Accelerated Antarctic ice loss from satellite gravity measurements

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Supplementary Information

1. Forward Modeling

The goal of the forward modeling approach is to construct an estimated mass rate map that agrees with the GRACE map, is consistent with geographical knowledge of likely mass sources, and is free of biases arising from GRACE data limitations and processing procedures. Biases result from the limited range of spherical harmonics, treatment of low-degree harmonics, and both decorrelation and Gaussian filtering. The forward modeling approach has been successfully applied in several GRACE studies of polar ice sheets and mountain glaciers[11,14,16].

To simplify the explanation of the forward modeling approach, we combine Figs. 1, 2, and 4 into Figure S1. The goal is to find a mass rate spatial distribution (Fig. S1b) yielding an apparent rate map (Fig. S1c) close to that observed by GRACE (Fig. S1a). Fig. S1c is determined from Fig. S1b using all features of GRACE data and data processing leading to Fig. S1a.

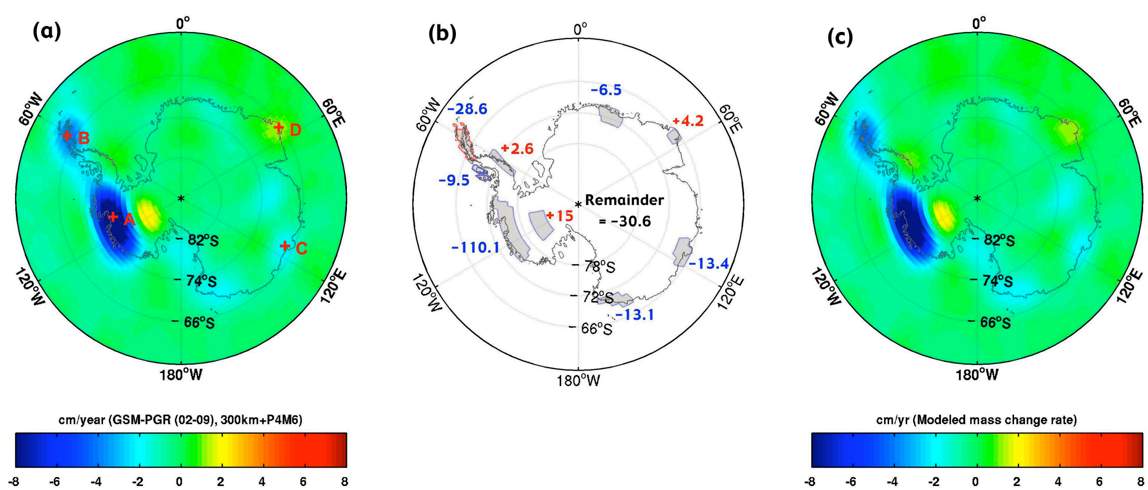

Figure S1. a) GRACE apparent mass rate over Antarctica (units of cm of equivalent water height change per year, cm/yr) after the PGR effect is removed. b) The 9 selected areas (shaded) are used in the forward modeling scheme with mass rates uniformly distributed over each area. The two areas circled by teal and magenta lines are selected for modeling the Antarctic Peninsula. c) Forward modeled apparent mass rate map (cm/yr) that best matches GRACE map in Fig. S1a.

The forward modeling approach employs the following steps

1) We selected 9 regions (shaded in Fig. S1b) where the GRACE map (Fig. S1a) shows prominent signals. In each region defined on a (1° x 1°) grid, a trial mass rate is distributed uniformly.
2) The remainder of the grid over Antarctica (within the area circled by the blue lines in Fig. S2a) retains GRACE mass rates (with only the decorrelation filter applied). Mass rates over the ocean (in areas outside the region circled by red lines in Fig. S2b) also retain GRACE mass rates (with only the decorrelation filter applied). When choosing the remainder of the grid over Antarctica and mass rates over the ocean, areas with evident leakage from the 9 selected regions (based on GRACE observations, Fig. S1a) are excluded. Those grid points (not in the 9 shaded regions, nor in the defined remainder grid over Antarctica and ocean areas) are given a zero rate.
3) The trial mass rate map is expressed in fully normalized spherical harmonics, truncated to degree and order 60, then filtered with the 2-step process (P4M6 + 300km Gaussian) applied to GRACE data. Degree-1 spherical harmonics, representing geocenter motion are not in GRACE solutions, and are therefore excluded. The degree-0 term is set zero, forcing the total mass of the Earth system to be conserved.
4) Model rates and region shapes are adjusted until good agreement with the GRACE map is obtained.
5) Finally, the integrated mass rate for each of the 9 regions (a sum over grid points with cosine of latitude weights over a surrounding region where rates exceed 1 cm/year) is adjusted to agree with the integrated rate from GRACE. This requires multiple trials.

We show in Fig. S1c the model apparent rate map, corresponding to the 9 regional mass sources in Fig. S1b. The total mass rate from the remainder of the grid over Antarctica (within the area circled by the blue lines in Fig. S2a) is ~ – 30.6 Gt/yr, which is computed from simple summation of GRACE mass rates (with decorrelation filtering but not 300 km Gaussian smoothing) with cosine of latitude weights. GRACE total Antarctic mass rate, ~ – 190 Gt/yr is computed as the sum of the 9 regional rates, together with the rate, ~ – 30.6 Gt/yr for the remainder of the grid.

The selection of the 9 modeled regions is based on two main considerations. One is to place them in locations where the GRACE map (Fig. S1a) shows evident signals, and the second is to consider signals are mostly in coastal areas. However, the modeled region south of the ASE is not near the coast. The signal in this area may be from PGR model error, but it is very close to the ASE region where the rate is negative, and by estimating mass rates in both regions we can correct for spatial leakage between the two regions. There are other inland signals above the estimated noise level which we have not included in the model. An example is the region of negative rates between Points D and C. Excluding this and similar inland regions will not strongly affect estimates of either continental total or East Antarctic rates. The largest bias effect is associated with leakage between land and oceans, hence an emphasis on modeling mass rates in coastal regions.

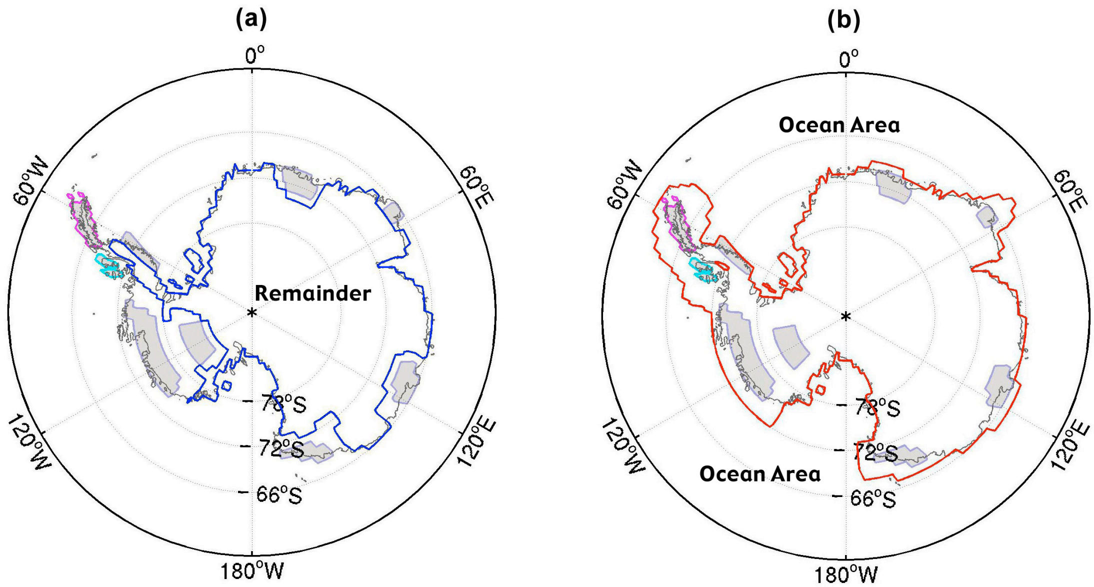

Figure S2. a) Aside from the 9 selected areas (shaded, including the two areas circled by teal and magenta), the remainder of Antarctica as defined by the area circled by the blue line. Mass rates in this area (Remainder) retain those from GRACE measurements (after the decorrelation filter is applied); b) In the forward modeling, mass rates over ocean areas, outside the area circled by red lines, are assigned GRACE values (after just the decorrelation filter is applied).

2. More on PGR Error

We show in Fig. S3 the difference ICE5G[24] minus IJ05[20] expressed as an equivalent surface mass rate. The same 2-step filter (P4M6 + 300km Gaussian smoothing) is applied to both models. The largest difference is south of the ASE, extending to East Antarctica. ICE5G predicts a significantly larger PGR signal (over 2 cm/year after filtering). In most inland regions in East Antarctica, ICE5G also shows larger PGR signals (with difference of ~ 1 cm/year after filtering). In some of the coastal regions, IJ05 predicts slightly larger PGR signal (with negative difference shown in Fig. S3).

The total difference between ICE5G and IJ05 over Antarctica, integrated with cosine of latitude weights when no filter is applied, is about 60 Gt/yr equivalent mass rate. However, PGR model error effects may be much larger than this. As demonstrated by a recent study[23] varied choices of solid Earth parameters and deglaciation models can lead to integrated PGR model error as large as 290 Gt/yr.

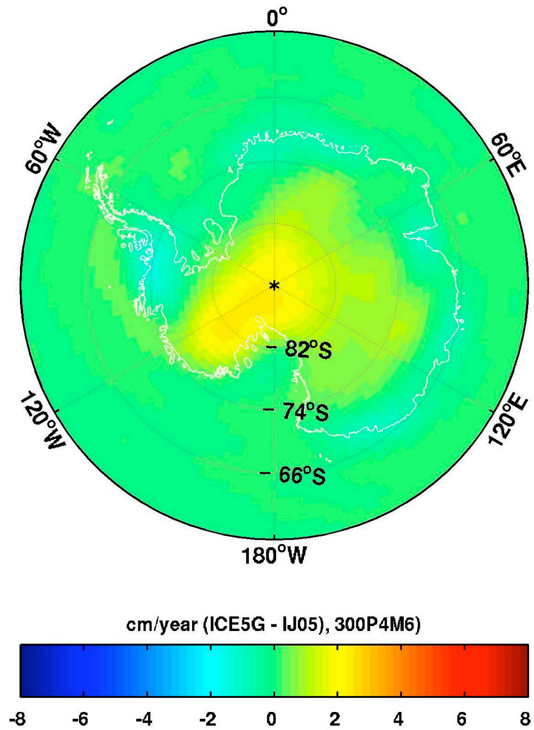

Figure S3. PGR model difference ICE5G minus IJ05, expressed as surface mass rate (equivalent water height rate, cm/year). The 2-step filter (P4M6 + 300km Gaussian) has been applied to the PGR models.

3. Other Error Sources

Atmospheric pressure and barotropic ocean signals are removed in the dealiasing part of GRACE data processing using climate and ocean general circulation models[18]. As a result, over land, GRACE mass change should reflect mainly water storage change (ice and snow in Antarctica) and solid Earth deformation (such as PGR). At long (multi-year) time scales, ocean and atmospheric mass (barometric pressure) variability are expected to be much smaller than ice mass variability, because these fluids cannot accumulate in the same manner as water in its solid forms. However, at shorter time scales, perhaps less than a year, deficiencies in GRACE dealiasing climate models may influence ice rate estimates.

Here we show nonseasonal atmospheric pressure changes taken from GRACE dealiasing data[18] in 4 selected regions (A, B, C, & D) in Fig. S1a corresponding to averages in regions in Fig. S1b. Annual and semiannual changes were removed using a least squares fit. In West Antarctica, ASE (A) and the Antarctic Peninsula (B), interannual atmospheric pressure variability is significantly smaller than GRACE estimates of ice mass change (see Fig. 3). Barometric pressure effects are therefore less of a concern. In East Antarctica, however, error in barometric pressure may have a larger influence on GRACE estimates of ice mass change (see Figs. S4c & S4d). Further study of atmospheric pressure uncertainty and its contribution to GRACE estimates is needed.

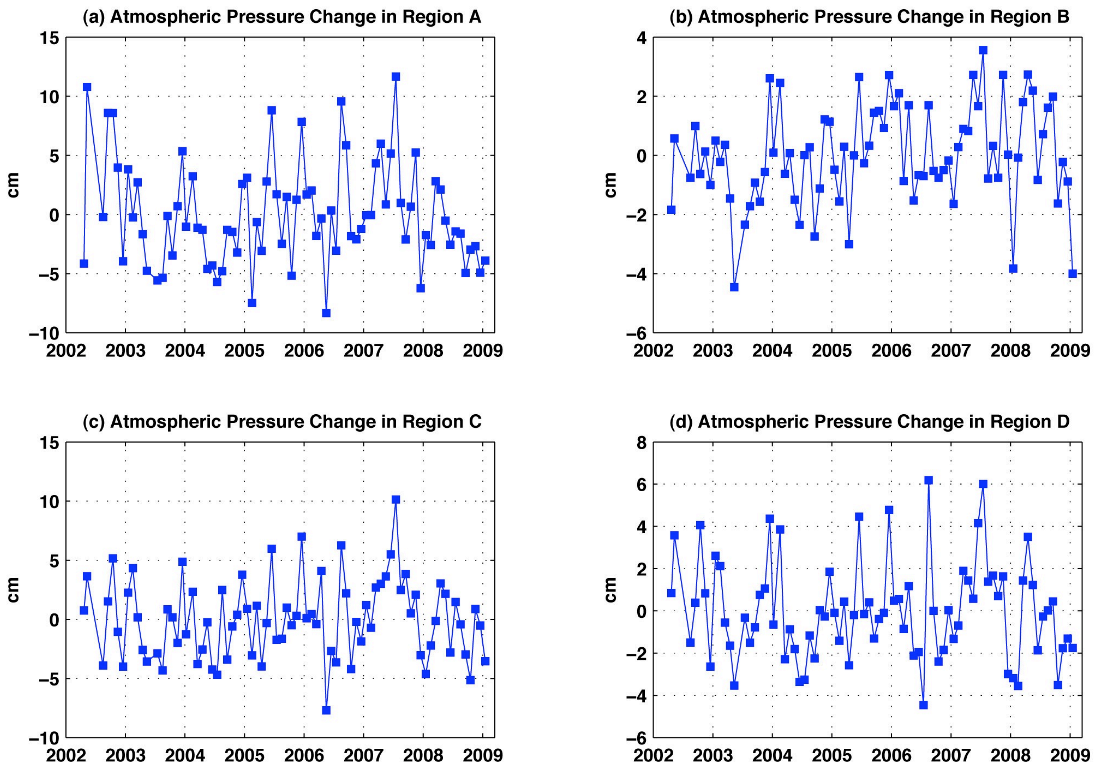

Figure S4. Nonseasonal atmospheric pressure change in the 4 regions (A, B, C, & D) marked in Fig. S1a and corresponding to averages in the regions in Fig. S1b, computed from GRACE dealiasing data. Annual and semiannual changes are removed using a least squares fit.

Measurement errors remaining after corrections and data processing may also affect GRACE estimates. Fairly large differences among different GRACE spherical harmonic solutions (e.g., CSR vs. GFZ[S1] solutions) have been noted, although all solutions are derived from the same satellite range-rate data. Similarly, differences exist between spherical harmonic and localized mascon solutions[7,17]. These differences are not fully understood, and both processing methods and their influences on mass rate estimates remain continuing areas of research.

3. Accelerated Antarctic Ice Loss Rates

To further illustrate our finding of accelerated Antarctic loss rates, we calculate simple estimates of continent-wide mass rates for the two periods 2002-05 and 2006-09. We compute GRACE mass change time series of the 9 modeled regions (by integrating mass rates in the 9 shaded areas on Fig. S1b with cosine of latitude as weighting) and computed mass rates for three periods, 2002-05, 2006-09, and 2002-09 (in similar same way as presented in Fig. 3). If we assume that the leakage effect (not corrected yet) is proportional to the apparent mass rates observed by GRACE, for each region we could use the ratios between mass rates for the entire time span (2002-09) and for the two shorter periods (2002-05, 2006-09) to linearly project the 'true' mass rates for the period 2002-05 and 2006-09 based on the forward modeled mass rate (marked in

Fig. S1b). Based on this simple linear projection and assuming that the remainder of Antarctica (Fig. S2a) retains a constant rate, Antarctic continent-wide values are – 144 ± 58 Gt/yr for 2002-05 and – 220 ± 89 Gt/yr for 2006-09. These compare with – 190 ± 77 Gt/yr for the entire 2002-09 period.

References and Notes:

S1. Flechtner, F., GFZ Level-2 Processing Standards Document For Level-2 Product Release 0004, GRACE 327-743, The GRACE Project, GeoForschungszentrum Potsdam (2007)