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Key Points:

- Regionally optimized GRACE mascons at sub-basin scale reveal mass loss of East Antarctic glaciers with multimeter sea level rise potential
- Multiple lines of evidence from GRACE and mass budget method indicate significant mass loss from Totten and Moscow University glaciers
- Sub-basin mass balance assessments from GRACE help evaluate and compare regional atmospheric climate models

Supporting Information:

- Supporting Information S1

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Mass Loss of Totten and Moscow University Glaciers, East Antarctica, Using Regionally Optimized GRACE Mascons

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Abstract Totten and Moscow University glaciers, in the marine-based sector of East Antarctica, contain enough ice to raise sea level by 5 m. Obtaining precise measurements of their mass balance is challenging owing to large area of the basins and the small mass balance signal compared to West Antarctic glaciers. Here we employ a locally optimized processing of Gravity Recovery and Climate Experiment (GRACE) harmonics to evaluate their mass balance at the sub-basin scale and compare the results with mass budget method (MBM) estimates using regional atmospheric climate model version 2.3 (RACMO2.3) or Modèle Atmosphérique Régional version 3.6.4 (MAR3.6.4). The sub-basin mass loss estimate for April 2002 to November 2015 is 14.8 ± 4.3 Gt/yr, which is weakly affected by glacial isostatic adjustment uncertainties (±1.4 Gt/yr). This result agrees with MBM/RACMO2.3 (15.8 ± 2.0 Gt/yr), whereas MBM/MAR3.6.4 underestimates the loss (6.6 ± 1.6 Gt/yr). For the entire drainage, the mass loss for April 2002 to August 2016 is 18.5 ± 6.6 Gt/yr, or 15 ± 4% of its ice flux. These results provide unequivocal evidence for mass loss in this East Antarctic sector.

Plain Language Summary Totten and Moscow University glaciers in East Antarctica drain a marine-based sector that holds an ice volume equivalent to several meters of global sea level rise. Recent observations of warm water intrusion on the continental shelf suggest that the glaciers may be changing in response to ocean warming. Understanding this glacier evolution is therefore of global significance. Measurements are difficult to obtain in this region due to the shear size of the basins and small rate of mass loss compared to other parts of Antarctica. To resolve this problem and evaluate independent estimates, we present a new methodology to process Gravity Recovery and Climate Experiment satellite gravity data that is optimized at the regional scale for these basins. Our results are in excellent agreement with independent estimates and provide unequivocal evidence that these glaciers have been losing mass rapidly for the past 15 years. We also compare different reconstructions of surface mass balance and determine that one model significantly underestimates the mass loss in this sector. A similar approach would be applicable to other parts of Antarctica to resolve residual uncertainties in its mass budget and contribution to sea level rise.

1. Introduction

The Antarctic ice sheet has been losing mass at a mean rate of 67 ± 44 Gt/yr for the time period January 2003 to December 2013, with an acceleration of 10.6 ± 3.7 Gt/yr^2 (Velicogna et al., 2014). Most of this mass loss originates in West Antarctica (WAIS) and the Antarctic Peninsula (Rignot et al., 2008). Shepherd et al. (2012) found that WAIS and Antarctic Peninsula lost 65 ± 26 and 20 ± 14 Gt/yr between 1992 and 2011, while East Antarctica (EAIS) gained 14 ± 43 Gt/yr. There are, however, large drainage sectors in EAIS that exhibit a significant mass loss and hold potential for major sea level rise. In particular, Totten glacier has a sea level rise potential of 3.9 m (Li et al., 2015) versus 3.3 m for the entire marine sector of WAIS (Bamber et al., 2009). Totten is the largest outlet glacier in EAIS (Li et al., 2016; Pritchard et al., 2009) in terms of its grounding line discharge of 71 ± 3 Gt/yr between 2003 and 2008 (Rignot et al., 2013). Li et al. (2016) reported a significant mass loss for this glacier and linked its temporal variability to changes in oceanic forcing from warm, modified, circumpolar deep water (mCDW) coming in contact with the glacier. The glacier has been thinning rapidly, up to 1.9 m/yr at low elevation between 2003 and 2007 (Pritchard et al., 2009); however, a period of cold polynya water production that reduced intrusion of warm water beneath the ice shelf reduced thinning (Khazendar et al., 2013). The nearby Moscow University ice shelf glacier—or Moscow University—has a grounding line flux of 52.3 ± 1 Gt/yr (Rignot et al., 2013). The glacier is marine based (Young et al., 2011) and contains 1.3-m sea level rise equivalent; however, evidence for ice thinning is less strong for Moscow University (Pritchard et al., 2009). Actual ice shelf basal melt rates for the time period 2003–2008 are about half (4.7 ± 0.8 m/yr) of those estimated for Totten (10.5 ± 0.7 m/yr) (Rignot et al., 2013).

Recently, intrusion of warm (+0°C to +0.5°C), salty, mCDW was found at the entrance of the sub-ice-shelf cavity in front of Totten glacier (Silvano et al., 2017). This relatively warm mCDW is present year round and fuels intensified ice shelf melt rates of magnitudes almost comparable to those observed in the Amundsen Sea Embayment of WAIS. Oceanic wind stress upwells mCDW at the continental shelf break near the Totten ice tongue, modulating its melt rate with a 19-month lag period (Greene et al., 2017). Spence et al. (2014) showed that the projected strengthening and poleward shift of southern hemispheric westerly winds under a more positive Southern Annular Mode (SAM) phase can induce significant warming of subsurface coastal waters, suggesting an acceleration in ice shelf melt in the future. Due to the vulnerability of these glaciers to enhanced mCDW intrusion in the future and its potential for considerable sea level rise, it is critical to evaluate, understand, and monitor the mass changes of these glaciers and ice shelves.

Gathering measurements in these two basins is difficult for a number of reasons. First, the glaciers have smaller rates of mass loss compared to their fast-moving counterparts in WAIS (Rignot et al., 2013), which reduces the signal-to-noise ratio when estimating mass balance. Second, the glaciers are difficult to access to airborne surveys and cover a large area, especially Totten glacier (537,900 km^2 (Li et al., 2015) versus 221,600 km^2 for Moscow University). Third, there is a lack of reference velocity near the glacier fronts for ice motion measurements, so that reference velocities required for calibration of ice motion maps must be taken from the ice divides, hundreds of kilometers away inland, yielding long calibration baselines (Li et al., 2016). Fourth, strong katabatic winds and pronounced gradients in snowfall accumulation along the coast compared to the rest of EAIS make measurements from satellites challenging because of rapidly changing surface conditions (Li et al., 2016). It is therefore important to obtain and compare independent estimates of the mass balance to gain confidence in the results and reduce uncertainties.

Li et al. (2015) documented a 3-km grounding line retreat of Totten glacier between 1996 and 2013 with interferometric synthetic aperture radar) data. Li et al. (2016) combined estimates of ice discharge with surface mass balance (SMB) data from the regional atmospheric climate model version 2.3 (RACMO2.3; Van Wessem et al., 2014) to report a mass loss of 6.8 ± 2.2 Gt/yr, with an acceleration of 0.55±0.27 Gt/yr^2 for the time period 1989 to 2015. The trend is dominated by the dynamic loss (73%), but the acceleration is almost entirely due to SMB (80%). The mass budget method (MBM) study is limited by the precision of the SMB models in this region and by a time series of only 13 ice velocity measurements from 1989 to 2015.

These limitations are partly overcome by comparing the results with monthly gravity data from the Gravity Recovery and Climate Experiment (GRACE) satellite (Tapley et al., 2004), which is not affected by the uncertainty of SMB models and provides data on a monthly basis. GRACE estimates are provided at a coarse spatial resolution, however, due to the truncation of spherical harmonics at degree 60, or 333 km (Wahr et al., 1998). This coarse resolution makes it difficult to derive basin-scale estimates of mass balance, especially if the change signal is small. A few studies have used GRACE data to study the Totten area. Chen et al. (2009) used a forward modeling scheme to estimate the mass balance of Antarctica as the sum of nine uniform areas of large change plus the remaining area of the continent. For Wilkes Land, they found an ice loss rate of 13.4 Gt/yr for the period 2002 to 2009. More recently, Williams et al. (2014) used an AR1 autoregressive model to yield a mass change of only 0.52 ± 0.98 Gt/yr with no significant acceleration near Totten glacier for the period March 2003 to July 2012. In contrast, Velicogna et al. (2014) used a uniform spherical cap least squares fit method to estimate the mass loss of the larger domain of Totten/Moscow/Frost sector at 17 ± 4 Gt/yr, with an acceleration of 4.0 ± 0.7 Gt/yr^2 for the period January 2003 to December 2013.

In this study, we employ an optimized regional spherical cap basis to recover a regional time series at the sub-basin level in the Totten/Moscow area. The goal is to reduce the uncertainty of the mass balance estimates and compare them with the MBM to improve confidence in the results. Our methodology optimizes the signal retrieval over relatively small areas, where the mass loss signal is the strongest, and fully quantifies the errors, especially those associated with the leakage of the mascons. We compare MBM estimates using two SMB models to evaluate the SMB models using GRACE. We conclude on the mass balance of the Totten and Moscow University glaciers using these multiple estimates.

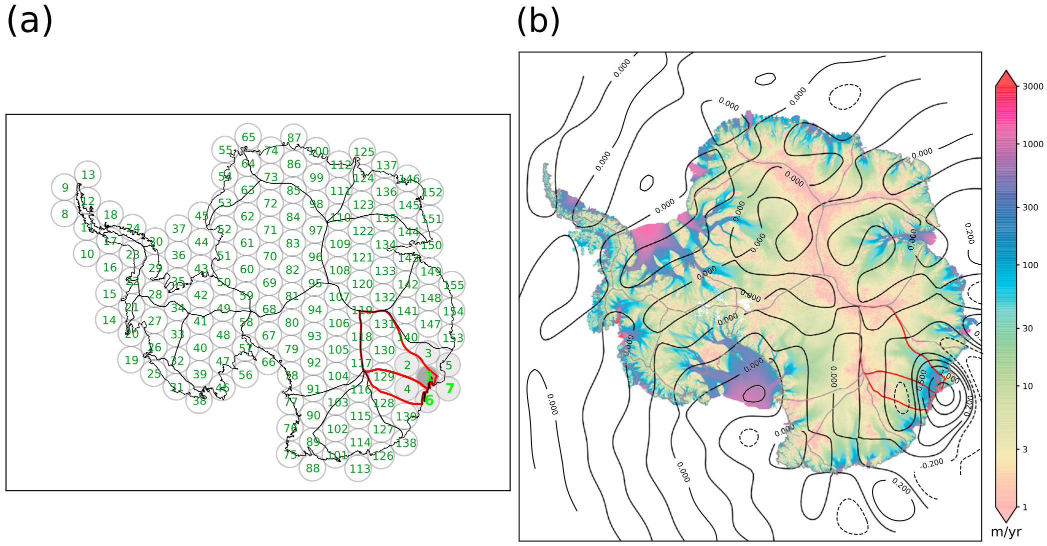

Figure 1. (a) Spherical cap basis used to derive sub-basin regional estimates of the mass balance of Totten and Moscow University glaciers, EAIS using GRACE data. Caps are inscribed in a three-layer hexagonal grid with diameters 2.7° (dark gray), 2.9° (light gray), and 3.2° (white). Black lines show Antarctic drainage basins (see Rignot et al., 2011). Red lines show the Totten and Moscow University glacier basins. The caps used for the sub-basin estimates are labeled with bold bright green numbers. (b) Sensitivity kernel for configuration 1-6-7 superimposed on ice velocity (Mouginot et al., 2012; Rignot et al., 2011, 2017). Gray lines show the major Antarctic drainage basins as in Figure 1a. Black lines show the contour levels of the sensitivity kernel. The zero-contour lines display small fluctuations in the kernel throughout the ice sheet that result in minimal leakage. EAIS = East Antarctica; GRACE = Gravity Recovery and Climate Experiment.

2. Data and Methodology

GRACE data. We use GRACE spherical harmonics of up to degree and order 60 provided in the RL05 solution from the Center for Space Research at the University of Texas (Bettadpur, 2012). Degree 1 harmonics, which are not measured in GRACE's center-of-mass frame, are calculated from the Ocean Model for Circulation and Tides (OMCT) that is already removed from the GRACE harmonics (Dobslaw et al., 2013) following Swenson et al. (2008). In our calculation of degree 1, we destripe (Swenson & Wahr, 2006) and smooth the harmonics with a 300-km Gaussian smoothing filter (as described by Wahr et al., 1998), apply pole-tide correction (Wahr et al., 2015), and subtract the glacial isostatic adjustment (GIA) signal from three different models: (1) IJ05 (Ivins et al., 2013), (2) AW13 (Geruo et al., 2013 combined with IJ05 in Antarctica), and (3) W12a (Whitehouse et al., 2012). We use an ocean function that extends 300 km from the coast. We solve the geocenter iteratively, starting from an initial estimate for ocean-land fluxes from Chen et al. (1999). We replace the $C_{2,0}$ (degree 2, order 0) harmonic by monthly solutions obtained from satellite laser ranging estimates (Cheng et al., 2013) both for the calculation of the geocenter term and for all subsequent calculations.

Spherical caps. To get regional estimates, we perform a simultaneous least squares fit of the corrected spherical harmonics to spatially defined mascons as in Jacob et al. (2012). These spatially defined regions form an orthogonal basis that allows us to transform the spherical harmonics into independent regional time series. The key to obtaining regional time series is to find an optimized basis for a given area. We use the spherical cap formalism outlined in Sutterley et al. (2014). We assume that each cap has a uniform unitary mass distribution, which is converted into the harmonic domain and smoothed with a 250-km Gaussian filter (Wahr et al., 1998). By simultaneously fitting the corrected GRACE harmonics to the spherical caps, we get a coefficient for each cap, which allows us to evaluate the regional time series. In contrast to using uniform mascons, we optimize the size and position of the spherical caps for the Totten/Moscow drainage basin. The size of a spherical cap is a compromise between the desired spatial resolution and the minimization of leakage and measurement errors. The noisy higher degree harmonics tend to increase the measurement error as the size of the caps decreases. Where we have a large signal-to-noise ratio, for example, in areas of large mass loss in the lower reaches of Totten glacier, we select smaller caps since the signal will not be masked by higher noise levels. With variable sized caps, we minimize the ringing that results from the truncation of the spherical harmonics (e.g., Swenson & Wahr, 2002). To avoid the resulting leakage, both the size and position of the caps need

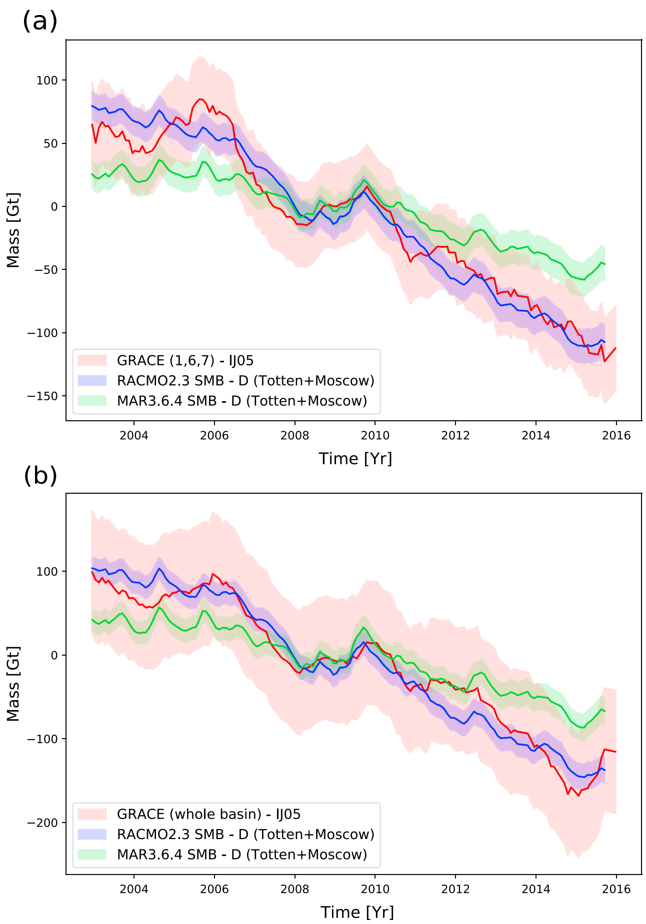

Figure 2. Optimized GRACE time series of the mass (in gigatons = 10^{12} kg) of the Totten and Moscow University glaciers, East Antarctica using IJ05 GIA correction (red) compared with ice discharge subtracted from surface mass balance estimates from RACMO2.3 (blue) and MAR3.6.4 (green) for the (a) sub-basin and (b) whole-basin configurations. GRACE = Gravity Recovery and Climate Experiment; RACMO2.3 = regional atmospheric climate model version 2.3; GIA = glacial isostatic adjustment.

to be optimized. To have truly orthogonal caps in the harmonic domain, the sensitivity kernel described in Jacob et al. (2012) needs to be 1 inside and 0 outside the cap. To optimize the spherical cap basis at a sub-basin level, we place smaller caps on regions of fast change, minimize the gap between the spherical caps, and position the caps to have more or less uniform change inside each cap. To do this, a three-layer hexagonal grid is used to inscribe caps of diameters 2.7°, 2.9°, and 3.2°. The sizes are experimentally determined to take advantage of the signal-to-noise ratio where there is large mass change while maintaining reasonable errors. The geometry of the caps is optimized to avoid leakage into or out of the Totten/Moscow glacier basin. The spherical cap configuration is shown in Figure 1a.

We follow the procedure of Velicogna and Wahr (2013) to calculate the leakage error for a given area of interest. We divide a synthetic field spatially into individual mascons, convert them to harmonics, and perform a least squares regression with the spherical caps to see how much signal is recovered. We perform the test in two ways: (1) fit each individual synthetic mascon separately to see how much signal is recovered; and (2) fit all other mascons to see how much signal leaks into the mascon of interest. We take the larger value as our leakage error. For the synthetic field, we use SMB values from the RACMO2.3 regional climate model (Van Wessem et al., 2014) and dynamic losses linearly spread as a function of speed and thickness (Rignot et al., 2011). To quantify the land/ocean leakage, we scale the sea level fingerprint of the sub-region of interest (Farrell & Clark, 1976; Hsu & Velicogna, 2017) with our GRACE-derived mass change and assume a 100% error in the leakage as a conservative estimate. Note that the GRACE harmonics have atmospheric and oceanic components removed from them (Swenson et al., 2008), and as such the nonzero sensitivity kernel (Jacob et al., 2012) of the mascons over the ocean does not contribute significantly to our estimates. We quantify the ocean-to-land leakage by fitting the GRACE-derived ocean signal coefficients (representing ocean bottom pressure) to our mascons and assume 100% error in the signal (Velicogna & Wahr, 2013). We also use monthly ocean bottom pressure from the Estimating the Circulation and Climate of the Ocean (ECCO)(Wunsch et al., 2009) model, convert them to harmonics of degree and order 60, and fit them to our Totten mascons. Taking the difference between the ECCO and GRACE-derived ocean leakages as an error estimate decreases the total error in mass loss by 0.1 Gt/yr. We use the largest of the two error estimates, that is, we assume that the leakage error is as large as the correction.

Mass budget method. To compare our estimates with independent data, we use the MBM estimates from Li et al. (2016) for Totten, where the total mass balance is SMB minus the grounding line ice flux. For Moscow University, we employ a similar approach, calculating mass fluxes from 1989 to present using ice motion measurements from various satellite data with ice thickness data from Operation IceBridge. We use SMB data from RACMO2.3 (Van Wessem et al., 2014) and MAR3.6.4 (Gallée et al., 2013) extending from January 1979 to December 2015. Cumulative SMB is calculated over the drainage area using a reference period of January 1979 to December 2008 (Shepherd et al., 2012). Total mass is calculated as the difference between cumulative SMB and cumulative discharge. The choice of the reference period does not affect the MBM results because the same value is subtracted from both the anomalies in SMB and discharge. SMB errors are calculated assuming a 6.1% error in monthly values as in Li et al. (2016). Ice discharge errors are calculated as fixed rates from the sum of percentage errors in thickness and speed, scaled by the long-term flux (Li et al., 2016). The monthly discharge errors are 2.6 Gt/yr and 2.1 Gt/yr for Totten and Moscow University glaciers, respectively, which are added cumulatively in the time series. The MBM time series only extends to November 2015.

When comparing the MBM estimates to our sub-basin GRACE results, we integrate SMB values only within the area covered by the mascons of interest to have comparable quantities. Grounding line flux anomalies

Table 1
GRACE Trends and Corresponding Errors Obtained for the Totten/Moscow University Glaciers and Comparison With the MBM Estimates at the Sub-Basin and Whole-Basin Scales

	Trend (Gt/yr)	Total error (Gt/yr)	Leakage error (Gt/yr)	Regression error (Gt/yr)	Ocean leakage (Gt/yr)	GIA error (Gt/yr)
			Sub-Basin Estimates			
April 2002 to August 2016						
GRACE (IJ05)	−14.6	4.1	2.9	2.5	0.9	0.9
GRACE (AW13)	−17.2	4.0	2.8	2.5	0.9	0.8
GRACE (W12a)	−17.5	3.9	2.8	2.5	0.9	0.8
April 2002 to November 2015						
GRACE (IJ05)	−14.8	4.3	3.0	2.7	1.0	0.9
GRACE (AW13)	−17.5	4.2	2.9	2.7	1.0	0.8
GRACE (W12a)	−17.7	4.1	2.8	2.7	1.0	0.8
MBM (MAR3.6.4)	−6.6	1.6				
MBM (RACMO2.3)	−15.8	2.0				
			Whole-Basin Estimates			
April 2002 to August 2016						
GRACE (IJ05)	−18.5	6.6	5.2	2.4	0.5	3.1
GRACE (AW13)	−17.6	6.3	5.0	2.4	0.5	2.8
GRACE (W12a)	−17.3	6.3	4.9	2.4	0.5	3.1
April 2002 to November 2015						
GRACE (IJ05)	−18.6	6.8	5.3	2.7	0.4	3.1
GRACE (AW13)	−17.7	6.4	5.1	2.7	0.4	2.8
GRACE (W12a)	−17.4	6.4	4.9	2.7	0.4	3.1
MBM (MAR3.6.4)	−9.5	2.1				
MBM (RACMO2.3)	−20.6	2.7				

Note. Leakage error refers only to the mascon-to-mascon leakage error quantified by a synthetic field on land, while ocean leakage refers to the full ocean/land leakage determined from GRACE GAD coefficients. GRACE = Gravity Recovery and Climate Experiment; RACMO2.3 = regional atmospheric climate model version 2.3; MBM = mass budget method.

are calculated with respect to the mean discharge of the entire basin for the reference period. We assume that most of the areas outside of the sensitivity kernel are not contributing to dynamic thinning of the glacier, in accordance with altimetry studies that show ice thinning only at low elevation, along fast-moving portion of the glaciers with Ice, Cloud, and Land Elevation Satellite (Khazendar et al., 2013; Pritchard et al., 2009) and CryoSat-2 (McMillan et al., 2014). We also calculate that the average ice velocity of the glaciers over the sub-basins of interest is about 14 times larger than for the rest of the basin.

3. Results

While the resolution and signal-to-noise ratio of GRACE data do not allow time series to be extracted from single caps, the most optimal sensitivity kernels are found for the triple-cap configurations 1-6-7 and 1-5-7 (see cap numbers in Figure 1). Both of these configurations pick up signal from the nearby Moscow University as well, especially 1-6-7. By examining the sensitivity kernels with respect to the drainage basins, we conclude that while 1-5-7 is more concentrated on Totten itself, it picks up a fraction of the signal from Moscow University, which makes the results more difficult to interpret. Therefore, we pick 1-6-7 for the rest of the sub-basin analysis and consider both Totten and Moscow University glaciers together. The sensitivity kernel of this configuration superimposed on top of drainage Cp-D and ice velocity (see Rignot et al., 2011, 2017) is shown in Figure 1b.

We compare the optimized GRACE time series with the MBM estimates over the subregion defined by our caps (Figures 1b and 2a). The monthly GRACE error is 33 Gt for the three caps combined. The annual MBM error is 6 Gt/yr (Li et al., 2016), which translates into a monthly error of 21 Gt. The annual MBM error does not change significantly with time during the study period. The AW13 and W12a time series produce slightly more negative trends than IJ05, but the difference is within errors. The results range from 14.8 ± 4.3 Gt/yr to 17.7 ± 4.1 Gt/yr for the period April 2002 to November 2015. More important, the GRACE time series are in excellent agreement with the MBM time series obtained with RACMO2.3 at 15.8 ± 2 Gt/yr. The MBM time series using MAR3.6.4 shows a smaller trend of 6.6±2 Gt/yr (Table 1). Note that we include the autocorrelation of the residuals when calculating the regression error. The sub-basin estimates are focused in areas with the stronger signal, allowing for smaller mascons.

Farther inland, we experience more leakage from the surrounding areas and get a noisier signal. We compare the MBM trends for the entire drainage basins versus the sub-basin area sampled by caps 1-6-7 to evaluate the proportion of the mass change that is sampled by our sub-basin configuration. Using RACMO2.3 and MAR3.6.4, we find that we recover about 81.0 ± 2.6% and 70.7 ± 4.4% of the Totten basin, respectively, and 68.7 ± 3.1% and 64.1 ± 6.0% of the Moscow University basin, respectively. The basin-wide estimates for the Totten and Moscow University glaciers are obtained by adding up mascons 1, 2, 4, 6, 7, 129, 130, and 131. As expected, this time series has larger errors, with estimates ranging from 17.4 ± 6.1 Gt/yr to 18.7 ± 6.4 Gt/yr. The basin-wide MBM trend obtained from RACMO2.3 at 20.6 ± 3 Gt/yr is in good agreement with the GRACE estimates, although the trend obtained from MAR3.6.4 (9.5 ± 2 Gt/yr) is also within uncertainty for the AW13 and W12a GIA model estimates (Table 1 and Figure S2 in the supporting information).

For the period April 2002 to August 2016, we consider a linear model based on the Akaike information criterion (Burnham & Anderson, 2004) with annual and semi-annual components. We obtain a trend in mass loss of 18.5 ± 6.6 Gt/yr using IJ05 GIA for the entire Totten and Moscow University basins. For the sub-basin, the trend is 14.6 ± 4.1 Gt/yr. We take into account the autocorrelation of the residuals with an AR1 model for the residuals, which gives us an autocorrelation coefficient of 0.08 ± 0.04. The error in the autocorrelation coefficient is found by a bootstrapping method where random Gaussian errors with a standard deviation equal to the satellite measurement error are introduced into the time series and the spread in coefficient was found within 50 iterations. The trends and the associated errors obtained from the optimized spherical cap solutions for the sub-basin and basin-wide estimates are outlined in Table 1.

4. Discussion

Our results indicate a remarkable agreement at the 5% level between the optimized GRACE time series using IJ05 GIA and the MBM time series with RACMO2.3 at a sub-basin scale. The trends for the period April 2002 to November 2015, as reported in Table 1, with all GIA models, are within error of the MBM trend obtained using RACMO2.3. The results obtained from AW13 and W12a in the Totten and Moscow University drainage basins are also in agreement, although slightly more negative than for the IJ05 time series. While all estimates agree within error, IJ05 displays the best agreement with the MBM estimates using RACMO2.3.

The MBM estimates obtained with MAR3.6.4 underestimate the mass loss in these two drainage basins, with the sub-basin trends falling outside of uncertainty bounds. Given that the same reference mean is subtracted from the SMB and discharge time series in the calculation of cumulative anomalies, we attribute the difference between the MBM time series to a low-bias in MBM/MAR3.6.4 cumulative ice loss in this region. Spatial differences in trend between the two SMB models (Figure S2) reveal that MAR3.6.4 shows less negative trends in cumulative SMB close to the grounding line. The same conclusion may not apply to other basins.

The basin-wide estimates of mass change have a larger leakage error from the surrounding areas than the sub-basin estimates. The GIA uncertainty increases as we include more interior regions in the estimate. The IJ05 GIA error increases from 0.87 Gt/yr for the sub-basin estimate to 3.13 Gt/yr for the basin-wide estimate, or 360%. The drainage-basin estimates are still in agreement with the MBM estimates. For the common period between April 2002 and November 2015, the GRACE estimate is a mass loss of 18.6 ± 6.4 Gt/yr using IJ05 GIA versus MBM estimates of 20.6 ± 2.7 Gt/yr and 9.5 ± 2.1 Gt/yr with RACMO2.3 and MAR3.6.4, respectively. While showing smaller losses over the entire drainage, MAR3.6.4 is within error of the AW13 and W12a GRACE time series.

Few studies have evaluated SMB models in this part of Antarctica. Wang et al. (2016) used in situ data to evaluate precipitation-evaporation/sublimation from global reanalyses and regional climate models including RACMO2.1 and RACMO2.3, but not MAR3.6.4. They found that RACMO2.3 shows the best agreement with in situ measurements over the whole ice sheet and in particular over the coastal sector Cp-D of the Totten and Moscow University drainage basins, which provides independent support to our findings. Velicogna et al. (2014) reported a good agreement between GRACE and RACMO2.3 cumulative SMB anomalies in the larger Totten-Moscow-Frost area, but the study did not take ice discharge into account and did not evaluate other SMB models. Gallée et al. (2005) evaluated MAR along the Wilkes Land transect in the vicinity of the Totten and Moscow University drainage basins and found discrepancies with in situ measurements in precipitation and wind transport at different locations.

The use of regionally optimized variable spherical caps for the processing of GRACE harmonics allows us to reconcile up-to-date estimates of the mass balance of Totten and Moscow University glaciers. Our results suggest a state of negative mass balance, with multiple lines of evidence. With this approach, we evaluate the performance of SMB models and identify a bias in the long-term SMB values from MAR3.6.4. The agreement indirectly provides additional confidence to the MBM results of Li et al. (2016). Our findings are weakly affected by the uncertainties in the GIA correction. Even for the basin-wide estimates where the GIA errors are larger, the GIA errors do not affect the agreement between GRACE and MBM estimates. We recommend that a similar approach be employed in other basins of Antarctica where the mass balance signal is small and not well constrained by observations. The approach also provides a pathway to evaluate and compare various SMB models.

Our study illustrates that even though the whole-basin estimates are most useful to inform us about the total contribution of each basin to sea level rise, the sub-basin analysis enables a more refined comparison, with lower uncertainties, of various estimates of the mass loss. A comparison at the sub-basin level hence provides more opportunities to interpret differences between models, here caused by a difference in the long-term average SMB between models.

The study demonstrates that the sub-basin approach with optimized spherical caps helps evaluate mass balance over small areas, with low errors because we focus on the areas with the largest signal. This methodology could be applied to similarly small parts of the ice sheets. More broadly, our approach could be used in geophysics and hydrology, for example, to evaluate ground water withdrawal more precisely over a small region. Data from the GRACE Follow-On (FO) (Flechtner et al., 2014) mission will likely improve the quality of sub-basin estimates due to the expected lower noise levels of GRACE-FO than with GRACE.

5. Conclusions

We use a set of regionally optimized spherical caps to evaluate the mass balance of the Totten and Moscow University glaciers, EAIS using GRACE harmonics at the sub-basin and entire basin scales. The spherical cap basis is designed from the signal-to-noise ratio and the geometry of mass change to extract regional time series with the lowest error. We find a good agreement with the MBM estimates using the RACMO2.3 SMB model, independent of the GIA corrections, whereas the MAR3.6.4 results yield an underestimation of the mass loss in the sub-basin region. MAR3.6.4 is within error for the whole basin with W12a and AW13 GIA corrections, but not with IJ05. For the entire Totten and Moscow University basins, the trend is 18.5 $\pm$ 6.6 Gt/yr using IJ05 for the period April 2002 to September 2016. Our results provide reduced uncertainties and higher confidence that the Totten/Moscow sector of EAIS has been losing mass relatively rapidly in the last 15 years. We recommend that a similar sub-basin approach using optimized spherical caps be used over other parts of Antarctica where independent mass balance methods must be compared or in Greenland at the regional scale.

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References

Bamber, J. L., Riva, R. E., Vermeersen, B. L., & LeBrocq, A. M. (2009). Reassessment of the potential sea-level rise from a collapse of the west Antarctic ice sheet. *Science*, *324*(5929), 901–903.

Bettadpur, S. (2012). Gravity Recovery and Climate Experiment UTCSR level-2 processing standards document (GRACE Doc. 327742, p. 16). Austin: University of Texas at Austin.

Burnham, K. P., & Anderson, D. R. (2004). Multimodel inference: Understanding AIC and BIC in model selection. *Sociological Methods & Research*, *33*(2), 261–304.

Chen, J., Wilson, C., Blankenship, D., & Tapley, B. (2009). Accelerated Antarctic ice loss from satellite gravity measurements. *Nature Geoscience*, *2*(12), 859–862.

Chen, J., Wilson, C., Eanes, R., & Nerem, R. (1999). Geophysical interpretation of observed geocenter variations. *Journal of Geophysical Research*, *104*(B2), 2683–2690.

Cheng, M., Tapley, B. D., & Ries, J. C. (2013). Deceleration in the Earth's oblateness. *Journal of Geophysical Research: Solid Earth*, *118*, 740–747. https://doi.org/10.1002/jgrb.50058

Dobslaw, H., Flechtner, F., Bergmann-Wolf, I., Dahle, C., Dill, R., Esselborn, S., et al. (2013). Simulating high-frequency atmosphere-ocean mass variability for dealiasing of satellite gravity observations: Aod1b rl05. *Journal of Geophysical Research: Oceans*, *118*, 3704–3711. https://doi.org/10.1002/jgrc.20271

Farrell, W., & Clark, J. A. (1976). On postglacial sea level. *Geophysical Journal International*, *46*(3), 647–667.

Flechtner, F., Morton, P., Watkins, M., & Webb, F. (2014). Status of the GRACE Follow-On mission. In U. Marti (Ed.), *Gravity, Geoid and Height Systems, Proceed. IAG Symp.* (Vol. 141, pp. 117–121). Berlin: Springer.

Gallée, H., Peyaud, V., & Goodwin, I. (2005). Simulation of the net snow accumulation along the Wilkes Land transect, Antarctica, with a regional climate model. *Annals of Glaciology*, *41*(1), 17–22.

Gallée, H., Trouvilliez, A., Agosta, C., Genthon, C., Favier, V., & Naaim-Bouvet, F. (2013). Transport of snow by the wind: A comparison between observations in Adélie land, Antarctica, and simulations made with the regional climate model MAR. *Boundary-Layer Meteorology*, *146*(1), 133–147.

Geruo, A., Wahr, J., & Zhong, S. (2013). Computations of the viscoelastic response of a 3-D compressible Earth to surface loading: An application to glacial isostatic adjustment in Antarctica and Canada. *Geophysical Journal International*, *192*(2), 557–572.

Greene, C. A., Blankenship, D. D., Gwyther, D. E., Silvano, A., & van Wijk, E. (2017). Wind causes Totten ice shelf melt and acceleration. *Science Advances*, *3*(11), e1701681.

Hsu, C.-W., & Velicogna, I. (2017). Detection of sea level fingerprints derived from GRACE gravity data. *Geophysical Research Letters*, *44*, 8953–8961. https://doi.org/10.1002/2017GL074070

Ivins, E. R., James, T. S., Wahr, J., Schrama, O., Ernst, J., Landerer, F. W., & Simon, K. M. (2013). Antarctic contribution to sea level rise observed by GRACE with improved GIA correction. *Journal of Geophysical Research: Solid Earth*, *118*, 3126–3141. https://doi.org/10.1002/jgrb.50208

Jacob, T., Wahr, J., Pfeffer, W. T., & Swenson, S. (2012). Recent contributions of glaciers and ice caps to sea level rise. *Nature*, *482*(7386), 514–518.

Khazendar, A., Schodlok, M., Fenty, I., Ligtenberg, S., Rignot, E., & Van den Broeke, M. (2013). Observed thinning of Totten glacier is linked to coastal polynya variability. *Nature communications*, *4*, 2857.

Li, X., Rignot, E., Morlighem, M., Mouginot, J., & Scheuchl, B. (2015). Grounding line retreat of Totten glacier, East Antarctica, 1996 to 2013. *Geophysical Research Letters*, *42*, 8049–8056. https://doi.org/10.1002/2015GL065701

Li, X., Rignot, E., Mouginot, J., & Scheuchl, B. (2016). Ice flow dynamics and mass loss of Totten glacier, East Antarctica, from 1989 to 2015. *Geophysical Research Letters*, *43*, 6366–6373. https://doi.org/10.1002/2016GL069173

McMillan, M., Shepherd, A., Sundal, A., Briggs, K., Muir, A., Ridout, A., et al. (2014). Increased ice losses from Antarctica detected by CryoSat-2. *Geophysical Research Letters*, *41*, 3899–3905. https://doi.org/10.1002/2014GL060111

Mouginot, J., Scheuchl, B., & Rignot, E. (2012). Mapping of ice motion in Antarctica using synthetic-aperture radar data. *Remote Sensing*, *4*(9), 2753–2767.

Pritchard, H. D., Arthern, R. J., Vaughan, D. G., & Edwards, L. A. (2009). Extensive dynamic thinning on the margins of the Greenland and Antarctic ice sheets. *Nature*, *461*(7266), 971–975.

Rignot, E., Bamber, J. L., Van Den Broeke, M. R., Davis, C., Li, Y., Van De Berg, W. J., & Van Meijgaard, E. (2008). Recent Antarctic ice mass loss from radar interferometry and regional climate modelling. *Nature Geoscience*, *1*(2), 106–110.

Rignot, E., Jacobs, S., Mouginot, J., & Scheuchl, B. (2013). Ice-shelf melting around Antarctica. *Science*, *341*(6143), 266–270.

Rignot, E., Mouginot, J., & Scheuchl, B. (2011). Ice flow of the Antarctic ice sheet. *Science*, *333*(6048), 1427–1430.

Rignot, E., Mouginot, J., & Scheuchl, B. (2017). *Measures InSAR-based Antarctica ice velocity map, version 2*. Boulder, CO: NASA National Snow and Ice Data Center Distributed Active Archive Center. Accessed 15 February 2018.

Shepherd, A., Ivins, E. R., Geruo, A., Barletta, V. R., Bentley, M. J., Bettadpur, S., et al. (2012). A reconciled estimate of ice-sheet mass balance. *Science*, *338*(6111), 1183–1189.

Silvano, A., Rintoul, S. R., Peña-Molino, B., & Williams, G. D. (2017). Distribution of water masses and meltwater on the continental shelf near the Totten and Moscow University ice shelves. *Journal of Geophysical Research: Oceans*, *122*, 2050–2068. https://doi.org/10.1002/2016JC012115

Spence, P., Griffies, S. M., England, M. H., Hogg, A. M., Saenko, O. A., & Jourdain, N. C. (2014). Rapid subsurface warming and circulation changes of Antarctic coastal waters by poleward shifting winds. *Geophysical Research Letters*, *41*, 4601–4610. https://doi.org/10.1002/2014GL060613

Sutterley, T. C., Velicogna, I., Csatho, B., van den Broeke, M., Rezvan-Behbahani, S., & Babonis, G. (2014). Evaluating Greenland glacial isostatic adjustment corrections using GRACE, altimetry and surface mass balance data. *Environmental Research Letters*, *9*(1), 014004.

Swenson, S., Chambers, D., & Wahr, J. (2008). Estimating geocenter variations from a combination of GRACE and ocean model output. *Journal of Geophysical Research*, *113*, B08410. https://doi.org/10.1029/2007JB005338

Swenson, S., & Wahr, J. (2002). Methods for inferring regional surface-mass anomalies from Gravity Recovery and Climate Experiment (GRACE) measurements of time-variable gravity. *Journal of Geophysical Research*, *107*(B9), 2193. https://doi.org/10.1029/2001JB000576

Swenson, S., & Wahr, J. (2006). Post-processing removal of correlated errors in GRACE data. *Geophysical Research Letters*, *33*, L08402. https://doi.org/10.1029/2005GL025285

Tapley, B. D., Bettadpur, S., Watkins, M., & Reigber, C. (2004). The Gravity Recovery and Climate Experiment: Mission overview and early results. *Geophysical Research Letters*, *31*, L09607. https://doi.org/10.1029/2004GL019920

Van Wessem, J., Reijmer, C., Morlighem, M., Mouginot, J., Rignot, E., Medley, B., et al. (2014). Improved representation of east Antarctic surface mass balance in a regional atmospheric climate model. *Journal of Glaciology*, *60*(222), 761–770.

Velicogna, I., Sutterley, T., & van den Broeke, M. (2014). Regional acceleration in ice mass loss from Greenland and Antarctica using GRACE time-variable gravity data. *Geophysical Research Letters*, *41*, 8130–8137. https://doi.org/10.1002/2014GL061052

Velicogna, I., & Wahr, J. (2013). Time-variable gravity observations of ice sheet mass balance: Precision and limitations of the GRACE satellite data. *Geophysical Research Letters*, *40*, 3055–3063. https://doi.org/10.1002/grl.50527

Wahr, J., Molenaar, M., & Bryan, F. (1998). Time variability of the Earth's gravity field: Hydrological and oceanic effects and their possible detection using GRACE. *Journal of Geophysical Research*, *103*(B12), 30,205–30,229.

Wahr, J., Nerem, R. S., & Bettadpur, S. V. (2015). The pole tide and its effect on GRACE time-variable gravity measurements: Implications for estimates of surface mass variations. *Journal of Geophysical Research: Solid Earth*, *120*, 4597–4615. https://doi.org/10.1002/2015JB011986

Wang, Y., Ding, M., Van Wessem, J., Schlosser, E., Altnau, S., van den Broeke, M. R., et al. (2016). A comparison of Antarctic ice sheet surface mass balance from atmospheric climate models and in situ observations. *Journal of Climate*, *29*(14), 5317–5337.

Whitehouse, P. L., Bentley, M. J., Milne, G. A., King, M. A., & Thomas, I. D. (2012). A new glacial isostatic adjustment model for Antarctica: Calibrated and tested using observations of relative sea-level change and present-day uplift rates. *Geophysical Journal International*, *190*(3), 1464–1482.

Williams, S. D., Moore, P., King, M. A., & Whitehouse, P. L. (2014). Revisiting GRACE Antarctic ice mass trends and accelerations considering autocorrelation. *Earth and Planetary Science Letters*, *385*, 12–21.
Wunsch, C., Heimbach, P., Ponte, R. M., & Fukumori, I. (2009). The global general circulation of the ocean estimated by the ECCO-Consortium. *Oceanography*, *22*(2), 88–103.
Young, D. A., Wright, A. P., Roberts, J. L., Warner, R. C., Young, N. W., Greenbaum, J. S., et al. (2011). A dynamic early East Antarctic ice sheet suggested by ice-covered fjord landscapes. *Nature*, *474*(7349), 72–75.