Interactive comment on “Precipitation Ansatz dependent Future Sea Level Contribution by Antarctica based on CMIP5 Model Forcing” by Christian B. Rodehacke et al.

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General comments:

Rodehacke and colleagues investigate the effects of multiple climate model forcings (from CMIP5) in Antarctica. They assess the spatial heterogeneity in temperature and precipitation estimates over the period 1850-2100 for different emission scenarios and the spread among the 9 selected climate models. The ratio of precipitation anomalies and temperature anomalies is compared to paleo estimates at 6 ice core locations and regional variations from the spatial mean are discussed. Applied to the ice sheet model PISM they run an ensemble of simulations up to the year 5000 with both the anomaly forcing fields from the climate models and the simplified (spatial mean) parameterization (as often used in previous studies) and find quite some differences in the projected ice mass changes (converted in units of sea-level equivalents).

While in this study the temperature-scaled precipitation results in long-term ice losses, the directly applied precipitation anomalies generate net mass gains. Given the numerous previous projection studies, this is a surprising result. However, for given model settings this discrepancy can to some extent be explained in the manuscript. Overall, the study is well structured and the manuscript clearly-arranged. The main manuscript is separated into introduction, material and methods, results and discussions, conclusions and an appendix part. Due to its length of 42 pages including figures and references and 20 pages in the Appendix, it is sometimes difficult for the reader to follow the line of thought. The conclusions with almost 3 pages should be condensed, many discussed aspects could be merged into the introduction and discussion part. In general, the manuscript needs some additional work to improve the readability and to clarify the main key messages for the reader and avoid redundant informations. Also typos and the german-style syntax sometimes hampers the reader to fully grasp the content of the manuscript.

Figures have good quality and are informative, some are overloaded with up to 27 curves. Literature is sufficiently covered with 97 references. The investigation of the impact of climate boundary conditions on the future evolution of the Antarctic ice sheet supports the publication in ESD. However, as the main focus seems to be on the evaluation of climate model result and the systematic and comprehensive sensitivity analysis of the ice sheet model to the two different types of precipitation forcing, this study would also very well fit into a model-specific journal like GMD.

This study by Rodehacke et al. has the potential to be a valuable contribution to the scientific community of ice sheet modelers, as it considers relevant aspects of commonly used boundary conditions with potentially serious consequences for estimates of future sea-level change.

I encourage the authors to consider the following detailed suggestions and to improve the manuscript accordingly.

Thank you very much for reviewing our manuscript, your engagement, and your encouraging comments.

Specific comments:

1. The title should be refomulated. It is not easy to understand the content before having read the abstract. Also I wonder, if the more word “Ansatz” is commonly known in the wider scientific community apart from mathematicians. I would suggest: “Future sea-level contribution from the Antarctic Ice Sheet for different precipitation forcings based on CMIP5 models”

We are aware that the word Ansatz of German-origin is not widely used. But we prefer concise wording. Ansatz describes precisely the problem. The way how the precipitation is described/implemented in a mathematically and physical sense. In contrast, the suggested title is misleading because we do not use a different set of forcings, actually. However, we implement the available climate states differently to drive our ensemble of ice-sheet simulations.

2. As a surprising result the simulated Antarctic Ice Sheet gains mass under future global warming for directly applied climate model anomalies (temperature and precipitation). As this part has some delicate political implications it needs a clear discussion of the responsible model settings.

We are aware of the political implications of our results. Therefore, we have already discussed various influencing factors in the conclusion section, which you suggest to shorten. Hence, we do not see the need to expand this conclusion and the extensive discussion further because those parts would not be read by those who would like to misuse our results for their agenda. However, we extend both the "abstract" and "Plain Language Summary" sections to indicate the limitations of our study. In addition, we introduce the limitation of our forcing choices and its physical foundation.

In the abstract, we add “In contrast to various former studies, only the historical (1850--2005) and scenario (2006--2100) forcing drive our ensemble of simulations, which neglects unavoidable continuous warming consistent with the higher climate scenarios beyond the year 2100.”

We append to the "Plain Language Summary" section: “Since we use only the available climate scenarios until the year 2100, any additional warming after 2100 may turn the ice gain into an ice loss under a strongly changing climate.”

In addition, we add to the “Material and Methods” section, a paragraph discussing the above-indicated limitation: “The repetition of the last 30 years of climate forcing beyond the year 2100 is a simplification, which is not entirely consistent with the applied climate scenarios. An ongoing growing atmospheric greenhouse concentration triggers changes in the climate system. While the atmospheric radiation reacts immediately, the redistribution of the accompanied heating within the global ocean is much slower (Hansen et al., 2011). This delay is critical because the majority of the additional heat ends in the worldwide ocean (Church et al., 2011, 2013b). Consequently, further warming is inevitable after the cessation of greenhouse emissions (Hansen et al., 2005). Our simulations do not reflect this ongoing warming. Also, a disintegrating Greenland ice sheet will raise the global sea level, and, as a consequence of Greenland’s reduced gravitational pull (Whitehouse, 2018), the sea level rise is in particular pronounced around Antarctica (Mitrovica et al., 2001). A rising sea level potentially migrates the grounding lines inshore, which ultimately destabilizes ice shelves and causes a more vulnerable Antarctic ice sheet. Despite, the same gravitational effect may buttress Antarctica, whether Antarctica’s ice loss is slow enough (Gomez et al., 2010) and Greenland stabilizes. However, the ongoing thermal expansion of the ocean, which is currently the driver of the rising sea level (Rietbroek et al., 2016), will probably destabilize Antarctica. Therefore, our ensemble of ice sheet simulations is not a projection.”

2a. Although the equilibrium state fits well observations of ice thickness and grounding line, the involved mass fluxes may not. Total ice loss rates by melting and in particular by calving are overestimated by a factor of 2-3 depending on the used eigencalving rate constant. Hence also the surface mass balance seems to be overestimated accordingly. The authors imply that the uncertainties in the regional climate model results (RACMO), which are used as a present day reference field, are large enough to overestimate in particular the large slow-flowing and very dry inner-continental regions of the EAIS, where small absolute changes in precipitation can have large consequences for the total mass balance of the equilibrium state. Also, it is not clear from the description in the manuscript how the yearly cycle in the PDD scheme is estimated from the climate models (annual mean and summer temperatures) in order to obtain estimates of the surface mass balance components for given air temperature and precipitation forcing. A potential misfit in boundary conditions may be compensated for by a well-chosen set of model parameters, such that the equilibrium state bounds observational constraints. However, this potential overfitting of the initial equilibrium state may then have consequences for the projected ice mass changes, as the authors already speculate. In general, the equilibrium state method favors rather stable ice sheet configurations, which may not be realistic.

PDD: We have utilized the in PISM implemented PDD. During our analysis, we've compared the original surface mass balance (SMB) coming from the named RACMO data set with the SMB calculated by the PDD approach with and without considering a lapse rate of -7K km^{-1}. All these SMB are identical. Only if the surface elevation between the RACMO data set and the simulated elevation differ, the lapse rate shifts the air temperature, which introduces a difference in the SMB. The contemporary near-surface air temperature (we use the 2m-air temperature), except for the Antarctic Peninsula, is well below the freezing point temperature of meteoric freshwater (Figure A1a). Even the maximal warming of 8 Kelvin (Figure A1d), which occurs offshore, does not drive widespread surface melting generating ice mass loss. Therefore, the here used parametrized SMB calculated by the PDD approach is not critical. Please see, also, specific technical comment l.143 below, where we address the issue with the used PDD approach in more detail. In addition, we added a new appendix figure highlighting the surface mass balance; please see figure A16.

2b. The authors state one main difference to previous studies related to the forcing after the year 2100, which is commonly extrapolated into the future, while in this study it remains quasi constant (within 30 years variability). There seems to be another important difference in the methodology of this study in comparison to other studies. All climate model anomalies are inferred with respect to a preindustrial control simulation. However, the reference climate of the 19th century does not really match the modern climate, which the used mean background fields (from RACMO as mean over period 1979–2011 and from World Ocean Atlas as climatological mean) are related to. This precedure minimized the shock at the beginning of each simulation at 1850, but it adds some anomaly to the present-day background field when arriving at present-day in the simulations and it overestimates the future temperatures and precipitation rates applied to the Antarctic Ice Sheet. I encourage the authors to run some test simulations with shifted anomaly (negative anomaly in the preindustrial era and vanishing anomaly in present-day period).

It is right that we have not corrected the difference between the pre-industrial and the recent historical period (RACMO: 1979—2011, WOA: 1955—2006), since this difference is neglectable, e.g., 2m-air temperature (Figure 3b).

We would have liked to use instead of the RACMO atmospheric fields verified and validated distributions representing the pre-industrial state. However, these are not available (to our knowledge), except you consider spatially regridded shallow ice cores, which are subject to a distinct uncertainty, or fields coming from global climate models or could be deduced from these climate models. Since global climate models are not free of biases, we would have introduced an error, which is probably much larger than the mentioned offset. We have done experiments where CMIP5 model output has driven our ice-sheet model directly. We see that the simulations, which are driven by anomalies, are much less impacted by climate model biases.

Nevertheless, let us do a gedankenexperiment (Popper, 1935), where we would have considered this effect. A most probably slightly reduced surface mass balance would have been balanced by a slightly lower lateral ice loss via iceberg calving and basal melting to obtain a quasi-equilibrium state. This state would have been our initial state. Now we would run our ensemble from 1850 to the year 2100 and continue as we have done. The precipitation increase would be slightly less, the basal melting loss would also be slightly less, and the balance between these would be similar. We are confident about this conclusion because of our already existing ensemble with members showing a small increase. These members support this conclusion. With the current setup, which considers a slightly too strong forcing, we may promote enhanced basal melting (quadratic equation). However, the diagnostically deduced sea-level impact of the two ways to describe the sea-level dependence of the precipitation boundary condition (Figure 6b and 6d) is independent of the used reference state.

To conclude, the here used setup could be improved, but the conclusion is robust about the mentioned reference period of the background data set.

Popper, Karl. 1935. Logik Der Forschung. Edited by Philipp Frank and Moritz Schlick. Schriften zur Wissenschaftlichen Weltauffassung. Vienna: Springer Vienna. ISBN: 978-3-7091-2021-7.

2c. Regarding the basal melt parameterization, no details on sensitivity can be found in this study nor in the cited study by Sutter et al., 2019. What technique is used to extrapolate ocean temperatures into the ice shelf cavities? Are basin-wise overflow depths considered? Are extrapolated ocean temperatures vertically interpolated at the ice shelf base? Can refreezing occur? A simimar melt parameterization with quadratic dependency on thermal forcing has been calibrated in Jourdain et al., 2019 (https://doi.org/10.5194/tc-2019-277). They show that the choice of the particular parameterization and the associate parameters can have a huge impact on the ice sheet response. The authors discuss that the used melt parameterization may underestimate the melting and therefore apply bias-corrected melt rates as a sensitivity check, which does not cause considerable changes in the ice sheet response. The effect of basal melt could be also strongly intensified by using the melt interpolation across the grounding line (optional in PISM).

We have extended the description regarding the extrapolation (please see specific issue l.144), which also answers the question regarding the overflow depths. As part of the ocean forcing, we use the full 3D ocean temperature distribution so that the actual temperature at the ice shelf base drives the ocean melting, whereas our approach does not consider refreezing. In our understanding, ocean-driven basal melting does not occur beyond (inshore) the grounding line, because grounded ice stifles the flow of ocean water.

Since we use a sub-grid scale grounding line parameterization, we could have allowed partial basal melting proportional to the floating fraction. In pilot studies, the impact of the fractional basal melting has shown a minor effect on our simulations. Studies suggest that tides amplify frontal melting and locally also basal melting (Padman et al., 2018). In contrast, a tidal-driven front, which develops near the groundling line, hinders the flow of water which ultimately lowers the basal melting near the grounding line (Holland, 2008). First ocean observations in the groundline zone of the Ross Ice Shelf show low basal melting rates (Begemann et al., 2018). We decided to compute melting only for fully floating grid cells.

Begeman, Carolyn Branecky, Slawek M. Tulaczyk, Oliver J. Marsh, Jill A. Mikucki, Timothy P. Stanton, Timothy O. Hodson, Matthew R. Siegfried, Ross D. Powell, Knut Christianson, and Matt A. King. 2018. “Ocean Stratification and Low Melt Rates at the Ross Ice Shelf Grounding Zone.” Journal of Geophysical Research: Oceans 123 (10): 7438–52. https://doi.org/10.1029/2018JC013987.

Holland, Paul R. 2008. “A Model of Tidally Dominated Ocean Processes near Ice Shelf Grounding Lines.” Journal of Geophysical Research 113 (C11): C11002.

https://doi.org/10.1029/2007JC004576.

Padman, Laurie, Matthew R. Siegfried, and Helen A. Fricker. 2018. “Ocean Tide Influences on the Antarctic and Greenland Ice Sheets.” Reviews of Geophysics 56 (1): 142–84. https://doi.org/10.1002/2016RG000546.

If we drive a newer PISM version (V1.1.4), where the ocean-driven basal melting is parameterized with the PICO submodel as part of PISM (Reese et al., 2018), with climate forcing from our climate model (AWI-CM, which is not part of the here use CMIP5 models), we also detect a growing Antarctic ice sheet. Therefore, we are confident that our parameter choices are not decisive and that our results are robust.

Reese, Ronja, Torsten Albrecht, Matthias Mengel, Xylar Asay-Davis, and Ricarda Winkelmann. 2018. “Antarctic Sub-Shelf Melt Rates via PICO.” The Cryosphere 12 (6): 1969–85. https://doi.org/10.5194/tc-12-1969-2018.

3. The authors define different ways of expressing (integrated) mass changes in terms of sea-level equivalent changes and I would wish that it should be made clear when just a theoretical unit conversion is applied (potential sea level change) or when it is an actual sea-level contribution in terms of projected ice mass change. And if the latter it should be clearly defined whether only ice masses above flotation are considered. What diagnostic has been in fact used here?

Clarified by adding the following paragraph and applying related changes through the manuscript: ”In this manuscript, we distinguish between potential sea level and simulated sea level. The potential sea level is the transformation of an ice mass or freshwater volume into a global sea level by applying a global ocean area of $3.61 \cdot 10^{14}$ m^2 (Gill, 1982). In contrast, the simulated sea level is a diagnostic of the ice sheet model, which takes into account the total mass above flotation and the global ocean area. ”

4. The manuscript states that the used coarse resolution of 16km may have consequences for the adequate representation of ice stream dynamics. I assume that this model choice is a consequence of the initial equilibriumn state, which requires hundred thousands model years to evolve. The authors state that basal resistance is described by a Mohr-Coulomb law with plastic till, but they do not discuss relevant parameters involved, such as the till friction angle or the till water decay rate. What is the vertical resolution of the enthalpy module? These parameters can strongly affect the ice stream dynamics also for coarse resolutions.

The till water decay rate amounts to 3.1687646154128e-11 meter $seconds^{-1}$. We have not activated the hydrological model. The till fraction angle ranges from 10° for our bedrock at and below 700 m below the contemporary sea level at the start in the year 1950. With rising bedrock altitude, the friction angle increases linearly until 200 m above sea level and stabilizes at 30° (Figure I). Our mean vertical resolution is 67.9 m. Albrecht et al. (2020) show that a lower vertical resolution leads to a bigger ice sheet under transient forcing and, also, it promotes a more stable ice sheet.

Albrecht, Torsten, Ricarda Winkelmann, and Anders Levermann. 2020. “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 (2): 599–632. https://doi.org/10.5194/tc-14-599-2020.

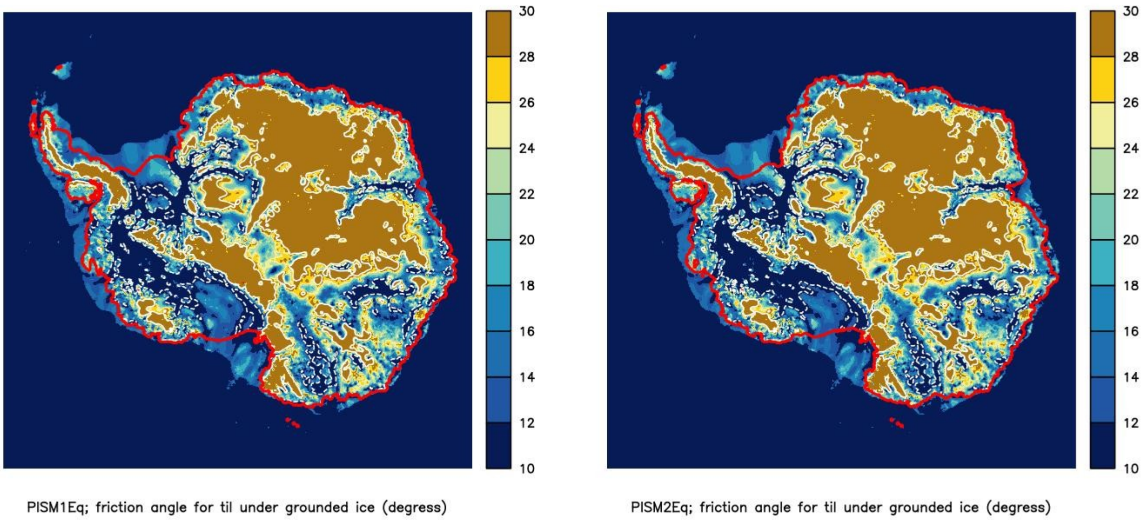

Figure I: Till fraction angle for till under grounded ice. The left (right) side shows the fraction angle for the initial states PISM1Eq (PISM2Eq). The red contour outlines the ice sheet or ice shelf outer edge. Under ice, the dash, and white contour line follow the -700m and the 200m, respectively, bedrock altitude in the year 1850.

5. The authors use a rather old PISM version (v0.7), most likely for consistency reasons (initMIP and other model intercomparisons). However, PISM has evolved over the last years and some relevant aspects have been improved, which may affect the results of this study. For instance, the authors mention a bug in the elastic part of the LC solid Earth model, but also the viscous part was flawed and considered changes in ice shelf thickness as loads. Accordingly strong melt would cause uplift of the cavity bed and hence result in a stabilized grounding line. Also the till water distribution along the grounding line has been fixed meanwhile causing a much higher grounding line sensitivity. I guess also the sea-level potential diagnostic has been fixed meanwhile (now substracting the part below flotation). These are many good arguments in favor of a more recent PISM version and they suggest that Antarctic Ice Sheet simulations could respond with much higher sensitivity to the same forcing applied.

In our code basis, we fixed some code issues, such as the reproducibility and restart issues, which are also related to the bedrock code. In our simulations, we consider the viscous-part of the glacial isostatic adjustment (GIA) and do not use the elastic part. As explained below, an improved GIA model would maintain a more stable configuration of the grounding line, so that the discussed sea-level decline under a warming climate would be even more pronounced. Please see the special technical comment l.151. Please see also our reply to the technical issue of the appendix figure A15, where we state that we have a relatively stable grounding line in our simulations while the calving front retreat is more pronounced.

Technical corrections:

l.2: “heavier precipitation fallen on Antarctica will counteract any stronger iceberg discharge...”=>“precipitation will likely increase even more and may counteract stronger iceberg discharge...”

A warming climate accompanies increased precipitation due to the Clausius-Clapeyron relation. Hence we prefer: “Simulated future projections reveal that heavier precipitation, fallen on Antarctica, may counteract amplified iceberg discharge and increased basal melting of floating ice shelves driven by a warming ocean.”

l.3: “from nine CMIP5 models future projections”=>“future projections from nine CMIP5 models”

We follow your request.

l.5: “The spatial and temporal varying climate forcings drive ice-sheet simulations. Hence, our ensemble inherits all spatial and temporal climate patterns, which is in contrast to a spatial mean forcing.:” => “The spatially and temporally varying climatic forcing drive the ice-sheet simulations, such that all climate patterns are represented in our ensemble, which is fundamentally different from using spatial means as forcing.”

We follow your suggestion and use: “The spatially and temporally varying climatic forcing drives ice-sheet simulations, such that our ensemble represents all climate patterns, which is fundamentally different from using spatial means as forcing.”

l.7: Regardless of the applied boundary condition and forcing, some areas will lose ice in the future, such as the glaciers from the West Antarctic Ice Sheet draining into the Amundsen Sea.” => ..., our ensemble study suggests that some areas will lose ice in the future, …

Done.

l.10: “This strip also shows...” instead of using “... too.”

Rewritten as requested.

l.25: “How strong the precipitation grows in a warming atmosphere, may be explained by the dissimilarity between the applied methods to describe the precipitation.” => The discrepancy of the simulation results between the applied methods to describe the precipitation illustrates the uncertainty of the possible range of future precipitation growth in a warming atmosphere.

We follow your suggestion and use: “The discrepancy of the simulation results between both methods describing the precipitation illustrates the uncertainty of the possible range of future precipitation growth in a warming atmosphere.”

l.30: “...impacts globally numerous economic activities...” => “...impacts numerous economic activities globally...”

Done.

l.31: “... or dedicated model simulations of, for instance, ice-sheet models.” => “... or process-based model simulation, e.g. ice-sheet models.”

Changed.

l.34: “... are simplified descriptions by analytical equations” => “... are either simplified descriptions based on linear multiple-regression analysis ... or”

Rephrased as requested.

l.36: “The simplified forcing, which usually does not show a dedicated spatial structure” => As surface elevation is a key variable in those parameterizations, the geometry of the ice sheet in fact leave some characteristic spatial structure.

We might have been misunderstood, hence we clarify: “The simplified temporal forcing, which usually does not show a dedicated spatial structure ...”

l.58: “temperature scaling” => “temperature scaling factor for precipitation” or “precipitation-temperature scaling ”

Thanks, we use: “temperature scaling factor for precipitation”

l.71: Add comma before “probably”

Done.

l.124: Maybe omit “full” here.

It's like the term “Full Stokes”, which is not entirely correct but everybody uses this term. We would like to keep it for clarity.

l.126: As in the title, I would recommend to use: “The type of precipitation forcing” or “the used method for applying precipitation forcing” instead of “the Ansatz of the precipitation”.

Since a noun has to start with a lower case at the beginning, we correct it. As stated above, the word ansatz describes what we mean precisely.

l.130: “The latter is common, while some keep the surface mass balance constant.” => “The latter approach is commonly used, in particular in paleo applications, while some sensitivity studies keep the surface mass balance constant.”

We follow your request.

l.138: It could help the reader to have some definition of the piControl simulation here, e.g. “pre-industrial coupled atmosphere/ocean are performed at constant pre-industrial CO2 levels for x model years”.

We cite literature and clarify the sentence introducing this paragraph: “Nine CMIP5 models deliver the following climate scenarios (see Table 1, Taylor et al. (2012)): control run under pre-industrial conditions (piControl), the historical period (1850-2005), as well as RCP2.6, RCP4.5, and RCP8.5 (2006-2100, Vuuren et al. (2011)).”

l.140: “... differ commonly marginally.” => “...show in general marginal differences.”

Rephrased as suggested.

l.144: How does this extrapolation works? Is there a diffusion scheme applied for each vertical ocean temperature level? What are the source regions, the continental shelf or also the deeper ocean regions (this is not so clear from Fig. 3e), which are separated from the deeper cavity regions by the continental shelf? There is also no detailed description in Sutter et al., 2019, even though sub-shelf melting is a key process here.

We clarify: “... extrapolated horizontally into the ice shelves to mimic isopycnical flow: The operator 'fillmiss2' of the Climate Data Operators' (\href{https://code.mpimet.mpg.de/projects/cdo}{cdo}) tool kit acts on the original CMIP5 ocean grid.”

l.146: “... following the positive degree day (PDD) approach, where the annual 2mair temperature standard deviation comes from daily CMIP5 model values.” Does this mean that every year one different PDD standard deviation is applied to the whole computational setup or is it grid-cell wise?

In l.143 it is mentioned that "annual mean forcing" is ued, but what about the summer temperature anomaly to estimate the yearly cycle?

We use the PDD implementation of the PISM and perform the computation for each grid-cell; we clarify: "To allow for surface melting under a warming climate, the surface mass balance (SMB) is calculated following the positive degree day (PDD) approach (Braithwaite, 1995; Hock, 2005; Ohmura, 2001) as implemented in the PISM model (ThePISM Authors, 2015a, b). The turn of the hydrological year occurs on day 91 and the PDD factor for snow and ice are 0.3296 cm(IE) $Kelvin^{-1}$ day^{-1} and 0.8792 cm(IE) $Kelvin^{-1}$ day^{-1}, respectively. Here, the evolving annual 2m-air temperature standard deviation is derived from daily CMIP5 model values for each ice sheet model grid-cell." Besides, at the end-of-the-21-century, summer temperatures are in general still too cold to drive widespread surface ablation.

l.148: "16 km" => What is the reason for this relatively coarse resolution, the availability of an equilibrium state?

We have run a much larger ensemble of several thousand members. Here we analyze only a subset of this full ensemble.

l.149: "utilizes" => "applies"

Changed to "employs"

l.151: Also the viscous part in v0.7 was somewhat unrealistic, as also ice shelf thickness change has been considered as loads in the LC bed deformation model, which has strong effects on grounding line sensitivity.

We are aware that the viscous part of the GIA model could better represent the impact of a changing ice shelf thickness. In our understanding, the updated implementation would maintain a more stable configuration of the grounding line, which would support firmer ice shelves and a more durable ice sheet. Ultimately, the here discussed sea-level decline under a warming climate would be even more pronounced.

l.154: "... pressure-dependent melting temperature" => Add "...of the ice"

Done.

l.157: "...while the grounding line position is determined on a sub-grid space (Feldmann et al., 2014)." => Add "... to interpolate basal friction."

Rephrased.

l.161: "...stress field divergence... " => "... divergence of the strain/velocity field" or "trace of the strain-rate field"

We accept the second suggestion, joyfully.

l.161: You should add units "m s" here as the Levermann et al. 2012 paper uses "m a".

Good point, we add as requested the units.

l.162: "(PISM1Eq and PISM2Eq)"=>This can be confusing, either you switch the order here or the order of the eigencalving constants in the sentence before.

We changed as suggested.

l.163: "Ocean temperatures from the World Ocean Atlas 2009 (Locarnini et al., 2010) and the multi-year mean surface mass balance (SMB) from the RACMO 2.3/ANT model (Van Wessem et al., 2014) drive PISM during spin-up (Table 2)." => Hence, this is a present-day forcing equilibrium.

This is correct. Please, also see our related reply to your specific comments 2b.

l.169: "... releasing less carbon dioxide." => Maybe add "(e.g. RCP2.6)."

We followed your suggestion.

l.171: "the RCP8.5 scenario path" => "the high emission RCP8.5 scenario path"

Done.

l.175: maybe add a "\," in the unit "\unit{cmyear−1}"

Good catch; done as suggested.

l.176: "...warms by nearly 1 ± 0.18 #C (Figure 3c)." => Add "in the same period"

Done.

l.177: "... these increases become stronger." => "this warming trend/rate becomes stronger."

We use: "this warming trend becomes stronger."

l.179: "current trends" => "currently observed trends"

Done.

l.189: "Areas of heavy precipitation under the reference climate (Figure 2b) also receive the highest increments."

Sorry, but it is unclear.

l.195: "Also, the Amundsen Sea in front of Pine Island Glacier and Thwaites Glacier is cold. Here, the temperature might be too cold, which justifies the applied melting correction." => Which melt correction did you use? And "too cold" with respect to World Ocean Atlas?

"Here, the climatological temperature distribution might be too cold because it does not replicate the confined flow of warm water masses through glacier-scoured troughs towards ice shelves. To overcome this limitation, we apply a spatially restricted melting correction. It increases the melting by 50% for the Ronne Ice Shelf region, and it quadruples melting for coastal parts of the West Antarctic Ice Sheet between the Antarctic Peninsula and the Getz Ice Shelf (east of the Ross Ice Shelf)."

l.205: "...do not necessarily grow in parallel." => Do you mean they are "not necessarily correlated"?

We use: "not necessarily correlate."

l.209: "ice-sheet" => "Ice-sheet"

Changed.

l.214: The unit of Eq. 1 should read % K−1, hence #T should be in the denominator.

Indeed! We corrected.

l.215: So P0 equals Pt=0 in Eq. 1?

We correct: "$P_{t=0}$=0=P(t_{ref})"

l.217: Eq. 2 should have a number. And should #P be replaced by P0?

We follow your advice and label this equation. In addition, we expanded the equation, so that it becomes clear that it should be ΔP.

l.221: "...these locations. The difference is distinct for Vostok..." =>"...ice core locations. The difference is most prominent for Vostok ice core..."

We revise as requested.

l.226: "Thus, we can safely restrict the analysis on the first 50 years." => of which simulation?

To avoid ambiguity, we expand the sentence: "Thus, we can safely restrict the analysis and use as a reference for the computation of the anomalies the first 50 years of the piControl climate."

l.230: "Map 1" => "Map in Figure 1"

We rephrase as suggested.

l.233: "... c-like area" => "...half-moon-shaped area" or just "... c-shaped area"

We prefer to use the second suggestion: "c-shaped area"

l.242: "We detect a slight trend to higher values if we restrict the analysis to ground ice." Maybe mention at this point that the difference results from excluded ice shelf regions, which are associated with x% of the total glacierized area and which are characterized by relatively shallow surface elevation along the ocean margin

We extend to: "We detect a slight trend to higher values if we restrict the analysis to ground ice (87.5 % of the glaciated area, see Table 4); it excludes floating ice shelves with low elevation along the coasts."

l.243: "the difference between scenarios is more decisive" => "the impact of the choice of the scenarios is larger..."

Rephrased with "However, the scenario selection is decisive, while the choice between … "

l.245: "... Within their variability, many ensemble members are invariant against the applied scenario..." => "The sensitivity of many ensemble members to the range of applied scenario is within their variability..."

Taken.

l.250: "... Antarctica's large-scale drainage basins." => Please provide a reference here, e.g. Zwally et al., 2015

As suggested we added citations for different oceanographic zones and drainage basins.

l.251: "This division..." => "This chosen division..."

Done.

l.253: "...with a tendency of higher values..." => "...with a tendency towards higher values..."

Done.

l.261: "The region "Siple Coast" as a part of the "WAIS" region is different in many aspects. It has the smallest area.." =>so it has a low weight in the spatial mean?!

Each area has its own spatial mean regardless of its actual area size. We clarify: "The region 'Siple Coast' (area $0.69 \cdot 10^6 km^2$, see Table 4) as a part of the 'WAIS' region (area $4.26 \cdot 10^6 km^2$) is different in many aspects. It has the smallest area compared to the other regions (Table 4)"

l.263: "...while the spread of trends among individual ensemble members is substantial." => Why not provide a number range at some points in the text?

We link to the requested information provided in one of our figures: “ the spread of trends among individual ensemble members is substantial (Figure 5).”

l.267: “... trend in snow accumulation ...” =>“... trend in observed snow accumulation...” to make sure that you switched from model results to observations in this paragraph

Yes, we adjust as requested.

l.273: “... a unrealistic declining February sea ice trend” => “... an unrealistically declining February sea ice trend”

We follow your suggestion.

l.280: “which is also reflected by the maxima in these regions.” => maxima in scaling factors?

Clarified by “the scaling factor maxima in these regions”

l.281: “Also, the Ross Ice Shelf and the adjacent Siple Coast feature on average the lowest scaling factors across the entire ice sheet. Some individual ensemble members project even negative scaling: precipitation deficit for rising temperatures.” Is this related to the Frieler et al., 2015 study or does this repeat the previous paragraph?

Clarified: “As before, the Ross Ice Shelf and the adjacent Siple Coast feature, on average, the lowest scaling factors across the entire ice sheet (Figures 4 and 5). Some individual ensemble members project even negative scaling: precipitation deficit for rising temperatures (Figures 4 and 5).”

l.296: “The integrated precipitation shows a more pronounced temporal change, because the integral and not the mean precipitation is calculated, where the vast light precipitation regions lessen the average precipitation signal.” Isn’t the difference just a scaling factor, i.e. the considered area? I guess you are talking about a power-law distribution with a large weight of the continental areas with very low precipitation?

Clarified: “The integrated precipitation shows a more pronounced temporal change because the vast interior, characterized by light precipitation, governs the integral.”

l.301: “... under the precipitation anomalies,” =>“... for applied precipitation anomalies,”

Rephrased as requested.

l.306: “if we would apply this low scaling of 2 % K^{-1}.” Isn’t this mentioned in the beginning of the sentence?

Indeed, hence it is discarded.

l.316: “Over the entire Antarctic continent, precipitation and temperature grow simultaneously in climate model simulations of the future.” => To summarize, precipitation and temperature, as average over the entire Antarctic continent, grow simultaneously in climate model simulations of the future.”

Done.

l.320: “the on Antarctica accumulated snowfall” => “the snowfall accumulated on Antarctica”

Done.

l.325: “... the implemented precipitation boundary condition...” => “... the applied precipitation boundary condition...” or “... the choice of the precipitation boundary condition...”

We follow your second suggestion.

l.327: “These together constitute the ensemble of ice-sheet simulations.” =>It would be nice to provide the size of the ensemble (3 sceanarios x 9 climate models x 2 reference periods x 2 precipitation forcing = 108 simulations?)

We write “ … ensemble of 208 ice-sheet simulations (Table 1)” and add additional information to the corresponding table caption “Since we do not use the RCP2.6 scenario of the CCSM4 model, the ensemble comprises 26 anomaly forcing scenarios. The climate anomalies are computed relative to the first or last 50 years of the corresponding piCtrl. Each scenario starts from the initial condition PISM1Eq (Figure A10) or PISM2Eq (Figure A11) and is driven by two precipitation conditions (see main text for details, e.g. section 3.2). Hence, the ensemble of anomaly ice sheet simulations has 208 members.”

l.332: “...detected trend of about 2 mm decade−1 (sea-level equivalent) fades within the first 400 years...” => How can this trend be justified? Is the present-day reference forcing different from the one used in the spin-up? Or is this due to bed deformation? What figure shows this trend? It should be shown somewhere (Fig. 6?) as it amount to about 2cm after 100 model year and is substracted from the prejection results, right?

We take the explanation from the discussion to here and address in addition the remark l548.

l.337: “ than the simulations” => than in the simulations

Done.

l.338: Insert comma

Done.

l.340: “A ring of a pronounced negative thickness difference follows the coast, where the precipitation anomaly (Figure 2e, h, k) is enhanced.” => “However, we find a negative thickness difference within a narrow band along the coast, where the precipitation anomalies (Figure 2e, h, k) suggest less accumulation that the scaling.”

We do not come to this conclusion about the scaling because the ocean also influences the ice thickness along the coast. So we keep the descriptive character.

l.344 “... are negative” Please be more precise in this paragraph, what quantity is negative.

Rephrased: “Furthermore, as part of the WAIS these values are present in the coastal strip from the Antarctic Peninsula to the Ross Ice Shelf and along the eastern flank of the Transantarctic Mountain Range (Figure 4).”

l.347: K-1 superscript

Good catch; done.

l.349: “... the ice thicknesses of the ensemble means..” => “... the mean ice thickness of each of the respective sub ensembles...”

Rephrased as requested.

l.354: “This reduction marks those outlet glaciers and ice shelves that are extremely vulnerable.” Doesn’t it say that ice losses under global warming are larger than gains?

Regardless of the applied RCP8.5 climate forcing coming from our pool of climate models (Table 1), these outlet glaciers and ice shelves lose mass, where the corresponding ice thickness is negative. Consequently, the loss outweighs the gain.

l.359: "... ice-shelf weakening, ice thinning ..." => "... ice-shelf weakening, as well as ice thinning ..."

Rephrased as suggest and reordered: "ice-shelf thinning, as well as ice-shelf weakening, "

l.365: "...and restrict ourselves first to the model year 2100, where the precipitation anomalies of the period 1850-2100 shape the ice-sheet thickness distribution of the year 2100." => "the history of precipitation anomalies"

Rephrased: "and restrict ourselves first to the model year 2100, when the transient forcing of period 1850--2100 excites changing ice thicknesses."

l.367: "Directly at margins apart from the vast ice shelves, the attributed model that drives either the maximum or minimum ice thickness shows a noisy small scale pattern, which is driven by the variety of the involved models (Figure 8d, e)." => I guess you want to say, that the maximum or minimum ice thickness in marginal regions cannot be associated with a particular climate model, while in contrast, for ice shelf regions...

Thanks, we modified as requested.

l.372: "... while it also drives its thinning of the Ross Ice Shelf (Figure 8e) predominantly." => "... while it causes predominantly thinning within the main Ross Ice Shelf (Figure 8e)."

Done.

l.373: "Since the spatial pattern of the atmospheric and ocean forcing that promotes or undermines the ice thickness is not necessarily aligned, this may explain the small scale noisy pattern along the coast." => Maybe this explanation is not sufficient. The coastal regions is where most of the (nonlinear) dynamical changes on the considered time scales occur in response to both ocean and atmospheric forcing.

Various studies show commonly a linear behavior, but we add this though, joyfully.

l.388: "NorESM1-M influences the WAIS, which is in accordance with the detected lowest scaling in the Siple Coast (Figure 5), CSIRO-Mk3-6-0 has an impact around the South Pole, MRI-CGCM3 has coastal zone in the EAIS, while the control of MPI-ESM-LR and, to a lesser extent, HadGEM2-ES spreads across the entire continent." => The reader may get lost here by the wording. Make sure that you are talking about the attribution of the minimum ice thickness to different climate models. You could also add percentages of the Antarctic area in the text to quantify the dominance. Similar issue for the maximum in l.398 ff.

Adding more information, such as the suggested percentages, would inflate the text and its complexity. Also, these values are most probably specific to the here used selection of climate models and do not represent a particular physical process. Therefore, we would like to drop this idea. Nevertheless, we simplify the sentence structure and break the sentences into pieces to help the reader: "NorESM1-M influences the WAIS, which is supported by its lowest scaling in the Siple Coast region (Figure 5). CSIRO-Mk3-6-0 has an impact around the South Pole, MRI-CGCM3 affects the coastal zone in the EAIS. The control of MPI-ESM-LR and, to a lesser extent, HadGEM2-ES spreads across the entire continent."

l.393: "If we now turn towards the temperature scaled model simulations, the mean, maximum, and minimum ice thickness distribution..." => "If we now turn towards those model simulations, in which the temperature-scaled precipitation forcing has been applied, both the mean, maximum, and minimum ice thickness distribution..."

Changed as requested.

l.396: "The latter shows that the ocean controls ice-shelf thickness changes in our simulations primarily.” => “The latter shows that primarily the ocean controls ice-shelf thickness changes in our simulations.” or “The latter shows that the ocean primarily controls ice-shelf thickness changes in our simulations.”

Changed as suggested.

l.402: “precipitation driven” => “precipitation-driven”

Done.

l.409: Are you referring to all three scenarios here or just RCP8.5?

Clarified: “For all climate scenarios, ...”

l.413: “...is quasi-constant until 2000 and declines afterward (Figure A15). For RCP8.5, the basal melting increases at the end of the 21st century quadratic.” => “...remains quasi-constant until 2000 and declines afterwards (Figure A15). For RCP8.5, the basal melting increases at the end of the 21st century quadratically.”

Done.

l.415: “... while the basal melting increases by approximately 33 % since the year 2000.” => until 2100?

Rephrased: “between the years 2000 and 2100.”

l.417: “The basal melting rates for PISM1Eq and PISM2Eq are similar, however, the loss rates for PISM1Eq are slightly larger than PISM2Eq (Figure A13).” => This means more basal melting for smaller ice shelf area? What is the portion of refreezing?

It is correct that smaller ice shelves are subject to more basal melting, while refreezing does not occur.

l.420: “Since floating ice shelves nourish both ice losses, these ice losses do not impact the sea-level directly.” => “Although floating ice shelves are subject to both types of ice loss, these ice losses do not directly impact the sea-level.

We follow your suggestion partly and write: “Since floating ice shelves nourish both ice losses, these ice losses do not directly impact the sea-level.”

l.423: “ generates ” => “ would consequently generate ”

Done.

l.425: “is not a 1:1 relation.” => “is obviously not a 1:1 relation.”

Done.

l.426: Shouldn’t there be a time period involved, e.g. by 2100?

To avoid any ambiguity, we added as requested, even if we haven't changed the discussed period (1850-2100).

l.427: “It is less than integrated precipitation anomalies...” => “This is less than the integrated precipitation anomalies..., which explains the total mass gains.”

Added.

l.429: “Anyhow, the integrated basal melting rates are too low and the calving rates are too high compared to observational estimates in our ensemble of ice-sheet model simulations.” => What does too low and too high mean here, beyond observational uncertainty? Maybe quantify in terms of percent?

We link to the corresponding figures, because in all figures depicting the total mass loss (Figure 11), calving rates (Figure A12), and basal melting rates (Figure A13), independent estimates are provided by symbols. In addition, the reported uncertainties of these estimates are provided, if they are larger than the corresponding symbol sizes, as stated in each corresponding figure caption.

l.436: “ loses mass ” => “ lost mass ”

Rephrased to “have lost mass”

l.449: “the basal melting rated of grounded ice” => “the basal melt rate at he base of the grounded ice”

I'm sorry, but to my knowledge, basal melting occurs at the base. Since we would like to avoid this pleonasm, we keep the original sentence.

l.449: “Please note that this is not driven by any trend in the continued ice-sheet simulations under the reference climate (Table 2) since we have substracted this trend.” => “Please note that there is no drift involved, as we subtracted the trend from the continued ice-sheet simulations under the reference climate (Table 2).”

Thanks, changed.

l.451: “We also detect an amplified signal for the simulations driven by the precipitation anomalies than scaled precipitation, which corresponds to the above diagnosed sea level impact of the precipitation (Figure 6).” => Please reformulate!

Reformulated: “We also detect an amplified signal for the simulations driven by the precipitation anomalies compared to those forced by temperature-scaled precipitation anomalies, which corresponds to the above diagnosed sea-level impact of the precipitation (Figure 6)”

l.453: Maybe add “net mass gain”, which is associated with a negative sea-level contribution, but whether the global sea level falls is not only determined by Antarctica.

Rephrased: “... , gain mass causing a falling sea level”

l.455: Please reformulate, such that the reader understands that you talk about a constant rate on the one hand and a linearly increasing integrated melt rate on the other hand.

Rewritten: “The basal melting of grounded ice does not impact the sea-level evolution, because this basal melting rate is nearly constant so that the corresponding integrated sea-level equivalent grows linearly for all scenarios from 1850 until 2100, and only after the year 2500 these curves diverge.”

l.456: “Ultimately, the more vibrant growth of the accumulation in comparison to the negligible increasing combined loss of iceberg calving and basal melting of ice shelves drive the falling sea level in our simulations after the year 2000 (Figure 12).” => “Also the combined loss of iceberg calving and basal melting of ice shelves does not vary much over the considered period. Consequently, the growth of the accumulation in our simulations explains the net mass gains and hence the negative sea-level contributions from Antarctica after the year 2000 (Figure 12).”

We follow your advice and use “Also, the combined loss of iceberg calving and basal melting of floating ice shelves does not vary considerably over the considered period. Consequently, the growth of simulated accumulation explains the net mass gains and, hence, the negative sea-level contributions from Antarctica after the year 2000 (Figure 12).”

l.461: “ temperature scaled precipitation ” Add hyphen!

Thanks for indicating. We followed your suggestion and adjusted the manuscript accordingly.

l.462: “As a consequence, these will contribute after the year 3200 (RCP8.5) and 3900 (RCP2.6) to a globally rising sea level on average in our simulations, which outruns the formerly fallen sea level since 1850.” =>“As a consequence, these simulations produce on average a positive contribution to the global sea level after the year 3200 (RCP8.5) and 3900 (RCP2.6), which compensates for the negative contributions since 1850.”

Done.

l.470: “the deduced Antarctica’s sea level contribution” => Please reformulate

Reformulated: “simulated sea-level contribution of Antarctica”

l.471: “representing the observational-based ocean-driven basal melting.” So you directly apply basal melt fluxes and no ocean-temperature based melt parameterization any more?

We still use the growth of the simulated basal melting rates covering the period from 1850 to 5000, but the time series are adjusted to reproduce current estimates of basal melting rates. Unfortunately, these observational estimates present only the contemporary period. Please see the appendix for further information. We replace “representing” by “emulating” so that we obtain: “a corrected time series emulating the observational-based ocean-driven basal melting.”

l.475: “Under the assumption that only a fraction of the adjusted basal mass contributes to the global sea level, we apply the simulated ratio of the sea level change to the total ice mass change.” => The authors should better motivate that this conversion serves to express mass changes in terms of sea-level equivalents.

The introduction of this section has been modified and offers a clear motivation: “This analysis shall reveal if a more vibrant basal melting rate in concert with the simulated ice sheet mass evolution leads to a less pronounced ice sheet growth or drives even ice loss. Ultimately, does a more vigorous melting of ice shelves raise the simulated sea level of all ensemble members?”

l.478: “ sea level correction” Or do you mean “adjusted basal melt flux”?

We clarify: “By adjusting the basal melting flux, the determined temporal evolution of the sea level correction”

l.480: Maybe omit “as its evolution, which considers the correction, highlights”

Good point, we follow your suggestion.

l.481: “..., we obtain too extensive corrections...” => “... we would obtain large corrections...”

Done.

l.482: “This sea-level rise is larger” => “This corresponding sea-level rise would be larger”

Changed.

l.485: “raises ” => “could raise”

We rephrase: “would raise”

l.486: “ do not impact the sea level.” => “ do not impact the sea level directly.”

Done.

l.487: “ration” => “ratio”

Fixed.

l.490: “ how the precipitation is implemented in ice-sheet simulations” => Better say: “how precipitation forcing is applied/estimated in ice-sheet simulations”

Rephrased: “specified”

l.493: “ In this case, numerical projections” => “ In this case, our numerical projections”

Extended as suggested.

l.498: “such as the ocean-ice-shelf-ice-sheet interactions.” => “such as the interaction between ocean, ice shelves, and ice sheet.”

Done.

l.497: “ thence”

Rarely use adverb with the meaning of 'therefrom.'

l.506: “ overwhelm ” or better overcompensate

Exchanged “overwhelm” by “overcome.”

l.508: “, the total amount would be identical,” => “, the average amount of precipitation change would be identical to the average precipitation anomaly,”

We prefer: “the integrated precipitation would be identical”

l.509: “proper” => “adequate” or “realistic”

Rephrased as suggested: “realistic”

l.510: “shall” => “should”

We use US English, where, to our knowledge, the auxiliary (modal) verb 'shall' is used in formal writing and expresses determination. It's different in British English. Hence, we would like to keep it.

l.514: “... which have been identified across sixteen models” => You should add “within a recent model intercomparison exercise”

Done.

l.523: “This observed retreat and the related ice loss will continue in our simulations under RCP8.5.” => “This observed retreat and the related ice loss will continue, most likely represented in our simulations by the scenario RCP8.5.”

Reordered: “In our simulations under the RCP8.5 scenario, this observed retreat and the related ice loss will continue.”

l.527: “ further to the west” => relative to where?

Further to the west of the discussed area (Wilkens Basin in the hinterland of George V Land) as part of the EAIS.

l.531: Maybe put references after “lose ice”, if they say so.

Indeed, references should be at the end.

l.532: “according to our simulations.” => “which is consistent in our simulations.”
l.532: “ will thin in the future.” => reference or does the ensemble suggest so?

Rephrased and clarified: “According to the ensemble projecting the future, for them, continuous ice loss is inevitable. It also shows that the Ferringo Ice Stream flowing into the Bellingshausen Sea will thin in the future.”

l.537: “ reproduces appropriate ” => “ adequately reproduces ”

Changed by “reasonably reproduces”

l.548: “Even if we apply anomalies on top of the reference background fields, we can not exclude a shock-like behavior of the simulations entirely directly following the decades after the year 1850.“ => This is strange, could you quantify the variability around the 50-years mean?

It is not strange because, at the start of the simulations, the climatic anomaly fields of the first years are not necessarily identical to the 50-years averages. The first few years may be warmer or colder than the mean. Please inspect the early decades of the ensemble mean's forcing (Figure 3) to obtain an impression of the climate variability.
We combine this point with the issue l332 above, where most of the paragraph is located now.

l.853: “because the water masses of this range flow into the ice-sheet cavities and are in contact with large parts of ice shelve bases. “ => “because the water masses at this depth potentially can flow into the ice-sheet cavities and reach large parts of ice shelves’ bases. “

I disagree with “potentially” because it is actually in contact with the ice shelf base either after direct inflow (for example in the Amundsen Sea) or after modification (for example in the Filchner-Ronne Ice Shelf); see for example Thompson et al. (2018). To avoid any ambiguity, we write: “because these water masses flow into the ice-sheet cavities and are in contact with the ice shelve bases.”

l.854: “Highest temperature increases occur in the Bellingshausen and Amundsen Seas...” => Is this an observation or does the climate models suggest so?

Clarified: “Highest temperature increases occur in the Bellingshausen and Amundsen Seas as part of the West Antarctic Ice Sheet (WAIS) and some spots along the East Antarctic Ice Sheet (EAIS) according to observations (Schmidtko et al., 2014; Jacobs, 2006).”

l.856: “ flow already ” => “already flow” as observations suggest?

We write: “In the Bellingshausen and the Amundsen Sea, warm water masses flow into ice-shelf cavities as indicated by observations (Arneborg et al., 2012; Thompson et al., 2018) and model simulations (Nakayama et al., 2018).”

l.857: “massive” => “largest”

Exchanged “tremendous” for “massive.”

l.865: “ Temperature Scaling” => “ Estimate of temperature scaling of precipitation from climate models”

We use instead: “Temperature Scaling of Precipitation derived from Climate Models”

l.868: “ depend on if we determine ” => “ depend on the time period we chose as a reference ”

Replace: “depend on if we determine the anomalies” by “depend on the time period we chose as a reference”.

l.871: “However, all these differences do not changes the spatial structure significantly, and they have a neglectable impact compared to the choice of the driving model.” => “However, these differences do not significantly change the spatial structure. Their impact is negligible compared to the choice of the driving model.”

Done as suggested.

l.877: “The detected precipitation deficit...” => Could you provide a definition here, is this negative scaling or just scaling below average?

Clarified: “the detected precipitation deficit (shrinking precipitation rates), captured by reanalysis data … .”

l.880: “is small” => you could mention the relative size of the ice shelves, or you could account for ice shelves separately?

Yes, we could, but the manuscript is already pretty long. Therefore we will not further investigate this point.

l.907: “while in both cases the thickness calving is active”=>It would be very interesting if PISM could differentiate between the three calving styles in the reporting.

I agree it would be nice, but I have not kept the data that allows differentiating the individual contributions due to storage space limitations.

l.909: Make sure you the reader notices that you switched to observations.

Clarified: “According to observational estimates control iceberg calving and basal ice-shelf melting the overall mass loss of Antarctica, while the relative contribution is the subject of current research.”

l.919: “just termed basal melting rates” => why not “basal melt rates”
l.919: “the second ice mass loss process” => second largest process or does this just relate to the previous paragraph?

We rephrase: “The basal melting rate of floating ice shelves (hereinafter basal melting rates) is the second ocean-driven ice mass loss process beside iceberg calving.”

l.920: “The basal melting rate anomaly is computed relative to the 50 years between 1951 and 2000.” Please indicate how this period compares to the observations of the World ocean atlas used as reference field?

The WOA2009 says: “For the present atlas we attempted to reduce the effects of irregular space-time sampling by the averaging of five 'climatologies' computed for the following time periods: 1955-1964, 1965-1974, 1975-1984, 1985- 1994, and 1995-2006. The first-guess field for each of these climatologies is the 'all- data' monthly mean objectively analyzed temperature data.” (Locarnini, et al., 2010; page 6).

Locarnini, R. A., A. V. Mishonov, T. P. Antonov, T.P. Boyer, and H.E. Garcia. 2010. “World Ocean Atlas 2009, Volume 1: Temperature.” Edited by S Levitus. Vol. 1. U.S. Government Printing Office, Washington, D.C. https://www.nodc.noaa.gov/OC5/WOA09/pr_woa09.html.

l.921: “ We could identify immediately that the basal melting rates have risen between 10 % and 100 % since the 1850s (Figure A13)” => “The inferred an increase in basal melt rates by 10-100% over the period 1850-x?”

Rephrased to: “In general, the basal melt rate increases by 10 %--100 % over the period 1850-2100 (Figure A13).”

l.922: “independent of the initial state selection” => “independent of the selection of the initial state” or simply “independent of the initial state”

Done.

l.922: “ and reference to compute the” => “ as well as to the reference period selected for the computation of the”

Done.

l.925: “ subject to not negligible trend ” => Please be more precises!

We quantified the trend: “For instance, the average of the global absolute 2m-air temperature difference between the first and last 50 years of piControl amounts 0.17 K (median 0.12 K) for all CMIP5 models considered in our study. In contrast, MIROC-ESM's value is 0.67 K.”

l.926: “In the future, the basal melting rate will further increase between 10 % and more than 100 %.” => In future projections, the modeled basal melt rate further increases … until the year x”

To avoid a pleonasm, we write: “In future projections, the basal melting rate increases between 10% and more than 100% until the year 2100”

l.927: “ specialized ocean simulations” => “high-resolution ocean simulations”

Rephrased to “dedicated ocean simulations.”

l.931: “ is apparent.” => “ is clear/distinct.”

Changed to “is self-evident.”

l.937: “ or reach a maximum of around 2100 and scenarios” => “and reach a maximum around the year 2100. Scenarios...” The maximum in basal melting in Fig. A13 and A14 seems to occur for all climate forcings a few decades before 2100, is there an explanation for this phenomenon?

The applied running mean of 5 years and the constructed forcing after the year 2100 causes the visual shift of the maximum. We use the forcing until the year 2100 and repeat afterward recurrently the last 30 years of the forcing (2071-2100). For instance, the depicted forcing in the year 2100 corresponds to the weighted sum of the forcing of the years 2098, 2099, 2100, 2101(=2071), and 2102(=2072). We have clarified it by reordering the sentences in the figure captions of Figure A12/A13 and adding, in addition, these two sentences: “After the year 2100, the forcing of the last thirty years until 2100 drives the model recurrently.” and “The applied running means shift the apparent maximum backward in time so that it occurs visually before the year 2100.”. The last sentence is added to figure caption A14 too.

l.939: “our approach works where the last 30 years of the forcing until 2100 is recurrently applied afterward.” Please reformulate

We reformulate: “Since the temporal variability remains high also after 2100, our approach works to construct the forcing beyond the year 2100 (see section 2: "Material and Methods").”

l.942: “ show a minimum of around 3500 ” => “ show a minimum around the year 3500”

We rephrase as suggested.

l.945: “ ocean temperature anomalies are warmer” => “ ocean temperature anomalies are larger” or “more pronounced”

We write now: “This result reflects the dependence of the basal melting on the ocean temperature because a warmer climate scenario induces higher ocean temperature anomalies.”

l.948: “ and an average decrement for RCP4.5 ” => What does this mean?

Rephrased: “and an intermediate decrement of RCP4.5”

l.954: “while the highest calving occurs under scenarios with a lower forcing.” => This is surprising, do you have ideas for an explanation? Might this be related to the much smaller ice shelf area and hence shorter ice shelf front? The sentence in l.964 is not so clear on this assessment.

Why is this surprising? However, we sharpen the last sentence of this paragraph: “The total area of ice shelves is, in general, smaller when a warmer climate scenario impacts these ice shelves (Figure A15) and the degraded total ice shelf area downgrades the calving probability. Ultimately, the integrated calving rate is lower under a warmer climate.”

l.967: “Starting from original simulated ablation flux...” => Please start even earlier and explain briefly what the intention of this correction is. You take the modeled fluxes, modify them and apply them in additional sensitivity simulations? Is the reference flux usually obtained from observations? Maybe provide a figure to visualize the magnitudes.

We write “Since the simulated ocean-driven basal melting rates are lower than observational-based estimates (Figure A13), the impact of flux corrected basal melting rates on the model results are discussed in the main text (Section 3.7.1 "Sea level contribution of corrected basal melting" on page 15). This section describes the method.”

l.980: Please provide some motivation here: “In order to provide an estimate of how ice shelf mass changes result in equivalent sea-level changes...”?

We write now: “To relate the sea-level change to the ice mass evolution, we define the ratio p(t) of the sea level temporal deviation to the ice mass temporal deviation as p(t) = … .”

l.998: “the sea level rise of 30 cm is larger than the actual sea level rise “ => “the corresponding sea level rise of 30 cm would be larger than the observed sea level rise“ Please make sure in the wording that this is just a unit conversion and no dynamical estimate.

Changed as requested.

l.1000: “rise the” => “contributes to the”

Done.

l.1001: omit “(Equation A5)”

Done.

l.1002: “If” => “Whether”

Done.

l.1006: “ losses” => “lose”

Corrected.

l.1009 and l.1010 and l.1012: “temperature scaled” => “temperature-scaled”

Thanks for indicating; we've adjusted the entire text accordingly.

Figures:

Fig. 1: As this is the overview figure, the reader may expect the sector definitions of Table 4 visualized here, as done in Fig. 4.

As requested, we added the boundaries of the defined regions and adjusted the figure caption accordingly.

Fig. 2: The color scale in panel a is somewhat counterintuitive with the coldest areas in red. Why not using a temperature colorscheme similar to panel c)?

We prefer different properties of different color schemes to avoid confusion. In addition, we use color schemes that are aware of different types of color blindnesses.

Fig. 3: "is an extension into the sea" => maybe provide some estimate of the width. Also, the anomaly seems to be relative to the start period (at 1850), while for the ocean forcing, in l.920 in the Appendix a reference period 1950-2000 is indicated?

We extend the caption:"… is an extension into the sea (typical width of about 500 km)."
It is indeed correct that we talk about a different reference period (1951-2000) in line 920 as part of the appendix section "A2 Marginal ice loss by ocean-driven basal melting and iceberg calving." There, we compare our growth rates of the basal melting rates with independent studies cited a few lines below (line 926-929). These studies determine the growth rates until the end of the century relative to 1951-2000.

Fig. 4: Which are the dotted regions here? Sector outline seem to overlay each other.

Solved. Indeed, in the submitted version, the dotted regions are absent while it is available in our version. Apparently, the size reduction of the submitted file has striped the dotted pattern. We apologize for being sloppy.

Fig. 6: This figure is simply overloaded, I recommend to split somehow.

We have worked with different versions of this plot because we initially shared your impression. However, a printed article allows taking the time needed to see the differences in this information-rich plot. In addition, splitting the figure may hinder the direct comparison of different model forcing scenarios. Therefore, we would like to keep the current figure.

Fig. 11: You should mention that ice loss is the combination of calving and melt.

The extended figure caption begins with: "Temporal evolution of the ocean-driven ice loss rates of the fringing ice shelves around Antarctica for the period from 1850 to 2100. The ice loss comprises iceberg discharge and basal melting of ice shelves. ... "

Fig. A1: You should mention in the caption that the 50 cm year−1 contour is larger than in previous figures.

I assume you refer to Figure 2 when you talk about the previous figure. The extended figure caption ends with "Figure 2 shows the corresponding ensemble mean fields, where the white contour line in the precipitation field corresponds to 30 cm year-1."

Fig. A2: Where are the "white-grey lines" mentioned in the caption?

We replaced "white-grey" with "light-grey"

Fig. A3: Please increase the size of the climate model labels.

The entire figure has a new label layout.

Fig. A4: It would help if the individual panels would use the same y-axis. Why is it important to distinguish between grounded ands glacierized here? Why not between grounded and floating?

This appendix figure has deliberately individual y-axis for each panel. Otherwise, the bunch of lines could not be separated in each panel. We are aware that this is a busy plot, but we are confident that the interested reader welcomes the provided rich set of information.

In simplified terms, the melting of grounded ice contributes to the global sea level, while the mere disintegration of floating ice does not. Hence the diagnosed sea-level contribution of grounded ice is vital.

To get an idea of how much snow accumulates on all glacierized ice, regardless if it is floating or grounded, we present these. Since we analyze precipitation anomalies, the change of precipitation rates may be of interest to the following communities. Those who have an interest in the evolution of the surface mass balance, use remote satellite products to analyze precipitation or water vapor transport changes in the Southern Ocean, and those running automated weather stations in coastal areas or floating ice shelves, for instance.

Fig. A5: “where all additional mass loss rises immediately the sea level” => “assuming that all additional mass loss is converted into a sea-level equivalent”

We change this part to “assuming that all additional mass loss rises the global sea level”

Fig. A6: unit for y-axis is also m?

Yes, we have indicated that this Figure is like Figure A5 and the y-axis says “Sea level contribution (m).” However, since your question expresses a misunderstanding, we adjust the figure caption and add explicitly the unit “(in meter)”: ”... The sea level (in meter) is computed relative to the year 2000. ...”

Fig. A7: Omit the in “of the each” in the caption.

We assume you suggest to erase “of the each ensemble member.” We follow your suggestion.

Figs. A10+11: It would be nice to indicate that the difference is simply the eigencalving parameter and describe whether and where differences (in calving front location) occur.

We have added for each state the total ice volume and ice area (grounded ice and floating ice) in an additional table as part of the appendix. We link from the figure captions of both Figures (A10 and A12) to this table. This table should allow the reader to distinguish both states. A copy of this table is listed below:

Field	PISM1Eq	PISM2Eq	Ratio: PISM1Eq/PIMS2Eq
Area: grounded ice (km2)	1.255e7	1.257e7	0.9985
Area: floating ice (km2)	2.005e6	1.569e6	1.278
Volume: grounded ice (km3)	2.588e7	2.605e7	0.9936
Volume: grounded ice above z=0 (km3)	2.313e7	2.325e7	0.9947
Ratio: all grounded ice / grounded ice above z=0 (%)	89.35	89.25	1.001
Volume: floating ice (km3)	6.681e5	5.421e5	1.232

Fig. A15: Could you state to what extent the trends can be attribute to grounding line retreat vs. calving front retreat?

If the grounding line retreated while the calving front stayed fixed, the ice shelf area would increase. Since the grounding does not advance on a large scale, a calving front that retreats faster than the grounding line is required to obtain a shrinking ice shelf area. Therefore the shrinking ice shelf area is dominated by a retreating calving front. We hope this answers your question.

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