Reply to Editor

Overall Comments

You have thoroughly addressed all of the comments of the reviewers, and the manuscript looks like it is near ready for publication. However, I find that the Methods section needs some major revision before going further.

Response: We sincerely thank the editor for the thoughtful and constructive comments, which have been invaluable in strengthening our manuscript. We are greatly encouraged by the overall positive assessment. Following your suggestions, we have revised the Methods section to provide further clarification and details on the basal melting schemes in both the initialization and projection, and have added Figure R1 as a schematic to illustrate the experimental procedure (Fig. 3 in the revised manuscript). Below, we provide a point-by-point response to the specific suggestions raised.

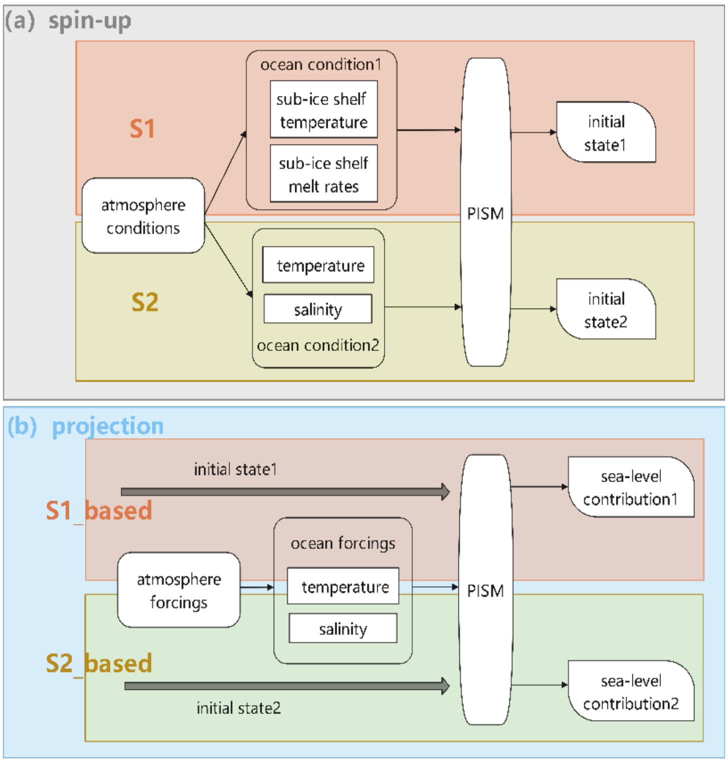

Figure R1: Overview of model initialization and projection processes. The schematic summarizes the model setup during (a) spin-up and (b) projection, using observed basal melt rates together with ice-shelf basal temperature (S1, orange box in a) and Southern Ocean temperature and salinity (S2, yellow box in a; LOW21). The projections initialized from these two states are denoted as S1-based and S2-based (LOW21), respectively.

The Methods (and relevant paragraph in the Introduction) still need to be improved for clarity. From the text alone, it is actually not clear at all what is done here. Through the revised manuscript, and the review responses, I understand that experiment S1 and experiment S2 have two different reference basal melting rates determined via Eqs. 1 & 2. These reference rates are used for spinning up the models. This allows comparison of the initial states in each case. For the projections, however, by the end of Section 2, it is actually not at all clear to me how the model was forced. I have to assume that the melt rates applied in the projection are anomalies added on to the reference rates.

Response: Thanks for your suggestions.

1. In the projection, the ice-sheet model is forced with ocean forcings extrapolated from the ISMIP6 protocol to simulate ice–ocean interactions. ISMIP6 derives annual-mean spatial anomalies distribution and time series of ocean properties (temperature and salinity) around Antarctica from CMIP outputs, in which anomalies are defined relative to a common modern period for each climate model. These anomalies are then added to a modern observational ocean climatology to obtain absolute salinity and temperature fields (Fig. R2). And using the sub-ice-shelf extrapolation scheme proposed by Jourdain et al. (2020)—which explicitly accounts for bathymetric features such as pinning points and troughs that influence ocean circulation—these fields are extrapolated into ice-shelf cavities and other ice-covered regions.
2. Therefore, throughout the projection period, we apply absolute, transient Southern Ocean forcings (temperature and salinity) for 2015–2100. Using the parameterization in Eq. 2, we calculate time-varying sub-shelf mass flux over the next 85 years directly, rather than applying anomalies relative to a reference value.

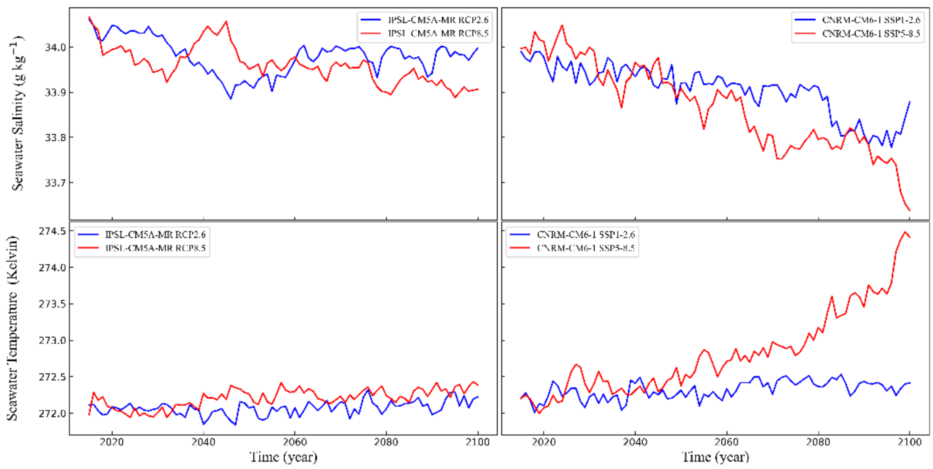

Figure R2: Time series (2015-2100) of annual mean oceanic forcing averaged over the AIS in projection. The oceanic forcings comprise absolute seawater salinity (g kg^{-1}) and temperature (Kelvin), corresponding to the IPSL-CM5A-MR RCP 2.6, IPSL-

CM5A-MR RCP 8.5, CNRM-CM6-1 SSP 1-2.6, and CNRM-CM6-1 SSP 5-8.5.

I would suggest introducing a general equation for the melt rate calculation, such as S = S_{ref}+ΔS, where S_{ref}=S_1 or S_2, but ΔS is always calculated in the same way, if this is the case. Or the appropriate formulation. If, on the other hand, the projections are performed with S_2 in both cases, then I would be concerned that the results are contaminated by a potential shock going from S_1 forcing in the spinup to S_2 forcing in the projection. For this, reason, I ask for clear revision of these methods.

Response: Thanks for your suggestions.

1. Regarding the similar point raised by the second reviewer about whether the ice-sheet change is smooth (i.e., whether there is any abrupt change) at the transition between initialization and projection: “I would like to see how a time series of ice volume for the spin-up and its continuation into the projections, to make sure the transition is smooth.”. As presented in Fig. R3, the time series of volume above flotation (VAF) from the historical spin-up (S1 scheme) to the subsequent projections exhibits a smooth transition, with no abrupt change in ice-sheet volume.

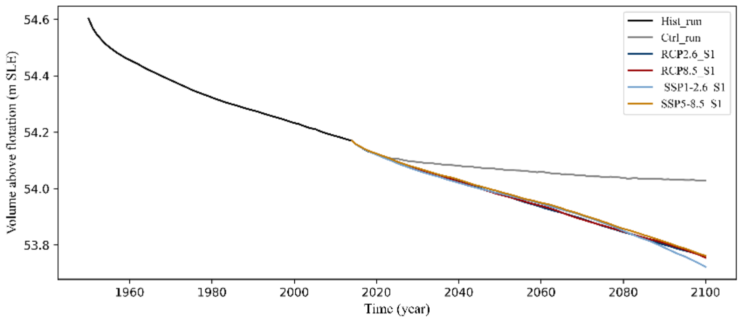

Figure R3: Ice volume above flotation (VAF) in spin-up and projection. Time series show S1-based historical period in spin-up (black), and projections under RCP/SSP scenarios (light blue, red, dark blue, orange) and constant-climate control projection (grey).

2. Thanks for the suggestion of the ΔS scheme for validating projections that apply the S2 parameterization to the S1 initialization, and for identifying the potential shock during this process. Following your suggestion, we have conducted an additional experiment designed to examine whether this “shock” exists: i) the spatial mean and temporal anomaly of the basal melting (ΔS, time=86, x, y; Eq. R-1) involved in the S2-based projection was derived by subtracting the S2 initialization from the S2-based projection. ii) This ΔS was then added to the S1 initialization to obtain a new oceanic forcing (S_{s1_s2}, time=86, x, y; Eq. R-2), which represents the absolute annual spatial distribution and time series incorporating the S2-derived perturbation. iii) Based on the S1-initial state, we conducted the

additional experiment forced by S_{s1_s2} to explicitly test for a potential shock, as formulated below:

$$\Delta S = S_{2\_proj} - S_{2\_init} \quad \text{(R-1)}$$

$$S_{s1\_s2} = S_{1\_init} + \Delta S \quad \text{(R-2)}$$

here, S_{2_proj} is derived from the S2-based projections (RCP 2.6/8.5, LOW21), S_{2_init} represents the initialization results using S2, which replicates the LOW21 experiment; S_{1_init} denotes the initialization results using S1. S_{s1_s2} is the new oceanic forcing produced via the ΔS scheme. The absence of shock when applying the S2 parameterization to S1-initialized projections, shown by the supplementary ice volume time series (Fig. R4), arises from two factors: the use of absolute oceanic forcings rather than anomalies in projections, and constant parameters values in the S2 parameterization that are derived from in-situ observations or empirically calibrated against them, ensuring that the resulting basal melt rate remains closely matches the observations.

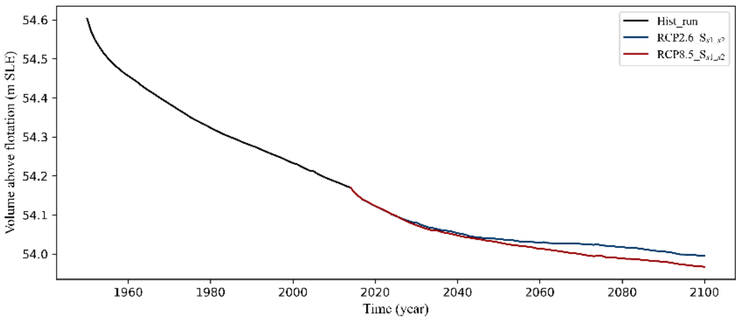

Figure R4: Ice volume above flotation (VAF) in S1-spin-up and S_{s1_s2}-projection. Time series show S1-based historical period in spin-up (black), and the subsequent projections forced by the S_{s1_s2} oceanic forcings (calculated via Eqs. R-1 and R-2) under RCP scenarios (light blue and red lines, respectively).

3. To enhance clarity, we have revised the description of oceanic forcings in projection and, derived from the parameterization in Eq. 2, the formula for calculating basal melt rates in the projections is given, thus distinguishing this procedure from that used in the initialization: *"The basal melting scheme was parameterized using the same linear thermodynamic framework for the ice-shelf-ocean boundary layer as that employed in LOW21—specifically, the approach defined in Eq. 2, which is driven by the annual-mean spatial distribution and time series of absolute salinity and temperature fields derived from the RCP/SSP scenarios (Jourdain et al., 2020; Nowicki et al., 2020) for 2015–2100:*

$$S_{proj} = \rho_{sw} c_m \gamma_T F_{melt} (T_{s\_proj} - T_{f\_proj}) / (L_i \rho_i), \quad (4)$$

here, S_{proj}, T_{s_proj}, and T_{f_proj} refer to values calculated by projected ocean *forcings. Therefore, following the two basal melt schemes that yielded distinct initial ice-sheet states and produced two projections (Fig. 3b): the S1-based projection simulates future Antarctic evolution under RCP/SSP scenarios, starting from the S1-initialized state using observed basal melt rates. While the S2-based projection utilizes the RCP-based sea-level contributions provided by LOW21, which were generated using the same parameter configuration as S2 reproduction initialization.".*

I have read the rest of the manuscript, assuming that they would not be affected by any shock after initialization, and that the forcing in both cases for the projections was identical. If that is the case, then indeed I think the results are quite interesting and would be valuable to publish.

Response: Thanks for your suggestions

1. The validation via the ΔS scheme, along with the inherent ice-sheet volume evolution throughout the initialization and projection experiments, indicates no discernible potential shock when transitioning from S1 forcing in the spin-up to S2 forcing in the projection.
2. Our study focuses on how variations in sub-ice shelf melt rates affect the initial ice-sheet state after spin-up and subsequently influence projected sea-level contributions. We directly utilized the projection results provided by Prof. Lowry, which were generated using the same optimal parameter set and identical climate forcings (CMIP5 IPSL-CM5A-MR RCP2.6/8.5 from the ISMIP6 21st Century Forcing Datasets) as applied in our S1-based projections. This was feasible because the structure of the projection script is identical to the final step of initialization, allowing for a direct substitution of the climate forcing. As the LOW21 did not perform simulations under SSP scenarios, the analysis is therefore restricted to a comparison of RCP-based results. We are grateful to Prof. Lowry for providing these scenario-specific projection results.

Please also find a list of minor comments below.

Minor comments

Title: the Antarctic ice sheet → Antarctic ice sheet

Response: Thanks for your suggestions. We have revised the title.

L24: varied ice-sheet mass changes → differences in ice-sheet mass changes over time

Response: Thanks for your suggestions. We have revised the corresponding expression.

L25: Antarctic Ice Sheet → Antarctic ice sheet [Check throughout the manuscript for consistency.]

Response: Thanks for your suggestions. We have made the corresponding changes — 6 in total across the manuscript.

L29: Delete "mainly"

Response: Thanks for your suggestions. We have revised the expression.

L39: Antarctic → Antarctica's

Response: Thanks for your suggestions. We have revised the content.

L55: It would also be appropriate to cite Juarez-Martinez et al. (2024, https://doi.org/10.5194/tc-18-4257-2024) here, as they do something similar. Disclaimer: I am a co-author of that study. They only use one basal melting parameterization, but vary melting coefficients. Thus it is less comprehensive, but complementary to what you do here.

Response: Thanks for your suggestions. We have added a citation to Juarez-Martínez et al. (2024) in the revised manuscript to further underscore the impact of variable basal melt rates on the uncertainty in future sea-level contributions from the Antarctic ice sheet. *"For instance, simulations with the Yelmo ice-sheet model indicate that the Antarctic ice sheet's sea-level contribution is highly sensitive to the ice-ocean interaction under varying basal melt coefficients, with several projections reaching up to 3 m SLE by 2500 (Juarez-Martínez et al., 2024)."*.

L67: What is done with basal friction in these experiments? This should be described clearly.

Response: Thanks for your suggestions.

1. PISM parameterizes the relationship between basal sliding and resistance using a generalized power law that ranges from plastic Coulomb sliding to a linear sliding law:

$$\tau_b = -\tau_c \frac{\boldsymbol{u}_b}{u_{th}^q |\boldsymbol{u}_b|^{1-q}} \quad \text{(R-3)}$$

here, τ_b denotes the non-zero basal friction (shear stress), τ_c represents the yield stress related to the effective till pressure, $\boldsymbol{u}_b$ is velocity, and u_{th} is a threshold velocity (100 m y^{-1}). q is the sliding exponent parameter, where q=0 is purely plastic sliding, and q=1 is sliding linearly related to the applied stress. The default value in PISM is q=0.25.

2. To improve clarity, we have added the following sentence: *"In PISM, basal resistance—which directly governs sliding velocities—is calculated using a generalized power law that ranges from plastic Coulomb sliding to a linear sliding law (Bueler and Brown, 2009; Winkelmann et al., 2011; Garbe et al., 2020)."*.

L74: optimized → determined

Response: Thanks for your suggestions. We have revised the content.

L87-90: What is done for grid points that become floating during the experiment, and thus have no observed values available? Which temperatures and melt rates does the model see?

Response: Thanks for your suggestions. In the source code, the PISM's ocean model uses the "extend_basal_melt_rates" function to spatially extrapolate basal melt rates into the partially floating cells, ensuring physical consistency and preventing discontinuities during simulation. For cells that transition to a floating state during the simulation, the function employs a "3×3" stencil to compute the mean of the basal melt rates from all surrounding grid points. This averaged value is then assigned to the current cell, effectively extending the basal melt rate field into these partially floating cells. This approach uses a simple arithmetic average and does not incorporate distance-based weighting.

L99: If T_S=271.45 K is imposed, then Eq. 2 is comprised entirely of constants. How is transient forcing for the projections included?

1. **Response:** Thanks for your suggestions. Upon re-examining the explanation of Eq. 2 in Martin et al. (2011), we recognize that T_S =271.45 K represents the NCEP reanalysis value for the Ross Ice Shelf, used in that study as an illustrative example to verify the correctness of their ocean–ice heat exchange formulation (as noted in the source, "For the present simulation…"), and is in fact not a fixed parameter in general. As noted by Beckmann and Goosse (2003), where T_S represents the vertical average of ocean temperature (between 200 m and 1000 m). We have adjusted the text by removing the mention of *"T_S=271.45 K"* in the manuscript: *"T_S is the vertically averaged ocean temperature between 200 m and 1000 m depth along the continental slope, representing relatively warm water masses of the coastal current (Holland and Jenkins, 1999; Beckmann and Goosse, 2003)."*.
2. In Eq. 3, it is also inappropriate to set S_0 as a constant 35 psu for calculating the freezing temperature of seawater. In the PISM source code, ocean salinity is read directly from input files when ocean conditions are provided. If no salinity is available, a constant value (~35 psu) is substituted. In this case, the model outputs an informational message to notify the user: "Variable '%s' not found; using constant

salinity". So, following Beckmann and Goosse (2003) and the source code, S_0 should represent the salinity at the given depth z_b, rather than a prescribed constant value. Accordingly, in the revised manuscript, we have removed the content: *"S_0=35 psu."*. Similar to the case of the parameter T_s, while earlier descriptions of certain parameters may have been imprecise, the actual ice-sheet model calculations are strictly governed by the source code and driven by the prescribed input conditions. **Therefore, the simulation results remain valid and are not affected by those descriptive inaccuracies.**

3. Additionally, in Eq. 3, z_b denotes the elevation (typically negative) of the base of the ice shelf. Therefore, the freezing temperature of ocean water T_f is not a fixed value but varies with z_b. As shown in Fig. R5, the parameterization employed here produces sub-shelf melt rates that depend on ice-shelf thickness, yielding a spatial pattern with the highest melt near the grounding lines. To improve clarity, we have revised the definition of z_b as follows: *"T_f denotes the freezing temperature of seawater: z_b as the elevation (generally negative) of the base of the ice shelf."*.

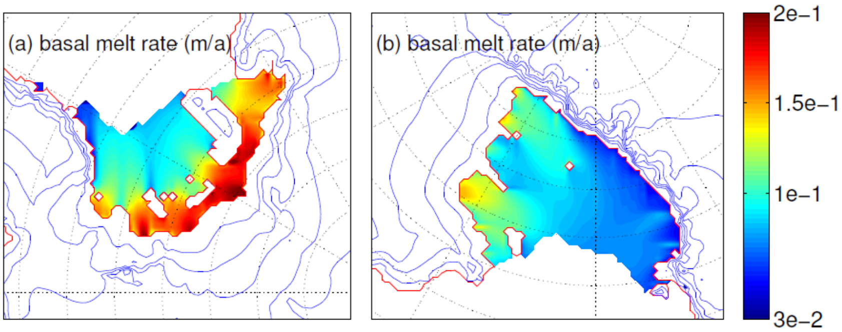

Figure R5: Basal melt rate for (a) Ronne-Filchner and (b) Ross Ice Shelves, as given by Eq. 2 (Martin et al.,2011).

L101: the temperature → the freezing temperature

Response: Thanks for your suggestions. We have revised this expression.

L103: I think you should introduce the "S1" case first. It makes more sense given the name of the experiment and it would match the order the equations were introduced above.

Response: Thanks for your suggestions. We have reorganized the introduction of S1 and S2 to enhance the logical structure of the manuscript: *"Experiment "S1" uses the same model configuration—including all parameters, stress balance approximation, resolution, topography, and atmospheric conditions—but replaces the basal melting scheme with observed basal melt rates derived from satellite altimetry (ICESat-1), radar (OIB and ALOS PALSAR), and model outputs (RACMO2), based on Eq. 1. While* *experiment "S2" replicates the single simulation from LOW21 that used the best-fit parameter set (the one minimizing mismatch with observations), employing a thermodynamic parameterization (Eq. 2) to estimate sub-ice shelf melt rates.".*

L118: Which physics are used in step 2, as this is not clear given what is stated for step 3. I assumed it was the full model physics here too.

Response: Thanks for your suggestions.

1. Step 2 aims to achieve a thermal equilibrium state under the initial climate conditions. In PISM, this step uses the "-no_mass" option, which disables the mass-continuity step. Normally, ice velocity from the stress balances is used for advection in the time-stepping solution of the mass conservation equation. With "-no_mass" enabled, the ice geometry remains fixed, allowing only the enthalpy field to evolve. This means that during this step, only the energy equation is solved forward in time, while mass conservation and stress balance are not active.
2. The conservation model in PISM is active by default and cannot be manually activated, only turned off. Consequently, the configuration for this step is effectively limited to disabling mass continuity via the "-no_mass" option, with no other specific physical options to specify.
3. To improve clarity, we have revised the content to *"(2) a 250,000-year thermal evolution run with the "no_mass" option, which fixes the ice geometry and allows the enthalpy field to evolve to equilibrium.".*

L130: Add a sentence here to state that the daily climate model forcing was averaged to obtain the annual mean to force the model with, as mentioned in the response to the reviewers. Please be precise.

Response: Thanks for your suggestions. To enhance clarity, we have split the original sentence into two and added an explicit clarification regarding the temporal averaging of the forcing data. We have revised the relevant description as follows: *"These daily data were pre-processed by averaging to produce annual mean forcings, which were then used to drive the ice-sheet model. This setup allowed us to assess and compare Antarctica's contribution to global mean sea-level rise by 2100.".*

L137: I would first mention the RMSE of the experiments themselves. Citing directly the "difference in root mean square error (RMSE) for the two experiments" is confusing, especially since the next sentences refer to comparison with observations.

Response: Thanks for your suggestions. As the purpose of the spin-up procedure is to achieve a present-day ice-sheet state close to observations, the ice-sheet geometry in experiments S1 and S2 naturally resembles the observational data after spin-up, resulting in similar RMSE values. To improve clarity, we have revised the content to *"The results show that both experiments achieve comparable accuracy against observations: the root mean square errors (RMSE) for ice thickness are approximately 89 m (S1) and 87 m (S2), differing by 2 m; the RMSE for ice surface velocity are roughly 270 m y^{-1} (S1) and 267 m y^{-1} (S2), differing by 3 m y^{-1}."*.

L151: sea level contributions → sea-level contributions

Response: Thanks for your suggestions. We have made the corresponding changes — 9 in total, with 5 in the manuscript and 2 in Figures 5 and 10.

L154: lends us → gives

Response: Thanks for your suggestions. We have revised the corresponding expression.

L294,310,326: sea level rise → sea-level rise [and throughout]

Response: Thanks for your suggestions. We have made the corresponding changes — 12 in total, with 11 in the manuscript and 1 in Figure 9.

L338: improve → provide

Response: Thanks for your suggestions. We have revised the content.

References:

Bueler, E. and Brown, J.: Shallow shelf approximation as a "sliding law" in a thermomechanically coupled ice sheet model, Journal of Geophysical Research, 114, https://doi.org/10.1029/2008jf001179, 2009.

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.

Holland, D. M. and Jenkins, A.: Modeling thermodynamic ice–ocean interactions at the base of an ice shelf, Journal of physical oceanography, 29, 1787-1800, https://doi.org/10.1175/1520-0485(1999)029%3C1787:MTIOIA%3E2.0.CO;2, 1999.

Jourdain, N. C., Asay-Davis, X., and Hattermann, T.: A protocol for calculating basal melt rates in the ISMIP6 Antarctic ice sheet projections, The Cryosphere, 14, 3111-3134, https://doi.org/10.5194/tc-14-3111-2020, 2020.

Juarez-Martinez, A., Blasco, J., Robinson, A., Montoya, M., and Alvarez-Solas, J.: Antarctic sensitivity to oceanic melting parameterizations, The Cryosphere, 18, 4257-4283, https://doi.org/10.5194/tc-18-4257-2024, 2024.

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.

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.

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.