Reply to the review of Pippa Whitehouse by Authors

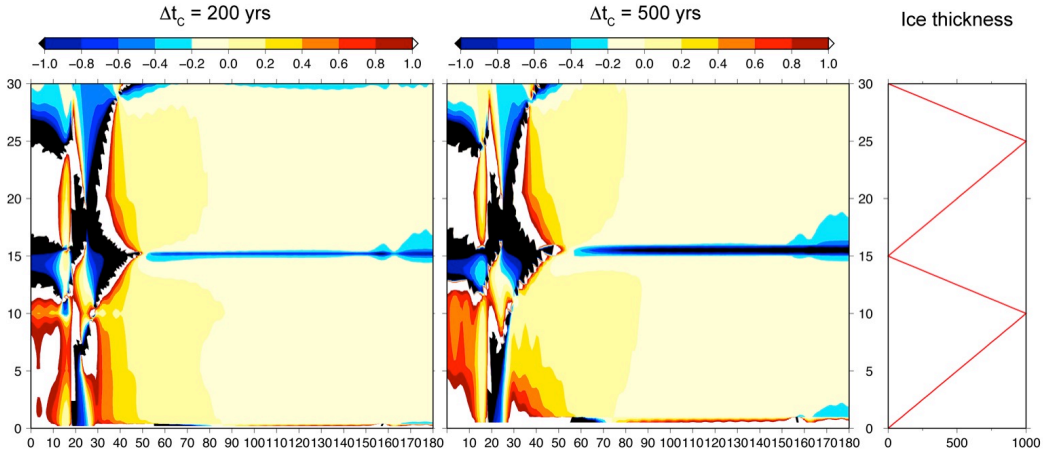
We would like to thank Pippa Whitehouse for her constructive and very clear comments. The remarks have definitely improved the manuscript. Below you will find a point-by-point reply. We hope that we have answered all questions sufficiently.

Major points

1. The paragraph has been changed to: "To explain the observed RSL changes over the past glacial cycles, a global ice-sheet model is needed to simulate the corresponding ice volume. At the same time the observed RSL changes are needed to justify the simulated ice volume with the global ice-sheet models. This problem of circularity follows from the fact that the evolution of the ice sheets is coupled to the RSL changes. The latter essentially define the variations of bedrock topography and sea-surface height. 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."

2. The same point was raised by Reviewer 2. The coupling interval is now called Δt_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) and we added a short discussion in section 4.1 on the choice of the coupling window.

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 (~ colatitude of 20°). 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.



3. For a stand alone run of ANICE (as in De Boer et al., 2013), a flexural Earth (ELRA) model is used as mentioned in section 2.1. This is not used in the coupled model, where we use the bedrock deformation (included in the RSL that is provided to ANICE) as calculated by SELEN. The 2-layer model as shown in Figure 5 is only used for the schematic experiments of SELEN with prescribed ice loading. We added this sentence to Section 3: "In the coupled ANICE-SELEN system the RSL change that is fed to ANICE includes bedrock deformation and changes in the sea surface and thus replaces the regional flexural Earth model used the uncoupled ANICE simulations".

And the sentence on page 3515 3-5: "in the uncoupled … ice sheets" (in the first version of the manuscript) has been placed at the end to explain the spin up, see major point 5.

4. We pass on RSL, so basically equation (2), including topography + geoid. See also previous point, the new sentence will clarify this. The text has been checked on this point.

5. The model is continuously forced with the benthic d18O record. From 490 to 410 kyr ago we use the standard stand-alone setup, eustatic sea level is internally calculated from ice volume and the ELRA model is used. At 410 kyr, SELEN is called for the first time and the model starts in the coupled mode using RSL from SELEN and the ELRA model is switched off.

Within the stand-alone mode the four regions use the ELRA model separate within each model domain, but it does take into account changes in the eustatic sea level, internally calculated from all changes in ice volume. We have added this point at the end of the second paragraph of section 3.

6. Yes, 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. Differences are largest within these regions, and are in the order of 10-100 meters (lower than the PD topography). We think your point is a good and we like to take this into account in future research. We have added a sentence on this in the discussion.

7. Yes, for the coupled ANICE-SELEN system the changes in ocean area are taken into account (Fig. 9e,f). For the uncoupled model, eustatic sea level is calculated from ice-volume changes using a constant ocean area of 3.62×10^{14} km^2. Note that

in the coupled model eustatic sea level is only used as an output variable for comparison, it is not used anywhere in the model.

Both simulations shown in Fig. 9e use the same benthic d18O forcing. We consider it not as an artefact of the model but merely that less ice volume in the coupled model is compensated by a reduction in ocean area. Small ice sheets, for example on the Tibetan Plateau and South America, possibly contribute a few meters (see Bintanja et al., 2002), which have a small influence on our modelling result and fall within the error margins of our methodology (see de Boer et al., 2014 for an uncertainty discussion as well).

Reference:
Bintanja, R., R. S. W. van de Wal, and J. Oerlemans. Global ice volume variations through the last glacial cycle simulated by a 3-D ice-dynamical model. *Quat. Int.*, **95-96**, 19-23.

8. ANICE is run for 1000 years, with an internal time step varying between 1 and 5 years, while using the RSL computed by SELEN at the start of this 1000-year period. During this interval we use the RSL field from SELEN, which is not changed or updated within this time period. So the four regions use the same global RSL field (projected on their own regional grid). For the four regions, any additional updates of RSL would be relatively small within this 1000 year time period, also this would be quite computational expensive since if one wants to update the RSL within this time period the SLE needs to be updated as well. We think the coupling interval is related to these uncertainties as well, as is now added in the discussion in Section 4.1.

9. In our simulation with ANICE we only include grounded ice for Greenland. This is now mentioned explicitly in Section 2.1. Naturally we thus miss some of the ice growth that has occurred during glacial maxima in reality, although only a few meters, regional differences could be quite large. With the current mask used as depicted in Fig. 3b we do include all variations that are modelled now. Since Greenland and North America are two separate ice sheets they do not merge, as could have happened during glacial maxima. For a future application we are aiming to include also ice shelves for the Greenland ice sheet and possibly include the ice sheet in a domain with the North American continent. We have added these remarks to the discussion.

10. We add a figure showing the RSL at a colatitude of 20^{o}, that illustrates the differences at the forebulge site (now the new Fig. 6c).

We have added some discussion on the choice of the 80-kyr time window. The new discussion on the coupling interval is added at the bottom of this paragraph.

11. Title changed to: “Simulations with coupled system over 410 kyr”. We have added some discussion on the figure, added 3 vertical dashed lines and pointed out that the dots are illustrated in the map.

Minor points

1. The sentences have been changed to: “Relative sea-level variations during the late Pleistocene can only be reconstructed with the knowledge of ice-sheet history. On the other hand, the knowledge of regional and global relative sea-level variations is necessary to learn about the changes in ice volume.”

2. We have added the sentence: “The derived surface-air temperature anomaly is applied on the present-day climatology to simulate glacial-interglacial changes in temperature and hence ice volume.”

3. Changed to: “the edges of the ice sheets”. Thank you for a very good suggestion: The text has been read and checked by a native speaker.

4. Deep-water temperature. The text has been checked and adapted were needed.

5. We have added the sentence: “However, the exact contribution of the different ice sheets to the spatially varying relative sea level (RSL), i.e. the change in the sea surface relative to the solid Earth, is unknown.” And the first sentence of the 2nd paragraph is changed to: “One of the best studied intervals in the past is the Last Glacial Maximum (LGM, ~21.0 kyr ago), for which a wealth of data has been collected on for example RSL and ice extent. The LGM was a glacial event during which ..”

6. Done
7. Done, include reference to Basset, 2005 and ..
8. Part between brackets is removed
9. Done

10. Yes we mean with ice-sheet models, we have adjusted the sentence with: “..regional sea level that include ice-sheet models over longer ..”

11. Sentence changed to: “During the mid 1970s the importance of including relative sea-level change that affect the instability of marine terminating ice sheet was already recognised (Weertman, 1974; Farrell and Clark, 1976).

12. Removed bedmap and added the third author.

13. We added an additional explanation: “The length of the mean window of 2 kyr and the scaling parameter of 20 were optimised by minimising the difference between modelled and observed d18O.

14. Any time an ice-sheet thickness variation occurs, and hence any time the SLE routine is called by ANICE, SELEN iteratively solves the SLE for the next time step (1 kyr later) and the viscous response in the 80 kyr moving time window. Within the iteration we take into account the additional contributions of the moving time window memory of the RSL, stored in the auxiliary array AS. We have changed the text on this at the end of Section 3.2 and added a sentence at then end of the Section 2.3: “Moreover, the SLE is solved by means of an iterative

procedure where, at time-step 0, the RSL change S is assumed to be eustatic. Then, after 3 iterations, the solution has converged and S is regionally varying (non eustatic, non globally uniform) according to GIA feedback (Farrell & Clark, 1976; Mitrovica and Peltier, 1991; Spada & Stocchi, 2007).

15. We agree that this is unclear. The sentence has been changed to: "the specific number of x and y grid points and SELEN elements of each ice-sheet grid are provided in Table 1". So the total number of grid points is nx × ny. The SELEN elements in Table 1 are the elements that could potentially be affected by ice-thickness variation through time, and consequently are recognised by SELEN as ice-sheet elements (as written a few sentences above).

16. The sentence has been removed. We think this is already explained in a following paragraph (that starts with "To avoid this …"). The ice thickness is maintained from t = [t, t+Δt_S].

17. We mean the number of time steps at which the time step is discretised. Sentence is changed to: "given the time step Δt_S, the total number of time steps and the .."

18. We agree that the definitions of our time steps and time window discretisation could be written down clearly. This has also been noted by Reviewer 2. The specific variables of time and time steps are now explained upon their first appearance in the text. The time step Δt_S is the discretisation time step of the moving time window (similarly to its use as described above). The coupling interval is now called Δt_C. Furthermore all time numbers are now described as relative to the start of a 410 kyr simulation, the first time when SELEN is called by ANICE, so the first time step is -410 kyr.

19. This part has been changed quite a lot. We have shifted some sentences and also paid well attention to the definition of each description of the variables. Now when referring the length L, we always state this is the length of the moving time window. Secondary there are two arrays defined called the auxiliary arrays for the RSL: AS and for the Ocean Function: AOF.

20. Added a sentence: Here H(t) is the ice thickness at time t, whereas I(t) is thus the change or variation in ice thickness relative to the previous time step.

21. At each new call to SELEN, a new auxiliary array is generated using the ice and water loading at that specific time step, as is illustrated in Fig. 4c. The sentence is changed to: "Both auxiliary arrays are generated using the ice and water loading at time *t* and both are discretised into NT time steps".

22. This part is clarified more. At each new Call from ANICE to SELEN the ocean function is updated using the ice and water loading at that time step and new auxiliary arrays AS and AOF are updated with the current RSL change.

23. Changed to: “To demonstrate how the moving time window works for a given ice load ..”. We use the schematic experiment to show how the calculated RSL changes with the moving time window differ from a full solution.

24. Variables are explained below the equation.

25. Higher than the eustatic curve, sentence has been changed.

26. Changed to: “In Fig. 9a-d, we compare the modelled ice volume of the coupled ANICE-SELEN simulation with a simulation that is not coupled to SELEN (ice volume from de Boer et al, 2014).”

27. Changed to: As a result

28. An additional sentence is added: “Thus by including the self-gravitation effects and RSL changes, the growth of the WAIS results in a local increase of sea level rather than a eustatic drop, which induces a slower advance of the ice sheet and thus a smaller ice volume.”

29. Changed

30. Changed to: “Additionally, ice-sheet model parameters can be changed as well. For example the mass balance parameters we use in ANICE (see de Boer et al, 2013) can be tested within a certain range of a physical parameter space (e.g. Fitzgerald et al., 2012). “

31. Complete last paragraph has been changed.

32. ΔT_{surf} is changed to ΔT_{NH}. The temperature module is the deep-water temperature module to compute deep-water temperatures from ΔT_{NH}. Ice loading on land is now changed to grounded ice thickness. ANICE provides only grounded ice to SELEN. But within 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.

33. This is due to the low resolution of the figure. For the final version of the manuscript this will be updated.

34. Correct, we have added ‘and the elastic response’ in the caption when explaining what the red dots represent.

35 Perhaps a good point, Fig. 4c explains basically the same, we have decided to left figure 6 out. The curve flattens because the ice thickness increase stops at 100 kyr, so ice thickness is added 20 m every 1 kyr for 100 kyr, so up to 2000 m thick. Then stays constant for 10 kyr.

36. Changed to: “.. of a run using rotational feedback (as in a) with a run without rotational feedback.”