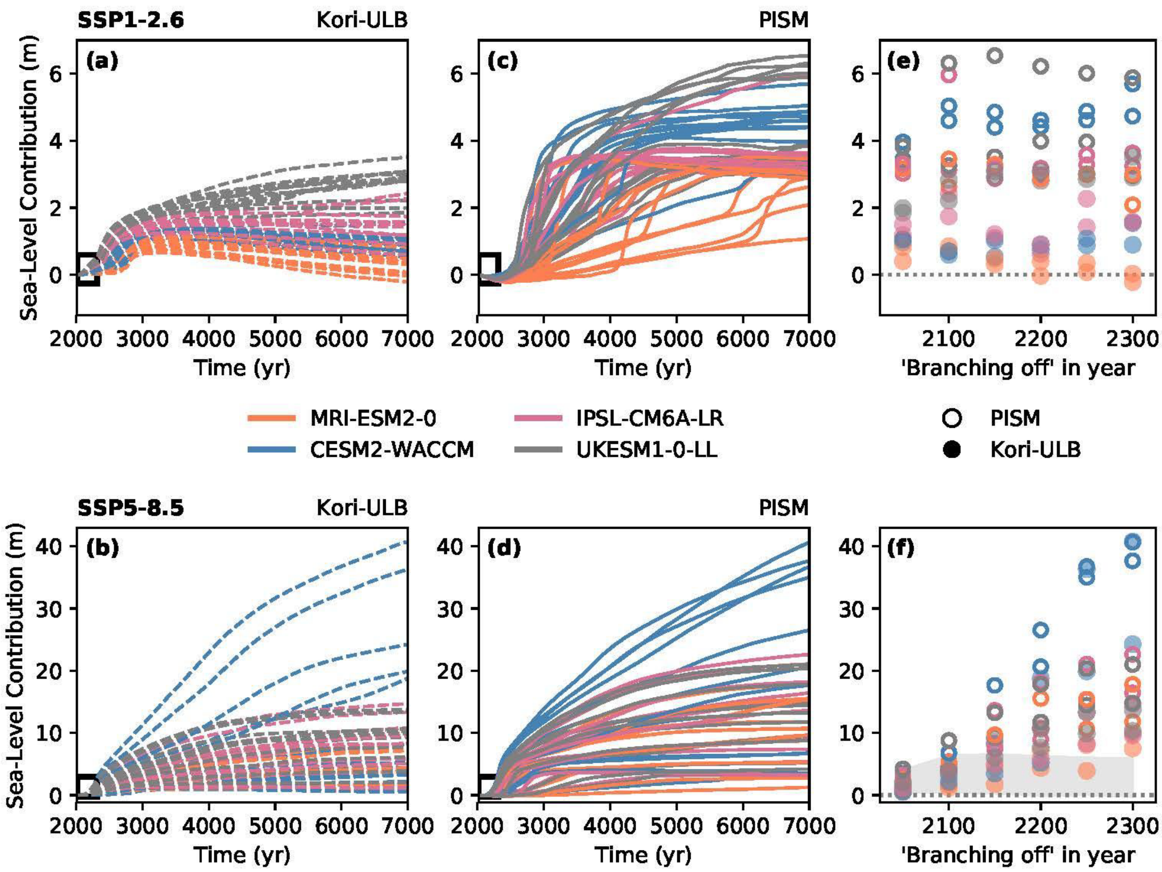


Figure 3: This caption is not clear. What is represented here? an averaged of Kori-ULB and PISM?

Yes, the mean ice thickness change determined by both ice-sheet models and for all GMC forcings at the given point in time is shown in Figure 3 of the original manuscript. We agree that this has not been clear in the original manuscript and have added an explanation to the caption where needed in the revised manuscript.

Line 419: we don't see this anywhere. I would suggest to make a similar figure but relative to oceanic warming,

> This region contributes up to +1.5 m to the long–term sea–level change, which may occur for a mean ocean–temperature change exceeding +0.5°C – +1°C in this basin (depending on the ice–sheet model, with earlier onset of retreat in Kori-ULB; Fig. 5i).

We agree that the related basin-averaged ocean temperature change for Wilkes subglacial basin is difficult to infer from the colouring in Figure 5i in the original manuscript.

In the revised manuscript, Figure 5 has been modified (also compare our response to the editor comment below and the related general editor comment), and the colouring by ocean temperature change was removed. Instead, an additional Figure S4 in the Supplementary Material was added to show the dependence of the committed ice loss from this basin on changes in the ocean.

Figure 4: What do the colors of symbols corresponds to? This is not indicated in the caption?

We thank the editor for pointing out the missing explanation / legend for the colouring of the markers in Figure 4 of the original manuscript. The colours of the markers refer to

- the emission pathways, where the blue-green colour scale indicates SSP1-2.6 while the orange-purple colour scale corresponds to SSP5-8.5
- the branchoff point in time going from light to darker colours for keeping climate constant later in time.

In addition, the GCMs used to derive changes in Antarctic climate are indicated by the marker shape. Filled and open markers refer to simulations by Kori-ULB and PISM, respectively.

In the revised manuscript, we have added a colourbar and legend to this figure, explaining the colours and shapes of the markers.

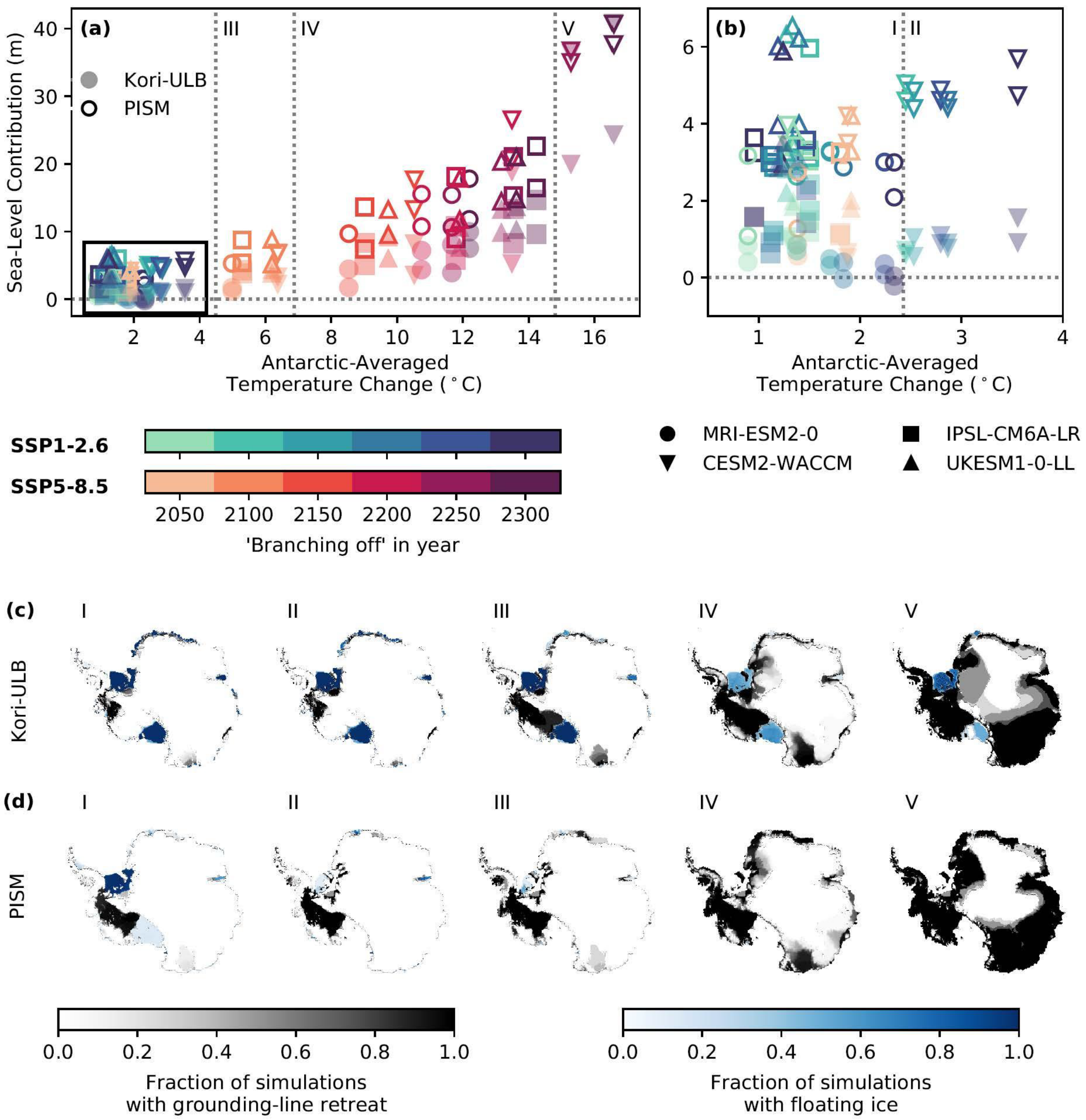
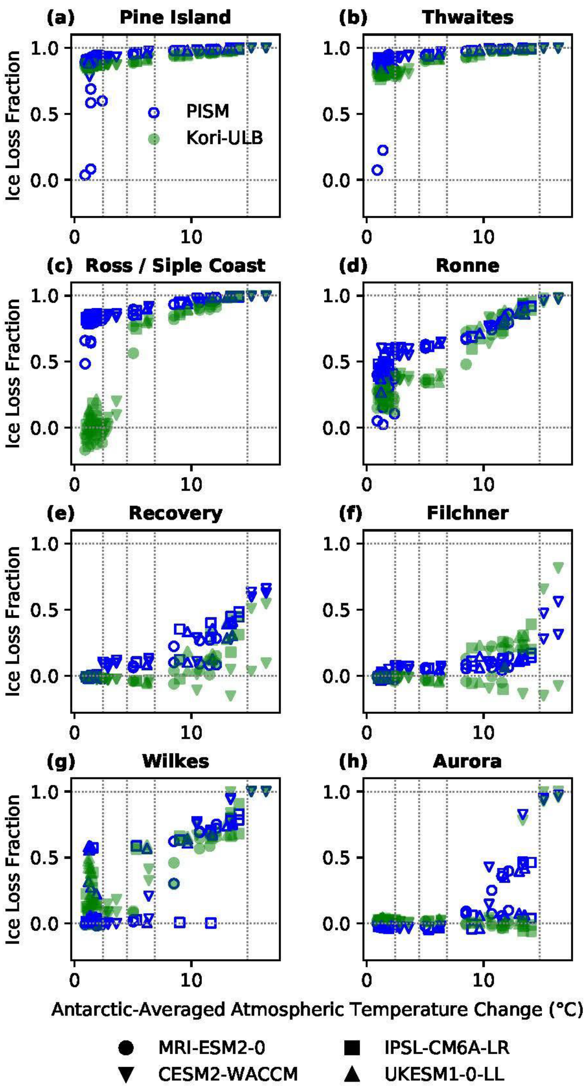


Figure 5: It is impossible to distinguish the two models here. The panels are too dense. As such, most of the description of the results in the main text is hard to follow and thus the arguments are not convincing. Please find a different display solution.

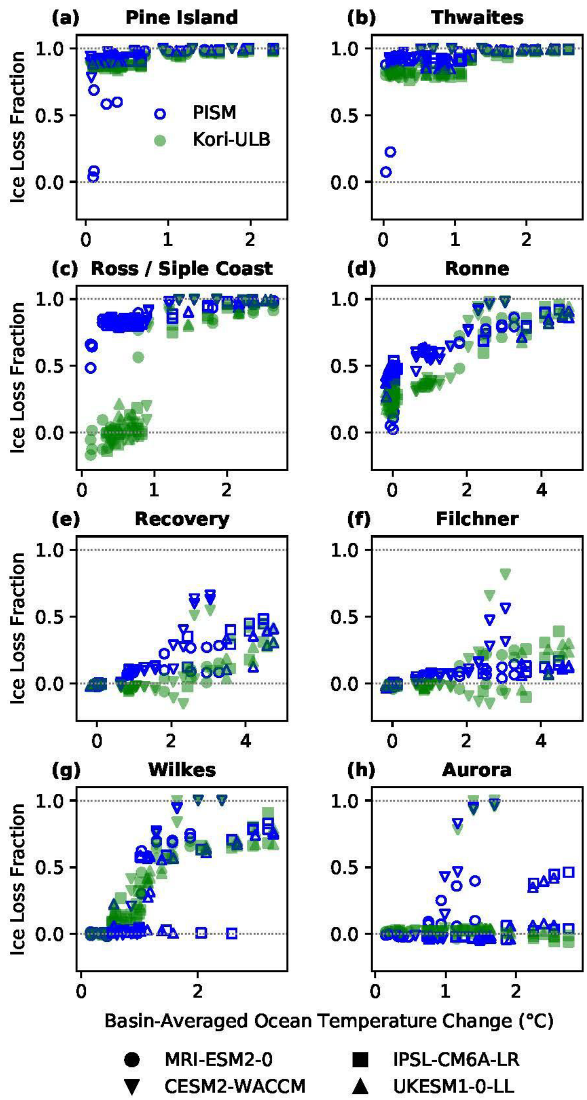
We agree with the editor and have changed Figure 5 of the original manuscript as follows:

- We have merged basins 'Ross / Siple Coast I' and 'Ross / Siple Coast II', as they show qualitatively similar behaviour.
- The colouring has been changed to indicate the ice-sheet model.
- The marker shape has been changed to refer to the GCM used to derive the changes in Antarctic climate.

In addition, the information on basin-averaged ocean temperature changes has been removed from Figure 8 in the revised manuscript. Instead, an additional Figure S4 in the Supplementary Material has been added to show the dependence of the committed ice loss from selected basins on changes in the ocean.



(a) Pine Island
(b) Thwaites
(c) Ross / Siple Coast
(d) Ronne
(e) Recovery
(f) Filchner
(g) Wilkes
(h) Aurora
Ice Loss Fraction
1.0
0.5
0.0
0
10
PISM
Kori-ULB
Antarctic-Averaged Atmospheric Temperature Change (°C)
MRI-ESM2-0
IPSL-CM6A-LR
CESM2-WACCM
UKESM1-0-LL



Line 479: I don't understand why you call it "a gap"? A gap would be when there is missing info. Here you have a substantial offset between the short-term and long-term sea level contribution.

Please see our response to a previous related editor comment. In the revised manuscript, we have changed the wording from ‘gap’ to ‘difference’, and hope this sentence is clearer now.

Lines 532 – 605: I think this section would benefit from a speach spearating PISM and Kori-ULB. First a section including all analysis of uncertainties for one model, and then another section for the model. Righ now, it is a bit complicated to follow.

In the revised manuscript, Section 4 and, in particular, the discussion of model uncertainties (including uncertainties in ice-sheet processes, their parameterization in ice-sheet models and distinct initialization approaches; Sect. 4.2; lines 693-765) have been reorganized and elaborate on differences in ice-sheet model behaviour on shorter (multi-centennial) and longer (multi-millennial) timescales, in relation to ice-sheet modelling and initialization choices. Please see the attached manuscript for changes in the text.

Lines 551 – 559: So this paragraph in general deals with the initialisation procedure, more than the difference in the physics. Please put a different hear then for this specific pargraph.

In the revised manuscript, Section 4 and, in particular, the discussion of model uncertainties (including uncertainties in ice-sheet processes, their parameterization in ice-sheet models and distinct initialization approaches; Sect. 4.2; lines 693-765) have been reorganized and elaborate on differences in ice-sheet model behaviour on shorter (multi-centennial) and longer (multi-millennial) timescales, in relation to ice-sheet modelling and initialization choices. Please see the attached manuscript for changes in the text.

Line 566: And actually the initial present-day Antarctic geometry is much better than that of PISM.

We agree that the Kori-ULB initial ice-sheet states are closer to the observed present-day geometry of the Antarctic Ice Sheet. This is related to the initialisation approach.

In the revised manuscript, we discuss these differences between the initial ice-sheet states and observed ice-sheet geometries in more detail by including an additional paragraph in Section 2.2.2. Please see our response to the related general editor and reviewer comments for a more detailed discussion of the application of different initialization approaches for assessing the Antarctic sea-level commitment in our study and related adjustments in the revised manuscript.

Line 572: not only, also the magnitude of melting and sublimation...RCMs are far from agreeing amoungst each other and are only calibratted on a present-day state with little melting so far.

This is correct. We here focused on precipitation and atmospheric temperatures as variables that are used as atmospheric climatologies for driving the ice-sheet models. This sentence has been reformulated in the revised manuscript and moved to lines 197-200, following the restructuring of Section 3 and Section 4:

> *While a recent intercomparison concluded that Antarctic climate is represented reasonably well compared to observations in state–of–the–art RCMs, disagreement between the RCMs with respect to surface mass balance components (such as precipitation and atmospheric temperatures as applied to the ice–sheet models here) exists for some areas (Mottram et al., 2021).*

References

Aschwanden, A., Aðalgeirsdóttir, G., & Khroulev, C. (2013). Hindcasting to measure ice sheet model sensitivity to initial states. *The Cryosphere*, *7*(4), 1083-1093.

Aschwanden, A., Bartholomaus, T. C., Brinkerhoff, D. J., & Truffer, M. (2021). Brief communication: a roadmap towards credible projections of ice sheet contribution to sea-level. *The Cryosphere*, *15*(12), 5705-5715.

Barthel, A., Agosta, C., Little, C. M., Hattermann, T., Jourdain, N. C., Goelzer, H., Nowicki, S., Seroussi, H., Straneo, F. & Bracegirdle, T. J. (2020). CMIP5 model selection for ISMIP6 ice sheet model forcing: Greenland and Antarctica. *The Cryosphere*, *14*(3), 855-879.

Bentsen, M., Bethke, I., Debernard, J. B., Iversen, T., Kirkevåg, A., Seland, Ø., Drange, H., Roelandt, C., Seierstad, I. A., Hoose, C. & Kristjansson, J. E. (2013). The Norwegian Earth System Model, NorESM1-M–Part 1: description and basic evaluation of the physical climate. *Geoscientific Model Development*, *6*(3), 687-720.

Berends, C. J., Van De Wal, R. S., Van Den Akker, T., & Lipscomb, W. H. (2023). Compensating errors in inversions for subglacial bed roughness: same steady state, different dynamic response. *The Cryosphere*, *17*(4), 1585-1600.

Blackburn, T., Edwards, G. H., Tulaczyk, S., Scudder, M., Piccione, G., Hallet, B., McLean, N., Zachos, J.C., Cheney, B., & Babbe, J. T. (2020). Ice retreat in Wilkes Basin of East Antarctica during a warm interglacial. *Nature*, *583*(7817), 554-559.

Chambers, C., Greve, R., Obase, T., Saito, F., & Abe-Ouchi, A. (2022). Mass loss of the Antarctic ice sheet until the year 3000 under a sustained late-21st-century climate. *Journal of Glaciology*, *68*(269), 605-617.

Coulon, V., Klose, A. K., Kittel, C., Edwards, T., Turner, F., Winkelmann, R., & Pattyn, F. (2024). Disentangling the drivers of future Antarctic ice loss with a historically calibrated ice-sheet model. *The Cryosphere*, *18*(2), 653-681.

DeConto, R. M., & Pollard, D. (2016). Contribution of Antarctica to past and future sea-level rise. *Nature*, *531*(7596), 591-597.

Edwards, T. L., Nowicki, S., Marzeion, B., Hock, R., Goelzer, H., Seroussi, H., ... & Zwinger, T. (2021). Projected land ice contributions to twenty-first-century sea level rise. *Nature*, *593*(7857), 74-82.

Fox-Kemper, B., Hewitt, H.T., Xiao, C., Aðalgeirsdóttir, G., Drijfhout, S.S., Edwards, T.L., Golledge, N.R., Hemer, M., Kopp, R.E., Krinner, G., Mix, A., Notz, D., Nowicki, S., Nurhati, I.S., Ruiz, L., Sallée, J.-B., Slangen, A.B.A. & Yu, Y. (2021). Ocean, Cryosphere and Sea Level Change. In Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S.L., Péan, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L., Gomis, M.I., Huang, M., Leitzell, K., Lonnoy, E., Matthews, J.B.R., Maycock, T.K., Waterfield, T., Yelekçi, O., Yu, R. & Zhou, B. (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1211–1362, doi:10.1017/9781009157896.011.

Garbe, J., Albrecht, T., Levermann, A., Donges, J. F., & Winkelmann, R. (2020). The hysteresis of the Antarctic ice sheet. *Nature*, *585*(7826), 538-544.

Golledge, N. R., Kowalewski, D. E., Naish, T. R., Levy, R. H., Fogwill, C. J., & Gasson, E. G. (2015). The multi-millennial Antarctic commitment to future sea-level rise. *Nature*, *526*(7573), 421-425.

Gulev, S., Thorne, P., Ahn, J., Dentener, F., Domingues, C., Gerland, S., Gong, D., Kaufman, D., Nnamchi, H., Quaas, J., Rivera, J., Sathyendranath, S., Smith, S., Trewin, B., von Schuckmann, K., and Vose, R.: Changing State of the Climate System. In Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)], Cambridge University Press, p. 287–422, 2021.

Fretwell, P., Pritchard, H. D., Vaughan, D. G., Bamber, J. L., Barrand, N. E., Bell, R., ... & Zirizzotti, A. (2013). Bedmap2: improved ice bed, surface and thickness datasets for Antarctica. *The Cryosphere*, *7*(1), 375-393.

Frieler, K., Clark, P. U., He, F., Buizert, C., Reese, R., Ligtenberg, S. R., van den Broeke, M. R., Winkelmann, R., & Levermann, A. (2015). Consistent evidence of increasing Antarctic accumulation with warming. *Nature Climate Change*, *5*(4), 348-352.

Lai, C. Y., Kingslake, J., Wearing, M. G., Chen, P. H. C., Gentine, P., Li, H., Spergel, J., & Van Wessem, J. M. (2020). Vulnerability of Antarctica's ice shelves to meltwater-driven fracture. *Nature*, *584*(7822), 574-578.

Lenton, T. M., Armstrong McKay, D., Loriani, S., Abrams, J., Lade, S., Donges, J., Milkoreit, M., Powell, M., Smith, S., Zimm, C., Buxton, C., Bailey, E., Laybourn, L., Ghadiali, A., and Dyke, J. (2023): The Global Tipping Points Report 2023, University of Exeter, Exeter, UK.

Lowry, D. P., Krapp, M., Golledge, N. R., & Alevropoulos-Borrill, A. (2021). The influence of emissions scenarios on future Antarctic ice loss is unlikely to emerge this century. *Communications Earth & Environment*, *2*(1), 221.

Morlighem, M., Rignot, E., Binder, T., Blankenship, D., Drews, R., Eagles, G., ... & Young, D. A. (2020). Deep glacial troughs and stabilizing ridges unveiled beneath the margins of the Antarctic ice sheet. *Nature Geoscience*, *13*(2), 132-137.

Nowicki, S., Payne, A. J., Goelzer, H., Seroussi, H., Lipscomb, W. H., Abe-Ouchi, A., ... & Van De Wal, R. (2020). Experimental protocol for sea level projections from ISMIP6 standalone ice sheet models. *The Cryosphere*, *14*(7), 2331-2368.

Otosaka, I. N., Shepherd, A., Ivins, E. R., Schlegel, N. J., Amory, C., van den Broeke, M., ... & Wouters, B. (2023). Mass balance of the Greenland and Antarctic ice sheets from 1992 to 2020. *Earth System Science Data*, *15*(4), 1597-1616.

Pollard, D., & DeConto, R. M. (2012). A simple inverse method for the distribution of basal sliding coefficients under ice sheets, applied to Antarctica. *The Cryosphere*, *6*(5), 953-971.

Pollard, D., DeConto, R. M., & Alley, R. B. (2015). Potential Antarctic Ice Sheet retreat driven by hydrofracturing and ice cliff failure. *Earth and Planetary Science Letters*, *412*, 112-121.

Reese, R., Albrecht, T., Mengel, M., Asay-Davis, X., & Winkelmann, R. (2018). Antarctic sub-shelf melt rates via PICO. *The Cryosphere*, *12*(6), 1969-1985.

Reese, R., Garbe, J., Hill, E., Urruty, B., Naughten, K., Gagliardini, O., Durand, G., Gillet-Chaulet, F., Gudmundsson, G. H., Chandler, D., Langebroek, P. M., & Winkelmann, R. (2023). The stability of present-day Antarctic grounding lines–Part 2: Onset of irreversible retreat of Amundsen Sea glaciers under current climate on centennial timescales cannot be excluded. *The Cryosphere*, *17*(9), 3761-3783.

Rosier, S. H., Reese, R., Donges, J. F., De Rydt, J., Gudmundsson, G. H., & Winkelmann, R. (2021). The tipping points and early-warning indicators for Pine Island Glacier, West Antarctica. *The Cryosphere*, *15*(3), 1501-1516.

Rignot, E., Mouginot, J., & Scheuchl, B. (2011). Ice flow of the Antarctic ice sheet. *Science*, *333*(6048), 1427-1430.

Seroussi, H., Nowicki, S., Simon, E., Abe-Ouchi, A., Albrecht, T., Brondex, J., ... & Zhang, T. (2019). initMIP-Antarctica: an ice sheet model initialization experiment of ISMIP6. *The Cryosphere*, *13*(5), 1441-1471.

Seroussi, H., Nowicki, S., Payne, A. J., Goelzer, H., Lipscomb, W. H., Abe Ouchi, A., ... & Zwinger, T. (2020). ISMIP6 Antarctica: a multi-model ensemble of the Antarctic ice sheet evolution over the 21 st century. *The Cryosphere*, *14*(9),3033-3070.

Smith, B., Fricker, H. A., Gardner, A. S., Medley, B., Nilsson, J., Paolo, F. S., ... & Zwally, H. J. (2020). Pervasive ice sheet mass loss reflects competing ocean and atmosphere processes. *Science*, *368*(6496), 1239-1242.

Sutter, J., Jones, A., Frölicher, T. L., Wirths, C., & Stocker, T. F. (2023). Climate intervention on a high-emissions pathway could delay but not prevent West Antarctic Ice Sheet demise. *Nature Climate Change*, *13*(9), 951-960.

Trusel, L. D., Frey, K. E., Das, S. B., Karnauskas, K. B., Kuipers Munneke, P., Van Meijgaard, E., & Van Den Broeke, M. R. (2015). Divergent trajectories of Antarctic surface melt under two twenty-first-century climate scenarios. *Nature Geoscience*, *8*(12), 927-932.

Turney, C. S., Fogwill, C. J., Golledge, N. R., McKay, N. P., van Sebille, E., Jones, R. T., ... & Cooper, A. (2020). Early Last Interglacial ocean warming drove substantial ice mass loss from Antarctica. *Proceedings of the National Academy of Sciences*, *117*(8), 3996-4006.

Wilson, D. J., Bertram, R. A., Needham, E. F., van de Flierdt, T., Welsh, K. J., McKay, R. M., Mazumder, A., Riesselman, C. R., Jimenez-Espejo, F.J., & Escutia, C. (2018). Ice loss from the East Antarctic Ice Sheet during late Pleistocene interglacials. *Nature*, *561*(7723), 383-386.

Van Wessem, J. M., van den Broeke, M. R., Wouters, B., & Lhermitte, S. (2023). Variable temperature thresholds of melt pond formation on Antarctic ice shelves. *Nature Climate Change*, *13*(2), 161-166.

The long–term sea–level commitment from Antarctica

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Abstract. The evolution of the Antarctic Ice Sheet is of vital importance given the coastal and societal implications of ice loss, with a potential to raise sea level by up to 58 m if melted entirely. However, future ice–sheet trajectories remain highly uncertain. One of the main sources of uncertainty is related to nonlinear processes and feedbacks of the ice sheet with the Earth system on different timescales. Due to these feedbacks and ice–sheet inertia, ice loss may already be triggered in the next decades or centuries and then unfolds delayed on multi–centennial to millennial timescales. This committed Antarctic sea–level contribution is not reflected in typical sea–level projections based on mass balance changes of the Antarctic Ice Sheet, which often cover decadal–to–centennial timescales. Here, using two ice–sheet models, we systematically assess the long–term multi–millennial sea–level commitment from Antarctica in response to warming projected over the next centuries under low– and high–emission pathways. This allows bringing together the time horizon of stakeholder planning with the much longer response times of the Antarctic Ice Sheet.

Our results show that warming levels representative of the lower–emission pathway SSP1-2.6 may already result in an Antarctic mass loss of up to 6 m sea–level equivalent on multi–millennial timescales. This committed mass loss is due to a strong grounding–line retreat in the West Antarctic Amundsen Sea Embayment as well as a potential drainage from the Ross Ice Shelf catchment and onset of ice loss from the Wilkes subglacial basin in East Antarctica. Beyond warming levels reached by the end of this century under the higher–emission trajectory SSP5-8.5, a collapse of the West Antarctic Ice Sheet is triggered in the entire ensemble of simulations from both ice–sheet models. Under enhanced warming, next to ice loss from the marine parts, we also find a substantial decline in ice volume of regions grounded above sea level in East Antarctica. Over the next millennia, this gives rise to a sea–level increase of up to 40 m in our experiments, stressing the importance of including the committed Antarctic sea–level contribution in future projections.

1 Introduction

The future sea–level contribution from the Antarctic Ice Sheet, which stores enough ice to raise sea level by up to 58 m (Fretwell et al., 2013), is of vital importance for coastal communities ranging from small islands to the world's mega–cities, ecosystems and the global economy (Clark et al., 2016).

The Antarctic Ice Sheet has experienced changing environmental conditions on various timescales from decadal to orbital–scale climate variability since its presumed inception at the Eocene–Oligocene transition about 34 Mry ago (Zachos et al., 2001; DeConto and Pollard, 2003). This resulted in strong variations in its volume and extent linked to the slow multi–millennial changes in the Earth's astronomical configuration during the early to mid–Miocene (Naish et al., 2001; Levy et al., 2016) and the Pliocene (Naish et al., 2009). While terrestrial parts of the East Antarctic Ice Sheet have persisted for millions of years (Sugden et al., 1995; Shakun et al., 2018), ice–sheet variability involved an occasional collapse of the West Antarctic Ice Sheet (Naish et al., 2009) and inward migration of ice–sheet margins in marine–based sectors of East Antarctica (that is, where the ice sheet is grounded below sea level) during Pliocene warm periods (Cook et al., 2013; Patterson et al., 2014; Aitken et al., 2016). During Pleistocene Interglacials, Antarctic ice loss from the East Antarctic Wilkes subglacial basin (Wilson et al., 2018; Blackburn et al., 2020) and across the Weddel Sea Embayment (Turney et al., 2020) contributed to sea–level high–stands of 6 m to 9 m higher than present (including a contribution from thermal expansion and mass loss from the Greenland Ice Sheet; Dutton et al., 2015).

The future trajectory of the Antarctic Ice Sheet under progressing warming, however, is highly uncertain. This is due to uncertainties in the understanding and representation of ice–sheet processes and ice–climate interactions (Fox-Kemper et al., 2021) as well as the potentially high magnitudes and rates of recent and projected warming. The present rate of warming is unprecedented in at least 2000 years, with an increase of 1.1 °C in the global mean surface temperature between 1850–1900 and 2011–2020 (Gulev et al., 2021). The amount of warming projected for the end of this century under the Shared Socioeconomic Pathways (e.g., for the higher–emission scenario SSP5-8.5 with an increase in global annual mean surface air temperature of 3.6 °C to 6.5 °C relative to 1850-1900; Lee et al., 2021) is comparable to the transition from the Last Glacial Maximum to the beginning of the Holocene approximately 11,700 years before present, but is expected to develop on much shorter timescales.

At present, accelerated mass loss of the Antarctic Ice Sheet is concentrated in West Antarctica and the East Antarctic Wilkes land (Otosaka et al., 2023; Rignot et al., 2019; Li et al., 2016; Miles et al., 2021), likely driven by ocean–induced melting due to the intrusion of warm water into the ice–shelf cavities (Paolo et al., 2015). In future projections so far, for instance provided by the recent Ice Sheet Model Intercomparison Project for CMIP6 (ISMIP6, Seroussi et al., 2020; Payne et al., 2021), the transient sea–level response to the projected warming ranges from a slight mass gain to a mass loss of Antarctica by the end of this century under multiple emission scenarios (with the largest spread in sea–level change given by higher–emission pathways RCP8.5 and SSP5-8.5). The bulk of sea–level rise, however, is expected to unfold beyond the end of this century (Clark et al., 2016; Fox-Kemper et al., 2021) due to (1) the inertia of the continental–scale ice sheet in combination with (2) the potential of crossing critical thresholds with ongoing global warming (Lenton et al., 2023). This long–term sea–level response, that has already been triggered or may be triggered during the next decades or centuries (but unfolds thereafter over multiple centuries and millennia), might be substantially higher than the transient sea–level change, while it is not represented in typical sea–level projections (Seroussi et al., 2020; Edwards et al., 2021). Here, we assess this expected long–term committed sea–level change, by stabilizing the climatic boundary conditions projected over the next centuries at specific points in time and letting the ice sheet evolve over several millennia. We furthermore quantify the difference or offset between the transient *realized* sea–level contribution from Antarctica at a particular point in time and the respective long–term *committed* sea–level contribution.

The slow ice–sheet response to perturbations in its climatic boundary conditions owing to high inertia results in a time–lag between forcing and the resulting mass change. As the ice–sheet response unfolds on centennial to multi–millennial timescales, sea level may keep rising for millennia to come even if warming is kept on a constant level (Golledge et al., 2015; Winkelmann et al., 2015). This is especially due to the softening–induced increase in the creep component of the ice flow and internal feedbacks (Golledge et al., 2015; Clarke et al., 1977).

In addition, the Antarctic Ice Sheet is subject to several ampliyfing (and dampening) feedback mechanisms determining its long–term stability (Fyke et al., 2018; Garbe et al., 2020). For example, accelerated ice loss may be triggered once the amplifying surface melt–elevation feedback (Levermann and Winkelmann, 2016; Oerlemans, 1981) kicks in. With the lowering of the ice–sheet surface due to melting, it is exposed to higher air temperatures. Surface melting is, in turn, enhanced, promoting persistent ice loss upon crossing a critical temperature threshold. Furthermore, the marine parts of the ice sheet, e.g., in West Antarctica or the East Antarctic Aurora and Wilkes subglacial basins, are found to be susceptible to self–sustained, potentially irreversible grounding–line retreat (Garbe et al., 2020; Rosier et al., 2021; Mengel and Levermann, 2014; Feldmann et al., 2014). The rapid grounding–line retreat is often associated with an amplifying feedback in which the increased ice flow across the grounding line caused by an initial retreat fosters further retreat. In a theoretical flowline setup, it was shown that, due to the ice flux being a nonlinear function of the ice thickness, ice sheets grounded below sea level on a retrograde, inland sloping bed are unstable (Marine Ice Sheet Instability; Weertman, 1974; Schoof, 2007). More complex stability conditions arise in three dimensions when accounting for additional processes such as, e.g., buttressing (Gudmundsson et al., 2012; Haseloff and Sergienko, 2018; Pegler, 2018), calving and submarine melting (Haseloff and Sergienko, 2022) or the presence of feedbacks between the ice sheet and its environment (Sergienko, 2022). Ice loss may be dampened, on the other hand, by negative feedbacks such as introduced by e.g., the isostatic rebound of the solid Earth underlying the ice sheet, which could potentially stabilize West Antarctic grounding lines (Coulon et al., 2021; Barletta et al., 2018).

Depending on the interplay of these feedbacks, persistent mass loss may be triggered once critical forcings or tipping points (Lenton et al., 2008; Armstrong McKay et al., 2022), for instance in temperature, are crossed. The Antarctic Ice Sheet was therefore classified as a tipping element of the climate system (Lenton et al., 2008; Armstrong McKay et al., 2022; Lenton et al., 2023). Due to the inertia of ice sheets and the related delay in their transient response following a realistic warming trajectory under e.g. a higher–emission pathway, the ice sheet's volume trajectory likely deviates from the ice–sheet equilibrium response to warming (Garbe et al., 2020; Rosier et al., 2021). While consequences of self–sustained ice loss potentially triggered in the next decades or centuries may play out and become visible over millennial timescales (Reese et al., 2023) (characterized as a slow onset of tipping; Ritchie et al., 2021), tipping may be sped up by forcing beyond the critical threshold. For the Greenland Ice Sheet, it was shown that the timescales of ice–sheet decline strongly depend on how far its critical temperature threshold is exceeded (Robinson et al., 2012).

Previous assessments of the long–term contribution to sea–level rise from the Antarctic Ice Sheet have been primarily restricted to a single ice–sheet model and have thus rarely explored *model uncertainties*, including uncertainties in ice–sheet processes, their parameterisations in ice–sheet models and distinct initialisation approaches, as well as uncertainties in the future climate (*climate forcing uncertainty*) (Golledge et al., 2015; Clark et al., 2016): They suggest that the grounding lines in the Amundsen Sea Embayment might at present already be undergoing a self–amplified retreat until a new stable geometric configuration is reached or that this retreat might be imminent under sustained present–day climate conditions (Reese et al., 2023; Joughin et al., 2014; Favier et al., 2014; Seroussi et al., 2017; Arthern and Williams, 2017; Golledge et al., 2019, 2021). The potential for pronounced grounding–line recession in marine–based portions of West Antarctica and the Wilkes subglacial basin in East Antarctica until the end of the millennium was illustrated for higher–emission scenarios (Golledge et al., 2015; Clark et al., 2016; Winkelmann et al., 2015; Bulthuis et al., 2019; Chambers et al., 2022; Coulon et al., 2024), giving rise to an Antarctic mass loss of multiple meters of sea–level equivalent. On multi–millennial timescales, the loss of the portion of the ice sheet grounded above sea level in East Antarctica may be locked in for strong atmospheric warming, which would eventually commit the Antarctic Ice Sheet to contribute several tens of meter to global mean sea–level rise (Clark et al., 2016; Winkelmann et al., 2015).

Here we systematically study the long–term multi–millennial evolution of the Antarctic Ice Sheet in response to a wide range of possible future climate trajectories and thereby quantify its sea–level commitment for stabilized climate at different points in time over the course of the next centuries taking into account uncertainties in climatic boundary conditions and ice–sheet processes, by means of two different ice–sheet models: PISM (Bueler and Brown, 2009; Winkelmann et al., 2011) and Kori-ULB (previously called f.ETISh; Pattyn, 2017). The remainder of this paper is structured as follows: In the following Sect. 2 we describe the methods for performing sea–level projections on multi–millennial timescales. Results are presented in Sect. 3 and discussed in Sect. 4 with a focus on different sources of uncertainties, arising from the divergence of future climate trajectories (*climate forcing uncertainty*) as well as from ice–sheet processes, their parameterisations in ice–sheet models and related parameter choices next to distinct initialisation approaches (*model uncertainties*).

2 Methods

2.1 Ice–sheet models

2.1.1 PISM

The Parallel Ice Sheet Model (PISM; Bueler and Brown, 2009; Winkelmann et al., 2011) is an open–source, thermo–mechanically–coupled ice sheet/stream/shelf model. In hybrid mode, the shallow–ice approximation (SIA) and shallow–shelf approximation (SSA) are solved and superimposed, giving rise to different dynamic regimes from the slow–flowing ice in the ice–sheet interior to the faster–flowing streams and ice shelves. We here use a modified version of PISM release v1.0 (Garbe et al., 2020). In particular, centered differences of the ice thickness across the grounding line are calculated to derive the surface gradient, which have been shown to improve the representation of the driving stress at the grounding line (Reese et al., 2023). We use a rectangular grid of 16 km horizontal resolution and a vertical grid structure with the highest resolution at the base of the ice sheet and shelves.

Basal shear stress τ_b and shallow–shelf approximation basal sliding velocities u_b are related in a general power law of the form

$$\tau_b = -\tau_c \frac{u_b}{u_{\mathrm{th}}^q |u_b|^{1-q}} \tag{1}$$

with the threshold velocity $u_{\mathrm{th}} = 100$ m yr^{-1} and the sliding exponent q. The yield stress τ_c is determined by the Mohr–Coulomb failure criterion (Cuffey and Paterson, 2010) as

$$\tau_c = \tan(\phi N_{\mathrm{till}}) \tag{2}$$

including the till friction angle ϕ and the effective pressure N_{till}. The till friction angle is parameterized as piecewise linear with bed elevation (Martin et al., 2011), in our simulations with a lower value of 24° for topography below -700 m and an upper value of 30° for topography above 500 m (following Reese et al., 2023). The effective pressure N_{till} in PISM is a function of the overburden pressure P_0 and the fraction of the effective water thickness in the till layer $s = W_{\mathrm{till}}/W_{\mathrm{max}}$:

$$N_{\mathrm{till}} = \min\{P_0, N_0 \left(\frac{\delta P_0}{N_0}\right)^s 10^{(e_0/C_c)(1-s)}\} \tag{3}$$

where the values for the constants N_0, e_0 and C_c are chosen following Bueler and van Pelt (2015). The amount of water from basal melt in the till layer W_{till} with a maximum of $W_{\mathrm{max}} = 2$ m evolves according to the non–conserving 'null' hydrology model (as described in Bueler and van Pelt, 2015) with a decay rate C of water in the till. The grounding–line position is simulated at a subgrid scale evolving freely without imposing additional flux conditions. Basal resistance is linearly interpolated on a sub–grid scale around the grounding line (Feldmann et al., 2014), while sub–shelf melt in partially floating cells is not applied in the experiments presented here. We apply eigencalving, which linearly relates the calving rate to the spreading rate tensor with a proportionality factor of $K = 1\mathrm{x}10^{17}$ m s (Levermann et al., 2012). Additionally, thin ice below 50 m is removed at the calving front (thickness calving) and a maximum extent for ice shelves is defined (Garbe et al., 2020; Albrecht et al., 2020). Our simulations include the effect of the viscous and elastic response of the bedrock to changes in ice load, following Lingle and Clark (1985) and Bueler et al. (2007), with an upper mantle viscosity $\eta = 1\mathrm{x}10^{21}$ Pa s and density $\rho = 3300$ kg m^{-3} as well as a flexural rigidity of the lithosphere of $5\mathrm{x}10^{24}$ N m.

2.1.2 Kori-ULB

The Kori-ULB ice flow model, which is the follow–up of the f.ETISh model (Pattyn, 2017), is a vertically–integrated, thermo–mechanically–coupled hybrid ice–sheet/ice–shelf model, and incorporates relevant features for studying the evolution of the Antarctic Ice Sheet such as the mass balance–elevation feedback, basal sliding, sub–shelf melting, calving, and bedrock deformation. The ice flow is governed by a combination of the shallow–ice (SIA) and shallow–shelf (SSA) approximations for grounded ice and by the shallow–shelf approximation for floating ice shelves (Bueler and Brown, 2009; Winkelmann et al., 2011). Simulations of the multi–millennial Antarctic sea–level contribution presented here were performed with Kori-ULB version 0.91 at a horizontal resolution of 16 km.

Basal sliding is parameterized using a Weertman sliding law, i.e.,

$$\tau_b = A_b^{-1/m} |\mathbf{v}_b|^{1/m-1} \mathbf{v}_b \quad (4)$$

where τ_b and $\mathbf{v}_b$ are the basal shear stress and the basal velocity, respectively, and with a basal sliding exponent $m = 3$. The values of the basal sliding coefficient A_b are inferred following the nudging method of Pollard and DeConto (2012b) and Bernales et al. (2017) (compare Sect. 2.2.2).

At the grounding line, a flux condition (related to the ice thickness at the grounding line; Schoof, 2007) is imposed as in Pollard and DeConto (2012a) and Pollard and DeConto (2020) to account for grounding–line migration. This implementation can reproduce the steady–state behaviour of the grounding line and its migration (Schoof, 2007) also at coarse resolution (Pattyn et al., 2013). Using this flux condition, the marine ice–sheet behaviour in Antarctica was simulated by large–scale ice–sheet models (Pollard and DeConto, 2012a; DeConto and Pollard, 2016; Pattyn, 2017; Sun et al., 2020), with similar results under buttressed conditions as in high–resolution models (Pollard and DeConto, 2020). Calving at the ice front depends on the parameterized combined penetration depths of surface and basal crevasses relative to the total ice thickness. Similar to Pollard et al. (2015) and DeConto and Pollard (2016), the parameterisation of the crevasse penetration depths involves the divergence of the ice velocity, the accumulated strain, and the ice thickness. Bedrock adjustment in response to changes in ice and ocean load is taken into account by means of the commonly used Elastic Lithosphere–Relaxed Asthenosphere (ELRA) model, where the solid–Earth system is represented by a relaxing viscous asthenosphere below a thin elastic lithosphere plate (Le Meur and Huybrechts, 1996; Coulon et al., 2021). A spatially uniform relaxation time of 3000 years and a flexural rigidity of the lithosphere of 10^{25} N m is chosen in the simulations presented here.

2.2 Experimental design

2.2.1 Assessing Antarctic sea–level commitment

We aim to determine the long–term multi–millennial sea–level contribution from the Antarctic Ice Sheet and thereby its sea–level commitment using the ice–sheet models PISM and Kori-ULB (compare Sect. 2.1). After initializing the models to obtain initial Antarctic Ice Sheet states and running historical simulations (described in more detail in the following Sect. 2.2.2 and 2.2.3, and illustrated in Figure 1), we assess the response of the Antarctic Ice Sheet to changes in the oceanic and atmospheric boundary conditions derived from state–of–the–art climate model projections available from the sixth phase of the Coupled Model Intercomparison Project (CMIP6) under the Shared Socioeconomic Pathways SSP1-2.6 and SSP5-8.5 (thereby covering a wide range from lower– to higher–emission scenarios). As we are interested in the long–term response, we focus on a set of CMIP6 General Circulation Models (GCMs) that provide forcing until the year 2300. Thereby, we obtain the transient *realized* sea–level contribution of the Antarctic Ice Sheet at given points in time (for instance, in the year 2100, filled dots in Figure 1). We then quantify the long–term *committed* sea–level contribution by stabilizing forcing conditions of the climate trajectories at regular intervals in time (‘branching off’ in the years 2050, 2100, 2150, 2200, 2250 and 2300, compare Table S1) and letting the ice sheet evolve over several millennia (until year 7000) under fixed climatic boundary conditions characteristic for the respective branchoff year (Fig. 1, open dots). Climate conditions of the distinct branchoff years are determined as the mean over the previous ten years before the branchoff.

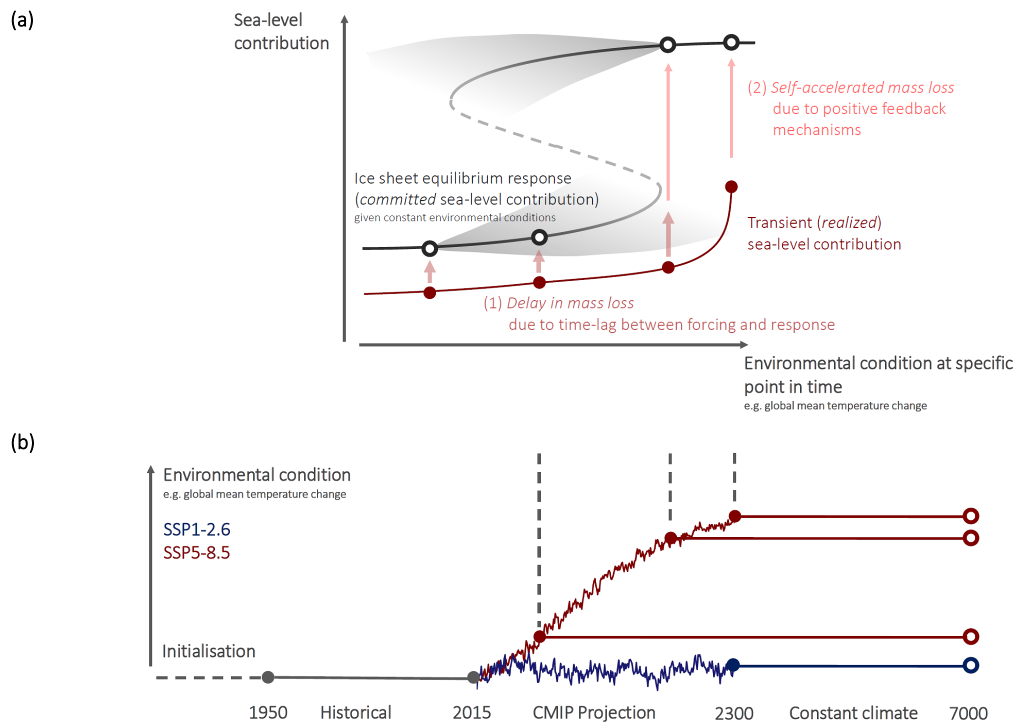

Figure 1. Schematic of the experimental design (a): Idealized and simplified stability diagram of the Antarctic Ice Sheet as possible tipping element, which illustrates some underlying factors potentially contributing to the substantial difference or offset between the transient realized and long–term committed ice–sheet response (in terms of sea–level contribution). For example, the crossing of critical thresholds with ongoing warming may result in accelerated mass loss. This is associated with the stepwise change (jump) towards a higher sea–level contribution indicated as (2). (b): Schematic summary of the experimental design used for assessing the long–term committed contribution from the Antarctic Ice Sheet to sea–level rise with the ice–sheet models PISM and Kori-ULB. Starting with the initialisation of the ice–sheet models to build ice–sheet representations in 1950, historical simulations are run until 2015 (present–day). Using potential future climate trajectories based on CMIP6 under emission pathways SSP1-2.6 (blue) and SSP5-8.5 (red), the transient realized Antarctic sea–level change is projected until the year 2300. Additional simulations branching off at regular intervals in time determine the sea–level commitment under stabilized climatic boundary conditions sustained over several millennia.

2.2.2 Initialisation

Both ice sheet models are initialized using constant climatic boundary conditions representing the year 1950 (Fig. 1). The historical climatic boundary conditions for the year 1950 are constructed using the historical changes in ocean and atmosphere with respect to the reference period from 1995 to 2014 from the Norwegian Earth System Model (NorESM1-M; Bentsen et al.,

2013) in CMIP5. The oceanic and atmospheric anomalies from NorESM1-M are averaged over the period 1945–1955 and subsequently added to present–day atmospheric temperatures and precipitation derived from Regional Climate Models (RCMs) as well as observed present–day ocean temperatures and salinities. Present–day atmospheric climatologies are derived from the RCMs Modèle Atmosphérique Régional (MARv3.11; Kittel et al., 2021) and the Regional Atmospheric Climate MOdel (RACMO2.3p2; Van Wessem et al., 2018) to take into account uncertainties in the representation of present–day Antarctic surface climate (compare Mottram et al., 2021). While a recent intercomparison concluded that Antarctic climate is represented reasonably well compared to observations in state–of–the–art RCMs, disagreement between the RCMs with respect to surface mass balance components (such as precipitation and atmospheric temperatures as applied to the ice–sheet models here) exists for some areas (Mottram et al., 2021). Both present–day atmospheric climatologies are involved in the initialisation of each ice–sheet model, resulting in four (initial) ice–sheet model configurations (Tab. S2). For ocean temperatures and salinities, present–day observations based on Schmidtko et al. (2014) are used.

To build initial ice–sheet states with PISM, a spin–up approach is applied for each of the historical atmospheric climatologies (around 1950, see above) individually. Uncertainties in ice–sheet model parameters are taken into account by running an ensemble of spin–up simulations and choosing the initial state which fits well to observations of present–day ice thickness, ice velocities and grounding–line position. More specifically, starting from Bedmap2 ice thickness and topography (Fretwell et al., 2013), PISM is run for 600 000 years with constant geometry to obtain a thermodynamic equilibrium. Applying the constant historical climatic boundary conditions associated with the year 1950, an ensemble of simulations with varying model parameters (guided by recent PISM ensembles; Reese et al., 2023; Albrecht et al., 2020) is run for several thousand years. Here, we include the SIA enhancement factor ($E_{SIA} \in 1.5, 2$; varied around the reference value of Albrecht et al., 2020) and parameters related to basal sliding, namely the pseudo–plastic sliding exponent ($q \in 0.25, 0.5, 0.75$, within the range investigated by Albrecht et al., 2020; Lowry et al., 2021), the till effective overburden fraction ($\delta \in 1.5, 2.0, 2.5$; Bueler and van Pelt, 2015) and the decay rate of till water content ($C \in 7, 10$ mm yr^{-1}, equivalent to the range explored by Albrecht et al., 2020). After 5000 years of simulation, the ensemble members are assessed with a scoring method following Albrecht et al. (2020) and Reese et al. (2020). The scoring method is based on the mean–square–error mismatch of grounded and floating ice area, ice thickness, grounding–line location and surface velocity compared to present–day observations (Fretwell et al., 2013; Rignot et al., 2011). Each indicator is evaluated for the entire Antarctic domain as well as for the Amundsen, Ronne–Filchner and Ross regions individually. The five best–scoring ensemble members in terms of the continental as well as the basin–scale indicators are continued until reaching 50 000 years of simulation, and experiments are performed with the ice–sheet configuration performing well in the scoring after 50 000 years. Respective ice-sheet model parameters are given in Table S2.

For Kori-ULB, ice–sheet initial states and basal sliding coefficients are obtained in an inverse simulation following Pollard and DeConto (2012b) for each of the historical atmospheric climatologies associated with the year 1950 (as described above). In this inverse procedure, the difference to the observed ice thickness (Bedmachine; Morlighem et al., 2020) is minimized by iteratively adjusting the basal sliding coefficients under grounded ice and sub–shelf melt rates under floating ice (Bernales et al., 2017). The optimized field of basal sliding coefficients in Kori-ULB is characterized by high basal sliding coefficients at the ice–sheet margins, turning into regions of low slipperiness (low basal sliding coefficients) towards the interior of West Antarctica. It thus differs from the basal friction experienced by the Antarctic Ice Sheet in experiments with PISM, where overall slippery bed conditions in the interior of marine subglacial basins are found, given the parameterized, bed–elevation dependent material properties of the subglacial till (in particular, the till friction angle; Sect. 2.1). These inter–model differences in basal friction linked to the applied initialization approaches are expected to influence the ice–sheet response. The resulting sub–shelf melt rates may be interpreted as balanced sub–shelf melt rates and are independent of the oceanic boundary conditions (forcing), while the ice–sheet states are in steady–state with the initial atmospheric climatologies. Applying constant historical ocean and atmospheric boundary conditions associated with the year 1950, a short relaxation is run for 10 years after the model initialisation and before the historical simulation. This limits an initial shock that may result from the transition from the balanced sub–shelf melt rates derived during the transient inverse simulation to the imposed sub–shelf melt parameterisation scheme. The two initial ice–sheet states resulting from the nudging procedure are therefore in quasi–equilibrium.

Given that we include two common ways of initializing ice-sheet models (compare e.g., Seroussi et al., 2019, 2020), we sample uncertainties associated with the choice of the initialization approach. While an inverse simulation allows to reproduce the present–day ice sheet geometry well, the resulting parameter fields (such as basal sliding coefficients in Kori-ULB) may compensate for errors or uncertainties in other ice–sheet processes (Berends et al., 2023b; Aschwanden et al., 2013). In addition, it is assumed that the field obtained in the inverse simulation to match present–day observations does not change in the future. In contrast, in the simulated ice–sheet state resulting from a spin-up the ice–sheet variables may be modelled in a consistent way, but its geometry might differ from the observed ice sheet. It is the result of the covered ice–sheet physics in the ice–sheet model for a set of uncertain parameters, without any nudging.

The simulated grounding–line position and ice thickness of the initial ice–sheet states are compared to present–day observations in Figure S1. As a result of the inverse simulation, the grounding–line position and ice thickness compare well to present–day observations in the initial ice–sheet states for Kori-ULB (Fig. S1a and c). With the spin–up approach applied in PISM, the initial ice–sheet states are characterized by larger ice thickness differences compared to present–day observations (Fig. S1b and d). Overall, ice in West Antarctica and in some coastal regions in East Antarctica (e.g,. in Dronning Maud Land, upstream of Amery Ice Shelf and in Wilkes Land) is thicker than observed at present (comparable to Reese et al., 2023), while the ice thickness in the interior of East Antarctica is underestimated. In addition, the grounding line in the Siple Coast area (and in the catchment draining Ronne–Filchner Ice Shelf for the MAR climatology) is located upstream of the observed grounding line in the present–day (Fig. S1 b and d), as previously seen in a model initialisation in a spin–up approach, e.g., Reese et al. (2023) and Sutter et al. (2023). These differences should be taken into account when interpreting the simulated long–term evolution of the Antarctic Ice Sheet.

2.2.3 Forcing and boundary conditions over the historical period and until 2300

Starting from the initial ice–sheet states and climate conditions of the year 1950 described above, we run historical simulations for the time period from 1950 to 2015 (Fig. 1). Changes in oceanic and atmospheric conditions over the historical period are derived from NorESM1-M, as recommended within ISMIP6 (Barthel et al., 2020; Nowicki et al., 2020). The atmospheric and oceanic forcing conditions until the year 2300, which are applied to the ice–sheet models for studying the future evolution of the

Antarctic Ice Sheet, rely on a subset of state–of–the–art GCM projections available within CMIP6 (MRI-ESM2-0, UKESM1-0-LL, CESM2-WACCM, and IPSL-CM6A-LR). We apply climate forcing under the Shared Socioeconomic Pathways SSP5-8.5 and SSP1-2.6. The selection of CMIP6 GCMs was guided by the limited availability of extended climate projections until 2300 within ScenarioMIP (O'Neill et al., 2016), while the climate sensitivity of the available GCMs (Meehl et al., 2020) and their performance in comparison with observations (e.g., Beadling et al., 2020; Purich and England, 2021; Bracegirdle et al., 2020) were considered as secondary criteria.

Following Nowicki et al. (2020), spatially–varying atmospheric (*near–surface air temperature*) as well as oceanic (*salinity* and *temperature*) anomalies with respect to the 1995–2014 mean climatology are derived from NorESM1-M over the historical period as well as from projections of the selected CMIP6 GCMs until the year 2300. Note that, for *precipitation*, ratios (instead of anomalies) with respect to the 1995–2014 mean precipitation are determined to avoid 'negative' absolute precipitation (e.g., Goosse et al., 2010, Equation 30). The respective anomalies are added to the present–day climatologies for the atmosphere (MAR, RACMO) and the ocean (Schmidtko et al., 2014). Thus, the resulting forcing matches present–day conditions in the 1995–2014 reference period (as in Reese et al., 2023). For the oceanic properties, yearly averaged forcing is applied to the ice–sheet models. Missing values for the oceanic forcing on the continental shelf (arising due to the coarse resolution of CMIP6 GCMs) and in currently ice–covered regions are filled following Kreuzer et al. (2021), i.e., by averaging over all existing values in neighbouring cells. In addition, the ocean properties derived from CMIP6 GCMs are linearly interpolated to the basin–averaged continental shelf depth (Kreuzer et al., 2021) to determine sub–shelf melt (see below). Monthly forcing is used at the interface of the ice sheet to the atmosphere (as in Golledge et al., 2019).

Surface melt and runoff are determined from monthly atmospheric temperature and precipitation (i.e., accounting for the seasonal cycle) using a positive–degree–day (PDD) scheme (Reeh, 1991). The amount of PDD follows the approach presented in Calov and Greve (2005), with a default value for the standard deviation of $\sigma = 5$ °C and $\sigma = 4$ °C for PISM and Kori-ULB, respectively. Snow accumulation rates are derived from precipitation via an atmospheric temperature threshold with a linear transition between snow and rain. In Kori-ULB, natural variability is considered when determining snow accumulation rates (similar to the calculation of the amount of positive–degree–days) using a standard deviation of $\sigma = 3.5$ °C. Melt coefficients of 3 mm w.e. per PDD for snow and 8 mm w.e. per PDD for ice are used in both ice–sheet models after a comparison to MAR estimates until the year 2100 (Kittel et al., 2021; Coulon et al., 2024). A constant fraction of surface melt refreezes in PISM (Reeh, 1991), while Kori-ULB applies a simple thermodynamic parameterisation of the refreezing process (Huybrechts and De Wolde, 1999; Coulon et al., 2024). Computing surface melt and runoff in a PDD approach follows Garbe et al. (2020) and DeConto et al. (2021), likewise studying the future Antarctic Ice Sheet response to changing environmental conditions and the ice–sheet stability on multi–millennial timescales. Applying the surface mass balance determined by RCMs, which are in turn forced by climate projections of GCMs, would be an alternative approach for projecting Antarctic sea–level change. However, surface mass balance estimates from RCMs are not yet available beyond the end of this century and may be biased by the use of a static ice–sheet geometry neglecting, for example, the surface melt–elevation feedback (Kittel et al., 2021).

To account for the **surface melt–elevation feedback**, the near–surface air temperature is corrected for changes in the ice–sheet surface elevation. More specifically, air temperatures T_{forcing} provided to the ice–sheet models are shifted linearly with a change in surface elevation Δh as

$$T = T_{\text{forcing}} + \Gamma \Delta h \tag{5}$$

following the atmospheric lapse rate Γ of 8°C / km.

Sub–shelf melt rates are computed by using the Potsdam Ice–shelf Cavity mOdel (PICO; Reese et al., 2018). PICO calculates sub–shelf melt rates from far–field salinities and temperatures and parameterizes the overturning circulation in ice–shelf cavities. The values of the PICO overturning strength parameter C and the turbulent heat exchange coefficient γ_T^* are an individual choice for each ice–sheet model to match sub–shelf melt sensitivities and / or observed melt rates. $C = 3\text{x}10^6$ m^6 s^{-1} kg^{-1} and $\gamma_T^* = 7\text{x}10^{-5}$ m s^{-1} (with correction of ocean properties of Schmidtko et al. (2014) to match observed present–day melt rates from Adusumilli et al. (2020)) are used for PISM experiments, as they have been found to fit melt sensitivities well (Reese et al., 2023). For Kori-ULB experiments, the overturning strength and the turbulent heat exchange coefficient are chosen as $C = 1\text{x}10^6$ m^6 s^{-1} kg^{-1} and $\gamma_T^* = 4\text{x}10^{-5}$ m s^{-1}, respectively.

3 Results

We here present the transient response of the Antarctic Ice Sheet over the historical period (Sect. 3.1) and to a range of possible future climate trajectories until the year 2300 (Sect. 3.2) along with the associated committed ice–sheet evolution on multi–millennial timescales (Sect. 3.3). The dependency of the committed Antarctic sea–level contribution on the environmental conditions in Antarctica sustained over several thousands of years after their stabilization at different points in time during the next centuries is assessed in Sect. 3.4.

3.1 Historical ice–sheet evolution

The pattern of observed present–day rates of ice–thickness change (e.g., Smith et al., 2020) is overall captured by both ice–sheet models in response to the historical NorESM1-M climate trajectory (Fig. 2a – c), with a thinning in the Amundsen and Bellingshausen Sea region and the Antarctic Peninsula and a thickening in the ice–sheet interior. The magnitude of ice–sheet thinning in the Amundsen Sea Embayment is, however, underestimated compared to present–day observations in the historical simulations with PISM presented here (Fig. 2a and c). In addition, we find ice loss for Ross, Ronne–Filchner and Amery ice shelves in PISM in contrast to observations (Fig. 2a and c).

The evolution of the continent–wide integrated surface mass balance is relatively similar for both ice–sheet models, but occurs on a higher, though still within RCM uncertainties, level in PISM than in Kori-ULB (Fig. 2d). While sub–shelf melt increases in PISM from about 300 Gt yr^{-1} in 1950 towards 1100 Gt yr^{-1} in 2015 at the lower end of present–day observations (Fig. 2e, solid lines), the basal mass balance is on the order of the observational record in Kori-ULB over the entire historical period, slightly exceeding its upper end in 2015 with about 1800 Gt yr^{-1} (Fig. 2e, dashed lines). The continent–wide aggregated sub–shelf melt rates observed in present–day are thus reproduced with both sets of PICO parameters (see Sect. 2.2.3), but they

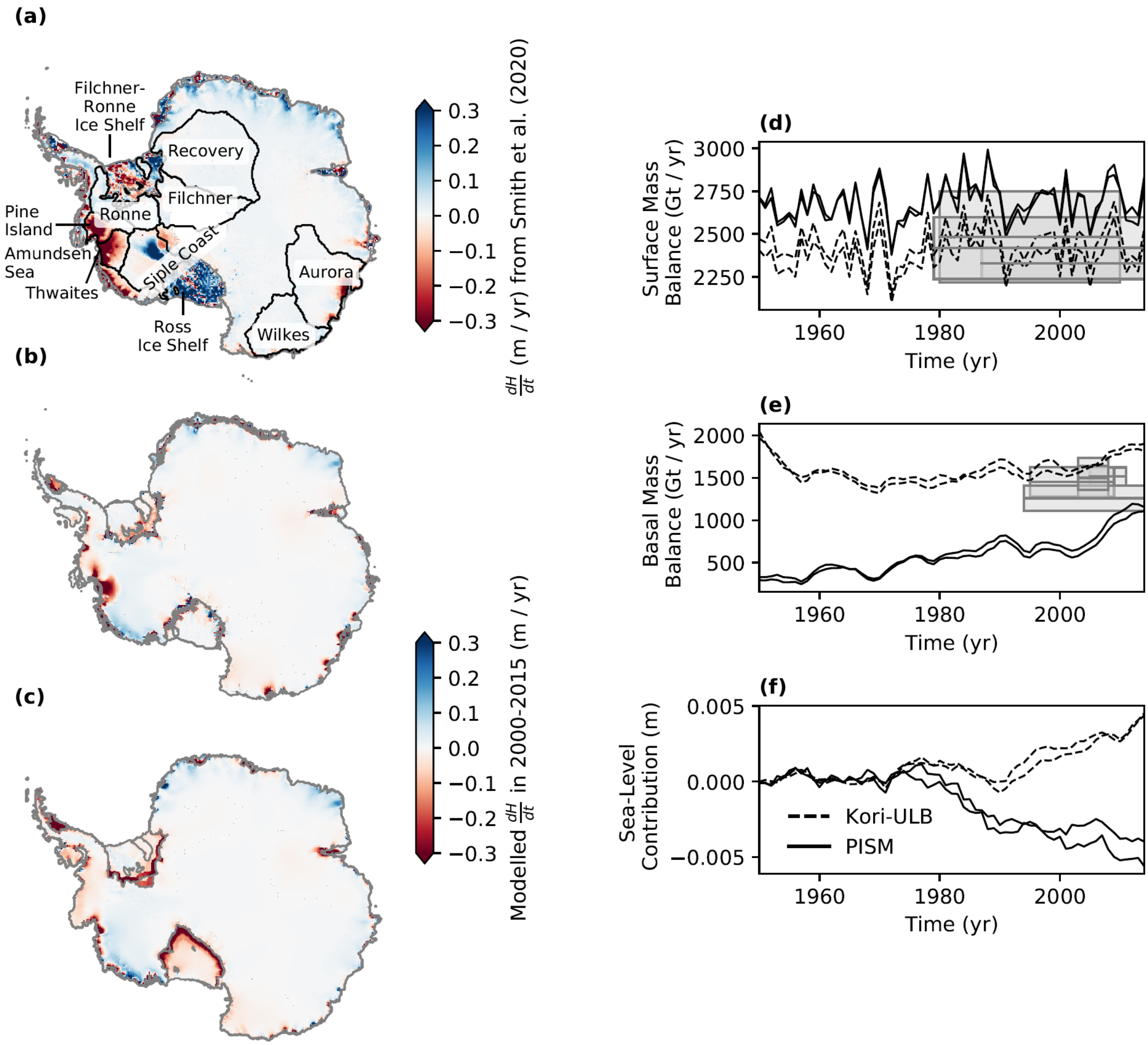

Figure 2. Trajectories of the Antarctic Ice Sheet over the historical period from 1950 to 2015. (a) – (c): Rate of ice–thickness change as observed based on Smith et al. (2020) (a) and as determined by the ice–sheet models Kori-ULB (b) and PISM (c) in response to historical changes in Antarctic climate derived from NorESM1-M. The modelled ice–thickness change is averaged across the ice–sheet model configurations associated with atmospheric climatologies based on MAR and RACMO (Tab. S2). (d) – (e): Evolution of the Antarctic Ice Sheet as determined by the ice–sheet models Kori-ULB (dashed lines) and PISM (solid lines) using atmospheric climatologies based on MAR and RACMO in terms of the surface mass balance (d), sub–shelf melt (e), and sea–level contribution (f), based on volume above floatation. Observations of the ice–sheet mass balance components (as in Coulon et al., 2024) are given by grey boxes (indicating the time period and uncertainties of the respective observations), where the solid line shows the mean.

result in different sensitivities of sub–shelf melt rates to ocean temperature changes over the historical period (Fig. 2e; Reese et al., 2023).

Mass loss in the Amundsen Sea sector dominates the overall observed ice sheet mass changes in Antarctica to date (Otosaka et al., 2023). Given the lower magnitude of ice–sheet thinning of Pine Island and Thwaites glaciers in PISM, and stronger sub–shelf melt in Kori-ULB, we find diverging ice–sheet trajectories with both ice–sheet models in terms of the Antarctic sea–level contribution over the **historical period** from 1950 to 2015: Kori-ULB shows an integrated mass loss with a sea–level contribution of about +4 mm in 2015 (Fig. 2f, dashed lines), while the ice sheet overall gains mass equivalent to a sea–level change ranging between -4 mm and -6 mm in PISM (Fig. 2f, solid lines; within spread of recent ensemble of historical ice–sheet trajectories, Reese et al., 2023).

In the future evolution of the Antarctic Ice Sheet determined by PISM (Sect. 3.2 – 3.4), changes in the regions of Ross and Ronne–Filchner ice shelves could thus be overestimated, while the lower thinning rates over the historical period in the Amundsen Sea Embayment could suggest a reduced sensitivity of Thwaites and Pine Island glaciers to changes in climate conditions in these experiments.

3.2 Future transient ice–sheet response until 2300

By the end of this century, the Antarctic sea–level contribution varies between -5.0 cm to +8.0 cm and -6.0 cm and +6.0 cm compared to present–day in response to SSP1-2.6 and SSP5-8.5 climate trajectories, respectively (Fig. 3a and c, Tab. 1). Projected ice–sheet changes by 2100 are comparable across emission pathways (Fig. 3; in line with Coulon et al., 2024; Lowry et al., 2021; Edwards et al., 2021), given a very similar evolution of Antarctic climate at least during the first half of the 21st century (Fig. 4). The global mean sea–level contribution due to mass balance changes of the Antarctic Ice Sheet projected by Kori-ULB and PISM by the end of this century is also within the range of recent estimates by ISMIP6, ranging from -9 cm to +30 cm under higher–emission pathways and from -1.4 cm to +15.5 cm under lower–emission pathways (Seroussi et al., 2020; Payne et al., 2021). The simulated trends of ice–sheet changes over the historical period are continued in these projections over this century with both ice–sheet models. That is, Kori-ULB projects a positive sea–level contribution (Fig. 3a and c, dashed lines). PISM projects a sea–level drop by 2100 compared to present–day (Fig. 3a and c, solid lines).

Following the **lower–emission pathway SSP1-2.6** to 2300 results in a sea–level change ranging from -0.2 m to +0.5 m compared to present–day (Fig. 3a, Tab. 1). Therein, Kori-ULB projects a steadily increasing Antarctic contribution to sea–level rise (Fig. 3a, dashed lines). While some PISM ice–sheet trajectories show the onset of mass loss after an initial mass gain (e.g. for CESM2-WACCM climate, indicated in blue), the Antarctic sea–level contribution projected by PISM in 2300 compared to present–day remains negative (Fig. 3a, solid lines).

The overall sign of ice–sheet mass changes contributing to a change in sea level depends on the balance between the dynamic response to sub–shelf melting and ice–shelf thinning and the surface mass balance, driven by changes in Antarctic climate (Fig. 4): We find that, with a projected Antarctic–averaged atmospheric warming of up to 3.6°C in 2300 (Fig. 4a, Tab. S1), the integrated surface mass balance remains positive and on its present–day level until 2300 for both ice–sheet models under this lower–emission pathway, with strong GCM–dependent variability (Fig. 4b). The evolution of sub–shelf melt to 2300 is

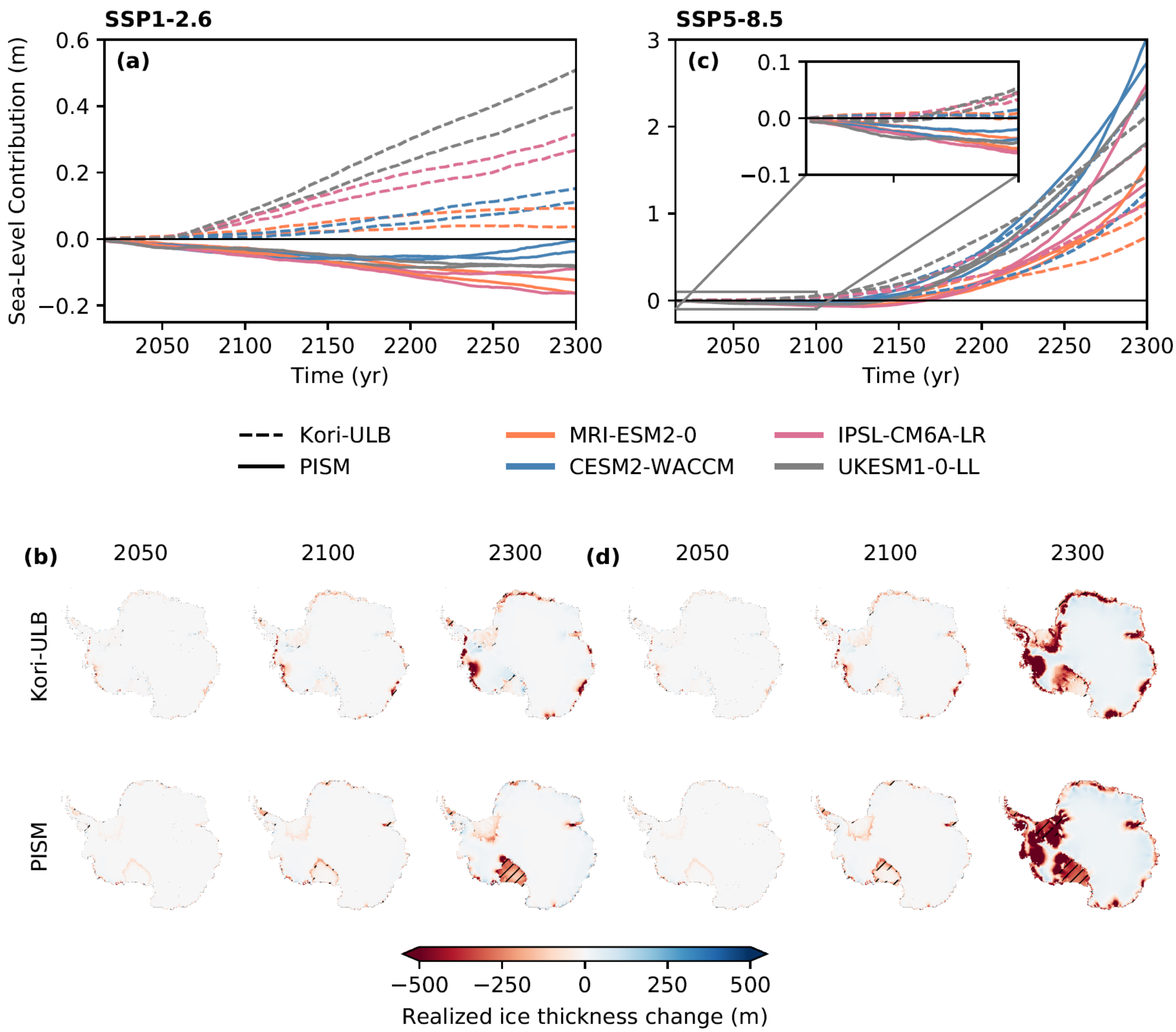

Figure 3. Projected Antarctic ice loss on multi–centennial timescales in response to changing climate conditions under emission pathways SSP1-2.6 (left column) and SSP5-8.5 (right column). (a) and (c): Transient sea–level contribution (in meters sea–level equivalent) from Antarctica until 2300 in response to changing climate conditions as projected by four CMIP6 GCMs (given by the colour), as determined by the ice–sheet models Kori-ULB (dashed lines) and PISM (solid lines). (b) and (d): Mean ice–thickness change in the years 2050, 2100 and 2300, as determined by the ice–sheet models Kori-ULB (uppper row) and PISM (lower row). The thickness change is averaged across the applied GCMs and the respective ice–sheet model configurations (Tab. S2). A potential loss of ice shelves is indicated by hatches.

overall consistent across Kori-ULB and PISM and follows the characteristics of the projected changes in circumantarctic ocean temperatures by each GCM (Fig. 4d and e): Abrupt circumantarctic ocean warming to 2050 in UKESM-1-0-LL and IPSL-CM6A-LR (of about 0.5°C and 0.3°C, respectively) results in a strong initial increase in sub–shelf melt (Fig. 4d and e, grey and pink). In contrast, a steady rise in CESM2-WACCM circumantarctic ocean temperatures to 0.7°C in 2300 is accompanied by a continuous increase in sub–shelf melt (Fig. 4d and e, blue). Overall, the magnitude of sub–shelf melt is higher for projections by Kori-ULB (dashed lines) compared to PISM (solid lines), following the respective levels reached at the end of the historical period (Fig. 4e, Fig. 2e). The response in dynamic discharge contributing to a sea–level increase is thus stronger in Kori-ULB than in PISM in the Amundsen Sea Embayment and the East Antarctic Totten Glacier (Fig. 3b), explaining the diverging sea–level contribution under SSP1-2.6 until 2300.

With significant changes in Antarctic climate from 2100 onwards under the **higher–emission pathway SSP5-8.5** (Fig. 4a and d), Antarctica's sea–level contribution increases to +0.7 – +3.1 m by 2300 (Fig. 3c, Tab. 1). The forced contribution of the Antarctic Ice Sheet to sea–level change until 2300 is in line with the results of e.g. Golledge et al. (2015) (showing an ice loss of +1.6 m – +2.96 m under RCP8.5) and is consistent with the Antarctic contribution to sea–level rise reported in the latest IPCC assessment of -0.3 m – +3.2 m sea–level equivalent (Fox-Kemper et al., 2021). It is caused by pronounced mass loss of the West Antarctica Thwaites and Pine Island glaciers as well as upstream of Ronne–Filchner and Ross ice shelves projected with both ice–sheet models (Fig. 3d). The grounded ice–sheet response is accompanied by thinning of the major Antarctic ice shelves including the Ross and Ronne–Filchner ice shelves, that are (in PISM only) eventually lost sequentially by 2150 and 2300, respectively (Fig. 3d).

At the same time, the integrated surface mass balance starts to decrease and may turn negative during the next centuries with strong atmospheric warming (Fig. 4c). This pattern is evident in projections by both Kori-ULB and PISM. The decline in the ice sheet's surface mass balance is most pronounced for CESM2-WACCM (Fig. 4a and c, blue), projecting an Antarctic temperature increase of more than 15°C beyond 2200 and, thereby, covering atmospheric warming ranges that are not found in any of the other GCMs (Fig. 4a, blue, Tab. S1). Following the progressing ocean warming under SSP5-8.5 (reaching an ocean temperature change of up to 3°C for UKESM1-0-LL in 2300; Fig. 4d), sub–shelf melt continues to increase beyond 2100 (Fig. 4f). It eventually levels off after 2150 with the loss of West Antarctic ice shelves (Fig. 4f, also compare Coulon et al., 2024). An additional increase of sub–shelf melt beyond 2150 occurs in some PISM experiments (Fig. 4f, solid lines) with a substantial contribution from smaller ice shelves in the Ross and Amundsen Sea Embayment formed during the grounding–line retreat in combination with the chosen PICO parameters (characterized by a relatively higher melt sensitivity; Reese et al., 2023), overtaking magnitudes of aggregated sub–shelf melt determined in Kori-ULB (Fig. 4f, dashed lines).

In summary, while the ice–sheet trajectories under SSP1-2.6 are still influenced by the simulated historical trends and differences in ice–sheet modelling choices (Seroussi et al., 2023), we find that climate drivers dominate the projected multi–centennial ice–sheet changes under the higher–emission pathway SSP5-8.5. In particular, in line with Coulon et al. (2024), our projections indicate that the atmosphere becomes an amplifying driver of Antarctic mass loss beyond the end of this century, irrespective of the ice–sheet model.

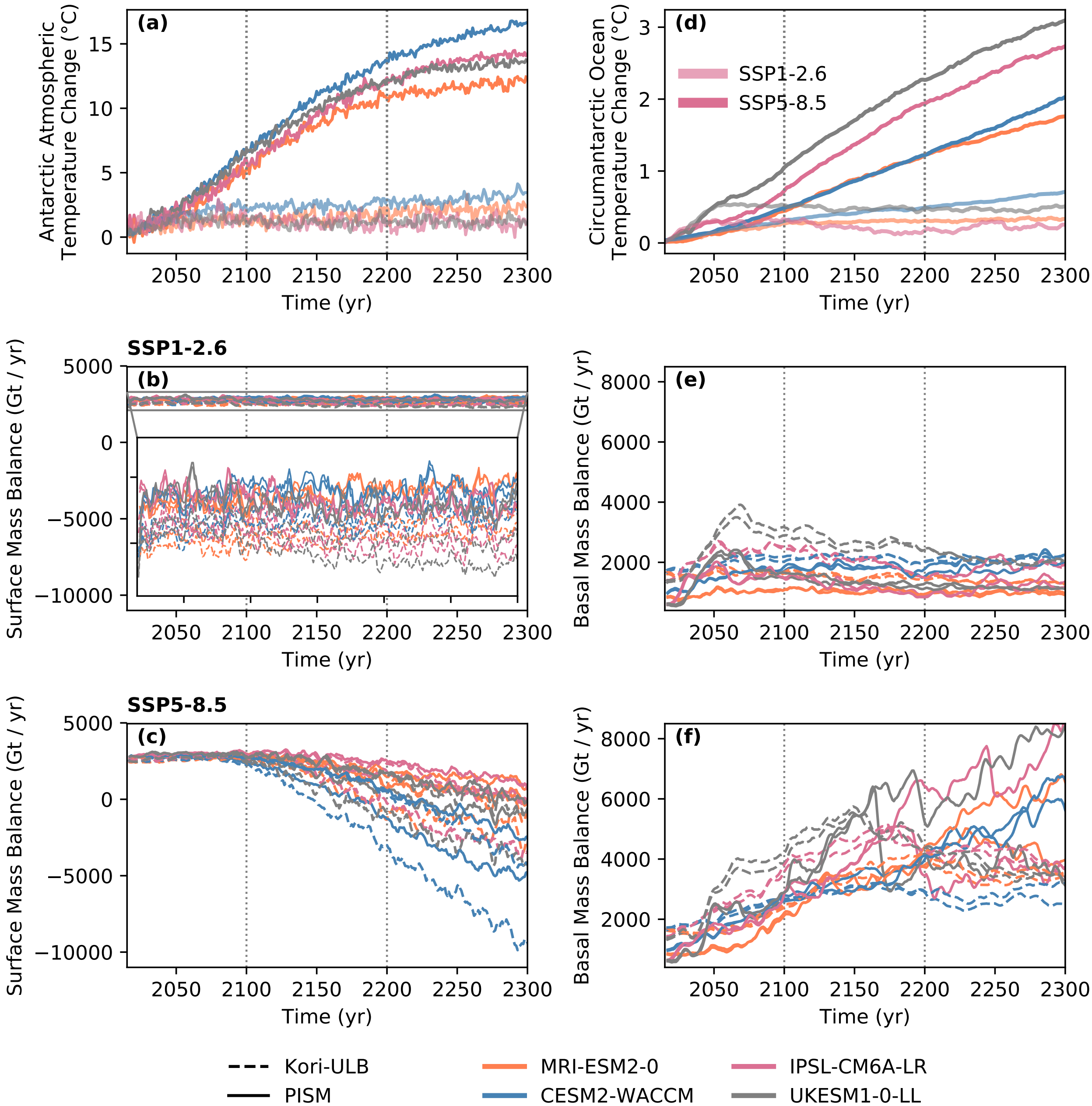

Figure 4. Future Antarctic climate and projected ice–sheet mass balance components on multi–centennial timescales, for four CMIP6 GCMs (given by the colour) under emission pathways SSP1-2.6 (transparent colors / upper row) and SSP5-8.5 (opaque colors / lower row) in terms of (a): Antarctic–averaged atmospheric temperature change, (b) and (c): Surface mass balance, (d): Circumantarctic oean temperature change, and (e) and (f): Sub–shelf melt, as determined by the ice–sheet models Kori-ULB (dashed lines) and PISM (solid lines).

3.3 Long–term committed ice–sheet evolution over the next millennia

Oceanic and atmospheric warming projected for the upcoming centuries may trigger changes in the dynamics and geometry of the Antarctic Ice Sheet that are not realized on the same timescales (as the forcing), but unfold thereafter over the course of the following millennia, due to ice–sheet inertia and nonlinear feedbacks. After determining the transient realized sea–level response over the next centuries (Sect. 3.2), we investigate this long–term committed evolution of the Antarctic Ice Sheet by keeping environmental conditions constant at different points in time and letting the ice sheet evolve over several millennia (see Sect. 2.2.1; Fig. 1).

The bulk of our simulations shows that sea level may keep rising for centuries to millennia to come even if warming is kept at a constant level (Fig. 5a – d; consistent with, e.g., Winkelmann et al., 2015; Van Breedam et al., 2020). The delayed response of the Antarctic Ice Sheet on millennial timescales gives rise to a substantial difference between the transient *realized* (described in the previous Sect. 3.2) and the long–term *committed* Antarctic sea–level contribution, being more than the 100 (10)–fold of the sea–level change projected by the year 2100 (2300) (Fig. 3, Fig. 5, Tab. 1).

We find a sharp increase in the Antarctic sea–level contribution over the next millennium, irrespective of the emission pathway (Fig. 5a – d).

3.3.1 Antarctic sea–level commitment highly dependent on climate model for lower–emission pathway

When following the **lower–emission pathway SSP1-2.6**, the ice–sheet response levels off after a peak in the rate of Antarctic ice loss within this millennium or at the latest by the beginning of the following millennium (Fig. 5a and c). Some of the ice–sheet trajectories eventually show a decline in the Antarctic sea–level contribution on multi–millennial timescales (Fig. 5a and c; e.g., for MRI-ESM2-0 climate indicated in orange), with a thickening trend upstream of Ross Ice Shelf (in Kori-ULB only, see below) and in the ice–sheet interior towards the year 7000, outweighting the initial mass loss. Abrupt changes in the Antarctic sea–level contribution may also occur delayed for MRI-ESM2-0 climate (Fig. 5a and c, orange), with a lag of up to multiple millennia to the onset of the perturbation in climatic boundary conditions in PISM experiments. This delay is related to a later onset of substantial grounding–line retreat in the Amundsen Sea Embayment in these simulations with comparably smaller projected oceanic changes in Antarctic climate in MRI-ESM2-0 (compared to other climate trajectories under the lower–emission pathway; Fig. 4a and d).

Irrespective of the timing of abrupt ice loss, the multi–millennial ice–sheet trajectories eventually are characterized by qualitatively different stages of ice–sheet decline with the same magnitude of the Antarctic sea–level contribution determined by the applied GCM forcing for each ice–sheet model (Fig. 5a and c). That is, in our simulations under the SSP1-2.6 pathway, we do not find a strong dependency of the long–term Antarctic sea–level commitment reached in year 7000 on the point in time after which climatic boundary conditions are kept constant (Fig. 5e, Fig. 6a). When sustaining the warming level potentially reached until year 2050, global mean sea–level may increase by +0.4 m to +4.0 m on the long–term (Fig. 5e, Tab. 1). For climatic boundary conditions representative of the end of this century and thereafter, Antarctic mass changes range between -0.2 m and +6.5 m of sea–level equivalent, which unfolds over the next millennia (Fig. 5e, Tab. 1).

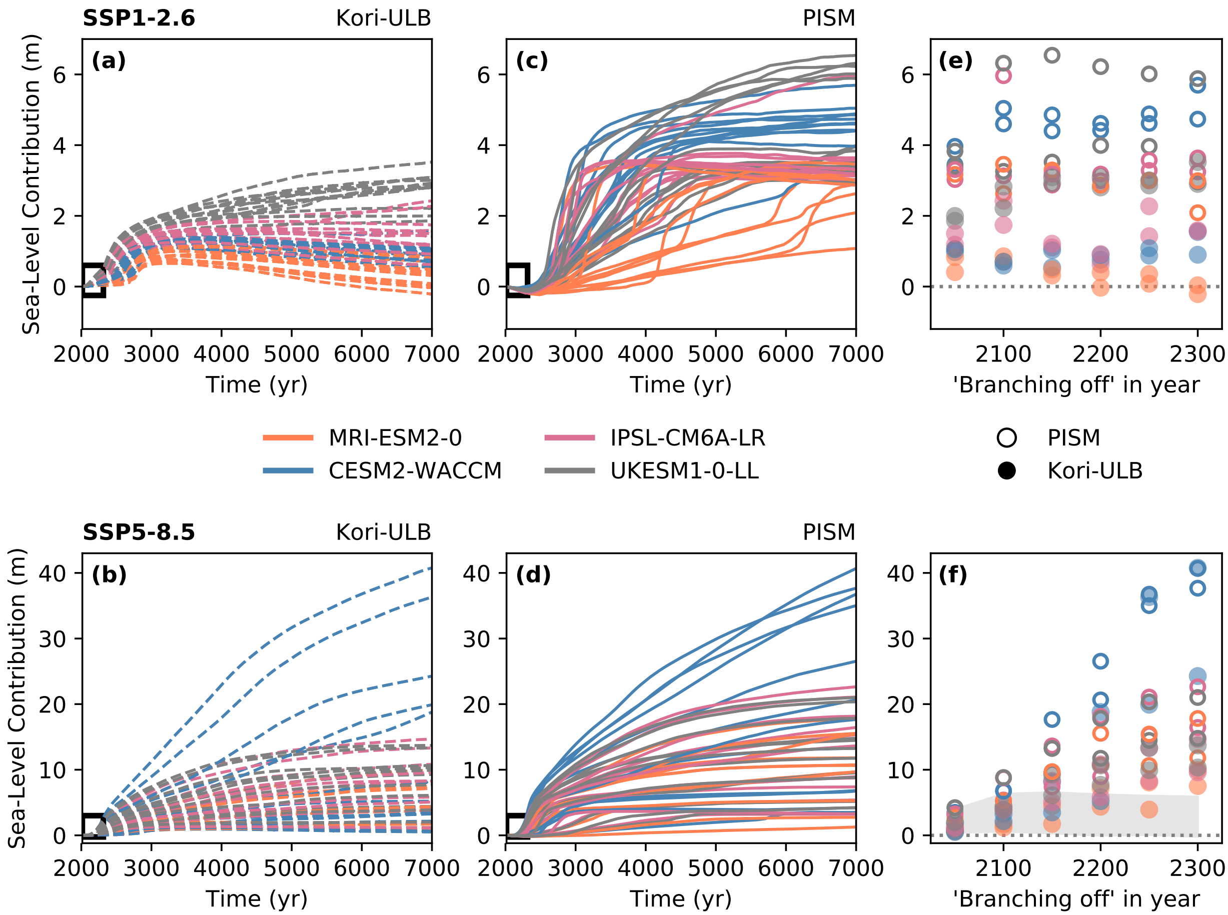

Figure 5. Projected Antarctic ice loss on multi–millennial timescales in response to changing climate conditions as projected by four CMIP6 GCMs (given by colour) under emission pathways SSP1-2.6 (upper row) and SSP5-8.5 (lower row). (a) – (d): Antarctic sea–level contribution (in meters sea–level equivalent) until the year 7000 to warming potentially reached at different points in time throughout the next centuries, as determined by the ice–sheet models Kori-ULB (dashed lines, left column) and PISM (solid lines, right column). (e) and (f): Committed Antarctic sea–level contribution in the year 7000 when stabilizing Antarctic climate at different points in time (that is, 'branching off' in the years 2050, 2100, 2150, 2200, 2250 and 2300; compare Sect. 2.2.1 and Fig. 1). Filled and open markers correspond to the long–term sea–level change determined by the ice–sheet models Kori-ULB and PISM, respectively. For comparison of the committed sea–level change under both emission pathways, the range of Antarctic ice loss by 7000 under SSP1-2.6 (e) is reported by the light grey shade in (f).

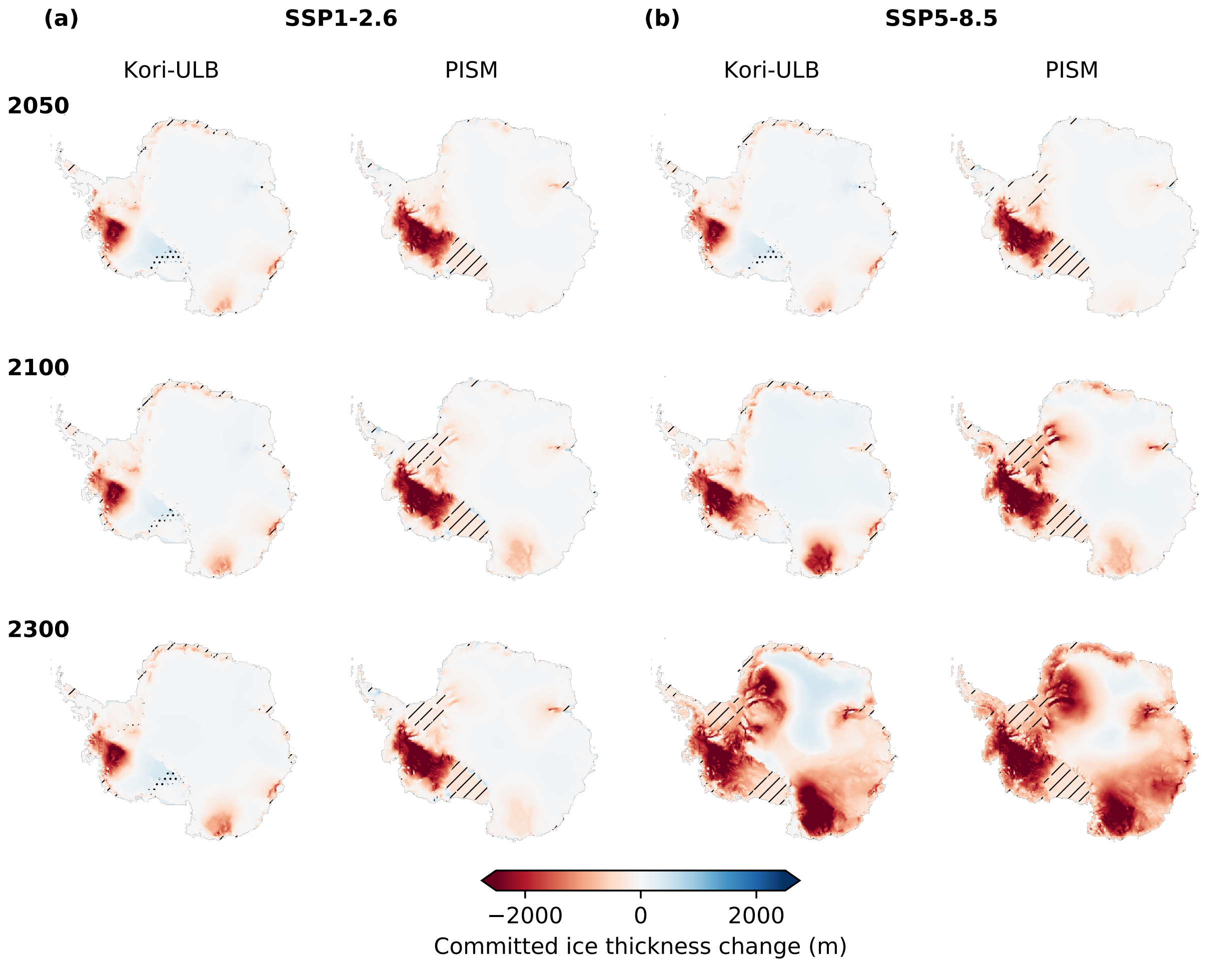

Figure 6. Committed ice–sheet response following emission pathways SSP1-2.6 (a) and SSP5-8.5 (b). Shown is the mean thickness change in the year 7000 when stabilizing climatic boundary conditions in the years 2050, 2100 and 2300 (from top to bottom), as determined by the ice–sheet models Kori-ULB (left column) and PISM (right column). For each ice–sheet model, the thickness change is averaged across the applied CMIP6 GCMs and the respective ice–sheet model configurations (Tab. S2). A potential loss of ice shelves is indicated by hatches. Dots mark areas of ice–sheet advance.

This strong modulation of the magnitude of the committed Antarctic sea–level contribution by the applied GCM forcing for each ice–sheet model (Fig. 5e, Fig. S2) is linked to substantial differences in the trajectories of atmospheric to oceanic warming between the applied GCMs under this lower–emission pathway (Fig. 4a and d). Their impact on the ice–sheet response plays out and becomes evident on longer timescales (on the order of millennia).

Across both ice–sheet models and all GCM forcings, we find a long–term recession of the grounding lines in the Amundsen Sea Embayment under this lower–emission pathway, with a connection from Pine Island Glacier to Ronne Ice Shelf (Fig. 6a).

Pronounced grounding–line retreat in the East Antarctic Wilkes subglacial basin in both Kori-ULB and PISM, potentially locked–in by 2050, adds up to +1.5 m to the long–term sea–level change (Fig. 5e, grey and pink, Fig. 6a). Long–term ice loss from this region is promoted by the abrupt and stronger ocean warming projected by IPSL-CM6A-LR and (especially) UKESM1-0-LL in the first half of this century compared to the other GCMs (Fig. 4d, Fig. S2). The grounding line in Wilkes subglacial basin experiences only very limited or no retreat under the other GCM trajectories in Kori-ULB and PISM experiments (Fig. S2), respectively, despite stronger atmospheric warming levels when following CESM2-WACCM climate under the lower–emission pathway. This is linked to the less abrupt, more gradual change in ocean temperatures compared to UKESM1-0-LL and IPSL-CM6A-LR in the next two centuries (Fig. 4a and d).

The magnitude of Antarctic sea–level commitment under SSP1-2.6 is further modulated by the long–term consequences of a potential collapse of Ross and Ronne–Filchner ice shelves: In Kori-ULB, both large ice shelves are preserved to year 7000, and we find a grounding–line advance and upstream thickening in the Siple Coast region (Fig. 6a). This long–term ice–sheet response in the Siple Coast may, in parts, result from a drift of the initialisation procedure, given lower sub–shelf melt rates obtained with PICO in this area compared to those that are obtained from the initialization approach to keep the ice sheet steady (Sect. 2.2.2). A thickening signal upstream of Ross Ice Shelf has also been observed over the past decades (with the stagnation of Kamb Ice Stream; Smith et al., 2020). The simulated thickening upstream of Ross Ice Shelf contributes to the decay in the long–term Antarctic sea–level contribution over time after the year 3000 in some Kori-ULB experiments, which is most pronounced for sustained MRI-ESM2-0 climate (Fig. 5a, orange). The preservation of these buttressing ice shelves limits the long–term sea–level change from Antarctica under SSP1-2.6 to less than +3.5 m in the Kori-ULB experiments (with the upper bound reached under UKESM1-0-LL and IPSL-CM6A-LR climate due to a combined grounding–line retreat in Wilkes subglacial basin and the Amundsen Sea sector; Fig. 5a and e, grey and pink filled markers). In PISM, a substantial portion of the marine ice–sheet in West Antarctica is lost with the collapse of Ross Ice Shelf and the subsequent retreat of the Siple Coast grounding line by year 7000 under most considered climate trajectories (Fig. 6a, Fig. S2). The loss of Ross Ice Shelf and the stronger sensitivity of the Siple Coast grounding line under SSP1-2.6 climate in the PISM experiments may be related to the initialized upstream grounding–line location compared to observations at present–day (compare Sect. 2.2.2, Fig. S1; as previously seen in a model initialisation in a spin–up approach, e.g., Reese et al., 2023; Sutter et al., 2023), and the simulated thinning in Ross Ice Shelf over the historical period (compare Sect. 3.1, Fig. 2c; also when determining the historical ice–sheet evolution on higher horizontal resolution using PISM,e.g., Reese et al., 2020, 2023). In addition, the higher basal melt sensitivity (compare Sect. 2.2.3 and Sect. 3.1) also translates the projected ocean warming into pronounced ice–shelf thinning (Fig. 4f, Fig. 6a). Furthermore, once grounding–line retreat is triggered, a collapse of the West Antarctic Ice Sheet may be more likely in PISM than in Kori-ULB, where low slipperiness towards the interior of West Antarctica (given low basal sliding coefficients retrieved in the inverse simulations, Sect. 2.2.2) slows down ice–sheet retreat. The combined ice loss from West Antarctica and the East Antarctic Wilkes subglacial basin in PISM gives rise to the upper end of the long–term Antarctic sea–level commitment of up to +6.5 m found under the lower–emission pathway in our experiments (Fig. 5c and e, grey open markers).

Ronne–Filchner Ice Shelf remains intact in most of our simulations under SSP1-2.6, except for CESM2-WACCM climate with strong atmospheric and oceanic changes in the Weddell Sea region in combination with higher sub–shelf melt sensitivities in PISM (Fig. 6a, Fig. S2). Its loss triggers ice–sheet retreat in the adjacent Recovery subglacial basin as a consequence of reduced buttressing, raising global mean sea level by up to +5 m on the long term (Fig. 5c and e, blue open markers, Fig. 6a, Fig. S2).

Overall, both ice–sheet models agree on a substantial committed retreat in the Amundsen Sea sector, when following the lower–emission pathway over the coming centuries. With the loss of Ross Ice Shelf, a collapse of the West Antarctic Ice Sheet may even unfold on multi–millennial timescales, as shown in the simulations with PISM presented here. Committed mass loss in East Antarctica seems less likely, based on our set of simulations, and strongly depends on the projected Antarctic climate trajectory under SSP1-2.6.

3.3.2 Substantial increase in Antarctic sea–level commitment under higher–emission pathway SSP5-8.5

Under the **SSP5-8.5 emission scenario**, the potential magnitude as well as the range of the long–term Antarctic sea–level response substantially increase with the point in time at which ocean and atmospheric warming is stabilized (Fig. 5f). The growing spread of the Antarctic sea–level commitment for a given (branchoff) point in time is, to a large part, caused by the divergence of the climate trajectories projected by the four GCMs under this higher–emission pathway (Figure 4a and d).

Under the sustained warming levels potentially reached during the next decades (that is, by 2050) under these high–warming climate trajectories, committed ice–sheet changes are comparable to committed changes under the lower–emission pathway SSP1-2.6 (Sect. 3.3.1). This results from a very similar projected evolution of the Antarctic climate over the first half of this century, irrespective of the emission pathway (see above). That is, long–term mass losses are likewise projected to mainly arise from marine regions in West Antarctica (Fig. 6), leading to +0.5 m – +4.2 m of global mean sea–level rise on multi–millennial timescales (Fig. 5f, Tab. 1).

With significant changes in climatic boundary conditions projected for the end of this century and the atmosphere shifting towards an amplifying driver of mass loss in the transient ice–sheet response (Fig. 4a–d, Sect. 3.2), we also find the committed Antarctic sea–level contribution to be substantially larger, with a doubling of the long–term mass loss ranging between +1.2 m and +8.8 m sea–level equivalent compared to ice–sheet changes triggered within the next decades (Fig. 5f, Tab. 1). The mass loss until year 3000 amounts to +1.0 m – +5.2 m sea–level equivalent (Tab. 1), consistent with Chambers et al. (2022). Marine parts of the West Antarctic Ice Sheet (now also including the Ross Ice Shelf catchment in experiments with Kori-ULB) show a significant retreat in our entire ensemble of simulations across both ice–sheet models, potentially accompanied by an inland retreat of the grounding line in the East Antarctic Wilkes subglacial basin on the long term (Fig. 6b).

For warming levels that are reached under SSP5-8.5 for any of the branchoff points in time after 2100, the pattern of the committed ice–sheet response is overall consistent across Kori-ULB and PISM. For these branchoff points in time, the difference in future Antarctic climates projected by the four GCMs is significant (Fig. 4a and d, Tab. S1). Mass loss from Antarctica may continue well beyond the end of this millennium, with high rates of the Antarctic contribution to sea–level rise until the end of our simulations in year 7000 (Fig. 5b and d). Depending on the GCM climate trajectory, the long–term ice loss is limited to West Antarctica and the East Antarctic marine Ronne–Filchner, Recovery, Wilkes and Aurora subglacial basins (Fig. 6b, Fig. S3) or also includes parts of the ice sheet grounded above sea level in East Antarctica, with very pronounced atmospheric warming in CESM2-WACCM (Fig. 4f, blue, Fig. 6b, Fig. S3). For sustained warming levels representative for the year 2300, the long–term contribution of the Antarctic Ice Sheet to global mean sea–level rise may then be as high as +40.8 m (given CESM2-WACCM climate; with ice loss of +7.5 m – +40.8 m, +5.9 m – +31.7 m and +3.3 m – +13.9 m sea–level equivalent by the year 7000, 5000 and 3000, respectively, compare Tab. 1).

Overall, the multi–millennial Antarctic ice loss is strongly enhanced with a stabilization of climatic boundary conditions later in time under SSP5-8.5 across both ice–sheet models, ranging from a long–term collapse of the West Antarctic Ice Sheet in response to warming projected by 2100 to the ice loss from major marine subglacial basins in East Antarctica with progressing atmospheric temperature changes after the end of this century. Antarctic sea–level commitment could even increase up to +40 m with the decline of terrestrial parts of the East Antarctic Ice Sheet for warming reached after 2200, but this is associated with substantial GCM uncertainty.

Comparing the long–term ice loss under both emission pathways, we find that the committed Antarctic sea–level contribution at a given point in time diverges beyond the end of this century (Fig. 5f, comparing projected multi–millennial ice loss under SSP5-8.5 to SSP1-2.6 indicated by light grey box). That is, the emission pathways also become increasingly relevant for the long–term mass loss from Antarctica after 2100, as for the projected transient sea–level change (Sect. 3.2 and Coulon et al., 2024), and thus every decade of additional warming raises the Antarctic sea–level commitment substantially in our experiments. At the same time, even the lower–emission scenario may pose a considerable risk of Antarctic ice loss raising global mean sea level by multiple meters over the next millennia, depending on the GCM climate trajectory and ice–sheet modelling choices.

It should be noted that our simulations end in the year 7000. As a consequence, in some cases the ice sheet has not yet reached a new equilibrium with the sustained climatic boundary conditions (Fig. 5b and d). The complete loss of the East Antarctic Ice Sheet can thus not be ruled out on even longer timescales.

3.4 Potential threshold behaviour in response to changing climatic boundary conditions

Figure 7 summarizes the committed sea–level contribution from the Antarctic Ice Sheet (in the year 7000) for a given Antarctic–averaged atmospheric warming level, thereby overcoming the dependency of ice loss on the diverging climate trajectories (Sect. 3.3). It also allows to explore potential thresholds in the relationship between climatic boundary conditions potentially reached throughout the next centuries and the long–term committed ice–sheet response.

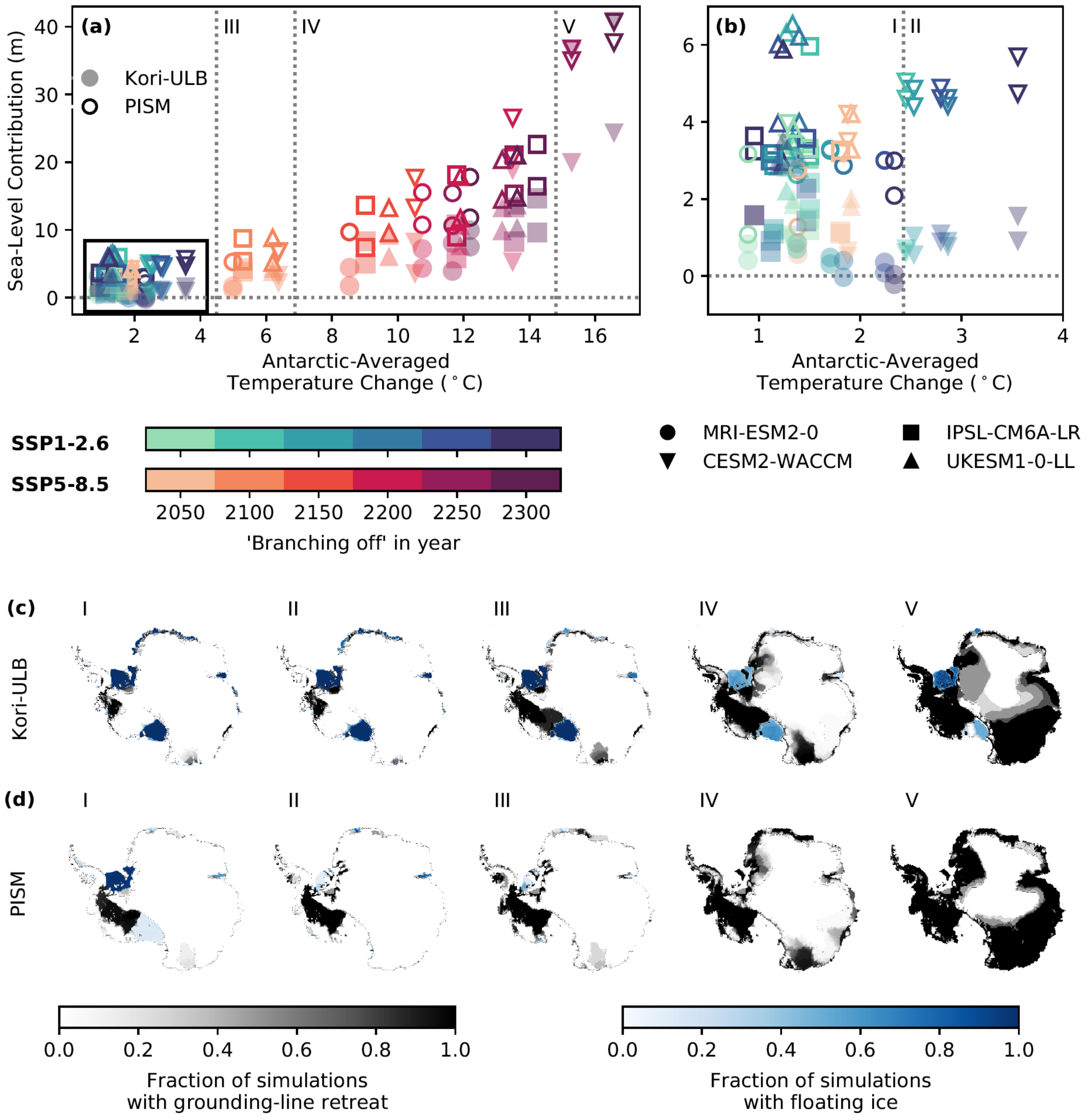

Figure 7. Committed sea–level contribution from the Antarctic Ice Sheet. (a) and (b): Long–term ice loss from the Antarctic Ice Sheet (in meters sea–level equivalent) for the year 7000 in response to Antarctic–averaged atmospheric temperature change (compared to 1995–2014) projected by four CMIP6 GCMs (given by marker shape), as determined by the ice–sheet models Kori-ULB (filled markers) and PISM (open markers). The change in climatic boundary conditions is sustained for several millennia. (b) is a zoom into (a) for a low to intermediate Antarctic–averaged atmospheric temperature change. (c) and (d): Fractions of experiments that show grounding–line retreat in the year 7000 in Kori-ULB (c) and PISM (d). The fraction is determined for all experiments that are assigned to the distinct clusters I–V.

Table 1. Mean, minimum and maximum value of the combined realized and committed ice loss (in meters sea–level equivalent) as determined by the ice–sheet models PISM and Kori-ULB under emission pathways SSP1-2.6 and SSP5-8.5. Ice loss is given for different points in time where climatic boundary conditions are stabilized. For a given point in time, upper rows represent SSP1-2.6 and lower rows correspond to SSP5-8.5.

		Realized	Committed in year 3000	Committed in year 5000	Committed in year 7000
2050	SSP1-2.6	-0.01	0.96	2.08	2.19
		(-0.03,0.01)	(-0.11,2.63)	(0.62,4.09)	(0.41,3.97)
	SSP5-8.5	-0.01	1.14	2.05	2.15
		(-0.03,0.01)	(-0.04,3.61)	(0.69,3.94)	(0.51,4.21)
2100	SSP1-2.6	0.00	1.35	2.64	2.90
		(-0.05,0.08)	(0.21,3.70)	(0.88,5.17)	(0.59,6.32)
	SSP5-8.5	-0.01	2.56	4.32	4.81
		(-0.06,0.06)	(0.98,5.17)	(1.07,8.01)	(1.18,8.81)
2150	SSP1-2.6	0.01	1.31	2.48	2.66
		(-0.08,0.19)	(0.10,3.36)	(0.67,5.71)	(0.31,6.54)
	SSP5-8.5	0.09	4.51	7.30	8.79
		(-0.04,0.28)	(1.74,7.61)	(1.84,13.67)	(1.74,17.66)
2200	SSP1-2.6	0.03	1.10	2.37	2.54
		(-0.11,0.3)	(-0.11,3.00)	(0.38,5.52)	(-0.03,6.22)
	SSP5-8.5	0.38	5.81	10.50	12.55
		(0.16,0.73)	(2.38,9.88)	(3.54,19.93)	(4.36,26.54)
2250	SSP1-2.6	0.05	1.24	2.67	2.77
		(-0.15,0.4)	(0.03,2.94)	(0.45,5.07)	(0.08,6.01)
	SSP5-8.5	0.93	7.15	14.14	17.63
		(0.40,1.48)	(2.42,12.44)	(3.21,27.14)	(3.92,36.76)
2300	SSP1-2.6	0.07	1.22	2.58	2.69
		(-0.16,0.51)	(-0.13,2.94)	(0.26,5.56)	(-0.21,5.88)
	SSP5-8.5	1.79	7.97	16.10	19.61
		(0.74,3.07)	(3.27,13.86)	(5.88,31.67)	(7.52,40.77)

In our experiments, we can identify distinct clusters of qualitatively different ice–sheet behaviour on the continental scale with increasing warming (Fig. 7) and locate critical thresholds in climatic boundary conditions inducing persistent ice loss on a basin scale (Fig. 8):

For **Antarctic atmospheric warming levels of up to 4°C**, as reached by 2300 under SSP1-2.6 and by 2050 under SSP5-8.5, we find a committed collapse of the Amundsen Sea basin, in some cases even a partial collapse of the West Antarctic Ice Sheet, resulting in a long–term Antarctic mass loss of up to +6.5 m sea–level equivalent over multi–millennial timescales (Fig. 7a and b as zoom–in, I and II).

The committed strong grounding–line retreat in the Amundsen Sea Embayment for this temperature range (consistently shown by both ice–sheet models; Fig. 7c and d, I and II, Fig. 8a and b) is in line with previous work (Golledge et al., 2017; Garbe et al., 2020; Coulon et al., 2024).

Uncertainties in the Antarctic sea–level commitment for an Antarctic–averaged atmospheric warming below 4°C (Fig. 7b) are related to (i) varying ice–sheet sensitivities in the Ross (Fig. 7c and d, I and II, Fig. 8c) and Ronne–Filchner catchments (Fig. 7c and d, II, Fig. 8e–f), depending on ice–sheet modelling choices (compare Sect. 3.3.1), and (ii) the onset of ice loss in the East Antarctic Wilkes subglacial basin, depending on the ocean warming in the applied GCMs (Fig. 7a, triangles, Fig.7c and d, I; compare Sect. 3.3.1). We find the committed grounding–line retreat in Wilkes subglacial basin being triggered by ocean warming with exceeding a basin–averaged ocean temperature change of +0.5°C – +1°C across both ice–sheet models (Fig. 7c and d, I, Fig. 8g, Fig. S4g). The loss of ice in this particular (Wilkes) basin is initiated for slightly lower ocean warming than in Garbe et al. (2020) and Golledge et al. (2015), but is located within the range of idealized experiments by Mengel and Levermann (2014). Long–term collapse of the Ronne–Filchner Ice Shelf and ice loss from ice streams draining the Eastern Weddell Sea sector is found in PISM experiments when atmospheric warming in Antarctica exceeds 2.5°C (Fig. 7b and d, II, Fig. 8e and f). This is in line with the long–term response found in Golledge et al. (2015) after following emission pathway RCP4.5 with Antarctic atmospheric warming of about 2.2°C. Given the lower sensitivity of the Ronne–Filchner Ice Shelf (Sect. 3.3.1), such a retreat of the basins connected to this major ice shelf occurs only at higher warming levels for Kori-ULB (see below, Fig. 8e and f).

Antarctic atmospheric warming levels of +5°C to +7°C are projected by the end of this century when following the higher–emission pathway, resulting in an ice loss ranging between +1.2 m and +8.8 m sea–level equivalent (Fig. 7a, III). This spread in Antarctic sea–level commitment contains the recent estimate by Van Breedam et al. (2020) of +6.6 m sea–level equivalent under warming of approximately +7°C over the next 10 000 years. In this warming range, ice loss from the Ross Ice Shelf catchment in West Antarctica substantially contributes to sea–level change also in Kori-ULB (Fig. 7c, III, Fig. 8c). That is, we find a committed complete collapse of the West Antarctic Ice Sheet in both ice–sheet models for an Antarctic–averaged atmospheric warming above +4°C (Fig. 7c and d, III). The inter–model spread in mass loss is explained by a stronger thinning of ice draining into the eastern Weddell Sea region in PISM (Fig. 7 c and d, III, Fig. 8e and f) in combination with a more pronounced thickening in the inner parts of East Antarctica in Kori-ULB within this warming range (Fig. S3, when sustaining warming projected for year 2100).

Exceeding an **atmospheric warming of +8°C in Antarctica** gives rise to a further increase in the fraction of ice that is lost on multi–millennial timescales to up to 40 % at +14°C (Fig. 7, IV). Enhanced long–term mass loss aligned with progressing Antarctic atmospheric warming is found in particular for Ronne–Filchner, Recovery and Wilkes subglacial basins (Fig. 7c and d, IV, Fig. 8d – g). In addition, some of our experiments suggest the onset of ice drainage from the East Antarctic Aurora subglacial basin for an Antarctic–averaged atmospheric temperature increase of +10°C (in accordance with Golledge et al., 2015), associated with a substantially increasing contribution to sea–level rise from this basin (for PISM, Fig. 7d, IV, Fig. 8h)

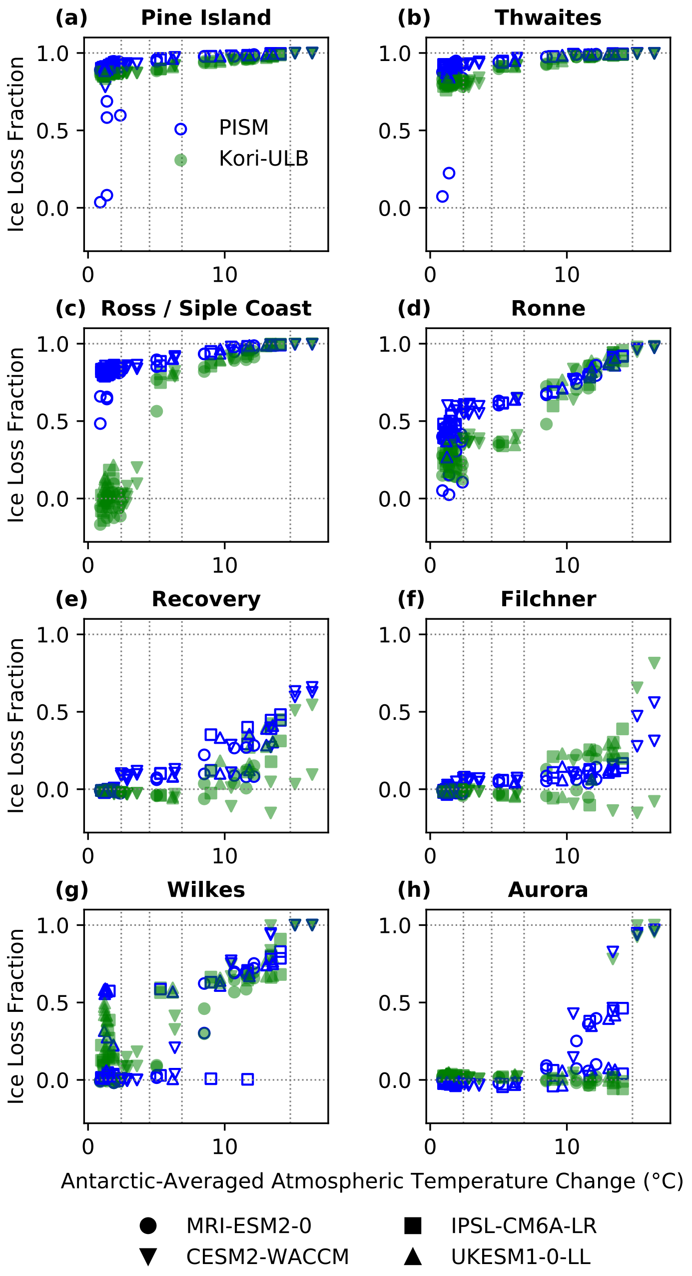

Figure 8. Ice loss from Antarctic drainage basins. Long–term ice loss from different Antarctic drainage basins (as fraction of respective sea–level rise potential) for the year 7000 in response to Antarctic–averaged atmospheric temperature change (compared to 1995–2014) as projected by four CMIP6 GCMs (given by marker shape). Filled, green and open, blue markers correspond to the long–term ice loss determined by the ice–sheet models Kori-ULB and PISM, respectively.

in this warming range. The ice stored in the Aurora subglacial basin is lost completely in both ice–sheet models for even higher atmospheric warming levels (see below and Fig. 8h). While the general dependency of ice loss from the Aurora region on the atmospheric forcing in our simulations (Fig. 8h, compared to Fig. S4h) is in agreement with Golledge et al. (2017), stronger warming of the atmosphere is required here for triggering the retreat.

For sustained **Antarctic–averaged atmospheric warming above +15°C** (projected by CESM2–WACCM after year 2200), we find that large parts of the Antarctic marine basins are lost and ice grounded above sea level in East Antarctica starts to decline substantially on multi–millennial timescales in our entire ensemble of simulations (Fig. 7 V). Over the next millennia, this gives rise to an ice loss equivalent to a sea–level change of up to +40.8 m. It cannot be ruled out that Antarctica could become ice–free under these high–warming trajectories, consistent with Garbe et al. (2020) and Winkelmann et al. (2015), given the continued increase of the Antarctic sea–level contribution at the end of our simulations (Fig. 5c and d).

Overall, the sea–level commitment increases nonlinearly with increasing atmospheric temperature change in Antarctica (Fig. 7a), consistent with the nonlinear response to warming in quasi–equilibrium (that is, when temperatures change much slower than typical rates of changes of an ice sheet; Garbe et al., 2020). Our committed ice–sheet states complement this quasi–equilibrium response of the Antarctic Ice Sheet (obtained by Garbe et al., 2020) as they record the long–term response to faster warming as projected under the different SSP scenarios.

Under equivalent warming, the long–term dynamical and topographical changes of the Antarctic Ice Sheet are largely consistent for each ice–sheet model configuration (compare Table S2). We find a spread in long–term mass loss at a given warming level due to model uncertainties (e.g., arising in the ice–sheet model initialisation and physics), which is pronounced for low to intermediate warming levels in Antarctica covered by the lower–emission pathway SSP1-2.6 (Fig. 7b). In other words, the ice–sheet sensitivity to warming, in particular in some marine Antarctic basins, varies with the ice–sheet model configuration (Tab. S2). In this warming range, varying trajectories of atmospheric to ocean warming across GCMs may also play out and modulate Antarctica's sea–level contribution on longer timescales (Sect. 3.3.1). Beyond the low to intermediate warming levels covered by the lower emission pathway SSP1-2.6, the pattern of mass loss and the resulting sea–level contribution from Antarctica are overall robust, with a step–wise long–term decline of the Antarctic Ice Sheet across two ice–sheet models (Fig. 7a, c and d): With increasing warming, our experiments suggest a committed partial collapse of the West Antarctic Ice Sheet (I and II), associated with a substantial retreat in the Amundsen Sea sector, up to its complete collapse (III), followed by enhanced mass loss from East Antarctic marine Wilkes, Recovery and Aurora subglacial basins (IV) and an eventual decline of terrestrial parts of the ice sheet (V).

4 Discussion

In this paper, we determine the multi–millennial sea–level contribution from the Antarctic Ice Sheet under a range of possible climate trajectories for both low– and high–emission pathways. In particular, we quantify the long–term Antarctic sea–level commitment when stabilising climatic boundary conditions at different points in time. That is, the atmospheric and oceanic changes potentially established during the upcoming decades and centuries in Antarctica are sustained for several thousands of years, and we explore their long–term impacts on the Antarctic Ice Sheet. Experiments were carried out systematically for stabilized Antarctic climate at different points in time over the course of the next centuries and in a consistent way with the stand–alone ice–sheet models Kori-ULB and PISM, thereby accounting for some model uncertainty.

Our experiments illustrate a substantial difference between the transient *realized* and long–term *committed* sea–level change from the Antarctic Ice Sheet. While the projected Antarctic mass change by the end of this century is limited (spanning a range from -0.1 m to +0.1 m sea–level equivalent), the Antarctic Ice Sheet may be committed to a strong grounding–line retreat in the Amundsen Sea Embayment up to a potential collapse of the West Antarctic Ice Sheet for sustained climate conditions at levels projected to be reached during this century even under the lower–emission pathway, depending on ice–sheet modelling choices. Mass loss from the marine Wilkes subglacial basin in East Antarctica may unfold on multi–millennial timescales for strong ocean warming projected by some GCMs as early as the second half of this century under the lower–emission scenario. With a stabilization of climate conditions beyond the end of this century under the higher–emission pathway SSP5-8.5, the Antarctic sea–level contribution under these high–warming trajectories diverges from the sea–level commitment under SSP1-2.6. This is due to a successive ice–sheet retreat in major East Antarctic marine basins, additionally triggered by progressing warming. Next to ice loss from these marine parts, a substantial decline of the non–marine East Antarctic Ice Sheet may eventually result in long–term mass losses of up to +40.8 m sea–level equivalent, subject to substantial uncertainties, especially due to the GCM climate forcing.

Determining the committed evolution of the Antarctic Ice Sheet triggered by the warming projected for the next decades and centuries extends previous studies of the long–term ice–sheet response under sustained *present–day* conditions. For example, Coulon et al. (2024), Reese et al. (2023) and Golledge et al. (2019) suggest a committed (potentially irreversible) grounding–line retreat in West Antarctica under present–day conditions in response to atmospheric and oceanic changes over the past decades. We also add to the assessment of the long–term Antarctic sea–level commitment to future warming by the end of this century (Chambers et al., 2022; Lowry et al., 2021) and by 2300 (Golledge et al., 2015; Bulthuis et al., 2019; Coulon et al., 2024) by exploring the multi–millennial consequences of stabilizing climatic boundary conditions at different points in time over the course of the next centuries, in a consistent way for two ice–sheet models. From a dynamical systems perspective, the long–term stability of the Antarctic Ice Sheet under present and potential future rates of warming (being much faster than typical rates of change in an ice sheet) is studied. This complements the quasi–equilibrium ice–sheet response to warming presented by Garbe et al. (2020) and, thereby, bridges the gap to the transient realized sea–level change from Antarctica (e.g., by the end of this century as in Seroussi et al., 2020).

The committed Antarctic sea–level contribution is subject to growing uncertainties related to the substantial spread of warming projected by the selected GCMs, in particular beyond the end of this century under SSP5-8.5 (*climate forcing uncertainty*). Ice–sheet sensitivities and critical temperature thresholds giving rise to self–sustained ice loss further vary in our experiments as a result of *model uncertainties*. These uncertainties may be induced by differences in the model structure and the parameterisation of certain ice–sheet processes (e.g., Seroussi et al., 2020), parameter choices (e.g., Bulthuis et al., 2019; Nias et al., 2016; Coulon et al., 2024) and well as initialisation procedures (e.g., Seroussi et al., 2019; Ađalgeirsdóttir et al., 2014). In the following, the role of these different sources of uncertainties for the multi–millennial Antarctic sea–level response presented in this work is discussed.

4.1 Uncertainties in Antarctic sea–level commitment due to climate forcing

Following recent efforts in projecting the Antarctic sea–level contribution on different timescales ranging from the next decades until 2100 to several millennia (Seroussi et al., 2020; Payne et al., 2021; Golledge et al., 2015), we base the imposed changes in Antarctic climate on state–of–the–art GCMs from the Coupled Model Intercomparison Project CMIP6. Biases in the chosen GCMs and a poor representation of conditions at the ice–sheet margins due to their coarse resolution (Beadling et al., 2020; Bracegirdle et al., 2020; Purich and England, 2021) may influence the simulated mass changes of the Antarctic Ice Sheet. In our experiments, the climate forcing from the four employed GCMs results in a wide spread of the realized and especially committed sea–level contribution from Antarctica, making it one of the most important sources of uncertainty.

For low to intermediate warming levels covered by the lower–emission pathway SSP1-2.6, the uncertainty introduced by the climate forcing at a given point in time is comparable to the uncertainty caused by ice–sheet models (compare Fig. 5e and following Sect. 4.2). Here, the Antarctic sea–level commitment is modulated by varying trajectories of atmospheric to oceanic warming across the GCMs for each ice–sheet model (Fig. 4a and d). We find that the growing spread of the committed Antarctic sea–level contribution under the higher–emission scenario SSP5-8.5 for stabilizing the ice–sheet boundary conditions later in time (Fig. 5e) can, to a large part, be attributed to the divergence of the climate trajectories projected by the four GCMs beyond the end of this century (Fig. 4a and d).

The GCMs providing available future changes in boundary conditions until 2300, on which our analysis is based, are characterized by different warming rates and a large range of climate sensitivities, with a high upper bound (Meehl et al., 2020), which may not be in accordance with paleoclimatic evidence (Zhu et al., 2021). This introduces a substantial climate forcing uncertainty at a specific point in time: While for MRI-ESM2-0 a comparably low equilibrium climate sensitivity was determined (3.2°C, below the multimodel mean of 3.7°C; Meehl et al., 2020), the equilibrium climate sensitivities of UKESM1-0-LL (5.3°C), CESM2-WACCM (4.8°C) and IPSL-CM6A-LR (4.6°C) are at the upper end of the range of climate sensitivities reported for CMIP6. CESM2-WACCM also shows a significantly stronger Antarctic–averaged atmospheric warming under SSP5-8.5 beyond 2200 than the other GCMs (Tab. S1).

This translates into a growing uncertainty in projected long–term Antarctic ice loss under SSP5-8.5 with a substantially higher committed sea–level contribution from Antarctica for the same year under CESM2-WACCM climate compared to the other applied CMIP6 GCMs. For example, the committed Antarctic sea–level contribution determined by Kori-ULB and PISM under CESM2-WACCM climate ranges between +24.3 m and +40.8 m (when assuming a stabilization of climatic conditions representative for the year 2300). In contrast, we find an Antarctic mass loss of up to +22.6 m for the other CMIP6 GCMs. These higher magnitudes of imposed warming in some of the selected GCMs employed here may also explain the substantially higher upper range of the long–term mass loss committed under constant climatic boundary conditions reached by the year 2300 in our experiments (with committed ice loss of +3.3 m – +13.9 m, +5.9 m – +31.7 m and +7.5 m – 40.8 m sea–level equivalent by the year 3000, 5000 and 7000; Tab. 1) compared to some previous estimates (under Representative Concentration Pathway

RCP8.5, Golledge et al., 2015; Bulthuis et al., 2019), Consequently, the derived future climate trajectories and respective projected multi–millennial Antarctic ice loss should only be related to emissions with care and can rather be seen as a potential range of climate futures for Antarctica.

As noted above, the majority of projections of future Antarctic climate to date cover this century only (O'Neill et al., 2016; Tebaldi et al., 2021). The pronounced projected changes in Antarctic climate and the substantial GCM uncertainty especially beyond the end of the century reflected in our assessment of the Antarctic sea–level commitment highlight the need for a through assessment of potential multi–centennial Antarctic climate trajectories in future research, as a basis for improving our understanding of the associated long–term Antarctic Ice Sheet response (on timescales on the order of centuries to multiple millennia).

For determining the long–term Antarctic sea–level commitment, we here assume constant climate conditions on multi–millennial timescales. This allows us to assess the long–term ice–sheet stability and committed sea–level contribution under an idealized combination of atmospheric and oceanic changes with respect to present–day. This approach has been invoked previously (e.g., Golledge et al., 2015), but comes with certain assumptions: For instance, a continued ocean response to changing CO_2 conditions and atmospheric warming (Li et al., 2013) may result in an altered ratio of atmospheric and oceanic changes beyond the point in time where a stabilization of climatic boundary conditions is assumed here. Observed interannual and decadal variability (Paolo et al., 2018; Jenkins et al., 2018) is neglected in the imposed constant climate conditions for simplicity, which has been shown to potentially result in a lower long–term ice–sheet volume (compared to a stable climate; Mikkelsen et al., 2018) up to ice–sheet retreat (Christian et al., 2020; Robel et al., 2019).

In addition, climate trajectories distinct from such climate stabilization scenarios, e.g. temperature overshoot pathways (Tokarska et al., 2019), may impact the ice–sheet response in the near and far future. The response of the Antarctic Ice Sheet to a reversal of climate conditions after exceeding a warming of, e.g., 1.5°C, including the potential for 'safe' overshoots (Ritchie et al., 2021), is not well constrained. Based on the long–term Antarctic sea–level contribution presented here, the (ir-)reversibility of this committed Antarctic mass loss for a reversal of climatic boundary conditions and relevant timescales can be assessed in a next step.

4.2 Uncertainties in Antarctic sea–level commitment arising from model uncertainties

Under strong atmospheric warming (with an Antarctic atmospheric temperature change above 8°C in our experiments), where the ice–sheet's decline is amplified by atmospheric changes rather than being mostly driven by ocean warming (compare Coulon et al., 2024), the pattern of long–term mass loss and the resulting sea–level contribution from Antarctica on multi–millennial timescales are overall robust across both ice–sheet models, irrespective of their initialization approaches and structural differences. This includes enhanced ice loss from major East Antarctic marine basins with progressing warming, following a collapse of the West Antarctic Ice Sheet (for warming projected for the end of this century under SSP5-8.5; Sect. 3.3.2, Sect. 3.4).

Model uncertainty is most pronounced for ice loss from Antarctic marine basins located within low to intermediate warming levels as covered by the lower–emission pathway SSP1-2.6. Depending on ice–sheet modelling choices, we find varying timings, basin–scale temperature thresholds and rates of grounding–line retreat in West Antarctica (Sect. 3.3.1, Sec. 3.4, Fig. 8).

On shorter, multi–centennial timescales, Kori-ULB projections are characterized by a higher sensitivity and an earlier onset of ice loss from the Amundsen Sea sector compared to the simulations with PISM under the lower–emission pathway (Fig. 3a and b). This stronger dynamical response of Thwaites and Pine Island glaciers in Kori-ULB results in a higher Antarctic sea–level contribution by 2300, continuing the simulated trends in this region over the historical period (Fig. 2). Both ice–sheet models agree on a long–term retreat of grounding lines of Pine Island and Thwaites glaciers already under SSP1-2.6, consistent with previous findings that the grounding lines at present might already be undergoing a self–sustained retreat or that this retreat might be imminent due to changes in the climatic boundary conditions over the past decades (Favier et al., 2014; Golledge et al., 2019; Reese et al., 2023; Coulon et al., 2024).

The multi–meter spread of the sea–level contribution on longer, multi–millennial timescales for an Antarctic–averaged atmospheric warming up to 4°C (covered by SSP1-2.6) is, to a large part, associated with varying ice–sheet sensitivities in the catchments draining Ross and Ronne–Filchner ice shelves, accompanied by different responses of these major buttressing Antarctic ice shelves (Fig. 7; Sect. 3.3.1 and Sect. 3.4).

Here, the uncertainty in the onset of ice–sheet retreat can be linked to certain geometrical features of the initial ice–sheet state as an outcome of the applied initialization approaches (Sect. 2.2.2) as well as different, but all plausible ice–sheet modelling choices e.g. for determining sub–shelf melt (Sect. 2.2.3): For example, Ross and Ronne–Filchner ice shelves, restraining the ice flowing from the grounded ice sheet, are overall sustained longer in Kori-ULB, potentially related to a combination of the calving schemes employed in the ice–sheet models (Levermann et al., 2012; Pollard et al., 2015; DeConto and Pollard, 2016) and different PICO sub–shelf melt sensitivities to changes in ocean temperatures (Sect. 2.2.3; Reese et al., 2018, 2023). A simulated upstream location of the Siple Coast grounding line (Fig. S1; Reese et al., 2023; Sutter et al., 2023) and thinning of Ross Ice Shelf over the historical period (Fig. 2; Reese et al., 2020, 2023) following a spin–up approach in PISM (Sect. 2.2.2) as well as a potential drift of the Siple Coast grounding line in Kori-ULB (Sect. 3.3.1), given lower sub-shelf melt rates obtained with PICO in this area compared to those that are obtained from the initialization approach to keep the ice sheet steady (Sect. 2.2.2), may also contribute to these varying ice–sheet sensitivities in the Siple Coast region.

The rates of grounding–line retreat are then dictated by basal friction (e.g., Cornford et al., 2020), that deviates spatially between both ice–sheet models: Once triggered, faster and large–scale West Antarctic grounding–line retreat unfolds in PISM for low to intermediate warming, promoted by overall slippery bed conditions in the interior of marine subglacial basins given the parameterized, bed–elevation dependent material properties of the subglacial till (in particular, the till friction angle; Sect. 2.1). Grounding lines face less slippery bed conditions when retreating towards the interior of the West Antarctic Ice Sheet in Kori-ULB, based on the optimized lower sliding coefficients from the inverse simulation (Sect. 2.2.2). Therefore, stronger forcing (that is, warming levels reached by the end of this century under SSP5-8.5) is required to overcome this low slipperiness towards the interior of West Antarctica and to induce a complete collapse of the West Antarctic Ice Sheet.

Overall, the uncertainty in Antarctic sea–level commitment to warming projected by 2300 under this lower–emission pathway SSP1-2.6 associated with ice–sheet modelling choices (ranging from -0.13 m to 2.94 m; Tab. 1) is, in the year 3000, comparable to the spread in Antarctic ice–sheet trajectories in terms of the sea–level change related to parametric uncertainties in ice–ocean and ice–atmosphere interactions by the end of the millennium (with -0.73 m – 2.90 m; Coulon et al., 2024).

The range of possible long–term ice–sheet trajectories under SSP1-2.6 suggests the Ross Ice Shelf catchment as an important focus region for future assessments of the multi–millennial Antarctic sea–level contribution, also given a possible intrusion of modified Circumpolar Deep Water into the eastern Ross Sea continental shelf followed by strong sub–shelf melting (Siahaan et al., 2022) as previously simulated for the Filchner Trough (e.g., Hellmer et al., 2012) and its potential to lead to a complete collapse of the West Antarctic Ice Sheet (e.g., Martin et al., 2019).

In a next step, the long–term ice–sheet response when including larger parts of the parameter space covered in the initial–state ensemble and beyond should also be explored, to quantify how parametric uncertainties translate into Antarctic sea–level commitment and extending Coulon et al. (2024) to multi–millennial timescales. While taking into account distinct Antarctic ice–sheet representations as a result of an initial–state ensemble covering relevant model parameters and including two ice–sheet models, parametric uncertainties cannot be fully explored here due to computational constraints in favor of sampling a wide range of possible future climates.

For example, to determine sub–shelf melt, PICO (Reese et al., 2018, 2023) is chosen out of a diverse set of available sub–shelf melt parameterisations (recently compared in e.g., Burgard et al., 2022; Berends et al., 2023a). PICO has been shown to reproduce observed basal melt rates averaged over Antarctic ice shelves related to the vertical overturning circulation in ice–shelf cavities and to resemble the typical pattern of strongest melt near the grounding line (Reese et al., 2018, 2023). However, smoother spatial fields of basal melt in PICO compared to observations (Reese et al., 2018) and here quantifying melt as linearly related to temperature (Reese et al., 2018; Burgard et al., 2022) may underestimate the long–term ice dynamics. While the chosen combinations of the overturning parameter and the effective turbulent heat exchange coefficient parameter resemble sub–shelf melt sensitivities and / or observed melt rates (Sect. 2.2.3, Sect. 3.1), substantial parametric uncertainty related to sub–shelf melt exists (e.g., Coulon et al., 2024; Seroussi et al., 2023) and cannot be further explored here.

Finally, our simulations are performed on a comparably coarse horizontal resolution of 16 km, allowing for a large number of long–term experiments as presented here, which is needed to cover a wide range of uncertainties. The migration of the grounding line in PISM is captured reasonably well, even on such a coarse resolution, with a sub–grid interpolation scheme (Feldmann et al., 2014), that allows to reproduce glacial cycles of the Antarctic Ice Sheet (Albrecht et al., 2020). Garbe et al. (2020) showed (using PISM) that the overall hysteresis behaviour of the Antarctic Ice Sheet is robust across model resolution. In Kori-ULB, resolving grounding–line dynamics at a coarse resolution is addressed by imposing a flux condition (Pollard and DeConto, 2012a, 2020), which results in a good agreement with high–resolution models.

4.3 Limitations in assessing Antarctic sea–level commitment related to missing processes and feedback mechanisms

Several amplifying and dampening feedbacks between the Antarctic Ice Sheet and the Earth system (Fyke et al., 2018) are missing in stand–alone ice–sheet model projections such as the ones presented here, but may be relevant for the long–term mass changes and stability of the Antarctic Ice Sheet. Including the missing feedbacks in future fully–coupled assessments of the Antarctic sea–level commitment could change the timing and rates of (abrupt) mass loss determined in our experiments, either by dampening or by accelerating Antarctic ice loss. However, such fully–coupled Earth system models including the ice sheets, which are capable of simulating the multi–millennial ice–sheet response as needed for this study, are not yet available.

We here include some of the relevant feedbacks using parametrisations: Atmospheric temperature imposed to the Antarctic Ice Sheet is modified in our experiments using the atmospheric lapse rate to account for the impact of a changing ice–surface elevation. This also feeds into the surface melt determined by the positive–degree–day approach, depicting the surface melt–elevation feedback (Levermann and Winkelmann, 2016).

The potentially strong decline of ice volume under warming projected for higher–emission pathways may, however, additionally result in changes of the atmospheric circulation and respective precipitation patterns (compare e.g., Merz et al., 2014, for Greenland), which are not covered in our experiments. By applying the positive–degree–day approach to determine the future ice–sheet surface melt, we do not account for the amplifying melt–albedo feedback (Jakobs et al., 2019, 2021). While polar–oriented regional climate models cannot provide boundary conditions (or dynamically interact with ice sheets) on multi–millennial timescales considered here as of yet, approaches of intermediate complexity such as the recently introduced (simple) diurnal Energy Balance Model (Garbe et al., 2023; Zeitz et al., 2021) may allow to include the potentially accelerating effect of changes in albedo on projected ice loss through enhanced surface melting (Garbe et al., 2023) in the future.

Surface melt on Antarctic ice shelves facilitates hydrofracturing and may, thereby, trigger ice–shelf collapse (Van Wessem et al., 2023; Lai et al., 2020; Pollard et al., 2015; Trusel et al., 2015) and potentially the Marine Ice Cliff Instability (MICI; Bassis and Walker, 2012; Pollard et al., 2015). While temperature thresholds for melt pond formation as a precursor for such ice–shelf loss may be exceeded by the end of the century (Van Wessem et al., 2023), the availability of parameterizations to include these processes in ice–sheet models is still limited (Pollard et al., 2015; DeConto and Pollard, 2016; Seroussi et al., 2020). Considering hydrofracturing (following Pollard et al., 2015; DeConto and Pollard, 2016; Seroussi et al., 2020) may speed–up grounding-line retreat in marine Antarctic basins due to an earlier ice-shelf breakup (Coulon et al., 2024; Seroussi et al., 2020).

In addition, freshwater fluxes from mass balance changes of the Antarctic Ice Sheet into the surrounding ocean have been suggested to result in atmospheric cooling in the Southern Hemisphere competing with a potential enhancement of ice loss by the end of the century in an amplifying feedback due to subsurface ocean warming (Golledge et al., 2019; DeConto et al., 2021). This amplifying feedback could have played a role in abrupt ice discharge events during the last deglaciation (Weber et al., 2014). It remains to be explored how such ice–ocean feedbacks could play out on multi–millennial timescales in Antarctica's future.

Finally, while bedrock adjustment to changes in ice load is included in our experiments, opposing Earth structures between West and East Antarctica are not considered: By assuming uniform solid–Earth properties, ocean–driven ice loss from marine basins in East Antarctica may be underestimated on millennial timescales (Coulon et al., 2021), such that our estimates of committed East Antarctic mass loss may be seen as conservative. On the other hand, taking into account characteristic rheological properties of the solid Earth in West Antarctica could promote rapid bedrock uplift, thereby delaying ice–sheet changes (Coulon et al., 2021).

5 Conclusion

While various sources of uncertainties remain to be explored for quantifying the long–term Antarctic sea–level commitment, our analysis shows across two ice–sheet models and a multitude of varying climate, model and parametric uncertainties that the long–term multi–millennial impacts on the Antarctic Ice Sheet of warming projected over the next decades and centuries are profound when compared to typical sea–level projections as for instance in the IPCC assessments. The Antarctic sea–level commitment to warming projected over the next centuries increases nonlinearly. The multi–millennial ice–sheet response grows steps–wise from a pronounced grounding–line retreat of Thwaites and Pine Island glaciers under SSP1-2.6 to a complete long–term collapse of the West Antarctic Ice Sheet triggered at latest for SSP5-8.5 warming in 2100 followed by mass loss from major marine basins in East Antarctica. It is possible that pronounced ice loss also from terrestrial ice–sheet parts of up to +40 m sea–level equivalent is locked in in response to projected SSP5-8.5 warming after 2200. Our findings thus stress the importance of complementing typical decadal–to–centennial projections of the future evolution of the Antarctic Ice Sheet by the respective committed Antarctic sea–level contribution for long–term decision making.

Code and data availability. The source code of PISM is publicly available on GitHub via https://www.pism.io. The exact PISM version used in this paper will be archived within the open access repository Zenodo upon publication of the manuscript. The code of the Kori-ULB ice–sheet model is publicly available on GitHub via https://github.com/FrankPat/Kori-dev. All datasets used in this study are freely accessible through their original references. The CMIP6 forcing data used in this study are accessible through the CMIP6 search interface (https://esgf-node.llnl.gov/search/cmip6/). The simulations outputs, the data needed to produce the figures and tables, and the scripts will be hosted on Zenodo upon publication of the final paper.

Author contributions. R.W. conceived the study. A.K.K. and V.C. processed the forcing data, initialized the ice–sheet models and ran the model simulations. A.K.K. performed the data analysis, produced the figures and wrote the original manuscript with regular inputs from V.C. All authors contributed to the final version of the manuscript.

Competing interests. The authors declare that they have no conflict of interest.

Acknowledgements. This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 869304 (PROTECT). The authors gratefully acknowledge the European Regional Development Fund (ERDF), the

German Federal Ministry of Education and Research (BMBF) and the Land Brandenburg for supporting this project by providing resources on the high-performance computer system at the Potsdam Institute for Climate Impact Research. Development of PISM is supported by NASA grants 20-CRYO2020-0052 and 80NSSC22K0274 and NSF grant OAC-2118285. Computational resources for Kori-ULB simulations have been provided by the Consortium des Équipements de Calcul Intensif (CÉCI), funded by the Fonds de la Recherche Scientifique de Belgique (F.R.S.-FNRS) under Grant No. 2.5020.11 and by the Walloon Region. A.K.K. and R.W. further acknowledge support by the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 820575 (TiPACCs). We acknowledge the World Climate Research Programme's Working Group on Coupled Modelling, which is responsible for CMIP, and we thank the climate modelling groups (whose models are listed in Table S1 of this paper) for producing and making their model output available. This work has been performed in the context of the FutureLab on Earth Resilience in the Anthropocene at the Potsdam Institute for Climate Impact Research.

References

Aðalgeirsdóttir, G., Aschwanden, A., Khroulev, C., Boberg, F., Mottram, R., Lucas-Picher, P., and Christensen, J.: Role of model initialization for projections of 21st-century Greenland ice sheet mass loss, Journal of Glaciology, 60, 782–794, https://doi.org/10.3189/2014JoG13J202, 2014.

Adusumilli, S., Fricker, H. A., Medley, B., Padman, L., and Siegfried, M. R.: Interannual variations in meltwater input to the Southern Ocean from Antarctic ice shelves, Nature Geoscience, 13, 616–620, https://doi.org/10.1038/s41561-020-0616-z, 2020.

Aitken, A., Roberts, J., Van Ommen, T., Young, D., Golledge, N., Greenbaum, J., Blankenship, D., and Siegert, M.: Repeated large-scale retreat and advance of Totten Glacier indicated by inland bed erosion, Nature, 533, 385–389, https://doi.org/10.1038/nature17447, 2016.

Albrecht, T., Winkelmann, R., and Levermann, A.: Glacial-cycle simulations of the Antarctic Ice Sheet with the Parallel Ice Sheet Model (PISM) – Part 1: Boundary conditions and climatic forcing, The Cryosphere, 14, 599–632, https://doi.org/10.5194/tc-14-599-2020, 2020.

Armstrong McKay, D. I., Staal, A., Abrams, J. F., Winkelmann, R., Sakschewski, B., Loriani, S., Fetzer, I., Cornell, S. E., Rockström, J., and Lenton, T. M.: Exceeding 1.5° C global warming could trigger multiple climate tipping points, Science, 377, eabn7950, https://doi.org/10.1126/science.abn7950, 2022.

Arthern, R. J. and Williams, C. R.: The sensitivity of West Antarctica to the submarine melting feedback, Geophysical Research Letters, 44, 2352–2359, https://doi.org/10.1002/2017GL072514, 2017.

Aschwanden, A., Aðalgeirsdóttir, G., and Khroulev, C.: Hindcasting to measure ice sheet model sensitivity to initial states, The Cryosphere, 7, 1083–1093, 2013.

Barletta, V. R., Bevis, M., Smith, B. E., Wilson, T., Brown, A., Bordoni, A., Willis, M., Khan, S. A., Rovira-Navarro, M., Dalziel, I., et al.: Observed rapid bedrock uplift in Amundsen Sea Embayment promotes ice-sheet stability, Science, 360, 1335–1339, https://doi.org/10.1126/science.aao1447, 2018.

Barthel, A., Agosta, C., Little, C. M., Hattermann, T., Jourdain, N. C., Goelzer, H., Nowicki, S., Seroussi, H., Straneo, F., and Bracegirdle, T. J.: CMIP5 model selection for ISMIP6 ice sheet model forcing: Greenland and Antarctica, The Cryosphere, 14, 855–879, https://doi.org/10.5194/tc-14-855-2020, 2020.

Bassis, J. N. and Walker, C. C.: Upper and lower limits on the stability of calving glaciers from the yield strength envelope of ice, Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences, 468, 913–931, 2012.

Beadling, R. L., Russell, J., Stouffer, R., Mazloff, M., Talley, L., Goodman, P., Sallée, J.-B., Hewitt, H., Hyder, P., and Pandde, A.: Representation of Southern Ocean properties across coupled model intercomparison project generations: CMIP3 to CMIP6, Journal of Climate, 33, 6555–6581, https://doi.org/10.1175/JCLI-D-19-0970.1, 2020.

Bentsen, M., Bethke, I., Debernard, J. B., Iversen, T., Kirkevåg, A., Seland, Ø., Drange, H., Roelandt, C., Seierstad, I. A., Hoose, C., et al.: The Norwegian Earth System Model, NorESM1-M–Part 1: description and basic evaluation of the physical climate, Geoscientific Model Development, 6, 687–720, https://doi.org/10.5194/gmd-6-687-2013, 2013.

Berends, C. J., Stap, L. B., and van de Wal, R. S.: Strong impact of sub-shelf melt parameterisation on ice-sheet retreat in idealised and realistic Antarctic topography, Journal of Glaciology, 69, 1434–1448, 2023a.

Berends, C. J., Van De Wal, R. S., Van Den Akker, T., and Lipscomb, W. H.: Compensating errors in inversions for subglacial bed roughness: same steady state, different dynamic response, The Cryosphere, 17, 1585–1600, https://doi.org/10.5194/tc-17-1585-2023, 2023b.

Bernales, J., Rogozhina, I., and Thomas, M.: Melting and freezing under Antarctic ice shelves from a combination of ice-sheet modelling and observations, Journal of Glaciology, 63, 731–744, https://doi.org/10.1017/jog.2017.42, 2017.

Blackburn, T., Edwards, G., Tulaczyk, S., Scudder, M., Piccione, G., Hallet, B., McLean, N., Zachos, J., Cheney, B., and Babbe, J.: Ice retreat in Wilkes Basin of East Antarctica during a warm interglacial, Nature, 583, 554–559, https://doi.org/10.1038/s41586-020-2484-5, 2020.

Bracegirdle, T., Holmes, C., Hosking, J., Marshall, G., Osman, M., Patterson, M., and Rackow, T.: Improvements in circumpolar Southern Hemisphere extratropical atmospheric circulation in CMIP6 compared to CMIP5, Earth and Space Science, 7, e2019EA001 065, https://doi.org/10.1029/2019EA001065, 2020.

Bueler, E. and Brown, J.: Shallow shelf approximation as a "sliding law" in a thermomechanically coupled ice sheet model, Journal of Geophysical Research: Earth Surface, 114, https://doi.org/10.1029/2008JF001179, 2009.

Bueler, E. and van Pelt, W.: Mass–conserving subglacial hydrology in the Parallel Ice Sheet Model version 0.6, Geoscientific Model Development, 8, 1613–1635, https://doi.org/gmd-8-1613-2015, 2015.

Bueler, E., Lingle, C. S., and Brown, J.: Fast computation of a viscoelastic deformable Earth model for ice-sheet simulations, Annals of Glaciology, 46, 97–105, https://doi.org/10.3189/172756407782871567, 2007.

Bulthuis, K., Arnst, M., Sun, S., and Pattyn, F.: Uncertainty quantification of the multi-centennial response of the Antarctic ice sheet to climate change, The Cryosphere, 13, 1349–1380, https://doi.org/10.5194/tc-13-1349-2019, 2019.

Burgard, C., Jourdain, N. C., Reese, R., Jenkins, A., and Mathiot, P.: An assessment of basal melt parameterisations for Antarctic ice shelves, The Cryosphere, 16, 4931–4975, https://doi.org/tc-16-4931-2022, 2022.

Calov, R. and Greve, R.: A semi-analytical solution for the positive degree-day model with stochastic temperature variations, Journal of Glaciology, 51, 173–175, https://doi.org/10.3189/172756505781829601, 2005.

Chambers, C., Greve, R., Obase, T., Saito, F., and Abe-Ouchi, A.: Mass loss of the Antarctic ice sheet until the year 3000 under a sustained late-21st-century climate, Journal of Glaciology, 68, 605–617, https://doi.org/10.1017/jog.2021.124, 2022.

Christian, J. E., Robel, A. A., Proistosescu, C., Roe, G., Koutnik, M., and Christianson, K.: The contrasting response of outlet glaciers to interior and ocean forcing, The Cryosphere, 14, 2515–2535, https://doi.org/10.5194/tc-14-2515-2020, 2020.

Clark, P. U., Shakun, J. D., Marcott, S. A., Mix, A. C., Eby, M., Kulp, S., Levermann, A., Milne, G. A., Pfister, P. L., Santer, B. D., et al.: Consequences of twenty-first-century policy for multi-millennial climate and sea-level change, Nature Climate Change, 6, 360–369, https://doi.org/10.1038/nclimate2923, 2016.

Clarke, G. K., Nitsan, U., and Paterson, W.: Strain heating and creep instability in glaciers and ice sheets, Reviews of Geophysics, 15, 235–247, https://doi.org/10.1029/RG015i002p00235, 1977.

Cook, C. P., Van De Flierdt, T., Williams, T., Hemming, S. R., Iwai, M., Kobayashi, M., Jimenez-Espejo, F. J., Escutia, C., González, J. J., Khim, B.-K., et al.: Dynamic behaviour of the East Antarctic ice sheet during Pliocene warmth, Nature Geoscience, 6, 765–769, https://doi.org/10.1038/ngeo1889, 2013.

Cornford, S. L., Seroussi, H., Asay-Davis, X. S., Gudmundsson, G. H., Arthern, R., Borstad, C., Christmann, J., Dias dos Santos, T., Feldmann, J., Goldberg, D., Hoffman, M. J., Humbert, A., Kleiner, T., Leguy, G., Lipscomb, W. H., Merino, N., Durand, G., Morlighem, M., Pollard, D., Rückamp, M., Williams, C. R., and Yu, H.: Results of the third marine ice sheet model intercomparison project (MISMIP+), The Cryosphere, 14, 2283–2301, https://doi.org/10.5194/tc-14-2283-2020, 2020.

Coulon, V., Bulthuis, K., Whitehouse, P. L., Sun, S., Haubner, K., Zipf, L., and Pattyn, F.: Contrasting response of West and East Antarctic ice sheets to glacial isostatic adjustment, Journal of Geophysical Research: Earth Surface, 126, e2020JF006 003, https://doi.org/10.1029/2020JF006003, 2021.

Coulon, V., Klose, A. K., Kittel, C., Edwards, T., Turner, F., Winkelmann, R., and Pattyn, F.: Disentangling the drivers of future Antarctic ice loss with a historically-calibrated ice-sheet model, The Cryosphere, 18, 653–681, https://doi.org/10.5194/tc-18-653-2024, 2024.

Cuffey, K. M. and Paterson, W. S. B.: The Physics of Glaciers, Academic Press, 2010.

DeConto, R. M. and Pollard, D.: Rapid Cenozoic glaciation of Antarctica induced by declining atmospheric CO2, Nature, 421, 245–249, https://doi.org/10.1038/nature01290, 2003.

DeConto, R. M. and Pollard, D.: Contribution of Antarctica to past and future sea-level rise, Nature, 531, 591–597, https://doi.org/10.1038/nature17145, 2016.

DeConto, R. M., Pollard, D., Alley, R. B., Velicogna, I., Gasson, E., Gomez, N., Sadai, S., Condron, A., Gilford, D. M., Ashe, E. L., et al.: The Paris Climate Agreement and future sea-level rise from Antarctica, Nature, 593, 83–89, https://doi.org/10.1038/s41586-021-03427-0, 2021.

Dutton, A., Carlson, A. E., Long, A. J., Milne, G. A., Clark, P. U., DeConto, R., Horton, B. P., Rahmstorf, S., and Raymo, M. E.: Sea-level rise due to polar ice-sheet mass loss during past warm periods, science, 349, aaa4019, 2015.

Edwards, T. L., Nowicki, S., Marzeion, B., Hock, R., Goelzer, H., Seroussi, H., Jourdain, N. C., Slater, D. A., Turner, F. E., Smith, C. J., et al.: Projected land ice contributions to twenty-first-century sea level rise, Nature, 593, 74–82, 2021.

Favier, L., Durand, G., Cornford, S. L., Gudmundsson, G. H., Gagliardini, O., Gillet-Chaulet, F., Zwinger, T., Payne, A., and Le Brocq, A. M.: Retreat of Pine Island Glacier controlled by marine ice-sheet instability, Nature Climate Change, 4, 117–121, https://doi.org/10.1038/nclimate2094, 2014.

Feldmann, J., Albrecht, T., Khroulev, C., Pattyn, F., and Levermann, A.: Resolution-dependent performance of grounding line motion in a shallow model compared with a full-Stokes model according to the MISMIP3d intercomparison, Journal of Glaciology, 60, 353–360, https://doi.org/10.3189/2014JoG13J093, 2014.

Fox-Kemper, B., Hewitt, H., Xiao, C., Aðalgeirsdóttir, G., Drijfhout, S., Edwards, T., Golledge, N., Hemer, M., Kopp, R., Krinner, G., Mix, A., Notz, D., Nowicki, S., Nurhati, I., Ruiz, L., Sallée, J.-B., Slangen, A., and Yu, Y.: Ocean, Cryosphere and Sea Level Change. In Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)], Cambridge University Press, pp. 1211–1362, 2021.

Fretwell, P., Pritchard, H. D., Vaughan, D. G., Bamber, J. L., Barrand, N. E., Bell, R., Bianchi, C., Bingham, R., Blankenship, D. D., Casassa, G., et al.: Bedmap2: improved ice bed, surface and thickness datasets for Antarctica, The Cryosphere, 7, 375–393, https://doi.org/10.5194/tc-7-375-2013, 2013.

Fyke, J., Sergienko, O., Löfverström, M., Price, S., and Lenaerts, J. T.: An overview of interactions and feedbacks between ice sheets and the Earth system, Reviews of Geophysics, 56, 361–408, https://doi.org/10.1029/2018RG000600, 2018.

Garbe, J., Albrecht, T., Levermann, A., Donges, J. F., and Winkelmann, R.: The hysteresis of the Antarctic Ice Sheet, Nature, 585, 538–544, https://doi.org/10.1038/s41586-020-2727-5, 2020.

Garbe, J., Zeitz, M., Krebs-Kanzow, U., and Winkelmann, R.: The evolution of future Antarctic surface melt using PISM-dEBM-simple, The Cryosphere Discussions, pp. 1–39, 2023.

Golledge, N., Levy, R., McKay, R., and Naish, T.: East Antarctic ice sheet most vulnerable to Weddell Sea warming, Geophysical Research Letters, 44, 2343–2351, https://doi.org/10.1002/2016GL072422, 2017.

Golledge, N. R., Kowalewski, D. E., Naish, T. R., Levy, R. H., Fogwill, C. J., and Gasson, E. G.: The multi-millennial Antarctic commitment to future sea-level rise, Nature, 526, 421–425, https://doi.org/10.1038/nature15706, 2015.

Golledge, N. R., Keller, E. D., Gomez, N., Naughten, K. A., Bernales, J., Trusel, L. D., and Edwards, T. L.: Global environmental consequences of twenty-first-century ice-sheet melt, Nature, 566, 65–72, https://doi.org/10.1038/s41586-019-0889-9, 2019.

Golledge, N. R., Clark, P. U., He, F., Dutton, A., Turney, C., Fogwill, C., Naish, T., Levy, R. H., McKay, R. M., Lowry, D. P., et al.: Retreat of the Antarctic Ice Sheet during the Last Interglaciation and implications for future change, Geophysical Research Letters, 48, e2021GL094 513, https://doi.org/10.1029/2021GL094513, 2021.

Goosse, H., Brovkin, V., Fichefet, T., Haarsma, R., Huybrechts, P., Jongma, J., Mouchet, A., Selten, F., Barriat, P.-Y., Campin, J.-M., Deleersnijder, E., Driesschaert, E., Goelzer, H., Janssens, I., Loutre, M.-F., Morales Maqueda, M. A., Opsteegh, T., Mathieu, P.-P., Munhoven, G., Pettersson, E. J., Renssen, H., Roche, D. M., Schaeffer, M., Tartinville, B., Timmermann, A., and Weber, S. L.: Description of the Earth system model of intermediate complexity LOVECLIM version 1.2, Geoscientific Model Development, 3, 603–633, https://doi.org/10.5194/gmd-3-603-2010, 2010.

Gudmundsson, G. H., Krug, J., Durand, G., Favier, L., and Gagliardini, O.: The stability of grounding lines on retrograde slopes, The Cryosphere, 6, 1497–1505, https://doi.org/10.5194/tc-6-1497-2012, 2012.

Gulev, S., Thorne, P., Ahn, J., Dentener, F., Domingues, C., Gerland, S., Gong, D., Kaufman, D., Nnamchi, H., Quaas, J., Rivera, J., Sathyendranath, S., Smith, S., Trewin, B., von Schuckmann, K., and Vose, R.: Changing State of the Climate System. In Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)], Cambridge University Press, p. 287–422, 2021.

Haseloff, M. and Sergienko, O. V.: The effect of buttressing on grounding line dynamics, Journal of Glaciology, 64, 417–431, https://doi.org/10.1017/jog.2018.30, 2018.

Haseloff, M. and Sergienko, O. V.: Effects of calving and submarine melting on steady states and stability of buttressed marine ice sheets, Journal of Glaciology, p. 1–18, https://doi.org/10.1017/jog.2022.29, 2022.

Hellmer, H. H., Kauker, F., Timmermann, R., Determann, J., and Rae, J.: Twenty-first-century warming of a large Antarctic ice-shelf cavity by a redirected coastal current, Nature, 485, 225–228, 2012.

Huybrechts, P. and De Wolde, J.: The dynamic response of the Greenland and Antarctic ice sheets to multiple-century climatic warming, Journal of Climate, 12, 2169–2188, https://doi.org/10.1175/1520-0442(1999)012<2169:TDROTG>2.0.CO;2, 1999.

Jakobs, C. L., Reijmer, C. H., Kuipers Munneke, P., König-Langlo, G., and Van Den Broeke, M. R.: Quantifying the snowmelt–albedo feedback at Neumayer Station, East Antarctica, The Cryosphere, 13, 1473–1485, https://doi.org/10.5194/tc-13-1473-2019, 2019.

Jakobs, C. L., Reijmer, C. H., van den Broeke, M. R., Van de Berg, W., and Van Wessem, J.: Spatial Variability of the Snowmelt-Albedo Feedback in Antarctica, Journal of Geophysical Research: Earth Surface, 126, e2020JF005 696, https://doi.org/10.1029/2020JF005696, 2021.

Jenkins, A., Shoosmith, D., Dutrieux, P., Jacobs, S., Kim, T. W., Lee, S. H., Ha, H. K., and Stammerjohn, S.: West Antarctic Ice Sheet retreat in the Amundsen Sea driven by decadal oceanic variability, Nature Geoscience, 11, 733–738, https://doi.org/10.1038/s41561-018-0207-4, 2018.

Joughin, I., Smith, B. E., and Medley, B.: Marine ice sheet collapse potentially under way for the Thwaites Glacier Basin, West Antarctica, Science, 344, 735–738, https://doi.org/10.1126/science.1249055, 2014.

Kittel, C., Amory, C., Agosta, C., Jourdain, N. C., Hofer, S., Delhasse, A., Doutreloup, S., Huot, P.-V., Lang, C., Fichefet, T., and Fettweis, X.: Diverging future surface mass balance between the Antarctic ice shelves and grounded ice sheet, The Cryosphere, 15, 1215–1236, https://doi.org/10.5194/tc-15-1215-2021, 2021.

Kreuzer, M., Reese, R., Huiskamp, W. N., Petri, S., Albrecht, T., Feulner, G., and Winkelmann, R.: Coupling framework (1.0) for the PISM (1.1.4) ice sheet model and the MOM5 (5.1.0) ocean model via the PICO ice shelf cavity model in an Antarctic domain, Geoscientific Model Development, 14, 3697–3714, https://doi.org/10.5194/gmd-14-3697-2021, 2021.

Lai, C.-Y., Kingslake, J., Wearing, M. G., Chen, P.-H. C., Gentine, P., Li, H., Spergel, J. J., and Van Wessem, J. M.: Vulnerability of Antarctica's ice shelves to meltwater-driven fracture, Nature, 584, 574–578, 2020.

Le Meur, E. and Huybrechts, P.: A comparison of different ways of dealing with isostasy: examples from modelling the Antarctic ice sheet during the last glacial cycle, Annals of Glaciology, 23, 309–317, https://doi.org/10.3189/S0260305500013586, 1996.

Lee, J.-Y., Marotzke, J., Bala, G., Cao, L., Corti, S., Dunne, J., Engelbrecht, F., Fischer, E., Fyfe, J., Jones, C., Maycock, A., Mutemi, J., Ndiaye, O., Panickal, S., and Zhou, T.: Future Global Climate: Scenario-Based Projections and Near- Term Information. In Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)], Cambridge University Press, pp. 553–672, 2021.

Lenton, T. M., Held, H., Kriegler, E., Hall, J. W., Lucht, W., Rahmstorf, S., and Schellnhuber, H. J.: Tipping elements in the Earth's climate system, Proceedings of the National Academy of Sciences, 105, 1786–1793, https://doi.org/10.1073/pnas.0705414105, 2008.

Lenton, T. M., Armstrong McKay, D., Loriani, S., Abrams, J., Lade, S., Donges, J., Milkoreit, M., Powell, M., Smith, S., Zimm, C., Buxton, C., Bailey, E., Laybourn, L., Ghadiali, A., and Dyke, J. e.: The Global Tipping Points Report 2023, University of Exeter, Exeter, UK., 2023.

Levermann, A. and Winkelmann, R.: A simple equation for the melt elevation feedback of ice sheets, The Cryosphere, 10, 1799–1807, https://doi.org/10.5194/tc-10-1799-2016, 2016.

Levermann, A., Albrecht, T., Winkelmann, R., Martin, M. A., Haseloff, M., and Joughin, I.: Kinematic first-order calving law implies potential for abrupt ice-shelf retreat, The Cryosphere, 6, 273–286, https://doi.org/10.5194/tc-6-273-2012, 2012.

Levy, R., Harwood, D., Florindo, F., Sangiorgi, F., Tripati, R., Von Eynatten, H., Gasson, E., Kuhn, G., Tripati, A., DeConto, R., et al.: Antarctic ice sheet sensitivity to atmospheric CO2 variations in the early to mid-Miocene, Proceedings of the National Academy of Sciences, 113, 3453–3458, https://doi.org/10.1073/pnas.1516030113, 2016.

Li, C., von Storch, J.-S., and Marotzke, J.: Deep-ocean heat uptake and equilibrium climate response, Climate Dynamics, 40, 1071–1086, https://doi.org/10.1007/s00382-012-1350-z, 2013.

Li, X., Rignot, E., Mouginot, J., and Scheuchl, B.: Ice flow dynamics and mass loss of Totten Glacier, East Antarctica, from 1989 to 2015, Geophysical Research Letters, 43, 6366–6373, https://doi.org/10.1002/2016GL069173, 2016.

Lingle, C. S. and Clark, J. A.: A numerical model of interactions between a marine ice sheet and the solid earth: Application to a West Antarctic ice stream, Journal of Geophysical Research: Oceans, 90, 1100–1114, https://doi.org/10.1029/JC090iC01p01100, 1985.

Lowry, D. P., Krapp, M., Golledge, N. R., and Alevropoulos-Borrill, A.: The influence of emissions scenarios on future Antarctic ice loss is unlikely to emerge this century, Communications Earth & Environment, 2, 1–14, 2021.

Martin, D. F., Cornford, S. L., and Payne, A. J.: Millennial-scale vulnerability of the Antarctic ice sheet to regional ice shelf collapse, Geophysical Research Letters, 46, 1467–1475, 2019.

Martin, M. A., Winkelmann, R., Haseloff, M., Albrecht, T., Bueler, E., Khroulev, C., and Levermann, A.: The Potsdam Parallel Ice Sheet Model (PISM-PIK)–Part 2: dynamic equilibrium simulation of the Antarctic ice sheet, The Cryosphere, 5, 727–740, https://doi.org/10.5194/tc-5-727-2011, 2011.

Meehl, G. A., Senior, C. A., Eyring, V., Flato, G., Lamarque, J.-F., Stouffer, R. J., Taylor, K. E., and Schlund, M.: Context for interpreting equilibrium climate sensitivity and transient climate response from the CMIP6 Earth system models, Science Advances, 6, eaba1981, https://doi.org/10.1126/sciadv.aba1981, 2020.

Mengel, M. and Levermann, A.: Ice plug prevents irreversible discharge from East Antarctica, Nature Climate Change, 4, 451–455, https://doi.org/10.1038/nclimate2226, 2014.

Merz, N., Gfeller, G., Born, A., Raible, C., Stocker, T., and Fischer, H.: Influence of ice sheet topography on Greenland precipitation during the Eemian interglacial, Journal of Geophysical Research: Atmospheres, 119, 10–749, https://doi.org/10.1002/2014JD021940, 2014.

Mikkelsen, T. B., Grinsted, A., and Ditlevsen, P.: Influence of temperature fluctuations on equilibrium ice sheet volume, The Cryosphere, 12, 39–47, https://doi.org/10.5194/tc-12-39-2018, 2018.

Miles, B. W., Jordan, J. R., Stokes, C. R., Jamieson, S. S., Gudmundsson, G. H., and Jenkins, A.: Recent acceleration of Denman Glacier (1972–2017), East Antarctica, driven by grounding line retreat and changes in ice tongue configuration, The Cryosphere, 15, 663–676, https://doi.org/10.5194/tc-15-663-2021, 2021.

Morlighem, M., Rignot, E., Binder, T., Blankenship, D., Drews, R., Eagles, G., Eisen, O., Ferraccioli, F., Forsberg, R., Fretwell, P., et al.: Deep glacial troughs and stabilizing ridges unveiled beneath the margins of the Antarctic ice sheet, Nature Geoscience, 13, 132–137, https://doi.org/10.1038/s41561-019-0510-8, 2020.

Mottram, R., Hansen, N., Kittel, C., Van Wessem, J. M., Agosta, C., Amory, C., Boberg, F., van de Berg, W. J., Fettweis, X., Gossart, A., et al.: What is the surface mass balance of Antarctica? An intercomparison of regional climate model estimates, The Cryosphere, 15, 3751–3784, https://doi.org/10.5194/tc-15-3751-2021, 2021.

Naish, T., Powell, R., Levy, R., Wilson, G., Scherer, R., Talarico, F., Krissek, L., Niessen, F., Pompilio, M., Wilson, T., et al.: Obliquity-paced Pliocene West Antarctic ice sheet oscillations, Nature, 458, 322–328, https://doi.org/10.1038/nature07867, 2009.

Naish, T. R., Woolfe, K. J., Barrett, P. J., Wilson, G. S., Atkins, C., Bohaty, S. M., Bücker, C. J., Claps, M., Davey, F. J., Dunbar, G. B., et al.: Orbitally induced oscillations in the East Antarctic ice sheet at the Oligocene/Miocene boundary, Nature, 413, 719–723, https://doi.org/10.1038/35099534, 2001.

Nias, I. J., Cornford, S. L., and Payne, A. J.: Contrasting the modelled sensitivity of the Amundsen Sea Embayment ice streams, Journal of Glaciology, 62, 552–562, https://doi.org/10.1017/jog.2016.40, 2016.

Nowicki, S., Goelzer, H., Seroussi, H., Payne, A. J., Lipscomb, W. H., Abe-Ouchi, A., Agosta, C., Alexander, P., Asay-Davis, X. S., Barthel, A., Bracegirdle, T. J., Cullather, R., Felikson, D., Fettweis, X., Gregory, J. M., Hattermann, T., Jourdain, N. C., Kuipers Munneke, P., Larour, E., Little, C. M., Morlighem, M., Nias, I., Shepherd, A., Simon, E., Slater, D., Smith, R. S., Straneo, F., Trusel, L. D., van den Broeke, M. R., and van de Wal, R.: Experimental protocol for sea level projections from ISMIP6 stand-alone ice sheet models, The Cryosphere, 14, 2331–2368, https://doi.org/10.5194/tc-14-2331-2020, 2020.

Oerlemans, J.: Some basic experiments with a vertically-integrated ice sheet model, Tellus, 33, 1–11, https://doi.org/10.3402/tellusa.v33i1.10690, 1981.

O'Neill, B. C., Tebaldi, C., Van Vuuren, D. P., Eyring, V., Friedlingstein, P., Hurtt, G., Knutti, R., Kriegler, E., Lamarque, J.-F., Lowe, J., et al.: The scenario model intercomparison project (ScenarioMIP) for CMIP6, Geoscientific Model Development, 9, 3461–3482, https://doi.org/10.5194/gmd-9-3461-2016, 2016.

Otosaka, I. N., Shepherd, A., Ivins, E. R., Schlegel, N.-J., Amory, C., van den Broeke, M. R., Horwath, M., Joughin, I., King, M. D., Krinner, G., Nowicki, S., Payne, A. J., Rignot, E., Scambos, T., Simon, K. M., Smith, B. E., Sørensen, L. S., Velicogna, I., Whitehouse, P. L., A, G., Agosta, C., Ahlstrøm, A. P., Blazquez, A., Colgan, W., Engdahl, M. E., Fettweis, X., Forsberg, R., Gallée, H., Gardner, A., Gilbert, L., Gourmelen, N., Groh, A., Gunter, B. C., Harig, C., Helm, V., Khan, S. A., Kittel, C., Konrad, H., Langen, P. L., Lecavalier, B. S., Liang, C.-C., Loomis, B. D., McMillan, M., Melini, D., Mernild, S. H., Mottram, R., Mouginot, J., Nilsson, J., Noël, B., Pattle, M. E., Peltier, W. R., Pie, N., Roca, M., Sasgen, I., Save, H. V., Seo, K.-W., Scheuchl, B., Schrama, E. J. O., Schröder, L., Simonsen, S. B., Slater, T., Spada, G., Sutterley, T. C., Vishwakarma, B. D., Van Wessem, J. M., Wiese, D., van der Wal, W., and Wouters, B.: Mass balance of the Greenland and Antarctic ice sheets from 1992 to 2020, Earth System Science Data, 15, 1597–1616, https://doi.org/10.5194/essd-15-1597-2023, 2023.

Paolo, F., Padman, L., Fricker, H., Adusumilli, S., Howard, S., and Siegfried, M.: Response of Pacific-sector Antarctic ice shelves to the El Niño/Southern oscillation, Nature geoscience, 11, 121–126, 2018.

Paolo, F. S., Fricker, H. A., and Padman, L.: Volume loss from Antarctic ice shelves is accelerating, Science, 348, 327–331, https://doi.org/10.1126/science.aaa0940, 2015.

Patterson, M. O., McKay, R., Naish, T., Escutia, C., Jimenez-Espejo, F., Raymo, M., Meyers, S., Tauxe, L., and Brinkhuis, H.: Orbital forcing of the East Antarctic ice sheet during the Pliocene and Early Pleistocene, Nature Geoscience, 7, 841–847, https://doi.org/10.1038/ngeo2273, 2014.

Pattyn, F.: Sea-level response to melting of Antarctic ice shelves on multi-centennial timescales with the fast Elementary Thermomechanical Ice Sheet model (f.ETISh v1.0), The Cryosphere, 11, 1851–1878, https://doi.org/10.5194/tc-11-1851-2017, 2017.

Pattyn, F., Perichon, L., Durand, G., Favier, L., Gagliardini, O., Hindmarsh, R. C., Zwinger, T., Albrecht, T., Cornford, S., Docquier, D., and et al.: Grounding-line migration in plan-view marine ice-sheet models: results of the ice2sea MISMIP3d intercomparison, Journal of Glaciology, 59, 410–422, https://doi.org/10.3189/2013JoG12J129, 2013.

Payne, A. J., Nowicki, S., Abe-Ouchi, A., Agosta, C., Alexander, P., Albrecht, T., Asay-Davis, X., Aschwanden, A., Barthel, A., Bracegirdle, T. J., 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, e2020GL091 741, https://doi.org/10.1029/2020GL091741, 2021.

Pegler, S. S.: Marine ice sheet dynamics: the impacts of ice-shelf buttressing, Journal of Fluid Mechanics, 857, 605–647, https://doi.org/10.1038/s41561-017-0033-0, 2018.

Pollard, D. and DeConto, R. M.: Description of a hybrid ice sheet-shelf model, and application to Antarctica, Geoscientific Model Development, 5, 1273–1295, https://doi.org/10.5194/gmd-5-1273-2012, 2012a.

Pollard, D. and DeConto, R. M.: A simple inverse method for the distribution of basal sliding coefficients under ice sheets, applied to Antarctica, The Cryosphere, 6, 953–971, https://doi.org/10.5194/tc-6-953-2012, 2012b.

Pollard, D. and DeConto, R. M.: Improvements in one-dimensional grounding-line parameterizations in an ice-sheet model with lateral variations (PSUICE3D v2.1), Geoscientific Model Development, 13, 6481–6500, https://doi.org/10.5194/gmd-13-6481-2020, 2020.

Pollard, D., DeConto, R. M., and Alley, R. B.: Potential Antarctic Ice Sheet retreat driven by hydrofracturing and ice cliff failure, Earth and Planetary Science Letters, 412, 112–121, https://doi.org/10.1016/j.epsl.2014.12.035, 2015.

Purich, A. and England, M. H.: Historical and future projected warming of Antarctic Shelf Bottom Water in CMIP6 models, Geophysical Research Letters, 48, e2021GL092 752, https://doi.org/10.1029/2021GL092752, 2021.

Reeh, N.: Parameterization of melt rate and surface temperature on the Greenland ice sheet, Polarforschung, 59, 113–128, 1991.

Reese, R., Albrecht, T., Mengel, M., Asay-Davis, X., and Winkelmann, R.: Antarctic sub-shelf melt rates via PICO, The Cryosphere, 12, 1969–1985, https://doi.org/10.5194/tc-12-1969-2018, 2018.

Reese, R., Levermann, A., Albrecht, T., Seroussi, H., and Winkelmann, R.: The role of history and strength of the oceanic forcing in sea level projections from Antarctica with the Parallel Ice Sheet Model, The Cryosphere, 14, 3097–3110, https://doi.org/10.5194/tc-14-3097-2020, 2020.

Reese, R., Garbe, J., Hill, E. A., Urruty, B., Naughten, K. A., Gagliardini, O., Durand, G., Gillet-Chaulet, F., Gudmundsson, G. H., Chandler, D., et al.: The stability of present-day Antarctic grounding lines–Part 2: Onset of irreversible retreat of Amundsen Sea glaciers under current climate on centennial timescales cannot be excluded, The Cryosphere, 17, 3761–3783, https://doi.org/10.5194/tc-17-3761-2023, 2023.

Rignot, E., Mouginot, J., and Scheuchl, B.: Ice flow of the Antarctic Ice Sheet, Science, 333, 1427–1430, https://doi.org/10.1126/science.1208336, 2011.

Rignot, E., Mouginot, J., Scheuchl, B., Van Den Broeke, M., Van Wessem, M. J., and Morlighem, M.: Four decades of Antarctic Ice Sheet mass balance from 1979–2017, Proceedings of the National Academy of Sciences, 116, 1095–1103, https://doi.org/10.1073/pnas.1812883116, 2019.

Ritchie, P. D., Clarke, J. J., Cox, P. M., and Huntingford, C.: Overshooting tipping point thresholds in a changing climate, Nature, 592, 517–523, https://doi.org/10.1038/s41586-021-03263-2, 2021.

Robel, A. A., Seroussi, H., and Roe, G. H.: Marine ice sheet instability amplifies and skews uncertainty in projections of future sea-level rise, Proceedings of the National Academy of Sciences, 116, 14 887–14 892, https://doi.org/10.1073/pnas.1904822116, 2019.

Robinson, A., Calov, R., and Ganopolski, A.: Multistability and critical thresholds of the Greenland ice sheet, Nature Climate Change, 2, 429–432, https://doi.org/10.1038/nclimate1449, 2012.

Rosier, S. H., Reese, R., Donges, J. F., De Rydt, J., Gudmundsson, G. H., and Winkelmann, R.: The tipping points and early warning indicators for Pine Island Glacier, West Antarctica, The Cryosphere, 15, 1501–1516, https://doi.org/10.5194/tc-15-1501-2021, 2021.

Schmidtko, S., Heywood, K. J., Thompson, A. F., and Aoki, S.: Multidecadal warming of Antarctic waters, Science, 346, 1227–1231, https://doi.org/10.1126/science.1256117, 2014.

Schoof, C.: Ice sheet grounding line dynamics: Steady states, stability, and hysteresis, Journal of Geophysical Research: Earth Surface, 112, https://doi.org/10.1029/2006JF000664, 2007.

Sergienko, O. V.: No general stability conditions for marine ice-sheet grounding lines in the presence of feedbacks, Nature Communications, 13, 2265, https://doi.org/10.1038/s41467-022-29892-3, 2022.

Seroussi, H., Nakayama, Y., Larour, E., Menemenlis, D., Morlighem, M., Rignot, E., and Khazendar, A.: Continued retreat of Thwaites Glacier, West Antarctica, controlled by bed topography and ocean circulation, Geophysical Research Letters, 44, 6191–6199, https://doi.org/10.1002/2017GL072910, 2017.

Seroussi, H., Nowicki, S., Simon, E., Abe-Ouchi, A., Albrecht, T., Brondex, J., Cornford, S., Dumas, C., Gillet-Chaulet, F., Goelzer, H., et al.: initMIP-Antarctica: an ice sheet model initialization experiment of ISMIP6, The Cryosphere, 13, 1441–1471, https://doi.org/10.5194/tc-13-1441-2019, 2019.

Seroussi, H., Nowicki, S., Payne, A. J., Goelzer, H., Lipscomb, W. H., Abe-Ouchi, A., Agosta, C., Albrecht, T., Asay-Davis, X., Barthel, A., et al.: ISMIP6 Antarctica: a multi-model ensemble of the Antarctic ice sheet evolution over the 21st century, The Cryosphere, 14, 3033–3070, https://doi.org/10.5194/tc-14-3033-2020, 2020.

Seroussi, H., Verjans, V., Nowicki, S., Payne, A. J., Goelzer, H., Lipscomb, W. H., Abe-Ouchi, A., Agosta, C., Albrecht, T., Asay-Davis, X., Barthel, A., Calov, R., Cullather, R., Dumas, C., Galton-Fenzi, B. K., Gladstone, R., Golledge, N. R., Gregory, J. M., Greve, R., Hattermann, T., Hoffman, M. J., Humbert, A., Huybrechts, P., Jourdain, N. C., Kleiner, T., Larour, E., Leguy, G. R., Lowry, D. P., Little,

C. M., Morlighem, M., Pattyn, F., Pelle, T., Price, S. F., Quiquet, A., Reese, R., Schlegel, N.-J., Shepherd, A., Simon, E., Smith, R. S., Straneo, F., Sun, S., Trusel, L. D., Van Breedam, J., Van Katwyk, P., van de Wal, R. S. W., Winkelmann, R., Zhao, C., Zhang, T., and Zwinger, T.: Insights into the vulnerability of Antarctic glaciers from the ISMIP6 ice sheet model ensemble and associated uncertainty, The Cryosphere, 17, 5197–5217, https://doi.org/10.5194/tc-17-5197-2023, 2023.

Shakun, J. D., Corbett, L. B., Bierman, P. R., Underwood, K., Rizzo, D. M., Zimmerman, S. R., Caffee, M. W., Naish, T., Golledge, N. R., and Hay, C. C.: Minimal East Antarctic Ice Sheet retreat onto land during the past eight million years, Nature, 558, 284–287, https://doi.org/10.1038/s41586-018-0155-6, 2018.

Siahaan, A., Smith, R. S., Holland, P. R., Jenkins, A., Gregory, J. M., Lee, V., Mathiot, P., Payne, A. J., Ridley, J. K., and Jones, C. G.: The Antarctic contribution to 21st-century sea-level rise predicted by the UK Earth System Model with an interactive ice sheet, The Cryosphere, 16, 4053–4086, 2022.

Smith, B., Fricker, H. A., Gardner, A. S., Medley, B., Nilsson, J., Paolo, F. S., Holschuh, N., Adusumilli, S., Brunt, K., Csatho, B., et al.: Pervasive ice sheet mass loss reflects competing ocean and atmosphere processes, Science, 368, 1239–1242, 2020.

Sugden, D. E., Marchant, D. R., Potter, N., Souchez, R. A., Denton, G. H., Swisher III, C. C., and Tison, J.-L.: Preservation of Miocene glacier ice in East Antarctica, Nature, 376, 412–414, https://doi.org/10.1038/376412a0, 1995.

Sun, S., Pattyn, F., Simon, E. G., Albrecht, T., Cornford, S., Calov, R., Dumas, C., Gillet-Chaulet, F., Goelzer, H., Golledge, N. R., and et al.: Antarctic ice sheet response to sudden and sustained ice-shelf collapse (ABUMIP), Journal of Glaciology, p. 891–904, https://doi.org/0.1017/jog.2020.67, 2020.

Sutter, J., Jones, A., Frölicher, T., Wirths, C., and Stocker, T.: Climate intervention on a high-emissions pathway could delay but not prevent West Antarctic Ice Sheet demise, Nature Climate Change, 13, 951–960, 2023.

Tebaldi, C., Debeire, K., Eyring, V., Fischer, E., Fyfe, J., Friedlingstein, P., Knutti, R., Lowe, J., O'Neill, B., Sanderson, B., van Vuuren, D., Riahi, K., Meinshausen, M., Nicholls, Z., Tokarska, K. B., Hurtt, G., Kriegler, E., Lamarque, J.-F., Meehl, G., Moss, R., Bauer, S. E., Boucher, O., Brovkin, V., Byun, Y.-H., Dix, M., Gualdi, S., Guo, H., John, J. G., Kharin, S., Kim, Y., Koshiro, T., Ma, L., Olivié, D., Panickal, S., Qiao, F., Rong, X., Rosenbloom, N., Schupfner, M., Séférian, R., Sellar, A., Semmler, T., Shi, X., Song, Z., Steger, C., Stouffer, R., Swart, N., Tachiiri, K., Tang, Q., Tatebe, H., Voldoire, A., Volodin, E., Wyser, K., Xin, X., Yang, S., Yu, Y., and Ziehn, T.: Climate model projections from the Scenario Model Intercomparison Project (ScenarioMIP) of CMIP6, Earth System Dynamics, 12, 253–293, https://doi.org/10.5194/esd-12-253-2021, 2021.

Tokarska, K. B., Zickfeld, K., and Rogelj, J.: Path independence of carbon budgets when meeting a stringent global mean temperature target after an overshoot, Earth's Future, 7, 1283–1295, https://doi.org/10.1029/2019EF001312, 2019.

Trusel, L. D., Frey, K. E., Das, S. B., Karnauskas, K. B., Kuipers Munneke, P., Van Meijgaard, E., and Van Den Broeke, M. R.: Divergent trajectories of Antarctic surface melt under two twenty-first-century climate scenarios, Nature Geoscience, 8, 927–932, 2015.

Turney, C. S., Fogwill, C. J., Golledge, N. R., McKay, N. P., van Sebille, E., Jones, R. T., Etheridge, D., Rubino, M., Thornton, D. P., Davies, S. M., et al.: Early Last Interglacial ocean warming drove substantial ice mass loss from Antarctica, Proceedings of the National Academy of Sciences, 117, 3996–4006, https://doi.org/10.1073/pnas.1902469117, 2020.

Van Breedam, J., Goelzer, H., and Huybrechts, P.: Semi-equilibrated global sea-level change projections for the next 10 000 years, Earth System Dynamics, 11, 953–976, https://doi.org/10.5194/esd-11-953-2020, 2020.

Van Wessem, J. M., Van De Berg, W. J., Noël, B. P., Van Meijgaard, E., Amory, C., Birnbaum, G., Jakobs, C. L., Krüger, K., Lenaerts, J., Lhermitte, S., et al.: Modelling the climate and surface mass balance of polar ice sheets using RACMO2–Part 2: Antarctica (1979–2016), The Cryosphere, 12, 1479–1498, https://doi.org/10.5194/tc-12-1479-2018, 2018.

Van Wessem, J. M., van den Broeke, M. R., Wouters, B., and Lhermitte, S.: Variable temperature thresholds of melt pond formation on Antarctic ice shelves, Nature Climate Change, 13, 161–166, 2023.

Weber, M., Clark, P., Kuhn, G., Timmermann, A., Sprenk, D., Gladstone, R., Zhang, X., Lohmann, G., Menviel, L., Chikamoto, M., et al.: Millennial-scale variability in Antarctic ice-sheet discharge during the last deglaciation, Nature, 510, 134–138, https://doi.org/10.1038/nature13397, 2014.

Weertman, J.: Stability of the junction of an ice sheet and an ice shelf, Journal of Glaciology, 13, 3–11, https://doi.org/10.3189/S0022143000023327, 1974.

Wilson, D. J., Bertram, R. A., Needham, E. F., van de Flierdt, T., Welsh, K. J., McKay, R. M., Mazumder, A., Riesselman, C. R., Jimenez-Espejo, F. J., and Escutia, C.: Ice loss from the East Antarctic Ice Sheet during late Pleistocene interglacials, Nature, 561, 383–386, https://doi.org/10.1038/s41586-018-0501-8, 2018.

Winkelmann, R., Martin, M. A., Haseloff, M., Albrecht, T., Bueler, E., Khroulev, C., and Levermann, A.: The Potsdam Parallel Ice Sheet Model (PISM-PIK)–Part 1: Model description, The Cryosphere, 5, 715–726, https://doi.org/10.5194/tc-5-715-2011, 2011.

Winkelmann, R., Levermann, A., Ridgwell, A., and Caldeira, K.: Combustion of available fossil fuel resources sufficient to eliminate the Antarctic Ice Sheet, Science Advances, 1, e1500 589, https://doi.org/10.1126/sciadv.1500589, 2015.

Zachos, J., Pagani, M., Sloan, L., Thomas, E., and Billups, K.: Trends, rhythms, and aberrations in global climate 65 Ma to present, Science, 292, 686–693, https://doi.org/10.1126/science.1059412, 2001.

Zeitz, M., Reese, R., Beckmann, J., Krebs-Kanzow, U., and Winkelmann, R.: Impact of the melt–albedo feedback on the future evolution of the Greenland Ice Sheet with PISM-dEBM-simple, The Cryosphere, 15, 5739–5764, https://doi.org/10.5194/tc-15-5739-2021, 2021.

Zhu, J., Otto-Bliesner, B. L., Brady, E. C., Poulsen, C. J., Tierney, J. E., Lofverstrom, M., and DiNezio, P.: Assessment of equilibrium climate sensitivity of the Community Earth System Model version 2 through simulation of the Last Glacial Maximum, Geophysical Research Letters, 48, e2020GL091 220, https://doi.org/10.1029/2020GL091220, 2021.

Supplementary Material: The long–term sea–level commitment from Antarctica

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Table S1. Forcings for assessing the Antarctic sea-level commitment in terms of projected atmospheric temperature change at different points in time. Projected Antarctic–averaged atmospheric temperature change with respect to mean over time period 1995–2014 at different points in time for the four CMIP6 GCMs used to force the ice–sheet models. For a given point in time, upper rows represent SSP1-2.6 and lower rows correspond to SSP5-8.5. The corresponding Antarctic sea-level commitment is determined with all ice-sheet model configurations given in Tab. S2.

		MRI-ESM2-0	CESM2-WACCM	IPSL-CM6A-LR	UKESM1-0-LL
2050	SSP1-2.6	0.90	1.26	1.54	1.34
	SSP5-8.5	1.38	1.90	1.85	1.86
2100	SSP1-2.6	1.38	2.43	1.56	1.26
	SSP5-8.5	5.02	6.35	5.30	6.20
2150	SSP1-2.6	1.77	2.50	1.10	1.35
	SSP5-8.5	8.50	10.47	8.99	9.66
2200	SSP1-2.6	1.89	2.86	1.16	1.39
	SSP5-8.5	10.70	13.36	11.67	11.80
2250	SSP1-2.6	2.26	2.81	1.44	1.18
	SSP5-8.5	11.57	15.14	13.39	13.05
2300	SSP1-2.6	2.36	3.58	0.98	1.22
	SSP5-8.5	12.14	16.4	14.08	13.52

Table S2. Ice-sheet model configurations. Ice-sheet model configurations used for assessing Antarctic sea-level commitment. While ice—sheet initial conditions with Kori-ULB are obtained in an inverse simulation for each of the atmospheric climatologies, it is derived from a spin–up ensemble for each atmospheric climatologies in PISM. The combinations of PISM parameters for the initial states selected from these ensembles are given as well.

	Atmospheric climatology	Sliding exponent	SIA enhancement factor	Tillwater decay rate	Till effective overburden fraction
Kori-ULB	MARv3.11	-	-	-	-
	RACMO2.3p2	-	-	-	-
PISM	MARv3.11	0.75	2.0	7 mm yr^{-1}	0.015
	RACMO2.3p2	0.5	1.5	7 mm yr^{-1}	0.015

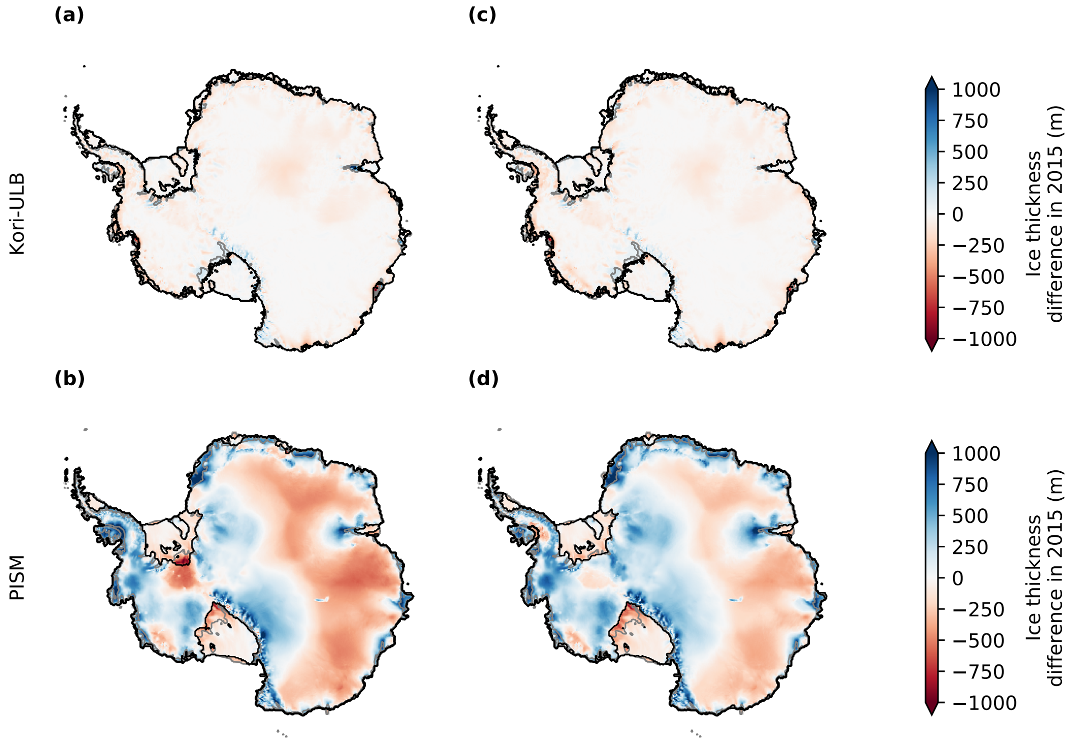

Figure S1. Comparison between modelled and observed ice–sheet geometry. Modelled present–day ice thickness in Kori-ULB (upper row) and PISM (lower row), using atmospheric climatologies based on MAR (left column) and RACMO (right column) relative to observed ice thickness (Bedmachine for Kori-ULB and Bedmap2 for PISM). Modelled and observed grounding line and calving front position are shown in black and grey, respectively. Note the different scales of the colourbar for Kori-ULB and PISM.

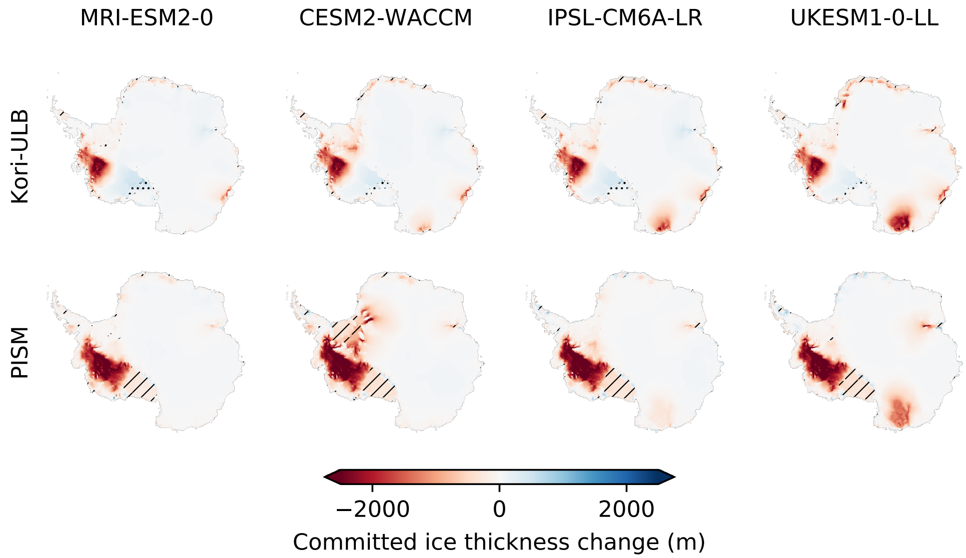

Figure S2. Committed ice–sheet configuration under lower–emission pathways SSP1-2.6 in response to changing climatic boundary conditions projected by CMIP6 GCMs following the lower–emission pathway SSP1-2.6, as determined by Kori-ULB and PISM. Shown is the mean committed thickness change and grounding–line location (marked in black), averaged across all branchoff points in time and the respective ice–sheet model configurations. A potential loss of ice shelves is indicated by hatches. Dots mark ice–sheet advance areas.

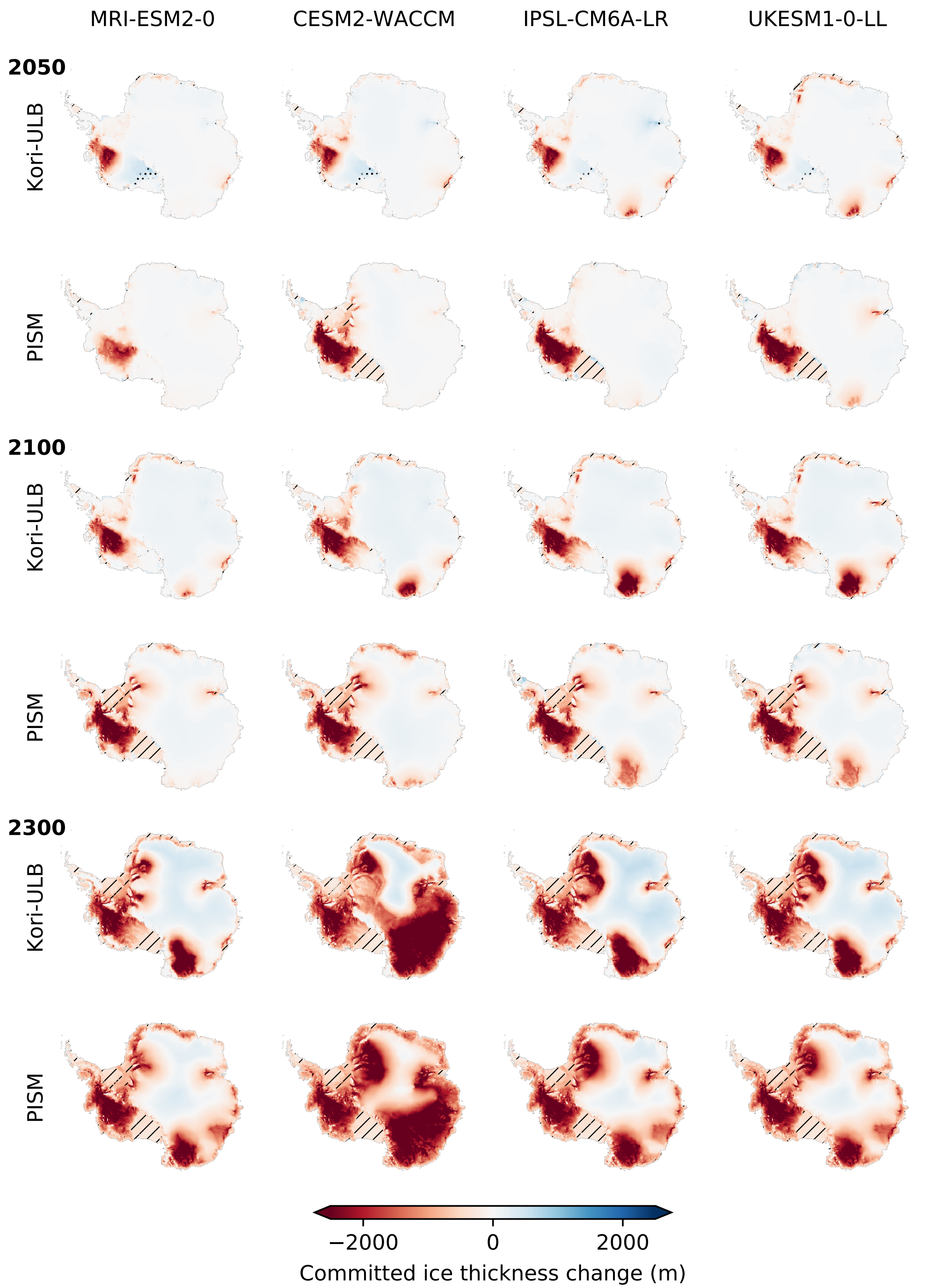

Figure S3. Committed ice–sheet configuration in response to changing climatic boundary conditions projected by CMIP6 GCMs in year 2050, 2100 and 2300 following the higher–emission pathway SSP5-8.5, as determined by Kori-ULB and PISM. Shown is the mean committed thickness change and grounding–line location (marked in black), averaged across the respective ice–sheet model configurations. A potential loss of ice shelves is indicated by hatches. Dots mark ice–sheet advance areas.

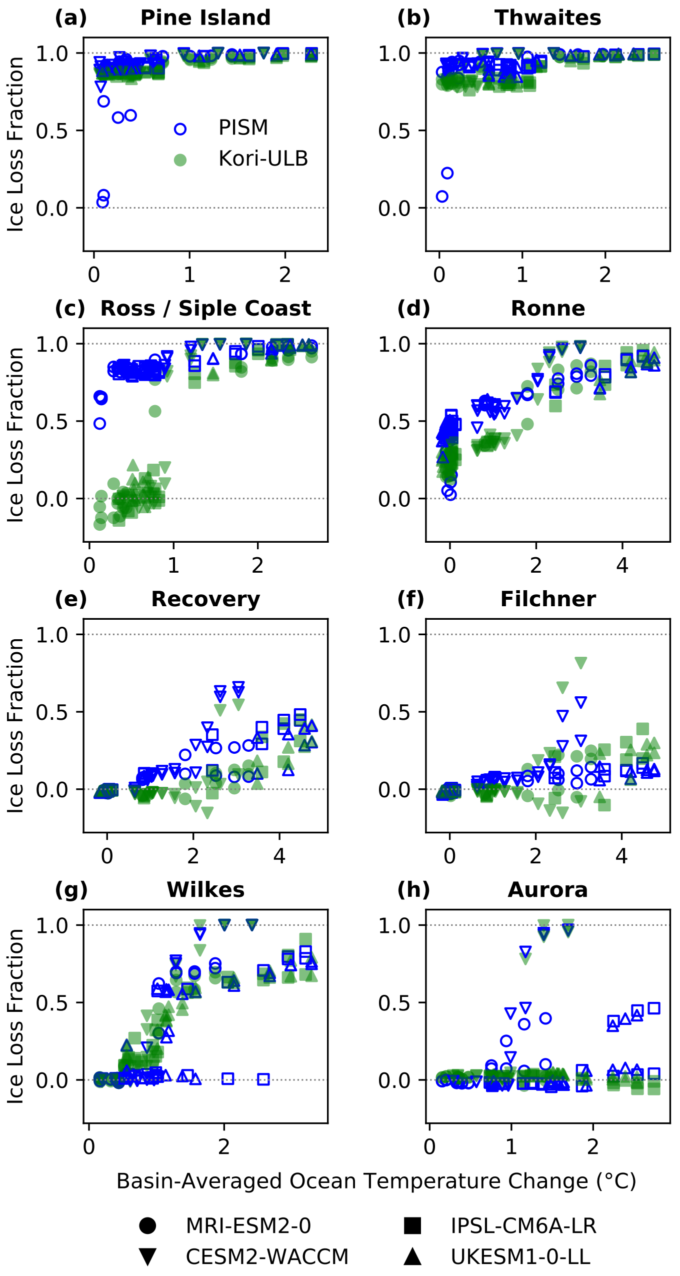

Figure S4. Ice loss from Antarctic drainage basins depending on ocean temperature change. Long–term ice loss from different Antarctic drainage basins (as fraction of respective sea–level rise potential) for the year 7000 in response to basin–averaged ocean temperature change (compared to 1995–2014) as projected by four different GCMs (given by marker shape). Filled, green and open, blue markers correspond to the long–term ice loss determined by Kori-ULB and PISM, respectively.