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Brief communication: On calculating the sea-level contribution in marine ice-sheet models

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Abstract.

Estimating the contribution of marine ice sheets to sea-level rise is complicated by ice grounded below sea level that is replaced by ocean water when melted. The common approach is to only consider the ice volume above flotation, defined as the volume of ice to be removed from an ice column to become afloat. With isostatic adjustment of the bedrock and external sea-level forcing, this approach breaks down, because ice volume above flotation can be modified without actual changes of the sea-level contribution. We discuss a consistent and generalised approach for estimating the sea-level contribution from marine ice sheets.

1. Introduction

Model simulations of past and future ice-sheet evolution are an important tool to understand and estimate the contribution of ice sheets to sea-level at different time scales (e.g. de Boer et al., 2015; Nowicki et al., 2016). The mass balance of ice sheets is controlled by mass gain and loss at the upper, lower and lateral boundaries by melting or sublimation, by accumulation and freeze-on, and discharge of ice into the surrounding oceans. The sea-level contribution from an ice sheet can in principle be estimated through these different mass balance terms, but is in practice typically based on changes in one prognostic variable (*ice thickness*) and considering corrections for the ice grounded below sea level (e.g. Bamber et al., 2013). However, complications arise, especially for longer timescales, when isostatic adjustment of the bedrock is considered, and external sea-level forcing is applied. The considerations in this communication apply for ice-sheet models that are not coupled to a sea-level equation (Gomez et al., 2013; de Boer et al., 2014). Consequently, the problem at hand is how to accurately estimate the contribution of the modelled ice sheet to global-mean geocentric sea-level rise (see Gregory et al., 2019).

In our own ice-sheet modelling experience and from exchange with colleagues in different groups it is not always clear how the sea-level contribution should exactly be calculated and what corrections need to be applied. This goes hand in hand with a lack of documentation and transparency in the published literature on how the sea-level contribution is estimated in different models. With this brief communication, we hope to stimulate awareness and discussion in the community to improve on this situation. We caution that it is well possible that the proposed solutions or equivalent approaches are already in use in several models, since the fundamental ideas have already been laid out (e.g. Bamber et al., 2013; de Boer et al., 2015) and are straightforward to implement. Nevertheless, we have so far missed a common understanding, concrete guidelines and a central reference of best practices for ice-sheet modellers.

We describe in the following how to calculate the sea-level contribution for a situation without bedrock changes (Sec. 1), the effect of bedrock changes and how to account for them (Sec. 2 and 3), a density correction (Sec. 4) and modifications required when the model is forced by external sea-level changes (Sec. 5). We conclude with a realistic modelling example (Sec. 6) and a discussion (Sec. 7).

1. Estimating the sea-level contribution

If changes in the bedrock elevation due to isostatic adjustment are zero or very small, e.g. for centennial time scale simulations (e.g. Nowicki et al., 2016), the sea-level contribution of an ice sheet is typically computed from differences in total ice volume above flotation

$$V_{af} = \sum_{i,j} \left(H_{(i,j)} + min(b_{(i,j)}, 0) \frac{\rho_{ocean}}{\rho_{ice}} \right) \frac{1}{k_{(i,j)}^2} dx\ dy, \tag{1}$$

where H is ice thickness, b is bedrock elevation and e.g. ρ_{ice}=910 kg m^{-3} and ρ_{ocean} =1028 kg m^{-3} are the densities of ice and ocean water, respectively. The unitless map scale factor k is applied when the model grid is laid out on a projected horizontal coordinate system, which is often the case for polar ice-sheet models (Snyder, 1987, Reerink et al. 2016). V_{af} of a single column of ice grounded below sea-level may be interpreted as the amount of ice volume that can be removed before the column starts to float. This considers that floating ice is in hydrostatic balance with the surrounding water, and assumes that the ice does not contribute to sea-level changes when melted. In reality, however, densities of sea water and melted land ice (freshwater) differ slightly, which is often neglected. An associated density correction is discussed below (Sec. 4). For ice grounded on land above sea-level, $b > 0$ and $V_{af} = H\ dx\ dy * \frac{1}{k^2}$.

To estimate the ice volume in global sea-level equivalent (SLE_{af} [m]), the total V_{af} has to be converted into the volume it will occupy when added to the ocean assuming a sea-water density ρ_{ocean}=1028 kg m^{-3} and divided by the ocean area A_{ocean} of typically 3.625 x 10^{14} m^2, which is assumed to be constant here, but on longer time scales this is not necessarily correct:

$$SLE_{af} = \frac{V_{af}}{A_{ocean}} \frac{\rho_{ice}}{\rho_{ocean}}. \tag{2}$$

The actual sea-level contribution of the modelled ice sheet (SLC) is typically calculated relative to a reference value, often the present day (modelled) configuration or the configuration at the start or end of an experiment.

$$SLC_{af} = -(SLE_{af} - SLE_{af}^{ref}). \tag{3}$$

Depending on the amount of ice grounded below sea level, estimating the sea-level contribution instead from the entire grounded ice volume (Eq. (4)) can lead to considerable biases.

$$SLC_{gr} = -\left[\frac{\mathrm{V}_{gr}}{A_{ocean}}\frac{\rho_{ice}}{\rho_{ocean}} - \left(\frac{V_{gr}}{A_{ocean}}\frac{\rho_{ice}}{\rho_{ocean}}\right)^{ref}\right] \tag{4}$$

2. Effect of bedrock changes

When changes in bedrock elevation occur under the ice, V_{af} cannot always be used without a correction as basis for sea-level calculations, because isostatic uplift or lowering can modify V_{af} without actual sea-level contribution. Figure 1 illustrates this problem with an uplift of the bedrock elevation (left to right in each panel), where the bars indicate the bedrock and ice for different possible configurations. In case A, bedrock is already above sea level (i.e. V_{af} includes all ice) and the vertical upward displacement has no apparent influence on the grounded configuration. In case B, ice is displaced upwards with the bedrock and some of the ice at flotation is 'transformed' into ice above flotation. In case C a transition from floating to grounded ice occurs and in case D, ocean water is displaced by the rising bedrock.

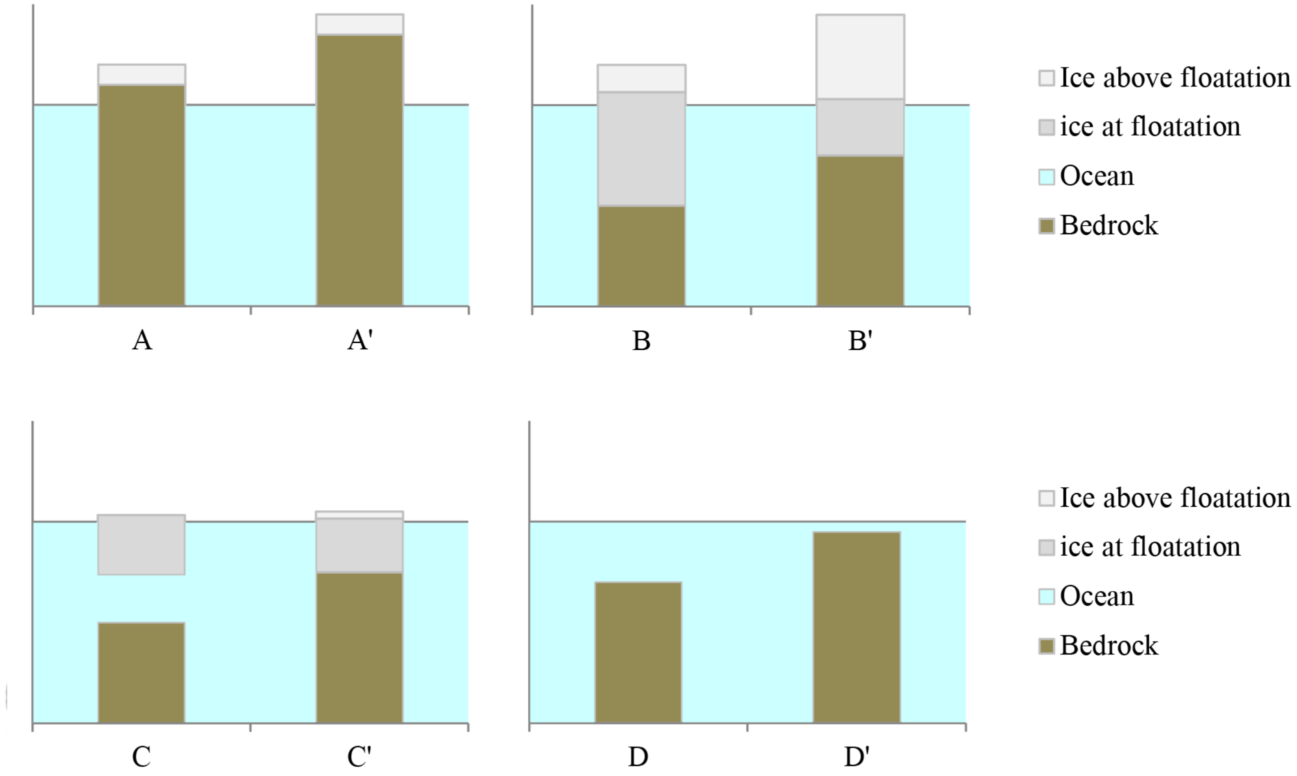

Figure 1 Different geometric configurations of ice, ocean and bedrock before and after (') a rise in bedrock elevation.

The problem how to interpret these changes in sea-level contribution in the presence of bedrock changes is further illustrated by an evolution of one grid box in time (Figure 2a). If we compare between t$_1$ and t$_4$ and only look at the ice column, we could assume that there was no net sea-level contribution since ice is at flotation in both cases. However, following the evolution through t$_2$ and t$_3$ gives rise to another interpretation. At t$_1$ the ice is at flotation with a low bedrock elevation. The bedrock then rises (t$_2$) and subsequently ice is lost e.g. by surface melting (t$_3$). Finally, more ice is lost e.g. by basal melting and the ice is floating at t$_4$. From t$_1$ to t$_2$, ice is merely displaced by the bedrock, but the actual sea-level contribution occurs between t$_2$ and t$_3$ and equals the ice above flotation in t$_2$ and (by construction) also the bedrock displacement between t$_1$ and t$_4$.

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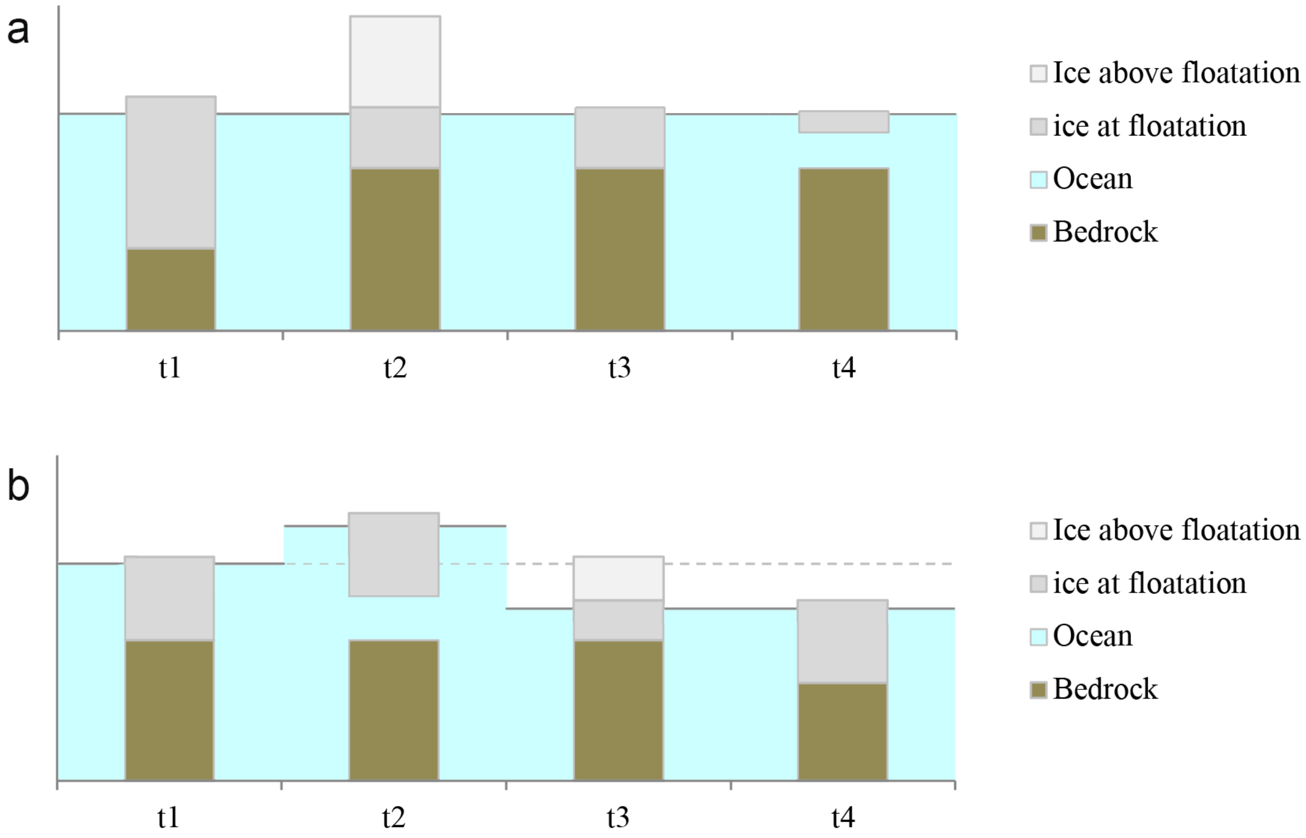

Figure 2: Geometric evolution of a grid box in time a) including bedrock changes and b) including externally forced sea-level variations.

We argue that differences in sea-level contribution from t_1 to t_4 must be independent from the interpretation of what happened between t_1 and t_4. Hence, bedrock changes have to be taken into account below the ice and in proximity to the ice sheet.

3. Correcting for bedrock changes

Under floating ice and ice-free ocean, rising bedrock displaces ocean water, and directly leads to a sea-level rise proportional to the bedrock elevation change. The additional sea-level contribution could be calculated from changes in the volume of the ocean water

$$V_{ocean} = \sum_{i,j} \left(max(-b_{(i,j)}, 0) - H_{(i,j)} \frac{\rho_{ice}}{\rho_{ocean}} \right) \frac{1}{k^2_{(i,j)}} dx\, dy \,, \tag{5}$$

where the term in brackets is the difference between lower ice boundary and bedrock for grid cells containing floating ice and the ocean depth where no ice is present.

However, while bedrock changes under grounded ice have no impact on the estimated ocean volume, they do modify the amount of V_{af}, which requires an additional correction. Consider an ice column near flotation but grounded below sea level at b_0, with a height above flotation $h_{af}=0$ (e.g. t_1 in Figure 2a). When the bedrock rises by a certain amount Δb (e.g. transition t_1 to t_2 in Figure 2a), the ice is lifted and h_{af} (in meter ice equivalent) increases by

$$\Delta h_{af} = \left(\frac{\rho_{water}}{\rho_{ice}}\right) \Delta b. \tag{6}$$

If the sea-level contribution was only computed from differences in total ice volume above flotation (SLE_{af}), this would be incorrectly recorded as a sea-level lowering. Furthermore, if the bedrock was lifted to or above sea-level, the final change in h_{af} would equal the ice thickness and

$$\Delta h_{af} = H = -\left(\frac{\rho_{water}}{\rho_{ice}}\right) b_0, \tag{7}$$

where b_0 is the initial bedrock elevation (e.g. at t_1 in Figure 2a).

In order to consider corrections for bedrock changes under grounded ice, floating ice and ice-free ocean consistently, we chose to modify the ocean volume estimate to incorporate bedrock changes. We suggest to replace the ocean volume calculation above by an estimate of the *potential* ocean volume (V_{pov}), i.e. the volume between bedrock and sea level if all ice was instantaneously removed:

$$V_{pov} = \sum_{i,j} max\left(-b_{(i,j)}, 0\right) \frac{1}{k_{(i,j)}^2} dx\, dy, \tag{8}$$

which requires no distinction anymore between grounded and floating ice. However, we have ignored the density difference between ocean water and freshwater, which we will treat separately below.

To convert potential ocean volume into a global sea-level component, V_{pov} has to be divided by the ocean area of typically 3.625 x 10^{14} m^2:

$$SLC_{pov} = -\left[\frac{\mathrm{V}_{pov}}{A_{ocean}} - \left(\frac{V_{pov}}{A_{ocean}}\right)^{ref}\right]. \tag{9}$$

4. Density correction

Transitions of ice below and above flotation and the associated sea-level change can occur both due to ice mass changes and due to bedrock changes, processes associated with a different density (ρ_{water} vs ρ_{ocean}). While changes of V_{af} due to bedrock adjustment and cavity changes are recorded in ocean water equivalent, we must assume that changes in ice mass (formation of new ice due to precipitation, loss of mass due to melting) occur in reality with a density of freshwater (ρ_{water}=1000 kg m^{-3}).

So far, we have calculated all changes in ocean water column equivalent, so now we will apply a density correction for all changes in ice thickness.

$$V_{den} = \sum_{i,j} H_{i,j} \left(\frac{\rho_{ice}}{\rho_{water}} - \frac{\rho_{ice}}{\rho_{ocean}} \right) \frac{1}{k^2_{(i,j)}} dx\, dy \tag{10}$$

and

$$SLC_{den} = -\left[\frac{\mathrm{V}_{den}}{A_{ocean}} - \left(\frac{V_{den}}{A_{ocean}} \right)^{ref} \right] \tag{11}$$

The density ratio $\rho_{water}/\rho_{ocean}$ implies that the correction amounts to ~3 % of the ice volume grounded at/below sea-level.

Finally, to calculate changes in global mean sea-level due to ice-sheet changes, contributions from ice volume above flotation, potential ocean volume and density correction are added:

$$SLC_{corr} = SLC_{af} + SLC_{pov} + SLC_{den}. \tag{12}$$

5. Externally forced sea-level variations

For long-term paleo ice-sheet simulations, it is common to force ice-sheet models with prescribed variations in (global) sea-level, mimicking changes in the northern hemisphere ice sheets. For a glacial-interglacial transition the external sea-level forcing may have an amplitude of more than 100 meters and can drive transitions between floating and grounded ice in the model. In the framework of such simulations, the calculation of sea-level contributions from the ice sheet must be re-considered, because the external sea-level forcing implies changes in V_{af} of the modelled ice sheet.

We illustrate the implied changes again with a schematic view of one grid box changing over time (Figure 2b). From t_1 to t_2, the external sea-level (horizontal solid line) is increased with respect to the starting value (horizontal dashed line) at constant bedrock elevation and ice thickness. Consequently, the geometry in the model grid box changes from just grounded to floating ice. From t_2 to t_3 the sea-level is lowered, such that some ice that was floating in t_{2i} is transformed into ice above flotation. At t_4, now with combined bedrock change and sea-level change of the same magnitude relative to t_1, the ice is just grounded on the lowered bedrock. Calculating the sea-level contribution as described above in Eq. (12), would indicate a change of the contribution from t_1 to t_2 and t_3. However, since these changes in SL are externally forced, they should not directly contribute to the calculated ice-sheet sea-level contribution itself. For example, the additional volume under the floating ice at t_2 occurs because the ice is lifted by the additional, externally-forced seawater. Equally, the additional ice above flotation created in t_3 is merely a consequence of the lower sea-level. Hence, V_{af} has to be corrected to calculate SLC in this case.

This problem is resolved by calculating changes in volume above flotation for the constructed case where sea-level is reset to a constant level z_0, typically at zero when the present day is the reference. Practically, Eqs. (1) and (8) must be adapted to calculate volume above flotation and potential ocean volume relative to z_0 as

$$V_{af}^{0} = \sum_{i,j} \left(H_{(i,j)} + min(b_{(i,j)} - z_0, 0) \frac{\rho_{ocean}}{\rho_{ice}} \right) \frac{1}{k_{(i,j)}^2} dx\, dy \tag{13}$$

and

$$V_{pov}^{0} = \sum_{i,j} max\left(z_0 - b_{(i,j)}, 0\right) \frac{1}{k_{(i,j)}^2} dx\, dy. \tag{14}$$

The density correction in Eq. (10) remains unchanged leading with Eqs. (3) and (9) to the corrected sea-level contribution

$$SLC_{corr}^{0} = SLC_{af}^{0} + SLC_{pov}^{0} + SLC_{den}. \tag{15}$$

6. Ice-sheet modelling example

Figure 3 illustrates differences in estimated sea-level contributions for an Antarctic ice-sheet model simulation (Pattyn, 2017). We have first applied a typical glacial-interglacial experiment (e.g. Golledge et al., 2014; Pollard et al., 2016; Albrecht et al., 2019) over the last 120 kyr (Figure 3a) with the prescribed external sea-level change (based on sea-level reconstructions by Bintanja et al. (2008) and Lambeck et al. (2014)) as a dominant forcing. Atmospheric forcing is produced by perturbing present-day surface temperatures (RACMO2, Van Wessem et al., 2014) with a spatially constant temperature anomaly following ice-core reconstructions from EPICA Dome C (Jouzel et al., 2007), while correcting surface temperatures for elevation changes (e.g. Huybrechts et al., 2002). The second part of the experiment (Figure 3b) continues from the present-day configuration and shows the response to an extreme basal melt forcing applied under floating ice shelves. In this schematic forcing scenario, present-day melt rates are multiplied by a constant factor of 200, resulting in melt rates of up to 100 m yr^{-1} in the Weddell and Ross sea sectors. This extreme melt forcing is not meant to represent a plausible scenario, it only serves to simulate a rapid removal of all floating ice shelves, leading to a retreat of the ice sheet (Pattyn, 2017; Nowicki et al., 2013).

Various SLC corrections and estimates are calculated against the initial configuration in Figure 3a (120 kyr BP) and Figure 3b (present day) and against the present day configuration in Figure 3c. Accounting for all grounded ice (SLC_{gr}) leads in all cases to the largest excursions in negative and positive sea-level contribution, due to ice grounded below the water level that should mostly be replaced by sea-water (Figure 3). The sea-level contribution calculated from changes in ice volume above flotation (SLC_{af}) includes signatures of bedrock and (in the past) externally-forced sea-level changes. In the future retreat scenario (Figure 3b), SLC_{af} is too low compared to our corrected estimate (SLC_{corr}^{0}) mainly because ice volume above flotation is ‘created’ by bedrock uplift. This effect of isostatic adjustment on SLC_{af} is exemplified by the steadily decreasing

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SLC_{af} towards the end of the experiment, while SLC_{corr}^{0} remains near constant (due to compensating SLC_{pov}). Accounting for density differences between ocean and fresh water (SLC_{den}) corrects an additional, but smaller underestimation of SLC_{af}. The proposed method (SLC_{corr}^{0}) is identical to (SLC_{corr}) for the future period (Figure 3b), where no external sea-level forcing is applied, and results in an estimate of the sea-level contribution between SLC_{gr} and SLC_{af}.

In the paleo simulation (Figure 3a), SLC_{af} is biased both by bedrock changes and external sea-level changes. Since SLC_{pov} is calculated in a fixed domain that includes grounded and floating ice and ice-free ocean areas, it is influenced by ice and ocean water loading. In a glaciation scenario with a growing (Antarctic) ice load and decreasing global sea level (Figure 3a, before 15 kyr BP), the correction SLC_{pov} is a combination of a subsiding bedrock under the ice sheet (negative SLC_{pov}) and a rising ocean floor in response to reduced water loading (positive SLC_{pov}). Although not fully separable, we have estimated the contribution of the two effects by calculating SLC_{pov} within and outside of the glacial ice mask (see supplementary Figure S1). Both effects are of similar magnitude in our setup but SLC_{pov} is slightly dominated by the changing ocean floor after periods of rapid sea-level forcing change. In addition, during ice-sheet growth, the negative sea-level excursion in SLC_{af} is exaggerated with increasing amplitude of the external sea-level forcing (cf. $SLC_{af}\ and\ SLC_{af}^{0}$). The proposed method ($SLC_{corr}^{0}$) results in an estimate of the negative sea-level contribution in the past of smaller amplitude compared to SLC_{gr} and SLC_{af} and shows that the magnitude and notably the timing of the Last Glacial Maximum low stand are subject to considerable biases in SLC_{af} (Figure 3c). The relative bias in SLC_{af} is larger for stronger ice-sheet retreat (not shown). Differences between the different approaches to calculate SLC become important after 2-3 kyr, roughly corresponding to the shortest response time of bedrock adjustment in the model.

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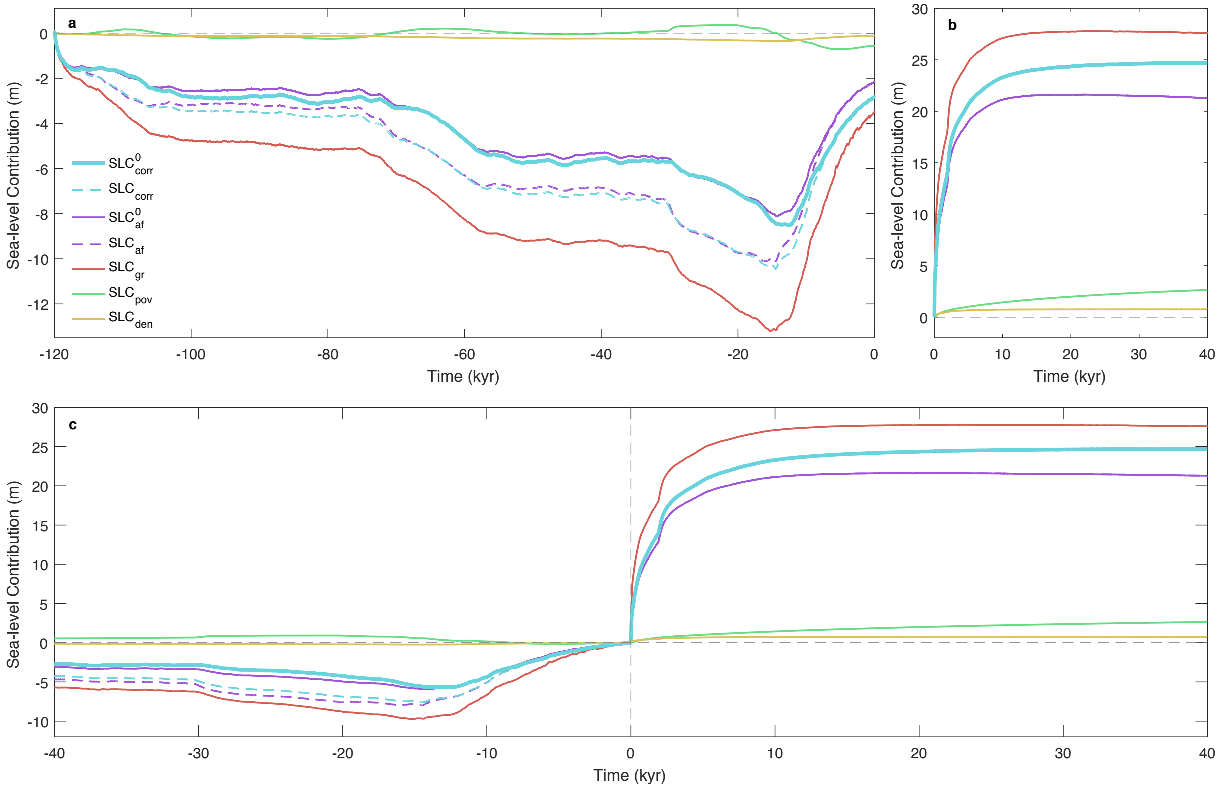

Figure 3 Different estimates of the sea-level contribution (SLC) from an Antarctic ice-sheet model simulation. (a) Sea-level contribution for the last glacial cycle under external sea-level forcing. (b) Schematic deglaciation experiment over the next 40 kyr in which an extreme sub-shelf basal melt perturbation is applied. The model experiment is continuous across year zero, but estimates in (a) and (b) are referenced to the beginning of each period. (c) Same as (a) and (b) combined, but both experiments are referenced to the present-day configuration. Some lines overlap in (b) and for the future in (c) because the external sea-level forcing is assumed zero for that period. Final corrected sea-level contribution (SLC^0_{corr}) calculated at constant external reference sea-level, based on volume above flotation (SLC^0_{af}), but corrected for potential ocean volume changes (SLC_{pov}) and density (SLC_{den}). The dashed lines (SLC_{corr} and SLC_{af}) show results calculated for a variable external sea-level forcing and SLC_{gr} is the sea-level contribution when considering all grounded ice without corrections.

7. Discussion and conclusions

We have presented a unified approach to calculate the sea-level contribution from a marine ice sheet simulated by an ice-sheet model. The formulation notably corrects for changes in ice volume above flotation in the presence of bedrock changes and external sea-level forcing. In this unified approach, sea-level contributions arise from changes in the ice volume above flotation and potential ocean volume, while changes in external sea-level forcing are accounted for.

When bedrock changes occur under ice that is grounded (below sea-level), changes in potential ocean volume compensate for changes in ice volume above flotation, resulting in a near zero net sea-level contribution as should be expected. Under floating ice (or open ocean), changes in volume above flotation are always zero, but bedrock changes imply ocean depth changes that lead to differences in the sea-level contribution. For changes from floating to grounded ice and vice versa, the combination of changes in ice volume above flotation and potential ocean volume yields unbiased results.

The region over which ice thickness changes and potential ocean volume changes are calculated must be fixed in time for the comparison and may contain the entire model grid (as done here) or a reasonable subset. It should include all locations that potentially see ice thickness and/or bedrock changes during a simulation. For models with local isostatic adjustment, the region could be the glacial ice mask for paleo simulations and the observed present-day sheet-shelf mask for future simulations dominated by retreat. For non-local isostatic models, the footprint would have to be extended.

In all calculations we have ignored any effects that arise e.g. from water storage in lakes on land and we also did not consider the equation of state of seawater, which implies a non-linear dependence of density on salinity and temperature.

Data availability. The SLC time series in Figure 3 and S1 are available as supplement to this publication.

Author contribution. HG conceived the project and developed the SLC corrections with assistance of VC. VC performed and analysed the model experiments. HG wrote the manuscript with assistance of all authors.

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

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8. References

Albrecht, T., Winkelmann, R., and Levermann, A.: Glacial cycles simulation of the Antarctic Ice Sheet with PISM - Part 1: Boundary conditions and climatic forcing, The Cryosphere Discuss., 2019, 1-56, doi:10.5194/tc-2019-71, 2019.

Bamber, J. L., Griggs, J. A., Hurkmans, R. T. W. L., Dowdeswell, J. A., Gogineni, S. P., Howat, I., Mouginot, J., Paden, J., Palmer, S., Rignot, E., and Steinhage, D.: A new bed elevation dataset for Greenland, Cryosphere, 7, 499-510, doi:10.5194/tc-7-499-2013, 2013.

Bintanja, R., and van de Wal, R. S. W.: North American ice-sheet dynamics and the onset of 100,000-year glacial cycles, Nature, 454, 869, doi:10.1038/nature07158, 2008.

de Boer, B., Dolan, A. M., Bernales, J., Gasson, E., Goelzer, H., Golledge, N. R., Sutter, J., Huybrechts, P., Lohmann, G., Rogozhina, I., Abe-Ouchi, A., Saito, F., and van de Wal, R. S. W.: Simulating the Antarctic ice sheet in the late-Pliocene warm period: PLISMIP-ANT, an ice-sheet model intercomparison project, The Cryosphere, 9, 881-903, doi:10.5194/tc-9-881-2015, 2015.

de Boer, B., Stocchi, P., and van de Wal, R. S. W.: A fully coupled 3-D ice-sheet-sea-level model: algorithm and applications, Geosci. Model Dev., 7, 2141-2156, doi:10.5194/gmd-7-2141-2014, 2014.

Golledge, N. R., Menviel, L., Carter, L., Fogwill, C. J., England, M. H., Cortese, G., and Levy, R. H.: Antarctic contribution to meltwater pulse 1A from reduced Southern Ocean overturning, Nature Communications, 5, 5107, doi:10.1038/ncomms6107, 2014.

Gomez, N., Pollard, D., and Mitrovica, J. X.: A 3-D coupled ice sheet – sea level model applied to Antarctica through the last 40 ky, Earth Planet. Sci. Lett., 384, 88-99, doi:https://doi.org/10.1016/j.epsl.2013.09.042, 2013.

Gregory, J. M., Griffies, S. M., Hughes, C. W., Lowe, J. A., Church, J. A., Fukimori, I., Gomez, N., Kopp, R. E., Landerer, F., Cozannet, G. L., Ponte, R. M., Stammer, D., Tamisiea, M. E., and van de Wal, R. S. W.: Concepts and Terminology for Sea Level: Mean, Variability and Change, Both Local and Global, Surv. Geophys., doi:10.1007/s10712-019-09525-z, 2019.

Huybrechts, P.: Sea-level changes at the LGM from ice-dynamic reconstructions of the Greenland and Antarctic ice sheets during the glacial cycles, Quat. Sci. Rev., 21, 203-231, doi:10.1016/S0277-3791(01)00082-8, 2002.

Jouzel, J., Masson-Delmotte, V., Cattani, O., Dreyfus, G., Falourd, S., Hoffmann, G., Minster, B., Nouet, J., Barnola, J. M., Chappellaz, J., Fischer, H., Gallet, J. C., Johnsen, S., Leuenberger, M., Loulergue, L., Luethi, D., Oerter, H., Parrenin, F., Raisbeck, G., Raynaud, D., Schilt, A., Schwander, J., Selmo, E., Souchez, R., Spahni, R., Stauffer, B., Steffensen, J. P., Stenni, B., Stocker, T. F., Tison, J. L., Werner, M., and Wolff, E. W.: Orbital and Millennial Antarctic Climate Variability over the Past 800,000 Years, Science, 317, 793, doi:10.1126/science.1141038, 2007.

Lambeck, K., Rouby, H., Purcell, A., Sun, Y., and Sambridge, M.: Sea level and global ice volumes from the Last Glacial Maximum to the Holocene, Proceedings of the National Academy of Sciences, 111, 15296, doi:10.1073/pnas.1411762111, 2014.

Nowicki, S., Bindschadler, R. A., Abe-Ouchi, A., Aschwanden, A., Bueler, E., Choi, H., Fastook, J., Granzow, G., Greve, R., Gutowski, G., Herzfeld, U., Jackson, C., Johnson, J., Khroulev, C., Larour, E., Levermann, A., Lipscomb, W. H., Martin, M. A., Morlighem, M., Parizek, B. R., Pollard, D., Price, S. F., Ren, D., Rignot, E., Saito, F., Sato, T., Seddik, H., Seroussi, H., Takahashi, K., Walker, R., and Wang, W. L.: Insights into spatial sensitivities of ice mass response to environmental change from the SeaRISE ice sheet modeling project I: Antarctica, Journal of Geophysical Research: Earth Surface, 118, 1002-1024, doi:10.1002/jgrf.20081, 2013.

Nowicki, S. M. J., Payne, A., Larour, E., Seroussi, H., Goelzer, H., Lipscomb, W., Gregory, J., Abe-Ouchi, A., and Shepherd, A.: Ice Sheet Model Intercomparison Project (ISMIP6) contribution to CMIP6, Geosci. Model Dev., 9, 4521-4545, doi:10.5194/gmd-9-4521-2016, 2016.

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

Pollard, D., Chang, W., Haran, M., Applegate, P., and DeConto, R.: Large ensemble modeling of the last deglacial retreat of the West Antarctic Ice Sheet: comparison of simple and advanced statistical techniques, Geosci. Model Dev., 9, 1697-1723, doi:10.5194/gmd-9-1697-2016, 2016.

Reerink, T. J., van de Berg, W. J., and van de Wal, R. S. W.: OBLIMAP 2.0: a fast climate model–ice sheet model coupler including online embeddable mapping routines, Geosci. Model Dev., 9, 4111-4132, doi:10.5194/gmd-9-4111-2016, 2016.

Snyder, J.: Map projections – a working manual (USGS Professional Paper 1395), United States Government Printing Office, Washington, USA., 1987.

van Wessem, J. M., Reijmer, C. H., Morlighem, M., Mouginot, J., Rignot, E., Medley, B., Joughin, I., Wouters, B., Depoorter, M. A., Bamber, J. L., Lenaerts, J. T. M., Van De Berg, W. J., Van Den Broeke, M. R., and Van Meijgaard, E.: Improved representation of East Antarctic surface mass balance in a regional atmospheric climate model, J. Glaciol., 60, 761-770, doi:10.3189/2014JoG14J051, 2014.