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Title

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Journal

Scientific Data, 13(1)

ISSN

2052-4463

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Publication Date

2026-09-16

DOI

10.1038/s41597-026-08088-0

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Peer reviewed

Mass balance of the Greenland and Antarctic ice sheets from the 1970s to 2023

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Abstract

The Greenland and Antarctic ice sheets are major drivers of global mean sea level rise and are predicted to continue to do so in the future. However, they also represent the largest source of uncertainty in projections of future sea level rise making robust estimates of observed ice sheet mass changes critical. Here, we compare and combine 45 independent estimates of ice sheet mass balance derived from satellite observations of temporal changes in ice sheet flow, volume, and gravitational attraction to determine the ice sheet mass balance from 1972 (Greenland) and 1979 (Antarctica) until 2023. We then use regional climate models to partition the total mass balance into contributions associated with surface mass balance and ice dynamical imbalance. The ice sheets lost $11,309 \pm 565$ billion tonnes of ice between 1979 and 2023, with glacier dynamical imbalance driving 84 % of the ice loss and surface mass balance the remainder. This dataset can be used to track the contribution of the ice sheets to sea level rise and constrain projections of future sea level rise.

Background & Summary

Since the 1990s, the pace of ice loss from the Antarctic and Greenland ice sheets has accelerated, contributing to the increase in global mean sea level rise¹, with the ice sheets now representing almost a quarter of global sea level rise². As ice losses from the ice sheets are predicted to further increase over the coming decades and centuries³, quantifying ice sheet mass balance – the rate of change in ice sheet mass – is thus critical to assess the ice sheets' contribution to rising sea levels and the risks associated for coastal communities around the world^{4,5}. The ice sheets also dominate uncertainties in future sea level rise, and high-end sea-level rise projections increase by a factor 2.6 by 2150 if ice sheet instability processes are included⁵. Maintaining the long-term observational record of ice sheet mass balance is a critical step towards improved ice sheet model skill^{6,7} and realistic projections of sea level rise⁸.

Fluctuations in ice sheet mass are the results of ice dynamical, surface mass balance (SMB), and basal mass balance processes. While ice sheets gain mass primarily from snowfall accumulation, they lose mass through several processes, including solid ice discharge at the grounding line, melting at the bed and at the ice-ocean interface, and through surface meltwater runoff, sublimation, evaporation, and blowing snow erosion. Ice velocity measured by radar and optical imaging sensors, volume changes measured by radar and laser altimeters, and Earth's gravity field variations measured by microwave ranging interferometers are the key satellite records used to monitor the state of the ice sheets⁹. When combined with models of SMB, firn processes, basal mass balance, and glacial isostatic adjustment (GIA), they provide estimates of ice sheet mass balance. In the input-output method^{10,11,12} (also called mass budget method), mass balance within glacier drainage basins is derived from combining solid ice discharge estimates (derived from ice velocity measurements and estimates of ice thickness at the grounding line) and regional climate model estimates of the individual SMB components^{13,14}. In marine-terminating glacier basins, ice discharge is calculated at flux gates defined in the vicinity of the grounding line, either at a fixed distance upstream from the grounding line, inland of the most retreated grounding line location recorded or where airborne measurements of ice thickness are available. The grounding line flux is then calculated by combining ice velocity and ice thickness measurements and is adjusted by adding the average SMB for the area between the flux gate and ice front. A correction is further applied to time-series of grounding line flux to account for temporal changes in ice thickness using surface elevation change measurements. Finally, mass balance is derived by differencing this ice discharge estimate and the basin integrated SMB. Altimetry-derived mass balance estimates^{15,16,17} are derived by correcting ice sheet volume changes (estimated from repeated

elevation surveys) for firn densification processes or by prescribing the density at which the volume changes are occurring with the aid of an external firn density model¹⁸. Gravimetry-derived mass balance estimates^{19,20,21} (computed using global spherical harmonic solutions or spatially discrete mass concentration units) are corrected for long-term GIA trends and mass change redistribution processes occurring outside the ice sheets^{22,23}.

With more than 50 published estimates of ice sheet mass balance computed using different satellite measurements, geophysical corrections, and ancillary datasets, now available, it is critical to assess differences between estimates, understand the associated uncertainties, and provide a robust combined dataset that can be used by the wider scientific community. This dataset builds on the most recent Ice Sheet Mass Balance Inter-comparison Exercise (IMBIE) assessments for the Antarctic and Greenland ice sheets, which reported a combined contribution of 21.0 ± 1.9 mm to GMSL between 1992 and 2020². Here, we present new consensus estimates of ice sheet mass balance of the Greenland and Antarctic ice sheets for the periods 1972 to 2023 and 1979 to 2023, respectively. Our assessment only accounts for ice sheet mass change that contributes to sea level and does not address the ice loss from ice shelf thinning^{24,25}, ice shelf retreat²⁶ or ice retreat for ice grounded below sea level²⁷. In addition to ice sheet net mass balance, our dataset also includes the partitioning of ice sheet mass trends into SMB and ice dynamical processes, providing key information on the drivers of observed mass changes.

Methods

Input Data

We use ice sheet mass balance estimates derived using data from 27 satellite missions spanning the years 1972 to 2023 plus a range of GIA and SMB models using common definitions^{28,29} of the Greenland, Antarctic, Antarctic Peninsula, East Antarctic, and West Antarctic ice sheet boundaries (GrIS, AIS, APIS, EAIS, WAIS) (Table 1). In this new assessment, we make use of early satellite velocity measurements going back to the start of the Landsat historical archive in 1972 for Greenland and in 1979 for Antarctica when spatial coverage was sufficient to interpolate or scale these partial velocity surveys to estimate ice discharge at the continental scale. In years with no or poor velocity measurements (for instance between Landsat-1/2 and Landsat-4/5), ice discharge is linearly interpolated, and its uncertainty is increased proportionally to the time span since the closest available velocity estimate. There are 24 estimates of Greenland mass balance altogether comprising 6 altimetry estimates, 15 gravimetry estimates, and 3 input-output estimates. Over Antarctica, we include 21 estimates altogether with 5 of those estimates derived from altimetry, 15 from gravimetry, and 1 from the input-output method. Each estimate is associated with a published study that describes the data and methods used to derive it, although in many cases the estimates have been updated to extend their temporal coverage beyond that of the original study (Table 2).

Table 1. Synthesis of satellite datasets, GIA, and SMB models used to derive the individual estimates of ice sheet mass balance from the input-output method (IOM), satellite altimetry (ALT), and satellite gravimetry (GMB) included in this study.

		1972-1979				1980-1989				1990-1999				2000-2009				2010-2019				2020	2021	2022	2023
Satellite Missions																									
IOM	Landsat-1																								
	Landsat-2																								
	Landsat-4																								
	Landsat-5																								
	ERS-1																								
	ERS-2																								
	Landsat-7																								
	RADARSAT-1																								
	ENVISAT																								
	ALOS/PALSAR																								
	RADARSAT-2																								
	TerraSAR-X																								
	COSMO-SkyMed																								
	Landsat-8																								
Sentinel-1																									
Sentinel-2																									
ALT	Seasat																								
	Geosat																								
	ERS-1																								
	ERS-2																								
	ENVISAT																								
	ICESat																								
	CryoSat-2																								
	Sentinel-3																								
	ICESat																								
	ICESat-2																								
GMB	GRACE																								
	GRACE-FO																								
GIA models																									
AIS	ICE-6G																								
	IJ05																								
	IJ05_R2																								
	Khan_2016_and_W12a																								
GrIS	Schrama14																								
	A13																								
	ICE-5G																								
	ICE-6G																								
SMB models	Schrama14																								
	RACMO2.3																								
	HIRHAM5																								
	MAR_3.12																								
GrIS	RACMO_2.3																								

Table 2. References of the datasets and methods, employed by participants of the input-output (IOM), altimetry (ALT) and gravimetry (GMB) experiment groups. Compared to the original publication, most datasets have been updated as part of this new reconciled mass balance assessment; both the original temporal coverage and the extended temporal coverage are indicated. To get access to the most recent version of specific individual dataset, please get in touch with the corresponding main point of contact.

	Participant name	Spatial Coverage	Original Temporal Coverage	Extended Temporal Coverage for this assessment	Email address of main point of contact
IOM	King ³⁰	GrIS	1985 to 2018	1985 to 2023	michalea@uw.edu
	Mankoff ³¹	GrIS	1840 to 2021	1986 to 2023	mankoff@gmail.com
	Mouginot ¹²	GrIS	1972 to 2018	1972 to	erignot@uci.edu
	Rignot ¹¹	AIS	1979 to 2017	1979 to 2021	erignot@uci.edu
ALT	Gourmelen ³²	GrIS	2010 to 2016	2011 to 2018	noel.gourmelen@ed.ac.uk
	Helm ³³	GrIS, AIS, APIS, EAIS, WAIS	2011 to 2013	1992 to 2023	veit.helm@awi.de
	Khan ³⁴	GrIS	2011 to 2020	1995 to 2023	abbas@space.dtu.dk
	Nilsson ³⁵	GrIS, AIS, APIS, EAIS, WAIS	1985 to 2020	1992 to 2023 (GrIS) 1992 to 2020 (AIS)	johann.n.nilsson@gep.uu.se
	Sørensen ³⁶	GrIS	2003 to 2008	2018 to 2021	slss@space.dtu.dk
	Schröder ³⁷	AIS, APIS, EAIS, WAIS	1978 to 2017	1992 to 2017	ludwig.schroeder@gmx.net
	Shepherd ¹⁶	AIS, APIS, EAIS, WAIS	1992 to 2017	1992 to 2023	andrew.shepherd@northumbria.ac.uk
	Simonsen ³⁸	GrIS	1992 to 2019	1992 to 2019	ssim@space.dtu.dk
	Smith ¹⁷	GrIS, AIS, APIS, EAIS, WAIS	2003 to 2019	2003 to 2019	besmith@uw.edu
GMB	Ditmar ³⁹	GrIS, AIS, APIS, EAIS, WAIS	2003 to 2015	2002 to 2023	P.G.Ditmar@tudelft.nl
	Döhne ⁴⁰	GrIS, AIS, APIS, EAIS, WAIS	2002 to 2020	2002 to 2023	martin.horwath@tu-dresden.de
	Forsberg ⁴¹	GrIS, AIS, APIS, EAIS, WAIS	2002 to 2015	2015 to 2023	rf@space.dtu.dk
	Groh ⁴²	GrIS, AIS, APIS, EAIS, WAIS	2002 to 2020	2002 to 2023	groh.andreas@gmx.de
	Harig ⁴³	GrIS, AIS, APIS, EAIS, WAIS	2002 to 2011	2002 to 2023	charig@arizona.edu
	Loomis ⁴⁴	GrIS, AIS, APIS, EAIS, WAIS	2003 to 2017	2002 to 2023	bryant.d.loomis@nasa.gov

	Sasgen ⁴⁵	GrIS, AIS, APIS, EAIS, WAIS	2003 to 2009	2002 to 2023	ingo.sasgen@awi.de
	Save ⁴⁶	GrIS, AIS, APIS, EAIS, WAIS	2003 to 2015	2002 to 2023	save@csr.utexas.edu
	Schrama ⁴⁷	GrIS, AIS, APIS, EAIS, WAIS	2003 to 2013	2002 to 2023	e.j.o.schrama@tudelft.nl
	Seo ⁴⁸	GrIS, AIS, APIS, EAIS, WAIS	2003 to 2014	2002 to 2023	seokiweon@snu.ac.kr
	Sutterley ⁴⁹	GrIS	2002 to 2019	2002 to 2023	tsutterl@uw.edu
	Velicogna ²⁰	AIS, APIS, EAIS, WAIS	2002 to 2019	2002 to 2021	isabella@uci.edu
	Vishwakarma ⁵⁰	GrIS, AIS	2004 to 2013	2018 to 2021	bramha@iisc.ac.in
	Wiese ⁵¹	GrIS, AIS, APIS, EAIS, WAIS	2003 to 2013	2002 to 2023	david.n.wiese@jpl.nasa.gov
	Wouters ⁵²	GrIS, AIS, APIS, EAIS, WAIS	2002 to 2016	2002 to 2023	Bert.Wouters@tudelft.nl

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150 *Standardisation of Input Datasets*

151 First, we standardise all input datasets as time-series of rates of ice sheet mass change posted at
152 regular monthly intervals. For input datasets originally posted as relative mass change, we estimate
153 the rate of mass change in each month of the record by fitting a linear trend to the temporal mass
154 changes falling within a 36-month sliding window centred around the given month using a weighted
155 least-squares approach (Figure 1). For the first and last 18 months of the time-series, we reduce the
156 width of the sliding window maintaining its symmetry, except for the very first and last six months for
157 which we use the mean rate calculated over a 12-month period. The error on the standardised mass
158 balance time-series is computed as the sum in quadrature of the standard error of the linear
159 regression and the mean of the input errors divided by the duration of the sliding window. In this
160 scheme, the only difference with the previous standardisation procedure² is that we now divide the
161 mean of the input errors by the duration of the sliding window.

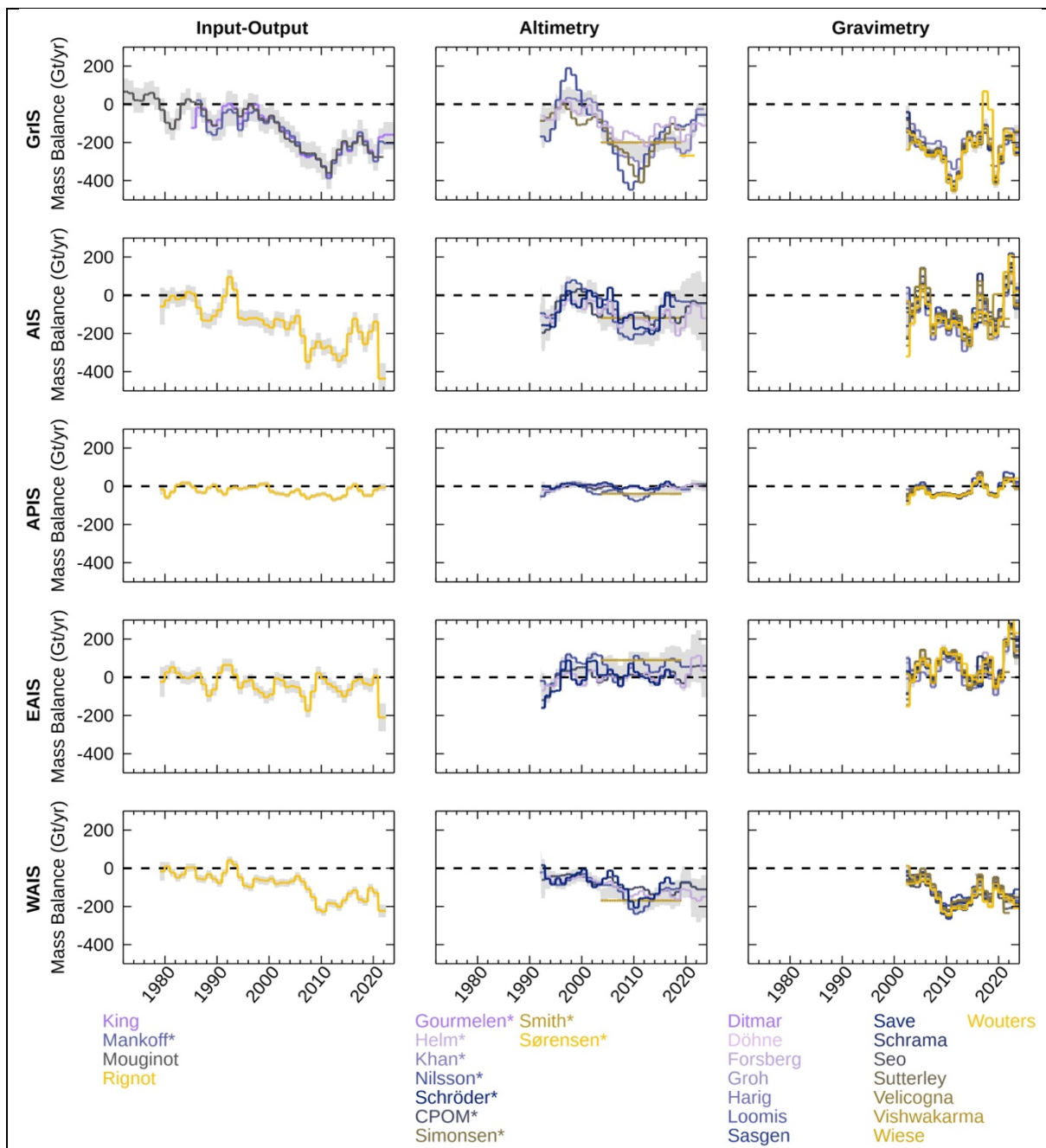


Figure 1. Standardised rates of ice sheet mass balance from the input-output, altimetry, and gravimetry individual estimates over the GrIS, AIS, APIS, EAIS, and WAIS included in this study. The grey shading shows the estimated uncertainty of the aggregated time-series per group. The individual estimates that do not include the peripheral glaciers and ice caps are indicated with an asterisk.

162

163 *Accounting for the Ice Sheets' Peripheral Glaciers and Ice Caps*

164 We correct the input datasets that do not originally account for the ice sheets' peripheral glaciers and
 165 ice caps (GICs) mass changes. While all our gravimetry estimates account for both the main ice sheets
 166 and their periphery (here we assume that this does not include the Canadian Arctic peripheral
 167 glaciers), this is not the case of our altimetry estimates and one of our input-output estimates. To

correct for the omission of Greenland's GICs, we aggregate two estimates from the input-output method^{12,30} and one from DEM differencing⁵³. The two input-output estimates are both derived based on the assumption that GICs mass changes are predominately SMB-driven and are in good agreement with a root-mean-square deviation (RMSD) of 6.9 Gt yr⁻¹ and correlation (r^2) of 0.62 during their overlap period (1985-2018). On the other hand, the rate of mass loss derived from DEM-differencing is 44% and 55% higher than that the two input-output estimates over the period 2002-2018, respectively. The discharge of the GICs has been independently estimated^{54,55} to be of the order of ~2-5 Gt yr⁻¹, which is not sufficient to reconcile the SMB-driven GICs estimates with the DEM differencing estimate. We standardise and aggregate these three GICs mass balance time-series, showing that over the period 1972-2023, Greenland's GICs lost mass at a rate of 8.0 ± 0.5 Gt yr⁻¹, which represents around 7% of the ice sheet mass loss. Our aggregated estimate further shows that the GICs started to lose mass in the 1990s at a rate of 4.4 ± 0.8 Gt yr⁻¹, followed by a fourfold increase in mass loss, reaching a rate of 18.9 ± 1.3 Gt yr⁻¹ in the 2010s. In Antarctica, there are fewer estimates available of the GICs and large disagreement between those estimates. One input-output estimate find the Antarctic periphery in balance over the period 1979-2017¹¹, while the DEM differencing method estimates the Antarctic GICs to be losing mass at a rate of 20.9 ± 4.9 Gt yr⁻¹ over the period 2010-2018⁵³, and an independent CryoSat-2 swath altimetry estimate records rate of mass loss 3.5 ± 0.4 Gt yr⁻¹ over the period 2010-2020⁵⁶. We thus do not attempt to correct the altimetry time-series for their omission of the GICs mass changes in Antarctica.

Aggregation of Ice Sheet Mass Balance Estimates

To produce a reconciled estimate of ice sheet mass balance, we use a similar approach than described in our previous mass balance assessment². Here we briefly summarise this approach. First, we aggregate our time-series of standardised ice sheet mass trends within the altimetry, gravimetry, and input-output groups separately. To do this, we calculated the error weighted average of the individual monthly rates of ice sheet mass change falling within the same satellite class. The only difference with our previous aggregation scheme² is that the weighting applied is the inverse square of the input error instead of the inverse of the error. The error on the technique aggregated time-series is computed at each epoch as the sum in quadrature of the errors of the contributing time-series divided by the square root of the number of estimates available. We then combine the resulting three aggregated time-series into a single reconciled time-series by taking the error-weighted average across the three techniques, using the inverse square of the associated errors as weighting factor, and estimate the associated error as the sum in quadrature of the aggregated time-series errors divided by the square root of the number of techniques available. Finally, we integrate our reconciled time-series of mass trends to generate a time-series of cumulative ice sheet mass change and estimate the cumulative errors as the root sum square of errors, divided by 12.

Partitioning of Mass Trends into SMB and Ice Dynamics

To determine the proportion of mass loss due to surface and ice dynamical processes, we compute the contemporaneous trend in ice sheet SMB and remove this from our reconciled total mass change estimates. Because direct observations of ice sheet SMB are too scarce to provide full temporal and spatial coverage^{57,58}, large scale estimates are taken from atmospheric models which are evaluated with available in situ observations. Previous studies showed that finer-spatial-resolution regional climate models produce consistent results due to their ability to capture localised changes and resolve the full extent of the ablation zone⁵⁹. Therefore, we combine estimates of ice sheet SMB from 4 regional climate models in Antarctica and 3 in Greenland (Table 3). When available, the uncertainty of individual SMB models is derived from model-observation comparisons. SMB error from MAR and HIRMHAM were computed using an error function based on a piecewise linear fit, calculated from the root-mean-square error (RMSE) of the 80 percent of model-observation comparison pairs that best

match^{13,14}. For the GSFC-FDM, SMB error was estimated in relative terms and is reported as the median of the absolute bias between each in-situ measurements and modelled estimates of SMB, resulting in a typical relative bias for the GrIS and AIS of 14% and 23%, respectively⁶⁰. Finally, a conservative 20% error estimate was applied to RACMO SMB products, based on previous comparisons with in-situ observations of SMB¹² and satellite observations of annual surface melt⁶¹.

Table 3. Summary of SMB models used to partition ice sheet mass balance.

	Participant	Model	Atmospheric Forcing	Spatial resolution (km)	Temporal coverage	Temporal resolution
AIS	Kittel-Amory-Agosta ⁶²	MAR v3.12.1	ERA5	35	1979-2023	Monthly
	Hansen ⁶³	HIRHAM5	ERA-interim (1980-2018) & ERA5 (2019-2021)	12.5	1980-2021	Monthly
	Medley ⁶⁴	GSFC-FDMv1.2.1	MERRA-2	12.5	1980-2021	5-day
	Van Wessem ⁶⁵	RACMO v2.3p2	ERA5	27	1979-2021	Monthly
GrIS	Fettweis ⁶⁶	MAR v3.12.1	ERA5	10	1950-2023	Monthly
	Hansen ⁶⁷	HIRHAM5	ERA-interim (1980-2018) & ERA5 (2019-2021)	5.5	1980-2021	Monthly
	Noël ⁶⁸	RACMO v2.3p2	ERA5	1	1958-2023	Monthly

First, we aggregate estimates from the individual SMB models onto a common monthly temporal sampling before averaging into a single combined estimate. We estimate the uncertainty on the combined SMB time series as the sum in quadrature of the individual uncertainty estimates divided by the number of independent estimates used per epoch. For each ice sheet, we then resample these to an annual temporal resolution and compute the anomaly from the SMB combined estimate with respect to reference periods of 1979-2008 and 1960-1990 for Antarctica and Greenland, respectively – approximately 30-year periods which correspond to a period when each ice sheet was in approximate balance^{11,69}. Finally, we compute rates of ice sheet dynamic imbalance anomaly as the difference between rates of total ice sheet mass balance and SMB anomaly. We estimate the uncertainty on the rate of ice sheet dynamic imbalance anomaly by taking the root sum square of the estimated uncertainty on the rate of total mass balance and surface mass change anomaly at each epoch. Finally, we integrate monthly rates of each component to obtain estimates of cumulative mass change, surface mass change, and ice dynamic mass change. We estimate the cumulative errors as the root sum square of annual errors, assuming they are not correlated over time.

Data Records

Our dataset is available at <https://doi.org/10.5285/128c5e33-5224-4197-82f0-19dcc95b80a070>.

The data consists of a single reconciled estimate of ice sheet mass balance covering the period 1st July 1971 to 31st December 2023 for the GrIS and the period 1st January 1979 to 31st December 2023 for the AIS, APIS, EAIS, and WAIS. Two CSV files are provided for each ice sheet region, one with the data provided in Gigatons (Gt) and one with the data provided in equivalent sea level contribution in millimetres (mm) (assuming that 360 Gt of ice lost is equivalent to 1 mm sea level rise), for a total of 10 files. Files with the data in Gt and mm follow the naming convention: imbie3_*[ice sheet name]*_partitioned_Gt.csv and imbie3_*[ice sheet name]*_partitioned_mm.csv, respectively. The

corresponding ice sheet names are: 'greenland', 'antarctica', 'antarctic_peninsula', 'east_antarctica', and 'west_antarctica'. These files contain both annual rates and cumulative anomalies in SMB, dynamics, and total mass change with their corresponding uncertainties.

Data Overview

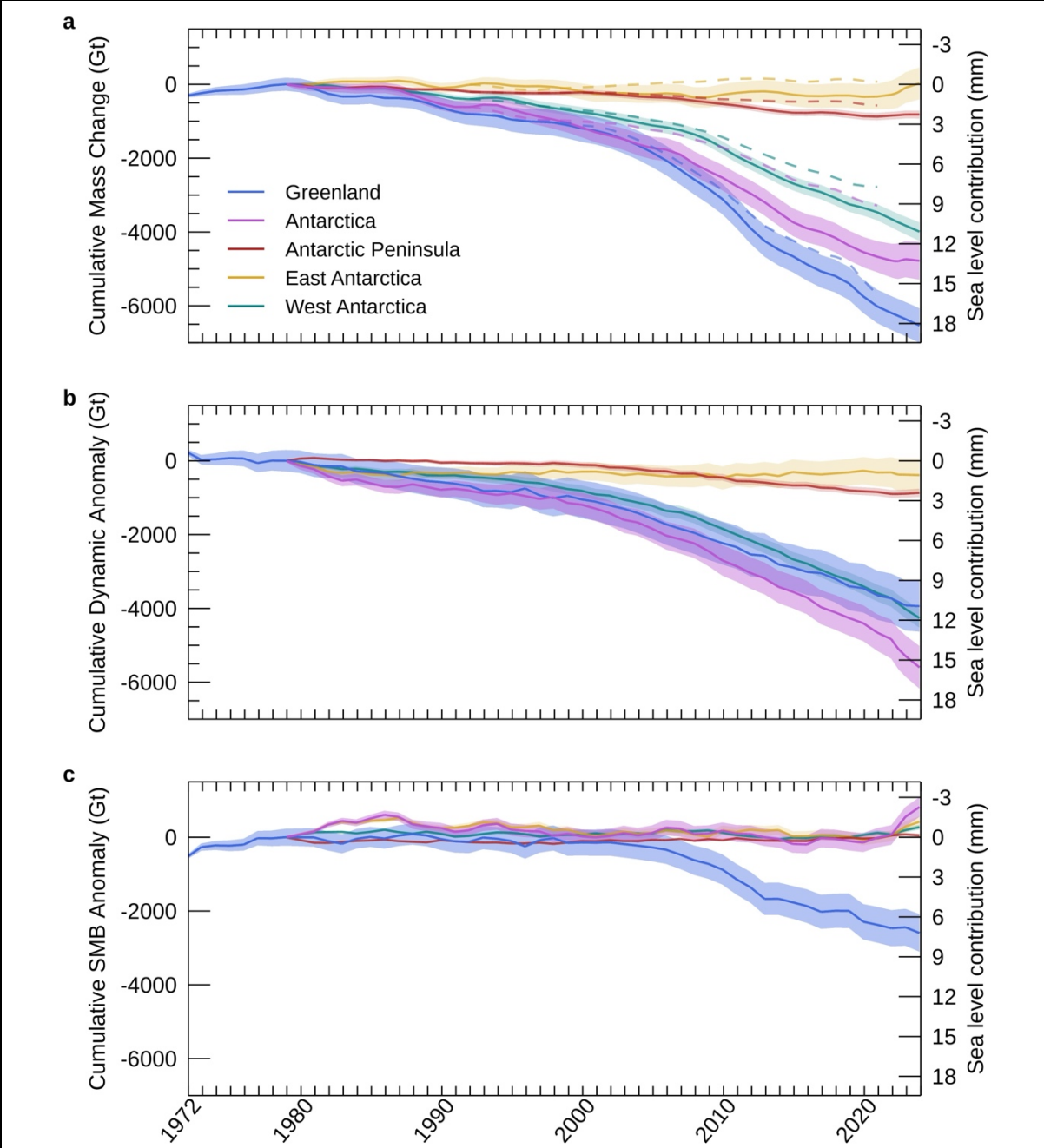


Figure 2. Cumulative ice sheet mass change and anomalies in SMB and dynamics. The shadings represent the associated uncertainties. The dashed lines show the results from a previous ice sheet mass balance assessment².

Our dataset shows that Antarctic mass loss continues to be dominated by ice discharge from West Antarctica where the mass loss signal is strongest (Figure 2) – rising in every decade of our record from $29 \pm 7 \text{ Gt yr}^{-1}$ in the 1980s to $163 \pm 12 \text{ Gt yr}^{-1}$ in the 2010s (Table 4). In the last four years of our survey, ice discharge in West Antarctica further increased by 38 % but this was accompanied by an increase

in SMB, offsetting this increase in ice discharge. At the Antarctic Peninsula the increase in losses since the early 2000s that is generally associated with ice-shelf collapse^{71,72} led to a rate of mass loss of $32 \pm 5 \text{ Gt yr}^{-1}$ in the 2000s, four times that of the 1990s. The Antarctic Peninsula lost mass at a similar pace in the 2010s, however during the last four years of our survey (2020 to 2023), the Peninsula was close to a state of balance due to increased snowfall accumulation ($22 \pm 2 \text{ Gt yr}^{-1}$) and reduced ice discharge ($11 \pm 11 \text{ Gt yr}^{-1}$). In East Antarctica, the average 45-year mass trend is $1 \pm 9 \text{ Gt yr}^{-1}$, however, record high snowfall precipitation in 2022 and 2023 led to a total positive mass gain of $92 \pm 63 \text{ Gt yr}^{-1}$ during the last four years of our record. This recent mass gain in East Antarctica counterbalanced the sustained mass loss in West Antarctica and as a result Antarctica's rate of mass loss was more than three times smaller during the period 2020-2023 than in the 2010s. In all, the Antarctic Ice Sheet lost $4,780 \pm 513 \text{ Gt}$ of ice between 1979 and 2023, raising the global sea level by $13.3 \pm 1.4 \text{ mm}$, with all of Antarctica's ice losses caused by ice dynamics. On the other hand, Greenland was close to a state of balance in the 1970s but started to lose mass in the following decades, with rates of mass loss of $60 \pm 19 \text{ Gt yr}^{-1}$ and $57 \pm 25 \text{ Gt yr}^{-1}$ in the 1980s and 1990s, respectively. Ice losses then accelerated, reaching a rate three times higher in the 2000s, at $192 \pm 19 \text{ Gt yr}^{-1}$. In the 2010s, the rate of Greenland mass loss reached $264 \pm 18 \text{ Gt yr}^{-1}$ and was the first decade for which ice losses from reduced SMB exceeded ice losses from ice dynamical processes. During the period 2020 to 2023, while dynamic ice losses continued at a similar pace, the rate of SMB ice losses was only half that of the 2010s, resulting in a rate of Greenland mass loss of $199 \pm 29 \text{ Gt yr}^{-1}$. Unlike the 2010s which were marked by several extreme summer melt events leading to record mass loss events, there was no such extreme events in the past four years of our record, resulting in SMB-driven mass loss returning to a similar level to that of the 2000s. In total, Greenland lost $6,215 \pm 467 \text{ Gt}$ of ice at an average rate of $119 \pm 9 \text{ Gt yr}^{-1}$ between 1972 and 2023, 67 % of which were caused by increased ice discharge and 33 % by reduced SMB. Combined, Antarctica and Greenland lost $11,309 \pm 565 \text{ Gt}$ of ice between 1979 and 2023, raising the global sea level by $31.4 \pm 1.6 \text{ mm}$. Increased glacier dynamical imbalance drove 84 % of the ice sheets mass loss and reduced SMB the remainder (16 %).

Table 4. Rates of ice sheet mass balance (MB), surface mass balance anomaly (SMB), and ice dynamics anomaly (D) (Gt yr⁻¹). Rates are calculated from the first day (1st January) of the first year quoted to the last day (31st December) of the final year quoted in the table.

		1980-1989	1990-1999	2000-2009	2010-2019	2020-2023	1972-2023	1979-2023
GriS (Gt yr ⁻¹)	MB	-60 ± 19	-57 ± 25	-192 ± 19	-264 ± 18	-199 ± 29	-120 ± 9	-146 ± 10
	SMB	-5 ± 17	-10 ± 19	-73 ± 20	-141 ± 24	-76 ± 43	-40 ± 9	-58 ± 10
	D	-55 ± 26	-47 ± 31	-119 ± 28	-123 ± 30	-123 ± 52	-80 ± 13	-88 ± 14
AIS (Gt yr ⁻¹)	MB	-48 ± 13	-63 ± 20	-136 ± 22	-202 ± 22	-59 ± 73	-	-106 ± 10
	SMB	18 ± 13	-23 ± 13	15 ± 13	-32 ± 13	241 ± 14	-	18 ± 6
	D	-66 ± 19	-40 ± 24	-151 ± 25	-170 ± 26	-300 ± 75	-	-124 ± 12
APIS (Gt yr ⁻¹)	MB	-12 ± 4	-8 ± 5	-32 ± 5	-33 ± 5	11 ± 10	-	-18 ± 2
	SMB	-1 ± 2	-2 ± 2	2 ± 2	5 ± 2	22 ± 2	-	1 ± 1
	D	-11 ± 4	-6 ± 6	-34 ± 5	-38 ± 5	-11 ± 11	-	-19 ± 3
EAIS (Gt yr ⁻¹)	MB	-8 ± 11	-9 ± 16	-9 ± 18	-6 ± 18	92 ± 63	-	1 ± 9
	SMB	17 ± 7	-14 ± 7	9 ± 7	-26 ± 7	122 ± 9	-	9 ± 3
	D	-24 ± 13	5 ± 18	-17 ± 20	20 ± 20	-30 ± 64	-	-9 ± 9
WAIS (Gt yr ⁻¹)	MB	-29 ± 7	-45 ± 11	-96 ± 10	-163 ± 12	-162 ± 34	-	-89 ± 5
	SMB	3 ± 3	-4 ± 3	7 ± 3	-7 ± 3	53 ± 4	-	6 ± 2
	D	-31 ± 7	-41 ± 11	-103 ± 11	-156 ± 12	-215 ± 34	-	-95 ± 5

285

286 Technical Validation

287 Comparison within the input-output, altimetry, and gravimetry groups

288 We assess the level of agreement among ice sheet mass balance estimates derived using the same
289 technique by comparing annual rates of mass balance and their standard deviation for each ice sheet
290 region (Figure 3). In Greenland, input-output estimates are in good agreement with a median
291 difference of 21 Gt yr⁻¹ and standard deviation of 48 Gt yr⁻¹ during their overlap period (1986-2021).
292 Gravimetry estimates reach a slightly higher level of agreement during their overlap period (2018-
293 2022) with a median difference 20 Gt yr⁻¹ and standard deviation of 43 Gt yr⁻¹. Finally, altimetry
294 solutions, because of their varying temporal resolution (from 1 month to 16 years) present larger
295 differences with a median difference of 64 Gt yr⁻¹ and standard deviation of 51 Gt yr⁻¹ when compared
296 over the period 2011-2018 (and excluding the shortest time-series that spans only two years of data
297 to allow for a more comprehensive comparison). In Antarctica, only one input-output estimate is
298 available and thus no comparison with similar estimates can be performed. Differences between
299 gravimetry estimates during their overlap period (2015-2022) are greatest in EAIS and smallest in APIS
300 followed by WAIS with median differences of 31, 7, and 23 Gt yr⁻¹ and standard deviations of 45, 11,
301 23 Gt yr⁻¹, respectively. Similarly, altimetry estimates also exhibit the largest disagreement in EAIS,
302 followed by WAIS and APIS with median differences of 42, 37, and 22 Gt yr⁻¹ and standard deviations
303 of 39, 36 and 20 Gt yr⁻¹ over the period 2003-2018, respectively. Overall, we find that the vast majority

304 of individual estimates of annual rates of mass balance included in this study fall within the uncertainty
 305 bounds of our reconciled estimate given their respective individual errors, with 93 %, 88 %, 87 %, 90
 306 %, and 94 % of those annual mass change rates falling within the reconciled uncertainty range at the
 307 GrIS, AIS, APIS, EAIS, and WAIS, respectively.

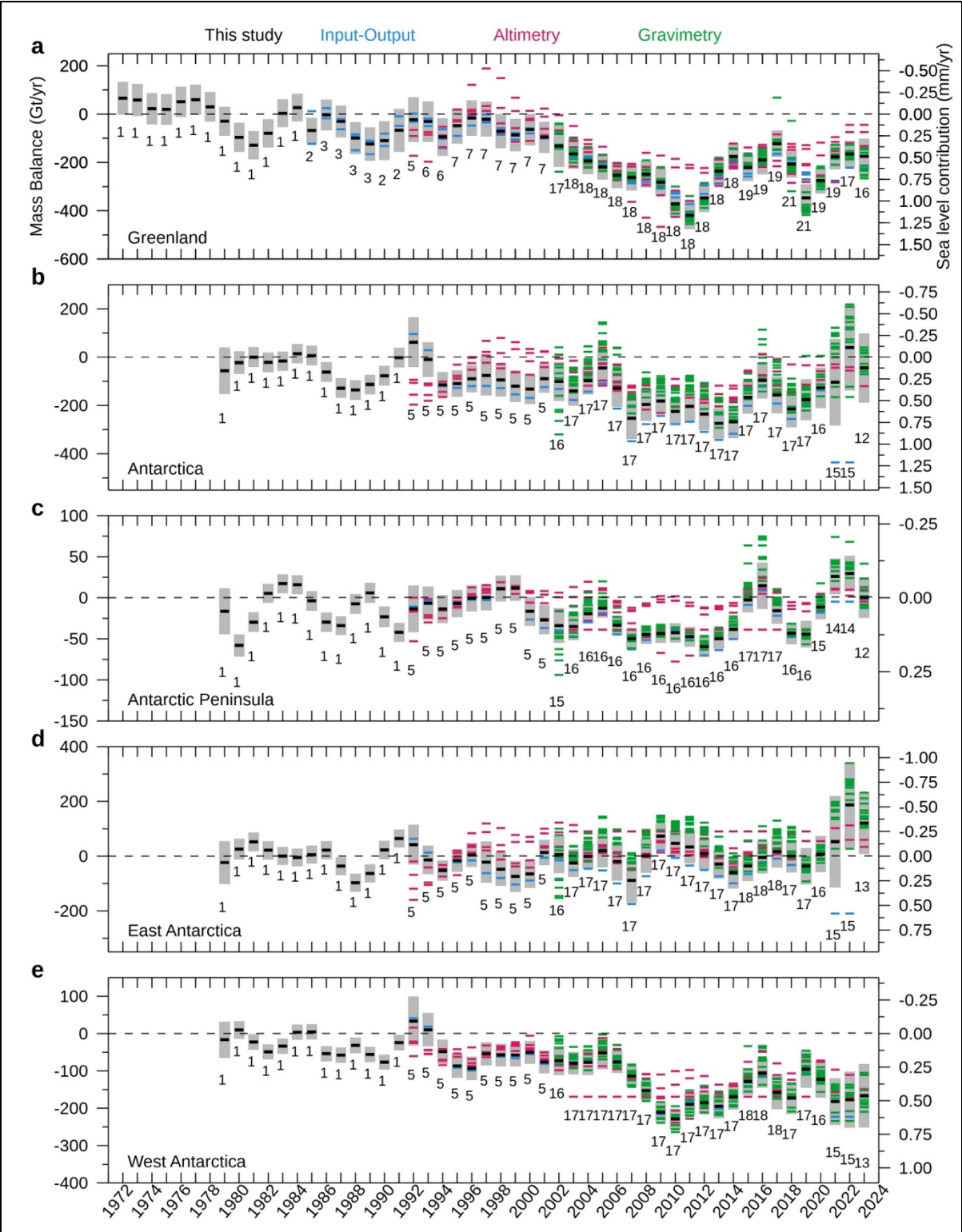
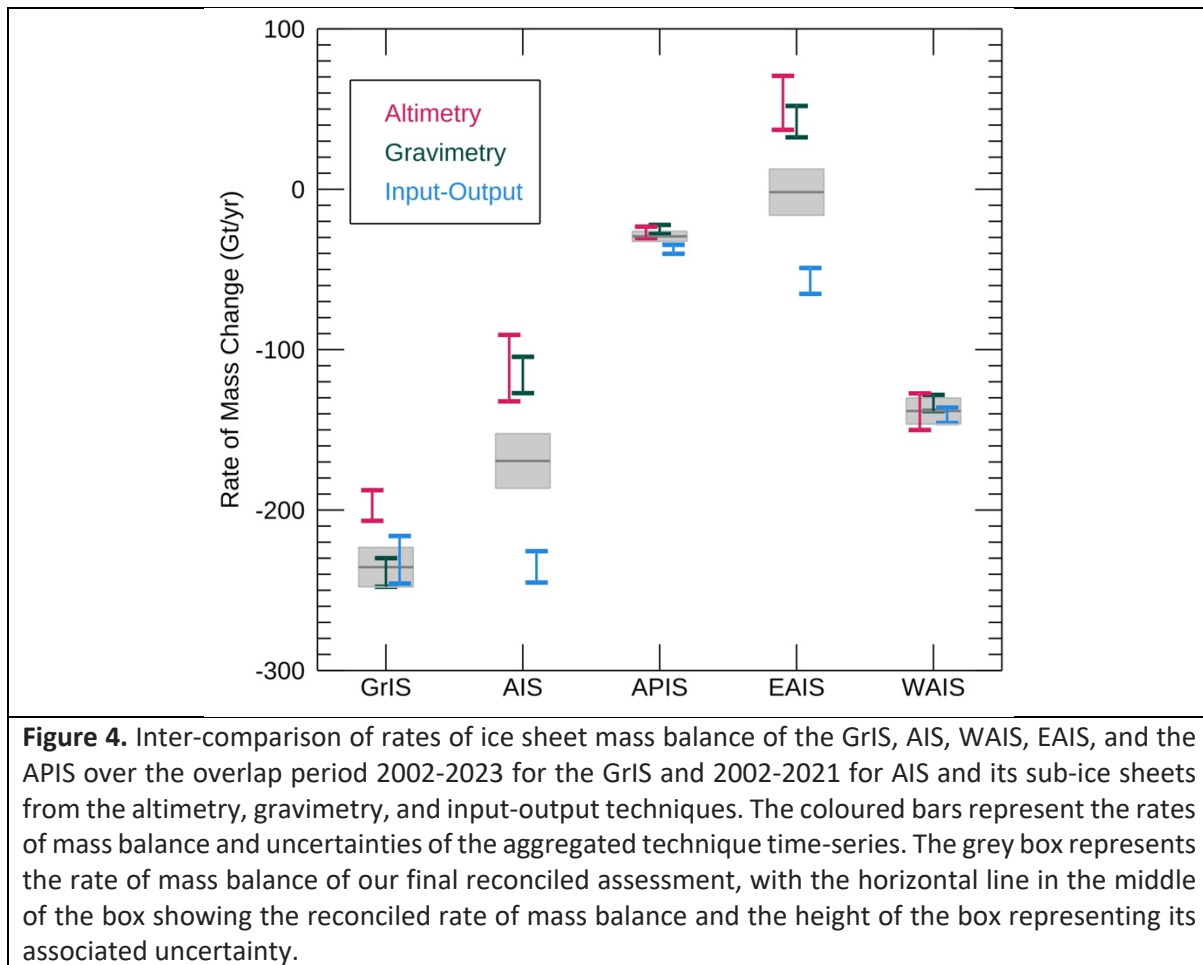


Figure 3. Annual rates of mass change of the (a) GrIS, (b) AIS, (c) APIS, (d) EAIS, and (e) WAIS from the altimetry, gravimetry and input-output estimates included in this study (shown by the coloured bars) and the reconciled estimate produced from combining those estimates (shown by the thick

black bars). The grey shading shows the uncertainty of our final reconciled estimate. The number of individual mass balance estimates collated at each epoch is shown below each bar. For Greenland, the individual time-series that did not originally include the GICs have been corrected.

Comparison across the input-output, altimetry, and gravimetry groups

We compare our three technique-aggregated input-output, altimetry, and gravimetry mass trends time-series during their overlapping period – over the period 2002-2023 for the GrIS and 2002-2021 for the AIS and its sub-ice sheets (Figure 4). In Greenland, all three techniques are in close agreement with a standard deviation of 24 Gt yr^{-1} and a reconciled rate of mass loss of $236 \pm 12 \text{ Gt yr}^{-1}$. In Antarctica, the reconciled rate of mass loss is $169 \pm 17 \text{ Gt yr}^{-1}$ but the spread of the altimetry, gravimetry and input-output estimates is three times larger (70 Gt yr^{-1}) than in Greenland. While at the WAIS and APIS the standard deviation between techniques is only 4 Gt yr^{-1} and 7 Gt yr^{-1} , respectively, estimates differ significantly at the EAIS with a standard deviation of 61 Gt yr^{-1} . At the EAIS, the three geodetic techniques disagree on even the sign of the mass change, with a maximum difference of $111 \pm 19 \text{ Gt yr}^{-1}$ between rates of mass change from the input-output method and altimetry estimates. We also note a substantial disagreement between the input-output group ($-210 \pm 73 \text{ Gt yr}^{-1}$) and the altimetry and gravimetry groups ($99 \pm 124 \text{ Gt yr}^{-1}$ and $166 \pm 50 \text{ Gt yr}^{-1}$) for 2021 calendar year, the last overlap year between the three techniques at the EAIS. Our assessment of Antarctica's mass balance includes only one input-output estimate, which leads to an over-weighting of this estimate in our reconciled estimate in comparison to the other individual estimates derived from satellite altimetry and gravimetry, potentially introducing a small underestimation of mass gains in East Antarctica where the three techniques are in disagreement. To understand the departure of the input-output estimate in East Antarctica, we suggest that it is necessary to assess the availability of ice thickness measurements. Indeed, in regions of East Antarctica such as Enderby Land, Princess Elizabeth Land, Dronning Maud Land, and Wilkes Land, the availability of bed topography measurements in the vicinity of the grounding line, a key input for the computation of ice discharge, is very limited with over 60 % of the grounding line of these regions lacking a measurement within 5 km of the actual grounding line location⁷³. Surveying ice thickness around the grounding line in these regions and analysing differences between techniques at a regional scale would help understand the potential sources of the over-estimation of mass loss in East Antarctica in the input-output method.



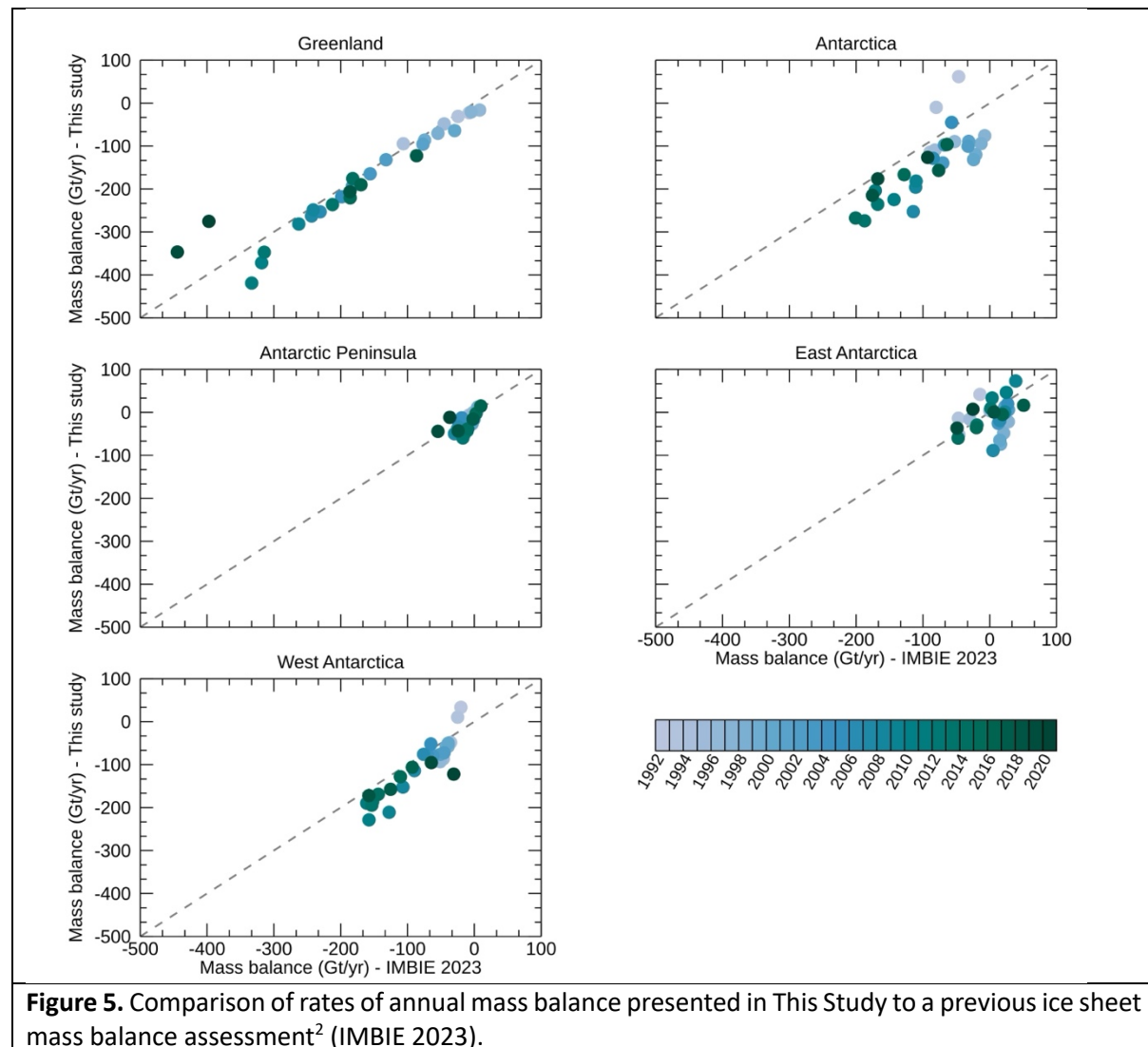
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337

338 *Comparison to previous IMBIE dataset*

339 We compare our dataset with the most recent consensus estimate of ice sheet mass balance²,
 340 produced as part of the Ice Sheet Mass Balance Inter-comparison Exercise (IMBIE) during their overlap
 341 period (1992-2020) (Figure 5). In Greenland, the two datasets agree within their respective
 342 uncertainties with rates of mass loss of $180 \pm 12 \text{ Gt yr}^{-1}$ and $169 \pm 16 \text{ Gt yr}^{-1}$, respectively. In Antarctica,
 343 our dataset indicates larger rates of mass loss compared to the previous IMBIE assessment with rates
 344 of $140 \pm 13 \text{ Gt yr}^{-1}$ and $92 \pm 18 \text{ Gt yr}^{-1}$, respectively. When comparing annual rates of mass balance, we
 345 find that in Greenland the two datasets also further agree within their respective uncertainties in every
 346 year of their overlapping period and differences between the two datasets are only statistically
 347 significant at the AIS and APIS with corresponding p-values of 0.01 and 0.03, respectively. Differences
 348 between the two datasets exceed uncertainty bounds in four individual years at the APIS (2010, 2012,
 349 2013, and 2014), in three years at the WAIS (2009, 2010, and 2020) and in two years for the Antarctic
 350 ice sheet as a whole (2000, 2007). We further investigate the origins of these differences by comparing
 351 the three technique-aggregated mass balance time-series (altimetry, gravimetry, and input-output)
 352 from the two datasets. Only our altimetry-aggregated mass balance time-series at the APIS is
 353 statistically different from the previous IMBIE assessment with a p-value of 0.001, primarily because
 354 the individual altimetry time-series included in this assessment have been significantly updated, with
 355 now more teams providing mass changes at finer temporal resolutions. As a result, we record a higher

altimetry-derived rate of mass loss at the APIS of $20 \pm 3 \text{ Gt yr}^{-1}$ between 1992 and 2018 compared to $6 \pm 1 \text{ Gt yr}^{-1}$ from the previous IMBIE assessment, bringing our altimetry-aggregated estimate closer to the gravimetry and input-output estimates, with all three estimates now in agreement at the APIS. The remaining small differences between our previous and current mass balance assessments at the GrIS, WAIS, and EAIS originate from the inclusion of new and updated participant datasets and in Greenland from the systematic inclusion of its peripheral GICs.



Data Availability

The aggregated Greenland and Antarctic ice sheet mass balance data and corresponding errors are available at <https://doi.org/10.5285/128c5e33-5224-4197-82f0-19dcc95b80a0>.

Code Availability

The code used to compute and aggregate rates of ice sheet mass change and their errors is freely available at <https://doi.org/10.5281/zenodo.14217192>⁷⁴

References

- [1] WCRP Global Sea Level Budget Group. Global sea-level budget 1993–present. *Earth Syst. Sci. Data* **10**, 1551–1590, <https://doi.org/10.5194/essd-10-1551-2018> (2018).
- [2] Otosaka, I. N. *et al.* Mass balance of the Greenland and Antarctic ice sheets from 1992 to 2020. *Earth Syst. Sci. Data* **15**, 1597–1616, <https://doi.org/10.5194/essd-15-1597-2023> (2023).
- [3] Edwards, T.L., Nowicki, S., Marzeion, B. *et al.* Projected land ice contributions to twenty-first-century sea level rise. *Nature* **593**, 74–82 (2021). <https://doi.org/10.1038/s41586-021-03302-y>
- [4] Vitousek, S. *et al.* Doubling of coastal flooding frequency within decades due to sea-level rise. *Sci Rep* **7**, 1–9, <https://doi.org/10.1038/s41598-017-01362-> (2017).
- [5] Kulp, S. A. & Strauss, B. H. New elevation data triple estimates of global vulnerability to sea-level rise and coastal flooding. *Nat Commun* **10**, 1–12, <https://doi.org/10.1038/s41467-019-12808-z> (2019).
- [6] Fox-Kemper, B. *et al.* Chapter 9: Ocean, Cryosphere, and Sea Level Change. In: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the IPCC* [Masson-Delmotte, V. *et al.* (eds.)]. <https://doi.org/10.1017/9781009157896.011> (Cambridge University Press, 2021).
- [7] Shepherd, A. & Nowicki, S. Improvements in ice-sheet sea-level projections. *Nature Climate Change* **7**, 672–674, <https://doi.org/10.1038/nclimate3400> (2017).
- [8] Slater, T., Hogg, A. E. & Mottram, R. Ice-sheet losses track high-end sea-level rise projections. *Nature Climate Change* **10**, 879–881, <https://doi.org/10.1038/s41558-020-0893-y> (2020).
- [9] Aschwanden, A., Bartholomäus, T. C., Brinkerhoff, D. J. & Truffer, M. Brief communication: A roadmap towards credible projections of ice sheet contribution to sea level. *The Cryosphere* **15**, 5705–5715, <https://doi.org/10.5194/tc-15-5705-2021> (2021).
- [9] Otosaka, I.N., Horwath, M., Mottram, R. *et al.* Mass Balances of the Antarctic and Greenland Ice Sheets Monitored from Space. *Surv Geophys* **44**, 1615–1652 (2023). <https://doi.org/10.1007/s10712-023-09795-8>
- [10] Gardner, A. S. *et al.* Increased West Antarctic and unchanged East Antarctic ice discharge over the last 7 years. *The Cryosphere* **12**, 521–547, <https://doi.org/10.5194/tc-12-521-2018> (2018).
- [11] Rignot, E. *et al.* Four decades of Antarctic Ice Sheet mass balance from 1979–2017. *Proceedings of the National Academy of Science* **116**, 1095–1103, <https://doi.org/10.1073/pnas.1812883116> (2019).
- [12] Mouginot, J. *et al.* Forty-six years of Greenland Ice Sheet mass balance from 1972 to 2018. *Proceedings of the National Academy of Sciences* **116**, 9239–9244, <https://doi.org/10.1073/pnas.1904242116> (2019).
- [13] Fettweis, X. *et al.* GrSMBMIP: intercomparison of the modelled 1980–2012 surface mass balance over the Greenland Ice Sheet. *The Cryosphere* **14**, 3935–3958, <https://doi.org/10.5194/tc-14-3935-2020> (2020).

- [14] Mottram, R. *et al.* What is the surface mass balance of Antarctica? An intercomparison of regional climate model estimates. *The Cryosphere* **15**, 3751–3784, <https://doi.org/10.5194/tc-15-3751-2021> (2021).
- [15] Sandberg Sørensen, L. *et al.* 25 years of elevation changes of the Greenland Ice Sheet from ERS, Envisat, and CryoSat-2 radar altimetry. *Earth and Planetary Science Letters* **495**, 234–241, <https://doi.org/10.1016/j.epsl.2018.05.015> (2018).
- [16] Shepherd, A. *et al.* Trends in Antarctic Ice Sheet Elevation and Mass. *Geophysical Research Letters* **46**, 8174–8183, <https://doi.org/10.1029/2019GL082182> (2019).
- [17] Smith, B. *et al.* Pervasive ice sheet mass loss reflects competing ocean and atmosphere processes. *Science* **368**, 1239–1242, <https://doi.org/10.1126/science.aaz5845> (2020).
- [18] The Firn Symposium team. Firn on ice sheets. *Nat. Rev. Earth. Environ.* **5**, 79–99, <https://doi.org/10.1038/s43017-023-00507-9> (2024).
- [19] Tapley, B. D. *et al.* Contributions of GRACE to understanding climate change. *Nature Climate Change* **5**, 358–369, <https://doi.org/10.1038/s41558-019-0456-2> (2019).
- [20] Velicogna, I. *et al.* Continuity of ice sheet mass loss in Greenland and Antarctica from the GRACE and GRACE Follow-On missions. *Geophysical Research Letters* **47**, e2020GL087291, <https://doi.org/10.1029/2020gl087291> (2020).
- [21] Sasgen, I. *et al.* Return to rapid ice loss in Greenland and record loss in 2019 detected by the GRACE-FO satellites. *Commun Earth Environ* **1**, 1–8, <https://doi.org/10.1038/s43247-020-0010-1> (2020).
- [22] Caron, L. & Ivins, E. R. A baseline Antarctic GIA correction for space gravimetry. *Earth and Planetary Science Letters*, 531, 115957, <https://doi.org/10.1016/j.epsl.2019.115957> (2020).
- [23] Sutterley, T. C., Velicogna, I., Csatho, B., van den Broeke, M., Rezvan-Behbahani, S. & Babonis, G. Evaluating Greenland glacial isostatic adjustment corrections using GRACE, altimetry and surface mass balance data. *Environmental Research Letters* **9**, 014004, <https://doi.org/10.1088/1748-9326/9/1/014004> (2014).
- [24] Adusumilli, S., Fricker, H. A., Medley, B., Padman, L. & Siegfried, M. B. Interannual variations in meltwater input to the Southern Ocean from Antarctic ice shelves. *Nat. Geosci.* **13**, 616–620, <https://doi.org/10.1038/s41561-020-0616-z> (2020).
- [25] Paolo, F. S. *et al.* Widespread slowdown in thinning rates of West Antarctic ice shelves. *The Cryosphere* **17**, 3409–3433, <https://doi.org/10.5194/tc-17-3409-2023> (2023).
- [26] Greene, C.A., Gardner, A.S., Schlegel, N.J. & Fraser, A.D. Antarctic calving loss rivals ice-shelf thinning. *Nature*, **609**, 948–953, <https://doi.org/10.1038/s41586-022-05037-w> (2022).
- [27] Greene, C.A., Gardner, A.S., Wood, M. & Cuzzone, J. K. Ubiquitous acceleration in Greenland Ice Sheet calving from 1985 to 2022. *Nature*, **625**, 523–528, <https://doi.org/10.1038/s41586-023-06863-2> (2024).

- [28] Rignot, E., Velicogna, I., van den Broeke, M. R., Monaghan, A. & Lenaerts, J. T. M. Acceleration of the contribution of the Greenland and Antarctic ice sheets to sea level rise. *Geophysical Research Letters* **38**, <https://doi.org/10.1029/2011GL046583> (2011).
- [29] Zwally, H. J., Giovinetto, M. B., Beckley, M. A. & Saba, J. L. Antarctic and Greenland Drainage Systems. *GSFC Cryospheric Sciences Laboratory*, http://icesat4.gsfc.nasa.gov/cryo_data/ant_grn_drainage_systems.php (2012).
- [30] King, M. D. *et al.* Dynamic ice loss from the Greenland Ice Sheet driven by sustained glacier retreat. *Communications Earth & Environment* **1**, 1–7, <https://doi.org/10.1038/s43247-020-0001-2> (2020).
- [31] Mankoff, K. D. *et al.* Greenland ice sheet mass balance from 1840 through next week. *Earth Syst. Sci. Data* **13**, 5001–5025, <https://doi.org/10.5194/essd-13-5001-2021> (2021).
- [32] Gourmelen, N. *et al.* CryoSat-2 swath interferometric altimetry for mapping ice elevation and elevation change. *Advances in Space Research* **62**, 1226–1242, <https://doi.org/10.1016/j.asr.2017.11.014> (2018).
- [33] Helm, V., Humbert, A. & Miller, H. Elevation and elevation change of Greenland and Antarctica derived from CryoSat-2. *The Cryosphere* **8**, 1539–1559, <https://doi.org/10.5194/tc-8-1539-2014> (2014).
- [34] Khan, S. A. *et al.* Greenland mass trends from airborne and satellite altimetry during 2011–2020. *JGR: Earth Surface*, **127**, e2021JF006505, <https://doi.org/10.1029/2021JF006505> (2022).
- [35] Nilsson, J., Gardner, A. S., & Paolo, F. S. Elevation change of the Antarctic Ice Sheet: 1985 to 2020. *Earth Syst. Sci. Data*, **14**, 3573–3598, <https://doi.org/10.5194/essd-14-3573-2022> (2022).
- [36] Sørensen, L. S. *et al.* Mass balance of the Greenland ice sheet (2003–2008) from ICESat data – the impact of interpolation, sampling and firn density. *The Cryosphere* **5**, 173–186, <https://doi.org/10.5194/tc-5-173-2011> (2011).
- [37] Schröder, L. *et al.* Four decades of Antarctic surface elevation changes from multi-mission satellite altimetry. *The Cryosphere* **13**(2), 427–449, <https://doi.org/10.5194/tc-13-427-2019> (2019).
- [38] Simonsen, S. B. *et al.* Greenland Ice Sheet Mass Balance (1992–2020) From Calibrated Radar Altimetry. *Geophysical Research Letters* **48**, e2020GL091216, <https://doi.org/10.1029/2020GL091216> (2021).
- [39] Ditmar, P. Conversion of time-varying Stokes coefficients into mass anomalies at the Earth’s surface considering the Earth’s oblateness. *Journal of Geodesy*, **92**, 1401–1412, <https://doi.org/10.1007/s00190-018-1128-0> (2018).
- [40] Döhne, T., Horwath, M., Groh, A., & Buchta, E. The sensitivity kernel perspective on GRACE mass change estimates. *Journal of Geodesy* **97**(1), 11, <https://doi.org/10.1007/s00190-022-01697-8> (2023).
- [41] Forsberg, R., Sørensen, L. & Simonsen, S. Greenland and Antarctica Ice Sheet Mass Changes and Effects on Global Sea Level. *Surv Geophys* **38**, 89–104, https://doi.org/10.1007/978-3-319-56490-6_5 (2017).

- [42] Groh, A., & Horwath, M. Antarctic Ice Mass Change Products from GRACE/GRACE-FO Using Tailored Sensitivity Kernels. *Remote Sensing* **13**, 1736, <https://doi.org/10.3390/rs13091736>, (2021).
- [43] Harig, C. & Simons, F. J. Mapping Greenland's mass loss in space and time. *PNAS* **109**, 19934–19937, <https://doi.org/10.1073/pnas.120678510> (2012).
- [44] Loomis, B. D., Luthcke, S. B. & Sabaka, T. J. Regularization and error characterization of GRACE mascons. *Journal of Geodesy*, 93, 1381–1398, <https://doi.org/10.1007/s00190-019-01252-y> (2019)
- [45] Sasgen, I. *et al.* Timing and origin of recent regional ice-mass loss in Greenland. *Earth and Planetary Science Letters*, 333–334, 293–303, <https://doi.org/10.1016/j.epsl.2012.03.033>. (2012)
- [46] Save, H., Bettadpur, S. & Tapley, B. D. High-resolution CSR GRACE RL05 mascons. *JGR: Solid Earth* **121**, 7547–7569, <https://doi.org/10.1002/2016JB013007> (2016).
- [47] Schrama, E. J. O., Wouters, B. & Rietbroek, R. A mascon approach to assess ice sheet and glacier mass balances and their uncertainties from GRACE data. *JGR: Solid Earth* **119**, 6048–6066, <https://doi.org/10.1002/2013JB010923>. (2014).
- [48] Jeon, T., Seo, K.-W., Youm, K., Chen, J. & Wilson, C. R. Global sea level change signatures observed by GRACE satellite gravimetry. *Scientific Reports* **8**, 13519, <https://doi.org/10.1038/s41598-018-31972-8> (2018).
- [49] Sutterley, T. C., Velicogna, I. & Hsu, C.-W. Self-Consistent Ice Mass Balance and Regional Sea Level From Time-Variable Gravity. *Earth and Space Science* **7**, e2019EA000860, <https://doi.org/10.1029/2019EA000860> (2020).
- [50] Vishwakarma, B. D. *et al.* A Data-Driven Approach for Repairing the Hydrological Catchment Signal Damage Due to Filtering of GRACE Products. *Water Resources Research* **53**, 9824–9844, <https://doi.org/10.1002/2017WR021150> (2017).
- [51] Watkins, M. M. *et al.* Improved methods for observing Earth's time variable mass distribution with GRACE using spherical cap mascons. *JGR: Solid Earth*, **120**, 2648–2671, <https://doi.org/10.1002/2014JB011547> (2015).
- [52] Wouters, B., Gardner, A. S. & Moholdt, G. Global Glacier Mass Loss During the GRACE Satellite Mission (2002–2016). *Frontiers in Earth Science*, **7**, <https://doi.org/10.3389/feart.2019.00096> (2019).
- [53] Hugonnet, R. *et al.* Accelerated global glacier mass loss in the early twenty-first century. *Nature*, **592**, 726–731, <https://doi.org/10.1038/s41586-021-03436-z> (2021).
- [54] Bollen, K.E., Enderlin E.M. & Muhlheim R. Dynamic mass loss from Greenland's marine-terminating peripheral glaciers (1985–2018). *Journal of Glaciology*, 1–11, <https://doi.org/10.1017/jog.2022.52> (2022).
- [55] Kochtitzky, W. *et al.* Closing Greenland's mass balance: Frontal ablation of every Greenlandic glacier from 2000 to 2020. *Geophysical Research Letters* **50**, e2023GL104095, <https://doi.org/10.1029/2023GL104095> (2023).

- [56] Jakob, L. & Goumelen, N. Glacier mass loss between 2010 and 2020 dominated by atmospheric forcing. *Geophysical Research Letters*, **50**, e2023GL102954, <https://doi.org/10.1029/2023GL102954> (2023).
- [57] Vernon, C. L. *et al.* Surface mass balance model intercomparison for the Greenland ice sheet. *The Cryosphere* **7**, 599–614, <https://doi.org/10.5194/tc-7-599-2013> (2013).
- [58] Favier, V. *et al.* An updated and quality-controlled surface mass balance dataset for Antarctica. *The Cryosphere* **7**, 583–597, <https://doi.org/10.5194/tc-7-583-2013> (2013).
- [59] IMBIE Team. Mass balance of the Greenland Ice Sheet from 1992 to 2018. *Nature*, **579**, 233–239, <https://doi.org/10.1038/s41586-019-1855-2> (2020).
- [60] Medley, B. *et al.* Simulations of firn processes over the Greenland and Antarctic ice sheets: 1980–2021. *The Cryosphere* **16**, 3971–4011, <https://doi.org/10.5194/tc-16-3971-2022>, 2022.
- [61] van den Broeke MR, Kuipers Munneke P, Noël B, Reijmer C, Smeets P, *et al.* (2023) Contrasting current and future surface melt rates on the ice sheets of Greenland and Antarctica: Lessons from in situ observations and climate models. *PLOS Climate* **2**(5): e0000203. <https://doi.org/10.1371/journal.pclm.0000203>
- [62] Agosta, C. *et al.* Estimation of the Antarctic surface mass balance using the regional climate model MAR (1979–2015) and identification of dominant processes. *The Cryosphere*, **13**, 281–296, <https://doi.org/10.5194/tc-13-281-2019> (2019).
- [63] Hansen, N. *et al.* Downscaled surface mass balance in Antarctica: impacts of subsurface processes and large-scale atmospheric circulation. *The Cryosphere* **15**, 4315–4333, <https://doi.org/10.5194/tc-15-4315-2021> (2021).
- [64] Medley, B. *et al.* Simulations of firn processes over the Greenland and Antarctic ice sheets: 1980–2021. *The Cryosphere* **16**, 3971–4011, <https://doi.org/10.5194/tc-16-3971-2022> (2022).
- [65] van Wessem, J. M *et al.* Modelling the climate and surface mass balance of polar ice sheets using RACMO2 – Part 2: Antarctica (1979–2016). *The Cryosphere*, **12**, 1479–1498, <https://doi.org/10.5194/tc-12-1479-2018> (2018).
- [66] Dethinne, T. *et al.* [Sensitivity of the MAR regional climate model snowpack to the parameterization of the assimilation of satellite-derived wet-snow masks on the Antarctic Peninsula](#). *The Cryosphere* **17**, 4267–4288, <https://doi.org/10.5194/tc-17-4267-2023> (2023).
- [67] Langen, P. L., R. S. Fausto, B. Vandecrux, R. H. Mottram & Box, J.E. Liquid Water Flow and Retention on the Greenland Ice Sheet in the Regional Climate Model HIRHAM5: Local and Large-Scale Impacts. *Frontiers in Earth Science* **4**, <https://doi.org/10.3389/feart.2016.00110> (2017).
- [68] Noël, B., van den Berg, W. J., Lhermitte, S., van den Broeke, M. Rapid ablation zone expansion amplifies north Greenland mass loss. *Sci. Adv.* **5**, eaaw0123, <https://doi.org/10.1126/sciadv.aaw01> (2019).
- [69] Trusel, L. D. *et al.* Nonlinear rise in Greenland runoff in response to post-industrial Arctic warming. *Nature* **564**, 104–108, <https://doi.org/10.1038/s41586-018-0752-4> (2018).

- [70] Otosaka *et al.* Mass balance of the Greenland and Antarctic Ice Sheets from the 1970s to 2023 (Version 1.0) [Data set]. NERC EDS UK Polar Data Centre, <https://doi.org/10.5285/128c5e33-5224-4197-82f0-19dcc95b80a0> (2026).
- [71] Cook, A. J. and Vaughan, D. G. Overview of areal changes of the ice shelves on the Antarctic Peninsula over the past 50 years. *The Cryosphere*, **4**, 77–98, <https://doi.org/10.5194/tc-4-77-2010> (2010).
- [72] Adusumilli, S. *et al.* Variable Basal Melt Rates of Antarctic Peninsula Ice Shelves, 1994–2016. *Geophysical Research Letters*, **45**, 4086–4095, <https://doi.org/10.1002/2017GL076652> (2018).
- [73] Matsuoka, K. *et al.* Toward an Improved Understanding of the Antarctic Coastal Zone and Its Contribution to Future Global Sea Level. *Reviews of Geophysics*, **64**, <https://doi.org/10.1029/2022RG000803> (2026).
- [74] Otosaka, I. N., Gilbert, L., Pattle, M., Roca-Aparici, M., & Shepherd, A. IMBIE software v3.1. *Zenodo*, <https://doi.org/10.5281/zenodo.14217193> (2024).

Author Contributions

Conceptualisation: the executive committee of IMBIE designed the study (AS, INO, ChA, MEE, MH, ERI, MDK, NJS, SN, AJP, ER, KMS, BES, LSS, TCS, MRVdB, and IV). Data/Model Contributions: ASG, NG, VH, SAK, MM, AM, JN, LSS, LS, AS, SBS, TS, and BES contributed altimetry estimates; TD, PD, RF, AG, CH, MH, BDL, IS, HVS, EJOS, KWS, TCS, IS, BDV, DNW, and BW contributed gravimetry estimates; MDK, ER, and BS contributed input-output estimates; CéA, ChA, XF, HG, NH, CK, PLL, ML, BM, RHM, BN, MRVdB, and NW contributed SMB estimates; GA, DM, GS contributed GIA estimates. Software: INO, LG, MEP, and MriA. Formal analysis: INO and AS. Visualisation: INO and AS. Writing – Original Draft Preparation: INO. Writing - Review and Editing: PD, MEE, ASG, NH, MH, MDK, BM, RHM, ER, LSS, NJS, AS, KMS, SBS, TS, BES, MRVdB, and BW.

Competing Interests

The authors declare no competing interests.

Funding

AS and INO acknowledge funding from the NERC Centre for Polar Observation and Modelling (NE/Y006178/1), and the ESA IMBIE (Contract Number 4000134549/21/I-NB) and CCI+ Antarctica projects (Contract Number 4000126813/19/I-NB). The work of TD was funded by the German Research Foundation (DFG, Grant SCHE 1426/28-1), the German Federal Ministry of Education and Research (BMBF) (Project Greenland Ice Sheet/Ocean Interaction GROCE, Grant No. 03F0855C) and by the ESA CCI+ Antarctica (Contract Number 4000126813/19/I-NB) and Greenland Ice Sheet CCI+ (contract number 4000126523/19/I-NB). Computational resources used to perform MARv3.12 simulations have been provided by the Consortium des Équipements de Calcul Intensif (CÉCI), funded by the F.R.S. FNRS under grant 2.5020.1. HG has received funding from the European Union's Horizon 2020 Research and Innovation Programme under grant agreement no. 869304 (PROTECT) and from the Research Council of Norway under project 324639. High-performance computing and storage resources were provided by Sigma2 - the National Infrastructure for High Performance Computing and Data Storage in Norway through projects NN8006K, NN8085K, NS8006K, NS8085K and NS5011K. ASG acknowledges NASA MEaSUREs program through funding of the ITS_LIVE project. NG received funding from the ESA CryoTEMPO-EOLIS project (4000128095/19/I-DT). NH was supported by the Danish State through the

663 National Centre for Climate Research (NCKF) and by the Novo Nordisk Foundation project PRECISE
664 (NNF23OC0081251). SAK was supported by Novo Nordisk foundation (NNF23OC00807040). MDK
665 received funding from the National Aeronautics and Space Administration award 80NSSC22K1709. BDL
666 was supported by NASA GRACE-FO Science Team (award NNH23ZDA001N-GRACEFO). MM was
667 supported by the NERC Centre for Polar Observation and Modelling and the UK Earth Observation
668 Climate Information Service [NE/X019071/1]. BM was supported by the NASA ICESat-2 Project Science
669 Office. DM was partly supported by the MACMAP project funded by INGV (Environment Department).
670 RHM acknowledges funding from the European Union's Horizon 2020 research and innovation
671 programme under grant agreement No 869304 and the Novo Nordisk Foundation Challenge project
672 PRECISE (NNF23OC0081251). JN's work was supported by the Jet Propulsion Laboratory, NASA
673 MEaSUREs, and NASA Cryosphere Science Program. BN is a Research Associate of the Fonds de la
674 Recherche Scientifique de Belgique F.R.S.-FNRS. ER acknowledges support from NASA MEaSUREs
675 80NSSC23M0146. LSS was supported by the ESA CCI+ Greenland project. IS acknowledges funding by
676 the Helmholtz Climate Initiative REKLIM (Regional Climate Change), a joint research project of the
677 Helmholtz Association of German Research Centres (HGF). HVS was supported by NASA MEaSUREs
678 Program. BES was supported by NASA grant 80NSSC20K1064. GS acknowledges funding from RFO
679 grant of DIFA. MRvdB acknowledges funding from the Netherlands Earth System Science Centre
680 (NESSC). IV was supported by NASA grant 80NSSC21K0917.