



A Regional Intercomparison of Ice Sheet Mass Balance Estimates of the Northwest Greenland Ice Sheet

Key Points:

- Input-output, gravimetry, and altimetry mass balance estimates agree to within 6 Gt in Northwest Greenland over the period 2010–2019
- Discrepancies at 2 of the sector's 74 glaciers explain most (55%) of the remaining difference between satellite techniques
- After a period of rapid mass loss in the 2010s, we record a 63% slowdown in the pace of ice loss over the period 2020–2023

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Abstract Changes in ice sheet mass manifest as changes in ice flow, ice thickness, and gravitational attraction. These parameters can be measured from space and used to track Greenland's contribution to sea level rise independently from each other. While an excellent level of agreement between these satellite techniques has been demonstrated at the ice sheet scale, less attention has been paid to whether this agreement is maintained at regional and local scales. However, regional mass balance assessments are key to validating and calibrating ice sheet models, ensuring they can accurately reproduce the spatial distribution of ice losses. Here, we compare mass balance estimates derived from satellite altimetry, satellite gravimetry, and the input-output method in Northwest Greenland, which we find to agree within 6 Gt yr^{−1} during their overlap period (2010–2019). We further investigate local sources of discrepancies between techniques and find that 55% of the remaining difference between our altimetry and input-output estimates can be explained by discrepancies at 2 of the sector's 74 glaciers, likely due to poor knowledge of ice thickness. Finally, owing to the good regional agreement between our estimates, we construct a reconciled mass balance record, showing that the Northwest sector contributed 5.1 ± 0.2 mm to sea level rise between 1972 and 2024. The pace of ice loss was fastest in the 2010s, with a record high mass loss rate of 65 ± 4 Gt yr^{−1}, before slowing down to 41 ± 10 Gt yr^{−1} in the last 4 years of our survey.

Plain Language Summary Measurements of ice sheet mass loss determined from different satellite techniques are in excellent agreement at the ice sheet scale. However, it is also critical to ensure that agreement is maintained at local scale. Here we compare different satellite estimates of ice loss from 74 glaciers in Northwest Greenland. We show that the three main satellite methods are in close agreement at the sector scale and at all but two of the glacier catchments, suggesting that ice sheet wide agreement is not underlain by spatially compensating regional discrepancies. Finally, owing to the good level of agreement between our estimates, we produce a 52-year reconciled record of Northwest Greenland ice sheet mass changes. This new record shows that this region has lost ice in every year since 1997, and was losing ice fastest in the 2010s at a pace five times faster than in the 1970s. However, since then, the pace of ice loss has slowed down by 63%. Our study adds confidence that satellite estimates are sufficiently robust to be used for calibrating and evaluating numerical simulations of regional ice sheet mass changes, a finding that will help improve estimates of future sea level rise.

1. Introduction

The Greenland Ice Sheet (GrIS) has accounted for about 20% of the total mean sea level rise since 1993 (WCRP Global Sea Level Budget Group, 2018) despite only storing 10% of Earth's total ice on land—about 3 million km³ of ice (Morlighem et al., 2017). In recent years, ice losses from the GrIS have accelerated, rising from 35 ± 29 Gt yr^{−1} in the early 1990s to 257 ± 42 Gt yr^{−1} between 2017 and 2020 (Otosaka, Shepherd, et al., 2023) as a consequence of widespread retreat (King et al., 2020) and thinning (Khan, Bamber, et al., 2022; Khan, Colgan, et al., 2022) of outlet glaciers. Among the different regions of the GrIS, the Northwest sector is the first contributor to sea level rise, accounting for a third of Greenland's total ice losses between 1972 and 2018 (Mouginot et al., 2019). The Northwest sector includes over 60 marine-terminating outlet glaciers, which have all experienced widespread retreat triggered by ocean-induced melting (Wood et al., 2018). Glacier retreat in this sector was first observed in aerial photographs acquired between 1985 and 1993 (Kjær et al., 2012), before

another period of sustained retreat occurred between 2000 up to at least 2015 (Bunce et al., 2018; Howat & Eddy, 2011). Since then, a brief regional readvance was observed in 2017 and 2018, but this was soon followed by a further episode of retreat (Black & Joughin, 2022). Despite a consistent broad regional response of the Northwest sector, the pace of retreating and thinning of the different glaciers is complex and suggests that their response to oceanic forcing is strongly modulated by their bed topography (Morlighem et al., 2019) and fjord geometry (Carr et al., 2013).

While satellite-based estimates of ice sheet mass balance have been aggregated and reconciled at the ice sheet scale, with a recent assessment demonstrating an agreement to within 19 Gt yr^{-1} between 27 independent estimates for the GrIS (Otosaka, Shepherd, et al., 2023), less attention has been paid to the agreement between satellite techniques at regional or glacier basin scales. Our ability to resolve mass changes for the individual glacier basins of the Northwest sector had previously been hindered by the lack of direct ice thickness measurements, the rugged terrain in the vicinity of the glaciers' grounding line, and the relatively small size of these glaciers. However, progress has been made over the past decade in the geophysical methods and ancillary data sets used to measure changes in ice thickness, glacier flow, and gravitational attraction (Otosaka, Horwath, et al., 2023) and it is thus timely to revisit our ability to reconcile mass balance estimates at finer spatial scales.

Ice sheet thickness changes are typically measured using repeated laser (Csatho et al., 2014; Smith et al., 2020) or radar (Sørensen et al., 2018) altimetry measurements of surface elevation from either airborne or space borne platforms. While conventional pulse-limited satellite radar altimeters struggled to survey the rugged terrain close to glaciers termini, CryoSat-2 with its interferometric mode and ICESat-2 with its fine footprint have led to more reliable surface elevation change retrievals near the margins of the ice sheet. Altimetry-derived elevation changes have subsequently been used to estimate mass change using a variety of approaches, including with the aid of a firn densification model to correct surface elevation changes for firn compaction before applying a density model (McMillan et al., 2016), by correcting for both firn compaction and surface mass balance (SMB) processes to derive ice thickness changes (Zwally et al., 2011), or by generating empirical calibration fields using a machine learning approach (Simonsen et al., 2021). Next, ice flow at outlet glaciers measured from optical satellite imagery or interferometric satellite synthetic radar aperture (InSAR) (Joughin et al., 2010; Mouginot et al., 2017; Nagler et al., 2015) has been combined with ice thickness measurements along flux gates and SMB models to estimate ice sheet mass changes in the so-called "input-output" method (King et al., 2020; Mankoff et al., 2021; Mouginot et al., 2019). The computation of input-output mass fluxes has benefited from recent improvements in regional climate models (Fettweis et al., 2020) and ice thickness data sets, both from additional direct observations (e.g., An et al., 2017) and from a data-driven inversion of an ice flow model (Morlighem et al., 2017). Finally, gravity measurements recorded using satellite gravimetry have been used to estimate ice sheet mass change within globally evaluated mass concentration units (mascons) solutions based on Level-1 observations or Level-2 spherical harmonic gravity field solutions (e.g., Croteau et al., 2021; Luthcke et al., 2013; Save et al., 2016; Watkins et al., 2015) or within regionally focused solutions using global spherical harmonics (e.g., Sasgen et al., 2020; Velicogna et al., 2020). Recent efforts have focused toward providing gravimetry estimates over finer spatial units, either from globally derived mascon solutions (e.g., Croteau et al., 2021; Save et al., 2016) or from regionally focused studies with improved methods to minimize gravimetric signal leakage errors (e.g., Döhne et al., 2023).

In addition to providing valuable information on the observed spatial distribution of mass changes, regional mass balance assessments are also a key input for evaluating and calibrating numerical projections of the ice sheets' contribution to future sea level rise at the regional scale (Nias et al., 2019; Seroussi et al., 2023). Here, we study the imbalance of the Northwest Greenland Ice Sheet with the aid of satellite altimetry, satellite gravimetry, and the input-output method between 1972 and 2024. We assess the degree of similarity of three independent estimates of mass balance during their overlap period and across different spatial scales to investigate whether agreement between estimates at the ice sheet scale translates to a similar level of agreement at a regional scale. Finally, we compute the reconciled mass imbalance of the region's glaciers to quantify their contribution to global sea level rise over time.

2. Methods

To investigate the spatial agreement between ice sheet mass balance estimates derived from the input-output method, satellite gravimetry, and satellite altimetry across the Northwest sector, we generate three mass

balance estimates at the finest spatial resolution allowed by the inherent spatial resolution of the geodetic techniques and use the same ice sheet and glacier basin delineations (Mouginot et al., 2019) for all three estimates. For our input-output estimate, we update the estimate from Mouginot et al. (2019), which is the only input-output estimate provided for all 74 glacier basins of the Northwest sector. For our altimetry estimate, we generate a new CryoSat-2 mass balance estimate at 2.5 km resolution that is optimized for measuring elevation changes over the small marine-terminating glaciers of this sector. For our gravimetry estimate, we generate a GRACE-GRACE-FO estimate on a 50 km by 50 km grid using tailored sensitivity kernels that are designed to minimize the signal leakage from the neighboring sectors and peripheral ice cap, allowing more detailed investigations of the spatial agreement between satellite techniques across the Northwest sector.

2.1. Input-Output

The input-output method combines estimates of ice discharge computed from satellite-derived surface velocity measurements with modeled estimates of surface mass balance. Our input-output estimate is an update of Mouginot et al. (2019), which has been found to be in good agreement with other input-output estimates at the scale of the Greenland Ice Sheet, with a median difference in mass balance of the order of 10% between estimates from the same class of observations (Otosaka, Shepherd, et al., 2023). For the Northwest sector, mass balance is computed for the 74 individual drainage basins of the sector, which include 63 tidewater glacier basins and 11 land-terminating glacier basins from June 1972 to June 2019 at annual resolution. For 49 out of the 63 tidewater basins, mass balance is computed by comparing ice discharge and SMB. The remainder tidewater basins and all the land-terminating basins are assumed to be in a steady state with ice discharge flux set to the mean SMB over the reference period for tidewater basins and set to zero for land-terminating basins. To calculate ice discharge, knowledge of ice thickness (the difference between the bed and surface elevations) at the flux gate is required. Bed elevations are extracted from BedMachine (version 3) for 37 glaciers and from direct radar sounder measurements for 3 glaciers. For the 24 glaciers where no ice thickness measurements are available, reference SMB is used instead to calculate the reference flux. Finally, time-series of surface elevations are extracted from various data sets including digital elevation models (DEMs) derived from aerial orthoimages (Bjørk et al., 2012; Korsgaard et al., 2016), IceBridge laser ATM (Krabill, 2010), ICESat (Zwally et al., 2014), GIMP (Howat et al., 2014), and ArcticDEM tiles (Porter et al., 2022) and are used to account for the ice flux caused by surface elevation changes. Ice discharge is extended by 2 years compared to Mouginot et al. (2019) using new velocities measurements from Sentinel-1a/b, Sentinel-2, and Landsat-8. SMB anomalies are extracted from the regional climate model RACMO v.2.3p2 at 5.5 km resolution, statistically downscaled to a 1 km grid (Noël et al., 2019) and calculated with reference to the period 1961–1989. The final uncertainty on our input-output estimate is computed as the sum in quadrature of the errors associated with the discharge term and the error associated with the mean SMB flux over the reference period.

2.2. Gravimetry

Next, we estimate the gravimetric mass balance from GRACE and GRACE-FO Level-2 spherical harmonic (SH) coefficients between May 2002 and May 2024 by applying sensitivity kernels following Groh and Horwath (2021) and Döhne et al. (2023). Mass balance estimates produced using tailored sensitivity kernels have been compared against other gravimetry estimates as part of the Ice Sheet Mass Balance Intercomparison Exercise (IMBIE) for the Greenland Ice Sheet as a whole, with mass balance differences between gravimetry solutions of 11% for the ice sheet (Otosaka, Shepherd, et al., 2023). Here, we tailor the sensitivity kernels (or weight functions) by minimizing the sum of the variances of propagated mission errors and leakage errors. Propagated mission errors are assessed by propagating an empirical error covariance matrix of the SH gravity field solutions. Leakage errors are assessed by prescribing signal variances of point masses on the nodes of a 50 km $\times$ 50 km grid for the ice sheet and for the surrounding glaciated regions as well as on the nodes of a coarser, globally defined grid. We select optimal parameters for the ratio between the signal variances in the different domains and between signal variances and propagated mission error variances based on simulation experiments as described by Groh et al. (2019). As a result, the signal standard deviations assumed for leakage assessment are 400, 200, and 33.6 kg m⁻² for the ice sheet, surrounding glaciated regions and the coarser grid, respectively, and the propagated mission errors are scaled with a factor of 0.1. For the Northwest sector, the requirements (minimizing the sum of variances of propagated mission errors and leakage errors) are fulfilled by an extension of the integration into the ocean. For other sectors with more complicated mass change geometries (e.g., from surrounding glaciated regions

in the Canadian Arctic Archipelago for the North sector), the resulting sensitivity kernels are not as straight forward. We apply the sensitivity kernels to Level-2 GRACE monthly gravity-field solutions of Release 06 provided by the Center of Space Research (CSR RL06) (Bettadpur, 2018; Save, 2019). We add degree-1 coefficients derived by a data combination of the monthly solutions and assumptions on ocean mass redistribution (Sun et al., 2016). We replace C2,0 coefficients for all months and C3,0 coefficients for the time period starting from October 2016 by estimates provided in TN-14 (Loomis et al., 2020). To correct for the effects of glacial isostatic adjustment, we remove linear trends using the model by Caron et al. (2018). The resulting time series of the gridded mass balance of the ice sheet is spatially sampled on the 50 km $\times$ 50 km grid used to express the signal variances. The error on trend estimates of the gravimetric mass balance is computed as the sum in quadrature of the formal error of the fit, the error due to leakage, the error due to uncertainty in the Glacial Isostatic Adjustment (GIA) effect and the errors due to the uncertainties of the degree-1 and C2,0 SH coefficients. The leakage error is assessed by applying the sensitivity kernels to high-resolution synthetic input data. For smaller regions, the leakage effect tends to be larger than for aggregated regions due to leakage-in and leakage-out signals across the borders between the smaller regions, which cancel out when these regions are aggregated.

2.3. Altimetry

Finally, we estimate the altimetric mass balance of the Northwest sector from CryoSat-2 observations between June 2010 and December 2024 by applying a least-square model fit following McMillan et al. (2016) on a 2.5 km $\times$ 2.5 km grid to produce monthly time-series of elevation changes. We use surface height measurements derived with a Threshold Centre of Gravity waveform retracker (TCOG) for the LRM waveforms in the interior of the ice sheet and with the Wingham-Wallis retracker for the SARIn waveforms over the margins of the ice sheet. Following McMillan et al. (2016), we fit a least-square model to those observations to produce monthly time-series of elevation change. We apply a correction for the 2012 melt event (Nghiem et al., 2012) for the interior of the ice sheet based on identified abrupt changes in the shape of the altimetry echoes. The subsequent formation of a refrozen melt layer at the surface of the ice sheet caused changes in the scattering of the snowpack, which is reflected in changes in the waveform shape (Otosaka et al., 2020) and, if uncorrected for, can lead to a spurious elevation change (Nilsson et al., 2015). We compute monthly time-series of leading edge width (LeW) of the waveforms within 50 km $\times$ 50 km grid cells, detrend these time-series to calculate the average seasonal cycle in LeW and identify grid cells where the amplitude in LeW between August and May is twice that of the corresponding LeW average seasonal amplitude. For these grid cells, which represent 95.8% of the LRM area, we add an extra term in our least-square model fit to correct for the impact of the 2012 extreme melt event on surface heights. We fill unobserved grid cells at each epoch with an inverse distance weighting scheme. Finally, we correct for the undersampling of CryoSat-2 at each epoch following McMillan et al. (2016) by applying a scaling factor of 1.18 to align our monthly fields of elevation change to the full dh/dt field. We estimate the uncertainty in our elevation change estimates as the sum in quadrature of the systematic and random errors. Systematic errors include the errors associated with the choice of our least-square model fit, our 2012 melt event correction, and our ability to calculate the long-term trend of the elevation change time-series and are combined in quadrature. Time-varying errors include the errors associated with the measurement imprecision, the correction of the under-sampling of CryoSat-2, our interpolation scheme which we estimate with a jackknife procedure (Que-nouille, 1956). Time-varying errors are each accumulated in time in quadrature and then summed together.

We evaluate our derived rates of surface elevation change against those derived from NASA's Operation Ice-Bridge (OIB) airborne laser altimetry (Studinger, 2018) during their overlap period (2010–2019). Unlike CryoSat-2, OIB rates of surface elevation change are computed by comparing flight lines from a combination of any two campaigns, resulting in a data set of varying temporal sampling. To match the time periods of the two data sets, we first compute the mean OIB rate of elevation change for each combination of campaigns within each of our 2.5 km $\times$ 2.5 km grid cells where airborne data are available. We then linearly interpolate the corresponding CryoSat-2 grid cell time-series to the OIB start and end campaign dates and estimate the corresponding CryoSat-2 rate of change as the surface elevation change difference between these two dates divided by the time difference between the start and end campaign dates. Finally, in grid cells where rates from multiple campaign combinations are available, we assess the consistency of the CryoSat-2 and OIB computed rates of surface elevation by comparing total elevation changes derived from the 2010–2019 long-term trend and from the short-term trends calculated between year-to-year campaigns. We exclude grid cells where these differ by more than 5 m, resulting in the exclusion of 10% of the grid cells and compute the median and standard deviation of the difference between

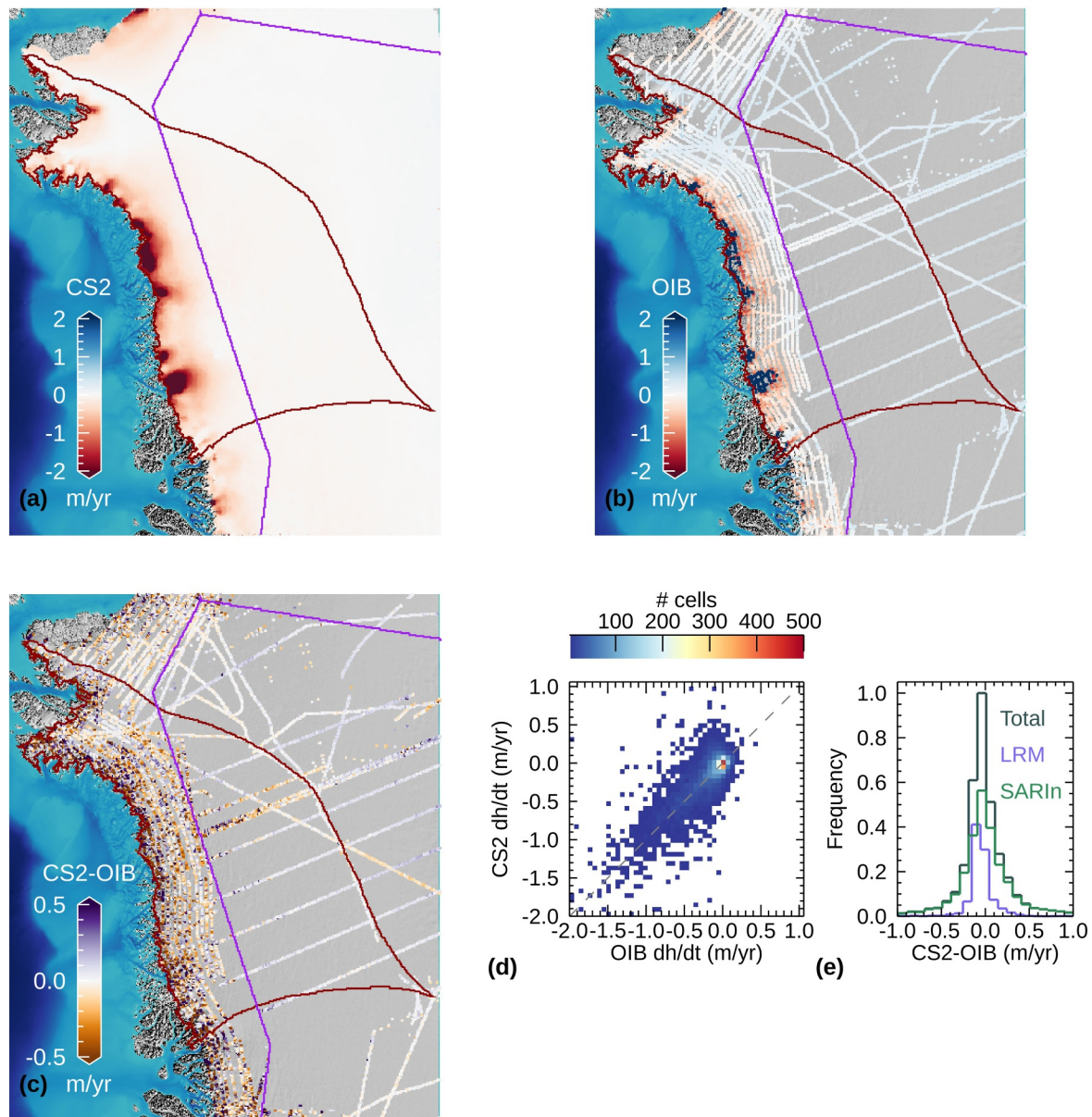


Figure 1. (a) Rates of surface elevation change derived from CryoSat-2 (CS2) between June 2010 and December 2024, (b) Rates of surface elevation change derived from Operation IceBridge (OIB) between June 2010 and December 2024 (c) Difference between CryoSat-2 and OIB rates of surface elevation change, (d) Scatterplot between CryoSat-2 and OIB rates of surface elevation change, and (e) Histogram of the difference between CryoSat-2 and OIB over the LRM and SARIn masks of CryoSat-2 and for the whole sector.

CryoSat-2 and OIB rates of elevation change over the remaining 7,236 grid cells. We find a very good level agreement between satellite radar and airborne laser rates of elevation change, with a median difference of 1.4 cm yr^{-1} and standard deviation of 97.0 cm yr^{-1} , in line with other published comparisons of satellite radar and airborne laser rates of elevation change (McMillan et al., 2016; Simonsen & Sorensen, 2017) (Figure 1).

Before converting our volume changes to mass changes, we correct our elevation change measurements for the vertical displacement induced by the solid Earth's response to past and present contemporary mass changes. The former correction is computed using the GIA simulation from Caron et al. (2018) and the latter correction is calculated using Green's function (Farrell, 1972).

To convert our volumetric changes to mass changes, we assume that all volume changes in the ablation zone occur at the density of ice (917 kg m^{-3}) and use temporally and spatially varying densities from the Modèle

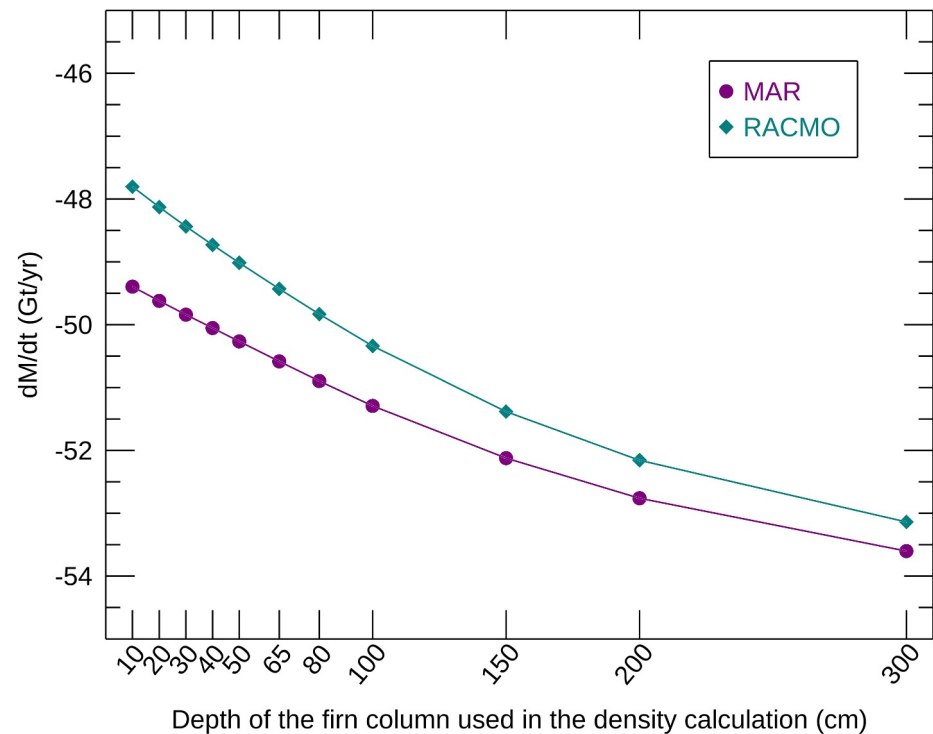


Figure 2. Mass balance sensitivity to the choice of ablation mask (derived from either MAR or RACMO) and depth of the firn column for computing the mean density (between 10 and 300 cm) for the volume to mass conversion.

Atmosphérique Régional (MAR version 3.14) for the interior of the ice sheet, using the mean density of the top first meter of the firn column and its standard deviation as uncertainty. The final uncertainty on our altimetry mass balance estimate is calculated by combining the uncertainties in volume changes and in density. We derive rates of mass change for all the individual glacier basins of the Northwest sector, with the exception of the Savissuaq-Helland-Yngvar_Nielson-Mohn-Carlos' basin which covers an area smaller than 1 km² and is thus too small to be resolved by our altimetry solution. We test the sensitivity of our mass balance estimate to the ablation zone definition used and to the depth of the firn density column used to convert volume changes in the interior of the ice sheet (Figure 2). We compare ablation masks derived from MAR and from the Regional Atmospheric Climate Model (RACMO version 2.3p2) and find that the MAR ablation area is 15% larger than that of RACMO, but choosing any of these definitions has a negligible impact on the final mass balance estimate of only 1 Gt yr⁻¹. On the other hand, varying the depth of the density column between 10 cm below the surface to 300 cm—producing 11 different mass balance solutions—shows that this has a small impact on our mass balance estimates, leading to a standard deviation of the mass balance solutions of 1.4 Gt yr⁻¹ and a maximum difference between solutions of 4.2 Gt yr⁻¹, smaller than our uncertainty bounds.

2.4. Combining and Partitioning of Mass Trends

We combine mass trends from our input-output, altimetry, and gravimetry estimates together following a similar approach than Otosaka, Shepherd, et al. (2023). We resample the three time-series of mass trends to common monthly epochs and take the mean of the three estimates at each epoch. Finally, we integrate the combined mass trend timeseries in time to generate a cumulative mass change timeseries. The uncertainty on mass trends is calculated as the mean of the three individual error timeseries and the uncertainty on the cumulative mass change is taken as the root sum square of epoch errors divided by 12.

We further partition our combined mass trends into SMB and dynamics components. We remove the SMB anomaly, calculated from the average of MAR and RACMO with reference to the period 1961–1989, from the total mass balance to derive the ice dynamic anomaly. We evaluate the sensitivity of our mass trend partitioning to the start and end dates of the time period chosen to calculate the reference SMB flux. To do so and quantify the

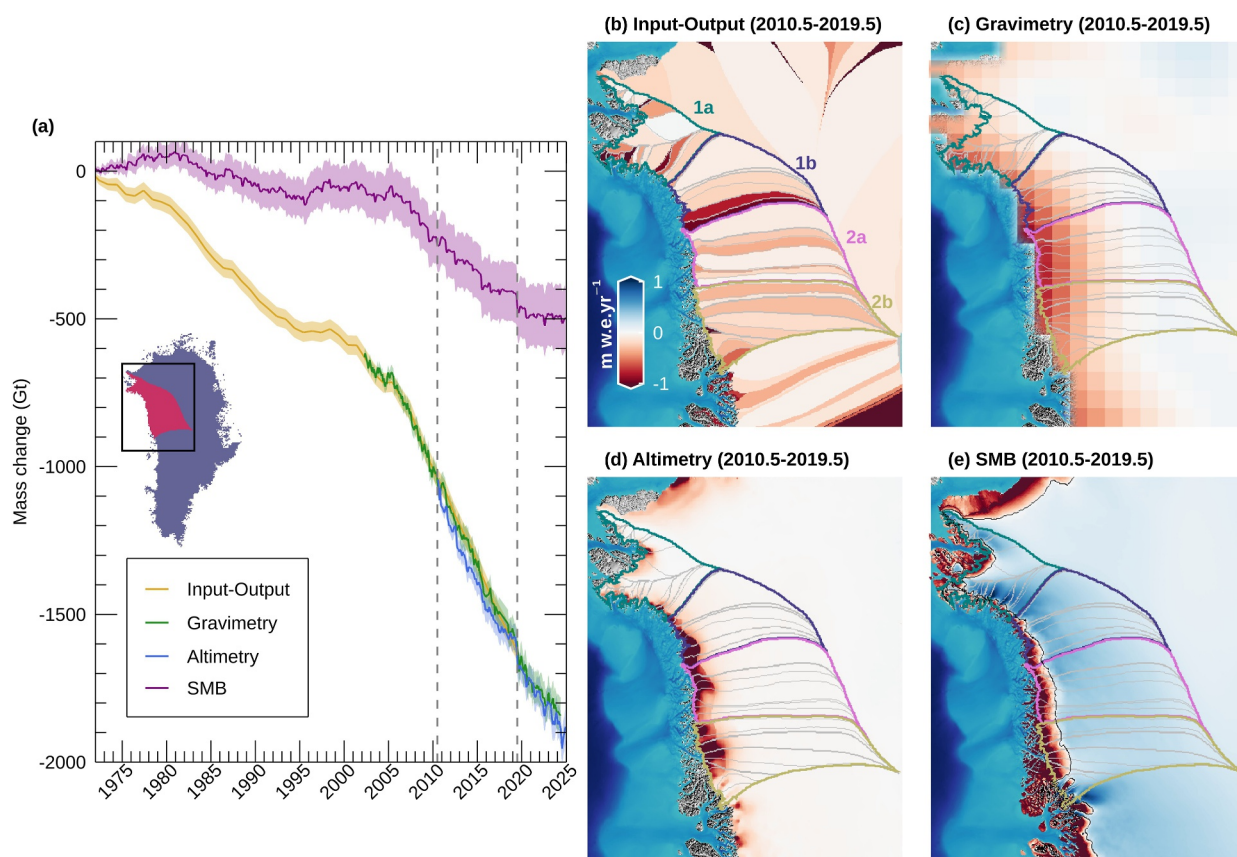


Figure 3. (a) Time-series of mass change from the three techniques over the Northwest sector of the Greenland Ice Sheet. The vertical dashed lines indicate the time period over which all three mass balance estimates are available (June 2010–June 2019) and are used in panels (b)–(e). Specific mass balance derived from (b) the input-output method, (c) satellite gravimetry, (d) satellite altimetry, and (e) specific surface mass balance calculated from the average of RACMO and MAR over the same period. Individual glacier drainage basins are outlined in gray and the sub-regions (1a, 1b, 2a, 2b) used in this study are outlined by the colored lines. The black line in (e) shows the delineation of the ablation zone. The inset map on (a) shows the location of the Northwest sector.

associated uncertainty, we run 100,000 Monte Carlo simulations allowing the reference time period to start in any year of the period 1940–1980, end in any year of the period 1950–1990, and of any duration between 10 and 30 years. These simulations result in a standard deviation of 7.8 Gt yr^{-1} in the reference SMB flux. We set the uncertainty on the SMB anomaly to 20% and add an uncertainty component reflecting the sensitivity of the reference time period chosen to the reference SMB flux, which we estimate to be 7.8 Gt yr^{-1} based on our sensitivity analysis. Finally, the resulting uncertainty on the ice sheet dynamic imbalance anomaly is taken as the sum in quadrature of the uncertainties on total mass balance and surface mass change anomaly.

3. Results

3.1. Individual Records of Ice Sheet Mass Changes

First, we examine our three individual records of ice sheet mass balance individually. As ice velocity measurements are available since the 1970s, the input-output method provides the longest record of mass changes of the GrIS. The available satellite data and technique produce mass balance estimates at moderate temporal (monthly to annual) and spatial resolution (at the individual glacier basin scale), resolving the imbalance of individual glacier catchments but with no further spatial information (Figure 3b). Over the input-output record (1972–2019), the Northwest sector lost $1,521 \pm 19 \text{ Gt}$ of ice, contributing $4.2 \pm 0.1 \text{ mm}$ to sea level rise. While the rate of mass loss was only $20 \pm 1 \text{ Gt yr}^{-1}$ in 1972–2000, the pace of mass loss was more than twice as high in 2000–2010 rising to $41 \pm 1 \text{ Gt yr}^{-1}$, before increasing further to $65 \pm 1 \text{ Gt yr}^{-1}$ in 2010–2019. Just 8 glacier basins contributed to more than half (51.1%) of the ice losses of the sector, with Steenstrup-Dietrichson and Upernavik

Isstrom northern tributary the largest contributors to the sector's mass imbalance with cumulative mass losses of 208 ± 5 Gt and 101 ± 5 Gt over the period 1972–2019, respectively.

Satellite gravimetry provides a direct estimation of mass change at fine temporal resolution (monthly) but at coarse spatial resolution, typically over hundreds of kilometres (Figure 3c). Over the satellite gravimetry record spanning the period from May 2002 to May 2024, Northwest Greenland lost mass at a rate of 55 ± 2 Gt yr^{−1}. We observe a small decrease in the rate of mass loss of 12% between the GRACE (May 2002–June 2017) and GRACE-FO (July 2018–May 2024) records. The gravimetry record is marked by large inter-annual variability in mass balance with a standard deviation in annual rates of mass loss of 22 Gt yr^{−1}. The start of the record shows a period of low mass loss during the hydrological years 2003–2004 and 2004–2005 with mass loss of 24 ± 4 Gt yr^{−1} and 11 ± 4 Gt yr^{−1}, respectively, before accelerating to an average rate of mass loss more than three times higher (63 ± 2 Gt yr^{−1}) during the following years. The highest mass losses were recorded during the hydrological years 2014–2015 and 2018–2019 due to large surface melt events that led to mass loss rates of 89 ± 8 Gt yr^{−1} and 86 ± 11 Gt yr^{−1}, respectively.

Satellite altimetry offers both fine spatial and temporal resolution (here over 2.5 km every month) and has been used to identify patterns of thinning around the glaciers in the margins of the Greenland Ice Sheet (McMillan et al., 2016; Pritchard et al., 2009). We record surface elevation and mass changes in 73 out of the 74 glacier drainage basins of the Northwest sector (Figure 3d); the only basin not resolved in our altimetry solution is the Savissuaq-Helland-Yngvar_Nielsen-Mohn-Carlos' basin, which covers an area less than 1 km². Using this new CryoSat-2 estimate, we find that the Northwest sector lost mass at a rate of 51 ± 4 Gt yr^{−1} between June 2010 and December 2024. The largest mass loss signals emerge from the Upernavik Isstrom N and Kjer Gletscher basins with a mass loss rate of 5 ± 0.4 Gt yr^{−1} and 4 ± 0.3 Gt yr^{−1}, respectively. Owing to its fine spatial resolution, our altimetry estimate can also be used to further explore the spatial patterns of thinning across the sector and within individual glacier basins. We identify 28 glacier drainage basins where thinning exceeds 5 m yr^{−1} locally (Figure 3d). While the maximum thinning rate is recorded close to the glaciers' grounding line (within a median distance to the grounding line of 20 km), we find that in 22 of the basins of the Northwest sector, thinning at a rate faster than 1 m yr^{−1} spread further inland, covering more than 10% of their basin area. Thinning spread inland up to 13 km at Upernavik Isstrom SS and up to 34 km at Docker Smith W covering 48% and 26% of the basin areas, respectively.

3.2. Regional Intercomparison of Ice Sheet Mass Changes

All three satellite methods show that the Northwest sector is in a state of imbalance with sustained thinning, ice discharge, and mass loss. During the overlap period (from June 2010 to June 2019), the Northwest sector lost mass at a rate of 65 ± 2 Gt yr^{−1} from the input-output method, 62 ± 2 Gt yr^{−1} from gravimetry, and 54 ± 5 Gt yr^{−1} from altimetry. To further assess the abilities of the three satellite techniques to measure mass changes, we divide the sector into two and four sub-regions of similar areas, the finest spatial resolution GRACE can reasonably achieve. While the input-output method estimate suggests that the spatial distribution of mass loss is equally split between the two main regions (1 and 2), the gravimetry and altimetry estimates both suggest that the Southern part of the sector (region 2) contributes more to the sector's imbalance, representing 60% and 56% of the mass loss, respectively (Figure 4). In the Southern part of the sector, we find very good agreement in sub-region 2b with estimates agreeing to within 1 Gt, while in sub-region 2a, our gravimetry estimate overestimates mass loss by 6 Gt compared to our input-output and altimetry estimates. The largest differences are located in the Northern part of the sector and more specifically from sub-region 1b where differences reach up to 8 Gt yr^{−1}, showing that this sub-region alone can account for the difference in mass balance at the sector level.

Next, to further isolate local areas of similarities and differences, we examine differences between our input-output and altimetry mass balance estimates within the individual glacier basins of the Northwest sector (Figure 5). Overall, we find that input-output and altimetry mass balance estimates of the 73 glacier basins are in good agreement with a correlation coefficient of 0.92. However, a paired samples T-test shows that differences between these two satellite techniques are statistically significant at basin scale ($p = 0.03$) and we thus investigate where these differences originate. Sub-region 1a counts 49 glaciers, where each glacier covers an area on average 10 times smaller than the other glaciers of the Northwest sector, and a large proportion of those glaciers are close to a state of balance—31 from altimetry and 24 from the input-output method. Within this region, the largest difference is found for Tracy Gletscher, with a difference in mass balance of 0.7 ± 0.2 Gt yr^{−1} and only four other

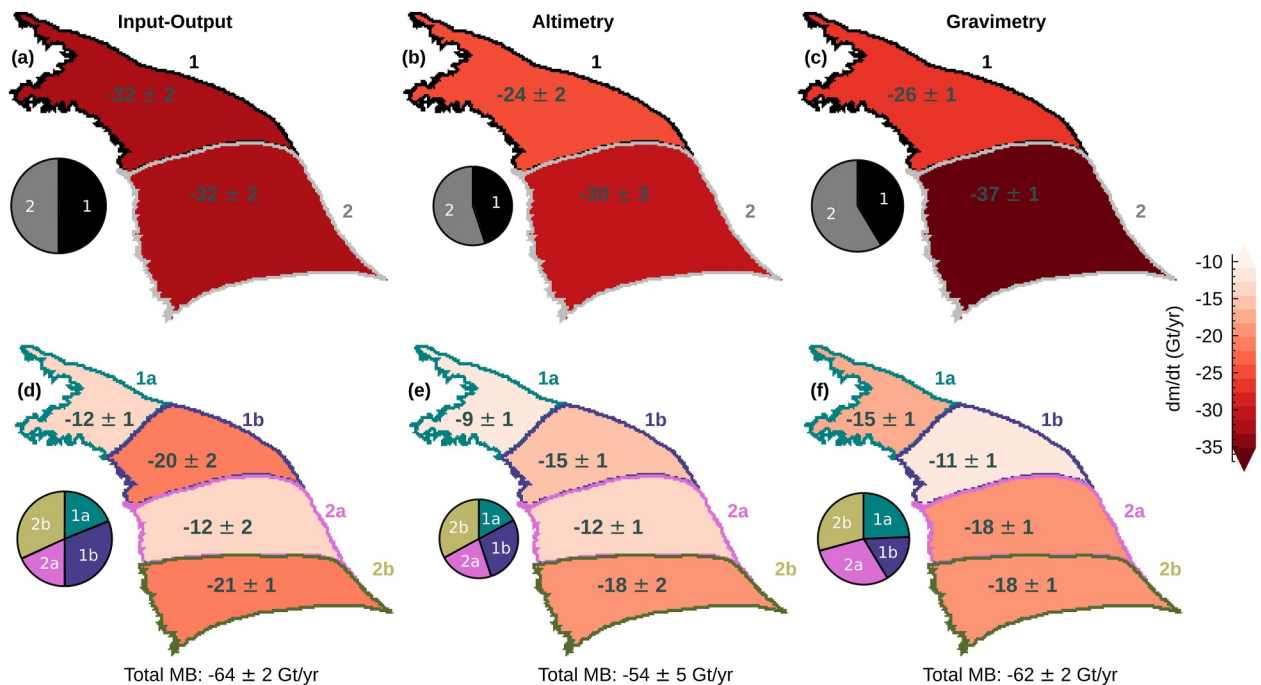


Figure 4. Rates of mass change over the Northwest sector divided into two (a–c) and four regions (d–f) between June 2010 and June 2019 derived from the input-output method (a and d), satellite altimetry (b and e), and satellite gravimetry (c and f). Rates of mass loss are indicated for each region. The pie charts indicate the distribution of the mass loss across the different regions and the size of the circle is proportional to the total mass balance of the sector.

basins show differences exceeding 0.5 Gt yr^{-1} . In sub-region 1b, the largest disagreement comes from the Steenstrup-Dietrichson basin, where the input-output method rate of mass loss is $7.3 \pm 0.3 \text{ Gt yr}^{-1}$, twice that of altimetry, followed by Kjer Gletscher where the input-output is 50% more negative than the altimetry with a rate of mass loss of $5.8 \pm 0.4 \text{ Gt yr}^{-1}$. Differences at those two neighboring glaciers account for most of the difference in sub-region 1b, and for 55% of the difference between the two estimates at the scale of the Northwest sector. Within sub-region 2a, the largest difference is found at Alison Gletscher with a difference of $1.4 \pm 0.3 \text{ Gt yr}^{-1}$, accounting for a quarter of the difference between altimetry and the input-output method in this sub-region. Finally, within sub-region 2b, the largest difference is found at Kakivfaat Sermiat, with a difference of $1.6 \pm 0.3 \text{ Gt yr}^{-1}$. This comparison shows that localized differences in mass balance can lead to a significant discrepancy at the regional scale between satellite techniques.

3.3. Reconciled Record of Ice Sheet Mass Changes

We combine our input-output method, altimetry, and gravimetry estimates to produce a single record of mass changes of the Northwest sector from 1972 to 2024 and estimate the relative contributions of ice dynamics and SMB processes with the aid of MAR and RACMO regional climate models. Over this 52-year record, the Northwest sector lost $1,817 \pm 72 \text{ Gt}$, contributing $5.1 \pm 0.2 \text{ mm}$ to global mean sea level rise (Figure 6). Ice dynamic processes were responsible for 72% of the mass loss and SMB processes for the remainder (28%). However, since 2005, SMB processes have played an increasing role in the mass loss of the sector, accounting for 38% of the mass loss compared to only 12% for the period pre-2005. Since 1997, Northwest Greenland has lost ice in every year of our record. The pace of mass loss was fastest during the 2010s, with a rate of mass loss of $65 \pm 4 \text{ Gt yr}^{-1}$, more than 5 times higher than that recorded during the period 1972–1980, caused by an increase in discharge of 31% and reduction in SMB of 38%. The 2010s was marked by extreme surface melt events and SMB was negative in both hydrological years 2014 and 2018 in our record. The pace of ice loss then slowed down to $41 \pm 10 \text{ Gt yr}^{-1}$ in the last 4 years of our survey (2020–2023), a similar pace to that of the 2000s.

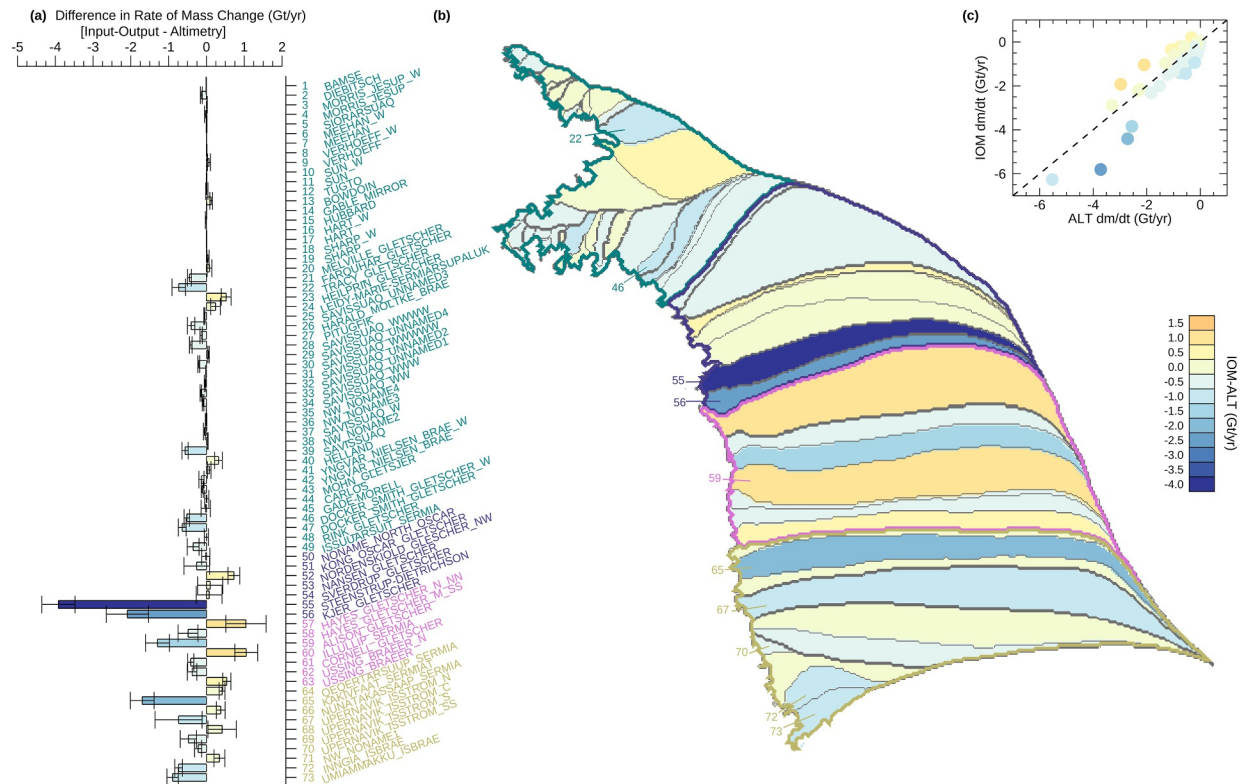


Figure 5. (a) Difference between the input-output and altimetry rates of mass balance within the individual glacier drainage basins of the Northwest sector over the period June 2010–June 2019. The names of the glacier basins are colored based on the sub-region they belong to. (b) Difference map between the two estimates using the same colors as in the bar chart. The locations of the glaciers mentioned in the text are indicated by the numbers on the map. (c) Scatterplot between input-output and altimetry rates of mass change during their overlap period.

4. Discussion

4.1. Comparison With Other Published Estimates of Northwest Greenland Mass Balance Estimates

We compare our individual and reconciled mass balance records to that of three other published estimates of satellite-based ice sheet mass balance: Simonsen et al. (2021), which uses a machine-learning approach to convert altimetric volume changes to mass changes, the PROMICE total mass balance solution (Larsen et al., 2021; Mankoff et al., 2021), which employs the input-output method, and Dahle et al. (2025), which derives gravimetric mass changes from Level-2 products provided by the Combination Service for Time-variable Gravity field (Figure 7). All estimates depict a similar temporal evolution in mass trends with an acceleration in the rate of ice loss starting in the early 2000s and a peak mass loss rate in the mid-2010s, followed by a slowdown in the pace of mass loss, with mass loss returning to a level similar to that of the early 2000s prior to the mass loss acceleration. However, despite this broad agreement in temporal evolution, there are significant differences in the magnitude of these mass trends, not only across techniques but also within techniques. During their respective overlap periods, we find differences in rates of mass loss of 11 Gt yr^{-1} between input-output estimates during the period January 1986–June 2019, 17 Gt yr^{-1} between altimetry estimates between May 2011 and June 2019, and 25 Gt yr^{-1} between gravimetry estimates between May 2002 and May 2024. When comparing rates of annual mass balance, we find the highest correlation between gravimetry estimates ($r^2 = 0.91$), followed by input-output estimates ($r^2 = 0.54$), and altimetry estimates ($r^2 = 0.50$). Finally, over the common period between all estimates (May 2011–June 2019), rates of mass loss range between $35 \pm 1 \text{ Gt yr}^{-1}$ (from Simonsen et al., 2021) and $77 \pm 3 \text{ Gt yr}^{-1}$ (derived from Larsen et al., 2021). The three individual mass balance estimates derived for the purpose of this study were optimized for the Northwest sector and achieved the best agreement together.

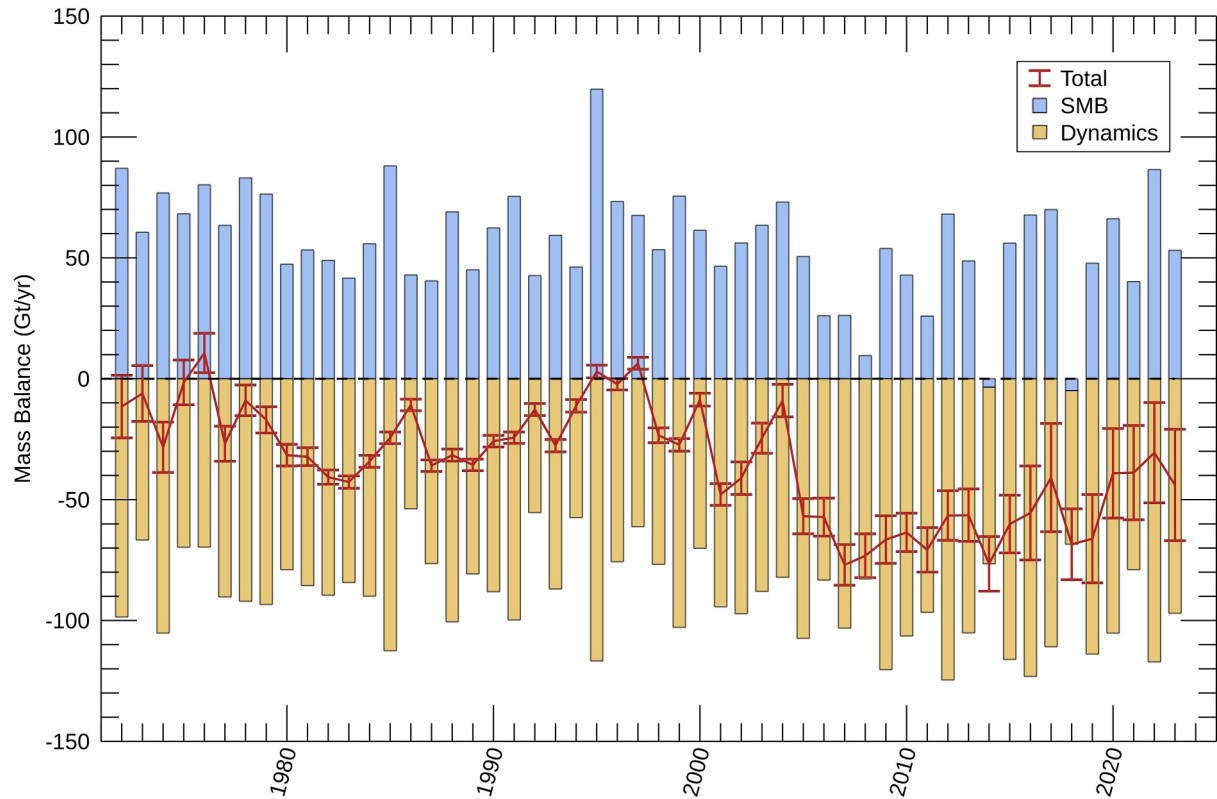


Figure 6. Annual mass balance of the Northwest sector and its SMB and ice dynamical components computed over hydrological years (from 1st September to 31st August of the following year).

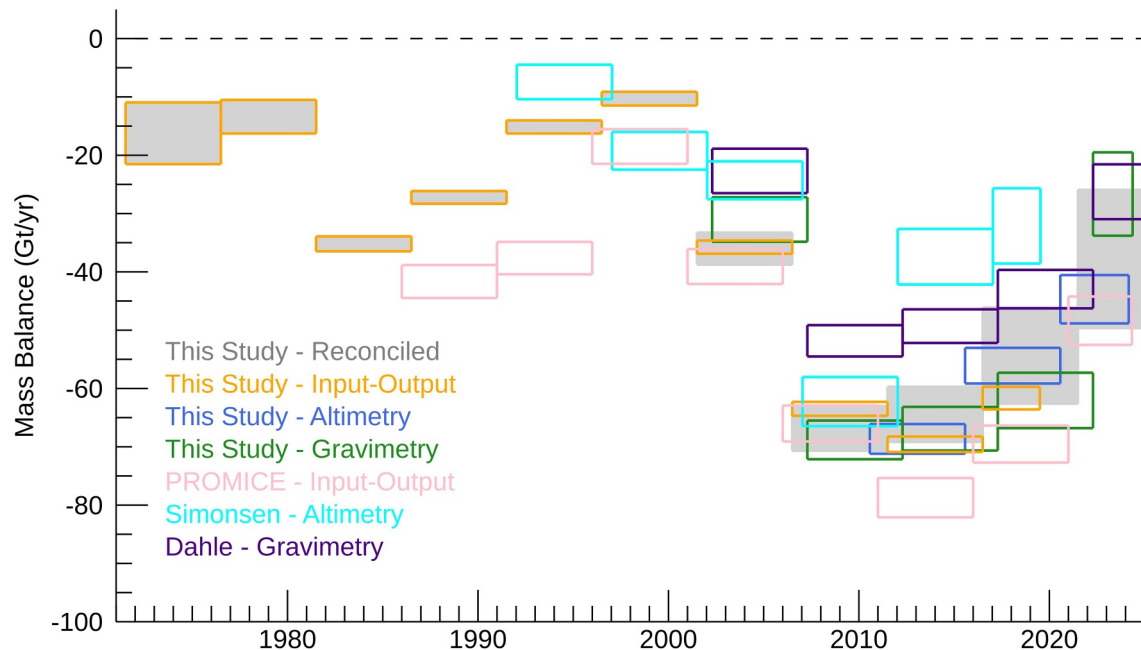


Figure 7. Rates of mass change of the Northwest sector from the estimates presented in this study and from three other published estimates computed over subsequent 5-year intervals (except for the very final time period, for which the calculation was done using the latest years of data available).

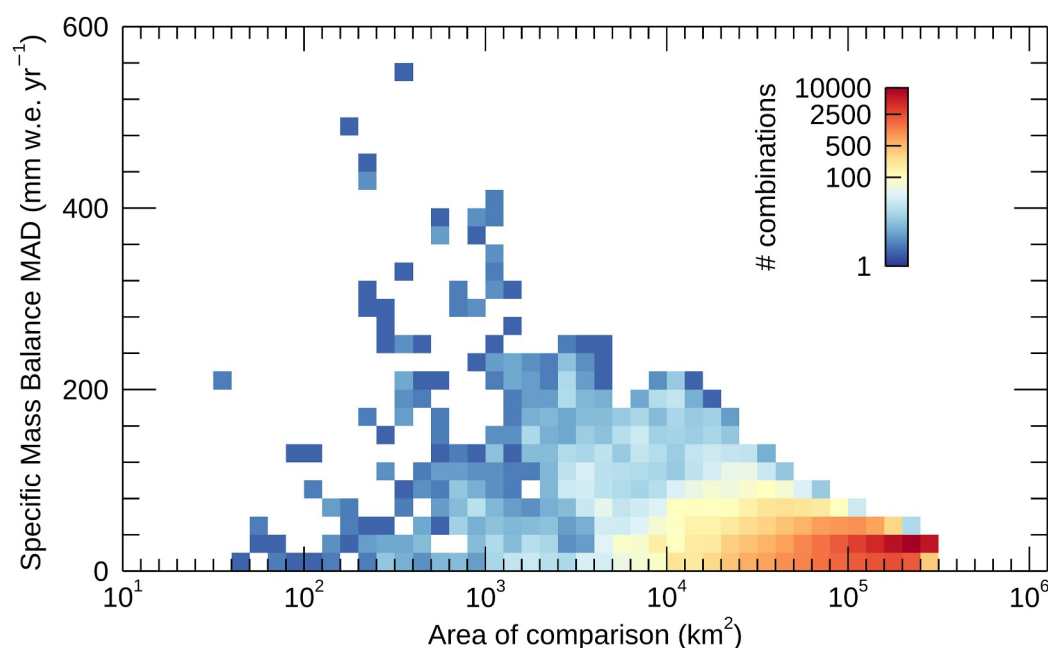


Figure 8. Mean Absolute Deviation (MAD) between our altimetry and input-output specific mass balance estimates as a function of area. Random combinations of glacier basins across the sector were drawn and for each combination (comprising a number of glacier basins between 2 and 74), the MAD was computed.

4.2. Scale-Dependency of the Agreement Between Ice Sheet Mass Balance Estimates

We explore whether the agreement between our altimetry and input-output estimates is scale dependent. To do so, we compare our altimetry and input-output specific mass balance estimates during their overlap period (June 2010–June 2019) over increasingly larger areas by adding one basin at a time, drawing one thousand random combinations of basins each time to avoid introducing biases in the choice of glacier basins, and we calculate the Mean Absolute Deviation (MAD) for each combination. For each random combination of basins, we calculate its corresponding mass balance by summing the individual glacier mass balance that make up this subset of basins from our altimetry and input-output estimates, respectively. We then calculate the average absolute distance between our altimetry and input-output estimates to their combined average. Finally, we normalize the MAD by the total area of the basins considered in the given combination. This experiment shows that the MAD rapidly decreases as the area of comparison increases as differences between estimates across individual basins are compensated. For regions under 100,000 km², the mean MAD is 37.7 mm w.e. yr^{−1} with a range of possible values of 660.6 mm w.e. yr^{−1}, whereas for regions over 100,000 km², the MAD is reduced by 32% (25.6 mm w.e. yr^{−1}) and its range to 70.8 mm w.e. yr^{−1}, demonstrating that differences between satellite techniques average out when aggregated over larger areas (Figure 8). This indicates that it is best to calibrate or evaluate ice sheet model outputs using satellite observations at regional or ice sheet scales rather than at glacier basin scales in order to reduce the dependency of the results on the choice of satellite estimate. However, detailed inter-comparison of mass balance can help identify local differences between estimates, contributing toward reconciling mass balance estimates across both local and ice sheet wide scales. In our mass balance assessment of the Northwest sector, we identify seven glacier basins where differences between our altimetry and input-output estimates exceed 1.0 Gt yr^{−1} and that require further investigation.

4.3. Local Sources of Discrepancies Between Estimates

First, we explore potential sources of biases in our input-output estimate by comparing our rates of discharge against those from Mankoff et al. (2020) and King et al. (2020) within coincident basins during the common time period with our altimetry and gravimetry estimate (June 2010–June 2019). All three discharge estimates were calculated using different flux gates, velocity, ice thickness, and ice thickness change products and their treatment of glacier basins with missing or incomplete bed topography also differed. For instance, in King et al. (2020) and

Mouginot et al. (2019), flux gates are positioned at the most retreated grounding line or ice front position, while in Mankoff et al. (2020), flux gates are automatically positioned around 5,000 m from the termini. Here, we restrict our comparison to Mankoff et al. (2020) to tidewater glacier basins where discharge data are valid, excluding basins where discharge was calculated using SMB-referenced fluxes or where there are no velocity measurements, resulting in a comparison in 45 glacier basins. To compare our estimate against that of King et al. (2020), which uses different glacier basin delineations, we select only the basins with identical names and valid discharge measurements, making up a total of 24 basins. We find correlation coefficients of 0.97 and 0.85 and RMSDs of 0.81 and 1.5 Gt yr⁻¹ when compared against King et al. (2020) and Mankoff et al. (2020) in 24 basins and 45 common glacier basins, respectively, and we find that overall differences between discharge estimates are not statistically significant with *p*-values of 0.18 and 0.85, respectively. The largest difference is found at the Upernavik Isstrom northern tributary, with a rate of discharge of 9.9 ± 0.3 Gt yr⁻¹ from our input-output estimate against 6.4 ± 0.3 Gt yr⁻¹ from King et al. (2020) and 7.2 ± 0.8 Gt yr⁻¹ from Mankoff et al. (2020). In addition, seven other glacier basins exhibit differences larger than 1 Gt yr⁻¹ among which are the Steenstrup-Dietrichson and Kjer Gletscher basins. Here, we suggest that both the location and thickness of the flux gates are likely to be responsible for most of the differences between different input-output estimates. We assess the sensitivity of our discharge estimate to the choice of thickness data set used by switching the bed elevation data set from the most recent BedMachine dataset (version 4) for all glacier basins, compared to using a combination of BedMachine version 3 and radar sounder measurements. Updating the thickness at all flux gates leads to a 32% reduction in ice discharge with a rate of mass loss for the sector between 2010 and 2019 reduced from 66.7 ± 1.0 Gt yr⁻¹ to 49.0 ± 2.2 Gt yr⁻¹. The largest differences are recorded in Steenstrup-Dietrichson, Kjer Gletscher, and Upernavik Isstrom North basins, with a reduction in their mass loss rates of 4.1 Gt yr⁻¹, 3.3 Gt yr⁻¹, and 2.4 Gt yr⁻¹ when switching the ice thickness data set, respectively. Updating the thickness data set results in a better agreement with our altimetry basin-scale estimates with a reduced RMSD of 0.57 Gt yr⁻¹ compared to 0.70 Gt yr⁻¹. While differences in flux gate location between studies have also been shown to have an impact locally, especially, as pointed out by King et al. (2020), when discharge at the flux gate is scaled based on the average velocity between the flux gate and ice front position such as what is done at Upernavik Isstrom North in Mouginot et al. (2019), our analysis shows that in this sector, ice thickness has a large impact on discharge estimate, affecting a larger number of flux gates. This comparison thus demonstrates the key role of ice thickness measurements in mass balance estimation and can also inform future surveys of bed elevations as prioritizing the mapping of glaciers with large differences between altimetry and input-output estimates will greatly contribute toward reconciling estimates at local and regional scales.

Next, we compare our CryoSat-2 rates of elevation change against those from NASA's Operation IceBridge (OIB) (Studinger, 2018) to explore potential sources of bias. Overall, there is a good agreement between satellite radar and airborne laser rates of elevation change with a median difference of 1.4 cm yr⁻¹ for the sector. We also examine local differences within the individual glacier basins of the Northwest sector by comparing the spatial coverage and sampling pattern of our CryoSat-2 solution and those of OIB. OIB's sampling pattern targets primarily the fastest flowing and thinning sections of outlet glaciers, while these areas can be particularly challenging for satellite radar altimeters. To test for a possible undersampling of CryoSat-2 and underestimation of mass loss in rapidly thinning areas, we include OIB rates of elevation change in grid cells where there are no direct CryoSat-2 observations and estimate the corresponding mass balance using this combined CryoSat-2 and OIB rates of elevation change data set. For the 29 basins for which we include additional OIB data in an area of at least 62.5 km², we find that it leads to a rate of mass loss of more than 0.25 Gt yr⁻¹ in only three basins (Inngia Isbrae, Tracy Gletscher, and Umiammakku Isbrae) compared to our CryoSat-2 original solution. For instance, CryoSat-2 covers 95% of the Tracy Gletscher basin (against 41% from OIB) but misses an area of 138 km² located within 50 km from the grounding line, likely due to the close proximity of the Smithsonian Range nunatak—which separates Tracy Gletscher from the neighboring Heilprin Gletscher. Thanks to its preferential sampling, OIB covers an extra 100 km² area thinning at an average rate of 3.7 m yr⁻¹, which leads to an additional mass loss of 0.4 Gt yr⁻¹ for Tracy Gletscher. This finding is also in line with Kjeldsen et al. (2013), who demonstrated that supplementing ICESat data with OIB data leads to a better spatial coverage along the ice sheet margins, resulting in an increase in the rate of mass loss recorded compared to using satellite altimetry data alone. Revisiting the mass balance of these 33 glaciers by including OIB observations leads to a slightly better agreement with our input-output estimate with a correlation coefficient of 0.88 and RMSD of 1.02 Gt yr⁻¹, compared to 0.86 and 0.98 Gt yr⁻¹ when using CryoSat-2 observations only, respectively.

The coarser spatial resolution and leakage error of satellite gravimetry prevent a more detailed comparison with our altimetry and input-output estimates across the individual basins of the Northwest sector; disentangling the mass change signals from the ice sheet and its peripheral glaciers and ice caps remains a challenge (Otosaka, Horwath, et al., 2023). In the Northwest sector, the mass change signal originating from the Nunatarssuaq ice cap is likely to be leaked to the main ice sheet, and especially to sub-region 1a, which could contribute to explaining the higher gravimetry rate of mass loss compared to the other estimates in that region. The Northwest peripheral glaciers lost mass at an average rate of $5.2 \pm 0.9 \text{ Gt yr}^{-1}$ between 2003 and 2021 (Khan, Bamber, et al., 2022; Khan, Colgan, et al., 2022), which, despite representing less than a tenth of the mass loss of the Northwest sector over this period, has the potential to significantly contribute to local differences between techniques. However, we note that the leakage of the gravimetry signal from neighboring ice bodies might have a larger impact in other parts of Greenland, for instance in Northern Greenland because of its proximity to the Canadian Arctic Archipelago.

5. Conclusions

In this study, we estimate the mass balance of the Northwest sector of the Greenland Ice Sheet using three independent satellite techniques. Together these records show that ice losses in Northwest Greenland started in the 1980s, followed by an acceleration in the pace of mass loss in the early 2000s that has been sustained throughout the 2010s due to increased ice discharge and reduced SMB, before slowing down in the last 4 years of our survey (2020–2023). During their overlap period from June 2010 to June 2019, our input-output, altimetry, and gravimetry estimates show sustained discharge, thinning, and mass loss leading to a mean rate of mass loss of $60 \pm 4 \text{ Gt yr}^{-1}$. Though marked with high interannual variability, the 2010s was the decade with the highest rate of mass loss recorded, more than five times higher compared to the period 1972–1980. However, since then, we record a 66% reduction in the pace of ice loss. The assessment produced here relies on a thorough comparison of mass balance estimates across different spatial scales demonstrating that differences between techniques vary spatially, depicting a more complex picture than comparisons at the ice sheet level. When examining differences across individual glacier basins, we find that only two glacier basins, Steenstrup-Dietrichson and Kjer glaciers, account for more than half of the remaining differences between altimetry and input-output estimates at the regional scale. These findings suggest that it is best to evaluate ice sheet models using satellite mass balance estimates at regional and ice sheet scales rather than at glacier scales where differences between techniques remain large in some glacier basins. Efforts dedicated to improving knowledge of ice thickness in the margins of the Greenland Ice Sheet for the computation of ice discharge, accounting for the sampling pattern of radar altimeters in regions with small and narrow glaciers, and better quantifying the leakage error of gravimetry estimates will contribute to further reconciling satellite measurements of ice sheet mass balance at local and regional scales.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Availability Statement

Mass balance from the input-output method, satellite gravimetry, and satellite altimetry presented in this study and combined time-series of total mass change, ice discharge, and surface mass balance and their respective uncertainties are available at <https://doi.org/10.5281/zenodo.19800408> (Otosaka et al., 2026) under the Creative Commons (CC-BY) license.

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