



Improving Spatial Resolution of Ice Sheet Mass Change using a Data Combination of Satellite Gravimetry and Altimetry

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Abstract. We present two decades of monthly Antarctic mass change at a spatial resolution of $(100 \text{ km})^2$, representing an order of magnitude improvement over the current state-of-the-art for gravity-derived estimates. This advancement is achieved by leveraging the accuracy of satellite gravimetry over larger spatial scales and the spatial resolution of altimetry at finer spatial scales. We do this through a formal data combination of satellite gravimetry and altimetry observations at the level of the gravimetry normal equations, estimating 1° circular disk mascon elements. The data combination yields independent mascon estimates, yielding effective spatial resolution of 1° . Gravimetry observations dominate the solution at long wavelengths, while altimetry observations are the dominant contributor at the spatial scale of an individual mascon. This yields a mass change solution that is closely aligned with gravimetry-only solutions from GRACE and GRACE-FO over larger spatial scales, yet spatially resolves mass change variability at finer scales. Additionally, we provide a set of gain factors to further downscale the mass within each mascon, providing monthly mass change estimates at a 1.92 km spatial scale. Uncertainties from measurement systems and model corrections (glacial isostatic adjustment, firn air content) are propagated through the data combination and presented. The methodology presented is extensible to other regions around the globe.

1 Introduction

The Gravity Recovery and Climate Experiment (GRACE) mission (Tapley et al., 2004), along with its successor, GRACE Follow-On (GRACE-FO) (Landerer et al., 2020), have cumulatively provided more than two decades of observations of mass change across the Earth system. These observations have greatly increased our understanding of changes in groundwater storage, ice sheet and glacier mass, and ocean mass (Rodell et al., 2018; Velicogna et al., 2020; Gardner et al., 2013; Chambers et al., 2009; Tapley et al., 2019). Observations from GRACE and GRACE-FO (GRACE/-FO) are limited to approximately $(300 \text{ km})^2$ spatial resolution at monthly timescales with an accuracy of approximately 2 cm equivalent water height (EWH)



(Wahr et al., 2006). Future satellite gravimetry mission architectures under consideration for implementation aim to improve this by about a factor of four, down to $(200 \text{ km})^2$ (Wiese et al., 2022; Daras et al., 2024). Improvements in spatial resolution beyond $(200 \text{ km})^2$ with satellite gravimetry alone are challenging due to limitations inherent to sampling near-surface mass variations at satellite altitudes of 400-500 km.

25 In contrast, radar and laser satellite altimeters measure surface height changes at high spatiotemporal resolution, providing monthly sampling at the kilometer scale. Altimeters measure changes in height between repeat observations and do not directly measure changes in mass. Surface height changes measured over land ice (glacier and ice sheets) can be converted to surface mass changes and compared against observations from GRACE and GRACE-FO, after applying a series of model corrections. Community reports comparing the two techniques show reasonable agreement (IMBIE et al., 2018); however, mass change
30 inferred from satellite altimetry observations exhibits higher errors. The limiting error in converting surface height change to mass change is uncertainties in modeled correction for changes in snow and ice density, or firn air content (FAC), that occur between repeat observations of surface height (Smith et al., 2020).

Due to their complementary sampling characteristics (i.e. the accuracy of gravimetry and spatial resolution of altimetry), these two observation types naturally lend themselves to a joint inversion framework. Several authors have had success with
35 such an approach. Forsberg et al. (2017) was one of the first to demonstrate its utility, showing improved spatial resolution trend maps from 2010–2015 over Greenland and Antarctica using a joint inversion approach. Sasgen et al. (2019) showed similar improvements in trend estimation over Antarctica (2011–2017) using a spectral combination of GRACE and CryoSat-2 data. Kim et al. (2022) estimated high-resolution monthly mass change from 2003–2016 over Antarctica where satellite altimetry observations were introduced as a constraint when post-processing Level-2 GRACE spherical harmonic solutions
40 using constrained linear deconvolution. Similarly, Wang et al. (2024) used a different technique, where 25 km mascons were fit to GRACE and GRACE-FO spherical harmonic solutions using satellite altimetry observations as a constraint to estimate high-resolution monthly mass change over Greenland from 2002–2022. Other studies have exploited a joint inversion framework to simultaneously estimate and separate ice sheet mass change trends from glacial isostatic adjustment (Martín-Español et al., 2016; Gao et al., 2019; Willén et al., 2024).

45 The data combination approach we present here is unique relative to previous work, combining altimetry observations with GRACE/-FO Level-1 data products (inter-satellite range-rate and GNSS carrier phase and pseudorange observations). The data combination happens at the level of the GRACE/-FO normal equations and has the explicit advantage of having all data types influence the estimation of monthly mass change simultaneously with nuisance parameters such as accelerometer biases/drifts/scales and empirical range-rate 1 cycle-per-revolution biases and rates to suppress correlated error in the system
50 due to non-isotropic observability in the GRACE/-FO measurement system (Wiese et al., 2012). Our approach explicitly quantifies spatial leakage error through inspection of the *a posteriori* covariance matrix from the normal equation combination, and propagates uncertainties from all measurement systems and systematic errors due to model corrections through the data combination.

Our goal is to improve the spatial resolution and accuracy of ice sheet mass change estimates, an objective that has been
55 called for in several recent community reports. Pail et al. (2015) set target requirements for observing mass change at a spatial



resolution of $(100 \text{ km})^2$ at monthly timescales with an error of 50 cm EWH, approximately an order of magnitude improvement in accuracy relative to the current state of the art. In this paper, we demonstrate fulfillment of this community target requirement for Antarctica. More recently, the community set a more ambitious goal of observing monthly ice sheet mass change at $(100 \text{ km})^2$ spatial resolution with an accuracy of 1 cm EWH (Wiese et al., 2022) based on recommendations from the 2017–2027 United States National Academy of Sciences Decadal Survey for Earth Science and Applications (National Academies of Sciences, Engineering, and Medicine, 2018). Our study makes significant progress towards satisfying the goals outlined in Wiese et al. (2022) for the Antarctic Ice Sheet, even achieving it in some regions of East Antarctica (Figure 1). The remainder of the paper describes the data and methods used (Section 2) followed by results (Section 3) and discussion (Section 4).

2 Data and Methods

We present a consistent framework within which satellite gravimetry and altimetry observations are combined to produce high accuracy estimates of mass change at spatial scales finer than $(300 \text{ km})^2$. The data combination occurs at the level of the normal equations utilized in satellite gravimetry data processing (Watkins et al., 2015). The system of equations solved is

$$\begin{cases} (H_G^T W_G H_G + \bar{P}_{0,G}^{-1}) \hat{x}_0 = H_G^T W_G y_G + \bar{P}_{0,G}^{-1} \bar{x}_{0,G}, \\ (H_A^T W_A H_A + \bar{P}_{0,A}^{-1}) \hat{x}_0 = H_A^T W_A y_A + \bar{P}_{0,A}^{-1} \bar{x}_{0,A}. \end{cases} \quad (1)$$

In Equation 1, H_G and H_A represent the design matrices relating gravimetry and altimetry observations (y_G and y_A) to a common set of state parameters, $\hat{x}_0$. W_G and W_A represent the data weight matrices for gravimetry and altimetry observations, respectively, where the diagonal elements of this matrix are defined as $1/\sigma^2$, with σ defined as the standard deviation of the observations. In our formulation, $\hat{x}_0$ is a set of 41,164 equal-area 1° flat mascon disks (Section 2.1) distributed on the surface of an ellipsoidal Earth. The radius of each mascon disk is 55.66 km. Analytical partial derivatives relate inter-satellite range-rate observations and GNSS carrier phase and pseudorange observations from GRACE/-FO to each mascon at all observation times; these partial derivatives are evaluated along the orbit and accumulated over a month to form the H_G matrix. H_A is the identity matrix after applying pre-processing corrections (Section 2.4.2) to derive altimetry observations (y_A) that can be interpreted as surface mass change. Finally, $\bar{P}_{0,G}$ and $\bar{P}_{0,A}$ represent the *a priori* covariance for each data type, while $\bar{x}_{0,G}$ and $\bar{x}_{0,A}$ are the *a priori* estimates of the state parameters $\hat{x}_0$ for each data type. Each of these terms and their application is discussed below.

2.1 Mascon Disk Model

The implementation of the flat mascon disk model for global gravity solutions is a simplification of the spherical cap mascon model described in Watkins et al. (2015), and represents the first such implementation to our knowledge. We note that this formulation is mathematically different from that used to estimate global 1° mascon solutions produced by other centers (Save et al., 2016; Loomis et al., 2019a), which rely on spherical harmonic expansions of mascon elements. Here, we describe the



85 flat mascon disk model (Sunseri, 2010), which represents a computationally efficient alternative to the spherical cap mascon model.

Each mascon disk i is centered at body-fixed spherical coordinates $(R_i, \lambda_i, \varphi_i)$, where R_i is the distance from the Earth's center of mass, λ_i is the longitude, and φ_i is the latitude. The coordinate transformation matrix $\mathbf{B}_i$ from the Earth-fixed frame to the local topographic mascon coordinate system (where the z -axis points radially outward from the Earth's center, the x -axis points south, and the y -axis points east) is given by:

$$\mathbf{B}_i = \mathbf{R}_y(\varphi_i - 90^\circ) \mathbf{R}_z(\lambda_i) \quad (2)$$

Let $\boldsymbol{\rho} = [\rho_x, \rho_y, \rho_z]^T$ represent the spacecraft position vector in the local mascon-centered coordinate system:

$$\boldsymbol{\rho} = \mathbf{B}_i \mathbf{r}_b - \begin{bmatrix} 0 \\ 0 \\ R_i \end{bmatrix} \quad (3)$$

where $\mathbf{r}_b$ is the body-fixed, Earth-centered spacecraft position vector.

95 Following Wong et al. (1971), the flat disk mascon is mathematically formulated by taking an oblate spheroid of uniform density and evaluating the limit as its semi-minor axis (thickness) $c \rightarrow 0$. Integrating the volume element in cylindrical coordinates yields a non-uniform surface mass density distribution $\sigma(r)$ across the disk of radius a :

$$\sigma(r) = \frac{3m}{2\pi a^2} \sqrt{1 - \frac{r^2}{a^2}}, \quad 0 \leq r \leq a \quad (4)$$

100 where r is the radial distance from the disk center, and m is the mass of the mascon. This density distribution concentrates the mass toward the center of the disk, tapering smoothly to zero at the disk boundaries.

The gravitational attraction exerted by this disk on an external spacecraft is evaluated using Ivory's Theorem (Moulton, 1914). The spacecraft is assumed to lie on a confocal boundary ellipsoid defined by:

$$\frac{\rho_x^2 + \rho_y^2}{a^2 + \kappa} + \frac{\rho_z^2}{\kappa} = 1 \quad (5)$$

Solving this relation for the positive parameter κ yields $\kappa = a^2 k$, where:

$$105 \quad k = \frac{1}{2} \left[\left(\frac{\rho^2}{a^2} - 1 \right) + \sqrt{\left(\frac{\rho^2}{a^2} - 1 \right)^2 + 4 \frac{\rho_z^2}{a^2}} \right] \quad (6)$$

and $\rho^2 = \rho_x^2 + \rho_y^2 + \rho_z^2$.

The gravitational potential V of the flat disk at the spacecraft's local position is then analytically integrated to yield:

$$V(\boldsymbol{\rho}) = \alpha \left\{ \frac{1}{2} (\rho_x^2 + \rho_y^2) \left[\tan^{-1} \left(\frac{1}{\sqrt{k}} \right) - \frac{\sqrt{k}}{1+k} \right] + \rho_z^2 \left[\frac{1}{\sqrt{k}} - \tan^{-1} \left(\frac{1}{\sqrt{k}} \right) \right] - a^2 \tan^{-1} \left(\frac{1}{\sqrt{k}} \right) \right\} \quad (7)$$

where the scaling factor α is defined as:

$$110 \quad \alpha = -\frac{3\mu}{2a^3} \quad (8)$$



with μ defined as the local Gm of the mascon, with G being the Gravitational Constant. Taking the gradient of the potential V with respect to the spacecraft local coordinates ρ yields the local gravitational acceleration vector $\mathbf{a}_{\text{local}}$:

$$\mathbf{a}_{\text{local}} = \nabla_{\rho} V = \mathbf{A} \mathbf{A} \rho \quad (9)$$

where $\mathbf{A}$ is a diagonal matrix containing elementary algebraic and trigonometric terms:

$$\mathbf{A} = \text{diag} \left[\tan^{-1} \left(\frac{1}{\sqrt{k}} \right) - \frac{\sqrt{k}}{1+k}, \tan^{-1} \left(\frac{1}{\sqrt{k}} \right) - \frac{\sqrt{k}}{1+k}, \frac{2}{\sqrt{k}} - 2 \tan^{-1} \left(\frac{1}{\sqrt{k}} \right) \right] \quad (10)$$

Finally, this local acceleration is rotated back to the Earth-fixed frame:

$$\mathbf{a}_{\text{fixed}} = \mathbf{B}_i^T \mathbf{a}_{\text{local}} \quad (11)$$

Numerical benchmark tests show that the flat mascon disk model improves computation time by a factor of eight relative to implementing the spherical cap model, while differing in solution content only at the level of microns of equivalent water height across the full spectral bandwidth—well below the uncertainty of the solution. This level of agreement is specific to 1° mascon elements; levels of agreement diverge for larger mascon sizes, such as 3° .

2.2 Gravity Observations and Processing

The gravimetry observations (y_G) used are the Level-1B (L1B) data from GRACE/-FO, namely the K-band Range-Rate (KBR) observations and the GNSS pseudorange and carrier phase observations (Wen et al., 2019). This is the first such data combination approach that utilizes these lower-level GRACE/-FO observations, allowing for the altimetry observations to directly influence the gravity estimation. The gravity solution approach (first line of Equation 1) mimics that described in Watkins et al. (2015) with three notable exceptions: 1) the basis function is changed to 1° flat mascon disks (Section 2.1), 2) the treatment of *a priori* information $\bar{P}_{0,G}$ and $\bar{x}_{0,G}$ is modified (discussed in Section 2.5), and 3) the background force models and estimated parameters are updated to be fully consistent with the JPL RL06.3 processing standards (Yuan, 2018).

2.3 Altimetry Observations and Processing

For this study, we use the Antarctic height-change product developed by Nilsson et al. (2022) to compute y_A . This dataset integrates observations from seven satellite altimetry missions to produce a 36-year record of Antarctic surface-elevation change spanning 1985–2020, with significant improvements in coverage starting in 1992. The altimetry product provides monthly height-change fields at $(1.92 \text{ km})^2$ spatial resolution and includes data from both radar and laser altimeters, specifically Geosat (1985–1989), ERS-1 (1992–1996), ERS-2 (1995–2003), Envisat (2003–2012), ICESat (2003–2009), ICESat-2 (2018–present), and CryoSat-2 (2010–present).

For our analysis, we subset and edit this record to match the study period (April 2002–December 2020). This effectively restricts the contributing missions to ERS-2 (few months), Envisat, ICESat, ICESat-2, and CryoSat-2. Because each mission has a different orbital inclination, the combined dataset has varying levels of coverage with a high-latitude data gap ranging from



140 81.5° S to 88° S. GRACE/-FO processing requires a complete spatial field, and the Nilsson et al. (2022) product provides this by filling missing regions using a spatial interpolation scheme based primarily on the higher-inclination missions: CryoSat-2, ICESat, and ICESat-2. There are only a few months early in the GRACE record that are without high-inclination observations and require a large area of interpolation.

To further improve height-change estimates in regions flagged as low-quality in the data product (`data_flag = 2`), we
145 replace those values using a hypsometric interpolation that is provided with the product. For each drainage basin and each month, height-change data are binned in 100 m elevation intervals, and a linear model is fitted to the median values within each bin. This model is then used to estimate height change in the flagged regions and is described in detail in Nilsson et al. (2022).

Uncertainty characterization is embedded within the altimetry product generation framework (Nilsson et al., 2022). Measurement uncertainties are quantified through crossover analyses, in which near-coincident (< 31 -day separation) ascending
150 and descending satellite passes are differenced and binned by surface slope. The zero-slope intercept of fitted error functions provides an estimate of relative mission accuracy, while monthly random errors are derived from the spatiotemporal variability of height differences within each epoch. These components are combined as a quadrature sum of random error and cross-calibration error to produce a spatially and temporally varying monthly RMS uncertainty field distributed with the dataset, which is used to compute W_A in Equation 1.

155 Independent validation of height-change rates from the multi-mission synthesis has historically relied on near-coincident airborne laser altimetry, including campaigns conducted as part of NASA Operation IceBridge (MacGregor et al., 2021), although such observations are spatially and temporally limited. The launch of ICESat-2 in 2018 enabled continent-wide comparisons using independent laser-derived height-change rates from Smith et al. (2020). Basin-scale comparisons for 2003–2019 indicate an ice-sheet-wide mean difference of -0.8 ± 7.8 mm/yr. Readers are referred to Nilsson et al. (2022) for full
160 details of the validation methodology.

2.4 Data Preprocessing

As described in Watkins et al. (2015), the mascon partial derivatives in the gravity estimation are written relative to local mascon Gm parameters, which constitute $\hat{x}_0$ in Equation 1. The estimate comprises the full geopotential change, including surface mass loading and Earth's elastic response to that load (Wahr et al., 1998). To ensure both input datasets represent the
165 same geophysical signal, observations are homogenized and preprocessed to reflect a local mascon Gm estimate of a surface mass anomaly (excluding the geocenter component) on a rigid Earth relative to a common reference epoch. This local surface mass anomaly is a combination of the surface mass change and the associated elastic loading response of the solid Earth. For this analysis, we choose September 2012 as the reference epoch. Sections 2.4.1 and 2.4.2 describe the series of corrections required to homogenize the observations.

170 2.4.1 GRACE/-FO Preprocessing

Solid Earth mass variations are removed from the gravimetry observations y_G to isolate surface mass anomalies. Sources of solid Earth mass variations in GRACE/-FO data include glacial isostatic adjustment (GIA), contemporary viscoelastic mass flux



due to glacier load changes during the Little Ice Age (LIA), and mass movement due to co-seismic and post-seismic relaxation from large ($M > 8.0$) earthquakes (Han et al., 2024). Note that solid Earth tides are already accounted for and removed during routine GRACE/-FO processing (Yuan, 2018). We neglect LIA contributions in this study because a global, mass-conserving model is presently unavailable. Earthquake contributions are additionally neglected since no large earthquakes are known to have occurred within the GRACE/-FO record over the Antarctic region. The GIA signal over Antarctica is large, and is removed using ICE-6GD (Peltier et al., 2015; Argus et al., 2014). This removal is performed by shifting the normal equations by the mass displacement predicted by the model relative to the reference epoch. Similarly, since the partial derivatives are written relative to the static gravity field, all normal equations are shifted relative to September 2012 using the solution for that month. Systematic uncertainty introduced due to the choice of GIA model is quantified by using the model from Caron et al. (2018) rather than ICE-6GD, and examining the impact on the data combination solution (Section 2.7).

2.4.2 Altimetry Preprocessing

The altimetry height change observations relative to a reference ellipsoid are spatially averaged over each mascon element (Δh_{obs}) and converted to a surface mass change on a rigid Earth relative to the Earth's center of mass (Δh_{SM}) in units of Gm using the following equation:

$$\Delta h_{\text{SM}} = C(\Delta h_{\text{obs}} - \Delta h_{\text{FAC}} - \Delta h_{\text{GIA}} - \Delta h_{\text{Atm}} - \Delta h_{\text{Geoc}} - \Delta h_{\text{EL}}) \quad (12)$$

Equation 12 removes height changes due to changes in firn air content (Δh_{FAC}), GIA (Δh_{GIA}), atmospheric loading (Δh_{Atm}), geocenter movement (Δh_{Geoc}), and elastic loading (Δh_{EL}) from the observed height changes (Δh_{obs}). These height changes are then converted to units of Gm by multiplying by C , where

$$C = GA\rho_{\text{ice}} \quad (13)$$

Here, G is the Gravitational Constant, A is the area of the observed portion of the bounding quadrilateral of the mascon element, and ρ_{ice} is the density of ice, 917 kg/m^3 . In this formulation, H_A in Equation 1 becomes the identity matrix. Each term in Equation 12 is expanded upon below.

2.4.3 Firn Air Content Correction

The evolution of the depth-average density of the snow and firn of an ice sheet can dominate the height change signal on seasonal time scales and in areas with little to no mass change. Consequently, to obtain accurate estimates of mass change, it is necessary to remove estimates of depth averaged density changes, or firn air content, from altimetric measurements of height and volume change.

To estimate firn air content, we use the Glacier Energy and Mass Balance (GEMB) model (code version 1.0), run within the Ice Sheet and Sea Level System Model (Gardner et al., 2023; Schlegel and Gardner, 2025). GEMB simulates the energy and mass balance of glacier ice and firn. The GEMB Antarctica implementation (Paolo et al., 2023) is forced with the ERA5 reanalysis (Hersbach et al., 2020), with a 5-day output from 1979-2024. It is converted to monthly output and interpolated



onto the same $(1.92 \text{ km})^2$ regular grid as the altimetry product. Since FAC uncertainties are poorly characterized, we assign a
205 monthly error of 30% of the model amplitude when propagating uncertainties into the data combination (prescription of W_A
in Equation 1). Figure A1 explores the solution sensitivity to this choice, showing differences in data combination solutions
where the FAC model error is prescribed to be zero versus 100% of the model amplitude. We note the error introduced by this
choice is marginal compared with the total uncertainty prescribed in the final data product (Figure 1d).

Systematic FAC errors due to the choice of model used in the analysis are addressed by additionally using GSFC-FDMv1.2.1
210 (Medley et al., 2022) to estimate firn air content. GSFC-FDM is forced by the MERRA-2/M2R12K (Tian et al., 2017) atmo-
spheric reanalysis, and results are derived at a 5-day interval from 1980–2022 using the Community Firn Model (Stevens et al.,
2020, 2021). Section 2.7 addresses systematic error due to the choice of FAC model. We deliberately choose to use a percentage
of the model amplitude to propagate error in the data combination rather than the difference of two models in order to reduce
dependencies on the number of input products required for the data combination to enable a streamlined operational workflow
215 in the future.

2.4.4 Glacial Isostatic Adjustment Correction

The same GIA models described in Section 2.4.1 are used to remove vertical land motion due to GIA from the altimetry
observations, ensuring consistency in the treatment of the two data types.

2.4.5 Atmospheric Loading Correction

220 Atmospheric loading causes elastic displacement of the Earth's surface. The GAC data product associated with the monthly
JPL GRACE/-FO solutions is used to model the mean monthly atmospheric loading effect (Dobslaw et al., 2017). The GAC
product reflects the monthly mean of the non-tidal atmospheric and oceanic geopotential coefficients used as a dealiasing
product in GRACE/-FO data processing. The atmospheric loading is removed using Equation 1 from Davis et al. (2004) by
computing the vertical deformation induced by the monthly GAC coefficients, ensuring consistency between the treatment of
225 the GRACE/-FO and altimetry observations.

2.4.6 Geocenter Correction

Satellite altimetry observations naturally observe geocenter movement since they measure movement of the height of Earth's
surface relative to Earth's center of mass (CM). GRACE/-FO observations are not sensitive to geocenter movement since the
satellites orbit the CM of Earth. Thus, to make the two observations fully consistent, the geocenter effect must be removed
230 from the altimetry observations prior to combining them with gravimetry observations. Geocenter movement is taken from
the TN-13 data product, which computes geocenter movement from a combination of GRACE/-FO data and an ocean model
(Swenson et al., 2008; Sun et al., 2016).



2.4.7 Elastic Loading Correction

Accounting for elastic loading is the final sequential correction applied to the satellite altimetry observations. After each of the
235 above corrections have been applied to the altimetry observations of height change, the height change observations represent
the integrated effect of the surface mass load and its induced solid Earth elastic deformation. This step separates the two in
order to remove the height change due to solid Earth elastic deformation.

The correction is performed iteratively. In the first iteration, it is assumed that the entire Δh is due to a surface mass load.
This height change is converted to normalized geopotential coefficients, and Equation 1 of Davis et al. (2004) is used to
240 compute the associated vertical solid earth deformation resulting from the surface mass load. The iteration loop begins here,
where the computed vertical deformation is subtracted from Δh to obtain a new Δh due to a surface mass load. This process is
repeated until the estimated vertical deformation is less than 1% of the computed deformation in the first iteration, and typically
converges in four iterations. After convergence, the final Δh represents a height change that is attributed solely to surface (i.e.,
ice) mass change, Δh_{SM} .

245 As GRACE/-FO observes the integral of the surface mass change and the induced solid Earth mass change (Wahr et al.,
1998), the final computation of y_A in Equation 1 is given as:

$$y_A = \Delta h_{SM} + \Delta h_{SM} k_l, \quad (14)$$

where k_l are the load Love numbers of degree l .

2.5 Solution Process

250 Here, we discuss the implementation of the solution to Equation 1 and the choices made regarding the selection of the W_G ,
 W_A , $\bar{P}_0$, and $\bar{x}_0$ matrices. The W_G matrix is consistent with that used in the JPL RL06.3M mascon solution (Wiese et al.,
2023), in which GNSS and KBR observations are optimally weighted each day to minimize the residual sum of squares of
a monthly solution. W_A is taken directly from the altimetry data product of Nilsson et al. (2022), with 30% of the model
amplitude of the FAC product from GEMB (Gardner et al., 2023) added. In a fully observable system of equations, $\bar{P}_0$ and
255 $\bar{x}_0$ would not be necessary. In testing, we found that $\bar{P}_{0,A}$ and $\bar{x}_{0,A}$ were not required, and thus these terms were dropped.
Conversely, $\bar{P}_{0,G}$ and $\bar{x}_{0,G}$ are necessary to break the correlated error in the system of equations arising from the observation
geometry of GRACE/-FO, which is limited to the north–south direction (Watkins et al., 2015; Wiese et al., 2011).

The solution procedure consists of three steps, which have been designed to remove correlated error from the GRACE/-FO
observations while preserving and localizing signal. Steps 1 and 2 are similar to the development of a white-noise solution
260 described in Section 4.1 of Watkins et al. (2015), and exist in parallel to derive a set of time-variable data-driven constraints
that are used in the final data combination solution executed in Step 3. Due to the large dynamic range of signals present in
Antarctica, static constraints are inadequate to sufficiently suppress noise in regions of high signal amplitude, absent imple-
menting a forward model of expected mass variations, which we deliberately choose to avoid as to not bias our estimate towards
a particular prior. Step 3 then serves the same foundational purpose as the time-correlated solution described in Section 4.2



265 of Watkins et al. (2015), but uses a different implementation that leverages the time-variable constraints derived from Step 2. Implementation details are provided below.

In Step 1, only the first line of Equation 1 is solved, prescribing $\bar{x}_{0,G}$ to be zero and $\bar{P}_{0,G}$ to be a diagonal matrix with expected variances over land, ocean, inland seas, and GIA computed consistently with the description in Watkins et al. (2015). In addition, a uniform loose constraint is prescribed over all ice-covered regions, consistent with a $1-\sigma$ value of 720 cm, and
270 the gravity normal equations are solved. The purpose of this step is to let the GRACE/FO data drive a solution where the mass anomalies are spatially allocated over Antarctica; the gravity solution output from Step 1 achieves this goal, however is contaminated significantly with noise. In Step 2, $\bar{x}_{0,G}$ is again ignored, and $\bar{P}_{0,G}$ is identical to Step 1 with the exception of ice-covered regions, where each mascon is given a $1-\sigma$ value consistent with the maximum value from the solution in Step 1. The resulting solution after combining the gravimetry and altimetry normal equations is successful at spatially allocating the
275 signal over Antarctica, but suffers from a high level of noise. In Step 3, $\bar{x}_{0,G}$ is taken to be the 13-month running mean of each ice mascon from the solution in Step 2, and $\bar{P}_{0,G}$ is defined from the $1-\sigma$ deviation about that running mean. The treatment of all non-ice covered mascons remains unchanged from Steps 1 and 2. The resulting solution from Step 3 retains the signal from the solution derived in Step 2 while greatly suppressing high-frequency noise.

We apply a consistent set of post-processing procedures with those used in JPL RL06.3M (Wiese et al., 2023) to convert to
280 surface mass change, including applying an elastic loading correction (Wahr et al., 1998), a geocenter correction from TN-13 (Swenson et al., 2008; Sun et al., 2016), a replacement of C_{20} (all months) and C_{30} (all single-accelerometer months from both GRACE and GRACE-FO) from TN-14 (Loomis et al., 2020, 2019b), and a GIA correction using ICE-6GD (Argus et al., 2014; Peltier et al., 2015). We additionally estimate and remove an S_2 tidal alias term with a period of 161 days (Ray and Luthcke, 2006).

285 2.6 Postprocessing: CRI Filter and Gain Factors

A Coastal Resolution Improvement (CRI) filter is applied to separate ocean and land mass from mascons that span coastlines using the same procedure as that described in Wiese et al. (2016). *A priori* estimates for the ocean and ice signals are derived from neighboring mascons, with *a priori* uncertainties for the ocean derived from the ECCO2 model (Menemenlis et al., 2008), and a uniform loose *a priori* uncertainty is prescribed for the ice.

290 Similarly, mass-conserving gain factors are derived using the same techniques outlined in Wiese et al. (2016), with the primary difference being that the gain factors are derived from the satellite altimetry data rather than modeled estimates of mass change. Application of the gain factors to the data combination mass change solution effectively downscales the observed mass change signals within each mascon element using the spatial information in the altimetry data. Two sets of data products and associated gain factors are provided: one at the native resolution of the altimetry observations at $(1.92 \text{ km})^2$ spatial scale on
295 a polar stereographic grid, and the second on an equal latitude/longitude grid at $1/8^\circ$ grid sizes. Total mass in each individual 1° mascon is conserved when applying either set of gain factors.



2.7 Solution Uncertainty

Uncertainty estimates are provided with the solution that include the effect of measurement error from the gravimetry and altimetry sensor systems, along with systematic errors from unknown model corrections. For systematic errors, we focus on the largest two sources: the FAC and GIA corrections. The final uncertainty for each mascon (Figure 1d) is prescribed as:

$$\sigma = \sqrt{(\sigma_{\text{ME}})^2 + (\sigma_{\text{FAC}})^2 + (\sigma_{\text{GIA}})^2} \quad (15)$$

In Equation 15, σ_{ME} is the combined measurement error from the gravimetry and altimetry measurement systems propagated through the normal equations, and is taken from the diagonal elements of the *a posteriori* covariance matrix from the solution in Step 2 (Figure 1c). The reason for not using the *a posteriori* covariance matrix from Step 3 is that the uncertainties were found to be artificially low due to the tight value used for $\bar{P}_{0,G}$. Systematic errors due to uncertainty in the FAC correction (σ_{FAC} ; Figure 1a) and the GIA correction (σ_{GIA} ; Figure 1b) are taken from the 1- σ value calculated from the two-member ensemble data combination solutions using the different models described in Section 2.4.2; thus, the total systematic error from both effects constitutes a four-member ensemble. We note that the GIA uncertainty accounted for in Equation 15 comes solely from the solution difference in applying different GIA models as pre-processing corrections for altimetry and gravimetry. It does not account for uncertainty in the separation of solid Earth mass variations from surface mass variations in the final postprocessing step after the data combination solution has taken place; this systematic error presents itself as a linear trend only and can be handled by users as such.

2.8 Solution Validation

The data product produced here is the first of its kind: monthly mass change over Antarctica at $(100 \text{ km})^2$ resolution, with possibilities to interpret at $(1.92 \text{ km})^2$ spatial scale after application of gain factors. Our validation campaign is restricted to assessing the observational behavior of the data combination solution relative to prior expectations.

These expectations include:

1. Mass change at continental scales and within large drainage basins should match that of existing GRACE/-FO data products;
2. Mass change at spatial scales $< 300 \text{ km}$ should more closely follow altimetry observations, especially in locations with large signals;
3. The addition of altimetry information to the gravity solution process should reduce correlations between adjacent mascons.

3 Results

Analysis and comparisons are restricted to time periods when GRACE/-FO observations are available, despite the continuous (gap-free) nature of the altimetry observations.

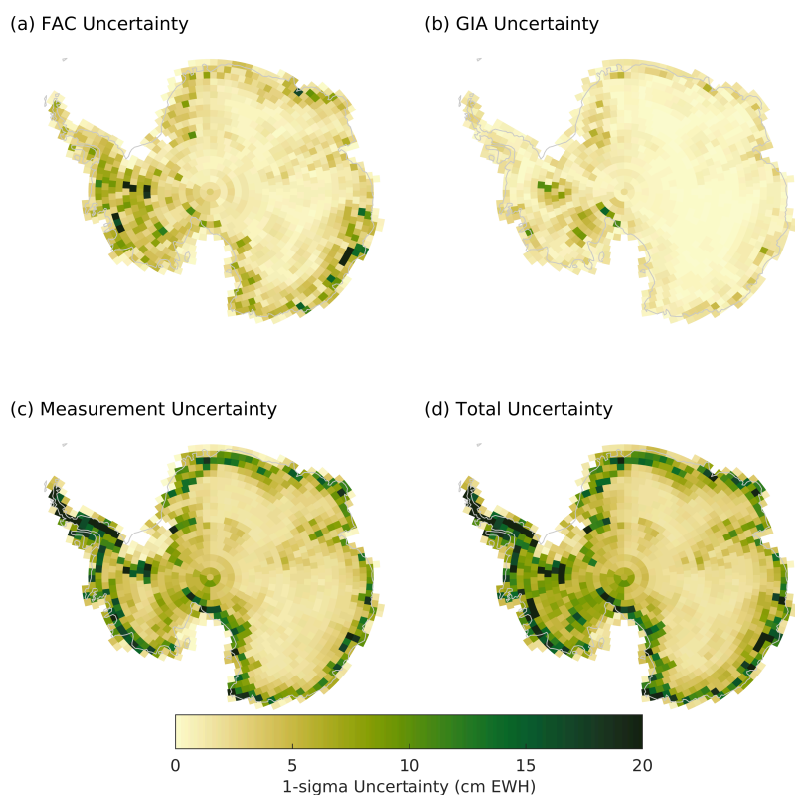


Figure 1. Uncertainty computations account for stochastic measurement error and systematic error due to geophysical model corrections. 1- σ uncertainty values from (a) firm air content correction, (b) glacial isostatic adjustment correction, (c) combined measurement system error of gravimetry and altimetry measurement systems, and (d) total uncertainty computed as the root sum of squares of each individual component.

3.1 Mass Balance over Large Regions

Mass balance time series for the Antarctic Ice Sheet and its three major regions—the West Antarctic Ice Sheet (WAIS), the East Antarctic Ice Sheet (EAIS), and the Antarctic Peninsula Ice Sheet (APIS)—derived from the data combination solution are compared against independent gravimetry-only and altimetry-only solutions (Figure 2). The gravimetry-only mass balance is computed from the JPL RL06.3M 3° mascon solution (Wiese et al., 2023) with measurement and leakage errors propagated according to Wiese et al. (2016). The altimetry-only mass balance is computed via Equation 12. Errors are propagated using the altimetry measurement uncertainties discussed in Section 2.3 and FAC model errors prescribed as the difference between GEMB and GSFC-FDMv1.2.1. Spatial autocorrelation is accounted for in the error computation using a correlation length of 100 km for the altimetry measurement errors (Nilsson et al., 2022) and 500 km for the FAC model errors, computed as

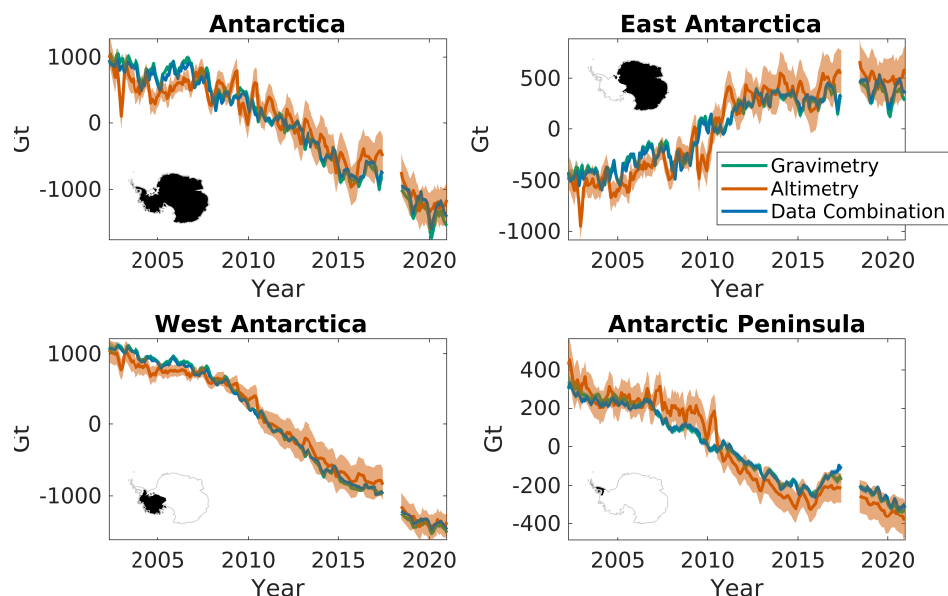


Figure 2. Mass balance of the data combination solution exhibits strong consistency with gravimetry observations for AIS, EAIS, and WAIS. Comparison of mass balance for the data combination solution, gravimetry-only solution, and altimetry-only solution for the Antarctic Ice Sheet (top-left), East Antarctic Ice Sheet (top-right), West Antarctic Ice Sheet (bottom-left), and Antarctic Peninsula (bottom-right) with 1- σ uncertainty. Basin definition is given by Rignot et al. (2011).

the ice-sheet-wide spatial average derived from GEMB. The land mask definition differs slightly between JPL RL06.3M and the altimetry and data combination solutions; consequently, each mass balance time series is computed using the land mask compatible with the respective data product. This difference in land mask accounts for a trend discrepancy of < 1 Gt/yr over Antarctica due to differing spatial sampling of the GIA model correction.

340 Similarly, mass balance is compared across 18 drainage basins (Rignot et al., 2011) in Antarctica (Figure 3). All three datasets generally demonstrate concordance within their prescribed confidence intervals. The Pearson correlation coefficient (computed after detrending) indicates that the data combination solution is highly correlated (mean coefficient of 0.94) with the gravimetry-only solution over each drainage basin. Conversely, the data combination solution displays a lower correlation with the altimetry data at the drainage basin scale (mean coefficient of 0.44). Mean absolute deviation (MAD) statistics additionally
 345 confirm closer alignment of the data combination solution with the gravimetry data than with the altimetry data at the basin scale (mean of 12 Gt versus 35 Gt), a trend mirrored by the trend comparisons over each basin (Table 1).

Basins where the data combination solution aligns more closely with the altimetry data are limited to those in and near the Antarctic Peninsula, where basins J–Jpp and Ipp–J yield lower MAD values despite manifesting lower correlation coefficients. In addition to their limited spatial extent, these sectors are known to be contaminated by tidal aliasing errors in satellite
 350 gravimetry solutions (Moore and King, 2008).

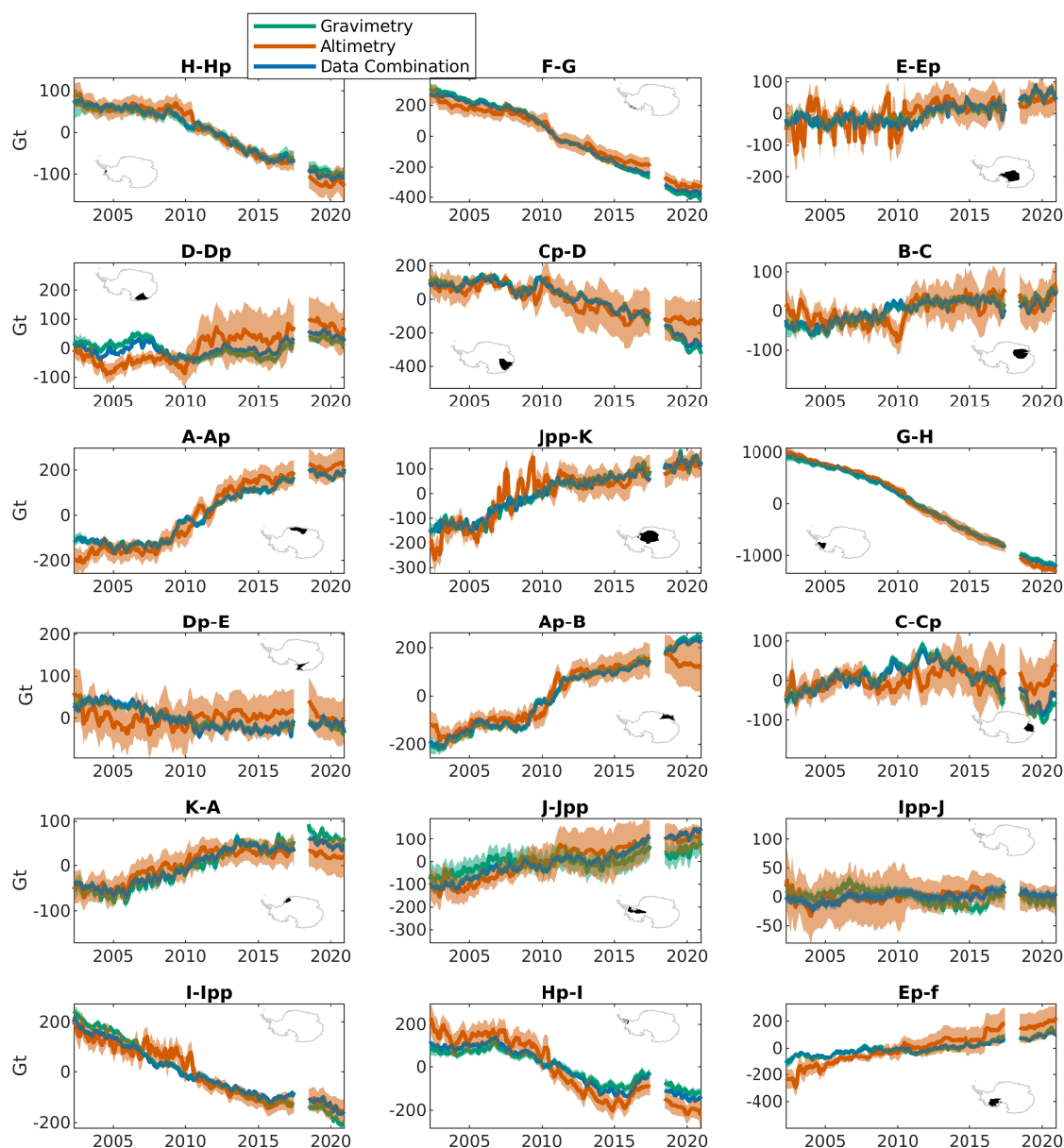


Figure 3. Mass balance of the data combination solution demonstrates strong alignment with gravimetry data over Antarctic drainage basins. Comparison of mass balance for the data combination solution, gravimetry-only solution, and altimetry-only solution for Antarctic drainage basins (Rignot et al., 2011) with 1- σ uncertainties.



Table 1. Comparison of data combination solution with a gravimetry-only solution and an altimetry-only solution over Antarctic regions. Shown are comparisons of trends over each region, along with Pearson correlation coefficients (after detrending) and Mean Absolute Deviation comparing the three solutions at the basin level, and as the mean value of the statistics computed on individual mascons contained within the region.

Region	Area (km^2)	Trend (Gt/yr)			Correlation Coefficient				Mean Absolute Deviation (MAD)			
		Data Comb	Gravimetry	Altimetry	Comb/Gravimetry		Comb/Altimetry		Comb/Gravimetry		Comb/Altimetry	
					Basin	Mascons	Basin	Mascons	Basin (Gt)	Mascons (cm)	Basin (Gt)	Mascons (cm)
I-Ipp	76,991	-18.45	-22.24	-18.91	0.97	0.52	0.36	0.53	20.32	78.29	31.92	64.68
Ipp-J	71,863	0.81	-1.22	0.56	0.60	0.44	0.41	0.49	15.11	18.39	6.27	25.07
Hp-I	191,809	-16.74	-12.87	-24.50	0.98	0.69	0.81	0.71	23.54	43.81	53.72	31.67
APIS	340,663	-34.37	-36.10	-42.85	0.97	0.56	0.67	0.60	12.32	46.15	78.57	37.93
H-Hp	81,206	-11.18	-10.29	-12.37	0.98	0.62	0.83	0.73	4.65	92.27	11.95	29.27
J-Jpp	670,784	12.72	5.09	13.53	0.84	0.42	0.01	0.40	40.45	19.12	28.28	8.59
G-H	449,563	-126.54	-123.55	-134.35	1.00	0.61	0.91	0.81	16.70	102.58	54.63	25.86
F-G	156,657	-39.47	-42.14	-33.66	0.99	0.54	0.84	0.73	13.05	101.38	38.10	34.09
Ep-f	833,112	8.67	9.52	21.26	0.94	0.37	0.09	0.53	7.69	28.39	72.94	10.55
WAIS	2,191,322	-155.78	-160.42	-145.56	0.99	0.45	0.81	0.58	32.64	49.54	94.38	16.41
E-Ep	1,710,160	5.08	4.70	4.95	0.95	0.29	0.15	0.45	5.68	4.93	26.78	4.82
D-Dp	693,134	2.56	-0.42	8.65	0.97	0.46	0.29	0.63	20.44	7.35	51.58	8.72
Cp-D	1,159,571	-19.80	-22.06	-14.18	0.99	0.54	0.42	0.53	10.69	13.44	42.75	7.06
B-C	1,334,658	4.22	5.16	3.54	0.96	0.38	0.02	0.53	6.22	3.60	23.48	3.67
A-Ap	790,502	21.80	21.56	27.43	0.99	0.54	0.77	0.60	3.99	12.22	38.02	7.88
Jpp-K	2,131,337	15.89	15.92	16.35	0.95	0.45	0.51	0.46	6.42	4.07	37.17	3.79
Dp-E	442,700	-3.85	-4.01	0.28	0.95	0.36	-0.09	0.42	5.44	9.87	38.57	14.26
Ap-B	650,653	25.17	26.59	20.23	0.99	0.51	0.56	0.56	8.71	13.88	30.60	9.62
C-Cp	710,514	-1.19	-2.51	1.30	0.99	0.63	0.41	0.60	7.42	6.96	29.48	6.53
K-A	275,808	6.94	8.39	5.09	0.90	0.53	0.66	0.49	8.52	15.10	17.38	9.66
EAIS	9,899,037	56.82	52.18	73.65	0.98	0.46	0.51	0.50	31.68	8.08	160.51	6.83
AIS	12,431,022	-133.35	-144.35	-114.77	0.98	0.46	0.53	0.53	65.84	18.04	199.96	10.19

3.2 Mass Balance over Individual Mascons

The mass balance of the data combination solution is compared to the gravimetry-only and altimetry-only solutions at the level of individual 1° mascons. The JPL RL06.3M 3° mascon solution is utilized to derive the gravimetry-only curves despite the mismatch in mascon size. Uncertainty is not prescribed for the gravimetry-only solution due to the effects of sampling data below its native resolution. At the scale of individual mascons, the data combination solution exhibits higher correlation with the altimetry data than with the gravimetry data (mean value of 0.53 versus 0.46 over the AIS) and manifests a lower MAD (10 cm vs. 18 cm) over AIS mascons. (Table 1). Spatially, the data combination solution is highly correlated with the altimetry data over the Pine Island and Thwaites glacier systems, in contrast to the pole hole area where altimetry errors are larger. Furthermore, the data combination solution demonstrates elevated correlations with gravimetry data, particularly near the Totten Glacier system (Figure A2).

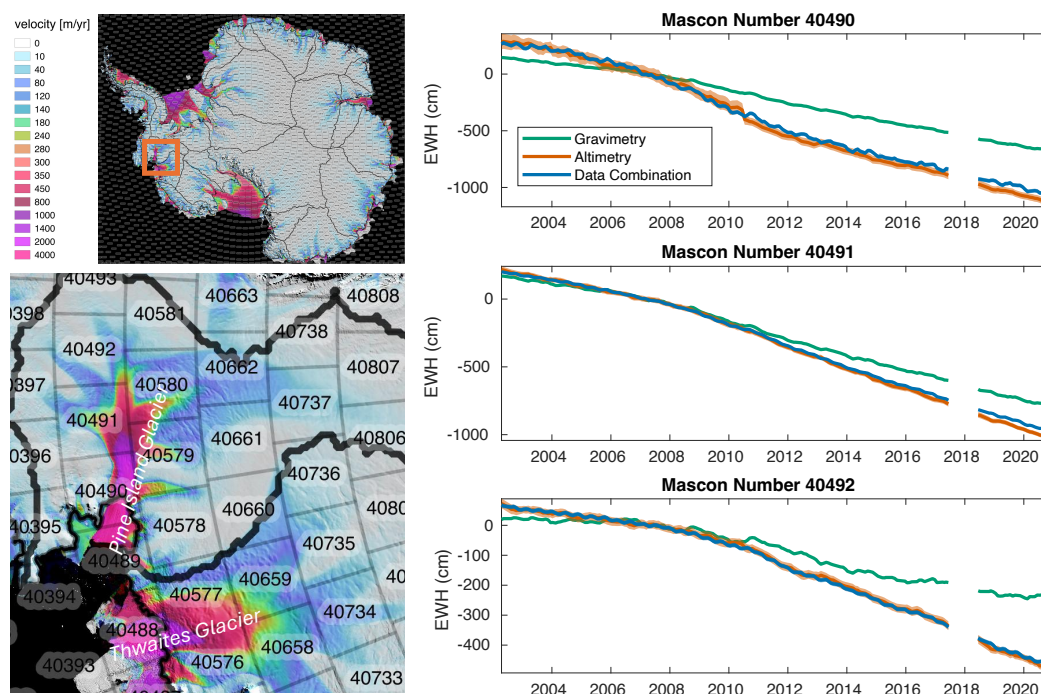


Figure 4. Data combination solution aligns with altimetry data at the level of individual mascons on Pine Island Glacier, resolving mass change at finer spatial resolutions than what is possible with gravimetry data alone. Mass balance time series for individual mascons over Pine Island Glacier comparing a gravimetry-only solution, altimetry-only solution, and the data combination solution. Mascon locations are shown over a ice velocity map (Gardner et al., 2022) for added context.

Individual mascon time series are compared across the Pine Island Glacier (Figure 4), the Siple Coast region (Figure 5), the Thwaites Glacier (Figure A3), and the Totten Glacier (Figure A4). For each comparison, the mascon outline is visualized over a velocity flow map (Gardner et al., 2022) for added context.

Over the Pine Island Glacier (Figure 4), mascons 40490, 40491, and 40492 are positioned parallel to and over the main trunk of the glacier, encompassing regions of high glacier flow velocity. The gravimetry-only solution consistently underestimates the magnitude of local mass loss, as anticipated given the $\sim(300 \text{ km})^2$ native resolution of the gravimetry data, which results in a smoothed representation of the local mass change signal. The data combination solution demonstrates strong agreement with the altimetry-only solution over each individual mascon.

Thwaites (Figure A3) and Totten (Figure A4) Glaciers manifest comparable behavior; in mascons contained within regions of high glacier flow velocity, the data combination solution resolves a higher local rate of mass loss than the gravimetry-only solution. Conversely, for mascons located in regions of lower glacier flow velocity upstream in the glacier system, the data combination solution shows lower rates of mass loss relative to the gravimetry-only solution.

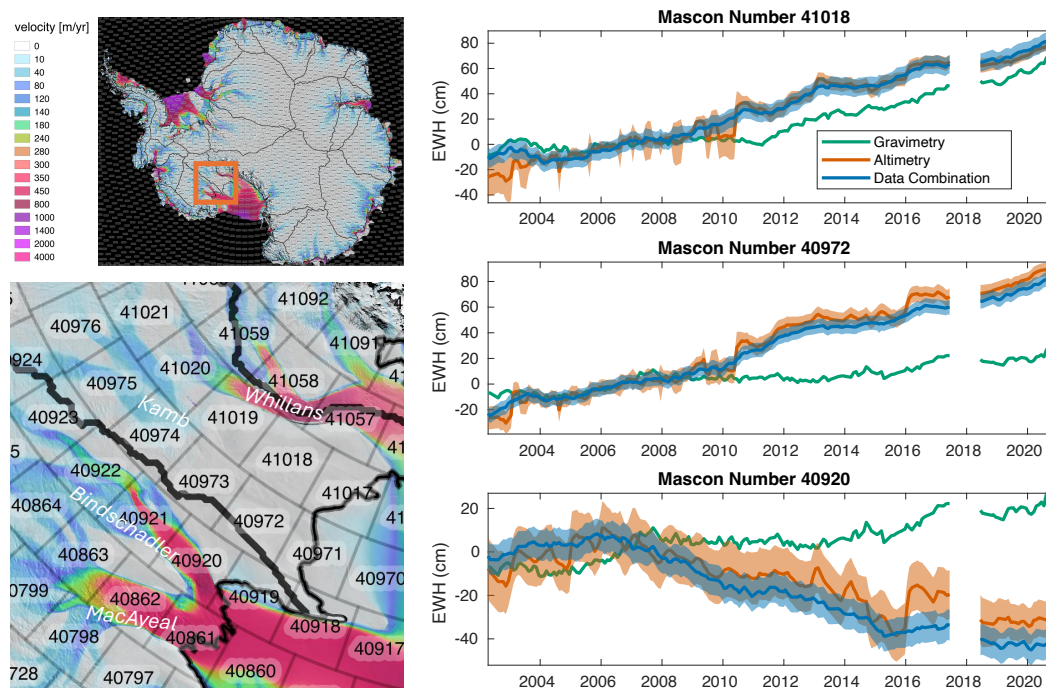


Figure 5. Data combination solution aligns with altimetry data at the level of individual mascons in the Siple Coast region, resolving mass change at finer spatial resolutions than what is possible with gravimetry data alone. Mass balance time series for individual mascons in the Siple Coast region comparing a gravimetry-only solution, altimetry-only solution, and the data combination solution. Mascon locations are shown over a velocity map (Gardner et al., 2022) for added context.

The Siple Coast (Figure 5) exhibits juxtaposed regions of both mass gain and mass loss in neighboring mascons. The gravimetry-only solution indicates positive mass trends in mascons 41018, 40972, and 40920. The data combination solution agrees with the altimetry-only solution within formal error, resolving higher rates of mass gain in mascons 41018 and 40972, due to the stagnation of the Kamb Ice Stream some 160 years ago (Retzlaff and Bentley, 1993), than the gravimetry-only solution, while simultaneously identifying long-term mass loss in mascon 40920 resulting from a mass imbalance of the Bindschadler Ice Stream (Gardner et al., 2018).

3.3 Data Contribution

Contributions of the satellite gravimetry and altimetry data to the data combination solution are computed by leveraging their individual normal equations (Koch, 1999; Yi et al., 2013) (Figure 6). Altimetry data constitutes the dominant contributor to the solution during the estimation of individual mascon elements (Figure 6), matching the results shown in Table 1 and Figure A2. Gravimetry data and *a priori* information contribute more significantly in areas with high topographic relief (APIS, Transantarctic Mountains, Ellsworth Mountains), where altimetry data uncertainties are higher. These contribution maps ex-

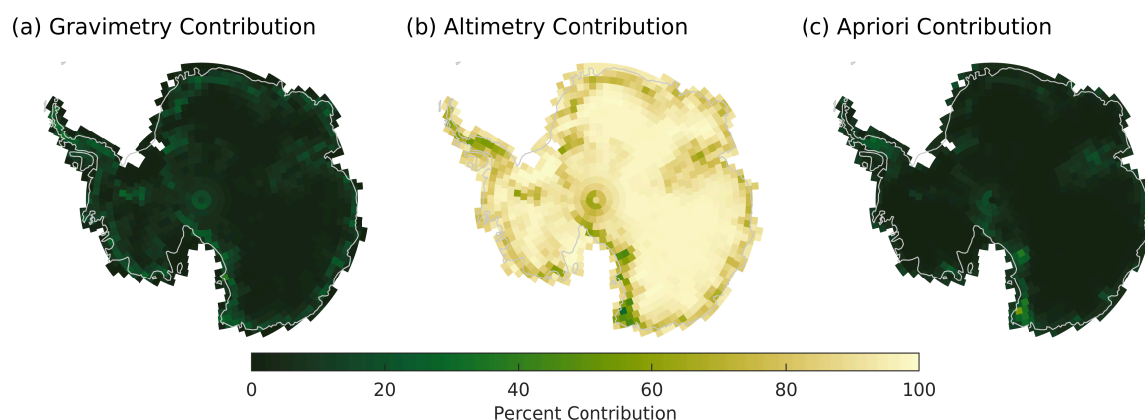


Figure 6. Altimetry data is the dominant contributor to the data combination solution for individual mascons. Percentage contribution to the data combination solution for a) gravimetry data, b) altimetry data, and c) *a priori* information.

385 plain the spatial characteristics observed in Figures 4–5, where the data combination solution closely follows the altimetry-only solution at the scale of an individual mascon.

To characterize the data contribution as a function of spatial wavelength, we propagate the normal equations into the spherical harmonic domain using the methods described in Rowlands et al. (2010). This allows us to examine data contributions in the spectral domain (Figure 7) for the global data combination solution. Gravimetry data contributes more than 50% of the information across degrees 2–25, and decreases exponentially to less than 10% beyond degree 50. The *a priori* constraint contributes the majority of the remainder to the data combination solution, whereas the altimetry data contributes < 5% even at high spherical harmonic degrees.

For reference, Figure 7 shows the impact of a 330 km Gaussian smoothing operator (Wahr et al., 1998). The *a priori* information acts in accordance with, but slightly more aggressively than, the 330 km smoothing. Figure A5 provides a more detailed comparison of the data contribution percentage for each spherical harmonic coefficient in a triangle plot. The *a priori* information primarily impacts sectorial and near-sectorial coefficients for lower spherical harmonic degrees. These are coefficients where the observability of the GRACE measurement system is the weakest (Wiese et al., 2012). Conversely, gravimetry data contributes the most to the zonal and near-zonal coefficients where the observability strength is the highest.

3.4 Correlation between Mascons

400 In 1° gravimetry-only mascon solutions, significant correlation exists between estimated adjacent mascons (Loomis et al., 2019a). Inspection of the *a posteriori* covariance matrix reveals that in a gravimetry-only solution, the average correlation coefficient for mascons separated by up to 2000 km is ~0.6, decreasing to ~0.3 at distances near 5500 km (Figure 8). However, incorporating altimetry observations effectively decouples this spatial relationship. In the data combination framework,

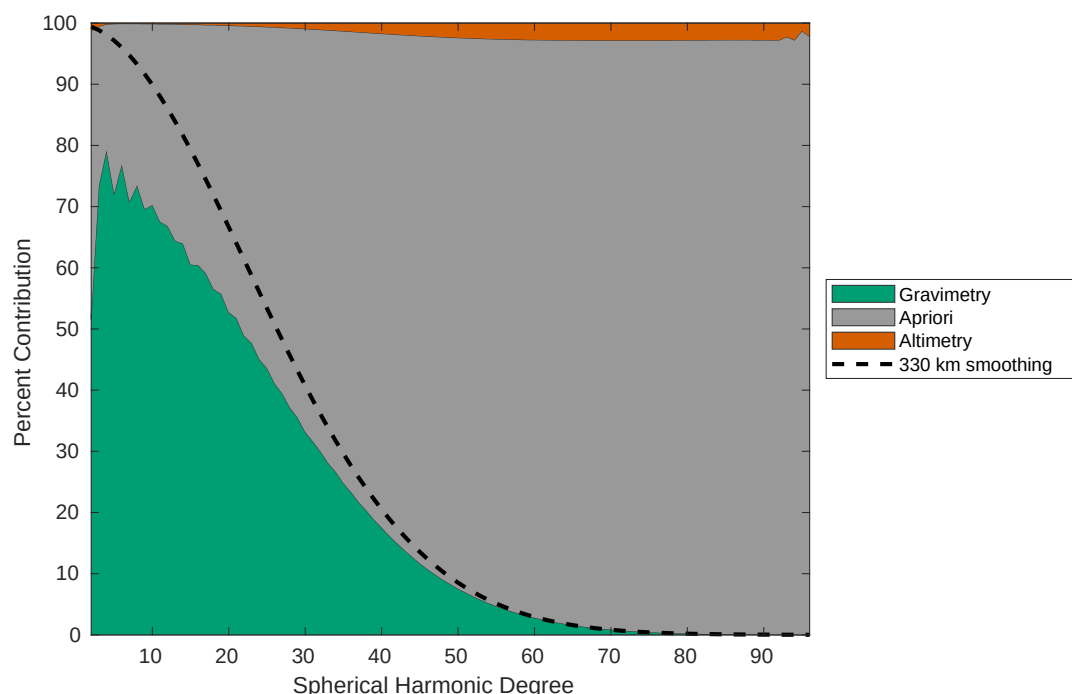


Figure 7. Gravimetry data dominates the global solution in the spectral domain out to spherical harmonic degree 25 (800 km length scales). Percentage contribution to the global data combination solution for gravimetry data, altimetry data, and *a priori* information in the spectral domain. For reference, a 330 km Gaussian smoothing operator is shown.

the mean correlation coefficient in the estimation between adjacent mascons is reduced to 0.02. Consequently, independent
405 interpretations of individual mascon elements can be performed, which drastically simplifies uncertainty propagation.

3.5 Mass Balance Trends and Application of Gain Factors

Since the data combination solution yields mascon elements that are uncorrelated with their neighbors (Figure 8), the applica-
tion of mass-conserving gain factors is expected to perform with high fidelity at the scale of individual mascons. To demonstrate
this capability, we apply the gain factors to the data combination solution and estimate long-term mass balance trends over the
410 Antarctic Ice Sheet (Figure 9). The native resolution of the solution is shown in Figure 9a, whereas the high-resolution, down-
scaled representation is provided in Figure 9b. The downscaled trend map exhibits strong spatial coherence with the trend field
derived solely from altimetry data (Figure 9c), validating the capacity of the gain factors to resolve and downscale mass change
at $(1.92 \text{ km})^2$ spatial scales. We note that total mass is strictly conserved at the scale of each individual mascon between Figure
9a and Figure 9b. Limitations of gain factors are that they best represent the dominant frequency present in each mascon - these
415 limitations are discussed in more detail in Wiese et al. (2016) and Landerer and Swenson (2012).

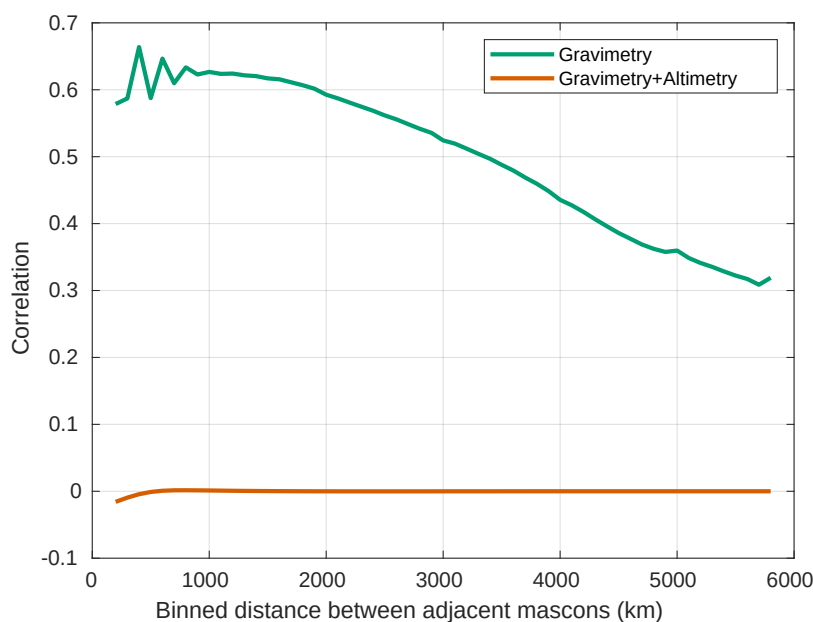


Figure 8. The combination of altimetry and gravimetry data breaks correlation between adjacent mascons, resulting in a solution where each mascon element is uncorrelated with its neighbor. Mean correlation coefficient for a gravimetry-only solution compared with a joint gravimetry–altimetry solution for mascons that have altimetry observations. The x-axis represents the spatial binning of mascon pairs; 200 km corresponds to all mascon elements whose centers are within 101 – 200 km of one another; 300 km corresponds to all mascon elements whose centers are within 201 – 300 km of one another, respectively.

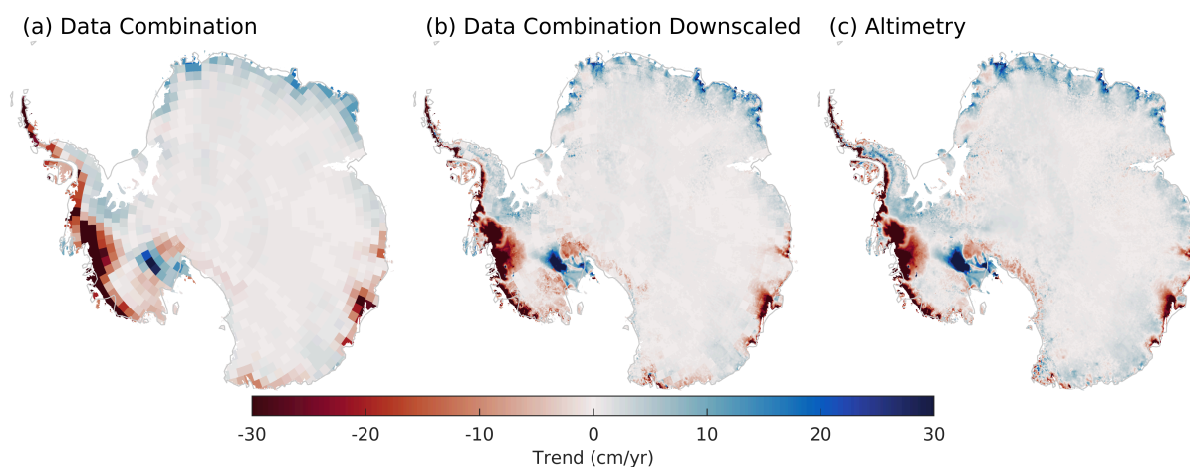


Figure 9. Downscaled data combination provides Antarctic mass change trends at spatial scales comparable to altimetry data. Antarctic mass trends (cm/yr) for (a) the data combination solution at native spatial resolution, (b) at 1.92-km spatial scales after applying gain factors to the data combination solution, and (c) the altimetry-only solution.



4 Discussion

The results presented in Section 3 provide a comprehensive assessment of the quality and characteristics of the data combination solution. For solution validation, each of the criteria established to demonstrate success have been fulfilled (Section 2.8). *A posteriori* covariance analysis revealed that altimetry observations dominate the data combination for individual mascon elements (Figure 6), whereas gravimetry observations dominate the underlying long-wavelength contributions at spatial scales > 800 km (Figures 7 and A5). These characteristics of the data combination solution explain the behavior of the mass balance time series, wherein the data combination solution is highly correlated with a gravimetry-only solution at the spatial scale of drainage basins and larger, yet is better correlated with the altimetry data at the scale of an individual mascon. Ultimately, incorporating altimetry data mitigates the leakage error (i.e. spatial resolution and along-track sensitivity limitations) inherent to a gravimetry-only solution that arises from sampling time variable gravity from orbit.

Through inspection of the *a posteriori* covariance matrix, we additionally found that the introduction of altimetry observations to the gravimetry normal equations eliminates correlations between adjacent mascons (Figure 8). Because adjacent mascons are no longer correlated, the ability to downscale mass within individual mascons using computed gain factors is highly effective. The decoupling of adjacent mascons eliminates the need for users to consider inter-mascon leakage error when computing mass balance time series aggregated over larger regions, as discussed in Wiese et al. (2016). This stands in contrast to existing 1° GRACE/-FO mascon solutions where the quantification of inter-mascon leakage error is critical (Chen et al., 2017; Loomis et al., 2019a) to computing mass balance over regions of interest.

In Pail et al. (2015), the community set a target requirement for determining mass change that was an order of magnitude improved relative to the state of the art: $(100 \text{ km})^2$ spatial resolution, monthly temporal resolution, and an accuracy of 50 cm EWH. We have fulfilled that target over Antarctica with the development of this data product. Further, in Wiese et al. (2022), while addressing the 2017–2027 United States National Academy of Sciences Decadal Survey for Earth Science and Applications (National Academies of Sciences, Engineering, and Medicine, 2018), the community set a future goal for observing mass change over the ice sheets at $(100 \text{ km})^2$ spatial resolution, monthly temporal resolution, and an accuracy of 15 mm EWH. Here, we make significant progress towards attaining that goal, meeting both the spatial and temporal resolutions required, but fall short of the targeted accuracy across the entirety of the ice sheet. Some regions in East Antarctica satisfy the 15 mm EWH target, but most regions, particularly those around the coasts and in areas of high topographic relief, exhibit errors that are considerably larger, up to and in excess of 20 cm EWH (Figure 1). Lowering the uncertainty to the 15 mm EWH goal will require both improved altimetry observing systems and improvements in FAC modeling.

We postulate that a rigorous combination of gravimetry and altimetry observations is optimal for increasing the spatial resolution of mass change over ice sheets and glaciers, and will continue to serve as the gold standard even as individual gravimetry or altimetry observing system architectures improve. These improved spatial resolution data products will facilitate an enhanced understanding of climate forcing on ice sheets and glaciers, cryosphere contributions to global and regional sea-level change, and improved modeling and prediction of ice sheets and mountain glacier systems (Pail et al., 2015). With the planned launch of the NASA/DLR GRACE-Continuity mission in 2028 (Wiese et al., 2022) and the selection of the



450 NASA's Earth Dynamics Geodetic Explorer mission to continue high-precision laser altimetry observations beyond ICESat-2 and GEDI, the data combination presented here provides a blueprint to enable an operationally-updated, sustained data product moving forward.

5 Conclusions

We provide a monthly mass change data product (JPL GravAlt-Antarctica) spanning April 2002–December 2020 that improves
455 knowledge of ice sheet dynamics by resolving mass changes at a spatial resolution an order of magnitude finer than the state-of-the-art. This improvement is achieved by rigorously combining gravimetry and altimetry satellite observations from seven distinct missions. We demonstrate that long-wavelength features are controlled by gravimetry data, while altimetry data dominates the data combination at smaller spatial scales. Mass balance time series for drainage basins are consistent between the data combination solution and existing GRACE/-FO data products, but are significantly improved at smaller spatial scales
460 corresponding to an individual mascon element ($(\sim 100 \text{ km})^2$). Further, the application of gain factors facilitates downscaling of mass changes to $(1.92 \text{ km})^2$ spatial scale. This data product will open up new fields of study for the glaciology and geophysics of the Antarctic Ice Sheet. Future work will expand this data product to include Greenland and glaciers globally.

Code and data availability. The JPL GravAlt Antarctic data combination solution files are available here: https://its-live-data.s3.amazonaws.com/mass_change/antarctic/GravAlt-Antarctica_JPL_MSCN_CRI.200204_202012.v0.1.zip. Two sets of data products and associated gain
465 factors are provided: one at the native resolution of the altimetry observations at $(1.92 \text{ km})^2$ spatial scale on a polar stereographic grid, and the second on an equal latitude/longitude grid at $1/8^\circ$ grid sizes. The GRACE L1B data is found at https://podaac.jpl.nasa.gov/dataset/GRACE_L1B_GRAV_JPL_RL03 and the GRACE-FO L1B data are found at https://podaac.jpl.nasa.gov/dataset/GRACEFO_L1B_ASCII_GRAV_JPL_RL04. The altimetry data used in the generation of the data combination solution can be found at <https://nsidc.org/data/nsidc-0782/versions/1>. The GEMB version 1.4 monthly firn and surface mass balance output used in this study can be found at
470 <https://doi.org/10.5281/zenodo.14714746>. Software used to generate the data combination solution are prohibited from being distributed due to compliance with United States Export Administration Regulations.

Appendix A: Appendix A

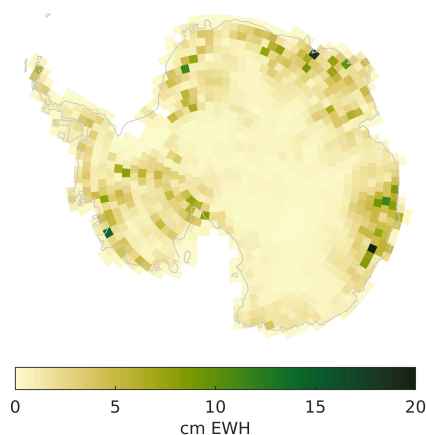


Figure A1. Solution sensitivity to the prescription of FAC model uncertainty in the data combination. RMS (in cm EWH) of monthly differences between two data combination solutions prescribing different values for FAC model uncertainty ranging from 0 to 100% of the FAC model amplitude.

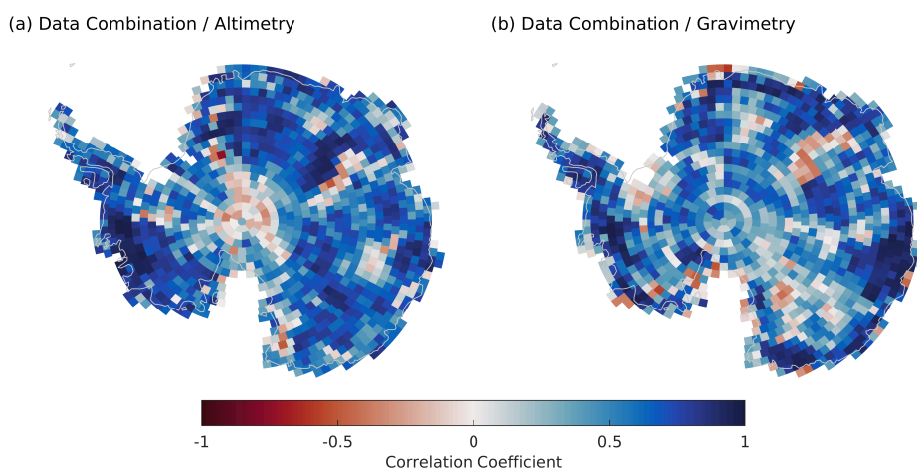


Figure A2. Individual mascons in the data combination solution exhibit higher correlation with altimetry data than with gravimetry data. Pearson correlation coefficient (after detrending) between the data combination solution and a) the altimetry-only solution and b) the gravimetry-only solution.

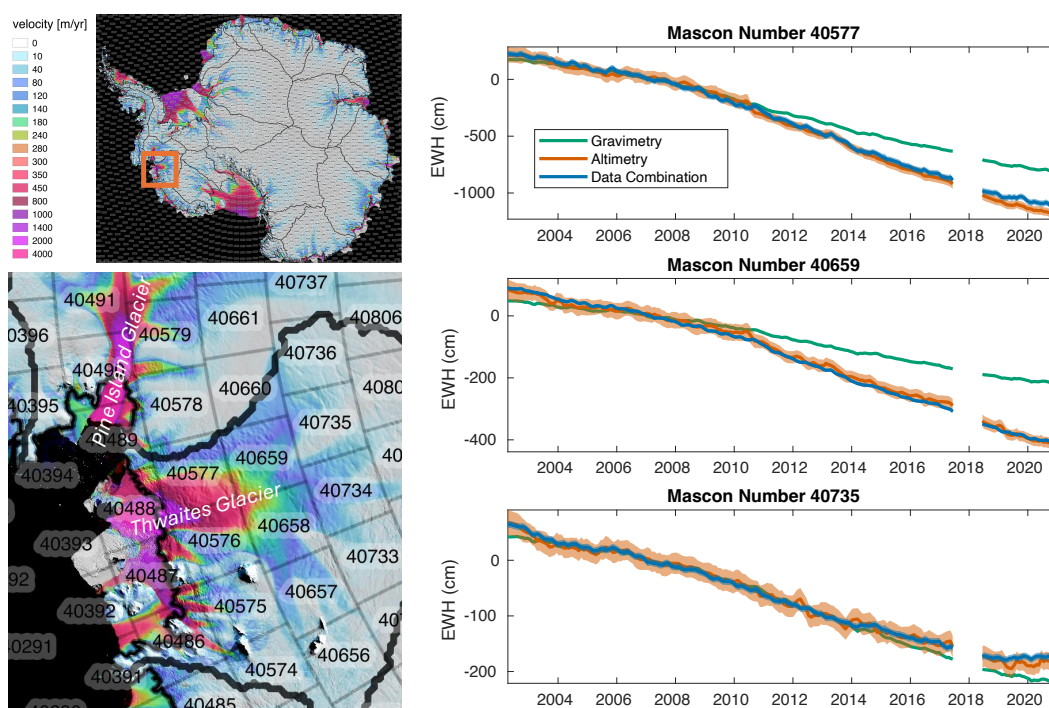


Figure A3. Data combination solution aligns with altimetry data at the level of individual mascons on the Thwaites Glacier, resolving mass change at finer spatial resolutions than what is possible with gravimetry data alone. Mass balance time series for individual mascons over the Thwaites Glacier comparing a gravimetry-only solution, an altimetry-only solution, and the data combination solution. Mascon locations are shown over a velocity map (Gardner et al., 2022) for added context.

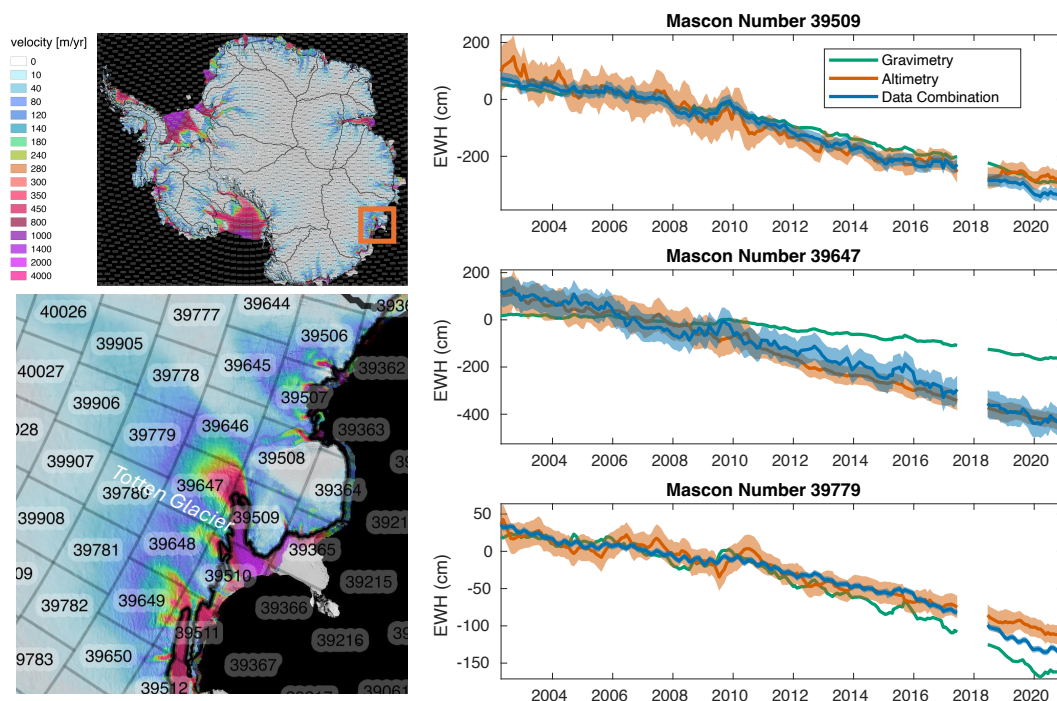


Figure A4. Data combination solution aligns with altimetry data at the level of individual mascons on the Totten Glacier, resolving mass change at finer spatial resolutions than what is possible with gravimetry data alone. Mass balance time series for individual mascons over the Totten Glacier comparing a gravimetry-only solution, an altimetry-only solution, and the data combination solution. Mascon locations are shown over a velocity map (Gardner et al., 2022) for added context.

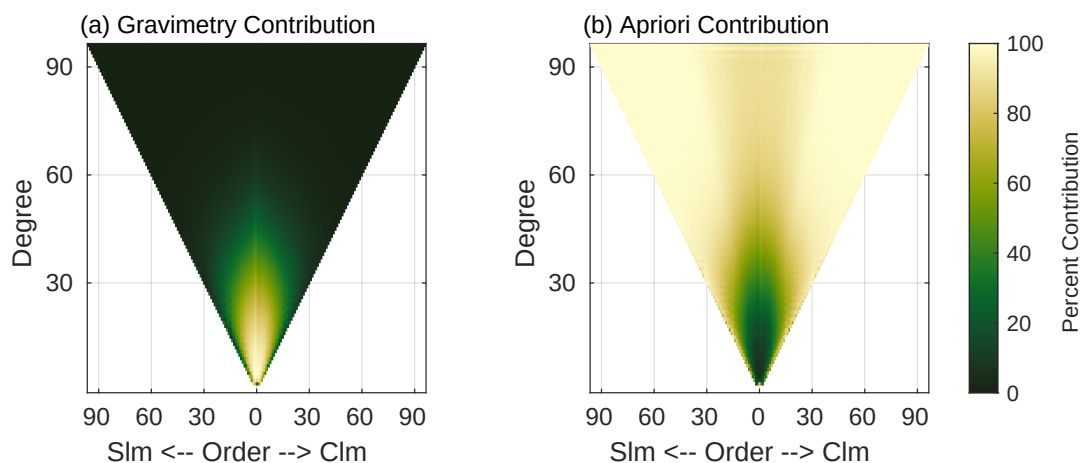


Figure A5. Satellite gravimetry data is the dominant contributor to zonal and near-zonal coefficients out to ~degree 45, while the *a priori* information dominates sectorial coefficients. Percentage contribution to the global data combination solution for each spherical harmonic coefficient for a) gravimetry data and b) *a priori* information.



Author contributions. DNW and ME led the gravimetry processing and production of the data combination solution. JN and ASG led the altimetry data processing. NJS and ASG led the FAC processing in GEMB. All authors contributed to writing and reviewing the manuscript.

475 *Competing interests.* There are no competing interests.

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