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Acceleration of the contribution of the Greenland and Antarctic ice sheets to sea level rise

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[1] Ice sheet mass balance estimates have improved substantially in recent years using a variety of techniques, over different time periods, and at various levels of spatial detail. Considerable disparity remains between these estimates due to the inherent uncertainties of each method, the lack of detailed comparison between independent estimates, and the effect of temporal modulations in ice sheet surface mass balance. Here, we present a consistent record of mass balance for the Greenland and Antarctic ice sheets over the past two decades, validated by the comparison of two independent techniques over the last 8 years: one differencing perimeter loss from net accumulation, and one using a dense time series of time-variable gravity. We find excellent agreement between the two techniques for absolute mass loss and acceleration of mass loss. In 2006, the Greenland and Antarctic ice sheets experienced a combined mass loss of 475 ± 158 Gt/yr, equivalent to 1.3 ± 0.4 mm/yr sea level rise. Notably, the acceleration in ice sheet loss over the last 18 years was 21.9 ± 1 Gt/yr^2 for Greenland and 14.5 ± 2 Gt/yr^2 for Antarctica, for a combined total of 36.3 ± 2 Gt/yr^2. This acceleration is 3 times larger than for mountain glaciers and ice caps (12 ± 6 Gt/yr^2). If this trend continues, ice sheets will be the dominant contributor to sea level rise in the 21st century. **Citation:** Rignot, E., I. Velicogna, M. R. van den Broeke, A. Monaghan, and J. Lenaerts (2011), Acceleration of the contribution of the Greenland and Antarctic ice sheets to sea level rise, *Geophys. Res. Lett.*, *38*, L05503, doi:10.1029/2011GL046583.

1. Introduction

[2] Multi-decadal observational records are required to assess long-term trends in ice sheet mass balance [*Shepherd and Wingham*, 2007; *Rignot and Thomas*, 2002]. Attempts at estimating ice sheet mass balance have focused on determining the temporal average in mass change, dM/dt, where M(t) is the ice sheet mass at time t and d/dt is the time derivative [*Chen et al.*, 2006; *Velicogna and Wahr*, 2006; *Ramilien et al.*, 2006; *Luthcke et al.*, 2006]. Less attention has been given to the rate of change, or acceleration of mass change, d^2M/dt^2, despite its importance for expressing the potentially nonlinear contribution of ice sheets to sea level rise. Reducing uncertainties in the estimates of d^2M/dt^2 directly reduces uncertainties in near-term sea level projections.

[3] Here, we present a 20-year record of monthly ice sheet mass balance for Greenland and Antarctica. We examine and reconcile two independent methods for estimating temporal variations in ice sheet mass balance, the mass budget method (MB) and the gravity method, during the last 8 years. The MBM compares the surface mass balance (SMB; i.e., the sum of snowfall minus surface ablation) reconstructed from regional atmospheric models with perimeter loss (D; ice discharge) calculated from a time series of glacier velocity and ice thickness to deduce the rate of mass change, dM/dt [*Rignot and Kanagaratnam*, 2006; *Howat et al.*, 2007; *Rignot et al.*, 2008a; *van den Broeke et al.*, 2009]. The gravity method employs a monthly time series of time-variable gravity data from the Gravity Recovery and Climate Experiment (GRACE) to estimate the relative mass as a function of time, M(t) [e.g., *Velicogna and Wahr*, 2006]. We resolve the differences between the two methods in terms of mass balance, dM(t)/dt, and acceleration of mass loss, d^2M/dt^2, and conclude by discussing the contribution of the ice sheets to sea level in recent and forthcoming decades.

2. Data and Methodology

[4] In prior MBM studies, we employed a 25-year average SMB field in Antarctica [*Rignot et al.*, 2008a] and a 3-year smoothed SMB field requiring in-situ data for calibration in Greenland [*Rignot et al.*, 2008b]. Averaged fields were selected to minimize the impact of inter-annual variations in SMB on estimates of the long-term total ice sheet mass balance. Here, we present a longer, finer and complete mass budget analysis that uses monthly SMB fields to facilitate the comparison with GRACE monthly data and we evaluate the effect of monthly variations in SMB on the results. The Antarctic and Greenland SMB fields are from the Regional Atmospheric Climate Model (RACMO2) [*van den Broeke et al.*, 2006], which is forced at the lateral boundary and at the sea surface by the latest reanalysis of the European Centre for Medium-Range Weather Forecasts (ERA-Interim, 1989–present) [*Simmons et al.*, 2007]. The most recent version of RACMO2 does not employ field data for calibration as by *van de Berg et al.* [2006], but uses them to estimate its absolute precision. In the Antarctic, the uncertainty (1-sigma) in SMB for the grounded ice sheet averages 7% or 144 Gt/yr (J. Lenaerts et al., A new, high-resolution surface mass balance of Antarctica (1989–2009) based on regional atmospheric climate modeling, submitted to *Geophysical Research Letters*, 2010). In Greenland, the uncertainty in SMB averages 9% or 41 Gt/yr [*Ettema et al.*, 2009].

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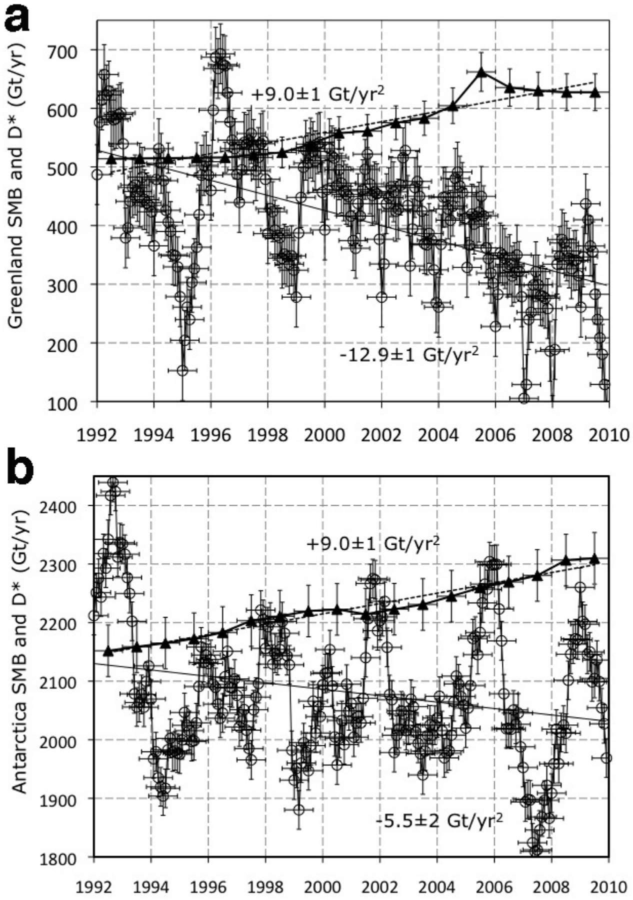

Figure 1. Monthly surface mass balance, SMB (open circle), and yearly ice discharge compensated for grounding line retreat, D* (solid triangle), for (a) Greenland and (b) Antarctic Ice Sheets between 1992 and 2009 over a grounded area of respectively, 1.7 million km^2 and 12.427 million km^2, with error bars in gigaton per year (10^{12} kg/yr or trillion tons per year). The acceleration rate in SMB and D*, in Gt/yr^2, is determined from a linear fit of the data (dotted lines).

Uncertainties quoted in the paper are 1-sigma. The monthly SMB fields are averaged using a 13-month sliding window to be consistent with the GRACE data analysis discussed below.

[5] Ice discharge, D, combines ice motion and ice thickness. Ice motion is measured using interferometric synthetic-aperture radar data (InSAR) from the European Space Agency Earth Remote Sensing satellites ERS-1/2 (1992, 1996), the Canadian Space Agency Radarsat-1 satellite (2000 to 2009) and the Japanese Space Agency Phased Array L-band Synthetic Aperture Radar PALSAR (2006–2009) satellite. Data gaps are filled in assuming that ice velocities change linearly in between measurement dates, which is a reasonable assumption given the 8–10% seasonal variability in Greenland [*Howat et al.*, 2007; *Luckman and Murray*, 2005] and the relative absence of known seasonal variability in ice flow in Antarctica. Finer time series of ice velocity exist for the largest, rapidly changing outlet glaciers.

[6] Ice thickness is from radio echo sounding (10-m uncertainty), except in half of East Antarctica where we use hydrostatic equilibrium to calculate ice thickness (80–120 m uncertainty), corrected for temporal changes in surface elevation for rapidly thinning glaciers in southeast and central west Greenland and coastal West Antarctica. A 10-m error in thickness corresponds to 1.7% uncertainty in Greenland (600 m average thickness) and 0.8% in Antarctica (1,200 m average thickness), i.e., a 2-3% error in ice flux if the error in ice velocity is 5 m/yr and the average velocity is 500 m/yr. Corrections for thickness changes over a time period of ±9 years around year 2000 are significant for glaciers thinning at rates greater than 3 m/yr in Greenland and 5 m/yr in Antarctica, since they would induce a 3% error in ice flux. In Greenland, we employ a thinning rate of 15 ± 3 m/yr for Jakobshavn, 25 ± 5 m/yr for Helheim and 10 ± 5 m/yr for southeast glaciers [*Howat et al.*, 2007; *Pritchard et al.*, 2009]. In Antarctica, we use 2 m/yr thinning in 1996 for Pine Island Glacier increasing to 9.5 m/yr in 2008 [*Wingham et al.*, 2009], 3 ± 1 m/yr for Thwaites and 7.5 ± 1.5 m/yr for Smith [*Pritchard et al.*, 2009; *Shepherd and Wingham*, 2007].

[7] In addition, we apply a novel correction for grounding line migration. Prior estimates of D assumed a fixed grounding line position. As grounding lines retreat inland, however, a significant amount of ice reaches floatation and displaces sea level. This effect is inherently included in the GRACE data because floating ice is isostatically compensated and does not affect the gravity field. To correct this effect in the MBM, however, we employ observations of changes in surface elevation collected by altimeters and convert them into rates of grounding line retreat assuming hydrostatic equilibrium of the ice [*Thomas and Bentley*, 1978]. We deduce a time-dependent mass loss caused by grounding line retreat, dG/dt, which is added to the calculated grounding line discharge to yield a corrected discharge, D* = D + dG/dt. Mass losses due to dG/dt are significant for Jakobshavn Isbrae in Greenland and Pine Island and Thwaites glaciers in West Antarctica. For Jakobshavn Glacier, we calculate dG/dt of 4 Gt/yr after year 2004 from a 20-km^2 retreat of an 800-m thick glacier in 2004–2008. For Pine Island Glacier, the quadratic thinning rate yields a dG/dt increasing linearly from 5 ± 2 Gt/yr in 1996 to 31 ± 11 Gt/yr in 2008 and stable in 2009. For Thwaites Glacier, we calculate dG/dt of 5 ± 1 Gt/yr for the entire time period. The total uncertainty in D* averages 31 Gt/yr in Greenland and 44 Gt/yr in Antarctica.

[8] The GRACE data are from the 4th release from the Center for Space Research at the University of Texas for the period April 2002 to June 2010. These data resolve mass, M(t), monthly, at a spatial scale of 300 km and larger. Leakage effects from other geophysical sources of gravity field variability are calculated as described by *Velicogna* [2009]. The signal associated with glacial isostatic adjustment (GIA), i.e., the viscoelastic response of the solid Earth to glacial unloading over the past several thousand years, is subtracted from the GRACE data [e.g., *Velicogna and Wahr*, 2006]. In addition, we evaluate the contamination to the GRACE results by the small glaciers and ice caps surrounding the ice sheets (GIC). To quantify this leakage, we simulated a uniform mass loss from the location of the Greenland GIC equivalent to a loss of 20 Gt/yr [*Hock et al.*, 2009]. We obtained a 1-Gt/yr leakage to our final ice mass value, which is negligible. In Antarctica, the GIC mass loss estimates range from 45 Gt/yr [*Kaser et al.*, 2006] for 2001–2004 using mass

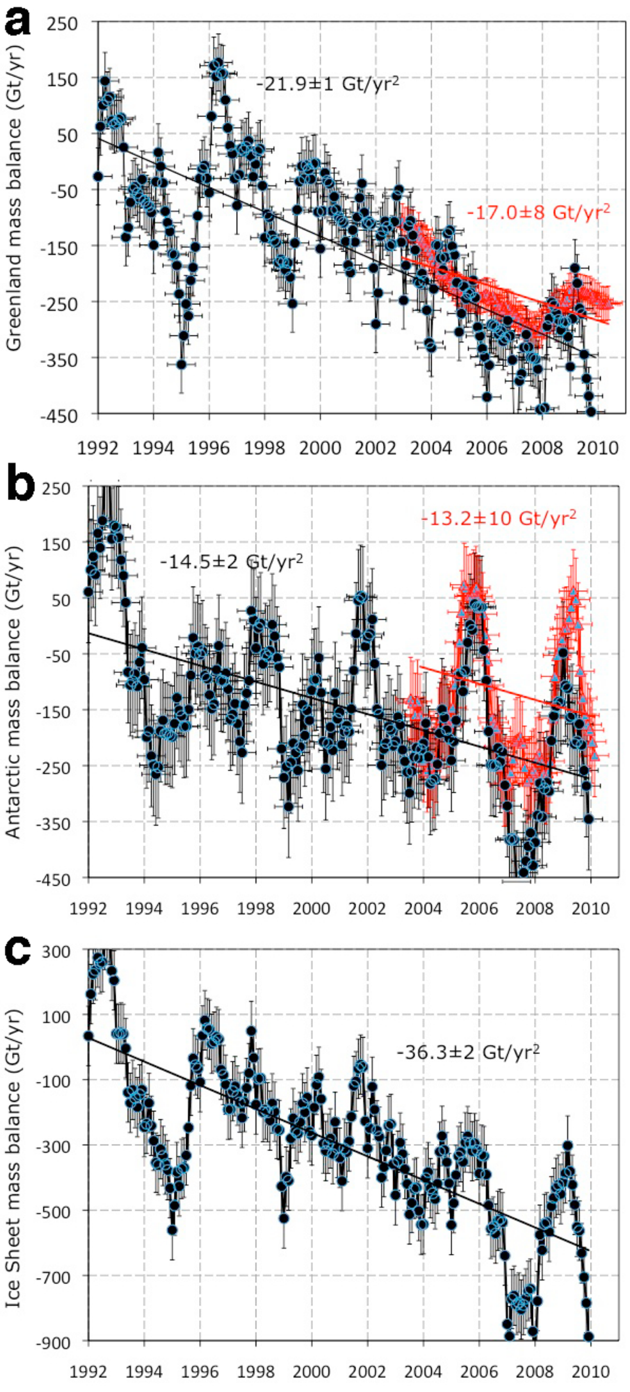

Figure 2. Total ice sheet mass balance, dM/dt, between 1992 and 2009 for (a) Greenland; (b) Antarctica; and c) the sum of Greenland and Antarctica, in Gt/yr from the Mass Budget Method (MBM) (solid black circle) and GRACE time-variable gravity (solid red triangle), with associated error bars. The acceleration rate in ice sheet mass balance, in gigatons per year squared, is determined from a linear fit of MBM over 18 yr (black line) and GRACE over 8 yr (red line).

balance specifics of dry Arctic glaciers to 79 Gt/yr [*Hock et al.*, 2009] for 1961–2004 based on a surface melt model, with losses concentrated mainly in the Antarctic Peninsula. A recent GRACE study, however, estimated the mass loss of the entire Peninsula including the surrounding GIC at 42 ± 9 Gt/yr for 2002–2009 [*Ivins et al.*, 2011]. This estimate is consistent with our MBM estimate of 42 ± 24 Gt/yr that excludes GIC [*Rignot et al.*, 2008a]. The GRACE result suggests that the Antarctic Peninsula GIC must contribute much less than 40 Gt/yr. As a typical upper bound for the Peninsula GIC, we assumed a loss of 25 Gt/yr and we obtained a 19-Gt/yr leakage into our ice sheet solution. We include this uncertainty into our final GRACE total error budget.

[9] To reduce contamination of the long-term trend by seasonal and inter-annual variability, a filtering procedure is applied on the M(t) and dM/dt data over 13-month windows [*Velicogna*, 2009]. For each window of M(t) values, we simultaneously solve for an annual cycle, a semi-annual, a linear trend and a constant to attribute a filtered mean value M(t) at the center month of each window. The filtered values are employed to calculate average mass changes over 13-month sliding windows centered on each month. The filtering is not applied on the first and last 6 months because a one year cycle is required to extract the seasonal signal. This analysis yields a robust estimation of both the mass change and the acceleration in mass change because we account for the entire range of temporal modulation in mass balance simultaneously.

3. Results

[10] Both ice sheets exhibit large inter-annual variations in SMB (Figure 1). Percentage-wise, these variations are comparable, but the absolute values are 3–4 times larger in Antarctica compared to Greenland due to the larger total SMB in Antarctica. In Greenland, SMB values have decreased by 12.9 ± 1 Gt/yr^2 since 1992 due to a steady increase in surface runoff, whereas precipitation has not changed at a detectable level. In Antarctica, we observe a 5.5 ± 2 Gt/yr^2 decrease in SMB since 1992, which is consistent with studies indicating no significant increase in SMB over the past 50 years [*Monaghan et al.*, 2006].

[11] In contrast, ice discharge, D*, exhibits smooth variations during the time period, and a steady increase with time, except in 2005 when two large glaciers accelerated simultaneously in East Greenland. The acceleration rate in ice discharge in Greenland is 9.0 ± 1 Gt/yr^2 for 1992–2009. In Antarctica, the acceleration is also 9.0 ± 1 Gt/yr^2 for the same time period.

[12] We compare the MBM and GRACE results for the same area, i.e., the grounded extent of ice sheets excluding GIC, on a monthly time scale but with a 13-month smoothing applied to the data, for the common time period 2002.9 to 2009.5. In Greenland, the agreement in M(t) demonstrated at seasonal and annual timescales [*van den Broeke et al.*, 2009] is extended here to dM/dt and d^{2}M/dt^2 (Figure 2a). The mass losses estimated from MBM and GRACE are within ±20 Gt/yr, or within their respective errors of ±51 Gt/yr and ±33 Gt/yr. The acceleration in mass loss is 19.3 ± 4 Gt/yr^2 for MBM and 17.0 ± 8 Gt/yr^2 for GRACE. The GRACE-derived acceleration is independent of the GIA reconstruction, a constant signal during the observational period.

[13] In Antarctica, we find an excellent agreement between the two techniques (Figure 2b). The dM/dt values differ by ±50 Gt/yr, or within the error bar of ±150 Gt/yr for MBM and ±75 Gt/yr for GRACE. In 2006, the MBM mass

loss was approximately 200 ± 150 Gt/yr (regression line), which is comparable to Greenland's 250 ± 40 Gt/yr, and equivalent to 0.6 ± 0.4 mm/yr sea level rise. The total contribution from both ice sheets amounted to 1.3 ± 0.4 mm/yr sea level rise.

[14] The temporal variability in Antarctic SMB introduces a large modulation of the GRACE signal with a 3.6-year periodicity according to the signal autocorrelation. Taking this periodic signal into account, we retrieve an acceleration in mass loss from the GRACE data of 13.2 ± 10 $\mathrm{Gt/yr^2}$ (Figure 2b). For the same time period, the acceleration in mass loss from the MBM data is 15.1 ± 12 $\mathrm{Gt/yr^2}$. Both estimates have a large uncertainty because of the short period of observation and the large temporal variability in SMB. As for Greenland, the GRACE-derived acceleration is independent of the GIA correction, a larger residual uncertainty in Antarctica than in Greenland.

[15] The excellent agreement of the GRACE and MBM records over the last 8 years validates the 18-year MBM record. The results also indicate that an observation period of 8 years is probably not sufficient for these methods to separate the long-term trend in ice sheet acceleration from temporal variations in SMB, especially in Antarctica. When we use the extended time period 1992–2009, the significance of the trend improves considerably. The MBM record indicates an acceleration in mass loss of 21.9 ± 1 $\mathrm{Gt/yr^2}$ for Greenland and 14.5 ± 2 $\mathrm{Gt/yr^2}$ for Antarctica. The lower uncertainty reflects the reduced influence of temporal variations in SMB for the longer record. The uncertainty in acceleration is thus reduced to 5% for Greenland and 10% for Antarctica. When the mass changes from both ice sheets are combined together (Figure 2c), the data reveal an increase in ice sheet mass loss of 36.3 ± 2 $\mathrm{Gt/yr^2}$.

4. Discussion

[16] Using techniques other than GRACE and MBM, the mass loss of mountain glaciers and ice caps (GIC), including the GIC surrounding Greenland and Antarctica, has been estimated at 402 ± 95 Gt/yr in 2006, with an acceleration of 11.8 ± 6 $\mathrm{Gt/yr^2}$ over the last few decades [*Kaser et al.*, 2006; *Meier et al.*, 2007]. Our GRACE estimates and associated errors account for the leakage from the Greenland and Antarctica GIC, and, as discussed earlier, this leakage is small. The MBM estimates completely exclude the GIC. In year 2006, the total ice sheet loss was 475 ± 158 Gt/yr (regression line in Figure 2c), which is comparable or greater than the 402 ± 95 Gt/yr estimate for the GIC. More important, the acceleration in ice sheet loss of 36.3 ± 2 $\mathrm{Gt/yr^2}$ is three times larger than that for the GIC. If this trend continues, ice sheets will become the dominant contribution to sea level rise in the next decades, well in advance of model forecasts [*Meehl et al.*, 2007].

[17] It is important to examine whether the acceleration in mass loss may continue. In Greenland, the increase in runoff, which contributes more than half the total loss, is likely to persist in a warming climate [*Hanna et al.*, 2008], and continue to exhibit large inter-annual variations. For ice dynamics, the GRACE data and the interferometric ice motion record indicate that the mass loss has decreased in southeast Greenland since 2005, yet still maintains above its level in 1996, but has increased in the northwest Greenland since 2006 [*Khan et al.*, 2010]. Collectively, these observations reveal an ice sheet still in transition to a regime of higher loss.

[18] In Antarctica, Pine Island Glacier accelerated exponentially over the last 30 years: 0.8% in the 1980s, 2.4% in the 1990s, 6% in 2006 and 16% in 2007–2008 [*Rignot*, 2008], and quadrupled its thinning rate in 1992–2008 [*Wingham et al.*, 2009]. Simple model projections predict a tripling in glacier speed once the grounding line retreats to a deeper and smoother bed [*Thomas et al.*, 2004]. Dynamic losses are therefore likely to persist and spread farther inland in this critical sector. A small positive increase in Antarctic SMB could offset these coastal losses, but this effect has not yet been observed.

[19] If the acceleration in ice sheet loss of 36.3 ± 2 $\mathrm{Gt/yr^2}$ continues for the next decades, the cumulative ice sheet loss would raise global sea level by 15 ± 2 cm in year 2050 compared to 2009/2010. The GIC would contribute a sea level rise of 8 ± 4 cm, and thermal expansion of the ocean would add another 9 ± 3 cm based on the average of scenarios A1B, A2 and B1 [*Meehl et al.*, 2007], for a total rise of 32 ± 5 cm. At the current rate of acceleration in ice sheet loss, starting at 500 Gt/yr in 2008 and increasing at 36.5 $\mathrm{Gt/yr^2}$, the contribution of ice sheets alone scales up to 56 cm by 2100. While this value may not be used as a projection given the considerable uncertainty in future acceleration of ice sheet mass loss, it provides one indication of the potential contribution of ice sheets to sea level in the coming century if the present trends continue.

5. Conclusions

[20] This study reconciles two totally independent methods for estimating ice sheet mass balance, in Greenland and Antarctica, for the first time: the MBM method comparing influx and outflux of ice, and the GRACE method based on time-variable gravity data. The two records agree in terms of mass, $M(t)$, mass change, $dM(t)/dt$, and acceleration in mass change, d^2M/dt^2. The results illustrate the major impact of monthly-to-annual variations in SMB on ice sheet mass balance. Using the two-decade long MBM observation record, we determine that ice sheet loss is accelerating by 36.3 ± 2 $\mathrm{Gt/yr^2}$, or 3 times larger than from mountain glaciers and ice caps (GIC). The magnitude of the acceleration suggests that ice sheets will be the dominant contributors to sea level rise in forthcoming decades, and will likely exceed the IPCC projections for the contribution of ice sheets to sea level rise in the 21st century [*Meehl et al.*, 2007].

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