

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

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

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

51 such estimates ¹⁸, demonstrated that the three principal satellite techniques provide similar results
52 at the continental scale and, when combined, lead to an estimated mass loss of 71 ± 53 Gt of ice per
53 year averaged over the period 1992 to 2011. Here, we extend this assessment to include twice as
54 many studies, doubling the overlap period and extending the record through to 2017.

55 We collated 24 independently-derived estimates of ice sheet mass balance (Figure 1) determined
56 within the period 1992 to 2017 and based upon the techniques of satellite altimetry (7 estimates),
57 gravimetry (15 estimates) or the input-output method (2 estimates). Altogether, there were 24, 24,
58 and 23 individual estimates of mass change computed within defined geographical limits ^{19,20} for the
59 East Antarctic, West Antarctic and the Antarctic Peninsula ice sheets, respectively. Rates of ice sheet
60 mass change were compared (see Methods) over common intervals of time ¹⁸. We then averaged
61 rates of ice sheet mass balance based on the same class of satellite observations to produce three
62 technique-dependent time series of mass change in each geographical region (see Methods). Within
63 each class, the annual mass rate uncertainty was computed as the mean uncertainty of the
64 individual contributions. The final, reconciled estimate of ice sheet mass change for each region was
65 computed as the mean of the technique-dependent values available at each epoch (Figure 1). In
66 computing the associated uncertainty, we assumed that the errors for each technique are
67 independent. To estimate the cumulative mass change and its uncertainty (Figure 2), we integrated
68 the reconciled estimates for each ice sheet and weighted the annual uncertainty by $1/\sqrt{n}$, where n is
69 the number of years elapsed relative to the start of each time series. Antarctic ice sheet mass trends
70 and their uncertainties (Table 1) were computed as the linear sum and root sum square of the
71 regional trends and their uncertainties, respectively.

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

76 aligned, though their spread increases in East Antarctica where glacial isostatic adjustment remains
77 poorly constrained ²¹ and is least certain when spatially integrated ²²⁻³³ due to the region's vast
78 extent. Solutions based on satellite altimetry and the input-output method run for the entire record,
79 roughly twice the duration of the gravimetry time series. Although most (59 %) estimates fall within
80 one standard deviation of the technique-dependent mean, a few (6 %) depart by more than three.
81 At the Antarctic Peninsula, the 25-year average rate of ice sheet mass balance is -20 ± 15 Gt/yr, with
82 a ~ 15 Gt/yr increase in losses since 2000. The strongest signal and trend has occurred in West
83 Antarctica, where rates of mass loss rise from 53 ± 29 Gt/yr to 159 ± 26 Gt/yr between the first and
84 final 5 years of our survey, with the largest increase occurring during the late 2000's when ice
85 discharge from the Amundsen Sea sector accelerated ³⁴. Both of these regional losses are driven by
86 reductions in the thickness and extent of floating ice shelves, which has triggering retreat,
87 acceleration, and drawdown of marine terminating glaciers ³⁵. The least certain result is in East
88 Antarctica, where the average 25-year mass trend is 5 ± 46 Gt/yr. Overall, the Antarctic ice sheet lost
89 2720 ± 1390 Gt of ice between 1992 and 2017, an average rate of 109 ± 56 Gt/yr.

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

102 and East Antarctica, respectively (Extended Data Figure 2 and Extended Data Figure 3). Compared to
103 the all-model average surface mass balance of 1994 Gt/yr, the regional climate models have 4.7%
104 higher and the reanalyses 7% lower values. These differences can be attributed to the higher
105 resolution of the regional models, which resolve the steep coastal precipitation gradients in greater
106 detail, and also their improved representation of polar processes. The temporal variability of all
107 products is similar, and they all agree on the absence of an ice sheet wide trend in surface mass
108 balance over the period 1979 to 2017, implying that recent Antarctic ice sheet mass loss is
109 dominated by increased solid ice discharge into the ocean.

110 Gravimetric estimates of mass change are strongly influenced by the method used to correct for
111 glacial isostatic adjustment (GIA)¹⁶. In this study, six different GIA models were used for this purpose
112 ^{22,25,27,31,32,44}. We also assessed nine continent-wide forward-model and two regional model
113 simulations to better understand uncertainties in the GIA signal itself, and we reprocessed the
114 gravimetry estimates of mass balance using just the W12a ²⁷ and IJ05_R2 ³² GIA models for
115 comparison with earlier work¹⁸ (see Methods). The net gravitational effect of GIA across Antarctica is
116 positive, and the mean and standard deviation of the continent-wide GIA models (54 ± 18 Gt/yr) is
117 very close to that of W12a (56 ± 27 Gt/yr) and IJ05_R2 (55 ± 13 Gt/yr). The narrow spread likely
118 reflects the difficulty of quantifying the timing and extent of past ice sheet change, and the absence
119 of lateral variations in Earth rheology within some models ⁴⁵. In areas where GIA is a significant
120 component of the regional mass change, such as the Amundsen, Ross and Filchner-Ronne sectors of
121 West Antarctica (see Extended Data Figure 4), models predict the greatest uplift rates (5 to 7 mm/yr
122 on average) but also the greatest variability (e.g. standard deviation > 10 mm/yr in the Amundsen
123 sector). Away from areas with large GIA signals there is low variance among the models and broad
124 agreement with GPS observations ⁴⁶. Nevertheless, most models considered here do not account for
125 ice sheet change during the last few millennia, because it is poorly known. Inaccurate treatment of
126 low degree harmonics associated with the global GIA signal can also bias gravimetric mass balance

127 calculations⁴⁷. If the GIA signal includes a transient component associated with recent ice sheet
128 change this will bias mass trend estimates and should be accounted for in future work.

129 Improvements in ice sheet mass balance assessments are still possible. Airborne snow radar^{48,49} is a
130 powerful tool for evaluating surface mass balance and firn compaction models over large spatial
131 (1000's of km) and temporal (centennial) scales, in addition to the ice cores that have been
132 traditionally used⁵⁰. Geological constraints on the ice sheet history²¹ and GPS measurements of
133 contemporary uplift^{46,51} allow GIA models to be scrutinised and calibrated. More of both these data
134 sets are needed, especially in East Antarctica. Given their apparent diversity, the spread of GIA and
135 surface mass balance models should be evaluated in concert with the satellite gravimetry, altimetry,
136 and velocity measurements. A reassessment of satellite measurements acquired during the 1990s
137 would address the imbalance that is present in the current record. Alternative techniques (e.g.⁵²) for
138 the combination of satellite data sets should be explored, and satellite measurements with common
139 temporal sampling should be contrasted. The ice sheet mass balance record should now be
140 separated into the contributions due to short-term fluctuations in surface mass balance and longer-
141 term trends in glacier ice. In addition to these obvious improvements, continued satellite
142 observations are, of course, essential.

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275

276 [Supplementary Information](#)

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

279

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283

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285 Andrew Shepherd and Erik Ivins designed and led the study. Eric Rignot, Ben Smith, Michiel van den
286 Broeke, Isabella Velicogna, and Pippa Whitehouse led the input-output, altimetry, surface mass
287 balance, gravimetry, and glacial isostatic adjustment experiments, respectively. Gorka Moyano and
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292 Pippa Whitehouse wrote and edited the manuscript. All authors participated in the data
293 interpretation and commented on the manuscript.

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297 no competing interests. Correspondence and requests for materials should be addressed to
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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.

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

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

309

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

313

314 [Methods](#)

315 [Data](#)

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

329 Drainage Basins

330 In this assessment, we analyse mass trends using two sets of ice sheet drainage basin (Extended
331 Data Figure 2), to ensure consistency with those used in the first IMBIE assessment ¹⁸, and to
332 evaluate an updated definition tailored towards input-output method assessments. The first
333 drainage basin set was delineated using surface elevation maps derived from ICESat-1 based on the
334 provenance of the ice, and includes 27 basins ³. The second set are updated to consider other factors
335 such as the direction of ice flow, and include 18 basins in Antarctica ^{2,20}. To assess the effect of the
336 different basin outline sets on the estimates of ice sheet mass balance, we compared mass balance
337 determinations between the two delineations of ice sheet drainage basins. This evaluation was
338 facilitated by seven estimates (altimetry or gravimetry) determined using both drainage basin sets.
339 At the scale of the major ice sheet divisions, the delineations produce similar total extents. By far the
340 largest differences occur in the delineation (or definition) of East and West Antarctica, due to
341 differences in the position of the ice divide separating them. Within these regions, the root mean-
342 square difference between 26 pairs of ice sheet mass balance estimates computed using the two
343 drainage basin sets is 8.7 Gt/yr. This difference is small in comparison to the certainty of individual
344 ice sheet mass balance assessments.

345 Computing Rates of Mass Change

346 The raw satellite mass balance data are either time-series of either relative mass change, $\Delta M(t)$, or
347 the rate of mass change, $dM(t)/dt$, plus their associated uncertainty, integrated over at least one of
348 the ice sheet regions defined in the standard drainage basin sets. In the case of $\Delta M(t)$, the time
349 series represents the change in mass through time relative to some nominal reference value. The
350 duration and sampling frequency of the time-series was not restricted. In practice, few mass time-
351 series were of $\Delta M(t)$ *and* $dM(t)/dt$. Because the inter-comparison exercise is based on comparing
352 and aggregating rates of mass change, $dM(t)/dt$, a common solution was implemented to derive
353 $dM(t)/dt$ values from data sets that comprised $\Delta M(t)$ only. Each $\Delta M(t)$ time series was used to

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

367 Surface Mass Balance

368 Ice sheet surface mass balance (SMB) comprises a variety of processes governed by the interaction
369 of the superficial snow and firn layer with the atmosphere. A direct mass exchange occurs via
370 precipitation and surface sublimation. Snow drift and the formation of meltwater and its subsequent
371 refreezing or retention redistribute mass spatially or lead to further mass loss via erosion and
372 sublimation, or runoff. In this assessment, a range of SMB products are compared. Four SMB model
373 solutions were considered for Antarctica (Extended Data Table 1); two regional models - RACMO2.3
374 ⁴¹ and MARv3.6 ⁵³ - and two global reanalysis products - JRA55 ⁵⁴ and ERA-Interim ⁵⁵. The two
375 regional climate models agree well in terms of their spatially integrated SMB, apart from the
376 Peninsula where there is an offset of about 10 Gt/month between them (Extended Data Figure 3).
377 However, the reanalysis data underestimated the average SMB compared to the regional climate
378 models by 200 to 350 Gt/yr. The SMB assessment illustrates that products of similar class (climate

379 models, reanalysis product) agree well, suggesting that groupings of their output may be
380 appropriate. Model resolution is, however, found to be an important factor when estimating SMB
381 and its components, as respective contributions where only the spatial resolution differed yield
382 regional differences.

383 [Glacial Isostatic Adjustment](#)

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

394 In the present analysis, the degree of similarity between the various GIA model solutions is assessed.
395 Areas of enhanced present-day vertical surface motion and (dis-)agreement between contributions
396 have been identified by averaging the uplift rates over the contributions and computing respective
397 standard deviations (Extended Data Figure 4). In some cases, it was necessary to estimate the GIA
398 contribution to gravimetric mass trends; this was done using common geographical masks and
399 truncation, and a standardized treatment of low degree harmonics. In Antarctica, the Amundsen Sea
400 sector and the regions covered by the Ross and Filchner Ronne Ice Shelves stand out as having both
401 high uplift rates (5-7 mm/yr on average) and high variability in uplift rates (peaking at >10 mm/yr
402 standard deviation in the Amundsen sector) among the models considered. Elsewhere in coastal
403 regions, uplift occurs at more moderate rates (~2 mm/yr on average), and the interior of East

404 Antarctica exhibits slow subsidence. In these regions, the average signal is accompanied by relatively
405 low variance among the GIA models (0-1.5 mm/yr standard deviation). None of the models fully
406 capture portions of the uplift that are observed to be very large (e.g. ⁵⁶), hence, we can anticipate a
407 bias toward low values for the GIA correction averaged over such regions. In areas of low mantle
408 viscosity, however, such as part of the WAIS, the LGM-related GIA signal may be over-predicted, and
409 it is not clear whether a bias exists at the continental scale.

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

430 accurate a representation of GIA in that region as is possible. However, it remains a difficult and
431 important challenge to incorporate these regional studies into a global framework. Finally, although
432 four of the considered GIA models do provide a measure of uncertainty, and a number of studies
433 have used an ensemble modelling approach ^{24,30}, an important future goal for the GIA modelling
434 community is the inclusion of robust error estimates for all model predictions.

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

454 Mass Balance Intra-comparison

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

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

480 Gravimetry Mass Balance Intra-comparison

481 Within the gravimetry experiment group, 15 estimates of mass balance derived from the GRACE
482 satellites were assessed, in entirety spanning the period July 2002 to September 2016. Of these
483 datasets, four (Luthcke, Moore, Save, Wiese) are derived with direct imposition of the GRACE Level-1
484 K-band range-data ⁵⁷⁻⁶⁰. These impositions result in 4 different, and quite independently derived,
485 mascon approaches. Other methods often refer to 'mascon analysis', but are conducted on post-
486 spherical harmonic (post-SH) expansions and without imposing the Level 1 K-band range data. We
487 distinguish the later methods, referring to them as 'post-SH mascons'. Eleven contributions are
488 derived from monthly spherical harmonic solutions of the global gravity field using somewhat
489 different approaches ⁶¹⁻⁶⁷, which can be loosely classified as region integration approaches for 3
490 contributions (Blazquez, Groh, Horvath), post-SH mascon approaches for 4 contributions (Bonin,
491 Forsberg, Schrama, Velicogna). Forward-modelling is also an approach used in two contributions
492 (Wouters, Seo) and this essentially involves modelling of mass change with iterative comparison to
493 the GRACE-derived signal. One estimate (Harig) uses Slepian functions ⁶⁸. One estimate (Rietbroek)
494 uses a hybrid approach involving satellite altimetry that does not fall within the above categories ⁶⁹;
495 although these results are excluded from our gravimetry-only average, we present them alongside
496 the gravimetry-only results for comparison. No restrictions were imposed on the choice of glacial
497 isostatic adjustment correction, and among the GRACE solutions we consider six different models
498 were used for this purpose ^{22,25,27,31,32,44}. We did, however, assess a wider set of nine continent-wide
499 forward models and two regional models to better understand uncertainties in the GIA signal itself.

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

505 Extended Data Figure 5 shows a comparison of rates of mass change obtained from all gravimetry
506 mass balance solutions, calculated over the three main ice sheet regions. At individual epochs,
507 differences between time-varying rates of mass change are generally smaller than 50 Gt/yr in each
508 ice sheet region, and typically fall in the range 10 to 20 Gt/yr. Over the full period of the data,
509 individual rates of mass balance for the APIS, WAIS, and EAIS vary between -80 to +10, -260 to -20,
510 and -120 to +200 Gt/yr, respectively. Considering all of the gravimetry data (Extended Data Table 3);
511 the standard deviation of mass trends estimated during the period 2005 to 2015 is less than 24 Gt/yr
512 in all three ice sheet regions, with the largest spread occurring in the EAIS. In all three ice sheet
513 regions, the spread of individual mass balance estimates is well represented by the mean
514 considering the uncertainties of the individual and aggregated datasets.

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

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

528 With a few exceptions, rates of mass change determined from radar and laser altimetry tend to
529 differ by less than 100 Gt/yr at all times in each ice sheet region (Extended Data Figure 5). The main

530 exceptions are in the EAIS, where one estimate (Zwally) reports mass trends that are ~100 Gt/yr
531 more positive than all others during the ERS and ICESat periods and the WAIS, where two estimates
532 (Zwally and Helm) report rates that are ~70 Gt/yr less negative than the others during the ICESat
533 period. Among the remaining data sets, the closest agreement occurs at the APIS, where mass
534 trends agree to within 30 Gt/yr at all times, and the poorest agreement occurs at the EAIS, where
535 mass trends depart by up to 100 Gt/yr. The largest differences are among datasets that are constant
536 in time during periods where rapid changes in mass balance occur in the annually resolved time
537 series, suggesting that a proportion of the difference is due to their poor temporal resolution. Mass
538 balance solutions from the relatively short (six-year) ICESat mission also appear to show larger
539 spreads compared to those determined from longer (decade-scale) radar-altimetry missions. This
540 larger spread is due in part to differences in the bias-correction models applied to ICESat data^{75,77-79}
541 and in part to the large influence of firn densification on altimetry measurements over short periods,
542 which have been corrected for using different models. Firn-densification models are generally not
543 applied to mass balance solutions determined from radar altimetry. Further analysis of the
544 corrections for bias between ICESat campaigns and firn compaction is required to establish the
545 significance of the differences and to reduce their collective uncertainty. Comparing rates of mass
546 change (Extended Data Table 3), the average standard deviation of all mass trends at each epoch
547 over the common period 2005 to 2015 is less than 54 Gt/yr in all four ice sheet regions. The largest
548 spread among the individual values occurs in the EAIS. Other than this sector, all of the individual
549 estimates lie close to the ensemble average, considering the respective uncertainty of the
550 measurements.

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

552 Although the input-output method is a most direct measure of changing in mass fluxes, a main
553 difficulty is that it must differ two large numbers - one for annual SMB and the other for discharge
554 plus grounding line migrations - *and* deal appropriately with the error budgets of both, in order to
555 assess mass balance. A consequence of this complexity is that few input-output method data sets

556 exist at the ice sheet scale. In this assessment, we collate just two input-output data sets, both based
557 on the same method⁸⁰ - far fewer than were considered for altimetry and gravimetry. The first
558 input-output method dataset spans the period 1992 to 2010¹⁸. The second input-output method
559 dataset is limited to the period 2002 to 2016. The same SMB model was used in both assessments -
560 RACMO2.3. Further details of the input-output method data sets and methods are included in
561 Supplementary Information Table 1.

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

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

571 To assess the degree to which the satellite techniques concur, we used the aggregated time series
572 emerging from each geodetic technique experiment group to compute changes in ice sheet mass
573 balance within common geographical regions and over a common interval of time (the overlap
574 period). The aggregated time series were calculated as the arithmetic mean of all available rates of
575 ice sheet mass balance derived from the same satellite technique at each available epoch. We used
576 the individual ice sheets and their integrals as common geographical regions. The maximum duration
577 of the overlap period is limited to the 14-year interval when all three satellite techniques were
578 optimally operational, namely 2002 to 2016. However, we also considered the availability of mass
579 balance data sets, which leads us to select the period 2003 to 2010 as the optimal interval (see
580 Figure 1). When the aggregated mass balance data emerging from all three experiment groups are

581 degraded to a common temporal resolution of 36 months, the time-series are on average well
582 correlated ($0.5 < r^2 < 0.9$) at the APIS and WAIS. At the EAIS, however, the aggregated altimetry mass
583 balance time series are poorly correlated ($r^2 < 0.1$) in time with the aggregated gravimetry and input-
584 output method data. Possible explanations for this include the relatively high short-term variability
585 in mass fluctuations in this region, the relatively low trend in mass, and the heterogeneous temporal
586 resolution of the aggregated altimetry data set. Over longer periods, marked increases in the rate of
587 mass loss from the WAIS are also recorded in all three satellite data sets.

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

601 Several noteworthy patterns in the distribution of mass balance estimates determined during the
602 overlap period (2003 to 2010) merit further discussion. Estimates of mass balance derived from
603 satellite altimetry and gravimetry are agree to within 15 Gt/yr, on average, and with the mean of all
604 three techniques, in all ice sheet regions. In contrast, estimates of mass balance determined from
605 the input-output method are 55 Gt/yr more negative, on average, than the mean in all ice sheet

606 regions. However, despite the bias, the input-output method estimates remain in agreement
607 because their estimated uncertainty is relatively large (approximately three times larger than that of
608 the other techniques). A more detailed analysis of the primary and ancillary datasets is required to
609 establish whether this bias is significant or systematic.

610 Ice Sheet Mass Balance Integration

611 We combined estimates of ice-sheet mass balance derived from each geodetic technique
612 experiment group to produce a single, *reconciled* assessment, following the same approach as the
613 first assessment exercise. This was computed as the arithmetic mean of the average rates of mass
614 change derived from each experiment group, within the regions of interest and at the time periods
615 for which the experiment group mass trends were determined. We estimated the uncertainty of the
616 mass balance data using the following approach. Within each experiment group, the uncertainty of
617 mass trends was estimated as the average of the errors associated with each individual estimate.
618 The uncertainty of *reconciled* rates of mass change (e.g. Table 1) was estimated as the root mean
619 square of the uncertainties associated with mass trends emerging from each experiment group.
620 When summing mass trends of multiple ice sheets, the combined uncertainty was estimated as the
621 root sum square of the uncertainties for each region. Finally, to estimate the cumulative uncertainty
622 of mass changes over time, we weighted the annual uncertainty by $1/\sqrt{n}$, where n is the number of
623 years elapsed relative to the start of each time series, and then summed the weighted annual
624 uncertainties over time⁸¹.

625 Across the full 25-year survey, the average rates of mass balance of the AIS was -109 ± 56 (Table 1).
626 To investigate inter-annual variability, we also calculated mass trends during successive 5-year
627 intervals. While the APIS and WAIS each lost mass throughout the entire survey period, the EAIS
628 experienced alternate periods of mass loss and mass gain, likely driven by inter-annual fluctuations
629 in SMB. The rate of mass loss from the WAIS has increased over time due to accelerated ice
630 discharge in the Amundsen Sea sector^{34,48,74,82-84}. The most significant rise – a twofold increase in the

631 rate of ice loss - occurred between the periods 2002-2007 and 2007-2012 (Table 1). Overall, the
632 WAIS accounts for the vast majority of ice mass losses from Antarctica. At the APIS, rates of ice mass
633 loss since the early 2000's are notably higher than during the previous decade, consistent with
634 observations of surface lowering^{72,74} and increased ice flow in southerly glacier catchments⁸⁵. The
635 approximate state of balance of the wider EAIS suggests that the reported dynamic thinning of the
636 Totten and Cook glaciers^{86,87} has been offset by accumulation gains elsewhere⁸⁸.

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731 [Data Availability](#)

732 The final mass balance datasets generated in this study are freely available at www.imbie.org.

733 [Extended Data Legends](#)

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

736 **Extended Data Figure 2 | Ice sheet drainage basins.** Antarctic ice sheet drainage basins according to
737 the definitions of Zwally³ (top) and Rignot^{2,20} (bottom). Basins falling within the Antarctic Peninsula,
738 West Antarctica, and East Antarctica are shown in green, pink and blue, respectively. For the Zwally
739 definition, the Antarctic Peninsula, West Antarctica, and East Antarctica basins cover areas of 227
740 725 km², 1 748 200 km² and 9 909 800 km², respectively. For the Rignot definition, the Antarctic
741 Peninsula, West Antarctica, and East Antarctica basins cover areas of 232 950 km², 2 039 525 km²
742 and 9 620 225 km², respectively.

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

747 **Extended Data Figure 3 | Temporal variations in Antarctic ice sheet surface mass balance.** Time
748 series of integrated surface mass balance in Antarctic ice sheet drainage regions (Rignot et al.,
749 2011a, 2011b) from the MAR (blue) and RACMO2.3p (red) models.

750 **Extended Data Figure 4 | Modeled glacial isostatic adjustment beneath the Antarctic Ice Sheet.**

751 Bedrock uplift rates in Antarctica averaged over the GIA model solutions submitted to the second
752 IMBIE assessment (a), as well as their respective standard deviation (b).

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

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

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

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

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

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

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

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

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

768 ⁱ 25

769 ^j 89

770 ^k 90

771 **Extended Data Figure 5 | Individual rates of ice sheet mass balance.** Mass balance estimates were
772 determined from satellite altimetry (left), gravimetry (centre), and the input-output method (right)
773 in the Antarctic Peninsula (top), East Antarctica (middle) and West Antarctica (bottom). The

774 ensemble average is shown as a dashed black line, with the estimates one sigma uncertainty as light
775 grey shading. Also shown is the standard error of the mean solutions, per epoch (dary grey).

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

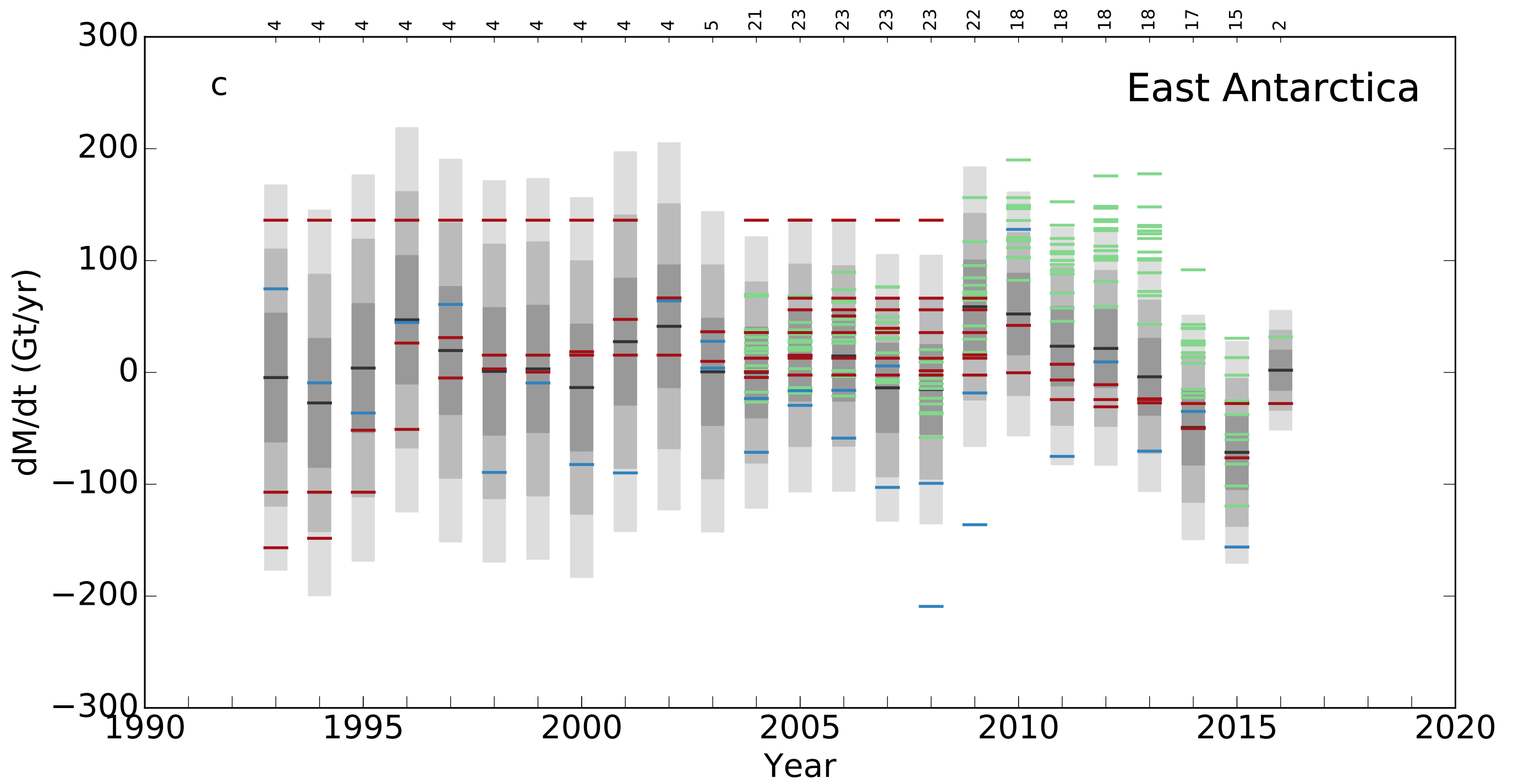
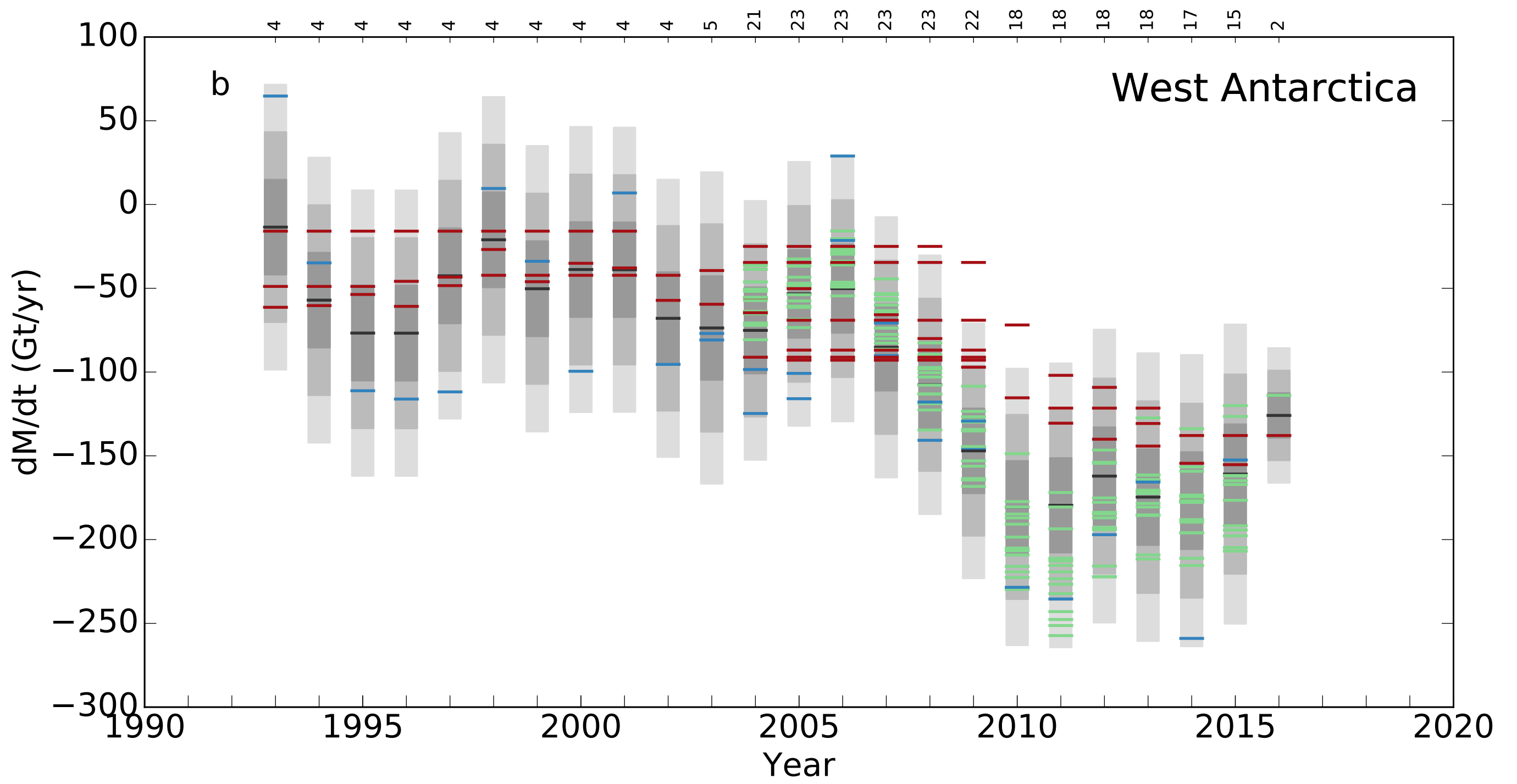
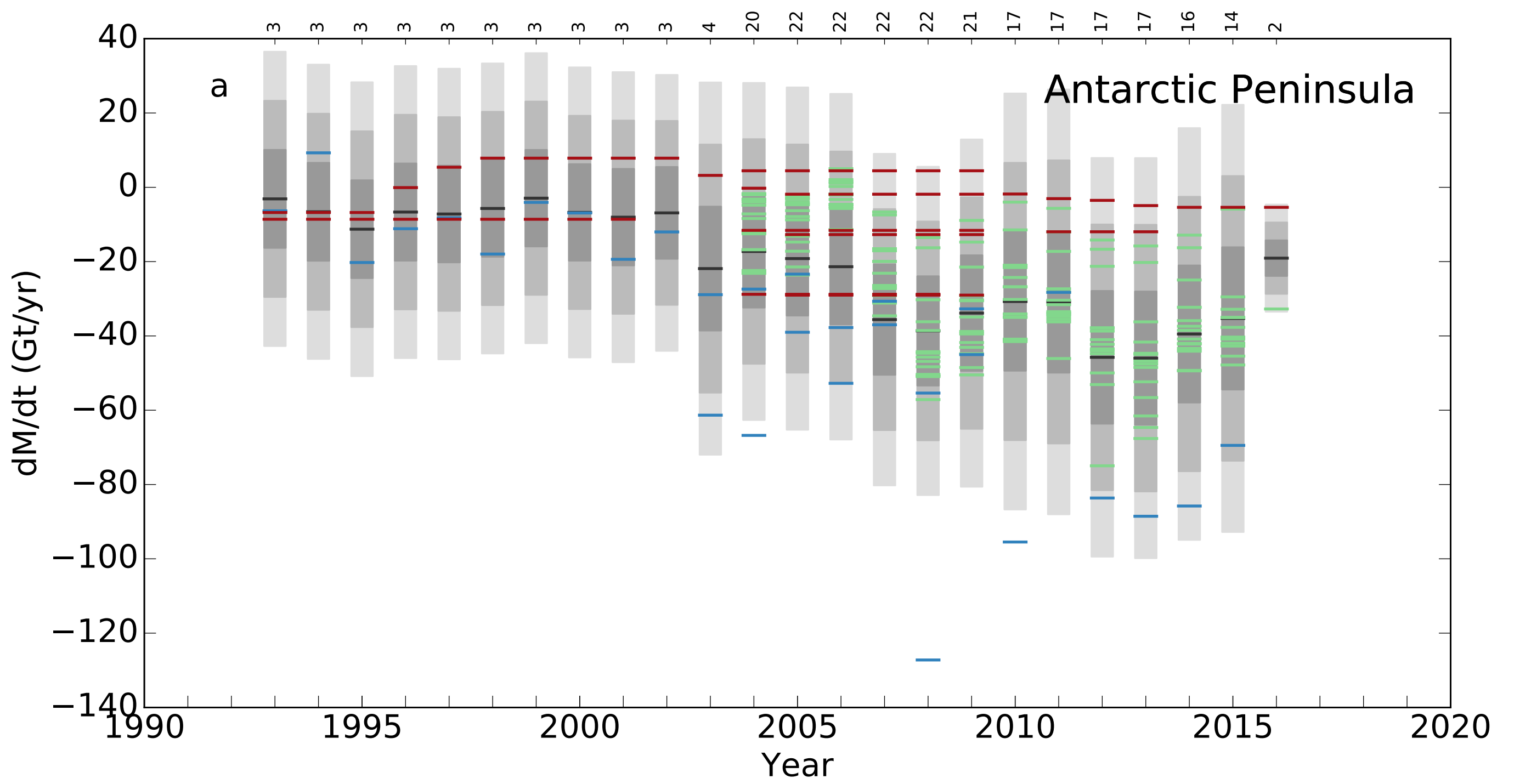
779 **Extended Data Table 4 | Aggregated estimates of ice sheet mass balance determined from satellite**
780 **altimetry, gravimetry, and input-output method.** In this comparison, the data were averaged over
781 the period 2003 to 2010. Also shown is the arithmetic mean of each individual result for given
782 regions, and the combined imbalance of the AIS, calculated as the sum of estimates from the
783 constituent regions.

784 [Extended data references](#)

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Antarctica

