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# Ice-sheet losses track high-end sea-level rise projections

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**Observed ice-sheet losses track the upper range of AR5 sea-level predictions. Recent mass loss is driven in Antarctica by ice dynamics and in Greenland by extreme surface melt events. Ice-sheet models must account for short-term variability in the atmosphere, oceans and climate to accurately predict sea-level rise.**

The Antarctic and Greenland ice-sheets contain enough water to raise global sea-level by 58 m[1] and 7 m[2], respectively. As the largest source of potential sea-level rise (SLR)[3], modest losses from these ice-sheets will increase coastal flooding[4] and affect oceans through freshwater input[5]. Accurately forecasting SLR improves flood risk assessment and adaptation. Since the satellite record began in the 1990s, Antarctica and Greenland together have raised global sea-levels by 17.8 mm, and the volume of ice lost has increased over time[1,2]. Of this, 7.2 mm originate from Antarctica, where ocean-driven melting and ice-shelf collapse have accelerated ice flow[1]; the remaining 10.6 mm come from Greenland which, despite holding less ice, accounts for 60% of the recent ice-sheet contribution as oceanic and atmospheric warming have increased ice discharge and surface meltwater runoff[2]. We compare observations of Antarctic[1] and Greenland mass change[2] to IPCC Fifth Assessment Report (AR5) SLR projections[3] during their 10-year overlap, and we assess model skill in predicting ice dynamic and surface mass change.

## Observed and predicted mass change

Projecting the ice-sheet contribution remains one of the most uncertain components of the global sea-level budget[3]. Progressive ice-sheet model development has improved their skill[6] and will continue to as descriptions of ice-sheet flow and climate system interactions advance[7]. In AR5, the ice-sheet contribution by 2100 is forecast from process-based models simulating changes in ice flow and surface mass balance (SMB) in response to climate warming[3]. Driven by the century-scale increase in temperature forced by representative concentration pathways (RCPs), global mean SLR estimates range from 280-980 mm by 2100 (Figure 1). Of this, the ice-sheet contribution constitutes 4–420 mm[3]. The spread of these scenarios is uncertain, scenario-dependent and increases rapidly after 2030 (Figure 1).

During 2007–2017, satellite observations show total ice-sheet losses increased global sea-level by 12.3 $\pm$ 2.3 mm and track closest to the AR5 upper range (13.7-14.1 mm for all emissions pathways) (Figure 1). Despite a reduction in ice-sheet losses during 2013-2017—when atmospheric circulation above Greenland promoted cooler summer conditions and heavy winter snowfall[2]—the observed average SLR rate (1.23 $\pm$ 0.24 mm/yr) is 45% above central predictions (0.85 $\pm$ 0.07 mm/yr) and closest to the upper range (1.39 $\pm$ 0.14 mm/yr) (Figure 2). These upper estimates predict an additional 145–230 mm (179 mm mean) of SLR from the ice-sheets above the central predictions by 2100. 150 mm of SLR will double storm-related flooding frequency across the west coasts of North America and Europe and in many of the world's largest coastal cities[4]. Ice-sheet losses at the upper end of AR5 predictions would expose 44–66 million people to annual coastal flooding worldwide[8]. SLR in excess of 1 m could require US$71 billion of annual investment in mitigation and adaptation strategies[9]

## Separating ice-sheet processes

The ice-sheet response to climate forcing comes from the SMB (net balance between accumulation and ablation processes) and the dynamic response to changes in ice flow, calving of icebergs, and melting at the ice-ocean interface. AR5 provides separate projections for these components (Figure 2)[3]. AR5 SMB simulations were based upon a regional climate model (RCM) ensemble, extended with temperature-based polynomials driven by surface air temperatures from general circulation models (GCMs)[3]. Ice dynamic contributions were derived from studies carried out using ice-sheet models forced by, but not coupled to, atmospheric and ocean model outputs. In this way, the atmosphere and ocean can impact the ice-sheet but not vice versa. In 2013, when AR5 was released, few models were available to simulate the complex calving processes and ice dynamical contributions to SLR. Instead, ice dynamics were projected using parameterisations for calving at selected outlet glaciers and scaled based on the published range of SLR[3]. Process-based models considered in AR5 have generally produced lower estimates of SLR than semi-empirical models based on paleoclimate reconstructions[10]. As SLR from SMB and dynamic components of ice-sheet mass balance differ substantially in Antarctica and Greenland, we consider their contributions separately.

We compare the observed[1,2] and modelled[3] ice dynamical and SMB contributions during the overlap period (Figure 2). During 2007–2017, Antarctic ice dynamics contributed $4.6 \pm 2.3$ mm

(Supplementary Figure 1) to global sea-level, at the same average rate projected by the AR5 mid-level scenario (0.47 ± 0.05 mm/yr) (Figure 2). We note, however, a large spread between AR5 Antarctic ice dynamic projections, which range from 3-34 mm by 2040 and predict a negative sea-level contribution in the lower scenarios from 2030 (Supplementary Figure 1). Despite all scenarios predicting Antarctic mass gains from increasing snowfall, the continent's estimated SMB (0.05 ± 0.13 mm/yr) has reduced slightly and is closest to the upper range (-0.02 ± 0.04 mm/yr). In Greenland, dynamic ice losses estimated from satellite observations during 2007–2017 (0.26 ± 0.13 mm/yr) track the lower range of predictions (0.22 ± 0.04 mm/yr). However, these AR5 projections were based on kinematic scaling and do not explicitly simulate ice flow[3]. Surface mass losses in Greenland raised global sea-levels by an estimated 4.6 ± 1.8 mm during 2007-2017 at an average rate of 0.46 ± 0.23 mm/yr, 28 % higher than the upper range of scenarios (0.36 ± 0.06 mm/yr).

High interannual variability in the observed mass change—notably for the Antarctic dynamic (0.46 ± 0.16 mm/yr) and Greenland surface (0.46 ± 0.23 mm/yr) components (Figure 2)—is not reproduced in AR5 and may not represent the longer-term mass imbalance. For Greenland in particular, changes in atmospheric circulation[11] induced extreme melting[12] and substantial variability meltwater runoff not captured in AR5 predictions[2], which are forced by annual temperature changes and do not reproduce the persistence in the North Atlantic driving these short-term weather events. In addition, clouds modulate[13] surface melting, and climate model biases in clouds and their formation processes may be partly responsible for both over- and under-estimating surface melt. Future studies would benefit from a comparison over the full 25-year observational record, during which satellites provide continuous and complete coverage over both ice-sheets, to better contextualize variability within the long-term record.

## Outlook

Advances in ice-sheet modelling are expected through experiments such as the Ice-sheet Model Intercomparison project for CMIP6 (ISMIP6)[6], which will deliver process-based projections from standalone ice-sheet models forced by output from coupled atmosphere-ocean GCMs, in time for AR6 in 2022. These efforts will improve predictions of the ice dynamical response, particularly in Antarctica where the spread among AR5 scenarios is large, through advanced representations of ice-ocean interactions which extrapolate GCM ocean forcing into ice-shelf cavities[7]. Modelling of surface processes is also improved by using RCMs to increase the spatial resolution of atmospheric GCM forcing and capture SMB variations found in steep topography at ice-sheet margins[6].

Challenges remain in modelling ice-sheet dynamic and SMB processes. Descriptions of ice-ocean interactions are hindered by coarse GCM resolution, and potential feedbacks in ocean circulation due to freshwater input are not accounted for[6]. Dynamic ice loss is driven by marine melt and iceberg calving; improved representations of these processes in ice-sheet models, and dense time series of outlet glacier observations, will improve understanding. Surface forcing for ISMIP6 experiments is provided as annual averages, and establishing the effects of shorter-term atmospheric variability and circulation changes on ice-sheet SMB requires further work. The quality of SMB forcing is also affected by inadequacies in GCM output—for example, in accurate representations of clouds and surface albedo. Such challenges can be partly addressed with two-way coupling of Antarctic and Greenland ice-sheet models to the atmosphere-ocean system. However, this remains a significant undertaking: differing spatial and temporal resolutions required by model components must be negotiated, and improving related parameterisations is essential.

Ice-sheet observational and modelling communities must also continue to collaborate. For example, regional case studies of extreme events driven by short-term variability can improve our understanding of ice-sheet processes. Partitioning ice-sheet projections into SMB and ice dynamics in AR6, as in AR5, will allow these processes to be further understood and evaluated separately. Recent experiments have assessed the ability of models to reproduce historical change[5,14,15], increasing confidence in sea-level projections and gauging the likelihood of extreme SLR from marine ice-sheet and ice-cliff instabilities. Reducing uncertainty in observational datasets through collaborative processes such as IMBIE, and generating new datasets (for example, of SMB and ice-shelf melt rates), will help reduce present-day biases in ice-sheet models. Used together, ice-sheet observations and models will continue to inform scientific debate and climate policy for decades to come.

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## Data availability

The satellite data used here are freely available at http://imbie.org/data-downloads/ as well as the IPCC sea-level rise projections, which can be downloaded from http://www.climatechange2013.org/report/full-report.

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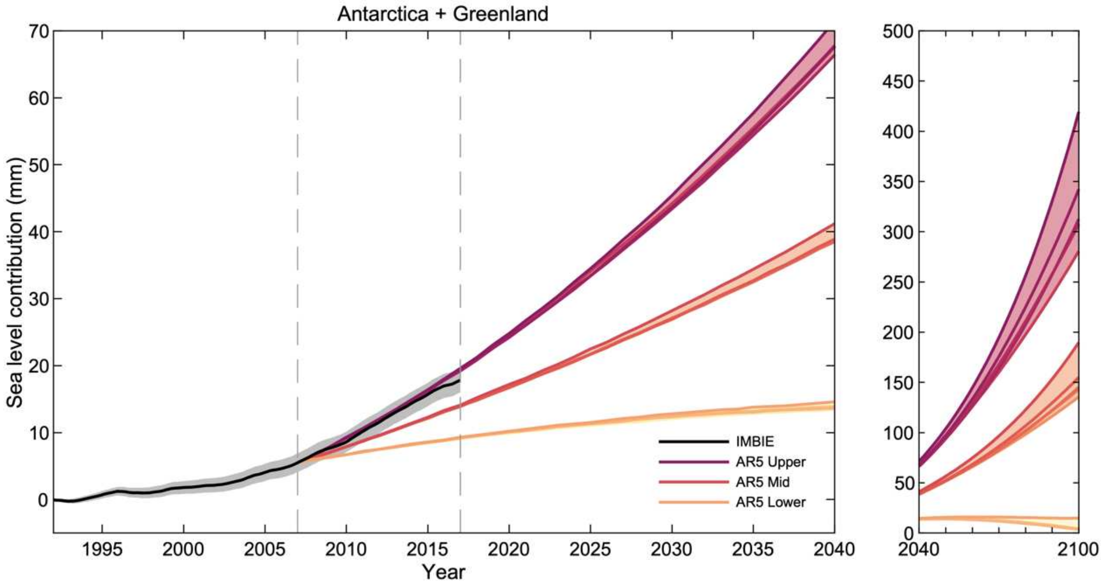


**Fig. 1 | Observed and predicted sea-level contribution from Antarctic and Greenland ice-sheet mass change.** The Antarctic and Greenland ice-sheet contribution to global sea-level according to IMBIE[1,2] (black) reconciled satellite observations and AR5[3] projections between 1992-2040 (left) and 2040-2100 (right). For each AR5 emission scenario, the upper (maroon), mid (orange) and lower (yellow) estimates are taken from the 95th percentile, median and 5th percentile values of the ensemble range, respectively[3]. Within the upper, mid and lower sets, AR5 pathways are represented by darker lines in order of increasing emissions: RCP 2.6, RCP 4.5, RCP 6.0, SRES A1B and RCP 8.5. Shaded areas represent the spread of AR5 scenarios and the 1σ estimated error on the observations. AR5 projections have been offset to equal to the satellite record at their start date (2007).

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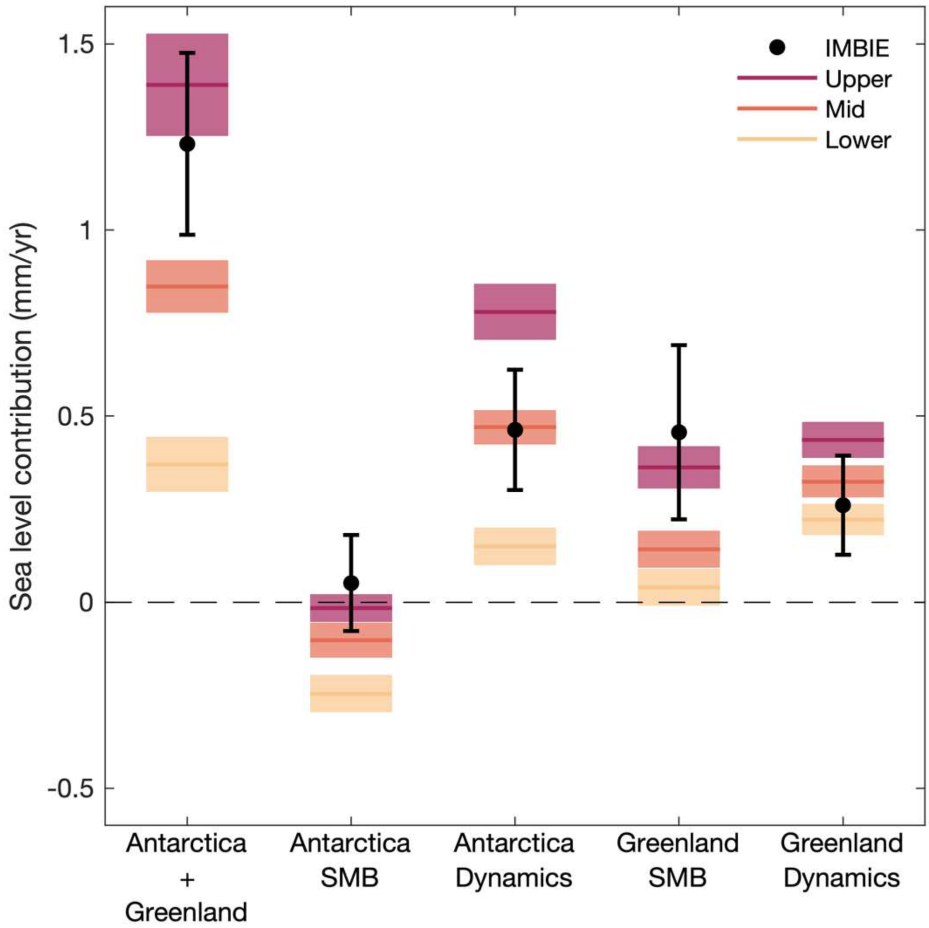


**Fig. 2 | Observed and predicted annual rates of sea level rise from Antarctic and Greenland ice-sheet mass change and their individual ice dynamic and surface mass components.** Average annual rates of sea-level rise, and their standard deviations, from IMBIE[1,2] (black) and AR5[3] projections during 2007-2017 including upper (95$^{th}$ percentile, maroon), mid (median, orange) and lower (5$^{th}$ percentile, yellow) estimates. Results are partitioned into the surface and ice dynamic mass change, along with the combined sea-level contribution from both ice-sheets.

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