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Discussions

Interactive comment on "Empirical estimation of present-day Antarctic glacial isostatic adjustment and ice mass change" *by* B. C. Gunter et al.

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This manuscript by Gunter et al. describes a novel method of empirically deriving GIA-related uplift rates by combining a number of Antarctic data sets. The manuscript covers material that is clearly within the scope of The Cryosphere, it is well written in all aspects (abstract, methods etc.), the methods are generally robust, and the work has been carefully executed. The results clearly support the conclusions, however, in order to compare their results with uplift rates derived using forward GIA models, Gunter et al. apply a number of bias corrections to their empirically-derived results: I raise a number of potential issues associated with these bias corrections below, and also list a number of more minor points. Overall, this is a good manuscript, and I recommend publication once the following points have been addressed.

Comments on bias corrections

1. GIA bias correction using LPZ, page 3513, line 8: The authors state that the 'rate of GIA' should be very small in the low precipitation zone (LPZ), and use this to estimate a 'GIA bias correction'. However, there is evidence (from the glaciological analysis of ice cores) of post-LGM ice thickening in this region, which would lead to regional subsidence at the present day – as predicted in both the IJ05 and W12 models, which are reproduced in the supplementary information, figure S3. If these models – which attempt to incorporate glaciological information relating to former ice thickness in this region – were correct, then the assumption that the rate of GIA-related uplift in this region should be zero would introduce a bias to all of the empirically-derived results. If the authors choose to retain their method, then I think this potential source of bias (and the underlying glaciological data) should be mentioned, and the implications for the final conclusions should be quantified in terms of Gt/yr (e.g. by comparing results that do and do not make use of the 'GIA bias correction').

As a follow-on query: was this 'GIA bias correction' also applied to the uplift rates from the previously-published GIA models, e.g. ICE-5G, IJ05 and W12, or just the empirical results?

2. Bias offset between GPS rates and GIA-related uplift rates: I understand the need to ensure that all the uplift rate estimates (from GPS, empirical methods, or forward GIA modelling) are in the same reference frame, but applying a uniform shift to the results of forward GIA models (e.g. ICE-5G, IJ05, W12) is unphysical. Consider the situation whereby a forward-modelled GIA solution fits the GPS data well in one region, say East Antarctica, but not in another, say West Antarctica, due to errors in the ice-loading model for West Antarctica. As I read it, the bias correction described in this manuscript would shift the entire field of GIA model-predicted uplift rates downwards in an attempt to better fit the GPS data in West Antarctica. This would lead to a worse fit in East Antarctica, where the model had originally been accurate. This is clearly an unsatisfactory situation if the purpose is to compare the accuracy of the various forward

and empirical models of GIA.

Also, it is stated (lines 25-27, page 3516) that the choice of Earth model in a forward GIA model can lead to the type of bias offset that the above method attempts to remove, however, changing the Earth model in a forward GIA model will alter the amplitude and wavelength of the solid Earth response, not simply the absolute magnitude. Therefore, a bias correction consisting of a uniform shift, as described above, does not cover the case whereby the misfit to the GPS rates is due to the incorrect choice of Earth model in a forward GIA model. Combining this point with the observation that misfits to GPS rates are more likely to be associated with errors in the ice-loading model (which will be spatially variable but likely regionally correlated, and hence cannot be accounted for by a uniform shift), and the fact that the spatial distribution of GPS sites in Antarctica provide very poor sampling of the spatial pattern of GIA-related uplift in some regions , this suggests that a number of caveats need to be carefully explored and explained before this bias correction is applied.

Minor points

1. There is frequent reference to 'the rate of GIA', however, GIA encompasses arrange of processes including solid Earth deformation and deformation of the shape of the geoid, and therefore it should be clarified that the authors are referring to the rate of solid Earth uplift associated with GIA. It is important that this shorthand does not creep into the literature to ensure that the range of processes associated with GIA is clearly understood. To this end, the text on lines 7-9, page 3499, should also be expanded to include a full description of GIA. 2. Page 3502, line 18: please include references for the Antarctic climate and firn densification models here. 3. Page 3502, lines 18-23: The authors describe the different data and processes that are considered on the floating and grounded portions of the ice sheet, respectively, mentioning that surface processes will not contribute to mass change over the ice shelves. By my interpretation of equation 3, all of the mass change observed over the ice shelves will therefore be attributed to solid Earth uplift. However, there will be a small contribution to the mass

C1716

signal in this region from sea-level change: is it necessary to account for this when interpreting the GRACE data? If not, then please justify this by roughly quantifying the magnitude of the signal due to ocean mass change. 4. A follow-on comment: GRACE data up to 400 km offshore of Antarctica are used (page 3514, lines 3-4). Given that mass change will take place over the oceans, please clarify whether you need to account for this contribution. 5. Page 3502, line 22: please clarify what is meant by "...the GRACE and solid earth densities were used..."; at the moment it reads as if you are referring to 'GRACE densities'. 6. Page 3503, line 8: please briefly explain the difference between 'unconstrained' and 'regularized' solutions when discussing the GRACE data. 7. Page 3503, lines 12-13: please provide a reference or more detailed explanation to accompany the comment that "...the secular trends that are removed from select zonal coefficients were restored, as these rates are believed to mostly represent the effects of GIA." 8. Page 3504, lines 23-28: it is stated that additional Gaussian smoothing (approximately 200 km) was applied to the unconstrained GFZ solutions, however, on page 3502, line 6, it is stated that, in general, 400 km Gaussian smoothing is applied to the various components of equation 1. How does the additional smoothing of the unconstrained GFZ solution affect the magnitude of the GIA uplift rates that are deduced for this solution? 9. Page 3506, line 14: 'total sum' rather than 'total distance'? 10. Page 3506, line 27: I could not find the Urban et al. (2013) article, which seems to include important information regarding the analysis of the ICESat data. Please ensure that this article is available by the time this article is published, or provide the necessary information here. 11. Page 3507, lines 1-2: Is this cut-off value reasonable, e.g. can you give an example of the maximum rates of glacial thinning or ablation processes that have been observed in Antarctica? How many pairs had to be rejected according to this criterion, and is there any regional clustering to the rejected pairs? 12. Page 3508, line 9: The phrase "...one or both..." is a little confusing since it is not clear to me how an overlapping footprint could only overlap with one laser shot. Please clarify. 13. Page 3509, line 25: please clarify the size of a 'grid cell'. 14. Page 3510, lines 9-12: Please give some detail as to how the densities are assigned

C1717

in the case that there is a positive height difference, i.e. how rho_surf is calculated? 15. Page 3510, equation 3: is there any difference between h_dot_GIA (left-hand side of equation 1) and h_dot_rock (left-hand side of equation 3)? If there is, then please define the difference. 16. Page 3510, equation 3: Not all of the mass change observed by GRACE that is then associated with GIA will be due to solid Earth uplift; there will be a small contribution from the deformation of the geoid, i.e. a change in sea surface height. Is this factor considered by the authors (perhaps folded into the value chosen for the density of the underlying rock?) or is this effect negligible? 17. Page 3510, equation 3: would it be possible to conceptually describe the terms included in this equation to aid understanding of your methods? E.g. I think the equation essentially says that the mass rates due to model-predicted SMB and firn compaction, and any mass change due to dynamic ice thinning or an underestimation of SMB, are subtracted from the observed rate of mass change, leaving the rate of mass change due to GIA, which is converted into an uplift rate by... 18. Page 3513, line 5: Does the value of 50 Gt/yr refer to the potential bias if uplift rates were incorrect by 1mm/yr over the whole continent? The spatial extent of this statement is not clear. 19. Page 3513, lines 22-23: '...contributions' of what from the northern hemisphere? 20. Please make sure that you differentiate between the GIA solutions derived using the methods outlined in this paper, and previously published GIA models; both are referred to as 'GIA models' at various points in the manuscript. 21. Page 3514, line 4: please explain how '...the GIA mass change rates were obtained'. 22. Page 3515, lines 20-21: why are higher uncertainties 'most expected' in the Amundsen Sea Sector and Wilkes/Adelie Land? 23. Page 3515, lines 25-27: The English is a little odd in the second-to-last sentence of section 5.1. 24. Did the authors consider using the updated version of the IJ05 model, as described in Ivins et al. (JGR, 2013)? 25. Page 3518, line 14: when you say '...not typically predicted...' please specify whether the empirical estimates are larger or smaller than previous estimates. 26. Page 3519, paragraph starting on line 21: it should probably be noted that some of the disagreement between forward-modelled and empirically-derived uplift rates may be due to the fact the forward GIA models do

C1718

not typically consider ice-load changes during the last 1000 years. The response to any ice-load changes during this period would be classified as a GIA response, and may dominate the present-day signal. 27. Table 2: Please clarify whether the LPZ bias rates listed in columns 3 and 4 are added onto, or subtracted from, the raw uplift rates. (ditto for Table 4) 28. Table 2: I find it very surprising that the total mass change rates derived from the GRACE data are so varied (columns 5-7) yet the ice-mass rates lie within 2 Gt/yr for all the GRACE solutions (columns 11-13). All of the uncertainty seems to be pushed into the empirically-estimated GIA rates. There is a brief comment about this in the discussion, but I think it warrants a closer analysis of your method, which does not seem to permit any flexibility in the ice-mass rates that are derived. 29. Please clarify in the caption of Tables 3 and 4 that the LPZ bias has been applied to all of the results listed in these tables. 30. Figure 5: Please clarify in the caption that the LPZ is outlined by the thick black line. The edge of the Ross and Filchner-Ronne Ice Shelves should be outlined. The caption for Wilkes/Adelie Land (WA) is incorrect on the figure (AW). 31. Figure 6: The cyan and blue lines are labelled differently in the caption and in the key on the figure. 32. If there is space, it would be useful to have 'Firn Densification Model' written out in full in the captions of figures 6 and 7 to save searching for the meaning of FDM back in the text. 33. Figure 9: Has the LPZ GIA bias correction already been applied to the rates plotted in this figure? 34. Does the magnitude of the empirically-derived GIA-associated uplift rates depend on the wavelength used to smooth the GRACE data? 35. Figure 11: Please state what is actually plotted here in the caption (presumably uplift rates).