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Antarctic mass rates from GRACE

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[1] We estimate mass trends over Antarctica using gravity variations observed by the Gravity Recovery and Climate Experiment (GRACE) satellite mission during its first 3.5 years (April 2002–November 2005). An image of surface mass trends is constructed from $1^\circ \times 1^\circ$ pixels over the entire continent, and shows two prominent features, a region of mass loss along the coast of West Antarctica, and one of accumulation in East Antarctica. After adjusting for bias due to smoothing and to GRACE's limited spatial resolution, and removing post glacial rebound (PGR) effects, the rate in West Antarctica is -77 ± 14 km^3/year, similar to a recent estimate of ice mass loss from satellite altimetry and remote sensing data. The prominent East Antarctic feature in the Enderby Land region has a rate of $+80 \pm 16$ km^3/year. Published snow/ice mass rates from remote sensing measurements indicate approximate ice mass balance in this region, suggesting that this feature is either from unquantified snow accumulation in this region or more likely due to unmodeled PGR. **Citation:** Chen, J. L., C. R. Wilson, D. D. Blankenship, and B. D. Tapley (2006), Antarctic mass rates from GRACE, *Geophys. Res. Lett.*, *33*, L11502, doi:10.1029/2006GL026369.

1. Introduction

[2] Assessment of Antarctic mass balance is an essential element in understanding past and present changes in global mean sea level and climate, and in understanding present variations in the global hydrological cycle, ocean temperature, salinity, ocean general circulation, atmospheric dynamics, and other problems. Measurements of Antarctic mass balance derived from observations from the Gravity Recovery and Climate Experiment (GRACE) mission, in the present study, reflect mainly changes in storage of ice/snow mass on the continent, and response of the crust and mantle to changing ice loads in the past. The two contributions are likely to be comparable in size. The effect of past ice load changes is predominantly to produce contemporary vertical motion of the crust, Post Glacial Rebound (PGR). Published models of PGR, from estimated ice load histories and assumed lithosphere and mantle properties are available for the entire globe [e.g., *Peltier*, 2004] and for the Antarctic continent [*Ivins and James*, 2005].

[3] There are also published estimates of contemporary snow/ice mass changes over Antarctica. Continental scale averages are difficult to obtain because in situ observations are sparse, and because imbalance between accumulation and discharge within individual catchment basins may be quite variable. The perspective from space is better suited to regional scale estimates. We use recent analyses by *Rignot and Thomas* [2002] and *Thomas et al.* [2004] based on satellite altimetry, InSAR, and GPS data. These studies provide balance estimates for many of the major Antarctic glaciers.

[4] GRACE was launched in March 2002, and has provided monthly measures of Earth gravity changes with unprecedented accuracy [*Tapley et al.*, 2004a]. Mission operations have been recently extended until early 2010, promising a time series of considerable length. GRACE gravity field changes interpreted as surface mass redistribution have an accuracy of ~1.5 cm equivalent water layer change at spatial scales greater than about 800 km [*Wahr et al.*, 2004]. Of greatest interest are estimates of terrestrial water storage change [e.g., *Wahr et al.*, 2004; *Tapley et al.*, 2004b], snow/ice sheet mass variation in polar regions [e.g., *Velicogna and Wahr*, 2005], and oceanic mass change [e.g., *Chambers et al.*, 2004]. In the first few years of the GRACE mission, the focus has been on seasonal water or ice mass changes in large regions, such as major river basins, continental scale ice sheets, or the entire ocean. As longer time series have become available, other studies have become possible. An example is the work of *Velicogna and Wahr* [2006], which estimates an average snow/ice rate for the entire Antarctic continent, of -152 ± 80 km^3/year, from the first 3 years of GRACE data. We examine a similar topic in this study (at regional scale).

[5] We examine GRACE data for the 3.5-year period April 2002 through November 2005 and construct an image of mass rate for 1×1 degree pixels for the entire continent. The image (Figure 1) shows a prominent region of mass loss in the Amundsen Sea Embayment in West Antarctica, where snow/ice losses have been independently estimated by remote sensing [*Rignot and Thomas*, 2002; *Thomas et al.*, 2004]. A prominent positive rate (accumulation) is observed in East Antarctica. Adjustments must be made for spatial leakage of variance due to the limited range of spherical harmonics (SH) available, and smoothing applied to suppress noise in high degree and order SH coefficients. Although limited spatial resolution makes it difficult to assess small regions, like coastal West Antarctica, numerical simulations permit estimates of leakage effects, and provide a way to approximately remove related biases.

2. Data Processing and Results

2.1. GRACE Data

[6] 40 approximately monthly average GRACE gravity solutions are provided by the Center for Space Research, University of Texas at Austin. These are fully normalized SH coefficients to degree and order 120, constrained by an empirical power law (a scaled Kaula's rule) [*Bettadpur*,

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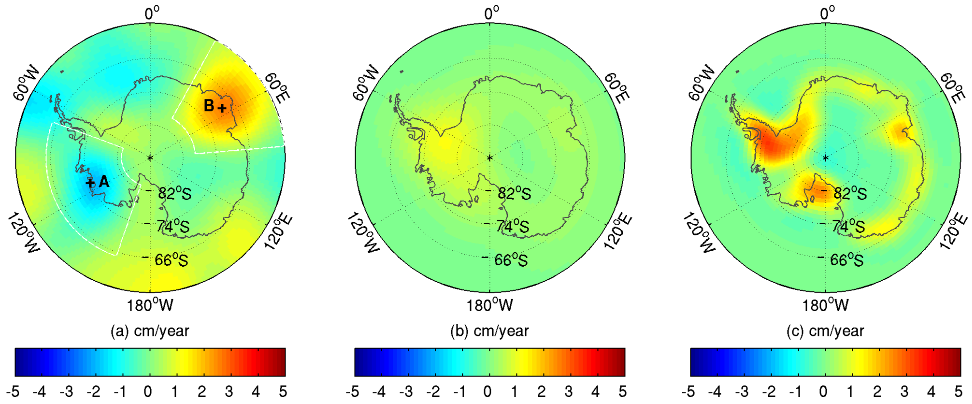

Figure 1. (a) Antarctic long-term mass change rates (in units of cm of equivalent water height change per year, cm/yr) observed by GRACE; (b) IJ05 predicted apparent mass change rates from PGR with 800 km Gaussian smoothing; and (c) IJ05 predicted apparent mass change rates from PGR without smoothing.

2004], which stabilizes the solutions at high degrees and orders. The 40 solutions cover the period April 2002 to November 2005, but poor data quality results in a few missing months (see *Bettadpur* [2003] for details of GRACE data processing). To minimize spatial noise, we apply Gaussian smoothing with an 800 km radius based on the analysis by *Chen et al.* [2005]. To simplify computations, solutions are truncated at SH degree and order 60, and the degree-2 zonal harmonic (C20) is excluded, due to apparently high noise level in the release-1 data. The mean of the 40 solutions is removed to obtain time series of gravity field variations.

2.2. Mass Rate Estimates

[7] Global monthly surface mass time series are computed on a 1° × 1° grid from the 40 monthly solutions. These time series mainly reflect snow/ice mass changes over ice sheets, unmodeled mass changes, errors in GRACE measurements, and errors in atmospheric, tide and ocean mass redistribution estimates that have been removed in GRACE data processing. At each grid point, we use unweighted least squares to first fit annual and semiannual sinusoids and then a linear trend. Figure 1 shows the map of linear rates, displaying two prominent features, mass loss (negative rate) centered along the coast of West Antarctica, and accumulation (positive rate) centered inland near the coast of East Antarctica. To examine these in more detail, we select two grid points, A (74.5°S, 249.5°E) and B (68.5°S, 54.5°E) (both marked in Figure 1), and show their time series in Figures 2a and 2b, respectively, with seasonal terms and linear trends retained. Time series for both A and B show steady change with relatively small seasonal variations superimposed. In contrast, GRACE time series for most major rivers basins show dominantly seasonal variations with small trends [e.g., *Wahr et al.*, 2004]. At point A, the rate estimate is −1.90 ± 0.20 cm/year (in equivalent water height change), while at point B, the rate is +2.59 ± 0.24 cm/year.

[8] Grid point time series represent mainly the sum of snow/ice mass changes and PGR effects, and to separately estimate one of these requires a model of the other. We focus first on estimating contemporary snow/ice mass changes by adopting a model for PGR, based on the IJ05 ice history model [*Ivins and James*, 2005]. Ivins and James show that PGR is strongly influenced by assumptions about recent changes in ice loading rates, as well as critical material properties of lithospheric thickness and mantle viscosity. A PGR model based on a lithosphere thickness of 100 km, lower mantle viscosity of 4.0 × 10^{22} Pa s, and upper mantle viscosity of 5.0 × 10^{20} Pa s. was provided by E. Ivins (personal communication, 2006). The model, in the form of Stokes coefficient rates, is converted to 'apparent' surface mass change. To be consistent with GRACE data, IJ05 rates are computed with the same 800 km Gaussian smoothing, truncation at degree and order 60, and removal of C20. Figure 1b shows the map of IJ05-predicted mass rates. For comparison, Figure 1c shows the map of IJ05-predicted PGR mass rates when no smoothing is applied.

[9] Figure 3a shows GRACE mass change rates over Antarctica after IJ05 predictions (Figure 1b) are subtracted. The mass loss and accumulation in the West and East

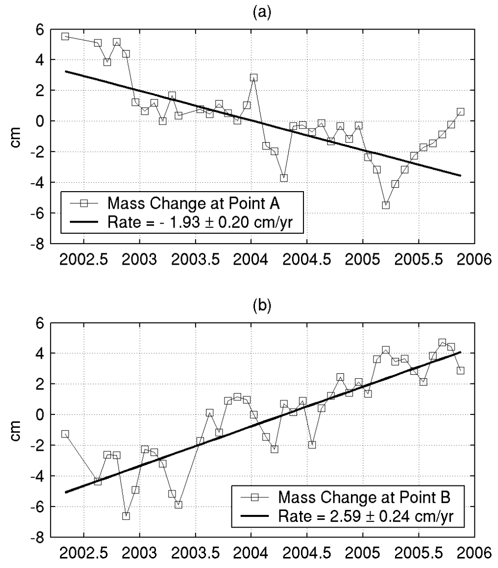

Figure 2. (a) GRACE observed mass changes at selected grid points A in West Antarctica (marked on Figure 1), with the trend estimated from unweighted least squares fit, and (b) GRACE observed mass changes at location B in East Antarctica.

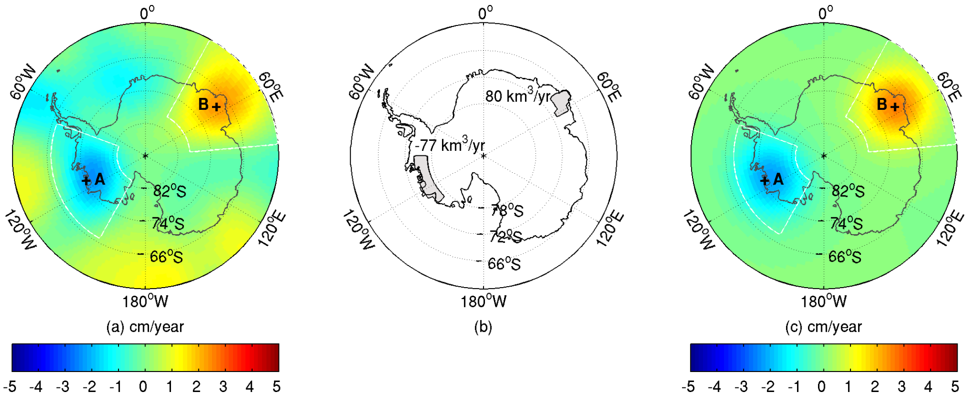

Figure 3. (a) GRACE observed snow/ice mass change rates (in units of cm/yr) over the Antarctica after PGR effects have been removed using the IJ05 model, with 800 km Gaussian smoothing. (b) Two regions (shaded) along and east and west coasts of Antarctica are chosen to simulate leakage effects. (c) Simulated long-term mass rates along west and east coasts of Antarctica using the same smoothing and truncation as in Figure 3a.

Antarctica become more evident after the PGR effects are removed. A raw GRACE estimate of mass loss rate in the circled region in West Antarctica (Figure 3a) is a sum over grid points using a cosine (latitude) weighting (i.e., the true area of each grid box). The result is about −50 ± 9 km^3/year. In East Antarctica a similar summation over the circled area provides a raw estimate of about +64 ± 13 km^3/year. Uncertainties in raw estimates are determined from standard deviations of residuals in the least squares fits at each grid point, and omit GRACE measurement error and PGR model uncertainties. In addition, both estimates are biased (low) due to leakage of variance and the applied smoothing, and this problem is addressed below. As discussed by *Ivins and James* [2005] and implied below, PGR model uncertainties may be large. GRACE errors are not likely to contribute more than several percent to uncertainty in rates, but uncertainties associated with the short time series contribute considerably more as demonstrated below.

2.3. Numerical Simulation of Bias

[10] Numerical simulations are used to quantify biases in the raw GRACE estimates. The simulations require three steps. First, we place time variable mass anomalies in the two shaded small areas (marked in Figure 3b) along the coast of West and East Antarctica. Total mass rate is the important variable, and because of limited spatial resolution, details of the shape and size of the two areas is not critical. At each grid point, we construct a linear mass load time series sampled at epochs of the 40 GRACE solutions. Outside the two areas, simulated mass change is zero. Second, we convert surface mass fields (40 monthly fields on 1° × 1° grids) into time-variable fully normalized Stokes coefficients to degree and order 100. Third, we replicate procedures used to transform GRACE data to surface mass changes, including truncation of Stokes coefficients at degree and order 60, excluding C20, and applying 800 km Gaussian smoothing. Degree-1 coefficients C10, C11, and S11, associated with geocenter motion, are also excluded, as these terms are not available in GRACE gravity fields [*Bettadpur*, 2003].

[11] In simulations for West Antarctica, after trial and error to match GRACE, we set the mass rate to −77 km^3/year, distributed uniformly over the area shown. The equivalent single grid point mass change is ∼−20 cm/year in an area of about 378,440 km^2. As shown in Figure 3c, the magnitude (∼2–3 cm/year) and the geographical pattern closely resemble the GRACE feature in West Antarctica after removing PGR effects, and the summation of simulated mass change within the same grid areas (as used in the previous section for GRACE observations) in the West Antarctica is ∼−50 km^3/year, the same as the GRACE estimate. We take the value −77 km^3/year as the bias-adjusted rate for West Antarctica. It is reasonably consistent with the rate for glaciers in this region of −72 km^3/year reported by *Rignot and Thomas* [2002]. However, the value is smaller than an updated estimate (∼−94 km^3/year) from a more recent study based on similar data [*Thomas et al.*, 2004]. The last several months of GRACE data (Figure 2a) suggest increased snow accumulation in West Antarctica, and a bias adjusted GRACE rate for West Antarctica excluding the last 5 months of GRACE data is −99 ± 18 km^3/year, more consistent with the updated estimate from *Thomas et al.* [2004].

[12] In East Antarctica, again after trial and error to find a good match with GRACE, we set the rate in the simulations at +80 km^3/year. equivalent to a point-wise mass increase of ∼+41 cm/year (over an area of ∼194,640 km^2). The simulated results again match GRACE observations, whether or not estimated PGR effects are removed. GRACE results in the East Antarctica are quite different from *Rignot and Thomas* [2002] or *Thomas et al.* [2004] ice mass rate estimates, which indicate that accumulation and loss are nearly balanced over the year in this region. This mass accumulation feature is so prominent, and unlikely attributed to GRACE measurement errors. In addition, if we exclude the first point in the time series shown in Figure 2b, which is normally regarded as a bad solution (April/May 2002), the increasing trend in the Enderby Land region is surprisingly steady (with virtually no notable seasonal variability). Here are two hypotheses: 1) this accumulation is caused by significant snow precipitation in the region in the last 3.5 years, which is mostly missed (not included) in previous studies [*Rignot and Thomas*, 2002; *Thomas et al.*, 2004], although historical seasonal accumulation is small in this region, and 2) this steady mass accumulation is (more likely) from unmodeled PGR, implying that the PGR model

Table 1. Long-Term Mass Change Rates (in km^3/yr) in West (W.) and East (E.) Antarctica Estimated From Numerical Simulations in 3 Cases When Using 500 km, 800 km, and 1000 km Gaussian Smoothings

Cases	W. Antarctica	E. Antarctica
500 km	-85 ± 21	$+88 \pm 23$
800 km	-77 ± 14	$+80 \pm 16$
1000 km	-73 ± 14	$+77 \pm 15$
Average	-78 ± 10	$+82 \pm 11$

in Figure 1c is largely incorrect in East Antarctica. A thorough evaluation of the PGR hypothesis is beyond the scope of the present study, but the discussion by *Ivins and James* [2005] suggests two possible causes. One is that East Antarctica is likely to have a thicker lithosphere and higher mantle viscosity than the average values used to produce Figures 1b or 1c because it is old cratonic material. Another is the demonstration (their Figure 5) that uncertainty in recent changes in ice load rates may affect East Antarctic PGR rates by 100%. A longer record of GRACE data (e.g., with a several more years of data) would provide a more convincing picture of what may really cause this significant and steady mass accumulation.

[13] Table 1 summarizes GRACE-estimated mass change rates in West and East Antarctica using different spatial smoothing radii of 500 km, 800 km, and 1000 km. Clearly, the choice of 800 km is not critical in our GRACE estimates, and other reasonable choices (500 and 1000 km) alter estimates by less than 10 percent.

3. Conclusions

[14] After adjusting for bias due to smoothing and a limited range of SH coefficients and removing PGR contributions using the IJ05 ice model, the GRACE snow/ice mass rate in West Antarctica is estimated at $\sim -77 \pm 14$ km^3/year (to -99 ± 18 excluding the last 5 months of GRACE), consistent with the assessments of $\sim -72 \pm 12$ km^3/year from *Rignot and Thomas* [2002] (or -94 km^3/year of *Thomas et al.* [2004]). In East Antarctica the estimate of $+80 \pm 16$ km^3/year is not accounted for by seasonal accumulation (based on available assessments), and is not a feature of the IJ05 PGR model, nor of others we have examined. This steady mass accumulation could be either from unquantified snow accumulation in the region in recent years or more likely from unmodeled PGR signal.

[15] The calculations here show that estimates of Antarctic snow/ice mass rates from GRACE data are completely dependent on the adopted PGR model, with uncertainties that might be on the order of 100% Our estimate of -99 or -77 km^3/year mass loss in West Antarctica is consistent with that of *Velicogna and Wahr* [2006] of -148 km^3/year, given the large PGR uncertainty and that here we only compute the mass loss in the Amundsen Sea Embayment in West Antarctica. The considerable uncertainty in PGR models constrains the ability of GRACE to provide confident estimates of snow/ice mass loss at present. Hopefully, GRACE can be used globally to assess and improve PGR models, and eventually provide firmer estimates of ice mass rates in Antarctica and elsewhere. Our analysis suggests that the large uncertainty of GRACE C20 estimates (in Release 01) has significant effects on GRACE estimated Antarctic mass change. Improved estimates of C20 from GRACE or other independent techniques appear important for accurately quantifying Antarctic mass balance using GRACE data.

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