

## Reply to the reviewer 2 by Authors

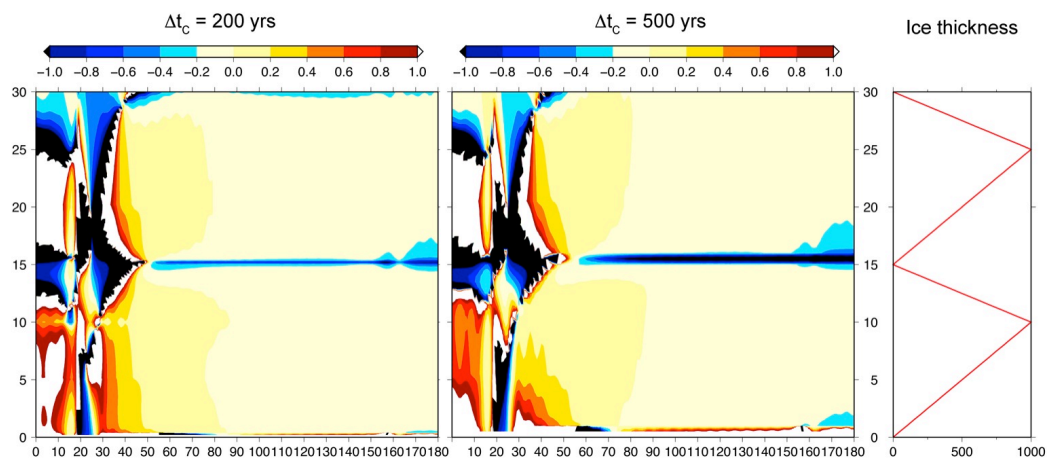
We would like to thank reviewer 2 for his/her constructive comments. The remarks are very clear and have definitely improved the manuscript. Below you will find a point-by-point reply. We hope that we have answered all questions sufficiently. Major comments are numbered according to the review, the minor comments of the reviewer are shown below in blue, our answers are shown in black.

### Major comments

1. Including the comments of both reviewers we believe the text has been improved considerably in terms of grammar and clarity. We also have checked the text for the use of adverbs/conjunctions.
2. All terms related to calculation of sea level, ice volume and topography change are defined upon first use. Acronyms are explained/described and checked throughout the text.
3. The same as major point 2 by the first review of Pippa Whitehouse:  
The coupling interval is now called  $\Delta t_c$  and is mentioned in the caption of Fig. 2. The terminology has been checked throughout the manuscript and the variables are explained when they are first used. We have added a small table that explains each of time window variables (now Table 2). We have performed a few small additional tests that are discussed in Section 4.1.
4. For the stand-alone runs of ANICE, without using SELEN, eustatic sea level is internally calculated from modelled ice volume change relative to present-day ice volume, and is internally used as a forcing to change sea level in each of the four regional ice-model grids. For the uncoupled simulation we do not take into account changes in ocean area and use a constant ocean area of  $3.62 \times 10^{14}$  km<sup>2</sup> to compute the change in eustatic sea level. For the coupled ANICE-SELEN model eustatic sea level is only calculated as output for comparison with the uncoupled results (Fig. 9e), and calculated as the mean RSL change. In the text this has been clarified in Sections 2 and 3.  
  
In the first paragraph of Section 3 we have replaced the sentences on the uncoupled model and hopefully it is now clearer what the differences are between the uncoupled ANICE simulation and the coupled ANICE-SELEN system. The similarity in the Fig. 9e is because less ice volume in the coupled model is compensated by a reduction in ocean area that is taken into account.
5. The difference between the coupled and uncoupled model is now stated at the beginning of Section 3. Yes, in the coupled system we use a 3-layer Earth model, relative to the 2-layer model used in the schematic experiments discussion in Section 4.1, but the model is the same, only a different number of layers is used (in the schematic for simplicity  $n=2$ ). We have added some remarks in the text.

6. The interval is mainly chosen for the sake of computational time, since we are already at our limit of what is currently possible on the system where we run the model. The limiting factor of our coupled model is computing the SLE, about 95% of the computational time is needed to solve the iterative SLE. So a coupling interval of 500 years for example would take a 410 kyr long run roughly twice as long.

We have performed a few small tests with the schematic setup (Fig. 5) we performed two short runs, with an ice sheet on the south pole over 2 cycles of each 15 kyr (right panel: thickness up to 1000 m). The figure shows the normalised residual, equation (3), left panel for a 200 kyr coupling interval, middle panel for 500 kyr, both with a moving time window of 30 kyr. As can be seen in the figure, the differences with the full solution are similar to the tests shown in the manuscript, at the forebulge region just outside the ice sheet ( $\sim$  colatitude of  $20^\circ$ ). These tests show that the difference between the runs is not so large. At least a shorter coupling interval does show large improvement in the results for these experiments. We added a short discussion in section 4.1 on the choice of the coupling window.



The coupling interval is definitely something we want to investigate. We have included a few tests with the schematic setup as discussed in Section 4.1 with shorter coupling intervals of 500 and 200 years to support our choice of 1000 years and what a different coupling interval might imply.

7. The difference between grounded and floating ice is determined with the floatation criterion and determined in ANICE every time step. Within SELEN, when solving the SLE, if the Ocean Function changes, the ice loading is always check if it is still grounded or floating and is adapted accordingly. The time step of ANICE is about 1-5 years; this information is now added in Section 2.1.

8. A similar comment was raised in the review of Pippa Whitehouse (her major comment 6): Yes, we use the present-day topography as initial state. We run the model forward in time without imposing any constraints on the present-day topography, hence at the very last time step of the run, the topography is not the

same as the present day topography. See also Fig. 9f, at 0 kyr the total ocean area is larger, since some areas of Canada and Russia are still below sea level. We think the point raised by the reviewer is good, which we like to take into account in future research. We have added a sentence on this in the discussion (see also point 10). It is not crucial for the methods and results, unless present-day values are compared in detail.

9. For this paper, we really would like to focus on the modelling algorithm and possible applications, rather than a thorough comparison with observations of ice extent, RSL and other ice sheet models for different events in the Earth's climate history. As raised in the next major point, we have added an additional paragraph in the discussion on future ideas. Here we added some additional remarks on a comparison, but we wish to not include any additional figures at this point. A thorough comparison with observational data would be best in combination with the sensitivity tests that we already suggested in this section in a future paper.

10. We have added an additional paragraph in the Discussion to raise some issues we would like to address in future studies.

### **Minor comments**

[Title: There are a lot of hyphens of different length in the title. Perhaps remove those between "ice sheet" and "sea level"?](#)

The hyphens between ice sheet and sea level are removed.

### **INTRODUCTION**

[P. 3507 4 -'definitely' is colloquial and unnecessary here](#)

Sentence has been changed to: "One of the best studied intervals in the past is the Last Glacial Maximum ..."

[5-6 -'ice sheets' is repeated twice. Perhaps change to something like ' .. when the Antarctic and Greenland ice sheets extended..'](#)

'ice sheets' after Greenland has been removed

[8 -'In fact' is unnecessary](#)

'In fact' has been removed

[p. 3508 10-why 'However'?](#)

'However' has been removed

[14-16 -Further referencing is needed here.](#)

We have added two references to Ranalli, 1985 and Turcotte and Schubert, 2002.

[27 -Grammar \(As a consequence of what?\)](#)

Removed 'As a consequence' and changed to: "Furthermore, due to the rotation of the Earth around its axis, any surface mass ..."

26 to end of paragraph -referencing here is sparse, and missing entirely for rotational effects.

References for rotational effects are added to Milne and Mitrovica, 1996 and Kendall et al., 2005.

P. 3509 5 -'According to GIA.' is grammatically incorrect. Do you mean 'according to the theory of GIA'? In addition, further clarification of what you mean by "GIA" could be helpful here. GIA is often associated with ongoing deformation associated with past ice and ocean loading effects, but in this sentence, I think you are referring additionally to the response in sea level to ongoing ice and ocean loading. Some clarification could be helpful.

Changed to 'the theory of GIA. It includes the changes in bedrock deformation and the geoid, this has been added in the text.

3-11 -This paragraph is hard to follow. Land-based sea level records reflect both GIA effects and sea level changes due to ongoing ice sheet variations. In addition, on line 9, the wording 'since' implies causation between the first and second half of the last sentence, where I don't think there is any. Finally, on line 10, the wording 'eventually an RSL indicator' is confusing. Also, I think RSL here refers to being relative to present day, whereas it has a different definition in other parts of the manuscript. I would recommend reworking this section.

RSL is explained earlier as the change of the sea surface relative to the solid Earth, is unknown. The last sentence of the paragraph has been changed to: "The GIA feedback results in the mutual motion of the solid Earth and of the geoid, and hence any land-based sea-level indicator is essentially a RSL indicator as it records the local variation of the vertical distance between the geoid and the bottom of the ocean."

20 -Further referencing needed. You say "the sea level equation has been widely employed..." but only reference Peltier (2004) and earlier only Spada and Stocchi (2007).

Additional examples are included.

21 -Grammar (incorrect use of 'However', and 'but' later in the same sentence)

Both 'however' and 'but' are removed, and a full stop is added between 'cycles' and 'At'.

23 -'ice sheets evolution' -remove the 's', add a hyphen.

Changed to: "the evolution of the ice sheets'

24 -Use of the word 'eventually' implies that at some point in time RSL changes do not define variations in topography and bathymetry. Is this what you mean? If so -I think more explanation is required.

Replaced with essentially.

25 -Distinguish between how the impact on marine ice is different from the impact on the "ice-flow pattern" in general, or remove the sentence on 26-27 if there is no difference.

Part of the sentence is removed and reads now: "Also, very importantly the ice-sheet induced RSL changes affect the growth and retreat of marine ice sheets, which are in direct contact with the ocean."

28-29 -'Thus far' is not true (e.g. Gomez et al. 2013's work that you mention below). Something like 'up until recently' would be more appropriate.

Changed to: Thus far most transient ..

p. 3510 18 -What is your algorithm an alternative to? How is it different from the one used in Gomez et al. (2013)? The concept of a fully coupled model, and the algorithm employed (e.g. shown in Figure 2) have already been presented in the literature. Be more specific about what this study adds (e.g. a way of performing calculations over a long time periods and multiple dynamic ice-sheet models.)

Two sentences are added: "Although Gomez et al. (2013) employed a similar system for the Antarctic ice sheet, our algorithm represents a method ..." and "Here, we include a temporal discretisation of past ice-sheet fluctuations with a moving time window that allows us to calculate RSL as a function ..."

## **METHODS**

P. 3511 see typos highlighted by other reviewer. In addition...

25 -"We adopted" -you have switched to the past tense here. Also, see my major comment about initial topography.

Changed to present tense

26 -Is the Greenland topography name and reference here correct?

No, this has been removed.

p. 3512 8 -typo -remove 's' from models

Done

15-17 -remove hyphen from 'sea-level'. Also, See 'major comment' above about eustatic sea level.

Done

25 -typo -represents

Done

26 -typo -missing comma before "a temperature...'

Comma added

p. 3512-3513 Section 2.2 – Does this section relate at all to the eustatic sea level used in some of the simulations? If so, explicitly saying that here would be useful.

If not, disregard this comment and simply address my “major comment” about eustatic sea level above.

Section 2.2. relates to how we infer the benthic d18O data to a temperature and ice volume record.

p. 3514 5 -self-gravitating, with a hyphen?

Yes, hyphen added

10 -'current' implies that you change these settings later -is this true? If not, perhaps "for the results shown in this study", or 'default' would be more appropriate wording.

'current' is changed to 'default'.

16 -self-consistent, with a hyphen?

Yes, hyphen added.

17-18 – I suggest you revise to something like "... change depends upon all surface mass displacements (both ice and melt water) which have occurred...). You could also consider using the term "loading" instead of displacements. Sentence has been changed accordingly.

22 -"We solved the model..." this sentence is awkwardly worded -I believe "solve" is not commonly used with "model".

Here 'model' has been replaced with 'SLE'.

27 -typo -sheets-shelf

Is now ice-sheet-shelf

p. 3515 2 -'sub system' is one word or hyphenated?

No hyphen is added

5 -see major comment about eustatic sea level change

Next sentence changed to: “The latter is internally calculated from the changes in ice volume and the only ...”

11 -remove the 'with' after SELEN

Removed

15-16 -space and time, instead of just space? Also, there should be commas before each "which"

Space and time, as in every time step a new field is updated. The usage of 'which' is checked throughout the manuscript.

19 -more explanation/justification of the 1000 year coupling time choice here would be helpful – see my major comment above.

We removed 'clearly'. We refer here to the coupling time step, this is now added to the text. The time step within the ice-sheet model is variable but basically between 1 and 5 years.

p. 3516 6 – Add reference Milne et al. (2002) Quat. Sci. Rev. 21, 361-376?  
Added reference to Milne and Mitrovica (1998), GRL, 25, 793-796.

23 -"Clearly" is unnecessary here. Also, what "time step" are you referring to here? 1000 years, or the ice-sheet model time step? How long is the latter?  
We removed 'clearly'. We refer here to the coupling time step, this is now added to the text. The time step within the ice-sheet model is variable but basically between 1 and 5 years.

p. 3517 Section 3.2 general comment -This section was very difficult to follow. It describes the most novel aspect of the modeling, so it is important to present it clearly. I found it challenging to keep track of all the variables, and also when the text was referring to a time in the past, a time interval, and a time in the future. I would recommend finding a new way to explain the traveling time window. You may also consider placing this section after the next section that introduces Figures 4 and 6, so you can make better use of these figures in your explanation. We agree that this is a very important section and have adjusted the definitions of all time variables. Upon their first appearance in the text, each variable is defined and explained as thorough as possible. Also the order of wording has been changed a bit.

15 -load Love, instead of Load love. Also, Peltier (1974) might be a more appropriate reference here?  
Changed reference and to 'load love'.

16-19 -This sentence is confusing -perhaps it is missing some words?  
The sentence has been changed to: "Accordingly, the change in RSL at any location on the Earth and at any time since the beginning of the ice-sheet chronology is determined by all the ice and ocean load variations that have occurred until that very time (see Section 2.3)."

p. 3518 11 -commas in the wrong place -no comma after follow, add a comma after l(t).  
Sentence has been changed

## **RESULTS**

P. 3519 7 -by "overlapping", do you mean adding together? Do you also add in a eustatic term? See "major comment" above. More explanation of how the results in all the ice model domains are added together is needed.  
Yes adding together, but sentence has been changed

p. 3520 2 -does NT refer to a set of time steps or a number of time steps?  
NT refers to the number of time steps in the moving time window. This is now explained in the text.

8 -It is not obvious why simulations here run for 480 ky but in the abstract and most figures you use 410 ky. I think I finally figured out that it could be related to the spin up of the ice sheet model?

We understand it could be confusing but the 480 kyr refers here to the schematic simulations as illustrated in Fig. 6 (the old Fig. 7) and discussed in Section 4.1. We clarified this in the text.

10-12 -this sentence is confusing.

Sentence has been reordered for clarity.

15 -linearly interpolated, not interpolations. Also, do you mean similar to Figure 4b, or as show in Figure 4b?

Changed, we mean similar to Fig. 4b, since here the moving time window has a different length than shown in Fig. 4b.

equation 3 -what are all of the terms in this equation?? As is, this equation is not helpful.

The terms are now explained below the equation.

26 -why is the simulation time now 410 ky again?

The last sentence discussed the fully coupled ANICE-SELEN simulation. To avoid confusion we have moved this sentence to the beginning of the next Section 4.2.

p. 3521 7 -missing some words in this sentence? And the next? Why are the changes higher than present day? More explanation is needed here.

Sentence changed to: "The largest differences relative to the eustatic curve are found in the Antarctic Peninsula. Here, the changes are always higher than the eustatic curve.". Additional explanation of these results is included.

8 -"reach up to" rather than "go up to"?

Changed

20 -comma after 'variations'. Also -is your coupling time of 1000 years really short enough to capture the full influence of sea-level variations on ice sheet dynamics?

Comma is added. Coupling interval is tested and discussion in Section 3.

p. 3522 5-6 -fix grammar

Done

5-8 -Gomez et al. (2013) also use the same treatment of Earth deformation and make this point.

Added reference to Gomez et al., 2013.

9 -in section 2.3, you say you use a 3-layer model. Which is it?

We refer here to the flexural Earth model in the uncoupled simulation. To avoid confusion we have remove 'two layer' here. But this is included when describing the uncoupled simulations above in Section 2.1.



17 -Perhaps add "treatment" after sea level?

Changed to: the gravitationally self-consistent solution of the SLE

28 -replace "that can be" with "reaching"?

Done

p. 3523 2 -results instead of result

Done

4-6 -this sentence needs rewording.

Done

14-15 -this sentence is confusing... I think you mean to refer to changes in RSL and eustatic sea level, rather than absolute values when describing this concept. We mean here RSL change relative to an uncoupled simulation that uses eustatic sea level changes. Changed to: "...when an ice sheet grows the RSL close to the ice sheets actually rises whereas the global mean sea level drops. The self-gravitational pull thus acts to ...".

p. 3524 Final paragraph -This paragraph could be removed. It largely repeats what you have already said in earlier paragraphs of the conclusions. I would recommend instead focusing on the novel aspects of your model, i.e., the addition of the traveling time window and incorporating multiple ice sheets into your coupled model.

We have changed this paragraph completely.

## FIGURES

In general, I think you could include more information in the figure captions. The caption of most figures has been changed, more referencing to other figures and explanation.

Fig 2: Can you explain how the  $T_{\text{surf}}$  is related to  $T_{\text{NH}}$  referred to in the caption?

Fig 2: They are the same,  $\Delta T_{\text{surf}}$  is changed to  $\Delta T_{\text{NH}}$ .

Figs 4 and 6: It would be useful to add more information into these figure captions. For example, say where this bedrock deformation plotted is occurring. Is this bedrock deformation at a specific location on the globe? I think Figure 6 could be included as a frame of Figure 4 -it would be useful to see all these frames on one page. Finally, on Figure 6, I recommend adding an explanation in the figure caption of why the bedrock deformations stored jump from starting at 0, -5, and -10 ky, and then -60 ky (whereas in Figure 4c, you plot the black curves every 1000 years).

Fig. 4: As also commented by the review of Pippa Whitehouse, we have decided to remove figure 6 and only refer to Figure 4c in its place, they explain the same thing. The bedrock deformation in Fig. 4 is from the ice sheet margin, so at a colatitude of  $18^\circ$ , this is added to the caption.

Figure 7: Include an explanation of the normalization of the residuals in the figure caption (or refer to where you explain it in the text). I am not sure if I correctly understand what the residuals are normalized by.

Fig. 6: (old figure 7): this is equation 3, this is now included in the caption.

Figure 8: add “predicted using the coupled model” to the caption. Also – where does the eustatic come from?

Fig. 7 (old figure 8): added to caption, eustatic is explained here as well.

Figure 10: I appreciated the supplemental movie. Perhaps refer to it in this figure caption so more people see it?

Fig. 9 (old figure 10): Good suggestion, reference to the movie added.