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Interactive comment on "Comparing a thermo-mechanical Weichselian ice sheet reconstruction to GIA driven reconstructions: aspects of earth response and ice configuration" *by* P. Schmidt et al.

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We thank the referee P. Whitehouse for a thorough and constructive review that have helped to improve the quality of the manuscript. Here we reply to the remarks raised by Whitehouse in the order they were listed.

1 Replies to "Main points"

1.
The abstract and conclusions have been rewritten with emphasis on making them more concise.

2.
As requested we have now added references to other reconstructions that are based on ice sheet modelling and includes the Weichselian ice sheet. However, we chose not to compare the UMISM model to these as the focus of this study is not on how to perform ice sheet modelling but how an ice sheet model based on physical principles compares to reconstructions based on solving the sea-level equation, especially when implemented in a GIA model since the former is not tuned for this purpose while the latter are.

3.
Yes it is correct that this leads to some inconsistency in the approach. This is now explicitly mentioned in the text. The implementation of the isostatic processes in UMISM, as a hydrostatically supported elastic plate model, is the most commonly used way to include isostatic response in numerical ice sheet models. The work by van den Berg et al. (2008) is interesting. However, one caveat with the study is that it isolates and investigates only one aspect (isostatic model) that influence ice sheet geometry. Other processes, that might be of even larger importance (specifically basal processes such as the coupling between basal hydrology and basal sliding), are excluded in the study. In order to do a full assessment of the influence of the choice of isostatic model, all major processes that affect the ice configurations needs to be included since they interact directly with each other, that could result in amplifying or dampening effects.

All in all, the degree to which the ice sheet reconstruction would have been different if UMISM would have used a similar Earth model as the GIA model is beyond the scope of this investigation, but an interesting topic worth investigating further in other studies.

4.

The sea-level curve used in the ice sheet modelling corresponds to 100 m of global sea-level lowering at LGM, as compared to the common value of 120 m (with error bars of c. 80-150 m). The southern and eastern margins of the Weichselaian ice sheet over Fennoscandia are not affected by the lowering of global sea level since they are either terrestrial margins or located in the Baltic Sea (with the sea level determined by the shallow sills in the southern Baltic Sea). The 20 m difference between the commonly used value and the value used in the simulation is considered not to have a large influence on the ice sheet margin location along the Atlantic coast, since, at this location, it is the location and width of the continental shelf that is the main determinator on how far the ice sheet might grow. In the simulations, the ice sheet did advance as far as it could with respect to the Atlantic coastal bathymetry, width of continental shelf. The text has been clarified regarding this issue.

5.

Point taken and in response to this and main points 11 and 12 below we have remove the comparison to RSL data entirely. We still present and compare uplift curves predicted by the three reconstructions as these reflect differences in the earth response induced by the reconstructions. We have further, in addition to the uplift along the Ångerman river, added uplift curves at Tromsö, Norway, and Blekinge, Sweden.

6.

It is correct that the ICE-X and VMn models have been developed in parallel and we also say so. However, VM2 was developed based on ICE-4G (Peltier and Jiang, 1996b,a) which in turn was initially developed based on VM1 (Peltier, 1994). ICE-4G was later slightly updated based on VM2 to yield ICE-4G(VM2) (Peltier, 1996). ICE-5G was then developed based on VM2 (Peltier, 2004) with the slight modification that the elastic thickness of the lithosphere were reduced from 120 to 90 km in VM2 as suggested by Peltier et al. (2002). However, it was later found that VM2 is not the optimal viscosity model of ICE-5G, this in turn has lead to the development of the VM5a model

(Argus and Peltier, 2010) which in turn has been used to develop the ICE-6G model (Toscano et al., 2011). In summary, the only modification to VM2 done when developing the ICE-5G model was a reduction in lithospheric thickness to fit RSL data from Scotland. The suitability of the VM2 model as discussed in Peltier (2004) is mainly based on the study by Peltier et al. (2002) where the ICE-4G model was used.

Regarding using using ICE-5G with a different viscosity structure than the VM2 model, Wu et al. (2013) has a thorough discussion as to why this is appropriate. In summary the vertical length scale on which the Fennoscandian GIA data can resolve the mantle viscosity is much larger than the vertical resolution in VM2. E.g. both Paulson et al. (2007) and Zhao et al. (2012) found that GIA data in Fennoscandia can only resolve 3 layers – the lithosphere and the upper and lower mantle. Secondly, Peltier himself has found the VM2 model not to be the optimal viscosity model of ICE-5G which has lead to the development of VM5a (Argus and Peltier, 2010). Thirdly, the data set we use here was not used in the reconstruction of ICE-5G, hence the VM2 model need not be the optimal viscosity model in fitting ICE-5G to the Bifrost data. Finally and most importantly, the main objective of this study is not to find the optimal earth model of the three reconstructions but to compare the reconstructions to each other. Therefore, varying the earth model parameters to better quantify the differences between the models is a vital part of this study. The ICE-X reconstruction and its predecessors have been used extensively in previous GIA studies in combinations with earth models different from the VMn model upon which they were developed. Most of these studies did not motivate why this could be done and we will neither do so here. In fact, should we have motivate the use of ICE-5G on an earth model different than VM2, then we should also motivate the use of ANU on an earth model different the optimal model found in the reconstruction of ANU.

The reviewer is correct in that we have not run a model that approximate VM2 in both the viscosity structure and the lithospheric thickness, neither have we tested the full range of lithospheric thickness found to be optimal in the ANU reconstruction. Although it would be very interesting to add misfits for additional lithospheric thicknesses we will not do so by two reasons. First of all the objective of this study is not to find the optimal Earth model parameters for the three ice reconstructions but to compare the reconstructions to each other. As we compare the GIA-predictions to observations it is however un-avoidable that we arrive at some estimates of the earth model parameters and therefore also that these be compared to estimates in other studies, but again this is not the objective of this study. Secondly a practical issue, these models do not run in an instance. In fact the total runtime of the models in a single panel in Figure 6 takes about 3/4 of a month to run and post-process on our system. To add misfits for two more lithospheric thicknesses, which would be needed to cover the range suggested in the reconstruction of ANU, would take about 4 months which is significantly longer the time period we have to revise the manuscript.

This being said we will tone down the comparison of our optimal earth model to the results of others including the reconstructions of ICE-5G and ANU.

7.
There is no discontinuity in the hybrid model, instead the load in ICE-5G at 37 kyr BP was linearly changed into the ANU load at 36 kyr BP. This was however not clearly stated in the manuscript. In the revised manuscript we have replaced this hybrid model by the test-models mentioned in the summary and discussion section. Basically we now test two scenarios for all ice sheets:

1. close to isostatic equilibrium at LGM: this is achieved by applying the LGM load of each reconstruction already at 68 kyr BP (linearly ramped from 0 load at 69 kyr BP) and keeping the load constant until LGM, after which the de-glaciation phase according to the reconstruction is applied.

2. Ice-free conditions prior to time t: this is achieved by linearly ramping the load from 0 at t-1 kyr to the reconstructed load at time t. We test models with t = 21 kyr BP, 25 kyr BP, 30 kyr BP,... up to 60 kyr BP in intervals of 5 kyr. Both

scenarios are tested on models with 120 km lithospheric thickness and uniform mantle viscosities in the range 1-6 x 10^{21} Pa s. The results are presented in a new subsection in the results section.

8.
In the revised version of the manuscript we are now using the 2010 Bifrost data.

9.
The reviewer is correct in that the maximum over-prediction by ICE-5G of the present day uplift rate is centered over eastern Finland while the velocities are under-predicted in northern Sweden. A comparison with Figure 4g then gives that the center of ICE-5G is located in between the maximum over-prediction and the region of under-prediction. This is entirely in line with our explanation for consider taking the difference between two similar but laterally shifted curves as displayed in Figure 1. Unless the curves are either periodical and shifted by exactly one period or consists of straight line segments, the maximum difference between the curves will not coincide with the maximum value of the curves. The simple sinusoidal curves displayed Figure 1 can be assumed a very crude approximation to the uplift velocity along a profile from northern Sweden through eastern Finland. Let curve C1 in Figure 1 be the observed uplift and C2 the uplift predicted by the GIA model. If the load in the GIA model is shifted to the east relative the real load then the uplift curve will also be shifted to the east in accordance with C2 in Figure 1. As seen from the figure the maximum over-prediction (min dC in the Figure 1) will then be found even further east while the maximum under-prediction (max dC in the Figure 1) will be found to the west. This is in agreement with the general trend observed for the residuals of ICE-5G in both Figure 7 and 8. Further, as this trend is seen for a range of earth model parameters it should be considered robust feature of the ice reconstruction as implemented in our GIA model.

10.
This is a very interesting question that however is a bit hard to answer. Several stud-

ies using different methods have shown that the lithospheric thickness changes from great thicknesses in the old cratonic parts in the East to a thinner lithosphere in the younger Western part (e.g. Pérez-Gussinyé and Watts, 2005; Priestley and M^{c}Kenzie, 2006; Artemieva and Thybo, 2008). It is therefore to be expected that also the GIA process will "see" an approximately east-west variation of the lithospheric thickness. (Whitehouse et al., 2006) presented a figure where the effect on the current uplift rates in Fennoscandia for such a lateral variation were shown. Figure 2 below complements that study by presenting the difference between models of uniform lithospheric thickness and models with laterally varying lithospheric thickness for all three ice reconstructions used in this study and two different earth models (for more details on the laterally varying models see the caption of Figure 2 or Lund et al. (2009)).

In general, over land, we find that the models with a uniform lithospheric thickness predict greater uplift velocities over Finland and in a narrow band stretching down to southern Sweden, while over Denmark, Norway and northern Sweden the uniform lithospheric thickness models predict lower velocities. These trends are seen for all three ice reconstructions, although the magnitude and specific details of the difference in the uplift rates differ between the reconstructions as well as varies with the earth model used.

Laterally varying lithospheric thickness may therefore resolve some of the observed residual trends for at least the ICE-5G model. However, a lateral variation in the elastic thickness will not only affect the present day uplift rate but also the uplift history and therefore the RSL predictions of the model. How this would affect the ice sheet reconstruction is unclear to us.

In response to this point we will add a comment along the lines above to our suggested potential edits to the three reconstructions.

11.
see reply to main point 5 above

12.
see reply to main point 5 above

13.
The revised manuscript have been thoroughly checked for any spelling or grammatical errors, including those listed by the reviewer.

2 Replies to "Minor points"

1.
The misspelling pointed out by the reviewer has been adjusted in the revised manuscript

2.
The misspelling pointed out by the reviewer has been adjusted in the revised manuscript

3.
By ambiguity we referred here to the bifurcation of the optimal earth model parameters. In the revised manuscript we have removed the term ambiguity and instead refer directly to the bifurcation.

4.
As pointed out by the reviewer, observational data on ice sheet thickness may be found in mountainous regions. We have therefore adjusted our statement about the availability of observational data on ice sheet thickness.

5.
This is a valid point and we have therefore added a comment about this to the sentence.

6.

The misspelling pointed out by the reviewer has been adjusted in the revised manuscript

7.
The misspelling pointed out by the reviewer has been adjusted in the revised manuscript

8.
The misspelling pointed out by the reviewer has been adjusted in the revised manuscript

9.
The reviewer is correct in that the loading due to ice-dammed lakes and marine limit data is treated differently in the ANU reconstruction. It is however out of scope in this study to go into the details on how the reconstruction is done. This is better described in Lambeck et al. (2010) and the interested reader is referred to that paper for the details. Here we are mainly interested in summarizing the main differences between previous and the current ANU reconstruction.

10.
The misspelling pointed out by the reviewer has been adjusted in the revised manuscript

11.
The misspelling pointed out by the reviewer has been adjusted in the revised manuscript

12.
The misspelling pointed out by the reviewer has been adjusted in the revised manuscript

13.
Our model have been updated by replacing the foundations with springs elements as

the method used to implement the pre-stress advection term. We have chosen not to elaborate further on this as this update is not of importance to our results, but mention the modification to give the reader the possibility to reproduce our model but leave the details to be found in Schmidt et al. (2012). (Note though that the modification is important for the models with laterally varying lithospheric thickness that we present the result of in Figure 2 herein)

14.
We use the flat earth approximation in our GIA model, however the sub-surface of our earth model is expanded to a half-sphere of great radius (the surface is still flat though). This is done to simulate infinite boundary conditions in a finite model. We have reworked the description of our model implementation to better reflect this and avoid confusion about the assumed geometry.

15.
The misspelling pointed out by the reviewer has been adjusted in the revised manuscript

16.
The reviewer is correct that the summation index shall start at 1 (especially since the counter runs to N) and we have modified the equation accordingly.

17.
The specific lines referred to here by the reviewer have been removed in the revised manuscript. We agree however with the reviewer that the proper thing to state is that the data is fit by the model rather than the other way around.

18.
The misspelling pointed out by the reviewer has been adjusted in the revised manuscript

19.

We have reformulated the sentence to avoid giving the impression that the rebound velocity increases with time.

20.
We have removed the 1-layer models from the revised manuscript rendering the first half of this remark un-applicable. In response to the second remark we have added additional references to figures being discussed, where appropriate.

21.
In short, LGM occurs about 2.8 kyr earlier in ANU than in UMISM, therefore at present time an earth model loaded by ANU have had longer time to rebound than an earth model loaded by UMISM. As a result, for identical earth models UMISM is expected to result in greater uplift velocities than predicted by ANU (as the rebound have proceeded further). We have reformulated the sentence to clarify this.

22.
We have adjusted the negatives in both places as pointed out by the reviewer.

23.
We have adjusted the sentence in accordance with the reviewer advice

24.
The referenced sentence have been edited and partly moved to a new subsection in the results section.

25.
The misspelling pointed out by the reviewer has been adjusted in the revised manuscript

26.
The reviewer is correct the residual velocities of ICE-5G are overall more similar to those of ANU than to those of UMISM. What we referred to here was a trend discussed in the results section where the residual velocity of ANU is greater at the Trondheim

station than at the Stavanger station in contrast to ICE-5G and UMISM who both display greater residual velocities at Stavanger than at Trondheim. This could unfortunately not be directly seen in Figure 7 as the residual velocity of ANU and ICE-5G at both Stavanger and Trondheim fell within the same color in the used color scale. Further the suggestion is not a very strong suggestion and has therefore been removed. We have also edited to color scales used to make it easier to interpret the figures.

27.
The misspelling pointed out by the reviewer has been adjusted in the revised manuscript

28.
We have removed the use of RSL data from the revised manuscript rendering this remark un-applicable.

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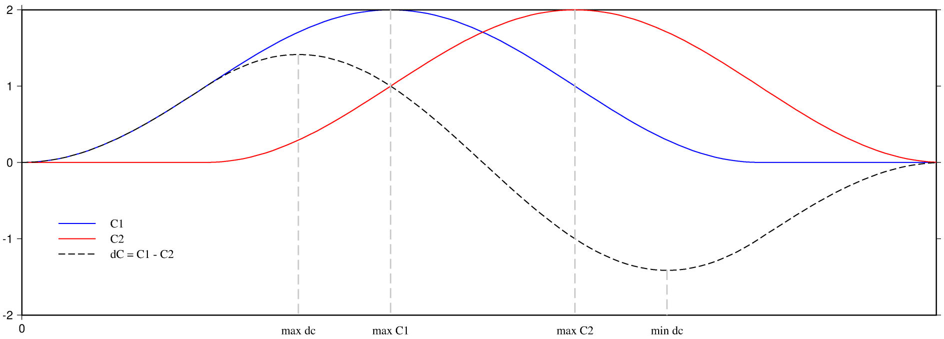

Fig. 1. Relation between max value of two identical but horizontally shifted curves and max/min of the difference between them. See reply to "Main points" 9 for more details.

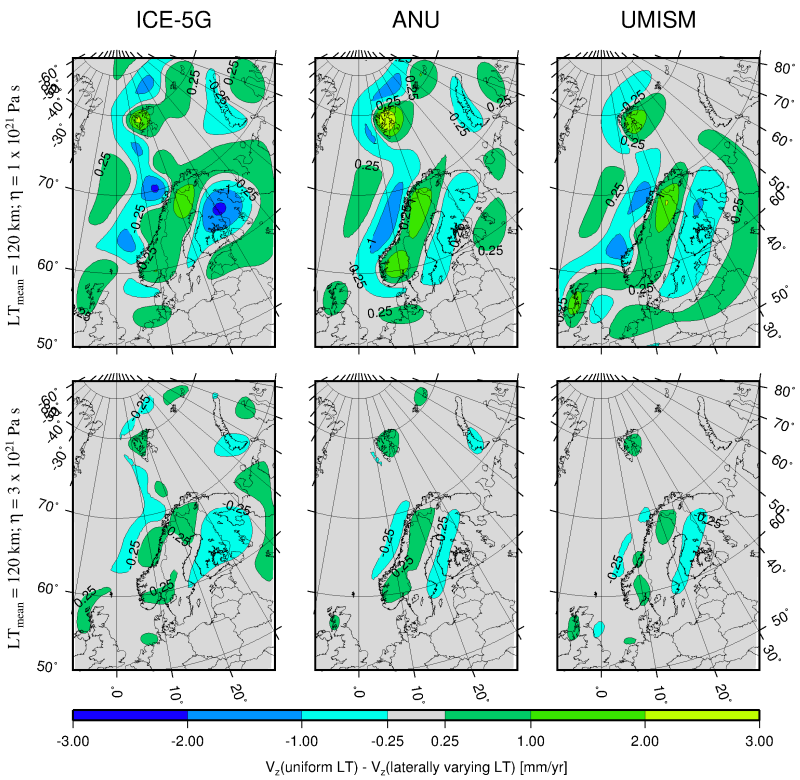

Fig. 2. Effect of laterally varying lithospheric thickness, LT, on present day uplift rates. Difference have been computed as (uniform model) - (laterally varying model) All models have an average lithospheri