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Mass Balance of the Greenland and Antarctic Ice Sheets from 1992 to 2020

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Abstract. Ice losses from the Greenland and Antarctic Ice Sheets have accelerated since the 1990s, accounting for a significant increase in global mean sea level. Here, we present a new 29-year record of ice sheet mass balance from 1992 to 2020 from the Ice Sheet Mass Balance Inter-comparison Exercise (IMBIE). We compare and combine 50 independent estimates of ice sheet mass balance derived from satellite observations of temporal changes in ice sheet flow, in ice sheet volume and in Earth's gravity field. Between 1992 and 2020, the ice sheets contributed 21.0 ± 1.9 mm to global mean sea-level, with the rate of mass loss rising from 105 Gt yr^{-1} between 1992 and 1996 to 372 Gt yr^{-1} between 2016 and 2020. In Greenland, the rate of mass loss is 169 ± 9 Gt yr^{-1} between 1992 and 2020 but there are large inter-annual variations in mass balance with mass loss ranging from 86 Gt yr^{-1} in 2017 to 444 Gt yr^{-1} in 2019 due to large variability in surface mass balance. In Antarctica, ice losses continue to be dominated by mass loss from West Antarctica (-82 ± 9 Gt yr^{-1}) and to a lesser extent from the Antarctic Peninsula (-13 ± 5 Gt yr^{-1}). East Antarctica remains close to a state of balance (3 ± 15 Gt yr^{-1}), but is the most uncertain component of Antarctica's mass balance.

1 Introduction

The Antarctic and Greenland Ice Sheets store the vast majority (99%) of Earth's freshwater ice on land. The rate of change in ice sheet mass - or ice sheet mass balance - is the net difference between mass loss through solid ice discharge at the grounding line, melting at the bed and at the ice-ocean interface and the surface mass balance (SMB; precipitation minus meltwater runoff, sublimation, evaporation, and erosion). Over the past three decades (between the 1990s and 2010s), ice losses from Antarctica and Greenland increased six-fold (The IMBIE Team, 2018, 2020), raising the global sea level (WCRP Global Sea Level Budget Group, 2018) and with it the risk of coastal flooding worldwide (Kulp and Strauss, 2019; Vitousek et al., 2017; Hanson et al., 2011). In Antarctica, the losses have arisen primarily due to ocean-driven melting of ice shelves (Adusumilli et al., 2020; Paolo et al., 2015) and their collapse (Cook and Vaughan, 2010), which have accelerated the ice flow (Hogg et al., 2017; Selley et al., 2021; Rignot et al., 2004), retreat (Konrad et al., 2018; Milillo et al., 2022; Jenkins et al., 2018) and drawdown (Konrad et al., 2017; Shepherd et al., 2019) of numerous marine-terminating ice streams. In Greenland, increasing air temperatures (Hanna et al., 2021) and decreasing cloud cover (Hofer et al., 2017) have exacerbated summertime surface melting (Leeson et al., 2015; Tedesco and Fettweis, 2020) and runoff (Trusel et al., 2018; Slater et al., 2021), in tandem with the speedup (Rignot and Kanagaratnam, 2006) and retreat (King et al., 2020) of outlet glaciers responding to a warming ocean (Straneo and Heimbach, 2013). While ice sheet response to climate forcing remains the least constrained component of the twenty-first-century sea level budget (Pattyn and Morlighem, 2020; Fox-Kemper et al., 2021), maintaining the long-term observational record of ice sheet mass balance is critical to improving ice sheet model skill (Edwards et al., 2021; Ritz et al., 2015) and confidence in projections of sea level rise (Aschwanden et al., 2021; Slater et al., 2020; Shepherd and Nowicki, 2017).

Thanks to the launch of new satellite missions and the development of improved geophysical corrections and models of SMB and glacial isostatic adjustment (GIA), it is now possible to routinely monitor ice sheet mass changes using observations of ice-flow derived from satellite radar and optical imagery (e.g. Gardner et al., 2018; Moon et al., 2012; Mouginot et al., 2017), surface elevation changes (derived from satellite altimetry) (e.g. Sandberg Sørensen et al., 2018; Smith et al., 2020), and fluctuations in Earth's gravity field (derived from satellite gravimetry) (e.g. Tapley et al., 2019; Velicogna et al., 2020; Sasgen et al., 2020). The Ice Sheet Mass Balance Inter-comparison Exercise (IMBIE) has shown that there is good agreement between these satellite methods (Shepherd et al., 2012) and that combining independent satellite-based ice sheet mass balance estimates reduces uncertainty in estimates of Greenland and Antarctica's contribution to sea level rise. By adopting a common framework to support the comparison and aggregation of ice sheet mass balance estimates generated by different participants, it is possible to assess differences between techniques and the impact of using different geophysical corrections, SMB or GIA models in ice sheet mass balance estimation to produce a reconciled time-series of ice sheet mass changes. The most recent IMBIE assessments for the Antarctic Ice Sheet and the Greenland Ice Sheet covered the periods 1992 to 2017 and 1992 to 2018, respectively, and reported a combined contribution of 17.8 ± 1.8 mm to global mean sea level (GMSL) between 1992 and 2017 (The IMBIE Team, 2018, 2020). Here, we extend these records to cover the same extended period (1992 to 2020) for both ice sheets.

In the years since our most recent assessment there have been notable changes in ice sheet mass in both hemispheres, and in the availability of satellite observations and ancillary datasets with which to detect these changes. In Greenland, for example, atmospheric blocking and reduced summertime snowfall (Tedesco and Fettweis, 2020) led to near-record levels of meltwater runoff in 2019 (Slater et al., 2021) which, in combination with progressively increasing ice discharge (Mouginot et al., 2019), set a new record for annual ice losses during the satellite era (Sasgen et al., 2020). In Antarctica, pervasive mass losses have continued in the Amundsen Sea Sector (Groh and Horwath, 2021) as a consequence of further grounding line retreat (Milillo et al., 2022) and the associated glacier speedup (Joughin et al., 2021). A follow on to the GRACE satellite gravimetry mission (GRACE-FO) was launched in May 2018 (Tapley et al., 2019), the ICESat-2 satellite laser altimeter mission was launched in September 2018 (Smith et al., 2020), and updated products have been released for many others - including swath altimetry from CryoSat-2 (Gourmelen et al., 2018). To accompany these observations, there have been updated models of GIA (e.g. Caron and Ivins, 2020) to correct mass and elevation changes associated with solid earth movement, of firn densification (e.g. Stevens et al., 2020) to correct changes in elevation for surface processes, and of SMB (e.g. Fettweis et al., 2020; Mottram et al., 2021) to aid mass budget and mass balance partitioning calculations.

Here, we make use of new satellite observations, new methods and models to provide an updated IMBIE assessment of Greenland and Antarctic ice sheet mass balance, extending our most recent records by 3 and 4 years, respectively. We provide a description of the datasets incorporated in this updated assessment and of the aggregation methods employed. We also discuss differences between the ice sheet mass balance estimates derived from altimetry, gravimetry and the input-output method, and we present extended reconciled time-series of ice sheet mass change. Finally, we contrast our findings with trends in GMSL and compare them with projections of future ice sheet mass changes from the Intergovernmental Panel on Climate Change's (IPCC) Sixth Assessment Report (AR6).

2 Data

Fluctuations in ice sheet mass are a key indicator of ice sheet stability and can be inferred using a range of satellite techniques (Shepherd et al., 2012). Satellite altimetry measures ice sheet elevation change, computed at orbit crossing (e.g. Wingham et al., 1998), using clusters of data points acquired along all ground tracks (e.g Pritchard et al., 2009), or by differencing height models separated over time (e.g. Csatho et al., 2014). Mass balance is estimated by accounting for changes in bedrock elevation (e.g. Caron and Ivins, 2020) and then by either prescribing the density associated to the elevation fluctuation (e.g. Shepherd et al., 2019) or by making a model-based correction for changes in firn compaction (Sørensen et al., 2011). The technique is unique in charting patterns of mass imbalance with fine (monthly) temporal sampling and fine (10^2 km^2) spatial resolution, and there are continental-scale measurements dating back to the early 1990s. Satellite measurements of ice velocity computed from sequential radar and optical imagery (e.g. Rignot and Kanagaratnam, 2006) are the basis of ice sheet input-output assessments (e.g. Rignot et al., 2019; Mouginot et al. 2019). Ice velocities are combined with estimates of ice thickness (e.g. Morlighem et al., 2017) to compute changes in marine-terminating glacier discharge, and then with regional climate model estimates of surface mass balance sources (snowfall, rainfall) and sinks (runoff, sublimation, evaporation, and erosion) (e.g. Fettweis et al., 2020; Mottram et al., 2021) to produce the year-to-year change in net mass balance. The technique provides moderate (annual) temporal sampling and drainage basin scale spatial resolution, and there are continental-scale measurements dating back to the late 1970s. Satellite gravimetry measures fluctuations in Earth's gravitational field, computed using either global spherical harmonic solutions (e.g. Velicogna and Wahr, 2006) or using spatially discrete mass concentration units (e.g. Luthcke et al., 2006). Ice sheet mass changes are determined after making model-based corrections for GIA (e.g.Caron and Ivins, 2020) and for the leakage of mass trends occurring elsewhere in the climate system. The technique provides fine (monthly) temporal sampling and moderate (10^4 km^2) spatial resolution, dating back to 2002.

To compile our assessment of Greenland Ice Sheet mass balance we use 27 satellite-based estimates of ice sheet mass change, including 8 estimates based on satellite altimetry, 16 based on satellite gravimetry and 3 based on the input-output method. Compared to the most recent IMBIE assessment, 12 of these estimates have been updated to include more recent data for Greenland. This set of updated estimates is made of 2 estimates from the input-output method, 1 altimetry estimate, and 9 gravimetry estimates including data from the new GRACE Follow-on mission (GRACE-FO). For our assessment of Antarctica's mass balance, we use 23 satellite-based estimates altogether, with 6 derived from altimetry, 16 from gravimetry and 1 from the input-output method. More than half of these estimates have been extended in time compared to IMBIE-2. These updated estimates for Antarctica include 1 input-output method estimate, 2 altimetry estimates, and 10 gravimetry estimates combining GRACE and GRACE-FO data. In total, this new IMBIE assessment includes data from 14 satellite missions, spanning the years 1992 to 2020 – with results from all three geodetic techniques available between 2003 and 2018 in Greenland and 2002 and 2018 in Antarctica – and, for the first time, includes data from the GRACE-FO mission launched in 2018 (Table 1).

To achieve a meaningful comparison of ice sheet mass balance estimates, we analyse mass trends using common definitions of the Antarctic, West Antarctic, East Antarctic, Antarctic Peninsula and Greenland Ice Sheet boundaries (AIS, WAIS, EAIS, APIS and GrIS, respectively). We use two ice sheet drainage basin sets, both previously used in the past IMBIE assessments (Shepherd et al., 2012; IMBIE Team, 2018; 2020). The first drainage basin set was derived based on ICESat surface elevation data and includes 27 basins in Antarctica covering an area of 11,885,725 km^2 and 19 in Greenland over an area of 1,703,625 km^2 (Zwally et al., 2012) and is retained for consistency with the first IMBIE assessment (Shepherd et al., 2012). The second set defines 18 basins in Antarctica covering 11,892,700 km^2 and 6 in Greenland covering 1,723,300 km^2 (Rignot et al., 2011a; Rignot et al., 2011b). The two ice sheet delineation differ by 1.1 % and 0.1 % of total ice sheet extent for the Greenland and Antarctic Ice Sheets, respectively, and thus using either of these definitions leads to a negligible difference in mass balance (The IMBIE Team, 2018; 2020).

Table 1. Synthesis of satellite datasets, GIA and SMB models used to derive the individual estimates of ice sheet mass balance included in this study. Details and references of the GIA and SMB models are available in Appendix A.

		1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Satellite Missions																														
IOM	ERS-1	X	X	X	X	X																								
	ERS-2					X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X								
	RADARSAT-1									X	X	X	X	X	X	X	X	X												
	ENVISAT												X	X	X	X	X	X	X	X	X	X								
	ALOS/PALSAR															X	X	X	X	X	X									
	RADARSAT-2																X	X	X	X	X	X	X	X	X	X				
	TerraSAR-X																	X	X	X	X	X	X	X	X	X	X	X	X	
	COSMO-SkyMed																	X	X	X	X	X	X	X	X	X	X	X	X	
	Landsat-8																						X	X	X	X	X	X	X	
	Sentinel-1																						X	X	X	X	X	X	X	
ALT	ERS-1	X	X	X	X	X																								
	ERS-2				X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X									
	ENVISAT												X	X	X	X	X	X	X	X	X	X								
	ICESat												X	X	X	X	X	X	X											
	CryoSat-2																				X	X	X	X	X	X	X	X		
GMB	GRACE												X	X	X	X	X	X	X	X	X	X	X	X	X	X				
	GRACE-FO																											X	X	X
GIA models																														
AIS	A13													X	X	X	X	X	X	X	X	X	X	X						
	A13 and W12a												X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X		
	ICE-5G and W12a												X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	
	ICE-6G												X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X		
	ICE-6G and A13												X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	
	ICE-6G and IJ05_R2												X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
	IJ05 and W12a													X	X	X	X	X	X	X	X	X	X	X						
	IJ05_R2	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X											
	IJ05_R2 and A13												X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	
	IJ05_R2 and Paulson07													X	X	X	X	X	X	X	X	X	X	X						
	IJ05_R2 and Simpson09												X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X		
	IJ05_R2 and W12a	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X			
	Khan_2016 and W12a																					X	X	X	X	X	X			
	Schrama14													X	X	X	X	X	X	X	X	X	X	X	X					
	W12a													X	X	X	X	X	X	X	X	X	X							
GrIS	A13												X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	
	ICE-5G												X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	
	ICE-6G												X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
	ICE-5G and ICE-6G												X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	
	ICE-6G and A13												X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	
	Paulson07												X	X	X	X	X	X	X	X	X	X	X	X	X	X				
	Schrama14												X	X	X	X	X	X	X	X	X	X	X	X	X	X				
	Simpson09												X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X		
SMB models																														
AIS	RACMO2.3	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	
GrIS	MAR 3.5	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	
	MAR 3.5.2					X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	
	RACMO 2.3																X	X	X	X	X									

3 Methods

IMBIE participants contributed time-series of either relative mass change, ΔM(t), or of rate of mass change, dM(t)/dt, with their associated uncertainty, integrated over at least one of the ice sheet regions defined in the standard drainage basin sets. To produce a reconciled estimate of ice sheet mass change from these individual estimates, we compare and aggregate dM(t)/dt from each satellite technique. We apply a consistent processing scheme to all submitted datasets and for all ice sheet regions which consists of: i) computing dM(t)/dt for all datasets that were submitted as ΔM(t), ii) aggregating time-series of mass trends within each class of satellite observations, iii) combining the altimetry, gravimetry and mass budget time-series to derive a single reconciled time-series of mass trends, and iv) integrating this reconciled time-series of mass trends to produce the final reconciled time-series of cumulative mass change. In what follows, we summarise each of these processing steps:

i) Computing time-series of mass trends

First, we derive time-series of monthly rates of ice sheet mass change, dM(t)/dt, for all datasets that were submitted as ΔM(t) to allow the aggregation of datasets within each satellite observations class as dM(t)/dt computed using a standardised approach. At each epoch, we estimate dM(t)/dt by fitting a linear trend to the ΔM(t) data falling within a sliding window of 36 months, centred around the given epoch, using a weighted least-squares approach, with each point weighted by its error. The error on the derived time-series is taken as the regression error which incorporates the original measurement error and the linear model structural error. Finally, the derived time-series of mass trends are truncated by half the window width at the start and end of their period.

ii) Aggregating time-series of mass trends from similar satellite observations

We aggregate the standardised time-series of mass trends within the altimetry, gravimetry and mass budget groups separately to produce three time-series over each ice sheet region. We calculate each aggregated time-series by taking the error-weighted average of monthly rates of ice sheet mass change computed using the same technique. The associated error is calculated as the root mean square of the contributing time-series errors.

iii) Combining the altimetry, gravimetry and mass budget time-series of mass trends

We combine the altimetry, gravimetry and input-output time-series to produce a single reconciled time-series of mass trends by taking the error-weighted mean of the available estimates at each epoch. We estimate the error on the reconciled mass trend time-series at each epoch as the root mean square error divided by the square root of the number of independent techniques for which a mass trend estimate is available. From this reconciled time-series of mass trends, we compute rates of mass balance over each calendar year and over different time periods as the average of the monthly rates falling within the defined time interval, with the associated error as the average of the contributing errors divided by the square root of the numbers of years of the time period. Finally, when summing mass trends of multiple ice sheets, the combined uncertainty is estimated as the root sum square of the uncertainties for each region.

iv) Generating the final reconciled time-series of cumulative mass change

We generate a time-series of cumulative ice sheet mass change by integrating our reconciled time-series of mass trends over time for each ice sheet. We estimate the cumulative errors as the root sum square of annual errors, assuming that errors are not correlated over time. Errors quoted in the text refer to the 1σ estimated error.

4 Results

First, we compare individual estimates of ice sheet mass balance within each of the three geodetic technique experiment groups, separately, to assess the level of agreement among estimates derived using the same technique. Within each group, we compare annual rates of mass change and their standard deviation for each ice sheet region. The input-output group includes significantly fewer mass balance estimates than the other technique experiment groups, but these estimates have the advantage of providing information on the partitioning of mass trends between signals related to SMB and ice dynamics, and they also cover relatively long periods of time. Ice discharge is measured from satellite observations of ice velocities combined with estimates of ice thickness at glaciers' termini, and SMB is derived from regional climate model outputs. In this study, all input-output estimates that we include use the same SMB model. We include 3 input-output method estimates of GrIS mass balance, all at annual resolution and that together span the period 1992 to 2020. During the period 2007 to 2011, annual rates of mass change determined from these three input-output datasets differ by up to 83 Gt yr^{-1} and their average standard deviation is 28 Gt yr^{-1}. For Antarctica and its ice sheet components, we include one input-output mass balance estimate which covers the entire 1992 to 2020 period at annual resolution.

The altimetry group includes 8 mass balance estimates for the GrIS that together span the years 2003 to 2018, with 4 of these solutions derived from radar altimetry, 2 from laser altimetry and 2 from a combination of both. We include 6 altimetry mass balance estimates for the AIS which together cover the period 1992 to 2019. In total we include 6 solutions for the EAIS, 6 for the WAIS and 5 for the APIS. Of these, 2 solutions are derived from radar altimetry, 1 from laser altimetry and 3 from a combination of both. To derive rates of surface elevation change, various methods were applied to the laser and radar altimetry data including repeat-track, plane fit or overlapping footprints techniques. For Greenland, half of the participants corrected the altimetry time-series for the GIA effect while for Antarctica, all participants applied a GIA correction. Next, to derive mass trends from rates of surface elevation change, either a constant density or a spatially and time varying density field from a firn density model forced by a regional climate model, were applied. These solutions have varying temporal resolutions ranging from 1 month to 7.1 yr for an average effective temporal resolution of 3.0 yr for Greenland and 2.6 yr for Antarctica. The temporal resolution of the altimetry group is thus lower than annual, mainly due to the fact that solutions derived from laser altimetry data were all provided as constant rates spanning the duration of ICESat-1 mission while the radar altimetry solutions have a higher temporal resolution of 0.35 yr for Greenland and 0.47 yr for Antarctica. As there is no overlap period during which all altimetry estimates are available, we compare solutions derived solely from radar altimetry and solutions incorporating laser altimetry data separately. In Greenland, radar altimetry solutions differ by up to 132 Gt yr^{-1} and their standard deviation is 102 Gt yr^{-1} during their two-year overlap period (2013 to 2015) while laser and combination solutions differ by less than 56 Gt yr^{-1} with an average standard deviation of 31 Gt yr^{-1} during their 6-year overlap (2004 to 2010). In Antarctica, the spread between laser solutions is largest at the EAIS with a standard deviation in annual rates of 57 Gt yr^{-1} between 2004 and 2009, followed by the WAIS and APIS with standard deviations of 31 Gt yr^{-1} and 13 Gt yr^{-1}, respectively. On the other hand, radar altimetry solutions show a larger spread at the WAIS (54 Gt yr^{-1}) than at the EAIS (12 Gt yr^{-1}) during their overlap period (2013 to 2019).

The gravimetry group has the largest number of estimates, with 16 for each ice sheet that together span the period 2002 to 2020. All gravimetry solutions were submitted as time-series of cumulative mass change at monthly resolution resulting in a collective effective resolution of 0.08 yr. All participants submitted estimates for all ice sheet regions, with 10 participants analysing spherical harmonic gravity field solutions using a wide range of approaches and 6 participants using mass concentration units (usually referred to as mascons) directly estimated from the GRACE and GRACE-FO level-1 K-band ranging data. Various GIA, hydrology leakage, and ocean leakage models were used to correct the gravimetry data for external signals. Overall, there is good agreement between rates of ice sheet mass balance derived from satellite gravimetry. In Greenland, we compare the different gravimetry solutions over the period 2002 to 2014 and find that annual rates of mass balance differ by up to 44 Gt yr^{-1}, and their standard deviation is 36 Gt yr^{-1}. In Antarctica, the different gravimetry solutions overlap over a decade from 2004 to 2014 during which their annual rates of mass balance have an average standard deviation of 41 Gt yr^{-1}. When comparing over the different regions of the Antarctic continent, the difference is greatest at the EAIS with a maximum difference of 45 Gt yr^{-1} and standard deviation of 31 Gt yr^{-1}. In the other regions, gravimetry estimates are in better agreement at the APIS with a maximum difference of 13 Gt yr^{-1} and standard deviation of 10 Gt yr^{-1}, followed by the WAIS where the maximum difference between estimates reaches 28 Gt yr^{-1} and their standard deviation is 19 Gt yr^{-1}.

Comparing mass balance estimates derived from similar satellite observations reveals that in Greenland, the standard deviation between estimates is the largest for the altimetry group and the smallest for the input-output group. In Antarctica, the standard deviation between altimetry estimates is less than 57 Gt yr^{-1} and less than 41 Gt yr^{-1} for gravimetry estimates during their respective overlap periods. However this comparison is limited by the varying temporal resolutions of the different datasets – especially for the altimetry group for which constant rates of mass change over long periods of time dampen temporal variation in ice sheet mass changes – and by the small number of input-output estimates – in particular in

Antarctica where only one estimate is available. This limits our ability to link differences between estimates derived from the same geodetic technique to methodological differences or to the use of different geophysical corrections or auxiliary datasets.

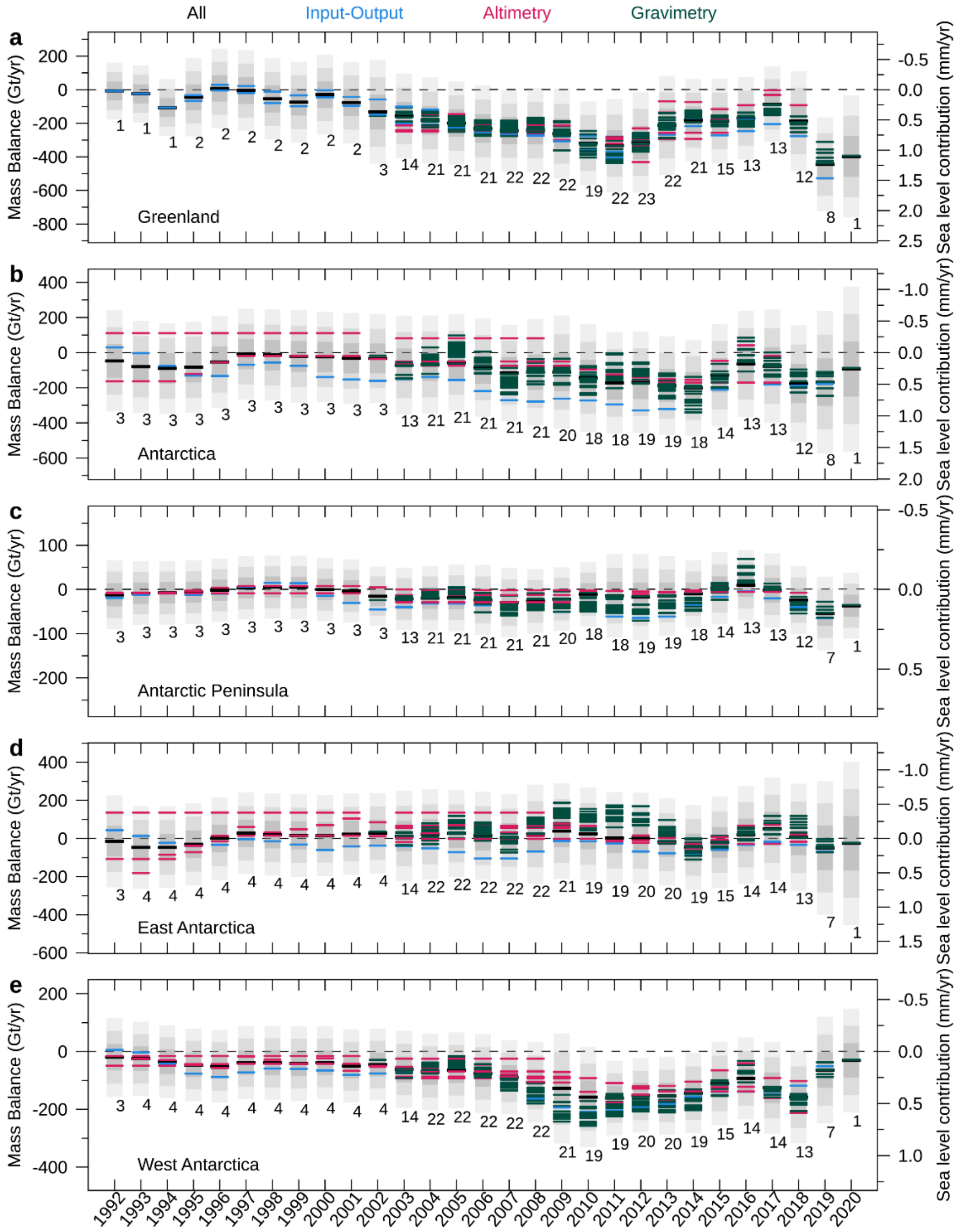

Figure 1. Annual rates of mass change of the (a) GrIS, (b) AIS, (c) APIS, (d) EAIS and (e) WAIS from the altimetry, gravimetry and input-output estimates included in this study and the reconciled estimate produced from the three techniques. The estimated 1σ, 2σ, and 3σ ranges of our final aggregated estimate are shaded in dark, mid and light grey, respectively. The number of individual mass balance estimates collated at each epoch is shown below each bar.

Next, we assess differences between the aggregated time-series derived within each class of satellite observations during the periods when estimates from all three geodetic techniques are available – from 2003 to 2018 for Greenland and from 2002 to 2019 for Antarctica. We compare rates of mass change during these overlap periods, which are 5 and 10 years longer than in the previous IMBIE assessments, respectively (Figure 2). In Greenland, rates of mass balance determined from altimetry, gravimetry, and the input-output method are in close agreement between 2003 and 2018, with a standard deviation of 19 Gt yr^{-1} and a reconciled rate of mass loss of 221 ± 22 Gt yr^{-1} from all three techniques. In Antarctica, the reconciled rate of mass loss between 2003 and 2019 is 115 ± 24 Gt yr^{-1} but the spread of the altimetry, gravimetry and mass budget estimates is 4 times larger than in Greenland (79 Gt yr^{-1}). Over the different regions of Antarctica, the spread of estimates of ice sheet mass balance increases with the size of the region considered, with standard deviations of 54 Gt yr^{-1}, 18 Gt yr^{-1}, and 16 Gt yr^{-1}, at the EAIS, WAIS, and APIS, respectively. Across all ice sheets, the input-output estimate is the most negative and the altimetry the most positive except at the EAIS, where the gravimetry estimate is the most positive. The greatest departure occurs at the EAIS where the three geodetic techniques disagree on even the sign of the mass change, with a maximum difference of 105 ± 33 Gt yr^{-1} between rates of mass change from the input-output method and gravimetry estimates. This indicates that the EAIS remains a challenging region for which to monitor mass changes, likely due to the large extent of this region, the poorly constrained GIA signal and paleo-ice reconstruction (Bentley et al., 2014; Martín-Español et al., 2016; Small et al., 2019), and the relatively small mass imbalance in comparison to natural fluctuations in SMB in East Antarctica (Mottram et al., 2021).

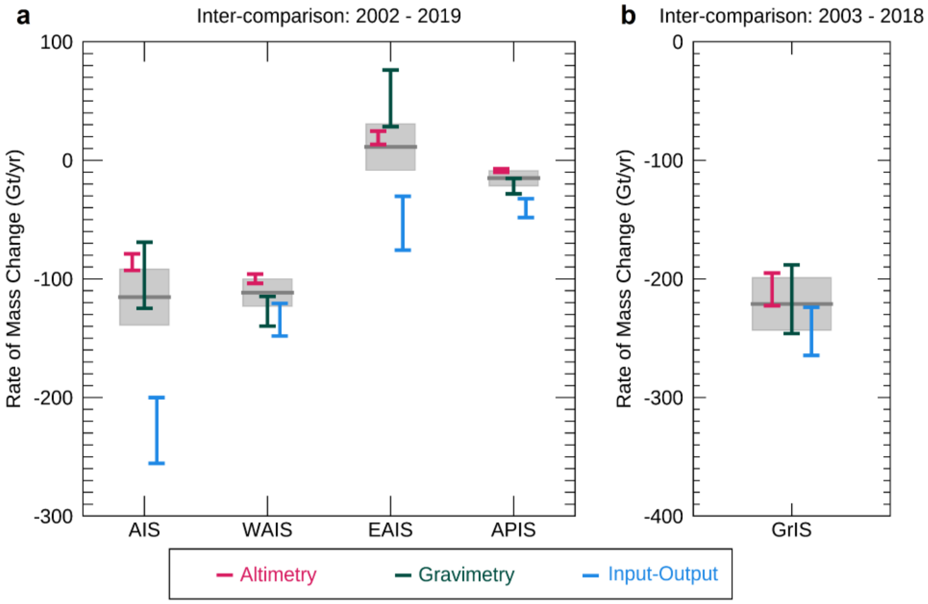

Figure 2. Inter-comparison of rates of ice sheet mass balance of (a) the AIS, WAIS, EAIS, and APIS over the overlap period 2002-2019 and of (b) the GrIS during the overlap period 2003-2018 derived from the altimetry, gravimetry and input-output techniques.

When examining the aggregated time-series of rate of mass change at annual resolution, we find the highest temporal correlation between the three time-series at the WAIS ($0.6 < r^2 < 0.9$). In addition, the gravimetry and input-output annual rates are also well-correlated at the APIS and GrIS ($r^2 > 0.5$). However, the altimetry mass balance time-series is poorly correlated with both the aggregated gravimetry and input-output time-series at the APIS, EAIS and GrIS ($r^2 < 0.2$). The better correlation between the gravimetry and input-output time-series can be explained by their higher temporal resolutions, sufficient to resolve annual fluctuations in ice sheet mass balance which are substantial in these regions. Nonetheless, we find that almost all individual estimates of annual rates of mass balance included in this study fall within one standard deviation (1σ) of our reconciled estimate given their respective individual errors, with 100 %, 96 %, 100 %, 96 % and 99 % of those annual rates of mass change falling within 1σ at the GrIS, AIS, APIS, EAIS, and WAIS, respectively.

We integrate the combined mass balance estimates from gravimetry, altimetry and the input-output method (Figure 1) to determine the cumulative mass lost from Antarctica and Greenland since 1992 (Figure 3). Antarctic mass loss continues to be dominated by ice discharge from West Antarctica where the signal is strongest – rising from 37 ± 19 Gt yr^{-1} between 1992 and 1996 to a maximum of 131 ± 21 Gt yr^{-1} between 2012 and 2016 (Table 2), before slowing slightly to 94 ± 25 Gt yr^{-1} during the last 5 years of our survey between 2017 and 2020. At the Antarctic Peninsula the increase in losses since the early

2000s that is generally associated with ice-shelf collapse (Rignot et al., 2004; Cook and Vaughan, 2010; Adusumilli et al., 2018) was masked briefly between 2012 and 2016, when the average rate of mass loss was reduced by 15 Gt yr^{-1} to 6 ± 13 Gt yr^{-1} in part due to an extreme snowfall event in 2016 (Wang et al., 2021; Chuter et al., 2021), before returning to 21 ± 12 Gt yr^{-1} between 2017 and 2020. East Antarctica remains the least certain component of Antarctic Ice Sheet mass balance, where the average 30-year mass trend is 3 ± 15 Gt yr^{-1}. In all, the Antarctic Ice Sheet lost 2671 ± 530 Gt of ice between 1992 and 2020, raising the global sea level by 7.4 ± 1.5 mm; after doubling in the mid-2000s from 62 ± 41 Gt yr^{-1} to 130 ± 45 Gt yr^{-1}, increased Antarctic ice losses – largely driven by an acceleration in ice discharge from the Amundsen Sea Sector (Mouginot et al., 2014) – have persisted to the present-day. The rate of Greenland ice loss has remained highly variable during the last 5-year period of our updated assessment, ranging from 86 ± 75 Gt yr^{-1} in 2017 to a new maximum of 444 ± 93 Gt yr^{-1} in 2019 driven by exceptional surface melting during the summer (Tedesco and Fettweis, 2020). The majority of ice sheet losses have arisen from Greenland during our 29-year survey: 4892 ± 457 Gt in total at an average rate of 169 ± 16 Gt yr^{-1}. Combined, Antarctica and Greenland lost 7563 ± 699 Gt of ice between 1992 and 2020, raising the global sea level by 21 ± 2 mm.

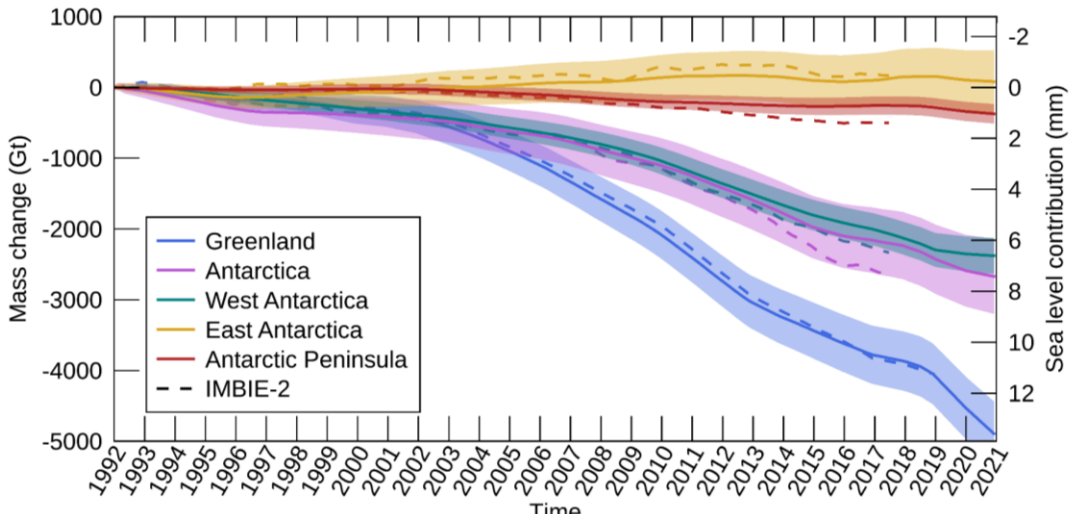

Figure 3. Cumulative ice sheet mass changes. The estimated 1σ uncertainty of the cumulative change is shaded. The dashed lines show the results from our previous assessments (IMBIE-2).

Table 2. Rates of ice sheet mass change (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.

	GrIS	**AIS**	**WAIS**	**EAIS**	**APIS**
1992-1996	-35 ± 29	-70 ± 40	-37 ± 19	-27 ± 33	-7 ± 11
1997-2001	-48 ± 36	-19 ± 39	-42 ±19	21 ± 32	2 ± 11
2002-2006	-180 ± 39	-62 ± 41	-64 ± 20	21 ± 34	-20 ± 11
2007-2011	-280 ± 38	-130 ± 45	-129 ± 23	19 ± 36	-21 ± 12
2012-2016	-213 ± 40	-150 ± 43	-131 ± 21	-13 ± 35	-6 ± 13
2017-2020	-257 ± 42	-115 ± 55	-94 ± 25	0 ± 47	-21 ± 12
1992-2020	-169 ± 16	-92 ± 18	-82 ± 9	3 ± 15	-13 ± 5

Finally, we assess the consistency of our results with our most recent assessment of ice sheet mass balance (IMBIE-2) to evaluate the impact of incorporating updated datasets and using an updated processing scheme. During their overlapping periods – 1992 to 2017 for Antarctica and 1992 to 2018 for Greenland – the results of this study and IMBIE-2 are in agreement within their respective uncertainties with rates of mass change of -150.0 ± 16 Gt yr^{-1} and -150 ± 12 Gt yr^{-1} for GrIS, respectively and rates of -86 ± 19 Gt yr^{-1} and -103 ± 22 Gt yr^{-1} for AIS, respectively. Next, comparing rates of mass balance within calendar years shows that results from this study and our previous assessment are consistent across all years for all ice sheets, except for two years at the start of our record (1992 and 1995) at the GrIS for which the difference between our mass balance assessments exceeds their respective uncertainty bounds. On average, the magnitude of the differences in annual rates of mass balance is 36 Gt yr^{-1} at GrIS, 33 Gt yr^{-1} at AIS, 12 Gt yr^{-1} at APIS, 31 Gt yr^{-1} at EAIS, and 23 Gt yr^{-1} at WAIS. The relatively small differences between our previous and current mass balance assessments originate from a combination of our inclusion of updated datasets and the implementation of an updated processing scheme in this study. In all ice sheet regions, participant datasets have been updated compared to our previous assessment. In addition, in this study we apply a common processing scheme to the AIS and GrIS, while in our previous study the mass balance assessments were aggregated with and without inverse-error weighting in the respective regions.

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5 Discussion

Our assessment of ice sheet mass balance also provides a means of tracking the contribution of the ice sheets to GMSL. Here, we discuss the relative contributions of Greenland and Antarctica to GMSL by comparing our results to the GMSL trend from the AVISO product (https://www.aviso.altimetry.fr/msl/, last access: 12th April 2022). Although numerous satellite-altimetry-based time-series of GMSL are available, differences between these products are less than 5 % of the GMSL trend (Ablain et al., 2019) and so the choice of one particular source does not affect our present discussion. From our updated assessment, Greenland and Antarctica have contributed 0.74 ± 0.07 mm yr^{-1} to GMSL during the AVISO record (1993-2020), contributing 14 % and 8 % to the overall trend, respectively. This is consistent with findings from previous studies which examined the relative contributions of the different components of the sea level budget (WCRP, 2018; Horwath et al., 2022). Compared to the pre-2000s period (1993-1999) when the ice sheets' contribution to GMSL was only 0.26 ± 0.11 mm yr^{-1} (9 % of the GMSL trend), Greenland and Antarctica now (2010 to 2020) contribute 1.09 ± 0.12 mm yr^{-1} (24 % of the GMSL trend) – four times higher. In particular, the acceleration of the ice sheets' contribution to GMSL was driven by increased ice losses from the GrIS (Chen et al., 2017; Dieng et al., 2017, Hamlington et al., 2020) with its contribution rising from 0.12 ± 0.08 mm yr^{-1} pre-2000s to 0.68 ± 0.08 mm yr^{-1} in the 2010s.

Satellite observations of ice sheet mass balance are important for evaluating ice sheet models and their climate model forcing (Shepherd and Nowicki, 2017; Slater et al., 2020; Aschwanden et al., 2021). In their 2021 assessment (AR6), the IPCC projected ice losses from Antarctica and Greenland due to SMB and glacier dynamics under a range of emission scenarios every ten years, beginning in 2020 (Fox-Kemper et al., 2021) (Figure 4). As a result, we compare satellite mass balance rates from the decade prior (2010-2020) to those at the beginning of the projection period (2020-2030) (Table 3). In Antarctica, the observed sea level contribution during the last 10 years of our survey is 0.42 ± 0.09 mm yr^{-1}, closest to the median sea level contribution projected by the IPCC for the following decade (0.6 mm yr^{-1}). We note the large spread between the lower (10th percentile) and upper (90th percentile) ranges of the projected sea level contribution from Antarctica during this period – between -0.1 mm yr^{-1} and 2.2 mm yr^{-1}, respectively – even in their first decade. Although Greenland ice losses were highly variable between 2010 and 2020, they raised the global sea level at an average rate of 0.68 ± 0.08 mm yr^{-1}, closest to the median sea level contribution between 2020 and 2030 predicted by the IPCC (0.7 mm yr^{-1}). If the recent acceleration in Greenland ice losses were to continue (1.2 ± 0.2 mm yr^{-1} between 2019 and 2020), however, they would track above the upper range predicted by the IPCC this decade (1.0 to 1.1 mm yr^{-1} for all emission pathways). If ice sheet losses were to continue on the median IPCC trajectory, the polar ice sheets will raise global sea levels by between 148 and 272 mm by 2100 (Figure 4). Because the AR6 projections incorporate a long-term dynamic ice sheet response based on observations from the last 40 years (Fox-Kemper et al., 2021), it follows that our assessment tracks closest to the median range in the near-term; as the overlap period between our survey and AR6 predictions is only one year, a longer period of comparison is required to establish the actual trajectory the ice sheets are following and the suitability of the time period used to assess the

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long-term dynamic response. Remaining uncertainties in the Antarctic Ice Sheet response to climate forcing still drive the spread of climate model projections, which range between -5 and 631 mm for both ice sheets at 2100.

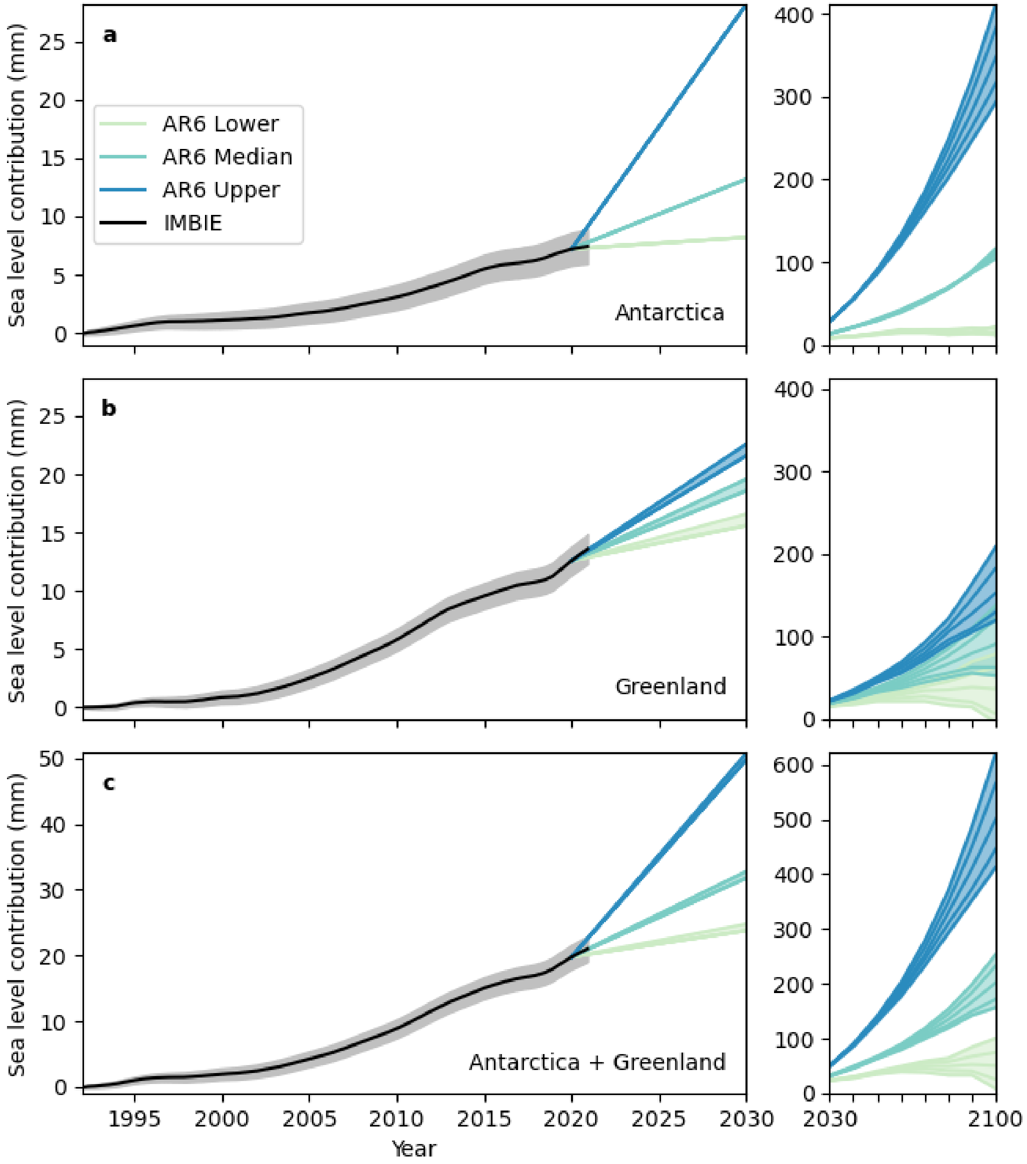

Figure 4.Comparison of observed sea level contributions from a) the Antarctic Ice Sheet, b) Greenland Ice Sheet, c) Antarctic and Greenland Ice Sheets from this study (IMBIE) and predicted by the IPCC AR6.

Table 3. Decadal rates of sea level contribution from IMBIE and AR6 projections

	2010-2020 (mm yr^{-1})	2020-2030 (mm yr^{-1})		
	IMBIE	**AR6 Lower**	**AR6 Median**	**AR6 Upper**
AIS	0.41 ± 0.09	-0.1 - 0.0	0.6	2.1 - 2.2
GrIS	0.68 ± 0.08	0.4 - 0.5	0.7	1.0 - 1.1

6 Conclusions

We combine 50 estimates of ice sheet mass balance, 26 for Greenland and 24 for Antarctica, to produce a new reconciled estimate of ice sheet mass balance showing that the ice sheets lost 7,563 ± 699 Gt of ice between 1992 and 2020. Ice losses have accelerated at both ice sheets over this 29-year record and the rate of ice loss is now 5 times higher in Greenland and 25 % higher in Antarctica compared to the early 1990s. Our assessment shows that the altimetry, gravimetry and input-output method are in close agreement in Greenland with a spread of 19 Gt yr^{-1} over their common time period, which represents only 10.9 % of the rate of imbalance. In Antarctica, the spread between techniques is 4 times larger than in Greenland, mostly due to large differences between estimates for the East Antarctic Ice Sheet. To further explore and interpret differences between geodetic techniques, producing altimetry estimates with a higher temporal resolution (especially during the first half of the satellite altimetry record), better GIA constraints for the gravimetry estimates, and additional estimates of ice sheet mass balance via the input-output method would improve the comparison and aggregation of ice sheet mass balance estimates. Continuously monitoring the mass balance of the ice sheets and producing annual updates of Greenland and Antarctica mass balance is critical to track their contribution to global mean sea level and constrain projections of future sea-level rise.

7 Data Availability

The aggregated Greenland and Antarctic Ice Sheets mass balance data and associated errors generated in this study are freely available at the NERC Polar Data Centre, https://doi.org/10.5285/77B64C55-7166-4A06-9DEF-2E400398E452 (The IMBIE Team, 2021).

8 Code Availability

The code used to compute and aggregate rates of ice sheet mass change and their errors is freely available at https://github.com/IMBIE.

Author Contribution

A.S. and E.I. designed and led the study. I.O. and M.E.P. performed the mass balance data collation and analysis. T. Slater performed the AR6 data analysis and prepared Fig 4 and Table 3. I.O. led the writing and prepared the other figures and tables. I.O, A.S. and T. Slater wrote the manuscript. All authors participated in the data interpretation and commented on the manuscript.

Competing interests

The authors declare that they have no conflict of interest.

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Appendix A

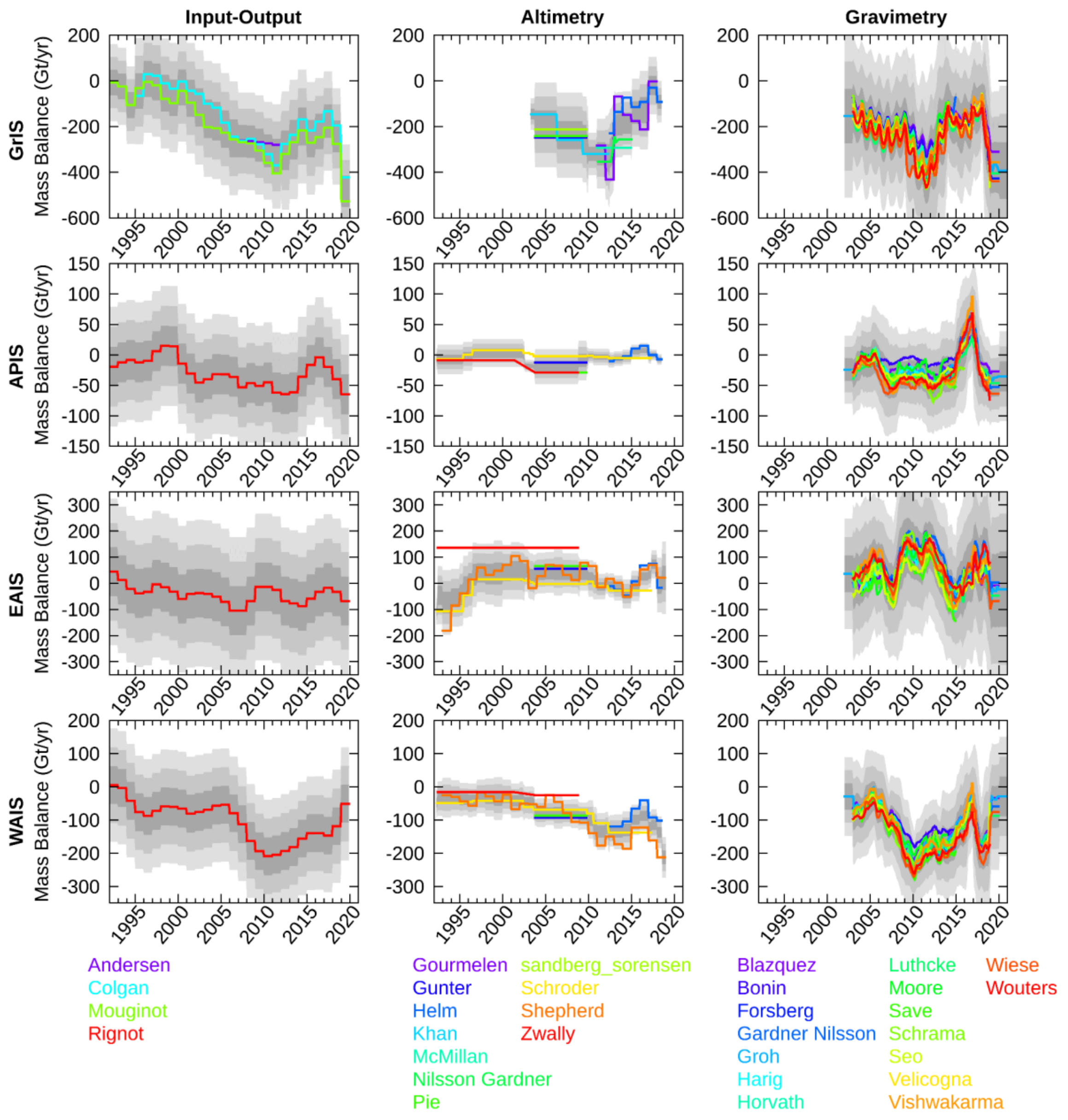

Figure A1. Individual rates of ice sheet mass balance from the input-output, altimetry and gravimetry groups over the GrIS, APIS, EAIS and WAIS included in this study. The grey shading shows the estimated 1σ, 2σ, and 3σ ranges of our final aggregated estimate are shaded in dark, mid and light grey, respectively.

Table A1. References of the datasets, methods, GIA and SMB models employed by participants of the input-output, altimetry and gravimetry experiment groups.

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ALT	Gourmelen	Gourmelen, N. *et al.* CryoSat-2 swath interferometric altimetry for mapping ice elevation and elevation change. *Advances in Space Research* **62**, 1226–1242 (2018).
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	Schroder	Schröder, L. *et al.* Four decades of Antarctic surface elevation changes from multi-mission satellite altimetry." *The Cryosphere* **13**(2), 427-449, (2019).
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	Zwally	Zwally, H. J. *et al.* Mass gains of the Antarctic ice sheet exceed losses. *J. Glaciol.* **61**, 1019-1036 (2015).
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