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1 Mass balance of the Antarctic ice sheet from 1992 to 2017

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31 **The Antarctic ice sheet is an important indicator of climate change and driver of sea level rise. Here,**
32 **we combine satellite observations of its changing volume, flow, and gravitational attraction and**
33 **surface mass balance modelling, to show that it lost 2720 ± 1390 Gt of ice between 1992 and 2017 -**
34 **a 7.6 ± 3.9 mm contribution to mean sea level. Ocean-driven melting has caused rates of ice loss**
35 **from West Antarctica to rise from 53 ± 29 Gt/yr in the 1990s to 159 ± 26 Gt/yr in the 2010s. Ice shelf**
36 **collapse has driven Antarctic Peninsula ice loss up from 7 ± 13 Gt/yr in the 1990s to 33 ± 16 Gt/yr in**
37 **the 2010s. We find large variations in and among model estimates of surface mass balance and**
38 **glacial isostatic adjustment in East Antarctica, and its 25-year mass trend (5 ± 46 Gt/yr) is still the**
39 **least certain.**

40 The Antarctic ice sheets hold enough water to raise global sea level by 58 metres ¹. They channel ice
41 to the oceans through a network of glaciers and ice streams ², each with a substantial inland catchment
42 ³. Fluctuations in the grounded ice sheet mass arise due to differences between net snow
43 accumulation at the surface, meltwater runoff, and ice discharge into the ocean. In recent decades,
44 reductions in the thickness ⁴ and extent ⁵ of floating ice shelves have disturbed inland ice flow,
45 triggering retreat ^{6,7}, acceleration ^{8,9}, and drawdown ^{10,11} of many marine terminating ice streams. A
46 variety of techniques have been developed to measure changes in ice sheet mass, based on satellite
47 observations of their speed ¹², volume ¹³, and gravitational attraction ¹⁴ combined with modelled
48 surface mass balance ¹⁵ and glacial isostatic adjustment¹⁶. Since 1989, there have been more than 150
49 assessments of ice loss from Antarctica based on these approaches ¹⁷. An inter-comparison of 12 such
50 estimates ¹⁸, demonstrated that the three principal satellite techniques provide similar results at the

51 continental scale and, when combined, lead to an estimated mass loss of 71 ± 53 Gt of ice per year
52 averaged over the period 1992 to 2011. Here, we extend this assessment to include twice as many
53 studies, doubling the overlap period and extending the record through to 2017.

54 We collated 24 independently-derived estimates of ice sheet mass balance (Figure 1) determined
55 within the period 1992 to 2017 and based upon the techniques of satellite altimetry (7 estimates),
56 gravimetry (15 estimates) or the input-output method (2 estimates). Altogether, there were 24, 24,
57 and 23 individual estimates of mass change computed within defined geographical limits^{19,20} for the
58 East Antarctic, West Antarctic and the Antarctic Peninsula ice sheets, respectively. Rates of ice sheet
59 mass change were compared (see Methods) over common intervals of time¹⁸. We then averaged
60 rates of ice sheet mass balance based on the same class of satellite observations to produce three
61 technique-dependent time series of mass change in each geographical region (see Methods). Within
62 each class, the annual mass rate uncertainty was computed as the mean uncertainty of the individual
63 contributions. The final, reconciled estimate of ice sheet mass change for each region was computed
64 as the mean of the technique-dependent values available at each epoch (Figure 1). In computing the
65 associated uncertainty, we assumed that the errors for each technique are independent. To estimate
66 the cumulative mass change and its uncertainty (Figure 2), we integrated the reconciled estimates for
67 each ice sheet and weighted the annual uncertainty by $1/\sqrt{n}$, where n is the number of years elapsed
68 relative to the start of each time series. Antarctic ice sheet mass trends and their uncertainties (Table
69 1) were computed as the linear sum and root sum square of the regional trends and their
70 uncertainties, respectively.

71 The level of disagreement between individual estimates of ice sheet mass balance increases with the
72 area of each ice sheet region, with average per-epoch standard deviations of 11, 21, and 37 Gt/yr at
73 the Antarctic Peninsula, West Antarctica, and East Antarctica, respectively (Figure 1 and Methods).
74 Among the techniques, gravimetric estimates are the most abundant and also the most closely
75 aligned, though their spread increases in East Antarctica where glacial isostatic adjustment remains

76 poorly constrained²¹ and is least certain when spatially integrated²²⁻³³ due to the region's vast extent.
77 Solutions based on satellite altimetry and the input-output method run for the entire record, roughly
78 twice the duration of the gravimetry time series. Although most (59 %) estimates fall within one
79 standard deviation of the technique-dependent mean, a few (6 %) depart by more than three. At the
80 Antarctic Peninsula, the 25-year average rate of ice sheet mass balance is -20 ± 15 Gt/yr, with a ~ 15
81 Gt/yr increase in losses since 2000. The strongest signal and trend has occurred in West Antarctica,
82 where rates of mass loss rise from 53 ± 29 Gt/yr to 159 ± 26 Gt/yr between the first and final 5 years
83 of our survey, with the largest increase occurring during the late 2000's when ice discharge from the
84 Amundsen Sea sector accelerated³⁴. Both of these regional losses are driven by reductions in the
85 thickness and extent of floating ice shelves, which has triggering retreat, acceleration, and drawdown
86 of marine terminating glaciers³⁵. The least certain result is in East Antarctica, where the average 25-
87 year mass trend is 5 ± 46 Gt/yr. Overall, the Antarctic ice sheet lost 2720 ± 1390 Gt of ice between
88 1992 and 2017, an average rate of 109 ± 56 Gt/yr.

89 Knowledge of the ice sheet surface mass balance is an essential component of the input-output
90 method, which subtracts solid ice discharge from net snow accumulation, and also aids interpretation
91 of mass trends derived from satellite altimetry and gravimetry. Snowfall is the major driver of
92 temporal and spatial variability in Antarctic ice sheet surface mass change^{36,37}. Although locally
93 important, spatially integrated sublimation and meltwater runoff are typically one to two orders of
94 magnitude smaller, respectively. In the absence of observation-based maps, Antarctic ice sheet
95 surface mass balance is usually taken from atmospheric models, evaluated with in-situ and remotely-
96 sensed observations^{15,38-41}. To assess Antarctic surface mass balance, we compared two global
97 reanalysis products (JRA55 and ERA-Interim) and two regional climate models (RACMO2 and
98 MARv3.6)(see Methods). ERA-Interim is usually regarded as the best performing reanalysis product
99 over Antarctica, albeit with a dry bias in the interior and overestimated rain fraction^{40,42,43}. Spatially
100 averaged accumulation rates peak at the Antarctic Peninsula, and are ~ 3 and ~ 7 times lower in West
101 and East Antarctica, respectively (Extended Data Figure 2 and Extended Data Figure 3). Compared to

102 the all-model average surface mass balance of 1994 Gt/yr, the regional climate models have 4.7%
103 higher and the reanalyses 7% lower values. These differences can be attributed to the higher
104 resolution of the regional models, which resolve the steep coastal precipitation gradients in greater
105 detail, and also their improved representation of polar processes. The temporal variability of all
106 products is similar, and they all agree on the absence of an ice sheet wide trend in surface mass
107 balance over the period 1979 to 2017, implying that recent Antarctic ice sheet mass loss is dominated
108 by increased solid ice discharge into the ocean.

109 Gravimetric estimates of mass change are strongly influenced by the method used to correct for glacial
110 isostatic adjustment (GIA)¹⁶. In this study, six different GIA models were used for this purpose
111 ^{22,25,27,31,32,44}. We also assessed nine continent-wide forward-model and two regional model
112 simulations to better understand uncertainties in the GIA signal itself, and we reprocessed the
113 gravimetry estimates of mass balance using just the W12a²⁷ and IJ05_R2³² GIA models for comparison
114 with earlier work¹⁸ (see Methods). The net gravitational effect of GIA across Antarctica is positive, and
115 the mean and standard deviation of the continent-wide GIA models (54 ± 18 Gt/yr) is very close to
116 that of W12a (56 ± 27 Gt/yr) and IJ05_R2 (55 ± 13 Gt/yr). The narrow spread likely reflects the difficulty
117 of quantifying the timing and extent of past ice sheet change, and the absence of lateral variations in
118 Earth rheology within some models⁴⁵. In areas where GIA is a significant component of the regional
119 mass change, such as the Amundsen, Ross and Filchner-Ronne sectors of West Antarctica (see
120 Extended Data Figure 4), models predict the greatest uplift rates (5 to 7 mm/yr on average) but also
121 the greatest variability (e.g. standard deviation > 10 mm/yr in the Amundsen sector). Away from areas
122 with large GIA signals there is low variance among the models and broad agreement with GPS
123 observations⁴⁶. Nevertheless, most models considered here do not account for ice sheet change
124 during the last few millennia, because it is poorly known. Inaccurate treatment of low degree
125 harmonics associated with the global GIA signal can also bias gravimetric mass balance calculations⁴⁷.
126 If the GIA signal includes a transient component associated with recent ice sheet change this will bias
127 mass trend estimates and should be accounted for in future work.

128 Improvements in ice sheet mass balance assessments are still possible. Airborne snow radar ^{48,49} is a
129 powerful tool for evaluating surface mass balance and firn compaction models over large spatial
130 (1000's of km) and temporal (centennial) scales, in addition to the ice cores that have been
131 traditionally used⁵⁰. Geological constraints on the ice sheet history ²¹ and GPS measurements of
132 contemporary uplift ^{46,51} allow GIA models to be scrutinised and calibrated. More of both these data
133 sets are needed, especially in East Antarctica. Given their apparent diversity, the spread of GIA and
134 surface mass balance models should be evaluated in concert with the satellite gravimetry, altimetry,
135 and velocity measurements. A reassessment of satellite measurements acquired during the 1990s
136 would address the imbalance that is present in the current record. Alternative techniques (e.g. ⁵²) for
137 the combination of satellite data sets should be explored, and satellite measurements with common
138 temporal sampling should be contrasted. The ice sheet mass balance record should now be separated
139 into the contributions due to short-term fluctuations in surface mass balance and longer-term trends
140 in glacier ice. In addition to these obvious improvements, continued satellite observations are, of
141 course, essential.

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272

273 [Supplementary Information](#)

274 A table summarising the details of the satellite datasets is included as Supplementary Information
275 (Supplementary Information Table 1).

276

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281

282 Author Contributions

283 Andrew Shepherd and Erik Ivins designed and led the study. Eric Rignot, Ben Smith, Michiel van den
284 Broeke, Isabella Velicogna, and Pippa Whitehouse led the input-output, altimetry, surface mass
285 balance, gravimetry, and glacial isostatic adjustment experiments, respectively. Gorka Moyano and
286 Mark Pattle performed the data collation and analysis. Andrew Shepherd, Erik Ivins, Kate Briggs,
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290 wrote and edited the manuscript. All authors participated in the data interpretation and commented
291 on the manuscript.

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Region	1992- 1997 (Gt/year)	1997- 2002 (Gt/year)	2002- 2007 (Gt/year)	2007- 2012 (Gt/year)	2012- 2017 (Gt/year)	1992- 2011 (Gt/year)	1992- 2017 (Gt/year)
EAIS	11 ± 58	8 ± 56	12 ± 43	23 ± 38	-28 ± 30	13 ± 50	5 ± 46
WAIS	-53 ± 29	-41 ± 28	-65 ± 27	-148 ± 27	-159 ± 26	-73 ± 28	-94 ± 27
APIS	-7 ± 13	-6 ± 13	-20 ± 15	-35 ± 17	-33 ± 16	-16 ± 14	-20 ± 15
AIS	-49 ± 67	-38 ± 64	-73 ± 53	-160 ± 50	-219 ± 43	-76 ± 59	-109 ± 56

Table 1 | Rates of ice sheet mass change. Rates were determined from all satellite measurements over various epochs for the East Antarctic (EAIS), West Antarctic (WAIS), Antarctic Peninsula (APIS) and Antarctic (AIS) ice sheets. The period 1992-2011 is included for comparison to a previous assessment¹⁸, which reported mass balance estimates of 14 ± 43 Gt/yr for the EAIS, -65 ± 26 Gt/yr for the WAIS, -20 ± 14 Gt/yr for the APIS, and -71 ± 53 Gt/yr for the AIS. The small differences in our updated estimates are due to increases in the datasets used.

300 Figure Legends

301 **Figure 1. Antarctic ice sheet mass balance.** Rate of mass change of the Antarctic Peninsula (a), West
302 Antarctic Ice Sheet (b), and East Antarctic Ice Sheet (c) as determined from satellite altimetry (red),
303 input-output (blue), and gravimetry (green) observations and an average of estimates across each
304 class of measurement technique (black) The estimated one-, two-, and three-sigma range of the class

305 average are shaded in dark, mid, and light grey, respectively, and the number of individual mass
306 balance estimates collated at each epoch is shown along the top of each chart.

307

308 **Figure 2. Cumulative Antarctic ice sheet mass change.** Cumulative ice sheet mass changes (solid lines)
309 are determined from the integral of the measurement class average (Figure 1) for each ice sheet. The
310 estimated one-sigma uncertainty of the cumulative change is shaded.

311

312 [Methods](#)

313 [Data](#)

314 We analyse five groups of data; mass balance estimates determined from satellite altimetry,
315 gravimetry, and the input-output method, and model estimates of surface mass balance and glacial
316 isostatic adjustment. The data sets are computed using common spatial and temporal domains to
317 facilitate their aggregation, and according to methods report in the peer reviewed literature. In total
318 24 individual mass balance data sets were included. The data include 25 years of satellite radar
319 altimeter measurements, 24 years of satellite input-output method measurements, and 14 years of
320 satellite gravimetry measurements (Extended Data Figure 1). Among these data are estimates of ice
321 sheet mass balance for each ice sheet derived from each satellite technique. In comparison to the first
322 IMBIE assessment, new satellite missions, updated methodologies and improvements in geophysical
323 corrections have contributed to an increase in the quantity, duration and overlap period of data used
324 in this second assessment. In addition, two new experiment groups have assessed 11 Glacial Isostatic
325 Adjustment models and 4 Surface Mass Balance models. The complete list of data sets can be found
326 in Supplementary Information Table 1.

327 Drainage Basins

328 In this assessment, we analyse mass trends using two sets of ice sheet drainage basin (Extended Data
329 Figure 2), to ensure consistency with those used in the first IMBIE assessment¹⁸, and to evaluate an
330 updated definition tailored towards input-output method assessments. The first drainage basin set
331 was delineated using surface elevation maps derived from ICESat-1 based on the provenance of the
332 ice, and includes 27 basins³. The second set are updated to consider other factors such as the direction
333 of ice flow, and include 18 basins in Antarctica^{2,20}. To assess the effect of the different basin outline
334 sets on the estimates of ice sheet mass balance, we compared mass balance determinations between
335 the two delineations of ice sheet drainage basins. This evaluation was facilitated by seven estimates
336 (altimetry or gravimetry) determined using both drainage basin sets. At the scale of the major ice
337 sheet divisions, the delineations produce similar total extents. By far the largest differences occur in
338 the delineation (or definition) of East and West Antarctica, due to differences in the position of the ice
339 divide separating them. Within these regions, the root mean-square difference between 26 pairs of
340 ice sheet mass balance estimates computed using the two drainage basin sets is 8.7 Gt/yr. This
341 difference is small in comparison to the certainty of individual ice sheet mass balance assessments.

342 Computing Rates of Mass Change

343 The raw satellite mass balance data are either time-series of either relative mass change, $\Delta M(t)$, or
344 the rate of mass change, $dM(t)/dt$, plus their associated uncertainty, integrated over at least one of
345 the ice sheet regions defined in the standard drainage basin sets. In the case of $\Delta M(t)$, the time series
346 represents the change in mass through time relative to some nominal reference value. The duration
347 and sampling frequency of the time-series was not restricted. In practice, few mass time-series were
348 of $\Delta M(t)$ and $dM(t)/dt$. Because the inter-comparison exercise is based on comparing and aggregating
349 rates of mass change, $dM(t)/dt$, a common solution was implemented to derive $dM(t)/dt$ values from
350 data sets that comprised $\Delta M(t)$ only. Each $\Delta M(t)$ time series was used to generate a time-varying
351 estimate of the rate of mass change, $d(\Delta M(t))/dt=dM(t)/dt$, and an estimate of the associated

352 uncertainty, using a consistent approach. Time varying rates of mass change were computed by
353 applying a sliding fixed-period window to the $\Delta M(t)$ time series. At each node, defined by the sampling
354 period of the input time series, $dM(t)/dt$ and its standard error, $\sigma_{dM(t)/dt}$, were estimated by fitting a
355 linear trend to data within the window using a weighted least-squares approach, with each point
356 weighted by its respective error variance, $\sigma_{\Delta M(t)}^2$. The regression error, $\sigma_{dM(t)/dt}$, incorporates
357 measurement errors and model structural error due to any variability that deviates from linear trends
358 in ice mass, and may be a conservative estimate in locations where such deviation is present. Time
359 series of $dM(t)/dt$ computed using this approach were truncated by half the moving average window
360 period. When integrated, the $dM(t)/dt$ time series correspond to a low-pass filtered version of the
361 original $\Delta M(t)$ time-series. Although the current linear regression assumes uncertainties are
362 uncorrelated, the smoothing we apply during the trend calculation does cause data points to be
363 correlated during a number of epochs beyond the sliding window.

364 Surface Mass Balance

365 Ice sheet surface mass balance (SMB) comprises a variety of processes governed by the interaction of
366 the superficial snow and firn layer with the atmosphere. A direct mass exchange occurs via
367 precipitation and surface sublimation. Snow drift and the formation of meltwater and its subsequent
368 refreezing or retention redistribute mass spatially or lead to further mass loss via erosion and
369 sublimation, or runoff. In this assessment, a range of SMB products are compared. Four SMB model
370 solutions were considered for Antarctica (Extended Data Table 1); two regional models - RACMO2.3⁴¹
371 and MARv3.6⁵³ - and two global reanalysis products - JRA55⁵⁴ and ERA-Interim⁵⁵. The two regional
372 climate models agree well in terms of their spatially integrated SMB, apart from the Peninsula where
373 there is an offset of about 10 Gt/month between them (Extended Data Figure 3). However, the
374 reanalysis data underestimated the average SMB compared to the regional climate models by 200 to
375 350 Gt/yr. The SMB assessment illustrates that products of similar class (climate models, reanalysis
376 product) agree well, suggesting that groupings of their output may be appropriate. Model resolution

377 is, however, found to be an important factor when estimating SMB and its components, as respective
378 contributions where only the spatial resolution differed yield regional differences.

379 [Glacial Isostatic Adjustment](#)

380 Glacial isostatic adjustment (GIA) is the delayed response of the solid Earth to changes in time-variable
381 surface loading through the growth and decay of ice sheets, and associated changes in sea level.
382 Because GIA contributes to changes in the ice sheet surface elevation and gravity field, it must be
383 accounted for in measurements of the change in elevation and gravity for the purpose of isolating the
384 contribution solely caused by ice sheet imbalance. In this assessment, we compare different solutions
385 derived from continuum-mechanical forward modelling to inform the interpretation of the satellite
386 altimetry and gravimetry data which depend on the correction, and to advise future assessment
387 exercises. Twelve GIA contributions were received covering Antarctica (Extended Data Table 2), ten of
388 which are global^{23-30,32} and two of which are regional models³³. As a broad array of data may be used
389 to constrain GIA forward models, we anticipate spread in the predictions.

390 In the present analysis, the degree of similarity between the various GIA model solutions is assessed.
391 Areas of enhanced present-day vertical surface motion and (dis-)agreement between contributions
392 have been identified by averaging the uplift rates over the contributions and computing respective
393 standard deviations (Extended Data Figure 4). In some cases, it was necessary to estimate the GIA
394 contribution to gravimetric mass trends; this was done using common geographical masks and
395 truncation, and a standardized treatment of low degree harmonics. In Antarctica, the Amundsen Sea
396 sector and the regions covered by the Ross and Filchner Ronne Ice Shelves stand out as having both
397 high uplift rates (5-7 mm/yr on average) and high variability in uplift rates (peaking at >10 mm/yr
398 standard deviation in the Amundsen sector) among the models considered. Elsewhere in coastal
399 regions, uplift occurs at more moderate rates (~2 mm/yr on average), and the interior of East
400 Antarctica exhibits slow subsidence. In these regions, the average signal is accompanied by relatively
401 low variance among the GIA models (0-1.5 mm/yr standard deviation). None of the models fully

402 capture portions of the uplift that are observed to be very large (e.g. ⁵⁶), hence, we can anticipate a
403 bias toward low values for the GIA correction averaged over such regions. In areas of low mantle
404 viscosity, however, such as part of the WAIS, the LGM-related GIA signal may be over-predicted, and
405 it is not clear whether a bias exists at the continental scale.

406 Differences between the model predictions arise for a variety of additional reasons. Technical
407 differences in the modelling approach, for example relating to the consideration of self-gravitation,
408 ocean loading, rotational feedback, and compressibility, will be most important at the global scale,
409 but may explain only small differences among the regional models. Differing treatment of ice/ocean
410 loading in regions that have experienced marine-based grounding line retreat during the last glacial
411 cycle may explain the differences in model predictions for the ICE_6G_C/VM5a combination (see
412 Supplementary Information Table 1). Some small differences should be expected when comparing
413 models that use spherical harmonic and finite element approaches. Looking beyond consideration of
414 the model physics, larger differences arise due to the various approaches used to determine the two
415 principal unknowns associated with forward modelling of GIA, namely ice history and Earth rheology.
416 There is no generally accepted ‘best approach’ to determining these inputs, and indeed useful
417 advances can be made by comparing the results of complementary approaches. In the models
418 considered here, approaches to determining the ice history include dynamical ice-sheet modelling,
419 coupled ice-sheet–GIA modelling, tuning to fit geodetic constraints, tuning to fit geological
420 constraints, and use of direct observations of historical ice sheet change. When defining the
421 rheological properties of the solid Earth, most studies have opted to use a Maxwell rheology to define
422 a radially-symmetric Earth, but the use of a power-law rheology and/or fully-3D Earth model to
423 capture the spatial complexity of mantle properties is increasingly popular. An intermediate approach
424 used in many of the data sets included in this study has been to develop a regional GIA model that
425 reflects local Earth structure. Such models can be tuned, albeit imperfectly, to provide as accurate a
426 representation of GIA in that region as is possible. However, it remains a difficult and important
427 challenge to incorporate these regional studies into a global framework. Finally, although four of the

428 considered GIA models do provide a measure of uncertainty, and a number of studies have used an
429 ensemble modelling approach ^{24,30}, an important future goal for the GIA modelling community is the
430 inclusion of robust error estimates for all model predictions.

431 To compare the GIA models, Stokes coefficients relating to their gravitational signal were used to
432 determine the approximate magnitude of the effect of applying each correction to GRACE data
433 (Extended Data Table 2). This is a preliminary assessment, because the effect of applying a GIA
434 correction depends also on the methods used to process the GRACE data. Moreover, an agreement
435 on the modelling of the rational feedbacks has so far not been reached within the GIA community,
436 leading to a large spread in the modeled degree 2 coefficients and possibly a strong bias when a
437 correction is applied that is inconsistent with the GRACE observations (up to ca. 40 Gt/yr). In addition,
438 none of the current GIA data sets include estimates of the GIA-induced geocenter motion (degree 1
439 coefficients). Therefore, we omit degree 1 and 2 coefficients in this assessment of the GIA-induced
440 apparent mass change at this stage. From models representing GIA in Antarctic only, we estimate that
441 this omission may change the apparent mass change value by up to 20 %, which is currently not
442 included in the GIA error budget. There is relatively good agreement between the ten models that
443 cover all of Antarctica (Extended Data Table 2); the estimated GIA contribution ranges from +12 to
444 +81 Gt/yr, and the mean value is 56 Gt/yr. Although van der Wal et al. is a notable outlier, this is the
445 only solution to account for 3D variations in Earth rheology, and it will be interesting to compare this
446 result with other such models that are in development. It is important to note that two of the GIA
447 models are regional (Nield, Barletta); although they cannot be directly compared with the continental-
448 scale models, the magnitude of their signals is nonetheless included for interest.

449 [Mass Balance Intra-comparison](#)

450 First, we compare estimates of mass change within each of the three geodetic technique experiment
451 groups, separately, to assess the degree to which results from common techniques concur and to then
452 arrive at individual, aggregated estimates of mass change derived from each technique alone. In each

453 case we compare estimated rates of mass change derived from a common technique over a common
454 geographical region and over the full period of the respective data sets. Where data sets were
455 computed using both drainage basin definitions, the arithmetic mean of the two estimates is
456 presented. This is justified because the choice of drainage basin set has a very small (<10 Gt/yr) impact
457 on estimates of mass balance at the ice sheet scale and even less at the regional scale. Within each
458 experiment group, we perform an unweighted average of all individual data to obtain a single estimate
459 of the rate of mass change per ice sheet for each geodetic technique. In a few cases, it was not possible
460 to determine time-varying rates of mass change from individual estimates, because only constant
461 rates of mass change and constant cumulative mass changes were supplied. Although the effect of
462 averaging these data sets with time-varying solutions is to dampen the temporal variability present
463 within the series of finer resolution, they are retained for completeness. We estimate the uncertainty
464 of the average mass trends emerging from each experiment group as the average of the errors
465 associated with each individual estimate at each epoch.

466 To aid comparison, we (i) computed time-variable rates of mass change and their associated
467 uncertainty over successive 36-month periods stepped in 1-month intervals from time-varying
468 cumulative mass changes, and we then (ii) average rates of mass change over 1-year periods to
469 remove signals associated with seasonal cycles. Time-varying rates of mass change are truncated at
470 the start and end of each series to reflect the half-width of the time interval over which rates are
471 computed, though this period is recovered on integration to cumulative mass changes. The extent to
472 which we are able to analyse differences in mass balance solutions emerging from common satellite
473 approaches is limited by the mismatch in temporal resolution of the individual datasets, which makes
474 methodological and sampling differences difficult to separate.

475 Gravimetry Mass Balance Intra-comparison

476 Within the gravimetry experiment group, 15 estimates of mass balance derived from the GRACE
477 satellites were assessed, in entirety spanning the period July 2002 to September 2016. Of these

478 datasets, four (Luthcke, Moore, Save, Wiese) are derived with direct imposition of the GRACE Level-1
479 K-band range-data ⁵⁷⁻⁶⁰. These impositions result in 4 different, and quite independently derived,
480 mascon approaches. Other methods often refer to ‘mascon analysis’, but are conducted on post-
481 spherical harmonic (post-SH) expansions and without imposing the Level 1 K-band range data. We
482 distinguish the later methods, referring to them as ‘post-SH mascons’. Eleven contributions are
483 derived from monthly spherical harmonic solutions of the global gravity field using somewhat
484 different approaches ⁶¹⁻⁶⁷, which can be loosely classified as region integration approaches for 3
485 contributions (Blazquez, Groh, Horvath), post-SH mascon approaches for 4 contributions (Bonin,
486 Forsberg, Schrama, Velicogna). Forward-modelling is also an approach used in two contributions
487 (Wouters, Seo) and this essentially involves modelling of mass change with iterative comparison to
488 the GRACE-derived signal. One estimate (Harig) uses Slepian functions ⁶⁸. One estimate (Rietbroek)
489 uses a hybrid approach involving satellite altimetry that does not fall within the above categories ⁶⁹;
490 although these results are excluded from our gravimetry-only average, we present them alongside the
491 gravimetry-only results for comparison. No restrictions were imposed on the choice of glacial isostatic
492 adjustment correction, and among the GRACE solutions we consider six different models were used
493 for this purpose ^{22,25,27,31,32,44}. We did, however, assess a wider set of nine continent-wide forward
494 models and two regional models to better understand uncertainties in the GIA signal itself.

495 In total, there were 15 estimates of mass balance for each of the APIS, WAIS, and EAIS. All were time-
496 varying cumulative mass change solutions - the primary GRACE observable - and we computed time-
497 varying rates of mass change from these data. Combining all of the individual mass balance estimates,
498 the effective (average) temporal resolution of the aggregated solution is 1 year. Further details of the
499 gravimetry data sets and methods are included in Supplementary Information Table 1.

500 Extended Data Figure 5 shows a comparison of rates of mass change obtained from all gravimetry
501 mass balance solutions, calculated over the three main ice sheet regions. At individual epochs,
502 differences between time-varying rates of mass change are generally smaller than 50 Gt/yr in each ice

503 sheet region, and typically fall in the range 10 to 20 Gt/yr. Over the full period of the data, individual
504 rates of mass balance for the APIS, WAIS, and EAIS vary between -80 to +10, -260 to -20, and -120 to
505 +200 Gt/yr, respectively. Considering all of the gravimetry data (Extended Data Table 3); the standard
506 deviation of mass trends estimated during the period 2005 to 2015 is less than 24 Gt/yr in all three ice
507 sheet regions, with the largest spread occurring in the EAIS. In all three ice sheet regions, the spread
508 of individual mass balance estimates is well represented by the mean considering the uncertainties of
509 the individual and aggregated datasets.

510 [Altimetry Mass Balance Intra-comparison](#)

511 We assessed 7 radar and laser altimetry derived estimates of Antarctic ice sheet mass balance data
512 sets, in entirety spanning the period April 1992 to July 2017. In total, 6 estimates of mass change were
513 for the APIS, 7 for the EAIS, and 7 for the WAIS. Of these, 4 included data from radar altimetry, and 6
514 from laser altimetry. A variety of different techniques were employed to arrive at elevation and mass
515 trends⁷⁰⁻⁷⁶. Only 2 of the altimetry data sets were time-series of cumulative mass change, from which
516 we computed time-varying rates of mass change. The remaining altimetry data sets were constant
517 rates of mass change, which appear in our altimetry average as time-invariant solutions. The period
518 over which altimetry rates of mass change were computed ranged from 2 to 24 years. In consequence,
519 the aggregated dataset has a temporal resolution that is lower than annual. Including all individual
520 mass balance data sets, the effective (average) temporal resolution of the aggregated solution is 3.3
521 years. Further details of the altimetry data sets and methods are included in Supplementary
522 Information Table 1.

523 With a few exceptions, rates of mass change determined from radar and laser altimetry tend to differ
524 by less than 100 Gt/yr at all times in each ice sheet region (Extended Data Figure 5). The main
525 exceptions are in the EAIS, where one estimate (Zwally) reports mass trends that are ~100 Gt/yr more
526 positive than all others during the ERS and ICESat periods and the WAIS, where two estimates (Zwally
527 and Helm) report rates that are ~70 Gt/yr less negative than the others during the ICESat period.

528 Among the remaining data sets, the closest agreement occurs at the APIS, where mass trends agree
529 to within 30 Gt/yr at all times, and the poorest agreement occurs at the EAIS, where mass trends
530 depart by up to 100 Gt/yr. The largest differences are among datasets that are constant in time during
531 periods where rapid changes in mass balance occur in the annually resolved time series, suggesting
532 that a proportion of the difference is due to their poor temporal resolution. Mass balance solutions
533 from the relatively short (six-year) ICESat mission also appear to show larger spreads compared to
534 those determined from longer (decade-scale) radar-altimetry missions. This larger spread is due in
535 part to differences in the bias-correction models applied to ICESat data ^{75,77-79} and in part to the large
536 influence of firn densification on altimetry measurements over short periods, which have been
537 corrected for using different models. Firn-densification models are generally not applied to mass
538 balance solutions determined from radar altimetry. Further analysis of the corrections for bias
539 between ICESat campaigns and firn compaction is required to establish the significance of the
540 differences and to reduce their collective uncertainty. Comparing rates of mass change (Extended Data
541 Table 3), the average standard deviation of all mass trends at each epoch over the common period
542 2005 to 2015 is less than 54 Gt/yr in all four ice sheet regions. The largest spread among the individual
543 values occurs in the EAIS. Other than this sector, all of the individual estimates lie close to the
544 ensemble average, considering the respective uncertainty of the measurements.

545 [Input-Output Method Intra-comparison](#)

546 Although the input-output method is a most direct measure of changing in mass fluxes, a main
547 difficulty is that it must differ two large numbers - one for annual SMB and the other for discharge
548 plus grounding line migrations - *and* deal appropriately with the error budgets of both, in order to
549 assess mass balance. A consequence of this complexity is that few input-output method data sets exist
550 at the ice sheet scale. In this assessment, we collate just two input-output data sets, both based on
551 the same method ⁸⁰ - far fewer than were considered for altimetry and gravimetry. The first input-
552 output method dataset spans the period 1992 to 2010 ¹⁸. The second input-output method dataset is
553 limited to the period 2002 to 2016. The same SMB model was used in both assessments - RACMO2.3.

554 Further details of the input-output method data sets and methods are included in Supplementary
555 Information Table 1.

556 We compared the two input-output method data sets during the period 2002 to 2010 when they
557 overlap (Extended Data Table 3). The smallest differences (up to 30 Gt/yr) arise in the APIS and the
558 WAIS, and the largest differences (up to 70 Gt/yr) occur at the EAIS. In all cases, the average difference
559 between estimates of mass balance derived from each dataset is comparable to the estimated
560 certainty. Including both datasets, rates of mass balance over the period 1992 to 2016 for the APIS,
561 WAIS and EAIS fall in the range -125 to +25 Gt/yr, -300 to +100 Gt/yr and -200 to +200 Gt/yr,
562 respectively (Extended Data Figure 5). The origin of the differences between the two datasets requires
563 further investigation.

564 [Ice Sheet Mass Balance Inter-comparison](#)

565 To assess the degree to which the satellite techniques concur, we used the aggregated time series
566 emerging from each geodetic technique experiment group to compute changes in ice sheet mass
567 balance within common geographical regions and over a common interval of time (the overlap
568 period). The aggregated time series were calculated as the arithmetic mean of all available rates of ice
569 sheet mass balance derived from the same satellite technique at each available epoch. We used the
570 individual ice sheets and their integrals as common geographical regions. The maximum duration of
571 the overlap period is limited to the 14-year interval when all three satellite techniques were optimally
572 operational, namely 2002 to 2016. However, we also considered the availability of mass balance data
573 sets, which leads us to select the period 2003 to 2010 as the optimal interval (see Figure 1). When the
574 aggregated mass balance data emerging from all three experiment groups are degraded to a common
575 temporal resolution of 36 months, the time-series are on average well correlated ($0.5 < r^2 < 0.9$) at the
576 APIS and WAIS. At the EAIS, however, the aggregated altimetry mass balance time series are poorly
577 correlated ($r^2 < 0.1$) in time with the aggregated gravimetry and input-output method data. Possible
578 explanations for this include the relatively high short-term variability in mass fluctuations in this

579 region, the relatively low trend in mass, and the heterogeneous temporal resolution of the aggregated
580 altimetry data set. Over longer periods, marked increases in the rate of mass loss from the WAIS are
581 also recorded in all three satellite data sets.

582 Because the comparison period is long in relation to the timescales over which surface mass balance
583 fluctuations typically occur, their potential impact on the overall inter-comparison is reduced. The
584 closest agreement between individual estimates of ice sheet mass balance occurs at the APIS and the
585 WAIS, where the standard deviation across all techniques falls between 15 and 41 Gt/yr (Extended
586 Data Table 4). The greatest departure occurs at the EAIS, where the input-output method and
587 gravimetry estimates of mass balance differ by ~ 80 Gt/yr, and where the standard deviation of all
588 three estimates is ~ 40 Gt/yr. This high degree of variance is expected due to the relatively large size
589 of the region, small amplitude of signals and poor independent controls on coastal SMB. When
590 compared to the mean, there are no significant differences between estimates of ice sheet mass
591 balance determined from the individual satellite techniques and, in contrast to the first assessment,
592 this finding also holds at continental and global scale. We conclude, therefore, that estimates of mass
593 balance determined from independent geodetic techniques agree when compared to their respective
594 uncertainties.

595 Several noteworthy patterns in the distribution of mass balance estimates determined during the
596 overlap period (2003 to 2010) merit further discussion. Estimates of mass balance derived from
597 satellite altimetry and gravimetry are agree to within 15 Gt/yr, on average, and with the mean of all
598 three techniques, in all ice sheet regions. In contrast, estimates of mass balance determined from the
599 input-output method are 55 Gt/yr more negative, on average, than the mean in all ice sheet regions.
600 However, despite the bias, the input-output method estimates remain in agreement because their
601 estimated uncertainty is relatively large (approximately three times larger than that of the other
602 techniques). A more detailed analysis of the primary and ancillary datasets is required to establish
603 whether this bias is significant or systematic.

604 Ice Sheet Mass Balance Integration

605 We combined estimates of ice-sheet mass balance derived from each geodetic technique experiment
606 group to produce a single, *reconciled* assessment, following the same approach as the first assessment
607 exercise. This was computed as the arithmetic mean of the average rates of mass change derived from
608 each experiment group, within the regions of interest and at the time periods for which the
609 experiment group mass trends were determined. We estimated the uncertainty of the mass balance
610 data using the following approach. Within each experiment group, the uncertainty of mass trends was
611 estimated as the average of the errors associated with each individual estimate. The uncertainty of
612 *reconciled* rates of mass change (e.g. Table 1) was estimated as the root mean square of the
613 uncertainties associated with mass trends emerging from each experiment group. When summing
614 mass trends of multiple ice sheets, the combined uncertainty was estimated as the root sum square
615 of the uncertainties for each region. Finally, to estimate the cumulative uncertainty of mass changes
616 over time, we weighted the annual uncertainty by $1/\sqrt{n}$, where n is the number of years elapsed
617 relative to the start of each time series, and then summed the weighted annual uncertainties over
618 time ⁸¹.

619 Across the full 25-year survey, the average rates of mass balance of the AIS was -109 ± 56 (Table 1).
620 To investigate inter-annual variability, we also calculated mass trends during successive 5-year
621 intervals. While the APIS and WAIS each lost mass throughout the entire survey period, the EAIS
622 experienced alternate periods of mass loss and mass gain, likely driven by inter-annual fluctuations in
623 SMB. The rate of mass loss from the WAIS has increased over time due to accelerated ice discharge in
624 the Amundsen Sea sector ^{34,48,74,82-84}. The most significant rise – a twofold increase in the rate of ice
625 loss - occurred between the periods 2002-2007 and 2007-2012 (Table 1). Overall, the WAIS accounts
626 for the vast majority of ice mass losses from Antarctica. At the APIS, rates of ice mass loss since the
627 early 2000's are notably higher than during the previous decade, consistent with observations of
628 surface lowering ^{72,74} and increased ice flow in southerly glacier catchments ⁸⁵. The approximate state

629 of balance of the wider EAIS suggests that the reported dynamic thinning of the Totten and Cook
630 glaciers^{86,87} has been offset by accumulation gains elsewhere⁸⁸.

631 [Methods References](#)

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723 [Data Availability](#)

724 [The final mass balance datasets generated in this study are freely available at www.imbie.org.](http://www.imbie.org)

725 [Extended Data Legends](#)

726 **Extended Data Figure 1 | Ice sheet mass balance data sets included in this assessment.** Some data
727 sets did not encompass all three ice sheets.

728 **Extended Data Figure 2 | Ice sheet drainage basins.** Antarctic ice sheet drainage basins according to
729 the definitions of Zwally³ (top) and Rignot^{2,20} (bottom). Basins falling within the Antarctic Peninsula,
730 West Antarctica, and East Antarctica are shown in green, pink and blue, respectively. For the Zwally
731 definition, the Antarctic Peninsula, West Antarctica, and East Antarctica basins cover areas of 227 725
732 km², 1 748 200 km² and 9 909 800 km², respectively. For the Rignot definition, the Antarctic Peninsula,
733 West Antarctica, and East Antarctica basins cover areas of 232 950 km², 2 039 525 km² and 9 620 225
734 km², respectively.

735 **Extended Data Table 1 | Spatially-averaged Antarctic ice sheet surface mass balance.** Estimates of
736 the average surface mass balance (SMB) over the period 1980 to 2012 were derived from regional
737 climate models (RCM) and global reanalyses (GCM). Data were evaluated using the Rignot drainage
738 basins^{2,20}.

739 **Extended Data Figure 3 | Temporal variations in Antarctic ice sheet surface mass balance.** Time
740 series of integrated surface mass balance in Antarctic ice sheet drainage regions (Rignot et al., 2011a,
741 2011b) from the MAR (blue) and RACMO2.3p (red) models.

742 **Extended Data Figure 4 | Modeled glacial isostatic adjustment beneath the Antarctic Ice Sheet.**
743 Bedrock uplift rates in Antarctica averaged over the GIA model solutions submitted to the second
744 IMBIE assessment (a), as well as their respective standard deviation (b).

745 **Extended Data Table 2 | Glacial Isostatic Adjustment model details.** Regional changes in mass
746 associated with the glacial isostatic adjustment signal were determined from the model data ([†]) or
747 calculated as an indicative rate using degrees 3-90 ([‡]).

748 ^a Main publication listed, in all cases additional supporting publications should be acknowledged in supp. info.

749 ^b Own model if not otherwise stated. Comma-separated values refer to properties of radially-varying (1D) Earth model: first
750 value is lithosphere thickness (km), other values reflect mantle viscosity ($\times 10^{21}$ Pa s) for specific layers – see relevant
751 publications for details

752 ^c Ice model covers at least Last Glacial Maximum to present, unless indicated

753 ^d GIA model details: SH=spherical harmonic (maximum degree indicated), FE=finite element, C=compressible,
754 IC=incompressible, RF=rotational feedback, SG=self-gravitation, OL=ocean loading, 'x' = feature not included,
755 UQ=uncertainty quantified

756 ^e RSL = relative sea-level data; GPS rates all corrected for elastic response to contemporary ice mass change

757 ^f Different to ICE-6G_C in Antarctica, due to use of BEDMAP2 ¹ topography in that region

758 ^g Model relates to GIA in the northern Antarctic Peninsula only

759 ^h Model relates to GIA in the Amundsen Sea Embayment only

760 ⁱ 25

761 ^j 89

762 ^k 90

763 **Extended Data Figure 5 | Individual rates of ice sheet mass balance.** Mass balance estimates were
764 determined from satellite altimetry (left), gravimetry (centre), and the input-output method (right) in
765 the Antarctic Peninsula (top), East Antarctica (middle) and West Antarctica (bottom). The ensemble
766 average is shown as a dashed black line, with the estimates one sigma uncertainty as light grey
767 shading. Also shown is the standard error of the mean solutions, per epoch (dary grey).

768 **Extended Data Table 3 | Features of mass balance data sets included in this study.** Details shown
769 include their maximum span and ranges of temporal sampling, amplitude, estimated error, and
770 standard deviation at each epoch.

771 **Extended Data Table 4 | Aggregated estimates of ice sheet mass balance determined from satellite**
772 **altimetry, gravimetry, and input-output method.** In this comparison, the data were averaged over
773 the period 2003 to 2010. Also shown is the arithmetic mean of each individual result for given regions,

774 and the combined imbalance of the AIS, calculated as the sum of estimates from the constituent
775 regions.

776 [Extended data references](#)

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