Antarctic Regional Ice Loss Rates From GRACE

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Abstract

Using recent improved time-variable gravity solutions from the Gravity Recovery and Climate Experiment (GRACE), we estimate rates of Antarctic ice mass change for the period January 2003 through September 2006. Combined improvements in data and filtering techniques allow observation of ice loss in the northern Antarctic Peninsula (AP) and along the coast of the west and central Amundsen Sea Embayment (ASE) in West Antarctica. There is also evidence of ice loss along the coast near the Stancomb-Wills (STA) and Jutulstraumen (JUT) glaciers in Queen Maud Land. Apparent rates are adjusted for influences of limited spatial resolution, filtering, and estimated postglacial rebound (PGR) to obtain ice loss rates for the northern AP, coastal ASE, and STA/JUT of –28.8 ± 7.9, – 81 ± 17, and – 16.7 ± 9.7 km^3/year, respectively. This is the first estimate for the northern AP from satellite gravity data. The ASE estimate (– 81 ± 17 km^3/year) is consistent with a previous value (– 77 ± 14 km^3/year) using an earlier GRACE data release. These results indicate significant improvement in GRACE data quality, increased spatial resolution, and applicability of GRACE data to a wider class of problems than previously possible.

Keywords: Antarctica, Ice Loss, Antarctic Peninsula, Satellite Gravimetry, GRACE, Gravity Change.

1. Introduction

Quantifying Antarctic ice sheet mass balance is a key issue in understanding changes in global mean sea level, climate, the global hydrological cycle, ocean temperature, salinity, and general circulation, atmospheric dynamics, and other problems. For some time, it has been uncertain whether Antarctic ice mass is growing, shrinking, or stable (Bentley, 1993). For example, the glaciological evidence examined by Bentley and Giovinetto (1990) suggested slow growth, while oceanographic evidence (e.g., Southern ocean temperature, salinity, and oxygen isotope ratios) indicated net ice mass loss (Jacobs et al., 1992). There are few *in situ* measurements in both space and time, but airborne and satellite remote sensing measurements have been useful in regional ice balance studies, though their temporal coverage is limited (e.g., Rignot and Thomas, 2002; Thomas et al., 2004; Zwally et al., 2006).

West Antarctic glaciers, especially along the coast of the Amundsen Sea Embayment (ASE) are targets of intensive study (e.g., Rignot and Thomas, 2002; Shepherd et al., 2004; Joughin and Tulaczyk, 2002; Chen et al., 2006a). Thomas et al. (2004) using satellite altimetry, InSAR and GPS data suggest an average mass rate of – 94 km^3/year in west and central ASE glaciers. This estimate was later independently confirmed by satellite gravity measurements from the Gravity Recovery And Climate Experiment (GRACE) (Chen et al., 2006a). Using the same GRACE data, Velicogna and Wahr (2006) estimate an ice mass rate for the entire Antarctic continent of ~ – 152 ± 80 km^3/year. They estimate that almost all (~ – 148 ± 21 km^3/year) may come from West Antarctica, but this is highly dependent on an uncertain but probably large postglacial rebound (PGR) effect in West Antarctica. GRACE data measure the sum of ice mass change and PGR, which together show a positive rate over the entire Antarctic continent (Velicogna and Wahr, 2006).

The Antarctic Peninsula (AP) has greater similarity to subpolar glacial systems (such as coastal Greenland, Svalbard, Patagonia, and Alaska), and is known to be more sensitive to atmospheric warming, than the ice sheets covering the rest of the Antarctic continent (Vaughan, 2006). Among the supporting evidence: Average AP temperature has increased about 2º C in the last 50 years (Vaughan et al., 2001); AP glaciers show frequent evidence of collapse (Scambos et al., 2004); InSAR (Interferometic Synthetic Aperture Radar) (Rignot et al., 2005)) shows ice loss rates of ~ 6.8 ± 0.3 km^3/yr in Wordie Bay, West AP; and most AP glaciers have been in retreat over the past half century (Cook et al., 2005). Quantitative estimates for much of the AP are lacking due to complex geography, steep slopes, and active ice flows, all limiting the use of InSAR and other remote sensing data, such as altimetry.

GRACE has been providing monthly measures of Earth gravity changes since soon after its March 2002 launch (Tapley et al., 2004a). Mission operations have been recently extended, promising a time series that may last 8 years or longer. GRACE data have been used successfully in geophysical problems ranging from continental water storage (e.g., Tapley et al., 2004a; Wahr et al., 2004; Schmidt, et al, 2006), global sea level (e.g., Chambers et al., 2004; Lombard, et al., 2007), polar ice sheet mass balance (e.g., Velicogna and Wahr, 2005, 2006; Ramillien et al., 2006; Chen et al., 2006a, 2006b), and mountain glacier mass balance (e.g., Tamisiea et al., 2005; Chen et al., 2006c). Most published studies have used the first data release (GRACE RL01), providing spatial resolution in the range of 500 km to 1000 km, depending upon data processing details (e.g., Chen et al., 2006a; Wahr et al., 2004).

This study uses recent Release 4 (RL04) GRACE time-variable gravity solutions to assess ice mass rates in several regions of Antarctica, including the Antarctic Peninsula (AP) and ASE in West Antarctica. Long-term ice loss is expected over the AP, especially in the north (Graham Land) (Cook et al., 2005). However, RL01 spatial resolution was not adequate to observe AP rates. RL04 solutions provide substantially improved resolution due to: a new background gravity model (a combination of GGM02C (Tapley et al., 2005) and EGM96 (Lemoine, et al., 1998)); a new semi-diurnal and diurnal ocean tide model (FES2004) (Lefevre et al., 2005); and an updated solid Earth pole tide model based on IERS2003 (McCarthy and Petit, 2003). Ocean pole tide effects are modeled using a self-consistent equilibrium model SCEQ based on satellite altimeter data (Desai, 2002). Details of RL04 data processing standards are documented by Bettadpur (2007b).

2. Data Processing and Results

2.1 RL04 Gravity Solutions

The RL04 data include 43 approximately monthly average fields from January 2003 to September 2006, from the Center for Space Research, University of Texas at Austin. Similar GRACE products are independently produced at GeoForschungsZentrum (GFZ) in Potsdam, Germany. Each monthly field consists of fully normalized spherical harmonic (SH) coefficients to degree and order 60.

2.2 Filtering Methods

High degree and order spherical harmonics of GRACE gravity solutions are dominated by noise, as evidenced by longitudinal stripes in global gravity field maps. The polar orbit of GRACE gives relatively dense ground track coverage near the poles, and there is generally less contamination in Antarctica. A recent study (Swenson and Wahr, 2006) found stripes are associated with correlations among certain SH coefficients. The exact cause is not certain, but stripes are significantly suppressed by removing correlated variations in coefficients. We apply a modified version of the Swenson and Wahr (2006) decorrelation filter to RL04 solutions. For SH order 6 and above, a least squares fit of order 4 polynomial is removed from even and odd coefficient pairs. We call this filter P4M6. Finally, a 300 km Gaussian smoothing (Jekeli,1981) is applied, and the mean of all 43 monthly solutions removed, yielding a time series of gravity field variations.

2.3 GRACE Observed Long-term Mass Rates Over the Antarctic

After filtering, a global gridded (1° x 1°) surface mass change field is estimated from each of the 43 solutions. The gridded field is dominated by geophysical signals over land due to variations in terrestrial water and ice or snow storage. In addition, there are PGR effects prominent in previously glaciated areas, and residuals arising from imperfect removal of oceanic and atmospheric mass redistribution during GRACE processing. (Bettadpur, 2007b). At each (1° x 1°) grid point, we fit the mass change time series with a linear trend and annual, semiannual, and 161-day sinusoidal functions using least squares. The slope of the linear trend provides an estimate of apparent mass rate that will include contributions from interannual and decadal fluctuations, due to the brevity of the time series. The 161-day term is an alias due to ocean tide model error in the S_2 solar tide. Both the GRACE orbit configuration and errors in the S_2 tide model make this alias relatively strong, and it has been recognized as a problem near the AP in earlier work with GRACE (Han et al., 2005). In a separate study, (not shown) we verified significant reductions in the 161-day alias in RL04 due to the improved ocean tide model. However, there is evidence of remaining problems in some locations as described below.

Figure 1a, the map of apparent mass rates, shows a number of features characteristic of signal, rather than noise. Regions with largest negative and positive rates, some with spatial scales as small as 300 km, are dominantly located over and near land, the expected geographical pattern for either water/ice storage change or PGR. However, leakage of water/ice changes from land may occur due to limited spatial resolution, and PGR offshore is possible if Pleistocene glaciers were grounded far out on the continental shelf. Mass rates in oceanic areas are on the order of 1 cm per year or smaller (Fig. 1a). Assuming the true rate in these regions is zero, this gives an independent measure of uncertainty in GRACE rate estimates. Figure 1a is evidence that RL04 offers significant resolution improvements relative to RL01, which required 800 km Gaussian smoothing to achieve similar results (compared with the 300 km Gaussian smoothing used here). RL04 also shows comparably improved resolution in other areas of the world. For example, Chen et al., (2007) observed a gravitational signature of the Sumatra-Andaman earthquake of December 26, 2004, which was not resolved in RL01.

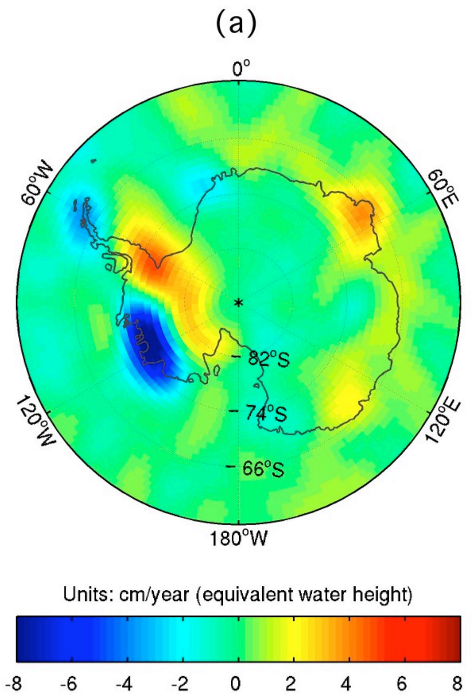

Figure 1. a) Mass rates (units of cm of equivalent water height change per year, cm/yr) estimated from 43 GRACE RL04 monthly gravity solutions, with a 2-step (P4M6 decorrelation and 300km Gaussian) filtering. b) The IJ05 PGR model expressed in equivalent units of surface mass change after processing with the same 2-step filter.

Further analysis is required to remove biases from the apparent rates (Fig. 1a) introduced by a limited range of spherical harmonics, Gaussian smoothing, and other processing steps, and to obtain a separate estimate for ice loss. We focus efforts on several geographical regions with relatively large apparent rates. These include areas with negative rates (northern AP, coastal ASE) and positive rates (Southern Ronne Ice Shelf, and Enderby Land, East Antarctica). The mass increase extending into the Ronne Ice Shelf region, is possibly from either PGR effect (Ivins and James, 2005; Peltier, 2004), residual error in GRACE data, leakage from land signal, or some combination of the three. Smaller negative rates are found along the coast near the Stancomb-Wills (STA) and Jutulstraumen (JUT) glaciers in Queen Maud Land in East Antarctica.

To remove PGR effects, we adopt the IJ05 model (Ivins and James, 2005) shown in Figure 1b in the same units of equivalent water layer change per year. The model was represented in SH, and filtered with P4M6 and 300km Gaussian smoothing. The Figure 1b color scale differs by a factor of 2 from Figure 1a. The IJ05 model predicts that most PGR is to be found in West Antarctica, with quite small effects in the AP, although uncertainty of PGR models over West Antarctic is expected to be quite large, due to limited data available to constrain the models (Velicogna and Wahr, 2006).

An estimated ice mass rate map (Figure 2a) is Figure 1a minus the PGR model (Figure 1b). AP and ASE rates change little from Figure 1a. A negative rate has been anticipated for the AP, but earlier GRACE data were not able to resolve it. The region with negative rate near STA/JUT (Point E) has larger magnitude, and has moved towards land. The Enderby Land rate is relatively unchanged by removal of PGR because IJ05 predicts a low PGR rate in this region. Negative rates in the ASE and positive rates in Enderby Land are similar to those found using earlier GRACE data (e.g., Chen et al., 2006a; Ramillien et al., 2006).

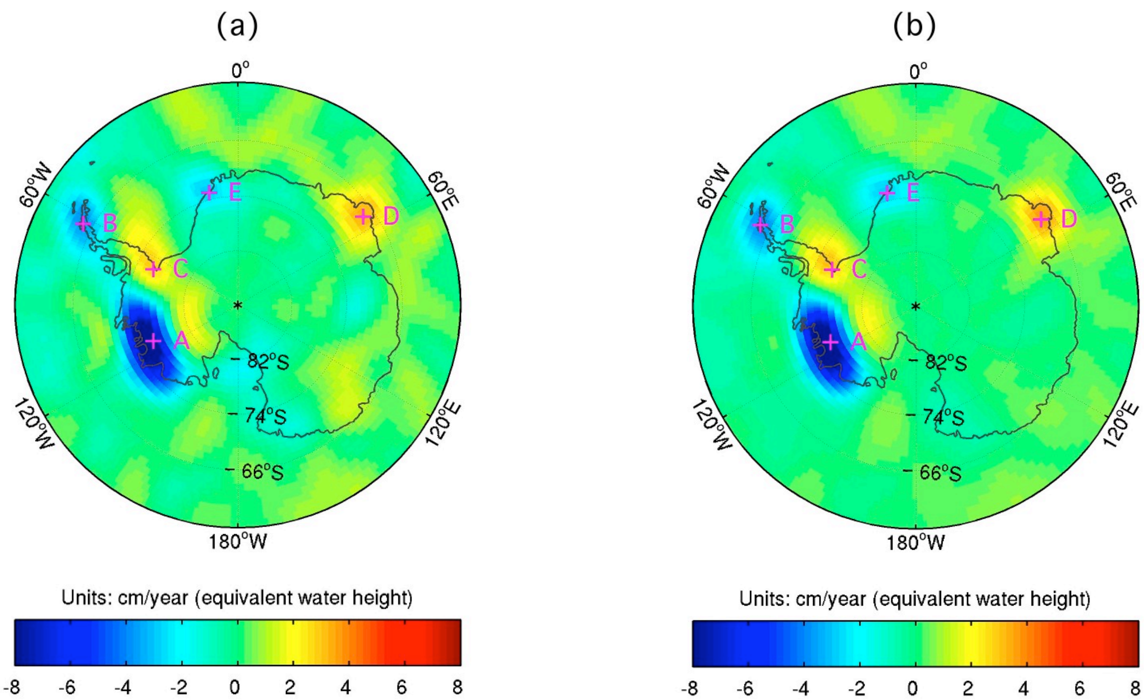

Figure 2. a) GRACE mass rates (units of cm of equivalent water height change per year, cm/yr) after PGR (Fig. 1b) is removed. b) Predicted mass rate map (cm/yr) from the model illustrated in Figure 3. Time series for five grid points (A, B, C, D, and E) are presented in later figures.

2.4 Corrected Mass Rates for Selected Regions

We examine mass rates in the ASE coastal, northern AP, and STA/JUT regions, correcting apparent rates in Figure 2b for biases due to filtering and limited spatial resolution. We employ a forward modeling technique developed in earlier studies (Chen et al., 2006a, 2006b, 2006c). Estimates are obtained by assuming that geographical locations of mass change are confined to land. This assumption leads to mass rate models with spatial resolution somewhat better than the fundamental resolution of GRACE data. The modeling technique involves the following steps:

1) We examine six regions (shaded in Fig. 3) where the corrected GRACE rate map (Figure 2a) shows prominent signals. In each region defined on the (1° x 1°) grid, a trial mass rate (in units of km^3/yr) is distributed uniformly. The remainder of the grid (outside Antarctica) retains GRACE mass rates. Therefore, spatial leakage from the 6 regions to

areas outside Antarctica should be evident when comparing the model and GRACE rate maps. This is a variation of the forward modeling technique in the previous studies (Chen et al., 2006a, 2006b, 2006c), in which the model map was obtained entirely from mass rates in the selected (shaded) regions.

2) The model map is obtained by representing the 1º x 1º grid of mass rates as fully normalized SH, and then truncating coefficients at degree and order 60, the same limit used in the RL04 solutions. Finally we apply the same 2-step filtering (P4M6 decorrelation and 300 Gaussian smoothing) to obtain the model rate map.

3) Model rates and region shapes are adjusted until there is general agreement with the GRACE map. As a final constraint, we force model integrated mass rate for each region (sum over grid points with cosine of latitude weights within boundaries where magnitude exceeds 1 cm/year) to agree with the GRACE map.

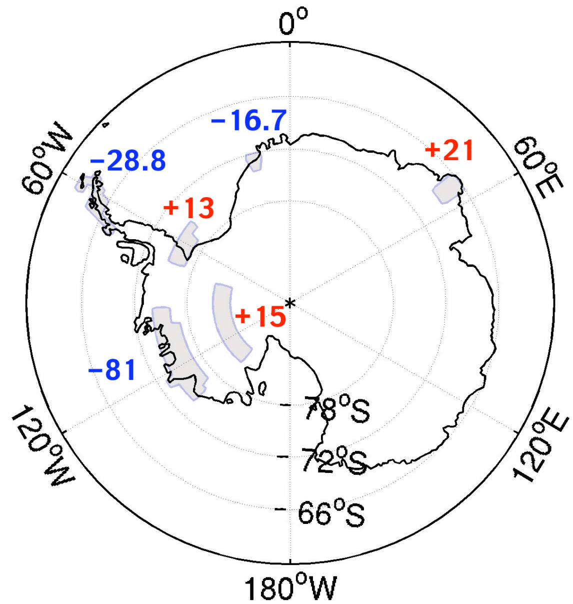

Figure 3. The forward model used to produce Figure 2b. Six shaded areas have uniformly distributed mass rates as shown, inuints of km^3/year. Mass rates have been adjusted so that (Fig. 2b) matches GRACE observation (Fig. 2a), and integrated mass rates in each region agree.

These six regions are selected because the GRACE rate map shows them to have clear spatially isolated signals. GRACE spatial resolution, controlled by the limited SH degree and order (60 in this case) and the need for spatial filtering to suppress noise, prevents us from making estimates at the scale of individual glaciers or drainage basins. The forward modeling technique enables estimates in selected regions, such as the ASE coastal and northern AP regions. The technique is not sensitive to the actual spatial distribution of mass rate in the center area of the studied region. In another word, as long as we place the same amount of total mass change in an area centered in the studied region (i.e., in a shrunk area shaped similarly to the observed mass change), after the SH truncation and spatial filtering(s), GRACE will produce the same or a very similar mass rate map.

We show the results (see Figure 2b) from one particular simulation over Antarctic (after extensive numerical simulations and experiments) that we believe best match (under the two criteria mentioned above) GRACE observations (Fig. 2a). The GRACE observation (Fig. 2a) and simulated result (Fig. 2b) are quite similar, especially in the 4 targeted areas, ASE, AP, and STA/JUT and Enderby Land area in East Antarctica. In this particular simulation, we place – 81, – 28.8, – 16.7 km^3/year total ice mass loss in the coastal ASE, northern AP, and STA/JUT areas, and + 21 km^3/year total ice mass increase in the Enderby Land area. To account for presumably unmodeled PGR and/or snow/ice accumulation effect, we have placed two positive mass rates, + 13 and + 15 km^3/year in two areas surrounding the ASE (see Fig. 3).

2.5 Uncertainty in Estimated Rates

The Antarctic ice sheet sees relatively dense GRACE ground track coverage, and is less affected by the striping spatial noise, though the decorrelation filter (Swenson and Wahr, 2006) further reduces this particular noise. Errors due to inadequate atmospheric and oceanic models used in GRACE processing (Bettadpur, 2007a) should have a negligible effect at the multi-year time scales, which influence mass rates. Long-term geocenter motion (changes in degree-1 SH terms, C_{11}, S_{11}, and C_{10}) may contaminate GRACE estimates, especially in Antarctica, because it tends to be along the polar axis (C_{10}). However, the geocenter problem is likely to be uniform over the continent, and have only a small effect on estimates in isolated regions.

We quantify uncertainty for mass rates by combining likely errors in the slope of the trend fit to time series at each grid point with estimated uncertainty in the IJ05 PGR model. A standard deviation for the slope is determined from the uncertainty of the slope of the least squares fit line (of 43 solutions) IJ05 model error standard deviation is assumed to be 100% of model value at each grid point. Squared error at each grid point is the sum of squares of the two contributions. Error in the rate estimate is the square root of the sum of squared errors over each region. For ASE we obtain – 81 ± 17 km^3/year, consistent with our earlier value [– 77 ± 14 km^3/year] from GRACE RL01 data. An increase in uncertainty reflects new assumptions about PGR error, previously neglected. The AP estimate is –28.8 ± 7.9 km^3/year. The northern AP (as defined in this study) represents a relatively small area (~ 70,000 km^2) and the average loss is ~ 0.41 m/year (of equivalent water thickness). To our knowledge, this is the first estimate of ice loss rate for the entire northern AP.

The estimate for STA/JUT is – 16.7 ± 9.7 km^3/year. The rate is large, given the relatively small size of active glaciers in that region. Remote sensing estimates indicate mass balance (Rignot and Thomas, 2002). The Enderby Land estimate of + 21 ± 11 km^3/year is much smaller than an earlier value [+ 80 ± 16 km^3/year] from RL01. This is due both to improvements in RL04 and to different time series durations, as shown below.

2.6 Mass Change Time Series

Apparent surface mass time series are shown for 5 grid points (A, B, C, D, and E) marked by crosses in Figure 2b. Figures 4a, b, and c show these RL04 time series for points A, B, and E, respectively. The red line is the least square fit trend. At Point A in the ASE, a negative trend dominates the time series. Seasonal variability appears relatively small, and there is a suggestion of an accelerating rate, with greater seasonal accumulation during the winter of 2005. At Point B, the apparent rate is ~ –3.72 ± 0.33 cm/year. At Point E, seasonal and inter-annual variability are superimposed on the trend.

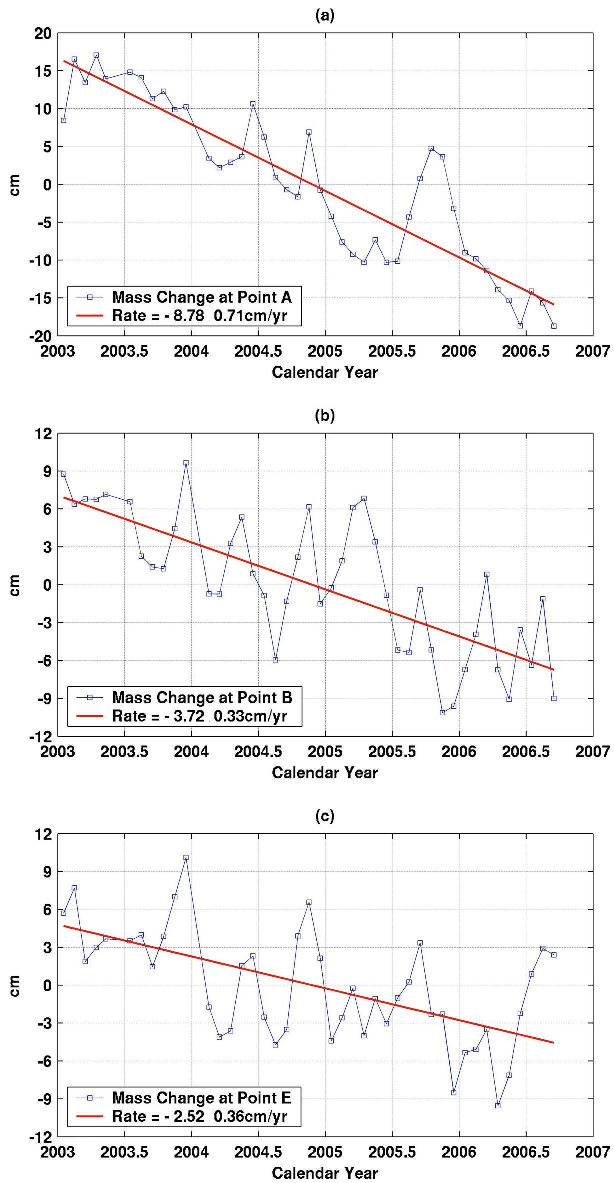

Figure 4 a, b, and c. GRACE mass time series from the 43 RL04 gravity solutions at 3 locations, a) Point A in coastal ASE, b) Point B in northern AP, and c) Point E in STA/JUT, as marked by crosses in Figs. 2a and 2b. PGR effects (from the IJ05 model) have been subtracted from all time series. The red lines are trends estimated by least squares.

Time series for Points C and D are shown in Figures 5a and b. At Point C, southern Ronne Ice Shelf, apparent mass accumulation may reflect an underestimated PGR rate, or snow accumulation, or a combination of the two. A regular oscillation is evident near the alias period of 161 days. Although RL04 employs a much improved ocean tide model, errors may persist in areas with few tide gauges. Evidence of the tidal alias also appears at points B and E (Figure 4). At Point D, the difference between the Enderby Land rate in the present study [+ 21 ± 11 km^3/year] relative to the previous [+ 80 ± 16 km^3/year] (Chen et al., 2006a) can be accounted for by increased time series duration and improved data quality. A downturn in the last year of the new series lowers the estimated rate.

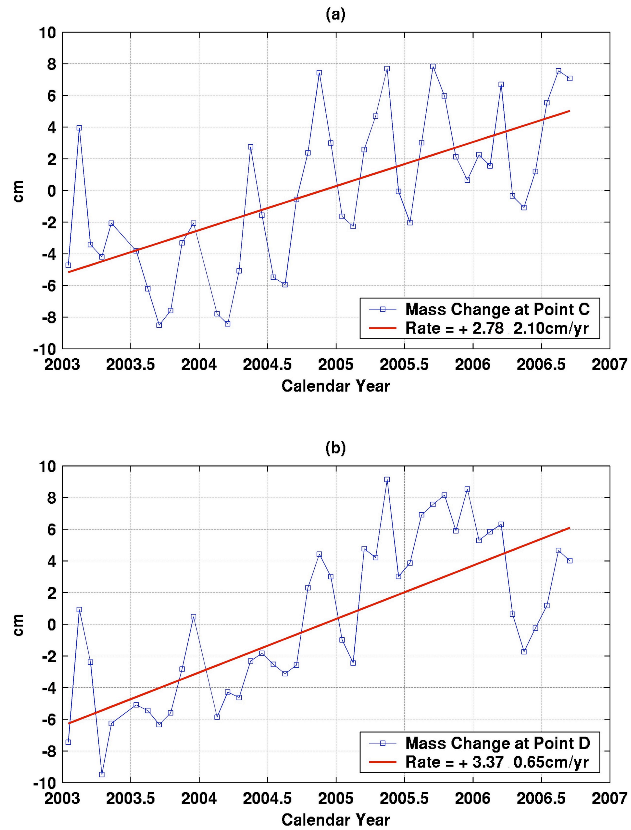

Figure 5 a and b. GRACE mass time series from the 43 RL04 gravity solutions at 2 locations, a) Point C in southern Ronne Ice Shelf, b) Point D in the Enderby Land region in East Antarctic, as marked by crosses in Figs. 2a and 2b. PGR effects (from the IJ05 model) have been subtracted from all time series. The red lines are trends estimated by least squares.

3. Conclusions

RL04 GRACE data provide improved spatial resolution and resultant estimates of mass rates. Negative rates in the ASE, northern AP, and STA/JUT, are interpreted as ice loss. The ASE coastal regions is losing – 81 ± 17 km^3/year, consistent with an earlier estimate, and remote sensing data (Thomas et al., 2004). An estimate for the northern AP, of –28.8 ± 7.9 km^3/year is a new contribution from GRACE. An independent estimate from remote sensing for the entire AP is challenging because of ice flow activity (e.g., Rignot et al., 2005) and complicated geography. GRACE observes – 16.7 ± 9.7 km^3/year of mass change in the STA/JUT region, an area where remote sensing indicates approximate balance (Rignot and Thomas, 2002). However, the two estimates are taken from different time periods. In addition, the source may not be confined to the STA/JUT glaciers. The combined ice loss from these three regions (– 127.5 ± 21 km^3/year) would contribute ~ 0.36 mm/year to global sea level rise.

4. Discussion

Improved estimates of ice mass rates from GRACE require attention to all aspects of data processing and analysis. Effects of long-term geocenter motion require further study. Ocean tide and PGR models require special attention in Antarctica. An assumed PGR error standard deviation equal to 100% of the model may underestimate error in some areas [Velicogna and Wahr, 2006]. Accurately quantifying PGR effect in the AP area could be particularly problematic, due to the lack of data to constrain the models. As the IJ05 PGR model predicts very minor PGR effect in the AP area, larger PGR rates would amplify estimated ice loss rate.

The estimated STA/JUT ice loss (– 16.7 ± 9.7 km^3/year) appears in the coastal region between the STA and JUD glaciers [see Figure 2 of Rignot and Thomas (2002)], and before the PGR correction, it (see Fig. 1a) is centered slightly off the coast in the ocean, and may be due to spatial leakage from the oceans or residual errors in GRACE data. Positive GRACE mass rates in Enderby Land, East Antarctic may reflect errors in the current PGR model or snow accumulation. The Enderby Land positive mass rate is clearly centered on land, and spatial leakage from the oceans is not likely the cause. Additional recent remote sensing data, in situ snow observations, and a longer record from GRACE will help understand the Enderby Land feature of the GRACE mass rate.

With improved spatial resolution and data quality, satellite gravity observations have great potential to monitor global water and ice mass redistribution at continental, regional, and even catchment scales. The approved extension of the GRACE mission until at least 2010, and reprocessing of the observations as tide and other geophysical models improve, will continue to improve understanding of global ice mass balance and related climate change.

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