Supplementary material to:

"Antarctic ice-mass balance 2003 to 2012: regional re-analysis of GRACE satellite gravimetry measurements with improved estimate of glacial-isostatic adjustment based on GPS uplift rate"

by Sasgen, I.; Konrad, H.; Ivins, E.; van den Broeke, M.; Bamber, J.; Martinec, Z.; and Klemann, V.

The supplementary material includes three sections with additional information the sub-division of Antarctica for sector-wise GIA modeling (Section 1), the treatment of the GRACE low-degree and order coefficients (Section 2) and the uncertainty associated with the GIA correction AGE1 (Section 3). In addition, we provide two data sets resulting from our analysis that are:

(1) Spectrum_of_e_for_AGE1a_GPS_only.sh: Fully normalized spherical-harmonic coefficients of the rate of geoid-height change in mm/yr for the GIA estimate AGE1a (GPS only). The ASCII file has four columns; spherical-harmonic degree (column 1), spherical-harmonic order (column 2), coefficient of cosine term of spherical-harmonic expansion (column 3), coefficient of sine term of spherical-harmonic expansion (column 4). The cut-off degrees are 0 to 170.

(2) Spectrum_of_e_for_AGE1b_GRACE_and_GPS_combined.sh: Fully normalized spherical-harmonic coefficients of the rate of geoid-height change in mm/yr for the GIA estimate AGE1b (GRACE & GPS comb.). The ASCII file has four columns; spherical-harmonic degree (column 1), spherical-harmonic order (column 2), coefficient of cosine term of spherical-harmonic expansion (column 3), coefficient of sine term of spherical-harmonic expansion (column 4). The cut-off degrees are 0 to 170.

1) Subdivision of Antarctica for sector-wise GIA modeling

In this study, we divide the Antarctic Ice Sheet in five main deglaciation sectors (Fig. 1). Note that e.g. Filchner-Ronne Ice Shelf (FRIS), Ross Ice Shelf (RIS) include the actual shelf regions where load changes occurred during the last glacial cycle. The GPS stations which we use are indicated in Fig. 1 and designated by the names used by Thomas *et al.* (2011).
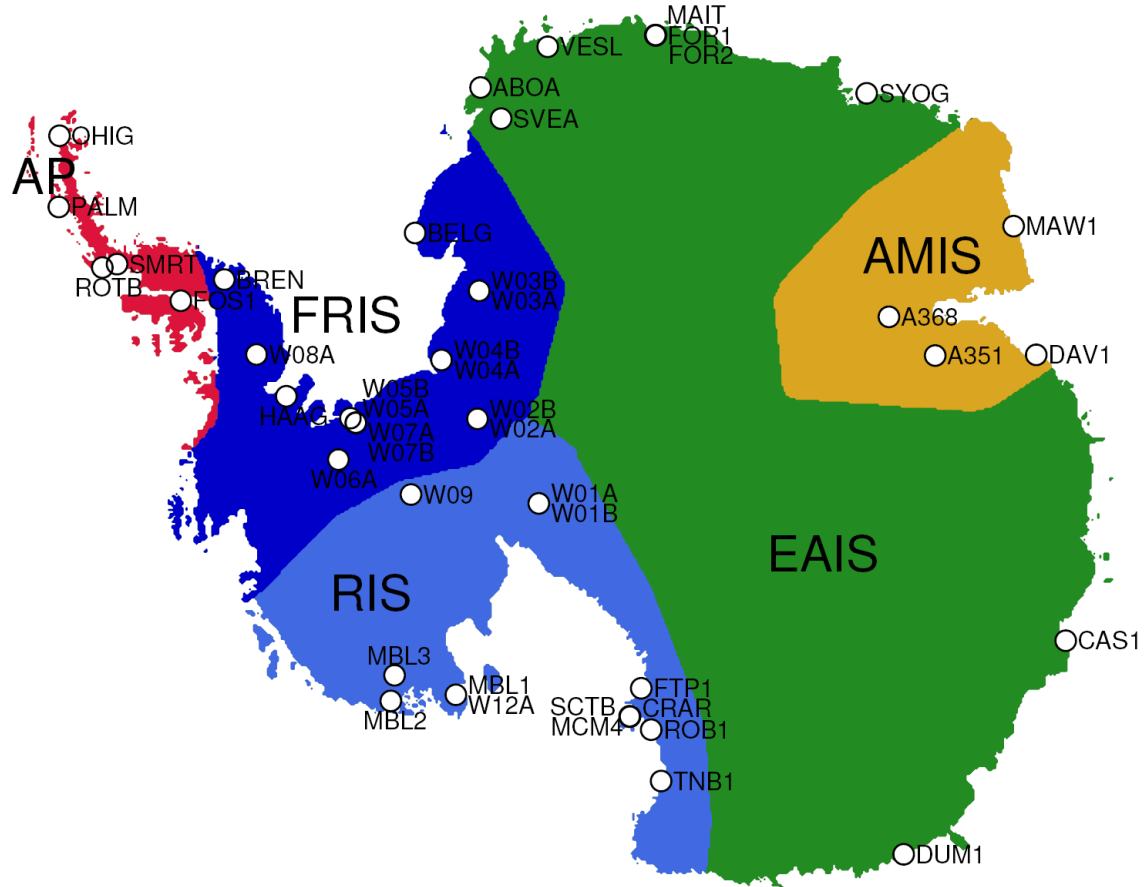
Fig. 1. Definition of sectors used for subdividing the load histories (LH1, LH2 and LH3). Color code corresponds to the one used in the Figure 3, main paper. The sectorial acronyms are; Antarctic Peninsula (AP), Filchner-Ronne Ice Shelf (FRIS), Ross Ice Shelf (RIS), Amery Ice Shelf (AMIS), remaining parts of East Antarctic Ice Sheet (EAIS).

2) Comment on the treatment of GRACE low-degree harmonics

In this paper we damp the low- and high-frequency GRACE coefficients, i.e. band-pass filter the data according to the function specified in Sasgen *et al.* (2012), supplement, in order to 1) reduce far-field signal over Antarctica, and 2) suppress high-frequency noise resulting from the harmonic downward continuation of the gravity-field measurement. An indication that this procedure may be of advantage is provided when looking at the difference in the CSR RL05 and GFZ RL05 gravity trends. The degree-power spectrum (Fig. 2) reveals very good agreement in the mid-spectral range, with large deviation in the upper spectral part (as expected), but also with decreasing amplitude for the low degree harmonics 2, 3 and 4. The spatial pattern of the difference (Fig. 3) shows a magnitude of the difference for degrees 2 and 3 comparable to that of the remaining spectrum (4 to 60). It should be kept in mind that it is difficult to sort the question of bias and/or errors in either solution release, or method. However, our treatment forces these lower degree and order terms to be effectively suppressed in amplitude. These are not the choices made in other GRACE solutions for ice mass balance in Antarctica, such as those assumed in the Shepherd *et al.* (2012) IMBIE study or in the new GIA corrections of the report by Ivins *et al.* (2013). Part of the differences in trends solved in the

study and these other recent treatments may owe to these differing treatments of the low order zonal terms for degrees 1 to 3. Our treatment has the advantage of freeing the GIA degree-1 terms from assumptions of the deepest mantle viscosity which are poorly resolved in GIA studies employing data combinations of laser ranging to passive satellites, sea-level histories, rotational data and terrestrial geodesy (Mitrovica and Wahr, 2011).
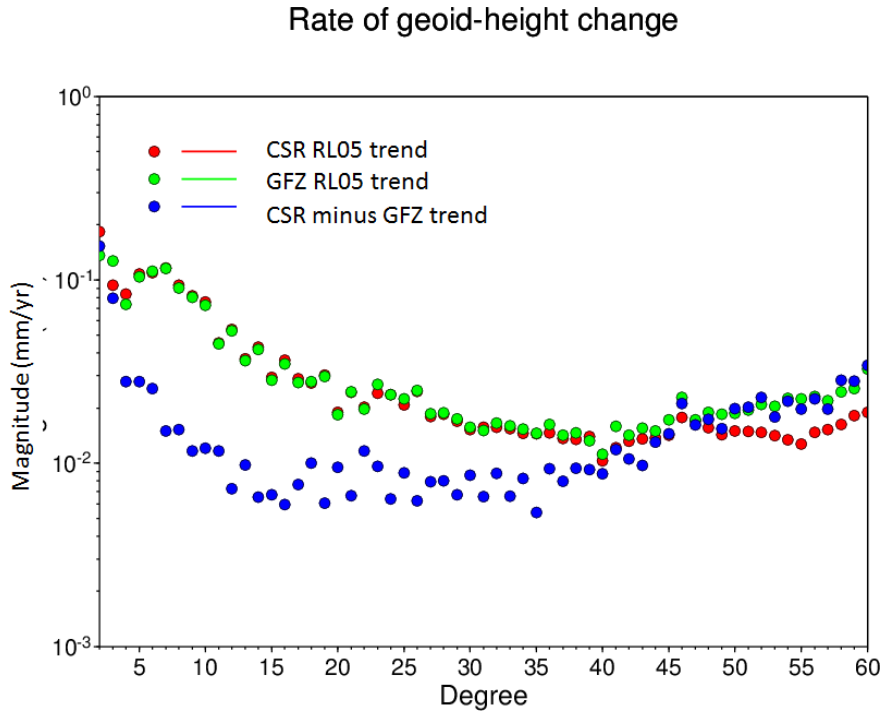

Fig. 2. Degree-power spectrum of the rate of geoid-height change obtained from CSR RL05 (red), GFZ RL05 (green) and the difference between CSR RL05 and GFZ RL05 (blue).
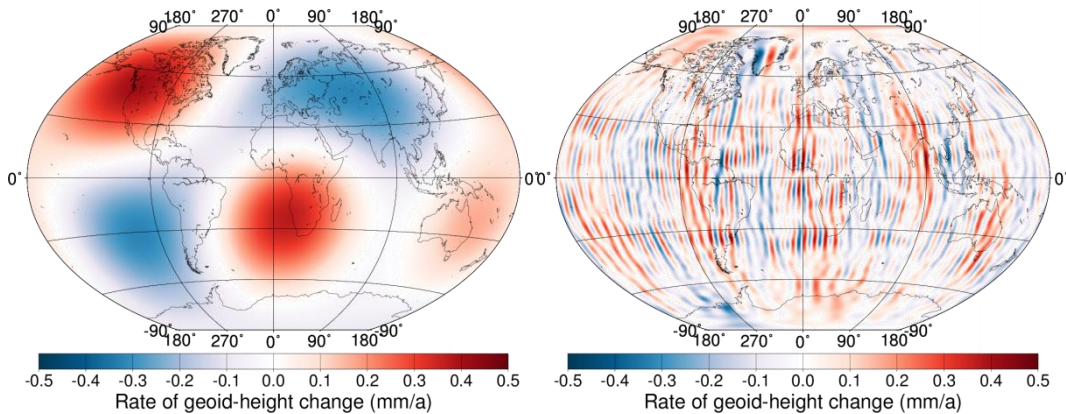

Fig. 3. Spatial representation of the difference in the rate of geoid-height change between CSR RL05 and GFZ RL05, for degree and order 2 and 3 (left) degree 4 to 60 (right).

Although, GIA-induced rotational variations are accommodated in our forward model, and, for test also the rotational variation caused by present-day ice mass changes in Greenland, we cannot currently reproduces the trends in degrees 2 and 3 (neither for GFZ RL05 nor for CSR RL05). This means that our model is incomplete in the sense that a process is missing and/or that the GRACE

coefficients in CSR or GFZ contain errors/artifacts, which is suggest by Fig. 3. In both cases, we consider it best to reduce the influence of these coefficients in the adjustment of the forward model (Fig. 5), which is, however, complete up to degree and order 512 (present-day changes) and 170 (GIA).
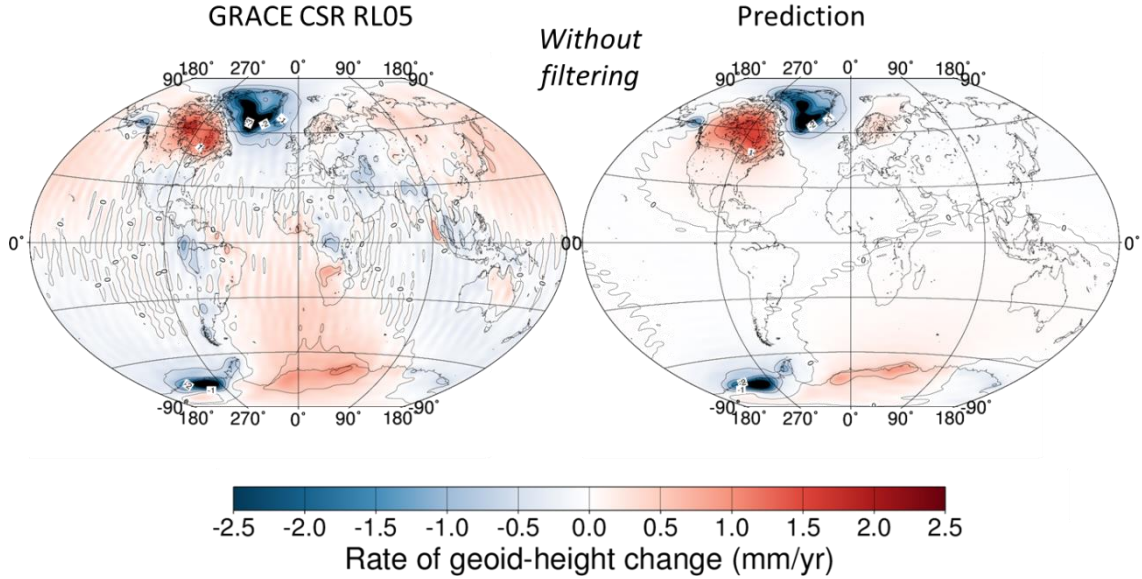

Fig. 4. GRACE trends from CSR RL05 (Jan. 2003 to Sep. 2012), and the adjusted forward model for cut-off degrees 2 to 60, without filtering. The model prediction consists of present-day ice-mass changes in Greenland, Antarctica, Alaska and Ellesmere Island; the GIA models consist of Huybrechts, 2002 and NAWI (Zweck & Huybrechts 2005) applied to VD3 (please see Table 1 of main paper). All model components are adjusted to the GRACE data.
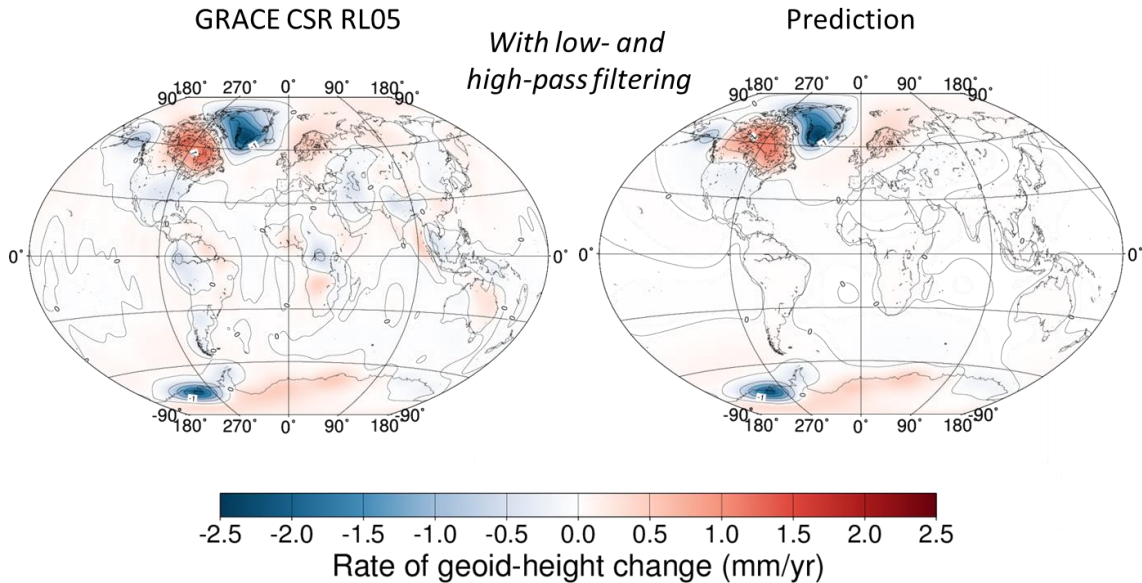

Fig. 5. Same as Fig. 4, but after low- and high-frequency damping, used before model adjustment.

Additionally, we neglect the degree 1 coefficients in the adjustment of our forward model due to 1) their large uncertainty of the trends, and 2) their strong representation of Northern Hemisphere GIA. Nevertheless, we show that the modeled degree 1 coefficients lie within the uncertainty range of the SLR estimate; Fig. 6 shows that that the model reproduces the degree-1 terms to a large extent, both

in direction and magnitude. The prediction, however, shows a lower amplitude which may be related to a too weak lower-mantle viscosity underlying our GIA prediction, to which our GRACE-adjustment is not sensitive. Nevertheless, observation and model agree within the uncertainties as depicted in Tab. 1.
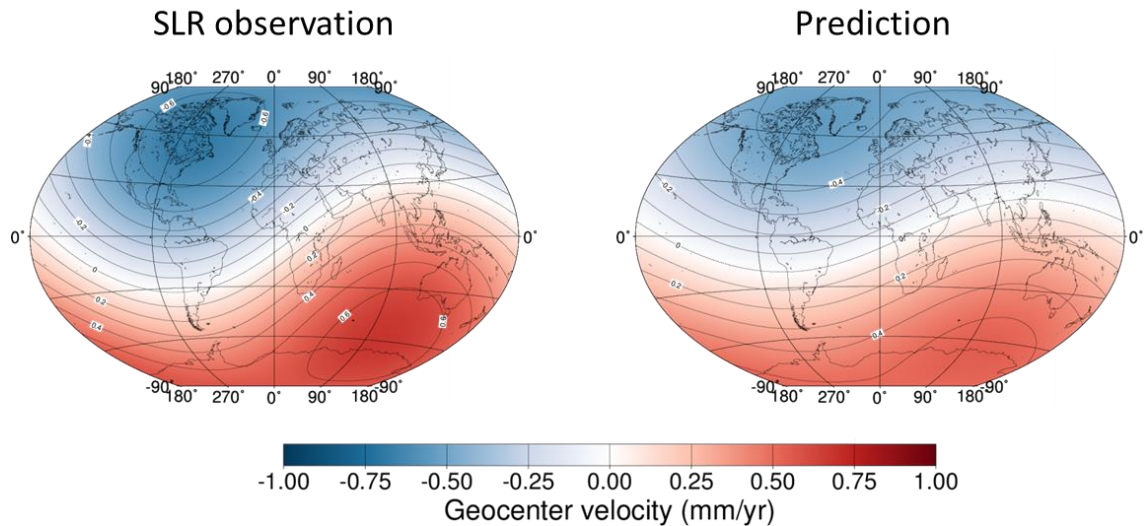

Fig. 6. Spatial representation of the geocenter motion obtained with SLR tracking (left; Cheng *et al.* 2010) and the model prediction (right) for January 2003 to September 2012.

Tab. 1. Geocenter velocity from SLR, including uncertainty and the model prediction without explicitely ajdusting the degree 1 terms.

Geocenter velocity (mm/yr)				
Component	SLR	Prediction	SLR-2sigma	SLR+2sigma
x	-0.10	-0.06	-0.26	0.06
y	0.35	0.18	0.18	0.53
z	-0.58	-0.51	-0.81	-0.34

3) Effect of sectorial adjustment to GPS data

In this study, only a single scaling factor is derived from GRACE based on gravity signal over the FRIS region (step 1). This is then applied to the load distributions of the LH1, LH2 and LH3 for all sectors, which homogenizes to some extent the ambiguity between load and viscosity distribution. As a consequence, the scaling factor changes the magnitude of the GIA prediction, not its spatial pattern, which can be interpreted as placing confidence in the initial distribution of load between the sectors of LH1, LH2 and LH3. In this sense, the GPS data are used for the sectoral refinement of the model.

Fig. 7 shows the apparent mass change of LH1, LH2 and LH3 for the viscosity distributions VD1, VD2, VD3 and VD4, for the initial prediction (pred), the GRACE-constrained model (GRACE), the GPS constrained model (GPSn) and the GRACE/GPS constrained model (GG). It becomes visible that applying the GRACE constraint (only one scaling factor for all sectors based on the signal over the FRIS) homogenizes the apparent mass change for different viscosities. Including the GPS data in the sectorial subdivision of the predictions, homogenizes the apparent mass change for the three different load histories. For example, the load history LH3 (ICE-5G), which has a large GIA signal over the RIS compared to FRIS retains a large mass change if adjusted to GRACE signal over the FRIS only. This is not the case, for Huybrechts, 2002 (LH1), which has the dominant load change and GIA signal over FRIS. Applying both GRACE and GPS data increases the apparent mass change w.r.t the GPS-only results, but has, due to the comparably large errors of the GRACE scaling factor with respect to the GPS data, only a minor effect.
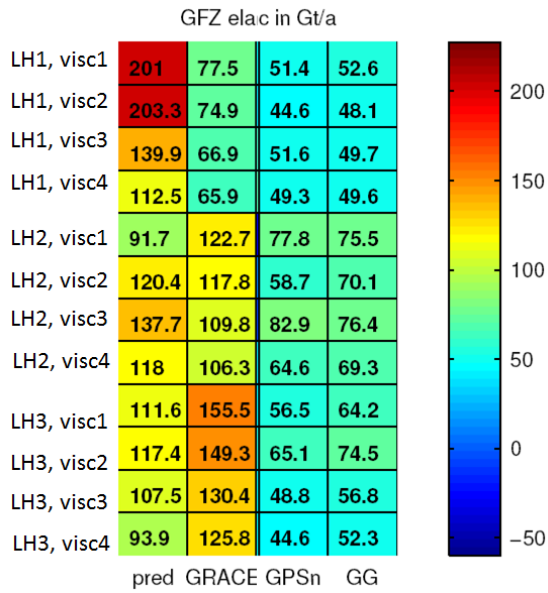

Fig. 7. Apparent mass change of the GIA prediction based on LH1, LH2 and LH3 and the viscosity distributions VD1 (visc1), VD2 (visc2), VD3 (visc3) and VD4 (visc4), for the initial prediction (pred), the GRACE-constrained GIA prediction (GRACE), the GPS constrained model (GPSn) and the GRACE/GPS constrained model (GG).

4) Uncertainty estimate for AGE1

In addition to the uncertainty estimate of the GIA-induced apparent mass change (Fig. 4, main paper), Fig. 8 shows the uncertainty of AGE1b (GRACE & GPS) as spatial fields, both for the rate of radial displacement and rate of geoid-height change. The uncertainty represents of the standard deviation computed from the 995328 samples obtained from the permutation of the load history, viscosity distribution, GRACE release and elastic correction (see main paper). It is visible that the largest uncertainty is associated with the GIA signal over the RIS; here, the ice histories constituting the ensemble of GIA simulations show large deviations, which cannot be constrained by the sparse

GPS uplift rates. It should also be noted that the uncertainty is only meaningful where signal is predicted. For example, for the Amundsen Sea Embayment, the uncertainty is probably underestimated given the new findings of Groh et al. 2012. GIA predictions It is expected that additional GPS data will in future significantly reduce the uncertainty of the GIA correction.
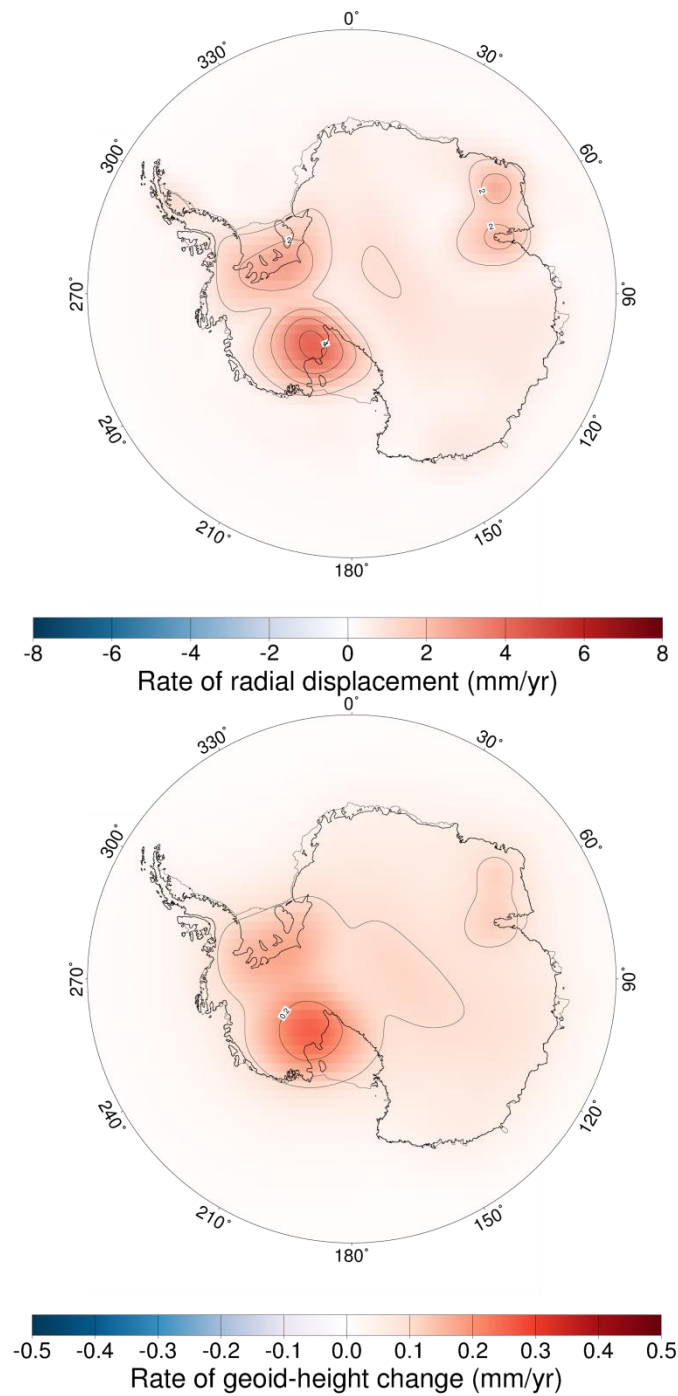

Fig. 8. Standard deviation of the rate of radial displacement (mm/yr) and the rate of geoid-height change (mm/yr) of estimates of AGE1b (GRACE & GPS) underlying for the ensemble shown in Fig. 4, main paper.

References

Cheng, M., Tapley, B., and Ries, J.: Geocenter Variations from Analysis of SLR data, IAG Commission 1 Symposium 2010, Reference Frames for Applications in Geosciences (REFAG2010), Marne-La-Vallee, France, 4-8 October 2010, 2010.

Groh, A., Ewert, H., Scheinert, M., Fritsche, M., R¨ulke, A., Richter, A., Rosenau, R., and Dietrich, R.: An investigation of Glacial Isostatic Adjustment over the Amundsen Sea sector,West Antarctica, Global and Planetary Change, 98–99, 45 – 53, doi:10.1016/j.gloplacha.2012.08.001, 2012.

Huybrechts, P.: Sea-level Changes at the LGM from Ice-dynamic Reconstructions of the Greenland and Antarctic ice sheets During the Glacial Cycles, Quat. Sci. Rev., 21, 203–231, 2002.

Mitovia, J. and Wahr, J.: Ice Age Earth Rotation, Annu. Rev. Earth Pl. Sc., 39, 577–616, doi: 10.1146/annurev-earth-040610-133404, 2011.

Sasgen, I., Broeke, M. v. d., Bamber, J. L., Rignot, E., Sandberg-Sørensen, L.,Wouters, B., Martinec, Z., Velicogna, I., and Simonsen, S. B.: Timing and origin of recent regional ice-mass loss in Greenland, Earth Planet. Sci. Lett., 333–334, 293–303, doi:10.1016/j.epsl.2012.03.033, 2012.

Shepherd, A., Ivins, E. R., A, G., Barletta, V. R., Bentley, M. J., Bettadpur, S., Briggs, K. H., Bromwich, D. H., Forsberg, R., Galin, N., Horwath, M., Jacobs, S., Joughin, I., King, M. A., Lenaerts, J. T. M., Li, J., Ligtenberg, S. R. M., Luckman, A., Luthcke, S. B., McMillan, M., Meister, R., Milne, G., Mouginot, J., Muir, A., Nicolas, J. P., Paden, J., Payne, A. J., Pritchard, H., Rignot, E., Rott, H., Sørensen, L. S., Scambos, T. A., Scheuchl, B., Schrama, E. J. O., Smith, B., Sundal, A. V., van Angelen, J. H., van de Berg,W. J., van den Broeke, M. R., Vaughan, D. G., Velicogna, I.,Wahr, J., Whitehouse, P. L., Wingham, D. J., Yi, D., Young, D., and Zwally, H. J.: A Reconciled Estimate of Ice-Sheet Mass Balance, Science, 338, 1183–1189, doi:10.1126/science.1228102, 2012.

Thomas, I. D., King, M. A., Bentley, M. J., Whitehouse, P. L., Penna, N. T., Williams, S. D. P., Riva, R. E. M., Lavallee, D. A., Clarke, P. J., King, E. C., Hindmarsh, R. C. A., and Koivula, H.: Widespread low rates of Antarctic glacial isostatic adjustment revealed by GPS observations, Geophys. Res. Lett., 38, L22 302, doi: 10.1029/2011GL049277, 2011.

Zweck, C. and Huybrechts, P.: Modelling the Northern Hemisphere ice sheet during the last glacial cycle and glaciological sensitivity, J. Geophys. Res., 110, D07 103, 2005.