Accelerated Antarctic ice loss from satellite gravity measurements

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Accurate quantification of Antarctic ice sheet mass balance and its contribution to global sea level rise remains challenging, because in situ measurements over both space and time are sparse. Satellite remote sensing data of ice elevations and ice motion show significant ice loss (in the range -31 to - 196 Gt/yr[1-4]) in West Antarctica in recent years, while East Antarctic appears to remain in balance or slightly gain mass (with estimated mass rates in the range –4 to 22 Gt/yr[1,2,4]). The Gravity Recovery and Climate Experiment (GRACE) is the first dedicated satellite gravity mission[5], and offers the opportunities for quantifying polar ice sheet mass balance from a different perspective[6,7]. Here we use an extended record of GRACE data spanning the period April 2002 through January 2009, to estimate Antarctic ice mass rates. The new GRACE estimate is -190 ± 77 Gt/yr, with the majority, -132 ± 26 Gt/yr, from West Antarctica, providing independent confirmation of recent estimates of an accelerated rate of loss[4]. In contrast with previous GRACE estimates, the estimated mass rate is -57 ± 52 Gt/yr in East Antarctica, mostly in coastal regions, apparently caused by increased ice loss since 2006.

Antarctic ice mass balance has long been a controversial topic, because of difficulties in estimating it, and because of its importance in understanding global climate and sea level rise. At various times, estimates have disagreed on the sign of the mass balance, as well as its magnitude[8]. Several space-based technologies have become available in the past two decades to improve the estimates. One of these, satellite radar altimetry, suggests a mass rate for the whole continent in the range of – 5 to + 85 Gigatonnes per year (Gt/yr) for the period 1992–2003[9]. This implies a negligible contribution to observed global sea-level rise. Estimates of rates from elevation change (from radar altimetry) are limited by spatial and temporal coverage and by uncertainties in snow density[8]. A second technology, Interferometric Synthetic Aperture Radar (InSAR) indicates that over the past decade, glacial mass discharge exceeds model predictions of snow accumulation. By this method, Antarctic ice loss is estimated to have increased 75% from 1996 to 2006, with 196 ± 92 Gt lost in 2006 alone[4].

A third space-based technique, GRACE satellite observations of gravity change, provides direct mass change estimates at monthly intervals since 2002. Many studies have used GRACE data to estimate Antarctic and Greenland ice mass balance [6,7,10-12]. Spatial resolution of GRACE is limited by its ~460 km altitude, to no better than a few hundred kilometers[10,13,14]. This exceeds the scale of most glacial drainage basins. However estimation techniques that supplement GRACE observations with geographical information of ice sheet and glacier locations[10,14], or directly utilize GRACE Level 1B range-rate data[7,15] can provide better spatial resolution. Examples include mass rate estimates for the Patagonia Ice Fields of South America[16], Graham Land of the Antarctic Peninsula[14] (using GRACE spherical harmonic solutions), and Alaskan mountain glaciers[15].

GRACE estimates of Antarctic mass balance have been variable, ranging from – 80 to – 152 Gt/yr [6,11,17]. The wide range is due in part to uncertainty associated with other geophysical signals in GRACE data, especially post-glacial rebound (PGR). Additional causes include variable time spans analyzed, varied analysis methods, and use of different versions of GRACE products. Still, all GRACE estimates show significant ice loss over the West Antarctic Ice Sheet (WAIS) since 2002, with estimated rates in the range -96 to -148 Gt/yr[6,11,17]. However, over the East Antarctic Ice Sheet (EAIS) there has been uncertainty in the sign of the estimated mass rate, from both GRACE and other remote sensing data[1].

This paper presents new estimates of Antarctic ice mass rates (Fig. 1) using 79 monthly samples of the most recent GRACE release-4 (RL04) spherical harmonic solutions for the period April 2002 to January 2009. RL04 is produced at the Center for Space Research (CSR) of the University of Texas of Austin[18]. With nearly 7 years of data, inter-annual variability is far more apparent, and associated uncertainty in average rates is significantly reduced using the longer time series. There is also better suppression of alias errors[19] associated with ocean tide model deficiencies. Although PGR effects are modeled using the IJ05 model[20], this remains the largest source of continuing uncertainty. Processing of RL04 data is a two step procedure, first removing correlated errors (longitudinal stripes), followed by 300 km Gaussian low-pass filtering. The resulting GRACE Antarctic rate map is in Fig. 1. It shows two distinct regions with negative rates in the Amundsen Sea Embayment (ASE) and in Graham Land of the Antarctic Peninsula (points A and B). The ASE negative rate is the dominant feature for the entire Antarctic continent. Negative rates are also present over the EAIS, especially along the coast in Wilkes Land (point C in Fig. 1) and Victoria Land, although magnitudes are much smaller than in the ASE and Antarctic Peninsula. Positive rates south of the ASE are likely due to underestimated PGR in the IJ05 model[14,21]. A small positive rate is present in Enderby Land (Point D) where an earlier GRACE estimate (+ 80 ± 16 Gt/yr) was so large as to suggest an un-modeled PGR contribution[21]. However, a recent study based on comparisons between predicted PGR models and observed GPS uplift rates suggests that this is not related to PGR[22].

Because atmospheric pressure and barotropic oceanic signals are removed in GRACE data processing[18], we can take variability over the oceans (far enough from land to avoid spatial leakage) as representative of GRACE noise levels. Figure 1 shows ocean mass rates are below 1 cm/year (RMS 0.45 cm/yr for ocean areas between 60°S and 65°S), implying that features identified in Figure 1 are well above the noise. The task now is to quantify mass rates in individual regions, and to estimate a rate for the entire continent.

Mass rates are estimated using a forward-modeling method that has been applied in number of recent studies[11,14,16] (see Methods section for details). This approach accounts for biases associated with the two-step filtering applied (decorrelation and Gaussian), and the limited range of spherical harmonics in RL04. Estimates are derived assuming mass changes concentrated in 9 geographical regions identified in Fig. 2. After this step, an estimate is obtained for the remainder of the continent. By separately estimating the 9 regions with high mass rates, spatial leakage effects are minimized, especially in coastal regions such as the Antarctic Peninsula where much of the variance leaks into the ocean.

Results for individual regions are indicated in Fig. 2. The largest rate is the ASE with -110.1 Gt/yr, followed by the Antarctic Peninsula at -38.1 Gt/yr with the majority (-28.6 Gt/yr) in the northern part (Graham Land) and the rest (-9.5 Gt/yr) from Alexander Island and nearby regions. Wilkes and Victoria Land rates are similar at -13.4 and -13.1 Gt/yr, respectively. The coastal region in Queen Maud Land shows a -6.5 Gt/yr rate. South of the ASE (Fig. 1) mass accumulation is estimated at +15 Gt/yr. Enderby and Palmer Land show accumulation of + 4.2 and +2.6 Gt/yr, respectively. After the 9 regional rates are estimated, the rate for the remainder of Antarctica is found to be – 30.6 Gt/yr, with the majority, – 29.1 Gt/yr from EAIS and – 1.5 Gt/yr from WAIS.

PGR model errors are likely the dominant limitation to Antarctic mass rate estimates[6,23]. PGR models in Antarctica suffer from lack of fundamental data available in Northern Hemisphere regions, including contemporary rates of vertical motion, and geomorphological evidence constraining ice load history. The result is variability among PGR models. The IJ05 model[20] predicts much smaller rates relative to others, such as ICE5G[24-26]. If PGR rates are in fact larger than IJ05, then values in Figure 2 are underestimates of loss rates. In the absence of better knowledge, we take the difference between the IJ05 and ICE5G models[20,24] as an estimate of PGR model error. With this assumption, and considering GRACE errors, our estimate and associated uncertainty for the entire continent is – 190 ± 77 Gt/yr, a rate much larger than previous GRACE estimates. If ICE5G is used in place of IJ05, the estimated rate is still larger, ~ – 250 Gt/yr.

Our new estimate (– 190 ± 77 Gt/yr) agrees well with a recent result (– 196 ± 92 Gt/yr) using InSAR mass fluxes in 2006, combined with snowfall estimates from a regional atmospheric climate model[4]. Acceleration of ice loss in recent years over the entire continent is thus indicated by these two independent studies. However, there are a number of regional differences between the two estimates. For example, our value for the WAIS (– 132 ± 26 Gt/yr) is well below the InSAR flux estimate[4] of – 192 ± 76 Gt/yr. For the EAIS, our estimate is - 57 ± 52 Gt/yr, while the InSAR estimate is far smaller, at -4 ± 61 Gt/yr, more similar to previous GRACE estimates[6,11,17]. Mass loss in the present GRACE estimate is mainly from coastal regions in Wilkes, Victoria, and Queen Maud Lands (Fig. 2). A number of factors may contribute to these regional differences between GRACE and InSAR flux estimates. One may be the PGR model, required for the GRACE estimate, but not necessary in the flux calculation. Apart from this the new GRACE estimate represents an average over nearly 7 years (2002 – 2009). The flux estimate combines InSAR measures of outflow in particular years with model precipitation estimates from a longer period (1980-2004), yielding values for two individual years, 1996 and 2006[4]. The comparison here is with the 2006 value, roughly the GRACE time series midpoint. An examination of the GRACE time series is useful in understanding interannual variability and consequent differences that may arise.

Figure 3 shows surface mass change time series for points A, B, C, and D in Figure 1, computed for 1° x 1° grid regions with large mass rates. Time series are shown after seasonal sinusoids (annual and semiannual) and recognized tide alias error sinusoids (S_2 at 161 days and K_2 at 3.74 years)[27] have been removed by unweighted least squares. Each series provides a representative time history for the location, but amplitudes reflect apparent surface mass change, uncorrected for biases related to filtering and other processing steps. At point A (ASE) an accelerated rate of loss is indicated within the last 3 years (2006 –09), by a greater slope (–11.35 cm/yr) relative to –7.86 cm/yr for 2002-05. Slopes for point B determined from separate sections (2002-05 and 2006-09) are similar to the slope from the entire series.

Time series at points C and D (EAIS) show greater variability in slope for early and late periods. For 2002-05 at point C (Wilkes Land) the slope is near zero, while the 2006-09 slope is negative, consistent with the InSAR 2006 flux estimate[4]. At point D (Enderby Land) there is similar variability among slopes. In this case, the early portion (2002-05) indicates mass accumulation, noted in previous GRACE studies[14,21]. The later period (2006-09) has a near-zero slope, and evidence of increased interannual variability. This indicates that the EAIS, widely considered to be in balance, may actually be out of balance in some regions. As a group, the four time series show that year-to-year variability will lead to varying interpretations when a single year or a short time series is analyzed. This clarifies the importance of continuing to extend time series through operation of GRACE over the next few years, and development of a GRACE follow-on mission.

Our results suggest that over the WAIS (especially the ASE) there is accelerated ice loss since around 2005 and/or 2006, with the EAIS showing correlated changes of the same sign in this period, attributed to increased ice loss over EAIS coastal regions in recent years. Using a simple linear projection for the period 2006-09, Antarctic ice loss rate can be as large as – 220 ± 89 Gt/yr (see Supplementary Information for details). These new GRACE estimates, on average, are consistent with recent InSAR fluxes[4] but, in contrast to previous estimates, they indicate that as a whole, Antarctica may soon be contributing significantly more to global sea level rise. More discussion of the results and analysis of uncertainty and variable ice loss rates are provided in Supplementary Information.

METHODS

GRACE MASS RATE ESTIMATES

Much of the spatial noise in GRACE surface mass change fields (longitudinal stripes) is apparently caused by correlations among estimated spherical harmonics[28], with additional noise increasing with spherical harmonic degree. A two-step filter is applied to reduce these affects. The first step (called P4M6) removes correlated noise by fitting and subtracting a fourth-order polynomial to even and odd coefficient pairs at spherical harmonic orders 6 and above. The second step involves smoothing with a 300-km Gaussian filter. After filtering, a global gridded (1° x 1°) surface mass change field is estimated from each of the 79 solutions, including harmonics up to degree and order 60. Long-term variability of low-degree zonal harmonics (C_{20}, C_{30}, C_{40}) removed during GRACE data processing was restored. At each (1° x 1°) grid point, we fit the mass change time series with a linear trend and seasonal (annual, semiannual) and tidal alias (161-day, and 3.74-year) sinusoidal functions by unweighted least squares. The slope of the linear trend provides an apparent mass rate estimate, whose magnitude is affected by various processing steps including filtering and a limited range of spherical harmonics. The 161-day and 3.74-year terms are aliases due to recognized ocean tide model errors in S_2 and K_2 tides[16]. Both the GRACE orbit configuration and errors in tide models make these aliases relatively strong in Antarctic coastal regions[27]. Fig. 1 shows GRACE mass change rates over Antarctica after PGR effects are removed using the IJ05 model[20]. The same 2-step filter (P4M6 + 300km Gaussian) has been applied to the IJ05 model.

FORWARD MODELING

The GRACE map shown in Fig. 1 gives an apparent mass rate, but does not represent true mass rate for a variety of reasons. Besides filtering and other biases, an important reason is that much of the variance leaks into surrounding areas. This is especially evident in regions with large mass rates near the oceans (where the mass rate is expected to be approximately zero), for example the Antarctic Peninsula. The forward modeling technique developed in earlier studies[11,14,16] provides a simple way to deal with spatial leakage and other biases introduced in the processing. The idea is to identify probable locations of mass change from geographical knowledge of likely sources, to estimate mass rates for these including all processing steps used with the GRACE data, and obtain, in the end, a mass rate map that matches the GRACE data in Figure 1. The estimate is consistent with geography, does not suffer from biases associated with filtering of spherical harmonics, and has spatial resolution somewhat better than the fundamental resolution of GRACE data. We show in Fig. 4 the resulting estimated (model) rate map, giving the 9 regional mass rates in Fig. 2. The details of the modeling technique and related computations are described in Supplementary Information.

UNCERTAINTY ESTIMATES

Mass rate uncertainty is estimated by combining two error sources. One is the conventional uncertainty in a least squares slope estimate from a time series with 79 points, while simultaneously fitting annual, semiannual, and tidal (S_2 and K_2) alias sinusoids. The second is

PGR model error, as we need to remove PGR effect from GRACE measurements before estimating Antarctic ice mass rates. GRACE Antarctic mass balance estimates can be greatly affected by the use of different PGR models[6,23]. Nevertheless, the true PGR model error over the Antarctica is unknown, due to the lack of *in situ* uplift measurements and other data. Here we use the difference between IJ05 and ICE5G model estimates to approximate PGR model error. Squared error for each region is the sum of squares of contributions from least squares fit and PGR model errors. In most cases, PGR error dominates, but there are regions where both models predict very small PGR (e.g. Graham Land and the ASE), suggesting an underestimate of PGR model error. A third error source (not quantified here) is in the GRACE data itself. Spatial filtering reduces this, and the forward modeling approach accounts for biases associated with spatial filtering and truncation of the spherical harmonic expansion. Various GRACE solutions produced by different institutions often show large differences from month to month. However errors in the mass rate estimate are probably below 1 cm/yr, as indicated by the fairly uniform green color in Figure 1, suggesting that PGR model errors are dominant (see Supplementary Information for more on PGR error).

References and Notes:

1. Zwally, J. et al., Mass changes of the Greenland and Antarctic ice sheets and shelves and contributions to sea-level rise: 1992–2002, J. Glaciol. 51, 509 (2005).
2. Rignot, E. and Thomas, R., Mass Balance of Polar Ice Sheets, Science, 297 (5586), 1502 – 1506, DOI: 10.1126/science.1073888 (2002).
3. Thomas, R., et al., Accelerated Sea-Level Rise from West Antarctica, Science, 306 (5694), 255 – 258, DOI: 10.1126/science.1099650 (2004).
4. Rignot, E. et al., Recent Antarctic ice mass loss from radar interferometry and regional climate modeling, Nature Geosci. 1, 106–110, doi:10.1038/ngeo102 (2008).
5. Tapley, B.D., Bettadpur, S., Watkins, M.M., Reigber, C., The Gravity Recovery and Climate Experiment; Mission Overview and Early Results, Geophys. Res. Lett., **31** (9), L09607, 10.1029/2004GL019920 (2004).
6. Velicogna, I., Wahr, J., Measurements of Time-Variable Gravity Show Mass Loss in Antarctica, Science 311, DOI: 10.1126/science.1123785 (2006).
7. Luthcke, S.B., Zwally, H.J., Abdalati, W., Rowlands, D.D., Ray, R.D., Nerem, R.S., Lemoine, F.G., McCarthy, J.J., and Chinn, D.S., Recent Greenland Ice Mass Loss by Drainage System from Satellite Gravity Observations. Science, 314:1286–1289, doi:10.1126/science.1130776. (2006).
8. Shepherd, A. & Wingham, D., Recent sea-level contributions of the Antarctic and Greenland Ice Sheets. Science 315, 1529–1532 (2007).
9. Davis, C.H., Li, Y., McConnell, J.R., Frey, M.M., Hanna, E., Snowfall-Driven Growth in East Antarctic Ice Sheet Mitigates Recent Sea-Level Rise, Science 308, 1898 (2005).

10. Chen, J.L., Wilson, C.R., Tapley, B.D., Satellite Gravity Measurements Confirm Accelerated Melting of Greenland Ice Sheet, Science, 313, DOI: 10.1126/science.1129007 (2006).
11. Ramillien, G., Lombard, A., Cazenave, A., Ivins, E. R., Llubes, M., Remy, F., and Biancale, R., Interannual variations of the mass balance of the Antarctica and Greenland ice sheets from GRACE Global and Planetary Change, Vol. 53, Issue 3, 198-208 (2006).
12. Horwath, M. and Dietrich, R., Signal and error in mass change inferences from GRACE: the case of Antarctica. Geophys. J. Intern., 177, 849–864, doi:10.1111/j.1365-246X.2009.04139.x (2009).
13. Wahr, J., Swenson, S., Zlotnicki, V., Velicogna, I., Time-Variable Gravity from GRACE: First Results, Geophys. Res. Lett., **31**, L11501, doi:10.1029/2004GL019779 (2004).
14. Chen, J.L., Wilson, C.R., Tapley, B.D., Blankenship, D.D., Young, D., Antarctic regional ice loss rates from GRACE. Earth and Planetary Science Letters, 266:140–148, doi:10.1016/j.epsl.2007.10.057 (2008).
15. Arendt, AA, Luthcke SB, Larsen CF, Abdalati W, Krabill, WB, Beedle MJ, Validation of high-resolution GRACE mascon estimates of glacier mass changes in the St. Elias Mountains, Alaska, USA, using aircraft laser altimetry. J. Glaciology, 54, 188, 778-787 (2008).
16. Chen, J.L., Wilson, C.R., Tapley, B.D., Blankenship, D.D., Ivins, E.R., Patagonia Icefield melting observed by Gravity Recovery and Climate Experiment (GRACE). Geophysical Research Letters, 34 (22) L22501, doi:10.1029/2007GL031871 (2007).
17. Luthcke, S.B., W., Rowlands, D.D., Arent, A., McCarthy, J.J., Zwally, H.J., Lemoine, F.G., Boy, J.P., GRACE observations of land ice evolution, Proceedings of the 2008 GRACE Science Team Meeting, page 617 – 631, The GRACE Project, Center for Space Research, University of Texas at Austin (2008).
18. Bettadpur, S., Level-2 Gravity Field Product User Handbook, GRACE 327-734, The GRACE Project, Center for Space Research, University of Texas at Austin (2007).
19. Ray, R.D., Rowlands, D.D., and Egbert, G.D., Tidal Models in a New Era of Satellite Gravimetry, Space Science Reviews, 108:271–282 (2003).
20. Ivins, E., James, T.S., Antarctic glacial isostatic adjustment: a new assessment, Antarctic Science 17, 541-553, DOI: 10.1017/S0954102005002968 (2005).
21. Chen, J.L., Wilson, C.R., Blankenship, D.D., Tapley, B.D., Antarctic Mass Change Rates From GRACE, Geophys. Res. Lett., 33, L11502, doi:10.1029/2006GL026369 (2006).
22. Tregoning, P., Ramillien, G., McQueen, H., and Zwartz, D., Glacial isostatic adjustment and nonstationary signals observed by GRACE. J. of Geophys. Res., 114, B06406, doi:10.1029/2008JB006161 (2009).
23. Barletta, V.R., Sabadini, R., Bordoni, A., Isolating the PGR signal in the GRACE data: impact on mass balance estimates in Antarctica and Greenland, Geophys. J. Int., 172, 18–30 (2008).

24. Paulson, A., Zhong, S., and Wahr, J., Limitations on the inversion for mantle viscosity from postglacial rebound. Geophysical Journal International, 168:1195–1209, doi:10.1111/j.1365-246X.2006.03222.x (2007).
25. Peltier, W.R., Global Glacial Isostasy and the Surface of the Ice-Age Earth: The ICE-5G (VM2) Model and GRACE, Invited Paper, Annual Review of Earth and Planetary Science, 32, 111-149 (2004).
26. Peltier, W.R., Closure of the budget of global sea level rise over the GRACE era: The importance and magnitudes of the required corrections for global isostatic adjustment. Quart. Sci. Rev. 28:1658-74 (2009).
27. Chen, J.L., Wilson, C.R., and Seo, K.-W., S_2 tide aliasing in GRACE time-variable gravity solutions. Journal of Geodesy, pp. 66, doi:10.1007/s00190-008-0282-1 (2008).
28. Swenson, S. and Wahr, J., Post-processing removal of correlated errors in GRACE data. Geophysical Research Letters, 33, L8402, doi:10.1029/2005GL025285 (2006).

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Figure Captions

Figure 1. GRACE mass rate over Antarctica (units of cm of equivalent water height change per year, cm/yr) after the PGR effect is removed. Time series from four grid points (A, B, C, and D) are selected for analysis.

Figure 2. The 9 selected areas (shaded) used in the forward modeling scheme with mass rates (in units of Gt/yr) uniformly distributed over each area. Mass rates are adjusted until the simulated map (Fig. 4) matches the GRACE observation (Fig. 1). Finally, regional rates are adjusted to agree with area-integrated values from Figure 1.

Figure 3 a, b, c, and d. GRACE apparent surface mass time series (in blue curves with square markers) from 79 RL04 gravity solutions at the 4 respective locations A-D in Fig. 1. PGR effects (IJ05 model) are removed from all time series. Red lines are slopes estimated from the entire time series, while cyan and green lines are slopes determined for early (2002-05) and late (2006-09 (06-09) periods.

Figure 4. Forward modeled mass change rate map (cm/yr) computed based on the 9 mass rates from Fig. 2. GRACE results are used for the remainder of Antarctica and ocean areas (see Supplementary Information for details).

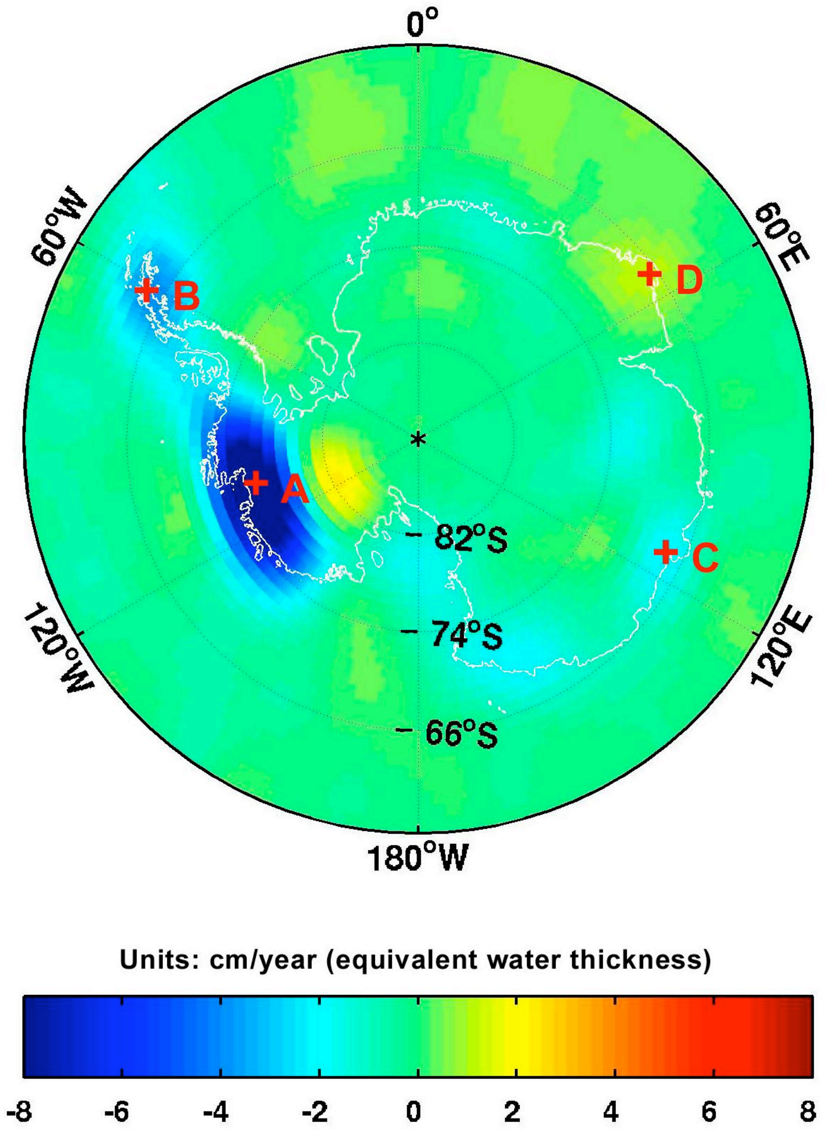
0°
60°W
60°E
B
D
A
C
82°S
74°S
66°S
120°W
120°E
180°W
Units: cm/year (equivalent water thickness)
-8
-6
-4
-2
0
2
4
6
8

Figure 1

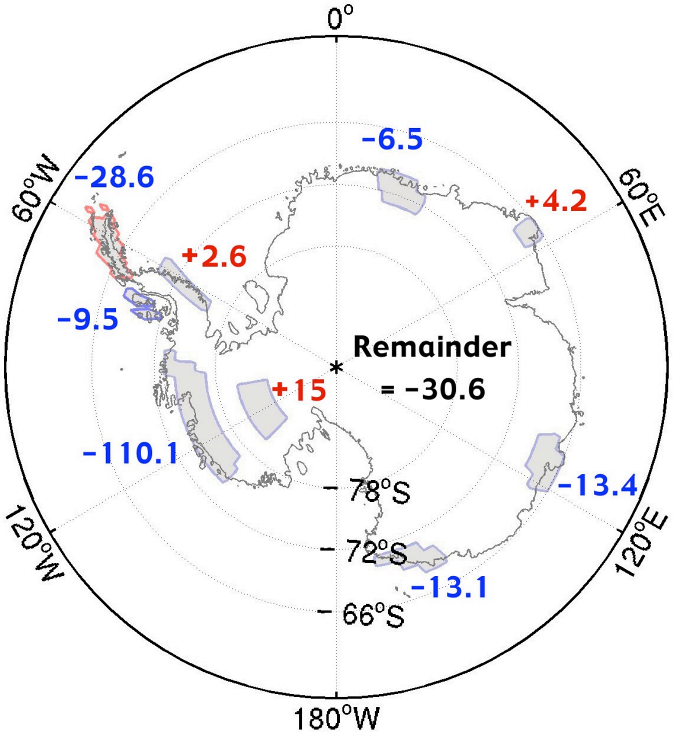
0°
60°W
60°E
120°W
120°E
180°W
78°S
72°S
66°S
-6.5
-28.6
+4.2
+2.6
-9.5
Remainder
= -30.6
+15
-110.1
-13.4
-13.1

Figure 2

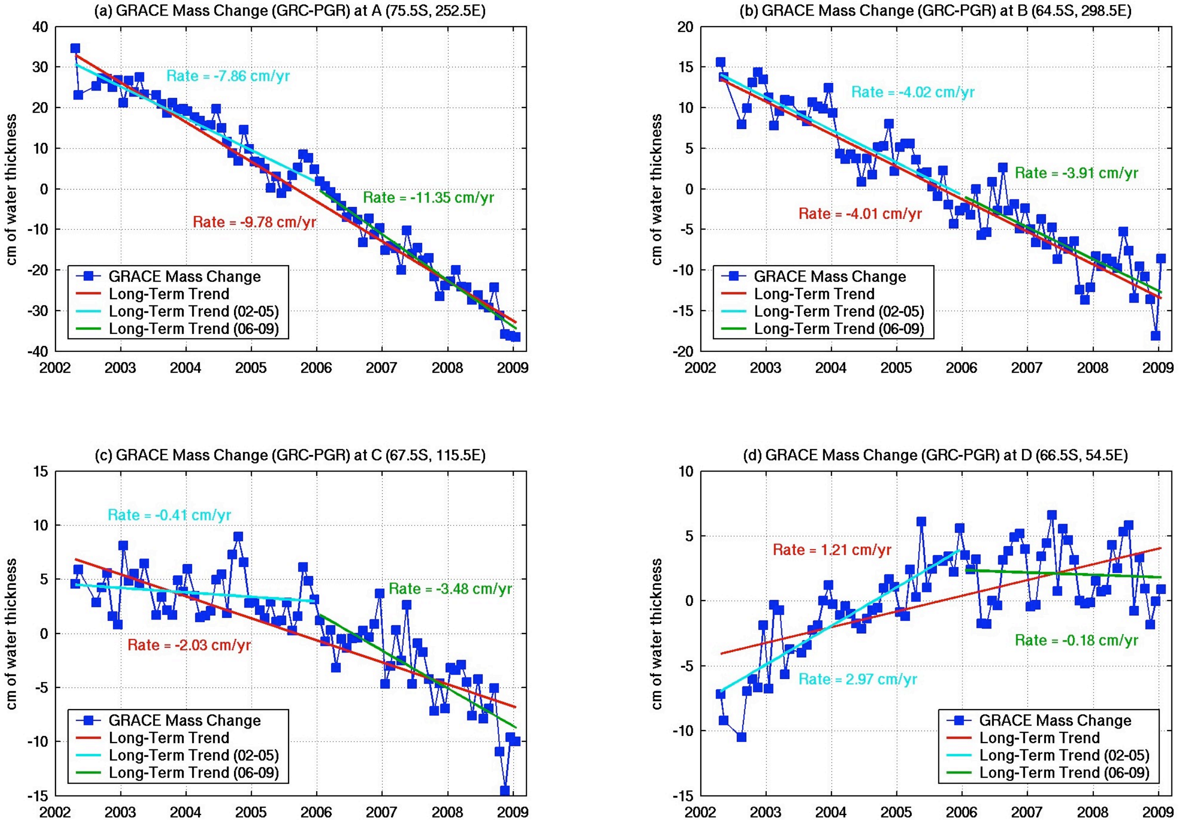
(a) GRACE Mass Change (GRC-PGR) at A (75.5S, 252.5E)
Rate = -7.86 cm/yr
Rate = -11.35 cm/yr
Rate = -9.78 cm/yr
(b) GRACE Mass Change (GRC-PGR) at B (64.5S, 298.5E)
Rate = -4.02 cm/yr
Rate = -3.91 cm/yr
Rate = -4.01 cm/yr
(c) GRACE Mass Change (GRC-PGR) at C (67.5S, 115.5E)
Rate = -0.41 cm/yr
Rate = -3.48 cm/yr
Rate = -2.03 cm/yr
(d) GRACE Mass Change (GRC-PGR) at D (66.5S, 54.5E)
Rate = 1.21 cm/yr
Rate = -0.18 cm/yr
Rate = 2.97 cm/yr
cm of water thickness
GRACE Mass Change
Long-Term Trend
Long-Term Trend (02-05)
Long-Term Trend (06-09)
2002
2003
2004
2005
2006
2007
2008
2009

Figure 3

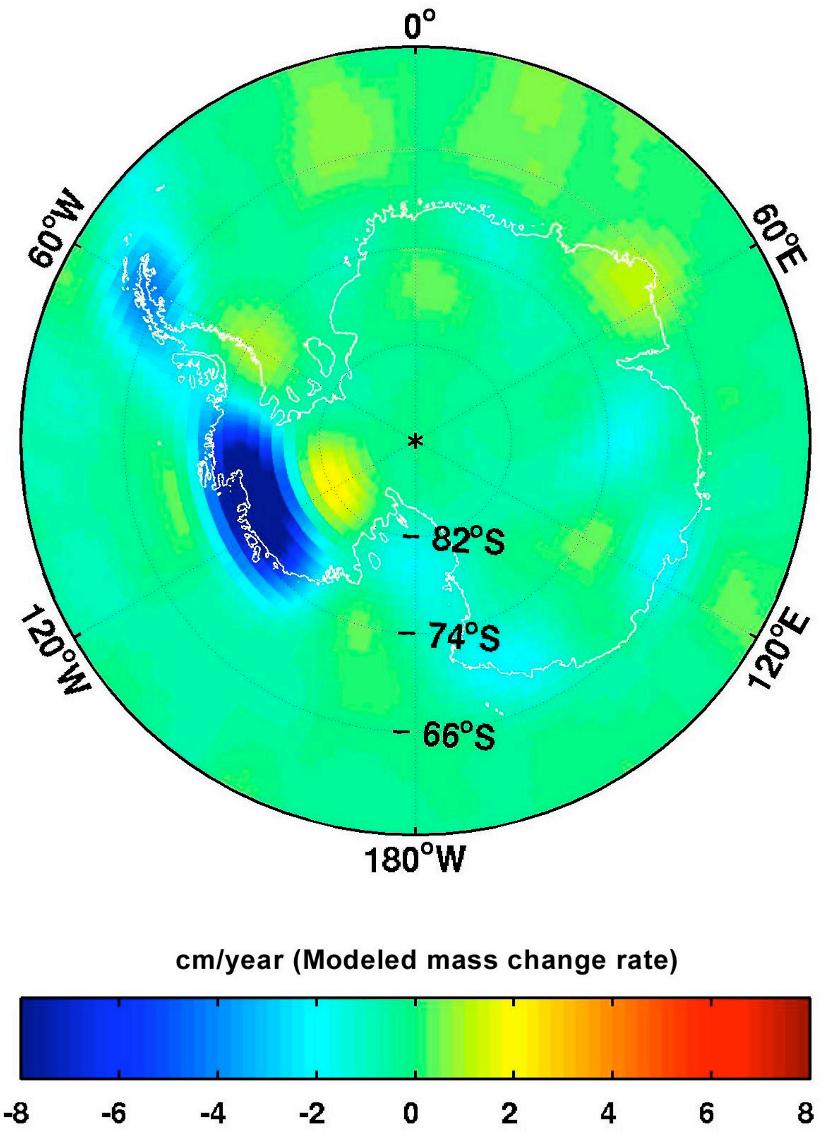
0°
60°W
60°E
120°W
120°E
180°W
82°S
74°S
66°S
cm/year (Modeled mass change rate)
-8
-6
-4
-2
0
2
4
6
8

Figure 4