Frequently Asked Questions

FAQ 13.2: Will the Greenland and Antarctic Ice Sheets Contribute to Sea Level Change over the Rest of the Century?

The Greenland, West and East Antarctic ice sheets are the largest reservoirs of freshwater on the planet. As such, they have contributed to sea level change over geological and recent times. They gain mass through accumulation (snowfall) and lose it by surface ablation (mostly ice melt) and outflow at their marine boundaries, either to a floating ice shelf, or directly to the ocean through iceberg calving. Increases in accumulation cause global mean sea level to fall, while increases in surface ablation and outflow cause it to rise. Fluctuations in these mass fluxes depend on a range of processes, both within the ice sheet and without, in the atmosphere and oceans. Over the course of this century, however, sources of mass loss appear set to exceed sources of mass gain, so that a continuing positive contribution to global sea level can be expected. This FAQ summarizes current research on the topic and provides indicative magnitudes for the various end-of-century (2081-2100 with respect to 1986-2005) sea level contributions from the full assessment, which are reported as the two-in-three probability level across all emission scenarios.

Over millennia, the slow horizontal flow of an ice sheet carries mass from areas of net accumulation (generally, in the high-elevation interior) to areas of net loss (generally, the low-elevation periphery and the coastal perimeter). At present, Greenland loses roughly half of its accumulated ice by surface ablation, and half by calving. Antarctica, on the other hand, loses virtually all its accumulation by calving and submarine melt from its fringing ice shelves. Ice shelves are floating, so their loss has only a negligible direct effect on sea level, although they can affect sea level indirectly by altering the mass budget of their parent ice sheet (see below).

In East Antarctica, some studies using satellite radar altimetry suggest that snowfall has increased, but recent atmospheric modelling and satellite measurements of changes in gravity find no significant increase. This apparent disagreement may be because relatively small long-term trends are masked by the strong interannual variability of snowfall. Projections suggest a substantial increase in 21st century Antarctic snowfall, mainly because a warmer atmosphere would be able to carry more moisture into polar regions. Regional changes in atmospheric circulation probably play a secondary role. For the whole of the Antarctic ice sheet, this process is projected to contribute between 0 and 70 mm to sea level fall.

Currently, air temperatures around Antarctica are too cold for substantial surface ablation. Field and satellite-based observations, however, indicate enhanced outflow—manifested as ice-surface lowering—in a few localized coastal regions. These areas (Pine Island and Thwaites Glaciers in West Antarctica, and Totten and Cook Glaciers in East Antarctica) all lie within kilometre-deep bedrock troughs towards the edge of Antarctica's continental shelf. The increase in outflow is thought to have been triggered by regional changes in ocean circulation, bringing warmer water in contact with floating ice shelves.

On the more northerly Antarctic Peninsula, there is a well-documented record of ice-shelf collapse, which appears to be related to the increased surface melting caused by atmospheric warming over recent decades. The subsequent thinning of glaciers draining into these ice shelves has had a positive—but minor—effect on sea level, as will any further such events on the Peninsula. Regional projections of 21st century atmospheric temperature change suggest that this process will probably not affect the stability of the large ice shelves of both the West and East Antarctica, although these ice shelves may be threatened by future oceanic change (see below).

Estimates of the contribution of the Antarctic ice sheets to sea level over the last few decades vary widely, but great strides have recently been made in reconciling the observations. There are strong indications that enhanced outflow (primarily in West Antarctica) currently outweighs any increase in snow accumulation (mainly in East Antarctica), implying a tendency towards sea level rise. Before reliable projections of outflow over the 21st century can be made with greater confidence, models that simulate ice flow need to be improved, especially of any changes in the grounding line that separates floating ice from that resting on bedrock and of interactions between ice shelves and the ocean. The concept of 'marine ice-sheet instability' is based on the idea that the outflow from an ice sheet resting on bedrock below sea level increases if ice at the grounding line is thicker and, therefore, faster flowing. On bedrock that slopes downward towards the ice-sheet interior, this creates a vicious cycle of increased outflow, causing ice at the grounding line to thin and go afloat. The grounding line then retreats down slope into thicker ice that, in turn, drives further increases in outflow. This feedback could potentially result in the rapid loss of parts of the ice sheet, as grounding lines retreat along troughs and basins that deepen towards the ice sheet's interior.

FAQ 13.2 (continued)

Future climate forcing could trigger such an unstable collapse, which may then continue independently of climate. This potential collapse might unfold over centuries for individual bedrock troughs in West Antarctica and sectors of East Antarctica. Much research is focussed on understanding how important this theoretical concept is for those ice sheets. Sea level could rise if the effects of marine instability become important, but there is not enough evidence at present to unambiguously identify the precursor of such an unstable retreat. Change in outflow is projected to contribute between –20 (i.e., fall) and 185 mm to sea level rise by year 2100, although the uncertain impact of marine ice-sheet instability could increase this figure by several tenths of a metre. Overall, increased snowfall seems set to only partially offset sea level rise caused by increased outflow.

In Greenland, mass loss through more surface ablation and outflow dominates a possible recent trend towards increased accumulation in the interior. Estimated mass loss due to surface ablation has doubled since the early 1990s. This trend is expected to continue over the next century as more of the ice sheet experiences surface ablation for longer periods. Indeed, projections for the 21st century suggest that increasing mass loss will dominate over weakly increasing accumulation. The refreezing of melt water within the snow pack high up on the ice sheet offers an important (though perhaps temporary) dampening effect on the relation between atmospheric warming and mass loss.

Although the observed response of outlet glaciers is both complex and highly variable, iceberg calving from many of Greenland's major outlet glaciers has increased substantially over the last decade, and constitutes an appreciable additional mass loss. This seems to be related to the intrusion of warm water into the coastal seas around Greenland, but it is not clear whether this phenomenon is related to inter-decadal variability, such as the North Atlantic

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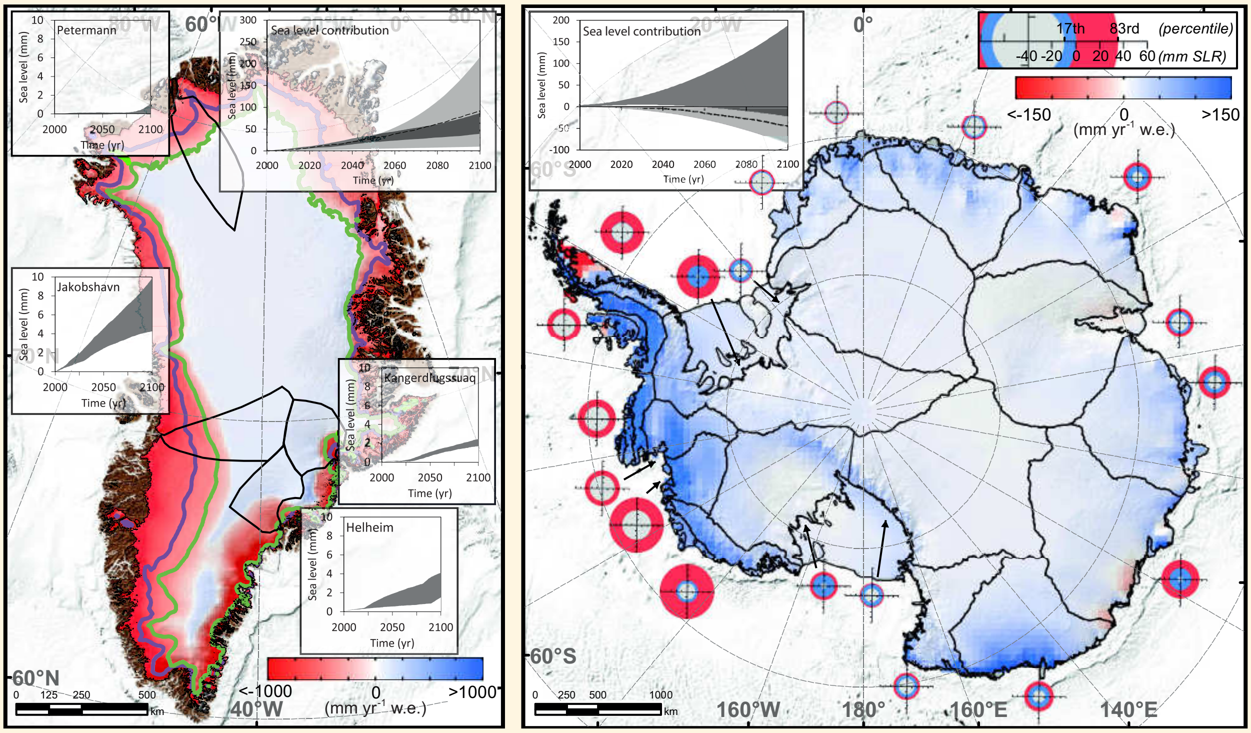

FAQ 13.2, Figure 1 | Illustrative synthesis of projected changes in SMB and outflow by 2100 for (a) Greenland and (b) Antarctic ice sheets. Colours shown on the maps refer to projected SMB change between the start and end of the 21st century using the RACMO2 regional atmospheric climate model under future warming scenarios A1B (Antarctic) and RCP4.5 (Greenland). For Greenland, average equilibrium line locations during both these time periods are shown in purple and green, respectively. Ice-sheet margins and grounding lines are shown as black lines, as are ice-sheet sectors. For Greenland, results of flowline modelling for four major outlet glaciers are shown as inserts, while for Antarctica the coloured rings reflect projected change in outflow based on a probabilistic extrapolation of observed trends. The outer and inner radius of each ring indicate the upper and lower bounds of the two-thirds probability range of the contribution, respectively (scale in upper right); red refers to mass loss (sea level rise) while blue refers to mass gain (sea level fall). Finally, the sea level contribution is shown for each ice sheet (insert located above maps) with light grey referring to SMB (model experiment used to generate the SMB map is shown as a dashed line) and dark grey to outflow. All projections refer to the two-in-three probability range across all scenarios.

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Oscillation, or a longer term trend associated with greenhouse gas–induced warming. Projecting its effect on 21st century outflow is therefore difficult, but it does highlight the apparent sensitivity of outflow to ocean warming. The effects of more surface melt water on the lubrication of the ice sheet's bed, and the ability of warmer ice to deform more easily, may lead to greater rates of flow, but the link to recent increases in outflow is unclear. Change in the net difference between surface ablation and accumulation is projected to contribute between 10 and 160 mm to sea level rise in 2081-2100 (relative to 1986-2005), while increased outflow is projected to contribute a further 10 to 70 mm (Table 13.5).

The Greenland ice sheet has contributed to a rise in global mean sea level over the last few decades, and this trend is expected to increase during this century. Unlike Antarctica, Greenland has no known large-scale instabilities that might generate an abrupt increase in sea level rise over the 21st century. A threshold may exist, however, so that continued shrinkage might become irreversible over multi-centennial time scales, even if the climate were to return to a pre-industrial state over centennial time scales. Although mass loss through the calving of icebergs may increase in future decades, this process will eventually end when the ice margin retreats onto bedrock above sea level where the bulk of the ice sheet resides.

have a rate of about 1% yr^{-1} of existing capacity (Lempérière, 2006; Lettenmaier and Milly, 2009). These two possibilities together indicate a range of about 0 to 30 mm of GMSL fall for the contribution of reservoir impoundment.

Our assessment thus leads to a range of –10 to +90 mm for the net contribution to GMSL rise from anthropogenic intervention in land water storage by 2081–2100 relative to 1986–2005. This range includes the range of 0 to 40 mm assumed by Katsman et al. (2008). Because of the limited information available, we do not have sufficient confidence to give ranges for individual RCP scenarios.

13.5 Projections of Global Mean Sea Level Rise

Process-based projections for GMSL rise during the 21st century, given in Section 13.5.1, are the sum of contributions derived from models that were evaluated by comparison with observations in Section 13.3 and used to project the contributions in Section 13.4. Projections of GMSL rise by semi-empirical models (SEMs) are given in Section 13.5.2. We compare these two and other approaches in Section 13.5.3 and assess the level of confidence that we can place in each approach. Longer term projections are discussed in Section 13.5.4.

13.5.1 Process-Based Projections for the 21st Century

The process-based projections of GMSL rise for each RCP scenario are based on results from 21 CMIP5 AOGCMs from which projections of SAT change and thermal expansion are available (see Section 13.4.1). Where CMIP5 results were not available for a particular AOGCM and scenario, they were estimated (Good et al., 2011; 2013) (Section 12.4.1.2; Supplementary Material). The projections of thermal expansion do not include an adjustment for the omission of volcanic forcing in AOGCM spin-up (Section 13.3.4.2), as this is uncertain and relatively small (about 10 mm during the 21st century). Changes in glacier and ice-sheet SMB are calculated from the global mean SAT projections using parameterizations derived from the results of process-based models of these components (note that glaciers on Antarctica are covered by the Antarctic ice-sheet SMB projection, and are therefore not included in the glacier projections) (Sections 13.4.2, 13.4.3.1, 13.4.4.1 and Supplementary Material). According to the assessment in Section 12.4.1.2, global mean SAT change is *likely* to lie within the 5 to 95% range of the projections of CMIP5 models. Following this assessment, the 5 to 95% range of model results for each of the GMSL rise contributions that is projected on the basis of CMIP5 results is interpreted as the *likely* range.

Possible ice-sheet dynamical changes by 2100 are assessed from the published literature (Sections 13.4.3.2 and 13.4.4.2), which as yet provides only a partial basis for making projections related to particular scenarios. They are thus treated as independent of scenario, except that a higher rate of change is used for Greenland ice sheet outflow under RCP8.5. Projections of changes in land water storage due to human intervention are also treated as independent of emissions scenario, because we do not have sufficient information to give ranges for individual scenarios. The scenario-independent treatment does not imply that the contributions concerned will not depend on the scenario followed, only that the current state of knowledge does not permit a quantitative assessment of the dependence. For each of these contributions, our assessment of the literature provides a 5-95% range for the late 21st century (2100 for Greenland and Antarctic ice-sheet dynamics, 2081-2100 for land water storage). For consistency with the treatment of the CMIP5-derived results, we interpret this range as the *likely* range. We assume that each of these contributions begins from its present-day rate and that the rate increases linearly in time, in order to interpolate from the present day to the late 21st century (see Supplementary Material for details).

The *likely* range of GMSL rise given for each RCP combines the uncertainty in global climate change, represented by the CMIP5 ensemble (Section 12.4.1.2), with the uncertainties in modelling the contributions to GMSL. The part of the uncertainty related to the magnitude of global