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Evaluation of Regional Climate Models using Regionally-Optimized GRACE Mascons in the Amery and Getz ice shelves basins, Antarctica

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Key Points:

- The drainage of Getz Ice Shelf, West Antarctica is rapidly losing mass whereas the drainage of Amery Ice Shelf is near balance.
- The GRACE mass balance agrees with the mass budget method with several regional climate models on Getz but only with RACMO2.3p1 on Amery.
- The GRACE-based methodology helps evaluate RCMs and increase confidence in mass balance estimates around Antarctica.

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Abstract

We develop regionally-optimized GRACE solutions to evaluate the mass balance of the drainage basins of Amery Ice Shelf, East Antarctica and Getz Ice Shelf, West Antarctica. We find that the Amery region is near-balance, while the Getz region is rapidly losing mass. We compare the results with the Mass Budget Method (MBM) combining ice discharge along the periphery with surface mass balance derived from three regional climate models: 1) Regional Atmospheric Climate Model (RACMO) 2.3p1 and 2) 2.3p2, and 3) Modèle Atmosphérique Régional 3.6.41. For Amery, MBM/RACMO2.3p1 agrees with GRACE while MBM/RACMO2.3p2 and MBM/MAR3.6.41 suggest a positive mass balance. For Getz, all estimates agree with a mass loss and the GRACE results are robust to uncertainties in Glacial Isostatic Adjustment (GIA) derived from an ensemble 128,000 forward models. Over the period 04/2002-11/2015, the mass loss of the Getz drainage basin is 22.9±10.9 Gt/yr with an acceleration of 1.6±0.9 Gt/yr^2.

Plain Language Summary

We use a regional optimization methodology for processing data from the Gravity Recovery and Climate Experiment (GRACE) to evaluate the ice mass change of the drainage basins of two major ice shelves in Antarctica and evaluate the performance of Regional Climate Models (RCMs). The Getz Ice Shelf basin in West Antarctica has shown previous disagreements between various mass balance estimates and is influenced by heterogenous conditions that make it vulnerable and challenging to study. We find this region to be in a state of accelerating mass loss. Furthermore, all three examined RCMs are in good agreement with GRACE in this region. The Amery Ice Shelf in East Antarctica is the third largest Antarctic ice shelf with a basin that has enough ice to raise sea level by 7.8 meters, but has presented challenges in previous mass balance efforts. We find the mass in this drainage basin is not changing significantly. Furthermore, only one out of the three examined RCMs agrees with GRACE observations in this region. These results suggest that the RCMs may need to be revisited in some regions of the ice sheet.

1 Introduction

The Antarctic ice sheet has been losing mass at an average rate of 109±56 Gt/yr from 1992 to 2017, equivalent to 7.6±3.9 mm of sea level rise (Shepherd et al., 2018). During that time period, the mass loss has been accelerating (Velicogna et al., 2014; Rignot et al., 2019). The evaluation of ice sheet mass balance has been primarily achieved using a combination of three techniques: 1. gravimetric estimates from the GRACE (Gravity Recovery and Climate Experiment) mission (Velicogna et al., 2014; Sasgen et al., 2013; Velicogna & Wahr, 2006); 2. volume changes estimated from a series of altimeter measurements (Pritchard et al., 2012; McMillan et al., 2014; Sutterley et al., 2018); and 3. Mass Budget Method (MBM) combining ice discharge along the periphery with Surface Mass Balance (SMB) reconstructed by regional climate models (RCMs) in the interior (Rignot et al., 2008, 2019). While there is reasonable agreement between these large-scale estimates in West Antarctica (Shepherd et al., 2018, 2012), differences exist in East Antarctica. For instance, Shepherd et al. (2018) finds a standard deviation of 37 Gt/yr across the various mass balance estimates for East Antarctica. Moreover, regional differences between mass balance estimates have not been fully evaluated around Antarctica. Differences in RCMs affect not only the confidence on mass budget and altimetry estimates, with the latter due to firn compaction models forced by RCMs (Shepherd et al., 2012), but also impact the estimation of the partitioning in mass loss between SMB processes and ice dynamics for all techniques.

In a prior study, Mohajerani et al. (2018) used a regional optimization approach for GRACE to calculate the mass balance of Totten and Moscow University glaciers at the basin and sub-basin scales and evaluate different RCMs. Here, we extend the methodology to two major drainage systems in Antarctica. First, we examine the drainage basin feeding into the Amery Ice Shelf, which includes three major glaciers: Fisher, Lambert, Mellor, and two large sectors on the flanks of Amery Ice Shelf: MacRobertson Land and American HighLand. Amery is the third largest ice shelf in area in Antarctica (Pittard et al., 2017). Here we are interested in the mass balance of the drainage basin of the Amery Ice Shelf, which holds enough ice to raise sea level by 7.8 m (Rignot et al., 2019). At present, the basin appears to be in balance based on the mass budget method (Rignot et al., 2019). This region has presented challenges in past studies caused by differences in the estimation of the position of the grounding line. While some studies place it north of the 35 km Minimum Ice Shelf Width (MISW) (Winkelmann et al., 2012; Golledge et al., 2015), others placing it to the south (DeConto & Pollard, 2016). Such differences result in major uncertainties in the mass balance of the Amery drainage basin.

Second is the drainage basin of the Getz Ice Shelf, which, according to the MBM, tripled its mass loss in 2017 compared to the 1979-2013 average, from 5 Gt/yr to 16.5

Gt/yr, for a cumulative contribution of 1mm to sea level rise from 1979 to 2017 (Rignot et al., 2019). Most of the glaciers feeding into Getz Ice Shelf have no name and are labeled using a latitude-longitude convention (Rignot et al., 2019). The ice shelf, which has a strong effect on the mass balance of the drainage basin due to its buttressing effect (Dupont & Alley, 2005), is located at a critical position in the Pacific-Antarctic coastline and strongly affected by decadal Pacific Oscillations (Jacobs et al., 2013). Spatial heterogeneity due to different oceanic regimes to the west and east of the ice self, as well as the complex bathymetry of the region make the analysis of the ice shelf evolution difficult (Jacobs et al., 2013), which in turns introduces uncertainty in the long-term mass balance of the drainage basin. In addition, previous assessments of the mass balance of the drainage basin have suggested major disagreements between GRACE and MBM estimates. For example, Sasgen et al. (2010) found that the GRACE estimate for the Getz Ice Shelf and Pine Island Glacier basins were 26 Gt/yr lower than the MBM estimate. This discrepancy could not be accounted for by the choice of the Glacial Isostatic Adjustment (GIA), or leakage from the atmosphere, ocean, or changes in other basins. The authors attributed it to an anomalous mass gain that took place during the GRACE period (August 2002 - August 2008) that was not included in their MBM estimate from 1980-2004, or possible errors in ice thickness along the grounding line. More recently, Chuter et al. (2017) used ice thickness values derived from Cryosat-2 to reassess the mass budget of Getz and deduced a near mass balance of 5±17Gt/yr for 2006 to 2008. This estimate is within one standard deviation of prior radar altimetry estimates (Shepherd et al., 2012) but far more positive than prior estimates. The authors attributed this difference to a 9 m positive bias in elevation near the grounding line in the ERS-1 digital elevation model (Griggs & Bamber, 2011). The most recent MBM estimates from this area are however based on actual thickness data, not on hydrostatic equilibrium (Rignot et al., 2019). In this study, we compare the mass balance estimates from GRACE and MBM using various RCMs to establish a greater level of confidence in the results, evaluate different RCMs, and resolve uncertainties from prior studies. We conclude on the mass loss of these major sectors and on the evaluation of RCMs.

2 Data and Methodology

We use three RCMs: 1) Regional Atmospheric Climate Model version 2.3p1 (RACMO2.3p1) (Van Wessem et al., 2014), 2) version 2.3p2 (RACMO2.3p2) (van Wessem et al., 2018), and 3) Modèle Atmosphérique Régional version 3.6.41 (MAR3.6.41) (Agosta et al., 2019). RACMO2, developed by the Institute for Marine and Atmospheric Research Utrecht (IMAU) at Utrecht University, uses the physics package of the Integrated Forecast System (IFS) of the European Centre for Medium-Range Weather Forecasts (ECMWF) along with the HIRLAM (High Resolution Limited Area Model) (Undén et al., 2002) dynamics to model SMB (Van Wessem et al., 2014) at 27km resolution. RACMO2.3p2 provides several updates to part 1, including improved topography, precipitation, and snow properties (van Wessem et al., 2018). RACMO2.3p1 is available from 1979 to 2015. RACMO2.3p2 is available from 1979 to 2016. MAR3.6.41 is a coupled surface-atmosphere regional climate model that uses the SISVAT surface scheme (Soil Ice Snow Vegetation Atmosphere Transfer) (De Ridder & Gallée, 1998), which uses the CROCUS snow model (Brun et al., 1992). The model estimates SMB at a spatial resolution of 35km for 1979 to 2017 (Agosta et al., 2019). We use the version of the model forced by the ECMWF ERA-Interim reanalysis (Dee et al., 2011) at the boundary to be consistent with RACMO2 (Agosta et al., 2019; Van Wessem et al., 2014). While the choice of the forcing reanalysis product introduces additional uncertainty, here we are interested in how the RCM parameterizations and processes diverge under the same forcing at the boundary.

To calculate MBM with each RCM, we interpolate the SMB fields to a 1km×1km polar stereographic grid and integrate the monthly values within each basin. Ice discharge is from Rignot et al. (2019) with the following errors: 3.6 Gt/yr for Amery and 4.8 Gt/yr for Getz. The regional SMB uncertainty is also from Rignot et al. (2019). The SMB and discharge time-series are added up cumulatively, and the difference of the cumulative time-series provides the total mass budget. By subtracting total cumulative discharge from SMB, we eliminate the reliance on calculating anomalies with respect to a chosen reference period, i.e. the calculation of total mass budget numbers does not depend on the choice of a reference period. Only the SMB and discharge anomalies depend on a reference period, not the total mass budget. Finally, a rate-of-change time-series is calculated by using a 36-month sliding window as described in the Supporting Information.

For each region, we get gravimetric estimates from GRACE (Tapley et al., 2004) for 2002 to 2017. We use RL06 Level-2 spherical harmonic coefficients from the Center for Space Research (CSR) at the University of Texas (Bettadpur, 2018) for the period April 2002 to August 2016. The $C_{2,0}$ coefficients, representing the oblateness of the geoid, are replaced with Satellite Laser Ranging coefficients (Cheng et al., 2013). Furthermore, in order to recover degree-1 terms representing geocenter translations not measured by GRACE in the gravitational frame of reference, we follow the methodology of the improved geocenter solution by Sutterley and Velicogna (2019), using the same corrections applied to the GRACE harmonics used in the spherical cap mascon calculation, outlined below, for consistency. The Sutterley and Velicogna (2019) solution uses an iterative method to calculate geocenter terms with the effects of self-attraction and loading. The Max-Planck-Institute for Meteorology Ocean Model (MPIOM) (Jungclaus et al., 2013) harmonics provided as part of the RL06 data release are used in combination with the GRACE mass change coefficients on land to iteratively solve for geocenter terms. The GRACE coefficients are de-striped following Swenson and Wahr (2006), smoothed with a 300-km radius Gaussian smoothing kernel (Wahr et al., 1998), and corrected with the A et al. (2013) GIA model for the geocenter calculation.

To ensure that our results are robust with respect to the GIA correction, we use the GIA statistics provided by Caron et al. (2018), which uses regional constraints and variations of ice history and earth structure through 128,000 forward modeling runs to provide a probability distribution function from which the expectation value of present-day GIA and the full covariance matrix associated with the errors are derived. Using a probability distribution function as opposed to a single GIA product allows us to assess the robustness of our results with regards to the GIA correction. We assess the GIA error using the full covariance matrix following Wahr et al. (2006). The GIA probability distribution samples a wide range of upper and lower mantle viscosities, lithosphere thicknesses, and ice history through separate scaling factors for Antarctic, Greenland, Laurentide, Cordilleran, and Fennoscandian ice sheets. The resulting covariance matrix from the Bayesian treatment of the ensemble of forward models provides larger uncertainty bounds than previous reports (Caron et al., 2018), allowing a conservative estimate of the role of GIA in the GRACE estimate.

To produce regionally-optimized estimates of mass balance from Level-2 GRACE harmonics we use the least-squares mascon approach, which uses variable-sized spherical caps described in Mohajerani et al. (2018). This procedure generates a set of regionally configured spherical caps based on the characteristics of the local mass change to calculate localized mass balance estimates from the GRACE harmonics. The caps are organized to sample roughly uniform distributions of mass. The design allows the sum of the designated mascons to capture the mass change only within the area of interest with minimal leakage from outside regions that exhibit significant mass change. A smaller size allows each cap to sample a more uniform region and refine the spatial extent of the area being sampled. However, smaller caps are more heavily influenced by noisier higher degree (shorter wavelength) harmonics (Wahr et al., 2006). Therefore, a higher mass change signal in the area of interest allows the use of slightly smaller caps without being dominated by noise. GRACE stokes coefficients are regressed against these regionally defined spherical caps with uniform and unitary mass using a simultaneous least-squares fit to calculate weights for each mascon (Jacob et al., 2012; Velicogna et al., 2014; Sutterley et al., 2014). For the areas of interest, multi-layer hexagonal grids with different resolutions are used to create the spherical caps. In the Amery region, the caps range from 2.7° to 3.2° in diameter. Our study area focuses on the sub-basin region spanning the Fisher, Lambert, Mellor, American HighLand, and MacRobertson Land basins. The basins are defined according to (Rignot et al., 2019). The sampled area is shown by caps 1,5,7 in the inset of Figure 1a. In the Getz region, the diameters range from 2.6° to 3.0°. Our study region is the drainage basin of the Getz Ice Shelf, and also covers some of the smaller neighboring regions of Hull, Land, Frostman, Lord, Shuman, Anandakrishnan, and Jackson-Perkins. The sampled area is shown by caps 1 and 2 in the inset of Figure 1b. The SMB under the kernel from these regions and the corresponding grounding line discharge are also included in our MBM estimate for the Getz region. The total discharge error for the region is 4.9 Gt/yr by adding regional errors from Rignot et al. (2019) in quadrature.

The sensitivity kernel of the mascon configuration (Jacob et al., 2012) shows that the signal is being captured by the mascons of interest in each configuration (Figure 1). Ideally, the kernel should have a value of 1 over the regions of interest and 0 elsewhere. The configurations focus on the areas of high ice velocity within each basin, or highest mass loss, with minimal uncertainty. In each region, the sensitivity kernel captures the areas of highest change and has minimal leakage elsewhere. Furthermore, by showing where the signal is being sampled, the kernel in Figure 1 illustrates that there are no effects from the small gaps between the spherical caps due to the tails of the truncated harmonics extending beyond the exact boundaries of the caps (Swenson & Wahr, 2002). While most of the ringing is diverted to the ocean where the mass change signal is smaller, there are small variations of the kernel around the zero contour throughout the ice sheet, yet both the land/ocean leakage and the leakage from other basins are fully quantified, as outlined below.

The land/ocean leakage is calculated in two ways. First, the sea level fingerprint of the region of interest (Hsu & Velicogna, 2017) is scaled by the total mass change derived from GRACE. This calculation produces an estimate of the contribution from land to ocean, which is used to adjust the mass loss trend. We assume a conservative error of 100% in the error budget for this correction. In addition, we take into account the contribution of the ocean signal that leaks into the mascons of interest. While the sensitivity kernels in Figure 1 have ringing over the ocean, the atmospheric and oceanic components are removed from the GRACE GSM harmonics and therefore there is minimal signal in these areas. As a conservative estimate, we use the total ocean signal provided by the GRACE ocean (GAD) harmonics, which correspond to the MPIOM ocean model (Jungclaus et al., 2013) to calculate the ocean leakage error. This is accomplished by fitting the GAD coefficients to the mascons of interest and calculating the trend and acceleration of this leakage signal. The mascon-to-mascon leakage on the ice sheet is taken into account in the error budget. We use a synthetic mass budget field derived from modeled SMB and linearly-distributed dynamic loss as a function of ice thickness and speed following Rignot et al. (2011). The synthetic field is divided up between the spherical caps for each configuration and converted to harmonics. The leakage is calculated by fitting the synthetic harmonics derived from each spherical cap to the mascons and quantifying the recovered signal for each cap. The leakage is calculated using two distinct measures: 1) "island leakage", which refers to how much signal leaks *outward* from a mascon of interest to other mascons, and 2) "hole leakage", which refers to how much signal leaks *inward* from other regions to the mascon of interest. This is similar to the leakage calculation in Mohajerani et al. (2018) with a few important updates: instead of taking the maximum value between the "island" and "hole" leakages as the total leakage, we calculate the difference between the two. This approach produces a better assessment of the overall effect of leakage in the regions of interest. While taking the differences reduces the leakage value in some cases, it may also increase it if the two leakage solutions have opposite signs. The other change in the leakage calculation is to use an updated synthetic field with discharge values from Rignot et al. (2019) and RACMO2.3 p1 and p2 SMB values. The total mass budget synthetic field is calculated by spreading the total discharge value in each basin as a function of the flux density calculated from ice speed and ice thickness. The ice speed is obtained from the MEaSUREs ice velocity data (Rignot et al., 2017) and ice thickness is from Bedmap2 (Fretwell et al., 2013). We use the total mass budget as the synthetic field instead of taking the maximum leakage obtained from SMB-only and MBM fields, which provides a more accurate leakage estimate with a more realistic synthetic field.

The interpolated SMB values are integrated within the kernel to produce analogous estimates to the GRACE measurements. We use a threshold of 5% in how much signal is captured by the kernel to construct polygons around the regions of interest for the integration. In other words, anything that is captured by GRACE at the 0.95 level will be present in the MBM integration. This threshold reduces the effect of small fluctuations near zero in the kernel field. However, because the mascons are designed around the areas of high mass change, the low values of the kernel are in regions of smaller change and thus the value of the threshold does not have a significant impact on the results.

3 Results

Figure 1 shows the time-series of mass change, dM/dt, of the regionally-optimized GRACE solutions and the corresponding mascon configuration and sensitivity kernels, and the MBM time-series derived from RACMO2.3p1, RACMO2.3p2, and MAR3.6.41 for Amery and Getz. The GRACE trend errors are calculated using the leakage, regression, GIA, and ocean leakage errors as described in the previous section. The corresponding errors for the MBM time-series are calculated from the regression error combined with the SMB and discharge errors outlined in the previous section. The full breakdown of the trend errors is in Table 1. For each region, we calculate a trend and acceleration according to the Bayesian Information Criterion (BIC) (Burnham & Anderson, 2004). For Amery, the GRACE estimate indicates near balance, with a linear trend of 1.8±5.0 Gt/yr. The MBM estimate using RACMO2.3p1 agrees with the GRACE estimate within -0.4±2.7 Gt/yr. While the GRACE and MBM/RACMO2.3p1 estimates are statistically in near-balance, the MBM/RACMO2.3p2 and MBM/MAR3.6.41 exhibit statistically significant positive trends. Table 1 lists all trends for the common period of April 2002 to November 2015.

In contrast to Amery, none of the RCMs show a bias with respect to GRACE in the Getz region. As shown in panel (b) of Figure 1, the GRACE and MBM time-series are in excellent agreement. As outlined in Table 1 the GRACE estimate yields a loss of 22.9±10.9 Gt/yr. The GRACE errors are larger in this area as a result of a larger leakage error. The leakage error poses a special challenge in this small sub-basin region given that it is adjacent to the highest mass loss of the entire ice sheet recorded in the Amundsen Sea Embayment sector of West Antarctica (Velicogna et al., 2014). The corresponding MBM mass loss estimates are 23.7±6.2 Gt/yr, 23.8±6.3 Gt/yr, and 25.4±6.3 Gt/yr for MAR3.6.41, RACMO2.3p1, and RACMO2.3p2 models, respectively, which are in excellent agreement with GRACE. The close agreement between estimates provide confidence in the mass balance assessment using these independent methods. This area also exhibits an acceleration in mass loss. Table 1 outlines the acceleration and corresponding error for regions where a quadratic regression model is applicable. This is analogous to Table 1, excluding the GIA errors, which do not affect the acceleration since the GIA correction is a constant signal. We find an acceleration in mass loss of 1.6±0.9 Gt/yr^2 with GRACE, in agreement with the acceleration of 2.0±0.2 Gt/yr^2 from MBM.

4 Discussion

Our regionally-optimized GRACE estimates indicate that the Amery region is near balance, which confirms Rignot et al. (2019) using the MBM/RACMO2.3p1. This is also in agreement with previous in-situ measurements. Wen et al. (2007) used a combination of remote-sensing and in-situ data to find a near-balance mass budget of -2.6±6.5 Gt/yr for Lambert, Mellor, and Fisher glaciers. Similarly, Wen et al. (2014) found these glaciers to be in balance within 2.9±3.6 Gt/yr by combining SMB from RACMO2.1 with discharge derived from interferometric synthetic-aperture radar (InSAR)-derived ice velocity and BEDMAP (Lythe & Vaughan, 2001) and PCMEGA (Prince Charles Mountains Expedition of Germany and Australia) (Damm, 2007) derived ice thickness, which is in agreement with MBM/RACMO2.3p1. In contrast, Yu et al. (2010) found a significantly more positive trend of 22.9±4.4 Gt/yr for the grounded portion of the Amery Ice Shelf system by utilizing ICESat and InSAR with a refined grounding line position derived from SAR and MODIS data. However, our findings suggest that this result overestimates mass gain in the region, which may reflect the quality of the SMB model in Vaughan et al. (1999). The RACMO model used by Wen et al. (2014) has lower accumulation levels in the Lambert region compared to that in Vaughan et al. (1999).

In the Getz area, GRACE yields a mass loss of 22.9±10.9 Gt/yr and acceleration of 1.6±0.9 Gt/yr^2, within errors of the mass loss of 16.5 Gt/yr in 2017 from Rignot et al. (2019). Our estimate agrees with radar altimetry results from McMillan et al. (2014)

(22±3Gt/yr for 2010-2013) and GRACE from King et al. (2012) (23±3Gt/yr for the larger drainage basin in 2002-2010). Previous MBM estimates using ice thickness from Cryosat-2 (Chuter et al., 2017) however yielded a positive trend of 5±17Gt/yr, which does not agree with GRACE despite the large uncertainty bound. Our MBM trends, all in excellent agreement with GRACE, do not confirm this positive estimate, which implies that the Cryosat-2 derived thicknesses were probably too low, which is probably a result of uncertainties in firn depth correction. Similarly, the gravimetric estimate of Bouman et al. (2014) yields a significantly larger loss of 55±9 Gt/yr from November 2009 to June 2012 by combining GRACE with GOCE (Gravity Field and Steady-State Ocean Circulation Explorer) (Visser et al., 2002). The agreement between our independent GRACE and MBM estimates suggest that this earlier estimate of the mass loss is too high. Furthermore, with the regionally-optimized mascon approach, we successfully isolated the mass balance of the Getz drainage basin with a mascon-to-mascon leakage error that is only 45% of the total signal (Table 1). Considering the proximity of this region to the high mass change signal of Amundsen Sea Sector glaciers, we conclude that this demonstrates the practicality of our approach at the sub-basin scale in Antarctica.

In the Amery region, we find that MBM/RACMO2.3p1 is in agreement with GRACE, while MBM/RACMO2.3p2 and MBM/MAR3.6.41 produce trends that are too positive. This result is consistent with those of Mohajerani et al. (2018) on Totten and Moscow University glaciers in East Antarctica (Figure S1). Given that all mass budget estimates in a given region share the same discharge values, the differences must be attributed to the SMB models. As outlined in Section 2, the cumulative time-series are calculated by integrating the total monthly SMB and discharge values through time. As a result, different trends in the MBM time-series must be attributed to either disagreeing temporal variability or differences in mean SMB across models. The monthly SMB time-series do not exhibit statistically significant trends in any of the regions. However, there are considerable differences in the mean magnitude of monthly SMB time-series, as outlined in Table S1 Larger monthly magnitudes lead to faster cumulative growth compared to the cumulative discharge time-series, resulting in a more positive MBM time-series. It is important to emphasize that this result does not depend on a reference period since the mass balance is simply the difference between absolute SMB and absolute discharge.

In the Amery region, where MBM/RACMO2.3p2 and MBM/MAR3.6.41 do not agree with GRACE, the mean SMB values appear to be more than 10 Gt/yr larger compared to RACMO2.3p1, yielding a more positive MBM trend consistent with Table 1. In the Getz area, the mean SMB values are in better agreement across all models, consistent with the agreement between MBM estimates and GRACE in Figure 1 and Table 1. Given that the monthly SMB time-series do not exhibit significant trends and the discharge values are the same across the MBM estimates, we conclude that the differences in mean SMB account for most of the disagreement between various MBM estimates. This conclusion enables us to perform a simple adjustment of the SMB time-series with the ratio of mean magnitude of RACMO2.3p1 to that of each model during the reference period, given that MBM/RACMO2.3p1 has the best agreement with GRACE. Figure S2 shows the adjusted time-series for Amery, where the mean SMB from RACMO2.3p2 and MAR3.6.41 are lowered by 87.9%, and 87.1% respectively.

The modifications brought to RACMO2.3 version p2 compared to p1 made the coastline of East Antarctica drier and the interior regions wetter. Our assessment suggests that the model modifications may need to be revisited in light of our multi-sensor assessment, at least in the regions examined herein. In contrast, the impact of the model upgrade is negligible in the examined portions of West Antarctica, where the multi-sensor results agree within errors. Importantly, our results increase confidence in the large mass loss observed in the Getz Ice Shelf sector of West Antarctica and its acceleration in mass loss. We posit that this sector is strongly affected by enhanced intrusion of warm CDW on the continental shelf and beneath the ice shelf, which melts the ice shelf and glaciers, allows the glacier grounding lines to retreat, speed up the ice flow, which contributes to sea level rise. In contrast, the Amery region is far from the sources of warm CDW and its unique geometry provides buttressing on three sides of the ice shelf. The drainage basin appears to be in a state of mass balance.

5 Conclusions

We quantify the mass balance of the drainage basins of two major regions of Antarctica, the Amery Ice Shelf in East Antarctica, and the Getz Ice Shelf in West Antarctica, using regionally-optimized GRACE mascons with minimal leakage. We compare the GRACE results with the Mass Budget Method (MBM) estimates using three different RCM output products. The Amery basin is in a state of mass balance, in agreement with MBM/RACMO2.3p1, but not with higher previous estimates of Yu et al. (2010). Furthermore, we find MBM/RACMO2.3p2 and MBM/MAR3.6.41 produce significant positive trends of 8.8 ± 2.9 and 9.4 ± 2.7 Gt/yr, respectively. These differences are attributed to the magnitude of the mean monthly SMB values. Over Getz, we report a significant mass loss of 22.9±10.9 Gt/yr, in agreement with all MBM estimates. These estimates do not confirm positive trends derived with Cryosat-2 (Chuter et al., 2017) and more negative trends from other gravimetric results (Bouman et al., 2014). The Getz region exhibits an accelerating loss at 1.6±0.9 Gt/yr^2, hence contributing to sea level rise at an accelerated pace. Overall, the regionally-optimized GRACE solutions provide an independent evaluation of the RCMs. Documenting and understanding the sources of these differences provides valuable insights about model performance that will subsequently help improve RCMs and remove residual uncertainties in the mass budget of Antarctica.

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Table 1. Trends and accelerations and associated errors for the Amery and Getz drainage basins, Antarctica, from April 2002 to November 2015 (shifted to mid-month values to match GRACE). For each drainage basin the results obtained from GRACE corrected with Caron et al. (2018) GIA model from the expectation of a probability distribution from 128,000 forward models, and the Mass Budget Method (MBM) estimates obtained from RACMO2.3p1, RACMO2.3p2, and MAR3.6.41 are shown. The leakage between mascons is estimated from a synthetic field, while the ocean leakage is obtained from the GRACE coefficients representing ocean-only changes (GAD coefficients).

	Trend / Acc.	Total Error	Leakage Error	Regression Error	Ocean Leakage	GIA Error
Trend[Gt/yr]						
Amery						
GRACE	1.77	5.04	2.36	1.55	-0.73	4.11
MBM/MAR3.6.41	9.45	2.72				
MBM/RACMO2.3p1	-0.39	2.65				
MBM/RACMO2.3p2	8.85	2.88				
Getz						
GRACE	-22.91	10.91	10.28	1.44	0.56	3.21
MBM/MAR3.6.41	-23.64	6.19				
MBM/RACMO2.3p1	-23.84	6.27				
MBM/RACMO2.3p2	-25.35	6.28				
Acceleration[Gt/yr^2]						
Getz						
GRACE	-1.57	0.88	0.25	0.82	0.04	–
MBM/MAR3.6.41	-1.56	0.21				
MBM/RACMO2.3p1	-2.01	0.19				
MBM/RACMO2.3p2	-1.77	0.24				

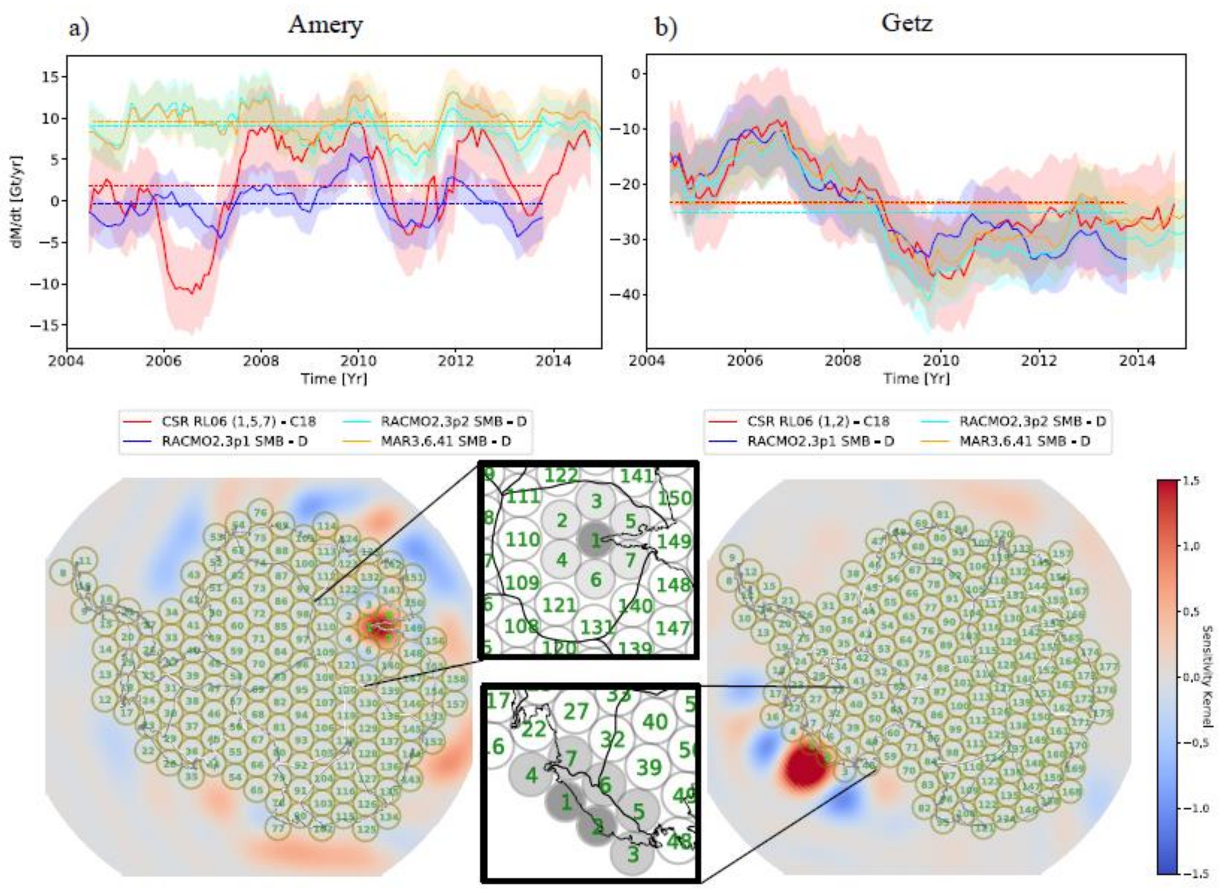

Figure 1. The rate of mass change time-series (dM/dt) in gigatons per year (10^{12} kg per year) obtained from a 36-month sliding window for **(a)** Amery and **(b)** Getz drainage basins, Antarctica, comparing the regionally optimized GRACE time-series (red) with the Mass Budget Method (MBM) estimate using RACMO2.3p1 (blue), RACMO2.3p2 (cyan), and MAR3.6.41 (orange). The dotted lines represent the mean trend during the common period. The corresponding mascon configurations and sensitivity kernels are shown below each time-series. The spherical caps are shown in gray circles, with the corresponding numerical labels in green. The caps used for the mass balance estimate are labelled in bright green. The insets show zoomed-in views of the caps of interest, with the lighter colors corresponding to increasing diameter — Amery: 2.7° (black), 2.9° (gray), and 3.2° (white); Getz: 2.6° (black), 2.8° (gray), and 3.0° (white).