We would like to thank the reviewers for their very constructive comments that helped to improve the manuscript 'Brief communication: On calculating the sea-level contribution in marine ice-sheet models'. We have revised the manuscript accordingly and would be happy to provide a new version

Please find below the reviewer's comments in regular italic and a point-by-point response in bold font.

Referee #1 (Stephen Price)

Summary
This paper discusses the complexities around making estimates of sea-level change (SLC) from models of marine-based ice sheets (i.e., ice sheets with portions of their domains grounded below sea level at some point during the course of a simulation). After pointing out complications that are commonly not addressed or discussed in assessing SLC from marine ice sheet models, the authors propose a mathematical framework for ensuring that such calculations are made consistently. Overall, this is a welcome contribution and one that should be of broad interest to anyone involved in ice sheet modeling for the purposes of estimating SLC. Questions, criticisms, and comments below are mainly in the interest of making the paper more legible and understandable, and thus (hopefully) achieving the authors' goals of having other modelers adopt and use the proposed framework.

Thank you very much for the positive evaluation and your comments.

Major Comments
It is probably important to note that, while your framework allows for ice sheet models that are coupled to a GIA model, what you consider for the latter here is actually a somewhat limited version of a GIA models. That is, here it is assumed to account strictly for uplift or sinking of the bedrock beneath or proximal to an ice sheet, but does not include other (global) effects, such as SLC due to changes in Earth's rotation, regional SLC due to changes in the Earth's gravitational field, etc. Since some coupled "ice sheet and GIA models" (e.g., Gomez et al.) do account for all of these effects in a consistent way, it might be good to clarify that, here, you separate some of these effects out into "external" sea level forcing.

Agreed. We have added a clarification in the introduction following your suggestion.

On that note, the use of "external" to describe all of the "other" ways in which sea level might change could be expanded on a bit (i.e., to clarify what you are lumping in as "external" here). To an ice sheet modeler, this partitioning might seem natural, but to someone else, it might not be immediately clear why you break things up this way.

OK. We have added a description in the introduction.

For Figures 1 and 2, you might consider adding a relative sea-level plot going from one subplot to the next. Specifically, showing the relative change in sea level that occurs as we move from one subpanel to the next. For example, in the top panel of Fig. 1, SLC should be zero, which could be represented by a horizontal line. For the bottom panel of Fig. 1, there would be SLC (a relative increase for both cases I believe?) due to the illustrated changes (increases) in bedrock elevation (which, as shown, imply a decrease in the volume of the ocean basin).

Thanks for the suggestion. We have thought about including SLC information in Figures 1 and 2 before, but decided against it for the following reasons. Until the end of section 2 we use Figures 1 and 2 to illustrate the problem and develop the argument why SLC should be independent of what happens between t1 and t4 (Fig 2a). Showing SLC information in the plot would distract from that line of thought and 'give away' the conclusion. We also believe the figures should be read in a schematic and not quantitative way.

A similar comment applies to Figure 3, but in this case, it would be helpful to include the time series of the "external" sea level forcing.

Agreed, we have included the external sea-level forcing in Figure 3.

For the section on including the effects of "external" sea level forcing in your SLC calculation, it would be good to note if Equations 13-14 can be easily adjusted for the case where external sea level forcing is not a uniform value. For example, if external forcing and/or the reference sea level is spatially variable (a function of x, y or lat, lon), can the "z_0" term simply be adjusted to be "z_0(i,j)", where the indices refer to the local (x,y) value of sea level for that particular grid cell? This would be important for the framework to still be useful in the case where external sea level forcing, or the reference sea level, are supplied by a more complex model (i.e., one in which sea level is allowed to vary spatially, as it does in reality).

Yes, agreed. The formulation in Equ. 13-14 remains valid for non-uniform changes of the external sea-level forcing. We have added a clarification in the text to confirm that.

In general, I think it would help the paper quite a bit if, with each new section where you introduce a new set of terms or corrections, you first state in brief and plain English what that term or correction is and how it affects sea level (some specific examples of this are called out below). While the equations are all carefully laid out and discussed, it seems like you are assuming the reader will naturally and easily parse their importance and meaning, their relative impact on the SLC calculations, etc. It's probably safer to assume that the reader is a bit lazy and help them along right from the start.

Agreed. We have added short introductions to section 3, 4 and 5 accordingly.

When you discuss the impact of changes in bedrock elevation on SLC, in the absence of changes in ice sheet volume, I think it would help to be explicit that the way this impacts sea level is through changes in the volume of the ocean basins. That is, as bedrock is uplifted, ocean basin volume decreases (positive SLC) and as bedrock is lowered, ocean basin volume decreases (negative SLC).

OK, we have included a description as suggested.

Minor Comments
Minor comments are given in the context of page and line number, e.g. "5,4-10" refers to page 5, lines 4-10.

1,13-14: Make it clear that by "external" forcing of sea level, you mean sea level change that is NOT a result of mass changes of the ice sheet you are considering here.

OK, added a sentence in the abstract.

1,23: " . . . one prognostic variable (ice thickness) . . ." -> " . . . one prognostic variable, ice thickness, . . ."

OK, corrected.

1,24-25: Again, clarify further what you mean by "external" – NOT from the ice seet being considered here.

OK, added a clarification.

1,26: The location of the reference to the Gomez and de Boer models here is odd, and makes it read as if these models are NOT coupled to the sea level equation, when if fact they are some of the few models that ARE. This could be corrected by re-writing the sentence more clearly.

Yes, agreed. The sentence has been reformulated.

1,26-27: "Consequently, the problem at hand is . . .". This would seem to need some additional wording to be clear. Specifically, here you are assuming that you have an ice sheet model and some form of a GIA model, but that you don't have a fully coupled ice sheet, sea-level model.

OK, included in the changes suggested in the major comments.

2,4-5: Last sentence -> "Our aim here is to provide guidelines and a central reference for ..."

OK, modified as suggested.

2,8: "external sea-level changes" – Maybe this is a good place to be a bit more explicit about what you mean by this? Probably the best way to do that is to be very explicit about what you do NOT consider to be external.

OK. We have captured that in the extended discussion above.

2, 14: Clarify if / that you are assuming that bedrock elevation is a negative number if below sea level.

OK, added clarification in the text.

2,16-17: Because you so often refer to what happens in a single column below here, I think you may want to call that out a bit more explicitly when you first introduce it. E.g., *something like, "Below, we will often simplify the discussion in order to examine the interplay between ice sheet thickness, bedrock elevation, and sea level for a single column, which can be conceptualized as the values occurring in any single model grid cell (in map view)."*

Thank you, included as suggested.

2,24: ". . . but on longer timescales this is not necessarily correct." This idea is left hanging here. It sounds like you intend to note that "A_ocean" can and should be allowed to change over time (at least for the two reference time periods you are calculating SLC over), and that will affect your SLC calculation. But you don't really follow through on that discussion, so it's left a bit ambiguous.

OK, Included a clarification in the text. "Estimating changes in Aocean would require a fully-coupled global GIA-ice sheet-sea-level model."

2, Equation 3: I puzzled over the negative sign out in front of the parentheses for a while before I was sure it was correct. You could help the reader here by pointing out that this is necessary since your SLE change is a function of VAF, and a positive change in VAF (increase) over time is associated with a drop in sea level.

OK, added a clarification in the text.

3,1-4: It's not clear to me why you discuss the SLC assuming all grounded ice contributes to sea level (here, and elsewhere). No one does this as far as I can tell, so it seems like a weird reference case (if that's what you intend it to be).

SLC_gr is not used as a reference, but we believe it is still interesting to compare to. Especially since the our final estimate in the future lies between SLC_gr and SLC_af. Therefore, we would like to keep it. We have added a clarification to that end in the manuscript: "… estimating the sea-level contribution instead from the entire grounded ice volume Vgr (Eq. (4)) can lead to considerable biases and is only used for comparison here."

3,6-12: You may want to remind the reader here that you are only considering a single column, not the entire ice sheet domain.

OK, added clarification in the text.

3,6-12: Somewhere here, you may want to just be very explicit about how uplift / lowering of bedrock affects relative sea level for an ocean basin of fixed area, and in the absence of any other forcing (i.e., bedrock uplift would be seen as a relative sea level rise and bedrock lowering would be seen as a relative sea level fall).

We have added a clarifying sentence at the end of the section to not destroy the story line we are setting up.

5,1: "We argue that the differences . . ." -> "The differences . . ."

OK

5,7-9: Here you are explicit about what the impacts of rising / falling bedrock are, but it would be helpful to say this earlier, as you've already gone through Fig. 1 at this point, where this concept is necessary to understand to interpret the figure and discussion.

OK, this has been added at the end of section 2.

5,8: "The additional contribution could be calculated from ..." The use of "could" is confusing as it sounds like you are going to suggest doing something else. If this is what you want us to understand / do (for now), then change "could" to "is".

We suggest doing something different below: "We suggest to replace the ocean volume calculation above by an estimate of the potential ocean volume".

7,1-7: This section was a little bit opaque to me. I think what you are doing is just coming up with the correction necessary to deal with the small difference between freshwater (melted snow / ice) and saline ocean water densities. If that is indeed the case, it would help to just come right out and say it explicitly and up front.

Agreed. We have included an introductory sentence following the suggestion.

7,9-11: I suggest omitting the lead in to this section related to paleo simulations. Since everything you write here applies at any time that sea level is changing – as it always is –

I think it would read better to simply start this section as, "External sea-level forcing can drive transitions between floating and grounded ice in the model . . ."

We have taken away the paleo reference, but have kept the rest of the introduction to make clear what the external forcing represents and what it is typically used for.

7,16-17: ". . . from just grounded to floating ice [ADD] (with no SLC from the ice sheet itself)."

OK

8, section 6: You should be explicit here up front that you are (presumably?) using an ice sheet model that is coupled to / with a GIA model.

OK

8,19-20: You have multiple "present day[s]" here. Suggesting rewording this as, "Various sea level corrections . . . against the initial configuration at 120 Ka BP (Figure 3a) and the present day configuration (Figure 3b,c)." Noting again that I'm not clear on the two "present days" discussed.

OK, reformulated as suggested.

8,20: Again, the use of a scenario where any / all ice grounded below sea level is counted for in the SLC calculation seems odd to me, as no one actually does this. It seems like the base / reference case should be what everyone already does, which is just naively calculate the change in volume above floatation without any of the other corrections you discuss here.

While we decided to keep SLC_gr in the discussion for comparison (see also response to general point), we have moved it to the end of the section to give it less weight.

9,5-9: Clarify if you allow the area of the ocean basins to change in these calculations. Is that one of the effects we are seeing here (even if it is buried in the overall change in ocean volume).

OK, Added a clarification in the text: "We remind that the global ocean area Aocean is assumed as constant here."

9,11: "dominated by the changing ocean floor" – for us to really understand this, I think you need to be clear about whether or not you are talking about open ocean (no ice) or under ice shelves / sheets.

OK, added "outside of the ice mask" to make that clearer.

10,15: ". . . while changes in external sea-level forcing are accounted for." It's not clear what "accounted for" means here. I think what you mean is that you remove or correct for them so that you end up with the SLC contribution from the ice sheet and bedrock changes alone.

Ok, reformulated.

10,16: "When bedrock changes occur under ice that is grounded . . ." – Do you mean bedrock changes that are independently driven (e.g., by tectonics) or driven in response to changes in the overlying ice volume (GIA)?

We mean GIA. Added a clarification.

11,2: "... that lead to differences in the sea-level contribution [ADD] (i.e., due to changes in ocean basin volume)."

OK, added as suggested

11,3: ". . . yields unbiased results." Be more specific. This is ambiguous.

OK, reformulated to emphasize consistent results for transitions between floating and grounded ice.

Editorial
I have a fairly extensive list of minor, editorial level suggestions that I did not include here, but that can be made available upon request (e.g., through an edited pdf file).

We would be happy to receive the commented pdf file to improve our manuscript further.

Thanks again for reviewing this paper.

Referee #2 (Rupert Gladstone)

The paper aims to bring consistency to the approach (and potentially terminology) used in estimating sea level contributions (SLC) from model-based studies of ice sheets. In general it is successful in this, though I would like to see a clearly defined proposal for appropriate terminology. I think this is a useful contribution to the conversation on SLC due to ice sheets, and would recommend it to be published after some improvements. The paper is in general fairly clear, but would benefit from a sentence or two at the start of each section providing context and motivation for the direction taken. The detail needs to be broken up with occasional text to orient the reader. I am not altogether sure that this article is short enough to be a "Brief communication", but that is for the editor to decide!

Thank you very much for the positive evaluation. We have improved the manuscript by reconsidering the terminology and adding introductory sentences in each section. We believe that even after the revisions the formal conditions for a "Brief communication" are met by our manuscript.

As to the problem of computing SLC from an ice sheet model, it is not clear whether the paper is trying to say "here is the right way to do it, everyone should do it this way" or "here is one way to do it, think carefully about these issues and use consistent terminology when describing your approach". I would argue it should be the latter, as I think alternative approaches to some aspects of the SLC calculation could be justified. In any case, please try to make this a bit clearer, and if it is the former, the authors need to make stronger arguments (mainly regarding external sea level forcing) why this is the right way!

We fully agree with the reviewer on the second mentioned aim of the paper ("here is one way to do it, …") and have clarified that by carefully revising the text in the paper.

The paper recommends using the initial sea level as a reference level for calculating SLC. This is a reasonable recommendation, but no consideration is given to other options, such as choosing a different reference level (final sea level? time mean sea level?), or calculating SLC at each timestep based on current sea level (the details of this would probably depend on the numerical scheme being used). Can the authors clarify why their suggestion is the best one? Alternatively, can the authors acknowledge that this is one of several possible approaches that may also be valid?

The choice of the reference sea-level is completely arbitrary, so other options are equally possible and correct. We say in the text "The actual sea-level contribution […] 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", which in our reading gives up to three different options and does not prioritise any of them. In Figure 3 we also show results for two different reference levels.

The whole paper is about using ice sheet model outputs to estimate a contribution to mean sea level. It would be good to see a paragraph that puts this in the context of the more complex real world picture. Specifically, there is the gravitational effect of redistribution of ice mass on sea levels. This probably causes a local decrease in sea level, and a far field increase. Also, coupled ice sheet – ocean (possibly also atmosphere) models might be able to simulate a spatial distribution of sea level change, in which it may not be trivial to distinguish between the ice sheet contribution and other effects, and the delivered product could be argued to be "superior" to global mean SLC predictions. Even in such a case, where the modelling approach allows a more complete prediction than simply mean sea level, it may be of value to calculate a mean sea level contribution in order to compare with other ice sheet models, and as such this paper can contribute to this situation also.

We have expanded the introduction by adding more information about the "full problem" and models that solve the coupled ice sheet-GIA-sea-level problem.

Specific comments:

[Page 2]

Line 12. I suggest "differences" -> "change" because differences implies comparing two different properties but her I think you mean change over time.

OK, modified as suggested.

Equation 1. The way dx, dy and I,j are used seems to imply (thought this isn't stated) summation over grid cells for a structured rectangular grid. Often in ice sheet modelling unstructured meshes are used, usually either 2D or extruded in the vertical. It should be easy to generalise the notation to all cases except for fully unstructured 3D meshes. Please also clarify in the text that this is an operation over the model grid/mesh.

Yes, thank you. We have modified all equations using the more general formulation summing over elements of a grid.

Equation 4. I don't see what this adds, I would leave it out. If you include it, you need to introduce V_gr.

Please see response to Reviewer 1 above on the same topic. V_gr has been introduced.

Page 3.
Line 11. "Ice at floatation" is an odd expression. When there is "ice above floatation" then the "ice at floatation" is clearly grounded ice. So the expression is not intuitive. When we talk about "ice above floatation" we really mean something like "ice above a fictional surface at which, if it formed the actual upper surface, the ice column would be at floatation". The fact is that all this ice is grounded, so talking "ice above floatation" and "ice at floatation" can be a bit confusing. Conceptually, we really mean "ice that can contribute to sea level" and "ice that can't contribute to sea level". I think I would find this discussion generally more ...er ... "natural" if we talked about a floatation thickness, and so the actual thickness can be above of below this floatation thickness. And ice above the floatation thickness can contribute to sea level whereas ice below cannot. And so bedrock uplift, which doesn't directly impact on ice thickness, does directly impact on the floatation thickness. I am not going to insist on this because the choice of terminology is subjective. But part of the purpose of this paper is to present definitions and terminology with which to discuss ice sheet contribution to sea level rise, so I think some careful thought should be given to this, and my first reaction to "ice at floatation" was that it is somewhat non-intuitive.

We agree that the term "ice at floatation" is uncommon and have removed it from the manuscript. Instead, we introduce and use "floatation thickness" as suggested.

Line 12. Perhaps would benefit from a summary sentence ending this paragraph to clarify that an uplift in bedrock will in general lead to SLC being underestimated if only the initial bedrock is used for calculating SLC.

We have added a sentence on the role of bedrock changes at the end of the section. Please also compare response to Reviewer 1.

Page 5.
Equation 5. Note that this only calculates ocean volume in the domain of the ice sheet model, which may be a limitation depending on what you want to do with it. I'll read on and find out. . .

Yes, please see comment below.

Page 6.
This seems a bit clunky. Equations 6 and 7 are only valid in certain situation depending on where the bedrock was or where it is going to. . . can you not go straight to one more generic equation, albeit slightly more complicated, that captures the change in h_af in general, as a function of change in bedrock (and perhaps also of change in thickness)? I am talking here about change just due to the direct bedrock effects, ignoring ocean volume change for the moment.

We chose this way of laying out the problem to first make clear why using V_{af} alone is not correct, before going to the generalised solution. We believe this is instructive since using V_{af} alone is what most people are used to.

Line 17. What is a "sea level component"? Perhaps you mean something like "to convert a change in potential ocean volume to a sea level contribution"?

OK, reformulated.

Lines 12-18. It seems that the plan here is to calculate changes in pov? So this would be a purely bedrock contribution, separate from an ice dynamic component.

Yes, the calculation is only dependent on bedrock changes.

Equation 9. Right, so now I can see that the limitation of calculating this on the ice model domain is simply that we assume all bedrock adjustment occurs within the ice model domain. This is probably a reasonable and practical assumption to make, but you should clarify that this assumption is being made, with the implication that any study attempting to include bedrock adjustment in an ice sheet model study aimed at projecting sea level rise should endeavour to consider both the extent of the ice sheet itself and of the region over which bedrock adjustment could occur when defining their model domain.

We have added a clarification in the text: "Note that we assume in the following that all bedrock adjustment occurs within the ice sheet model domain." And we also have a discussion item precisely on that question in the final section of the manuscript.

Lines 22-23. "changes in ice mass occur in reality with a density of freshwater". This is a strange sentence. Changes initially occur either at the density of ice (calving) or from ice density to fresh water density (melting), so it is not really correct to say that changes occur "with a density of freshwater". You might want to say something like "Ice loss from the ice sheet ultimately contributes to the ocean with a density of fresh water".
I would also definitely leave out precipitation because this will usually be in the form of snow, initially with a much lower density than ice, and I don't (yet) see why you would need to talk about precipitation?

OK, reformulated the text accordingly.

Page 7.
*Equation 10. I don't think V_den has been clearly defined in the text? Also, I am not clear why this is kept separate from the V_af calculation. I suppose I must be missing something, but since we've already calculated V_af in equation 1, why don't we just modify equation 2 like this: SLE_af = V_af/A_ocn * rho_ice/rho_freshwater So now we calculate the volume of freshwater being added to the ocean. This is much simpler than what is suggested in the paper. . . why is this wrong? Probably I missed something...*

V_den is treated separately, because the correction needs to be applied for all ice volume changes, including ice below flotation. This would not be the case if equation 2 was modified as suggested. An additional correction would still be required for the ice below flotation. We believe it is clearer to apply the correction for all ice volume changes.

We have added a clarification in the text "… we will apply a density correction for all changes in ice thickness (both above and below flotation)."

Line 17. What is "t2i"? Just t2 I guess?

Yes, corrected typo.

Page 8.
Equation 15. This is not "objectively correct", but rather is one way of making the calculation. If externally forced sea level at the end of a simulation is not the same as it was at the start, then should the simulated ice sheet contribution to sea level take into account this change or not? It seems to me one could make justification for different ways of doing this. I think a more objective approach in this paper might be to define terminology for different ways of making this calculation rather than to prescribe what appears to be presented as the "correct" way to do it.

We fully agree that there are different and equally valid ways to make the calculation. However, following the argumentation illustrated in Fig 2b, we cannot see any scenario in which contaminating the sea-level estimate with the external sea-level forcing is desirable. And this argument is independent of the choice of reference sea-level.
We have resolved what we believe to be a misunderstanding about the role of the reference level z0 by reformulating the description of Equ 13 and 14. The reference level z0 is only needed to compensate for changes in bedrock that are solely based on changes of ESLF. We have also clarified in the text that the choice of z0 is completely arbitrary. To give an example: for a an instantaneous change of ESLF to -100 m, b (measured in the model relative to sea-level) would increase by 100 m, which is compensated in turn by -z0 (equally measured in the model relative to sea-level) .

Figure3. The text is a bit on the small side, and I have to zoom in a lot to see the subscripts in the legend. Can this be made bigger?

Yes, the figure has been updated with larger text in the legend.

Thanks again for a constructive review of our manuscript.

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 that is not a result of mass changes of the ice sheet under consideration, 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. The discussions in this communication apply for ice-sheet models that include some form of a glacio-isostatic adjustment (GIA), but that are not coupled to the sea-level equation. While other examples exists (e.g. Gomez et al., 2013; de Boer et al., 2014), the models considered here typically account strictly for uplift or sinking of the bedrock beneath or proximal to an ice sheet, but do not include other (global) effects, such as sea-level changes due to changes in Earth's rotation and regional sea-level change due to changes in the Earth's gravitational field. However, the effect of mass changes from other ice sheets may be included in a simplified form using an external sea-level forcing. Such forcing is decoupled from mass changes of the ice sheet itself and

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prescribes sea-level changes in the model domain with the aim to capture its effect on ice flotation. The aim of this paper is to propose an approach to accurately estimate the contribution of the ice sheet in such a model 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. Our aim here is to provide 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 changes in total ice volume above flotation

$$V_{af} = \sum_n \left(H_n + min(b_n, 0) \frac{\rho_{ocean}}{\rho_{ice}} \right) \frac{1}{k_n^2} A_n, \qquad (1)$$

where H is ice thickness, b is bedrock elevation (negative if below sea level) 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 sum is over the number *n* of grid cells (elements) of an (un-) structured grid with area A_n. 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). Below, we will often simplify the discussion in order to examine the interplay between ice sheet thickness, bedrock elevation, and sea level for a single column, which can be conceptualized as the values occurring in any single model grid cell or element (in map view). In that framework, we will refer to the limit ice thickness required for the ice to start floating as the *floatation thickness,* which is determined by the local bedrock elevation and sea level. V_{af} of a column of ice grounded below sea-level may be interpreted as the amount of ice volume that has to be removed to reach the floatation thickness and for the column to start 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

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(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 $V_{af} = H\, A_n * \frac{1}{k^2}$.

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 (Gregory et al., 2019).

$$SLE_{af} = \frac{V_{af}}{A_{ocean}} \frac{\rho_{ice}}{\rho_{ocean}}. \qquad (2)$$

A_{ocean} is assumed to be constant here, but on longer time scales this is not necessarily correct. Estimating changes in A_{ocean} correctly would require a fully-coupled global ice sheet-GIA-sea-level model (e.g. Gomez et al., 2013; de Boer et al., 2014).

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.

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

Note that the minus sign in front of the parentheses in Eq. 3 is necessary since SLE_{af} is a function of V_{af}, for which an increase over time is associated with a drop in sea level.

Depending on the amount of ice grounded below sea level, estimating the sea-level contribution instead from the entire grounded ice volume V_{gr} (Eq. (4)) can lead to considerable biases and is only shown for comparison here.

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

2. Effect of bedrock changes

In this section we discuss additional considerations that are required when the model includes a GIA component that simulates 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 for a single ice column 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, the floatation thickness decreases and some of the ice 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.

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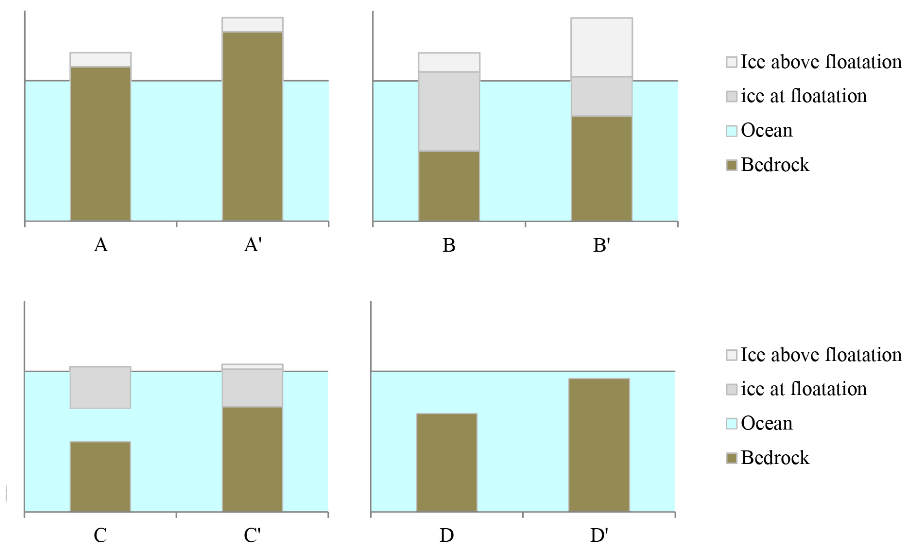

Figure 1 Effect of bedrock changes. Different geometric configurations of ice, ocean and bedrock before and after (') a rise in bedrock elevation.

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 the ice is just starting to float (t_1) or floating (t_4) in both cases. However, following the evolution through t_2 and t_3 gives rise to another interpretation. At t_1 the ice is just starting to float 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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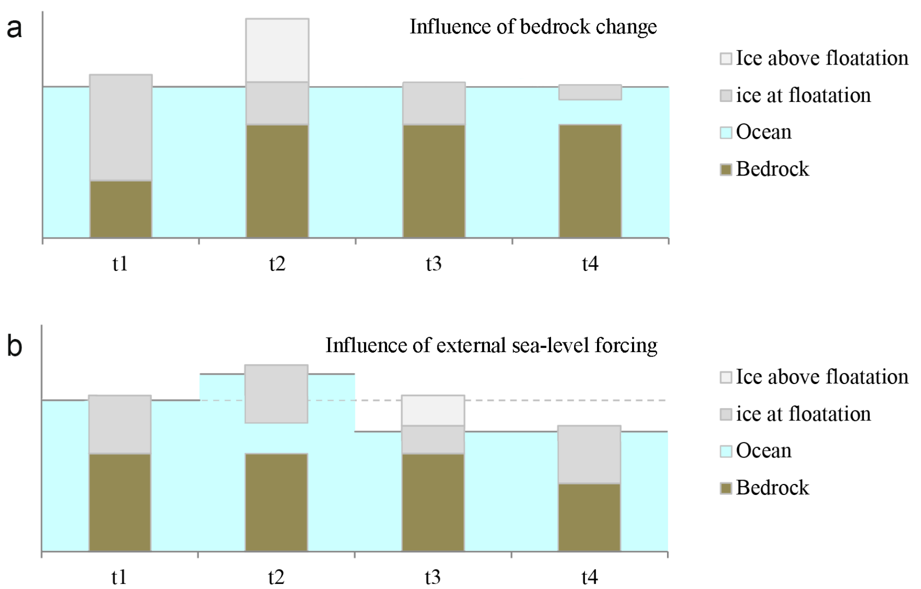
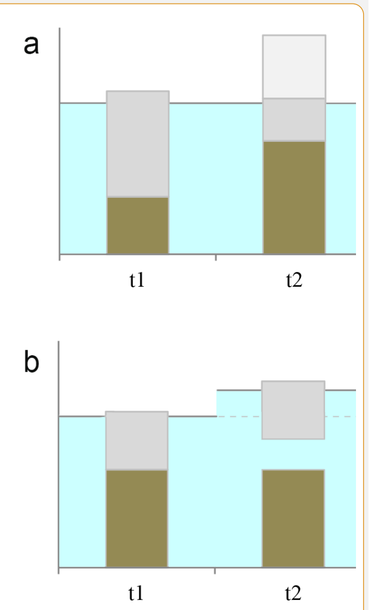


Figure 2: Geometric evolution of a grid box in time a) including bedrock changes and b) including externally forced sea-level variations.

The 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. The way bedrock changes impact sea level is through changes in the volume of the ocean basins. That is, as bedrock is uplifted, ocean basin volume decreases, leading to a positive sea-level contribution and vice versa.

3. Correcting for bedrock changes

Based on the discussion in the previous section, here we propose an approach to correct the sea-level estimate 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



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$$V_{ocean} = \sum_n \left(max(-b_n, 0) - H_n \frac{\rho_{ice}}{\rho_{ocean}} \right) \frac{1}{k_n^2} A_n \ , \tag{5}$$

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. Note that we assume in the following that all bedrock adjustment occurs within the ice sheet model domain. 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:

$$V_{pov} = \sum_n max(-b_n, 0) \frac{1}{k_n^2} A_n, \tag{8}$$

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 a change in potential ocean volume to a sea level contribution, V_{pov} has to be divided by the ocean area of typically 3.625 x 10^{14} m^2:

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

4. Density correction

In this section we discuss the correction necessary to deal with the small difference between fresh water (melted ice) and saline ocean water densities. Transitions of ice below and above flotation and the associated sea-level change can occur both

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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 sheet mass ultimately contributes to the ocean with a density of fresh water (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 (above and below flotation).

$$V_{den} = \sum_{n} H_n \left(\frac{\rho_{ice}}{\rho_{water}} - \frac{\rho_{ice}}{\rho_{ocean}} \right) \frac{1}{k_n^2} A_n \tag{10}$$

and

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

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 ice-sheet simulations, it is common to force ice-sheet models with prescribed variations in (global) sea-level, e.g. representing changes in the northern hemisphere ice sheets when solely simulating the Antarctic ice sheet. For a glacial-interglacial transition the external sea-level forcing (ESLF) 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 changes in ESLF imply changes in V_{af} of the modelled ice sheet.

We illustrate the implied changes again with a schematic view of one ice column changing over time (Figure 2b). From t_1 to t_2, the 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 column changes from just grounded to floating ice (with no sea-level contribution from the ice sheet itself). From t_2 to t_3 the sea-level is lowered, such that some ice that was floating in t_2 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

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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 can be resolved by calculating changes in V_{af} and V_{pov} for the constructed case where sea-level is fixed and ESLF has no direct impact on the results. Practically, Eqs. (1) and (8) can be modified to compensate changes in b_n that occur solely due to ESLF by corresponding changes in an arbitrary reference level z_0, e.g. taken as present-day sea-level, that is time-constant in the absolute reference frame but changes with ESLF (Eqs (13), (14)). In other words, the term (b_n - z_0) is constant with respect to changes in ESLF.

$$V_{af}^0 = \sum_n \left(H_n + min(b_n - z_0, 0)\frac{\rho_{ocean}}{\rho_{ice}}\right) \frac{1}{k_n^2} A_n \qquad (13)$$

and

$$V_{pov}^0 = \sum_n max(z_0 - b_n, 0)\frac{1}{k_n^2} A_n. \qquad (14)$$

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

$$SLC_{corr}^0 = SLC_{af}^0 + SLC_{pov}^0 + SLC_{den}. \qquad (15)$$

With this approach, ESLF can be applied for its effect on the flotation condition in the ice sheet model without contaminating the calculation of the sea-level contribution. Note that Equations 13-15 also hold for the case where ESLF is not a spatially uniform value.

6. Ice-sheet modelling example

Figure 3 illustrates differences in estimated sea-level contributions for an Antarctic ice-sheet simulation with a model that includes a simplified GIA component and external sea-level forcing (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).

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Various SLC corrections and estimates are calculated against the initial configuration in Figure 3a (120 kyr BP) and against the present day configuration in Figure 3b c. 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 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 well above 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}). We remind that the global ocean area A_{ocean} is assumed as constant here. 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 outside of the ice mask 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_{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). Accounting for all grounded ice (SLC_{gr}) would lead 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. 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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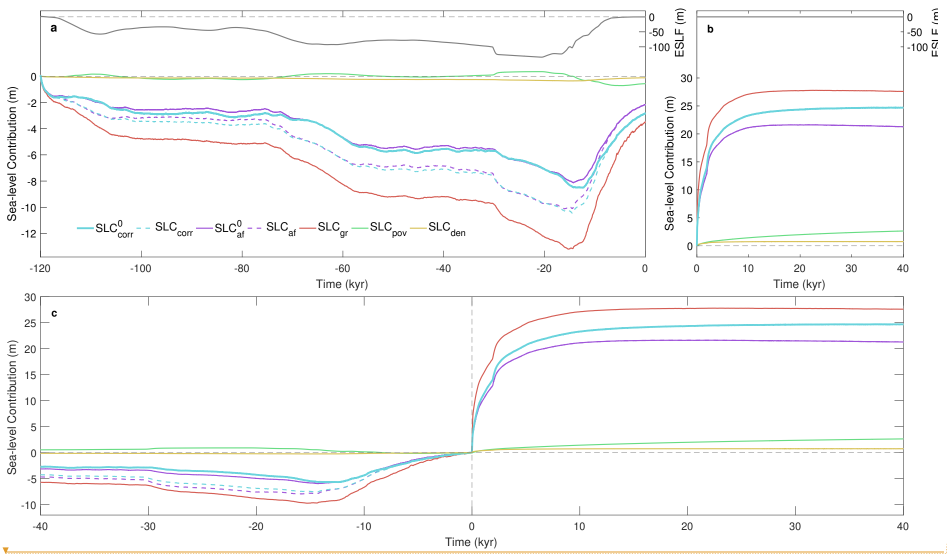
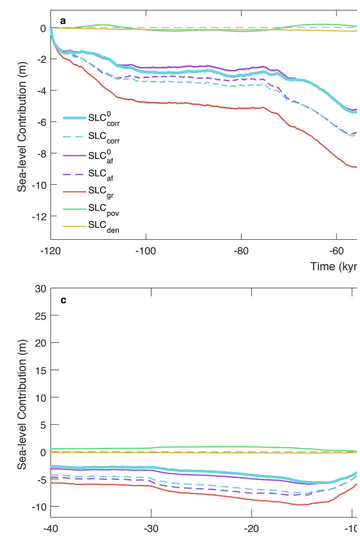


Figure 3 Different estimates of the sea-level contribution (SLC) from an Antarctic ice-sheet model simulation. (a) Sea-level contribution for the last glacial cycle under external sea-level forcing (ESLF). (b) Schematic deglaciation experiment over the next 40 kyr in which an extreme sub-shelf basal 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 ESLF 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 ESLF (grey lines and left y-axis in (a) and (b)) 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 corrected for.

When bedrock changes in response to ice loading 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 (i.e., due to changes in



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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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