Mass balance of the Antarctic ice sheet, 1992-2017

The IMBIE team

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Trends in the mass of the Antarctic ice sheet are an important indicator of global climate change and driver of sea level rise [1]. Here, we combine 24 individual estimates of the ice sheet mass balance determined from satellite observations of its changing volume, flow, and gravitational attraction and surface mass balance modelling. Between 1992 and 2017, the Antarctic ice sheet lost 2725 ± 1400 Gt of ice – a 7.6 ± 3.9 mm contribution to mean sea level. Ocean-driven melting in the Amundsen and Bellingshausen Seas [2] has caused rates of mass loss from the West Antarctic ice sheet to rise from 53 ± 29 Gt/yr in the 1990s to 159 ± 26 Gt/yr in the 2010s. Ice shelf collapse at the Antarctic Peninsula [3] has caused rates of mass loss from the inland ice to rise from 7 ± 13 Gt/yr in

the 1990s to 33 ± 16 Gt/yr in the 2010s. For East Antarctica, we find relatively large variations in and among model estimates of surface mass balance [4] and glacial isostatic adjustment [5-16], partly due to its considerable extent, and this is reflected in its 25-year mass trend (5 ± 46 Gt/yr) which, though numerically close to a state of balance, is the least certain.

The Antarctic ice sheets hold enough water to raise global sea level by 58 metres [17]. They channel ice to the oceans through a network of glaciers and ice streams [18], each with a substantial inland catchment [19]. Fluctuations in the grounded ice sheet mass arise due to differences between net snow accumulation at the surface, meltwater runoff, and ice discharge into the ocean. In recent decades, reductions in the thickness [20] and extent [3] of floating ice shelves have disturbed inland ice flow, triggering retreat [21,22], acceleration [23,24], and drawdown [25,26] of many marine terminating ice streams. A variety of techniques have been developed to measure changes in ice sheet mass, based on satellite observations of their speed [27], volume [28], and gravitational attraction [29] combined with modelled surface mass balance [4] and glacial isostatic adjustment[30]. Since 1989, there have been more than 150 assessments of ice loss from Antarctica based on these approaches [31]. An inter-comparison of 12 such estimates [32], demonstrated that the three principal satellite techniques provide similar results at the continental scale and, when combined, lead to an estimated mass loss of 71 ± 53 Gt of ice per year averaged over the period 1992 to 2011. Here, we extend this assessment to include twice as many studies, doubling the overlap period and extending the record through to 2017.

We collated 24 independently-derived estimates of ice sheet mass balance determined within the period 1992 to 2017 and based upon the techniques of satellite altimetry (7 estimates), gravimetry (15 estimates) or the mass budget method (2 estimates). Altogether, there were 24, 24, and 23 individual estimates of mass change computed within defined geographical limits [33,34] for the East Antarctic, West Antarctic and the Antarctic Peninsula ice sheets, respectively. Rates of ice sheet mass change were compared (Figure 1 a to c) over common intervals of time [32]. We then averaged rates of ice sheet mass balance based on the same class of satellite observations to produce three technique-dependent time series of mass change in each geographical region. Within each class, the annual mass rate uncertainty was computed as the mean uncertainty of the individual contributions. The final, reconciled estimate of ice sheet mass change for each region was computed as the mean of the technique-dependent values available at each epoch. In computing the associated uncertainty, we assumed that the errors for each technique are independent. To estimate the cumulative mass change and its uncertainty (Figure 1d), we integrated the reconciled estimates for each ice sheet and weighted the annual uncertainty by $1/\sqrt{n}$, where n is the number of years elapsed relative to the start of each time series. Antarctic ice sheet mass trends and their uncertainties were computed as the linear sum and root sum square of the regional trends and their uncertainties, respectively.

The level of agreement between individual estimates of ice sheet mass balance increases with the area of each ice sheet region, with per-epoch standard deviations of 11, 21, and 37 Gt/yr at the Antarctic Peninsula, West Antarctica, and East Antarctica, respectively (Figure 1). Among the techniques, gravimetric estimates are the most abundant and also the most closely aligned, though their spread increases in East Antarctica where glacial isostatic adjustment remains poorly constrained [35] and is least certain when integrated [5-16] due to the region's vast extent. Solutions based on satellite altimetry and the mass budget method run for the entire record, twice the duration of the gravimetry time series. Although most (59 %) estimates fall within one standard deviation of the technique-dependent mean, a few (6 %) depart by more than three. At the Antarctic Peninsula, the 25-year average rate of ice sheet mass balance is -20 ± 15 Gt/yr, with a ~15 Gt/yr increase in losses since 2000. The strongest signal and trend has occurred in West Antarctica, where rates of mass loss rise progressively from 53 ± 29 Gt/yr to 159 ± 26 Gt/yr between the first and final 5 years of our survey. The least certain result is in East Antarctica, where the average 25-year mass trend is 5 ± 46 Gt/yr. Overall, the Antarctic ice sheet lost 2725 ± 1400 Gt of ice between 1992 and 2017.

Snowfall is a major driver of both temporal and spatial variability in Antarctic ice sheet mass [36,37]. Knowledge of the ice sheet surface mass balance is therefore an essential component of the mass budget method, which subtracts solid ice discharge from net snow accumulation, and also aids the interpretation of mass trends derived from satellite altimetry and gravimetry. Although locally important, spatially integrated sublimation and meltwater runoff are typically one to two orders of magnitude smaller, respectively. In the absence of observation-based maps, Antarctic ice sheet surface mass balance is usually taken from atmospheric models, evaluated with in-situ and remotely-sensed observations [4,38-41]. To assess Antarctic surface mass balance, we compared two global reanalysis products (JRA55 and ERA-Interim) and two regional climate models (RACMO2 and MARv3.6)(see Supplementary Materials). ERA-Interim is usually regarded as the best performing reanalysis product over Antarctica, albeit with a dry bias in the interior and overestimated rain fraction [40,42,43]. Compared to the all-model average surface mass balance of 1994 Gt/yr, the regional climate models have 4.7% higher and the reanalyses 7% lower values. These differences can be attributed to the higher resolution of the regional models, which resolve the steep coastal precipitation gradients in greater detail, and also their improved representation of polar processes. The temporal variability of all products is similar, and they all agree on the absence of an ice sheet wide trend in surface mass balance over the period 1979 to 2017, implying that recent Antarctic ice sheet mass loss is dominated by increased solid ice discharge into the ocean.

Gravimetric estimates of mass change are strongly influenced by the method used to correct for glacial isostatic adjustment (GIA)[30]. In this study, six different GIA models were used for this purpose [5,8,10,14,15,44]. We also assessed nine continent-wide forward-model and two regional model simulations to better understand uncertainties in the GIA signal itself, and we reprocessed the gravimetry estimates of mass balance using just the W12a [10] and IJ05_R2 [15] models for comparison with earlier work[32] (see Supplementary Materials). The net gravitational effect of GIA across Antarctica is positive, and the mean and standard deviation of the continent-wide models (54 ± 18 Gt/yr) is very close to that of W12a (56 ± 27 Gt/yr) and IJ05_R2 (55 ± 13 Gt/yr). The narrow spread likely reflects the difficulty of quantifying the timing and extent of past ice sheet change, and the absence of lateral variations in Earth rheology within some models [45]. In areas where GIA is a significant component of the regional mass change, such as the Amundsen, Ross and Filchner-Ronne sectors of West Antarctica, models predict the greatest uplift rates (5 to 7 mm/yr on average) but also the greatest variability (e.g. standard deviation > 10 mm/yr in the Amundsen sector). Away from areas with large GIA signals there is low variance among the models and broad agreement with GPS observations [46]. Nevertheless, most models considered here do not account for ice sheet change during the last few millennia, because it is poorly known. Inaccurate treatment of low degree harmonics associated with the global GIA signal can also bias gravimetric mass balance calculations [47].

Improvements in ice sheet mass balance assessments are still possible. Airborne snow radar [48,49] is a powerful tool for evaluating surface mass balance and firn compaction models over large spatial (1000's of km) and temporal (centennial) scales. Geological constraints on the ice sheet history [35] and GPS measurements of contemporary uplift [46,50] allow GIA models to be scrutinised and calibrated. More of both these data sets are needed, especially in East Antarctica. Given their apparent diversity, the spread of GIA and surface mass balance models should be evaluated in concert with the satellite gravimetry, altimetry, and velocity measurements. A reassessment of satellite measurements acquired during the 1990s could address the imbalance that is present in the current record. Alternative techniques (e.g. [51]) for the combination of satellite data sets should be explored. In addition to these obvious improvements, the ice sheet mass balance record should now be separated into the contributions due to short-term fluctuations in surface mass balance and longer-term trends in glacier ice.

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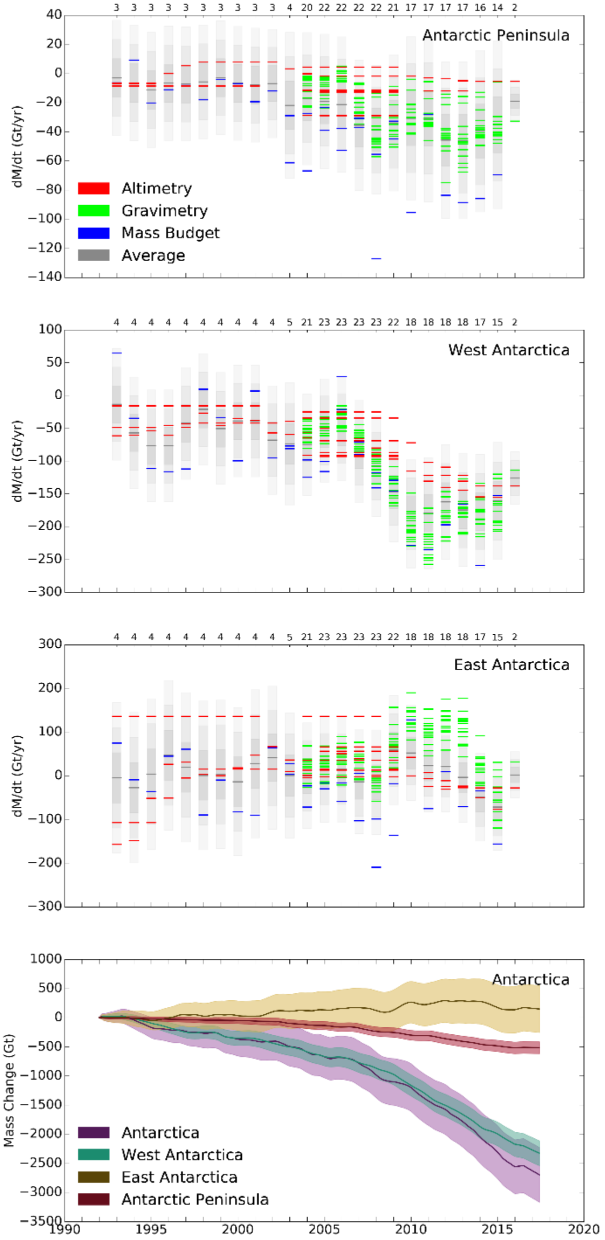

Figure 1 Rate of mass change of the Antarctic Peninsula (a), West Antarctic Ice Sheet (b), and East Antarctic Ice Sheet (c) as determined from satellite altimetry (red), mass budget (blue), and gravimetry (green) observations and a technique-weighted average (black), and the cumulative technique-weighted average mass change (solid lines) and their estimated uncertainty (d). The one-, two-, and three-sigma range of the technique-weighted average rate of mass changes are shaded in dark, mid, and light grey, respectively. The number of individual mass balance estimates collated at each epoch is shown along the top of each chart.

Supplementary Material

The accompanying supplementary material describes the assessment framework, the participants, the drainage basins used, the method employed to compute rates of mass change from cumulative mass changes, the results of the surface mass balance and glacial isostatic adjustment experiments, the results of the gravimetry, altimetry, and mass budget ice sheet mass balance experiments, the ice sheet mass balance inter-comparison, and the ice sheet mass balance integration.

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