Regional acceleration in ice mass loss from Greenland and Antarctica using GRACE time-variable gravity data

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Abstract We use Gravity Recovery and Climate Experiment (GRACE) monthly gravity fields to determine the regional acceleration in ice mass loss in Greenland and Antarctica for 2003–2013. We find that the total mass loss is controlled by only a few regions. In Greenland, the southeast and northwest generate 70% of the loss (280 ± 58 Gt/yr) mostly from ice dynamics, the southwest accounts for 54% of the total acceleration in loss (25.4 ± 1.2 Gt/yr^2) from a decrease in surface mass balance (SMB), followed by the northwest (34%), and we find no significant acceleration in the northeast. In Antarctica, the Amundsen Sea (AS) sector and the Antarctic Peninsula account for 64% and 17%, respectively, of the total loss (180 ± 10 Gt/yr) mainly from ice dynamics. The AS sector contributes most of the acceleration in loss (11 ± 4 Gt/yr^2), and Queen Maud Land, East Antarctica, is the only sector with a significant mass gain due to a local increase in SMB (63 ± 5 Gt/yr).

1. Introduction

At present, the Greenland and Antarctic ice sheets are undergoing significant changes in mass [e.g., *Shepherd et al.*, 2012]. In Greenland, the contribution to sea level has increased from 0.09 mm/yr over 1992–2001 to 0.59 mm/yr over 2002–2011, with the signal caused by a mix of increases in ice flow and increases in snow/ice melt [*Vaughan et al.*, 2013]. In Antarctica, the contribution to sea level has increased from 0.08 mm/yr over 1992–2001 to 0.4 mm/yr over 2002–2011, with the major part of the signal caused by increases in ice flow in West Antarctica and the Antarctic Peninsula. Time-variable gravity data from the Gravity Recovery and Climate Experiment (GRACE) mission have been used to estimate the mean ice sheet mass balance over certain time periods, dM/dt, where $M(t)$ is the ice sheet mass at time t. More recently, attempts have been made to estimate the changes in mass balance with time or acceleration, d^2M/dt^2, in Greenland and Antarctica at the continental scale [*Velicogna*, 2009; *Rignot et al.*, 2011; *Wouters et al.*, 2013; *Svendsen et al.*, 2013; *Williams et al.*, 2014]. Few attempts have been made, however, to determine accelerations at the regional level. One major difficulty of determining accelerations from GRACE time-variable gravity data is that the time series is limited to 11 years. Analyses of synoptic changes in surface mass balance indicate that several decades of observation may be necessary to separate the short-term variability in surface mass balance from the long-term trends in total mass balance [*Wouters et al.*, 2013]. In addition the GRACE resolution limits, the size of the region for which mass changes can be studied.

We use GRACE monthly measurements of time-variable gravity for the period January 2003 to December 2013 to estimate the spatial pattern in ice mass balance ($dM(t)/dt$), and acceleration in mass balance (d^2M/dt^2) for both Greenland and Antarctica at the regional and continental scale using a mascon approach. Our goal is to evaluate whether the ice mass loss is increasing with time, constant or not statistically significant. We compare the results with monthly time series of cumulative surface mass balance (SMB) from the Regional Atmospheric Climate Model (RACMO2) to determine the fraction of the GRACE signal that is explained by changes in SMB. Based on this, we conclude on the nature and statistical significance of changes in ice mass balance for key regions of Greenland and Antarctica.

2. Data and Methodology

We use RL05 GRACE gravity solutions in the form of spherical harmonic coefficients truncated to degree 60, from the Center for Space Research at the University of Texas for January 2003 to December 2013 [*Bettadpur*, 2012]. We use monthly C_{20} coefficients from satellite laser ranging [*Cheng et al.*, 2013] and include degree 1

coefficients calculated following *Swenson et al.* [2008]. Leakage effects from outside the ice sheet including the eustatic ocean are calculated as in *Velicogna and Wahr* [2013]. The glacial isostatic adjustment (GIA) signal is subtracted from the GRACE data. In Antarctica we use *Ivins et al.*'s [2013] regional ice deglaciation model combined with ICE-5G for the rest of the globe. In Greenland we use *Simpson et al.*'s [2009] regional ice deglaciation model combined with ICE-5G outside Greenland. The GIA correction error is calculated considering a range of viscosity profiles for the selected model. Over the time span of the mission, however, the GIA signal is a linear trend in $M(t)$, which is a constant in the rate of mass change, $dM(t)/dt$, and does not contribute to the acceleration in mass, d^2M/dt^2.

We smooth the Stokes coefficients using a Gaussian averaging function with a 250 km radius [*Wahr et al.*, 1998], and we calculate regular latitude-longitude monthly ice mass grids. Before calculating the ice mass grids for Greenland, we remove the contamination from the nearby Canadian glaciers and ice caps (GIC) from the GRACE data. To do this, we apply the least squares mascon approach described in *Sutterley et al.* [2014] to the Canadian GIC and the ice sheet. Each mascon is a 3° diameter equal-area spherical cap with a mass equal to a uniformly distributed centimeter of water [*Farrell*, 1972]. For each mascon, we calculate a set of Stokes coefficients, which we smooth with a 250 km Gaussian function and convert into mass. We simultaneously fit the Stokes coefficients to the monthly GIA-corrected GRACE coefficients to obtain estimates of the monthly mass variability of each mascon. We obtain an estimate of the GIC signal by combining the signal of the corresponding mascons. We remove this signal from the GRACE monthly coefficients, and we calculate regular latitude-longitude monthly ice mass grids.

We use these grids to form maps of the acceleration in ice mass loss by simultaneously fitting an annual and a semiannual signal, a quadratic trend, a linear trend, and a constant at each grid point. To be conservative in our error estimate when fitting the regression model, we do not make any assumption about the size of the error affecting the GRACE monthly estimates. We only consider points for which the acceleration is significant at the 2σ confidence level. To determine if the quadratic model is statistically more significant than the linear one, i.e., the mass loss is increasing with time instead of being constant at a specific grid point, we calculate the best fitting linear trend and the associated error. We select the points for which the trend is significant at the 2σ confidence level, and we use a variant of the Akaike information criterion for use with small sample sized data sets (AIC_c) to compare the quadratic and linear models and identify the model that best fits the signal [*Burnham and Anderson*, 2002].

To examine quantitatively the time evolution of ice mass changes at the regional scale, we cannot use the results in Figure 1 which is a smoothed signal. Rather, we calculate time series for selected regions using the corresponding mascons. The error of each regional ice mass estimate is due to leakage error, GRACE measurement error, GIA error, and statistical uncertainty of the model fit. We evaluate these contributions as follows. For each region, we calculate the corresponding sensitivity kernel to evaluate how mass at a given point within the region contributes to the total time series [*Sutterley et al.*, 2014]. If the GRACE mass anomalies are distributed uniformly over each mascon, the fit results will recover the total variability for each region. We evaluate the error introduced by assuming a uniform mass distribution within each mascon by estimating the leakage error within each region using a field of simulated, realistic ice mass change based on results from the mass budget method [*Rignot et al.*, 2011]. We evaluate the leakage within each region from the outside signal by convolving each sensitivity kernel with the simulated signal for all regions except the one selected. We include this leakage error in our regional error budget. The measurement errors in individual GRACE monthly fields are calculated by convolving each sensitivity kernel with uncertainty estimates for the GRACE Stokes coefficients following *Wahr et al.* [2006].

In Greenland, we distinguish five regions based on their ice dynamics and surface mass balance (SMB) characteristics [e.g., *van den Broeke et al.*, 2009]: (1) the northwest (NW), with high accumulation and fast-moving glaciers, (2) the north (N) with few, large, slow-moving glaciers and low accumulation, (3) the northeast (NE) similar to the N but with glaciers flowing through high mountain ranges, (4) the southeast (SE), with high accumulation and many fast, small outlet glaciers, and (5) the southwest (SW) where most glaciers are land terminating and the ablation area is the largest in size [*van den Broeke et al.*, 2009].

In Antarctica, we distinguish five regions identified based on changes highlighted in prior studies [*Rignot et al.*, 2008; *Chen et al.*, 2009; *Pritchard et al.*, 2009; *Shepherd et al.*, 2012]: (1) the Amundsen Sea (AS) sector of West Antarctica, (2) the Antarctic Peninsula, (3) Queen Maud Land, (4) the Totten/Moscow/Frost sector (TMF), and (5) Victoria/Wilkes land (VW) in East Antarctica. In Antarctica, the sum of all the regions is not
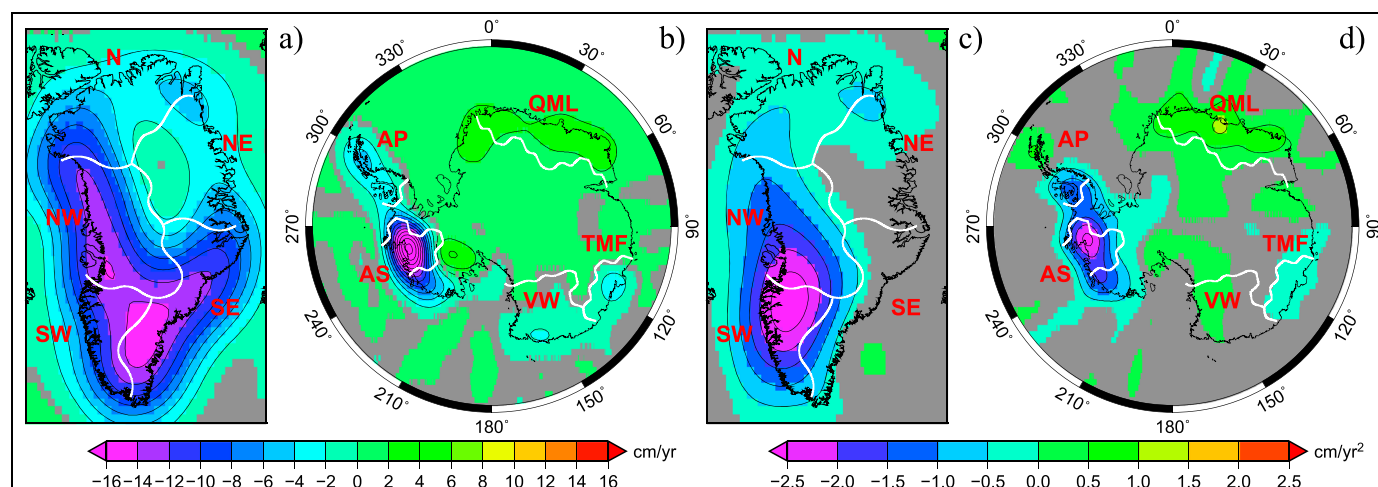
Figure 1. (a, b) GRACE-derived Greenland and Antarctica ice mass balance linear trends, d$M(t)$/dt, in cm/yr of water. (c, d) Accelerations, d^2M/dt^2, in cm/yr^2 for January 2003 to December 2013. Contour interval is 2 cm/yr for the linear trend (Figures 1a and 1b) and 0.5 cm/yr^2 for the acceleration (Figures 1c and 1d). White lines define regions for which time series are calculated in Figure 2.

equal to the entire ice sheet, but we also present results for the entire ice sheet (Antarctic ice sheet (AIS)). All regions are selected to be compatible with the GRACE errors and resolution. Figures S1 and S2 show the configuration of the mascons and the region boundaries.

We compare the GRACE-derived time series of ice mass change with time series of RACMO2 cumulative SMB anomalies [*van den Broeke et al.*, 2006]. RACMO2 is forced at the lateral boundary and at the sea surface by the latest European Centre for Medium-Range Weather Forecasts reanalysis [*Simmons et al.*, 2007]. Field data are used to estimate the RACMO2 absolute precision [*van de Berg et al.*, 2006]. In the Antarctic, the uncertainty (1σ) in SMB for the grounded ice sheet averages 7% or 144 Gt/yr [*Lenaerts et al.*, 2012]; data are available through July 2012. In Greenland, the uncertainty averages 17% or 77 Gt/yr [*Ettema et al.*, 2009]; data are available through December 2012. We calculate cumulative SMB anomalies relative to a long-term average. For Greenland, we use the period 1961–1990 when the ice sheet was close to balance [*van den Broeke et al.*, 2009]. For Antarctica, we use the reference period of 1979–2008 [*Shepherd et al.*, 2012]. Error in monthly cumulative SMB are calculated following *van den Broeke et al.* [2009]. The SMB data are processed in the same manner as the GRACE data, i.e., converted to the spectral domain, truncated to degree 60, and spatially averaged. To perform the comparison at the regional level, we apply the same mascon fitting technique as for the GRACE data to the SMB data. We determine how well the two time series agree in different regions and which fraction of the GRACE signal is explained by SMB variability.

3. Results

In Greenland, the ice mass loss has spread across the entire ice sheet. In total, we find a linear trend in mass loss of 280 ± 58 Gt/yr and an acceleration of 25.4 ± 1.2 Gt/yr^2 (Table S1 in the supporting information). The uncertainties include contributions added in quadrature from the GIA correction, leakage of signal from outside the ice sheet including the eustatic ocean, and the statistical uncertainty of the fit. The signal from the Canadian GIC, which was removed from the Greenland signal, corresponds to a mass loss of 74 ± 7 Gt/yr with an acceleration in loss of 10 ± 2 Gt/yr^2. These numbers agree with recent estimates [*Lenaerts et al.*, 2013; *Gardner et al.*, 2013].

The mass loss is increasing with time in several regions. Over most of the Greenland ice sheet, this acceleration is statistically significant at the 2σ level (Figure 1c). While the largest losses are recorded in SE and NW (Figure 1a), the largest acceleration in mass loss is from the SW. In the NW, the mass loss is also increasing at a significant level, but its magnitude is lower, and the signal is confined along the coast. In the N, the acceleration in ice loss is significant. In the SE and portions of NE, we detect significant losses during the analyzed period, but no significant increase in mass loss with time, i.e. the mass loss remains constant.
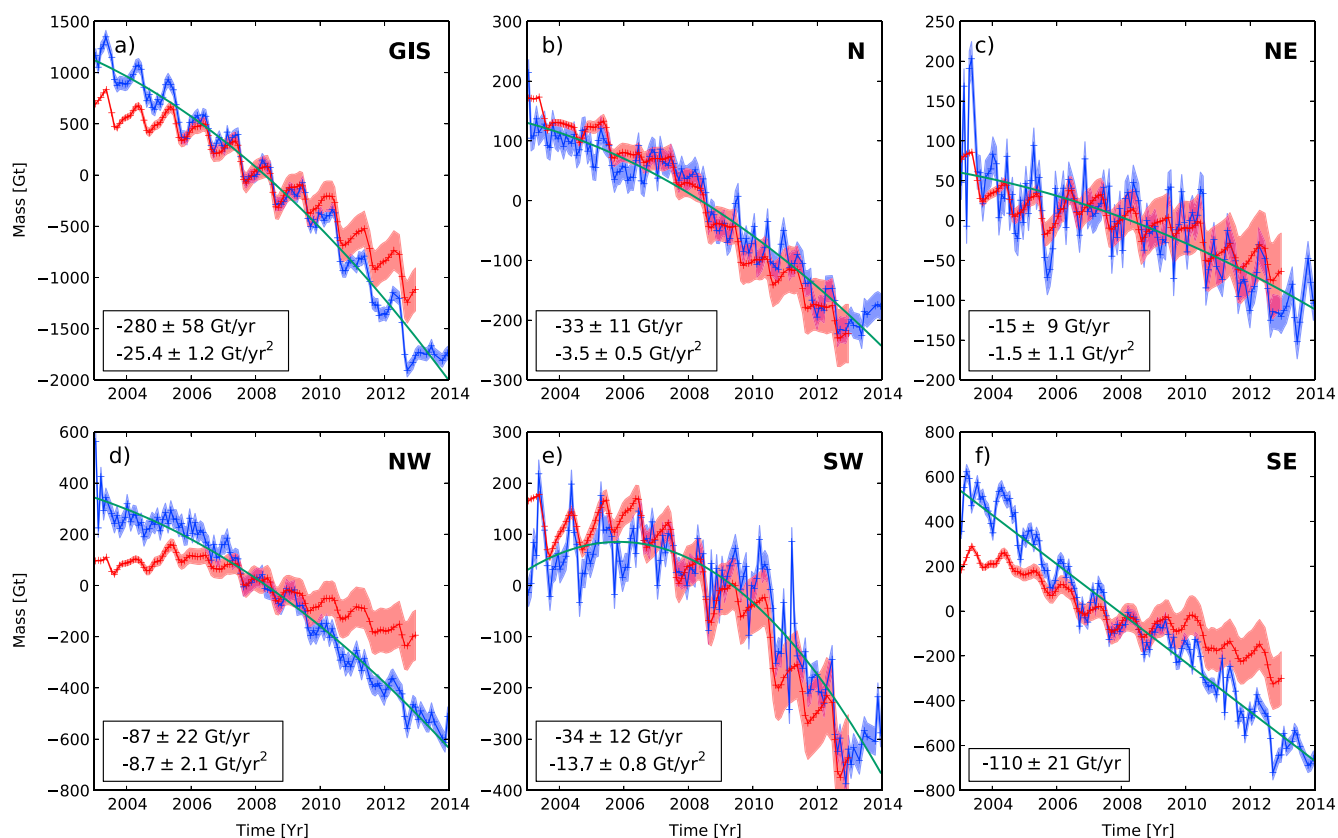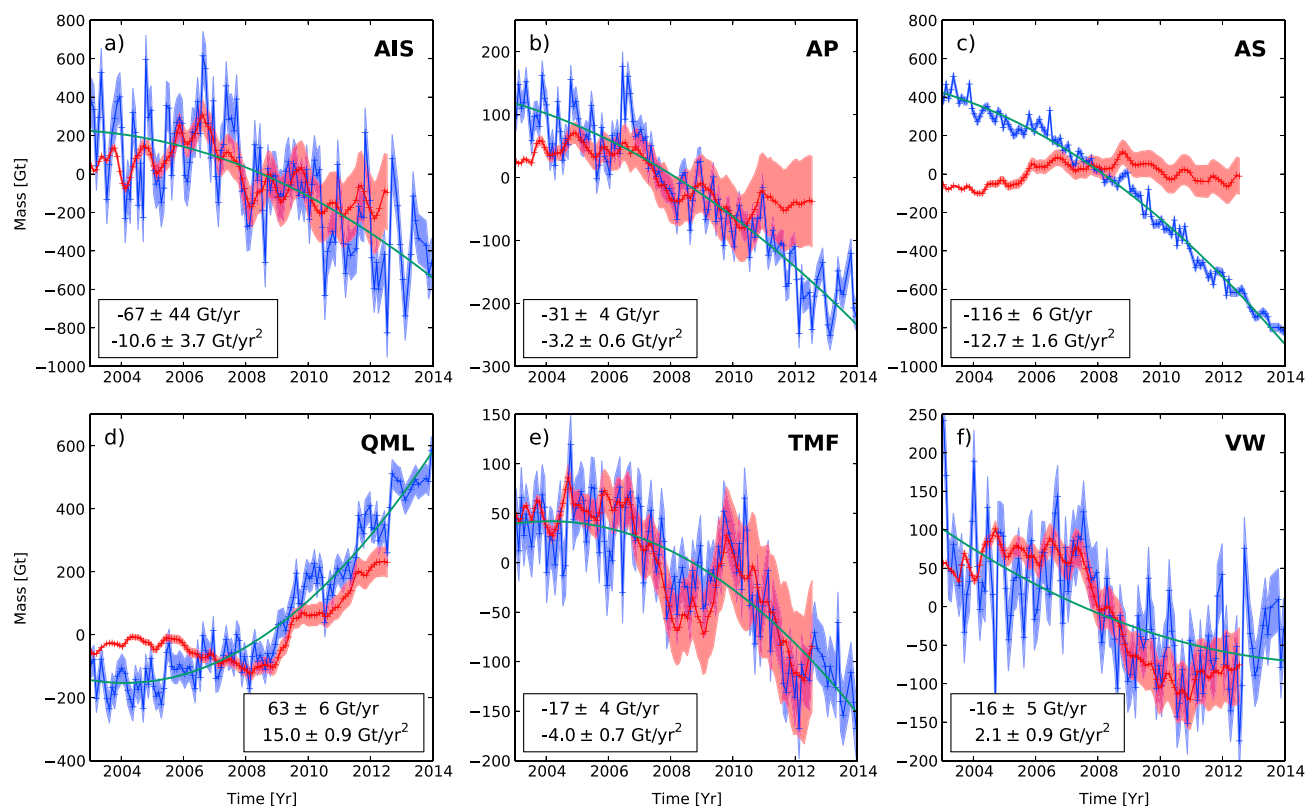
Figure 2. Time series of ice mass, $M(t)$, in Gt (Gigatonne) for (a) the entire Greenland ice sheet (GIS), (b) north (N), (c) northeast (NE), (d) northwest (NW), (e) southwest (SW), (f) southeast (SE) Greenland as shown in Figure 1. GRACE time series for January 2003 to December 2013 are in blue; the best fitting trend is in green. Light blue band are monthly errors. Time series of cumulative SMB anomaly for January 2003 to December 2012 are in red; light red band are monthly errors. Included are GRACE linear and quadratic trend estimates.

In Antarctica, we detect an overall mass loss of 67 ± 44 Gt/yr and an acceleration in loss of 11 ± 4 Gt/yr^2 during 2003–2013 (Table S1). The mass loss affects only a portion of the ice sheet (Figure 1b). The largest losses are in AS and the northern tip of AP. The mass loss in AS extends beyond its drainage into the surrounding basins. Much smaller losses are detected in VW and TMF, i.e., near Cook Ice Shelf or Totten Glacier in East Antarctica, where the GRACE signal is concentrated along the coast. Some areas are experiencing a mass gain, e.g., QML.

In contrast with Greenland, most Antarctic regions do not experience a significant acceleration in mass change (Figure 1d). We detect an acceleration in mass loss in the AS sector and on the western and southern tip of AP, and an acceleration in mass gain in QML, East Antarctica. Elsewhere in East Antarctica, acceleration values are low and generally not significant. Error maps for both ice sheets for linear trend and acceleration are shown in Figure S3.

To examine changes in ice mass quantitatively at the regional scale, we calculate time series of ice mass change for selected five regions of each ice sheet (Figures 2 and 3). Results for each region are summarized in Table S1. For Greenland, the mass loss in the SE is 110 ± 21 Gt/yr, with no significant acceleration (Figure 2f). The time series reveals that the region experienced large losses in 2003–2007, followed by a slow down in 2008–2009 and a small increase in mass loss since 2010, with the result that the overall mass change is best described as a constant. In the NW, the mass loss is 87 ± 22 Gt/yr with an acceleration in loss of 8.7 ± 2.1 Gt/yr^2. Combined together SE and NW generate 70% of the ice sheet mass loss. In the SW and N, we find accelerations in loss of 13.7 ± 0.8 Gt/yr^2 and 3.5 ± 0.5 Gt/yr^2, respectively. These regions are responsible, respectively, for 12%, or 34 ± 12 Gt/yr and 11.8%, or 33 ± 11 Gt/yr of the total loss. The SW and NW regions are the largest contributors to the total acceleration in loss, with 54% from the SW and 34% from the NW. In the NE, the mass loss of 15 ± 9 Gt/yr has an acceleration of only 1.5 ± 1.1 Gt/yr^2.

Figure 3. Time series of ice mass, $M(t)$, in Gt (Gigatonne) for (a) the entire Antarctic ice sheet (AIS), (b) the Antarctic Peninsula (AP), (c) the Amundsen Sea (AS) sector, (d) Queen Maud Land (QML), (e) the Totten/Moscow/Frost sector (TMF), and (f) Victoria/Wilkes land (VW) as shown in Figure 1. GRACE time series for January 2003 to December 2013 are in blue; the best fitting trend is in green. Light blue band are monthly errors. Time series of cumulative SMB anomalies for January 2003 to July 2012 are in red; light red band are monthly errors. Included are GRACE linear and quadratic trend estimates.

When comparing the GRACE results with the cumulative SMB anomaly time series during the common time period, January 2003 to December 2012 (Figure 2), we find that in the N, NE, and SW, most of the GRACE signal is explained by the variability in cumulative SMB anomaly (Table S2). In the SW the acceleration in loss from GRACE and SMB are 15.2 ± 0.9 Gt/yr^2 and 13.4 ± 2.6 Gt/yr^2, respectively, and 5.2 ± 0.6 Gt/yr^2 and 4.1 ± 1 Gt/yr^2, respectively, in the N. In contrast, in the SE and NW, the cumulative SMB anomaly only accounts for a small portion of the total mass change. In the SE, GRACE mass change is -108 ± 21 Gt/yr and SMB is -46 ± 9 Gt/yr. In the NW, SMB change is -33 ± 6 Gt/yr or 39% of the GRACE mass change (-85 ± 22 Gt/yr), but it accounts for most of the acceleration in loss, with 7.9 ± 1.7 Gt/yr^2 of the 10.8 ± 3.1 Gt/yr^2 detected by GRACE.

In Antarctica (Figure 3), the AP experiences a mass loss of 31 ± 4 Gt/yr, with an acceleration in loss of 3.2 ± 0.6 Gt/yr^2. The northern tip of AP, however, has a mass loss of 18 ± 3 Gt/yr and a positive acceleration of 2.5 ± 0.6 Gt/yr^2. We detect a net increase in mass loss for the entire AP after 2006, but the loss decreases in time along its northern tip. In the AS sector, the mass loss is 116 ± 6 Gt/yr, with an acceleration in loss of 13 ± 2 Gt/yr^2. This region accounts for 94% of the West Antarctic mass loss and dominates the total ice sheet mass loss. In the TMF sector, the mass loss is 17 ± 4 Gt/yr, with an acceleration in loss of 4 ± 0.7 Gt/yr^2. We note a large variability in cumulative SMB anomaly during the analyzed period. In QML, the mass balance and acceleration for the entire period are 63 ± 6 Gt/yr and 15 ± 1 Gt/yr^2, respectively. In VW, the mass change is -16 ± 5 Gt/yr, with most changes occurring between 2007 and 2010.

When comparing mass changes from GRACE and cumulative SMB anomaly during the common time period, January 2003 to July 2012, we find an excellent agreement in VW (-19 ± 5 Gt/yr for GRACE versus -24 ± 4 Gt/yr for SMB) and a good agreement in QML (16.8 ± 1.2 Gt/yr^2 for GRACE versus 18.2 ± 2.8 Gt/yr^2 for SMB) and TMF (-15 ± 4 Gt/yr for GRACE versus -17 ± 2 Gt/yr for SMB). In the AS and AP sectors, SMB only explains a small fraction of the total change in mass observed by GRACE. In AS, mass change from GRACE is -110 ± 6 Gt/yr and 6 ± 3 Gt/yr from SMB. In AP, the mass loss is 31 ± 4 Gt/yr from GRACE and 14 ± 4 Gt/yr from SMB.

Over the entire ice sheet, SMB only explains a small part of the evolution of the change in mass balance (Table S2).

4. Discussion

The agreement between GRACE and cumulative SMB anomaly in N, NE, and SW Greenland indicates that SMB dominates the variability of the GRACE data; i.e., in these regions, changes in ice dynamics are not affecting the time variability of the GRACE signal significantly. This is confirmed by observations of steady flow in these sectors, especially N and SW during the analyzed period [*Moon et al.*, 2012]. The modest acceleration of Zachariae Isstrom in the NE after 2004 [*Rignot et al.*, 2008] does not produce a detectable increase in mass loss in the GRACE data. In the SW, we find that the mass loss is mainly driven by SMB in agreement with *van den Broeke et al.* [2009] who showed that the decrease in SMB is caused by an increase in runoff. In this sector, the agreement between GRACE and cumulative SMB anomaly spans from the monthly to the decadal time scales, which increases confidence in both the GRACE analysis and the retrieval of SMB from RACMO2.

In SE and NW, we find that ice dynamics plays a significant role, which is consistent with recent studies [*Howat et al.*, 2007; *Moon et al.*, 2012]. In the SE, where the mass loss is the largest in Greenland and the contribution of ice dynamics is significant, the mass loss has remained more or less constant in time despite glacier acceleration in 2000–2005 followed by a deceleration after 2005 [*Howat et al.*, 2007]. This means that changes in SMB have coincidentally counteracted the changes in glacier discharge. Overall, in Greenland, SMB has contributed 68% of the GRACE-derived mass loss (-180 ± 33 Gt/yr versus a total loss of -265 ± 59 Gt/yr) and 79% of the observed acceleration (23.3 ± 4.7 Gt/yr^2 versus a total acceleration of 29.7 ± 1.3 Gt/yr^2) during 2003–2012.

In the NE, our mass loss and acceleration estimates do not agree with the recent analysis by *Khan et al.* [2014]. When we select a region covering the north east ice stream sector used by the same authors, we find a mass loss of 10 ± 4 Gt/yr for the entire period and an acceleration of 1 ± 0.7 Gt/yr^2 (Figure S4). The agreement between GRACE and cumulative SMB anomaly for the period January 2003 to December 2012 suggests that the mass loss is controlled mostly by a temporal variability in SMB. When we subtract the anomaly in discharge from Table 2 in *Khan et al.* [2014] from the cumulative SMB anomaly time series, the difference between the resulting time series of mass change and GRACE exceeds the error bars (Figure S4). The hypothesis that this sector is undergoing a major instability in discharge and that the glaciers sped up after 2006 is not confirmed by our data. Resolving this difference will require further study.

In Antarctica, GRACE and cumulative SMB anomaly agree in many regions, especially TMF and VW (Table S2). This provides strong support for the RACMO2 SMB reconstruction. Conversely, the difference between cumulative SMB anomaly and GRACE in the AS sector indicates that changes in glacier flow are dominant. Changes in ice flow in that region are well known [*Mouginot et al.*, 2014], and SMB accounts for less than 10% of the total mass balance during January 2003 to July 2012. In AP, SMB explains 45 ± 13% of the observed mass changes during the common period and displays no acceleration.

Prior work by *Williams et al.* [2014] compared GRACE time series at a single location inland of Totten Glacier representing an area of 250,000 km^2 with the time series of RACMO cumulative SMB anomaly for the entire drainage basin of Totten/Moscow/Frost (area 538,000 km^2). The authors found a consistent behavior between GRACE and SMB only for 2008–2010. Here our comparison of the data sets over TMF indicates a good agreement for the entire period of January 2003 to July 2012. Cumulative SMB anomaly accounts for most of the total mass balance during January 2003 to July 2012. However, increase in SMB only explains 40% of the GRACE acceleration signal during the common period. Ice dynamics may therefore play a role in this sector as suggested by recent studies [e.g., *Flament and Rémy*, 2012; *Khazendar et al.*, 2013]. Our time series is too short to be conclusive.

Similarly, over the VW region, we find that GRACE closely follows the fluctuations in cumulative SMB anomaly, which suggests that ice dynamics is currently not contributing significantly to the mass trend. There are no reports of large fluctuations in the velocities of these glaciers [*Shepherd et al.*, 2012]. Our results also do not confirm earlier conclusions for the time period 2002–2008 that a significant loss of ice is taking place in the Cook Ice Shelf region [*Chen et al.*, 2009]. We attribute these earlier reports to a temporal variability in SMB. In VW, our analysis complements the work of *Sasgen et al.* [2013] by showing that the

agreement between GRACE and cumulative SMB anomaly extends over the entire time period on a monthly basis.

We note that quadratic trends in SMB in QML, VW, and TMF do not represent a long-term trend in SMB. The increase in SMB in QML is an isolated event, while the trends in SMB in VW and TMF are well within interannual variations in SMB in those sectors [*Rignot et al.*, 2011].

Our results expand upon *Wouters et al.* [2013] who examined the entire ice sheet and concluded that most observed changes are controlled by SMB, and it is not possible to detect a projectable acceleration in loss in Antarctica with the existing GRACE time series. While their conclusion is correct for the entire ice sheet, the results are different at the regional scale. For example, in the AS sector, the uncertainty in acceleration is only 15% of the signal. Similarly, in Greenland, some regions exhibit a strong acceleration in loss, for example, 13.7 ± 0.8 Gt/yr^2 in the SW caused by an increase in runoff since the 1980s [*van den Broeke et al.*, 2009]. Hence, by examining data at the regional scale, our ability to observe acceleration in loss improves rather than degrades. Indeed, the mass changes are not uniform; hence, the signal-to-noise ratio of the mass change at the regional scale may be larger than the signal-to-noise ratio for the entire ice sheet.

The difference in fit skill between the quadratic and linear models is generally less than 5% over the analyzed regions, except for SW in Greenland and AS, QML, and TMF in Antarctica where the acceleration is large (Table S1). Yet the improvement in fitting of the GRACE data with a quadratic model is always significant at a very high confidence level (98–99%), except for VW in Antarctica (95%) and NE in Greenland (96%). SE of Greenland is the only region where a linear fit of the data is the best solution.

5. Conclusions

We evaluate the significance of linear and quadratic trends in Greenland and Antarctica at the continental and regional scales. The regions with acceleration signal appear clearly over the subcontinent and continent. The mascon analysis provides quantitative estimates of the mass loss and acceleration at the regional level. We find that the regions that drive the mass loss and acceleration are few. In Greenland, the mass loss is controlled by the SE (40%) and NW (30%); the acceleration by the SW (54%) and NW (34%). Surprisingly, the largest acceleration in loss is caused by a decrease in cumulative SMB anomaly in the SW, whereas fluctuations in ice dynamics in the SE and NW do not result in a large acceleration over the study period. In the NE, changes in mass are small, driven by changes in SMB and not suggestive of dynamic instability reported by *Khan et al.* [2014]. During 2003–2012, SMB accounts for 68% of the mass loss of the entire ice sheet and 79% of its acceleration.

In Antarctica, most of the mass loss is from AS and AP, and most of the acceleration is from the AS region. In QML, SMB has increased to yield a positive mass balance, but this is partially offset by a decrease in SMB elsewhere. Longer time series of GRACE data are required to determine the significance of changes in mass loss observed in other regions of Antarctica.

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