The Greenland and Antarctic ice sheets under 1.5°C global warming

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Even if anthropogenic warming were constrained to less than 2 °C above pre-industrial, the Greenland and Antarctic ice sheets will continue to lose mass this century, with rates similar to those observed over the last decade. However, nonlinear responses cannot be excluded, which may lead to larger rates of mass loss. Furthermore, large uncertainties in future projections still remain, pertaining to knowledge gaps in atmospheric (Greenland) and oceanic (Antarctica) forcing. On millennial time scales, both ice sheets have tipping points at or slightly above the 1.5-2.0 °C threshold; for Greenland, this may lead to irreversible mass loss due to the surface mass balance-elevation feedback, while for Antarctica, this could result in a collapse of major drainage basins due to ice-shelf weakening.

Projecting future sea-level rise (SLR, Box 1) is primarily hampered by our incomplete knowledge of the contributions of the Greenland and the Antarctic Ice Sheets (GrIS and AIS, respectively), Earth's largest ice masses. In this paper we review the potential contribution of both ice sheets under a strongly mitigated climate change scenario that limits the rise in global near-surface temperature to less than 2 °C above pre-industrial (targeting 1.5 °C), as agreed at the 21st UNFCCC climate conference in Paris. We base the review on both present-day observed/modelled changes and future forcings according to the RCP2.6 scenario. We use RCP2.6, the most conservative of the four Representative Concentration Pathways of greenhouse gas concentration trajectories adopted by the IPCC for its Fifth Assessment Report, because it is the scenario in the published literature that best approximates to the above warming range. Ice-sheet mass balance is defined as the net result of all mass gains and losses, and surface mass balance (SMB) as the net mass balance at the ice-sheet surface (where a negative mass balance means mass loss), including the firn layer. Hence, SMB does not include dynamical mass loss associated with ice flow at the ice-sheet margin or melting at the ice-ocean interface. Increased ice flow accounts for about one third of the recent GrIS mass loss[1]. For Antarctica, where mass lost through ice discharge past the grounding line (the limit between the grounded ice sheet and floating ice shelf) is roughly evenly shared between oceanic basal melt before reaching the ice front and iceberg calving, increased ice flow accounts for all of the recent mass loss[2,3].

In the following sections we synthesize: (i) the latest available evidence of GrIS and AIS mass balance changes together with possible climate forcings from the atmosphere/ocean; (ii) the expected responses of the ice sheets under conditions of limited (1.5 °C) global warming by 2100. In the concluding section, we highlight outstanding issues that require urgent attention by the research community in order to improve projections.

Greenland forcing and mass-balance changes

Greenland has warmed by $\sim$5 °C in winter and $\sim$2 °C in summer since the mid-1990s[4], which is more than double the global mean warming rate in that period. The GrIS has also been losing mass at an increasing rate since the 1990s[5] with a 0.65-0.73 mm a^{-1} mean sea-level rise equivalent (sle) for 2012-2016[6]. Since 2000, both SMB decrease and ice discharge increase contributed to mass loss, but the relative contribution of SMB decrease to the total mass loss went up from 42% to 68% between 2000 and 2012[1]. The current observed SMB decrease is mainly driven by increased melt and subsequent runoff[7] and is in part attributed to anthropogenic global warming and concurrent Arctic Amplification (exacerbated Arctic warming due to regional feedbacks of global warming), but also to recent atmospheric circulation changes in summer observed since the 2000's[8]. The occurrence of a negative North Atlantic Oscillation (NAO) and a concurrent positive phase of the East Atlantic Pattern since 2000 can be interpreted as a weakening and southward displacement of the jet stream[9,10], allowing for anomalous high pressure[8] and enhanced atmospheric blocking[11] over the GrIS. These circulation changes in summer have favoured the advection of warm southerly air masses[12] and increased incoming solar radiation[13], leading to more melt, which is further enhanced by the melt-albedo feedback. The relative contribution of global warming and natural climate variability to the recent atmospheric circulation changes of Greenland remains an open question[14]. However, the CMIP5 (Coupled Model Intercomparison Project Phase 5) models do not exhibit such circulation changes, either in future warming scenarios or in present-day simulations[12]. This explains why the recent observed SMB is lower and runoff is higher than predicted by these models (Fig. 1a,b).

That climate models have limited skill in representing future changes in the North Atlantic jet stream[9] also affects how well clouds and precipitation over Greenland are simulated in future scenarios. The general relation between precipitation and temperature

(+5% K^{-1}) derived using CMIP5 future projections[12] is subject to modification by structural changes in the North Atlantic atmospheric polar jet-stream. Moreover, model (mis-)representation of clouds has a major effect on projected melt and runoff[15]. In one CMIP5-forced regional climate model, runoff depends linearly on temperature for low-warming scenarios (Fig. 1b). In this model, runoff from the GrIS at the end of the 21st century is estimated at around 1 mm a^{-1} sle (360 Gt a^{-1}) for the +1.5 °C scenario. These end-of-century temperature and runoff values are close to what is currently observed, which may be attributed to the recent circulation changes mentioned above.

A decrease in SMB lowers the ice sheet surface, which in turn lowers SMB because at lower elevations, near-surface air temperature is generally higher[16,17]. Additional SMB changes due to the SMB-surface-elevation feedback are small for limited warming: in a coupled SMB-ice-dynamical simulation, the feedback contributes 11% to the GrIS runoff rate in an RCP2.6 scenario, or $\sim$3 mm of additional sea-level rise by 2100[17].

Apart from SMB, changes in the discharge of ice from iceberg calving and melt from the fronts of marine-terminating outlet glaciers have the potential to increase the rate at which the GrIS contributes to future SLR and many of these processes are starting to be included in state-of-the-art Greenland ice-sheet models[18]. Calving and frontal melt has already led to ice front retreat along most of the GrIS and acceleration of marine-terminating glaciers since about 2000[19]. GrIS discharge increased from 1960 to 2005 but stabilised thereafter, although with large interannual fluctuations[1,20]. These recent changes in discharge are thought to be linked in part to fluctuations in the North Atlantic ocean circulation[21,22]. There is evidence that the 1970s to early 2000s increase in ice discharge, as measured through changes in iceberg numbers, is also closely related to increasing runoff[20], for example through increased melting of ice fronts by upwelling freshwater plumes and the filling and hydro-fracturing of crevasses[23].

Increased runoff, percolation of meltwater to the base of the ice sheet and subsequent basal lubrication has also been proposed as a mechanism for general ice flow acceleration in the ablation zone (the Zwally effect)[24], but has since been shown to result in only moderate speedup at the beginning of the melt season, which can be counteracted by the development of an efficient drainage system[25]. Modelling studies indicate that on decadal to centennial timescales, the Zwally effect has a very limited contribution to global SLR[26,27].

Future SMB and discharge components of the mass budget cannot be separated entirely because of the SMB-elevation feedback and, more importantly, due to interaction between the two components as more negative SMB removes ice before it can reach the marine margins[27,28]. However, both these effects become more important with stronger climate forcing and therefore remain limited for the low-emission scenario considered here. Modelling studies indicate that the partitioning between mass losses from SMB and ice discharge and their spatial distribution are likely to remain similar to today[17,27], although these studies do not account for the full range of uncertainty associated with outlet-glacier changes. However, given that recent SMB changes dominate the recent GrIS mass loss[14], the largest source of uncertainty in future SLR is likely to be linked to SMB.

Expected Greenland response

Modelling studies of the GrIS, according to RCP2.6, report a large spread in ice-sheet volume change of 14-78 mm sle by 2100[17,27], with uncertainty arising mainly from differences between climate models. The largest discrepancies between different climate projections and ice-sheet models occur over the fast-flowing outlet glaciers[29]. Recent advances in high-resolution model simulations[30] highlight the importance of bed topography in controlling ice-front retreat for a given amount of ocean warming. However, capturing the dynamics of outlet glaciers remains difficult for several reasons: (i) outlet glacier flux is not always well determined due to the limited knowledge of the subglacial topography[31] despite the significant progress made through mass-conservation algorithms[32]; (ii) the impact of ocean temperature on ice discharge at the margin is poorly constrained; (iii) understanding of iceberg calving remains limited[33], while such mechanisms drive most of the dynamic changes of marine-terminating glaciers[34].

On longer timescales (Box 2), a tipping point (when the ice sheet enters a state of irreversible mass loss and complete melting is initiated) exists as part of the coupled ice sheet-atmospheric system. This consists of two inter-related feedback mechanisms: the SMB-elevation feedback, as described above, and the melt-albedo feedback[35–37]. The latter acts on the surface energy balance, by allowing more absorption of solar radiation from a melting and darkening snow surface, or removal of all snow leading to a darker ice surface. This feedback may be enhanced by ice-based biological processes, such as the growth of algae[38]. Thus, the activation of these feedbacks can lead to self-sustained melting of the entire ice sheet, even if the anomalous climatic forcing is removed.

It is clear that if the tipping point is crossed, a complete disappearance of the GrIS would occur on a multi-millennial time scale[39–41]. However, further work is urgently needed to diagnose how close the GrIS is to this tipping point. Fig. 2 shows results from an ensemble of simulations using one model varying key parameters related to precipitation changes and melt rates[40]. Simulations were performed with slowly increasing climatic forcing, allowing the ice sheet to maintain a state of quasi-equilibrium. Each simulation in the ensemble reached a tipping point, when the ice sheet could no longer sustain itself. Fig. 2a compares this equilibrium threshold with the diagnosed SMB of the GrIS given its present-day distribution, which can roughly be used as a proxy for stability. SMB is spatially inhomogeneous, however, with high accumulation and melt rates in the south, and cold, desert-like conditions in the north. These simulations show that the Northwest sector of the ice sheet is particularly sensitive to small changes in SMB, given the relatively low accumulation rates and associated slower flow of ice from inland as compared to the South. Thus, in this model, a negative SMB in the Northwest sector is a good predictor for the estimated threshold for complete melting of the ice sheet.

The 95% confidence interval for the regional summer temperature threshold leading to GrIS decline ranges from 1.1-2.3 °C above pre-industrial , with a best estimate of 1.8 °C[40]. This level of warming is well within the range of expected regional temperature changes given global warming limited to 1.5 °C, as CMIP5 models predict that Greenland near-surface air temperatures increase more than the global average and current levels of summer warming already reach this limit. This means that the threshold will likely be exceeded, even for aggressive anthropogenic carbon emissions reductions. However, in some peak-and-decline scenarios of CO_2 levels, full retreat can probably be avoided despite the threshold having been temporally crossed.

The committed SLR after 1000, 5000 or 15,000 years, i.e., how much the ice sheet will melt for a given climatic perturbation today (assumed constant in time), increases non-linearly for higher levels of warming (Fig. 2b). The lag in response implies that such a retreat would be set in motion much sooner, on timescales of the order of decades to centuries (see Box 2). Thus, crossing the limit of 1.5 °C global warming this century may impose a commitment to much larger and possibly irreversible changes in the far future[40,41].

Antarctic forcing and mass-balance changes

The AIS has been losing mass since the mid-1990s, contributing 0.15-0.46 mm a^{-1} sle on average between 1992 and 2017, accelerating to 0.49-0.73 mm a^{-1} between 2012 and 2017[42]. Observations over the last five years show that mass loss mainly occurs in the Antarctic Peninsula and West Antarctica (0.42-0.65 mm a^{-1} sle), with no significant contribution from East Antarctica (-0.01-0.16 mm a^{-1} sle)[42]. The mass loss from the West Antarctic Ice Sheet (WAIS) is primarily caused by the acceleration of outlet glaciers in the Amundsen Sea Embayment (ASE), where the ice discharge of large outlet glaciers like Pine Island and Thwaites Glaciers (PIG and TG, respectively) increased threefold since the early 1990s[42]. However, this ASE mass loss is not a recent phenomenon, as ocean sediment records indicate that PIG experienced grounding-line retreat since approximately the 1940s[43].

Antarctic SMB is projected to increase under atmospheric warming, governed by increased snowfall due to increased atmospheric saturation water vapour pressure, the availability of more open coastal water, and changing cloud properties[44]. Ice cores suggest that on centennial time scales SMB has increased especially in the Antarctic Peninsula, representing a net reduction in sea level of $\sim$0.04 mm per decade since 1900 CE[45]. According to CMIP5 model means for RCP2.6, increased snowfall mitigates SLR by 19 mm by 2100 and by 22 mm if only those CMIP5-models are used that best capture CloudSat-observed Antarctic snowfall rates[46]. Under atmospheric warming, Antarctic surface melt, estimated at $\sim$0.3 mm a^{-1} sle[47], is projected to increase approximately twofold by 2050, independent of the RCP forcing scenario[48]. Recent studies show that meltwater in Antarctica can be displaced laterally in flow networks[49], and sometimes even enters the ocean[50]. However, further research is needed to assess whether these processes can challenge the present view that almost all surface meltwater refreezes in the cold firn[47].

Major ice loss from the Antarctic ice sheet stems from an increased discharge of grounded ice into the ocean, with ice shelves (the floating extensions of the grounded ice sheet) playing a crucial role. The buttressing provided by ice shelves can affect inland ice hundreds of kilometres away[51], and hence controls grounding-line retreat and associated ice flow acceleration. Ice shelves are directly affected by oceanic and atmospheric conditions, and any change in these conditions may alter their buttressing effect and impact the glaciers feeding them. For instance, increased sub-shelf melting causes ice shelves to thin, increasing their sensitivity to mechanical weakening and fracturing. This causes changes in ice shelf rheology and reduces buttressing of the inland ice, leading to increased ice discharge[52]. Warming of the atmosphere promotes rainfall and surface melt on the ice shelves and cause hydrofracturing as water present at the ice sheet surface propagates into crevasses[53,54] or by tensile stresses induced by lake drainage[55]. Anomalously low sea ice cover and the associated increase in ocean swell has also been identified as an important precursor of Antarctic Peninsula ice shelf collapse[56]. These mechanisms were likely involved in the rapid breakup of Larsen B ice shelf in 2002[55]. While ice cores show that surface melting in the Antarctic Peninsula is currently larger than ever recorded in recent history[57], for low emission scenarios, the presence of significant rainfall and surface runoff is unlikely to spread far south of the Antarctic Peninsula by 2100[48,54]. Assessment of future surface melt-induced ice-shelf collapse is therefore highly uncertain for mitigated scenarios, with largely diverging estimates in recent literature. Parts of Larsen C, George VI, and Abbot ice shelves may become susceptible to hydrofracturing by 2100 under a mitigated climate scenario[54], but most studies identify significant potential ice-shelf collapse by 2100 only under unmitigated scenarios[48,58].

Major recent dynamic ice loss in the ASE is associated with high melt rates at the base of ice shelves that result from inflow of relatively warm Circumpolar Deep Water (CDW) in ice shelf cavities[59,60], which led to increased thinning of the area's ice shelves and to reduced buttressing of the grounded ice. Evidence from East Antarctica, as well as along the southern Antarctic Peninsula, also links glacier thinning and grounding-line retreat to CDW reaching the deep grounding lines[61,62].

However, the link between CDW upwelling and global climate change is not yet clearly demonstrated, and decadal variability, such as El Niño/Southern Oscillation (ENSO), may dominate ice-shelf mass variability in this sector[63]. This variability may increase as interannual atmospheric variability increases in a warming climate[63]. The CMIP5 ensemble also shows a modest mean warming of Antarctic Shelf Bottom Water (ASBW), the ocean water masses occupying the sea floor on the Antarctic continental shelf that provide the heat for basal melting of Antarctic ice shelves, of 0.25 ±0.5 °C by 2100 under RCP2.6[64]. Given that present-day biases in ASBW in CMIP5 models are of the same order or larger than this warming and that the main limitation is the ability of these models to resolve significant features in both bedrock topography and the ocean flow[65], RCP2.6 projections of future sub-ice shelf melt remain poorly constrained[64]. Moreover, the link between increased presence of warm deep water on the continental shelf and higher basal melt rates is not always clear; simulations of strengthened westerly winds near the western Antarctic Peninsula showed an increase in warm deep water on the continental shelf but a coincident decrease in ice-shelf basal melt[66].

Increasing the wind forcing over the Antarctic Circumpolar Current (ACC) has been shown to have little effect on ice shelf basal melting[67]. Ocean-sea ice projections that include ice-shelf cavities have indicated the possibility that significant amounts of warm deep water could gain access to the Filchner-Ronne ice-shelf cavities in the coming century, increasing melt rates by as much as two orders of magnitude[68,69]. This process was seen with forcing from only one of two CMIP3 models and was more dependent on the model that produced the forcing than on the emissions scenario[69], suggesting that this scenario has a low probability.

Reduction of buttressing of ice shelves via the processes described above may eventually lead to the so-called Marine Ice Sheet Instability (MISI; Fig. 3). For WAIS, where the bedrock lies below sea level and slopes down towards the interior of the ice sheet, MISI may lead to a (partial) collapse of this marine ice sheet. This process, first hypothesized in the 1970's, was recently theoretically confirmed[70] and demonstrated in numerical models[71]. It arises from thinning and eventually flotation of the ice near the grounding line, which moves the latter into deeper water where the ice is thicker. Thicker ice results in increased ice flux, which further thins (and eventually floats) the ice, which results in further retreat into deeper water (and thicker ice), and so on. The possibility that some glaciers, such as PIG and TG, are already undergoing MISI has been suggested by numerical simulations using state-of-the-art ice sheet models[72,73]. The past retreat (up to 2010) of PIG has been attributed to MISI[72,74] triggered by oceanic forcing, although its recent slowdown may be due to a combination of abated forcing[75] and concomitant increase in glacier buttressing. TG is currently in a less buttressed state, and several simulations using state-of-the-art ice sheet models indicate a continued mass loss and possibly MISI even under present climatic conditions[73,76,77].

Additionally, evidence from the observed Larsen B collapse and rapid front retreat of Jakobshavn Isbrae in Greenland, suggests that hydrofracturing could lead to rapid collapse of ice shelves and potentially produce high ice cliffs with vertical exposure above 90 m rendering the cliffs mechanically unsustainable, possibly resulting in what has been termed Marine Ice Cliff Instability (MICI; Fig. 3)[78]. This effect, if triggered by a rapid disintegration of ice shelves due to hydrofracturing could lead to an acceleration of ice discharge in Antarctica but is unlikely in a low emission scenario[58,79]. However, this process has not yet been observed in Antarctica, and may be prevented or delayed by refreezing of meltwater in firn[54] or if efficient surface drainage exists[50].

Expected Antarctic response

A major limiting factor in projecting future Antarctic ice sheet response is how global warming relates to ocean dynamics that bring CDW onto and across the continental shelf, potentially increasing sub-shelf melt. Because of this uncertainty, several studies apply linear extrapolations of present-day observed melt rates, while focusing on unmitigated scenarios (RCP8.5). Mass loss according to mitigated scenarios are essentially limited to dynamic losses in the Amundsen Sea Embayment of up to 0.05 m sle by 2100. This is not much different than a linear extrapolation of the present-day mass losses[76,77,80] and in contrast with the observed acceleration of mass loss over the last decade[42]. For the whole AIS, a mass loss between 0.01 and 0.1 m by 2100 is projected according to RCP2.6[81], which is not dissimilar (-0.11 to 0.15 m by 2100) from model simulations based on Pliocene sea-level (5-15 m higher than today) tuning[58], associated with a different melt parametrization at the grounding line (Fig. 4). Since the value of sea level at the Pliocene is still debated[82], tuning the model with a higher Pliocene sea-level target (10-20 m) increases the model sensitivity, with an upper bound of 0.22 m by 2100 according to the same scenario[58].

Because ocean heat supply is the crucial forcing for sub-shelf melting, oceanic forcing has the potential to modulate the retreat rate. Significant regional differences exist between Antarctic drainage basins in terms of oceanic heat fluxes and the topographic configuration of the ice sheet bed[83]. Consequently, the ice sheet response to ocean thermal forcing, even for small temperature anomalies, may be governed by bed geometry as much as by environmental conditions[83,84]. Observations and modelling show that surface melt occurs on some smaller ice shelves[44,47,48], but also that this may not be a recent phenomenon[49]. According to global and regional atmospheric modelling, under intermediate emissions scenarios, Antarctic ice shelf surface melt will likely increase gradually and linearly[48]. It should be noted, however, that while surface melt is not the major present-day forcing component, the high-end SLR contributions reached for RCP8.5 scenarios[58] stem from increased surface melting rather than oceanic forcing.

The projected long-term SLR contribution (500 years) of AIS for warming levels associated with the RCP2.6 scenario are limited to well below a metre, although with a probability distribution that is not Gaussian and presents a long tail toward high values due to potential MICI[58], with the caveats listed above. Importantly, substantial future retreat in some basins (e.g. TG) cannot be ruled out and grounding-line retreat may continue even with no additional forcing[73,77,85,86]. The long-term SLR contribution of AIS therefore crucially depends on the behaviour of individual ice shelves and outlet glacier systems and whether they enter into MISI for the given level of warming. Under sustained warming, a key threshold for survival of Antarctic ice shelves, and thus stability of the ice sheet, appears to lie between 1.5 and 2 °C mean annual air temperature above present (Figs. 1d and 4)[81]. Activation of several larger systems such as the Ross and Ronne-Filchner drainage basins and onset of much larger SLR contributions is estimated to be triggered by global warming between 2 and 2.7 °C[81]. This implies that substantial Antarctic ice loss can be prevented only by limiting greenhouse gas emissions to RCP2.6 levels or lower[58,81]. Crossing these thresholds implies commitment to large ice sheet changes and SLR that may take thousands of years to be fully realised and are irreversible on longer timescales.

Need for improvement

While considerable progress has been made over the last decade with respect to understanding processes at the interface between ice sheets, atmosphere and ocean, significant uncertainties in both forcing and response of the ice sheets remain[18,87]. For the AIS, for instance, the majority of present-day mass loss (essentially the ASE) is driven by changes in ocean circulation. The ability to simulate those changes into the future is so far limited, leading to large remaining uncertainties for any projection of AIS mass balance. Similar challenges remain in modelling changes in regional atmospheric circulation that affect GrIS mass loss. Therefore, it is not clear to what degree global warming must be limited to reduce future ice sheet-related SLR contributions.

Other challenges in climate and ice sheet modelling concern model resolution, initialization and coupling. Model resolution is a key issue, as climate and ocean models tend to be too diffusive. Higher model resolutions increase eddy activity and advective heat transfer more readily than at lower resolution[88]. Recent work[89] uses high-resolution, non-hydrostatic atmospheric and detailed SMB models to better represent surface physical processes at $<$10 km scales. Likewise, in order to resolve grounding-line dynamics, ice sheet models need high spatial resolution across the grounding line[90] and new numerical techniques, such as adaptive meshing, have been developed in recent years to achieve this[91]. Model initialization relies on two distinct, but often combined approaches (spin-up versus data assimilation; Box 1), the latter technique improving for centennial projections with the increasing access to high-resolution satellite products.

Further developments include the need for two-way coupling of ice sheets with coupled atmosphere-ocean models, meaning that climate models not only force ice-sheet models but the reverse is also true. This calls for closer collaborations across disciplines, which is exemplified by ice-sheet model intercomparisons (such as ISMIP6[92]) within the Coupled Model Intercomparison Project CMIP6. A similar intercomparison exercise for SMB and ocean models is urgently needed, given remaining uncertainties in absolute SMB values and sub-shelf melting, with the former especially relevant for Greenland[7,14,93] and the latter for Antarctica. For instance, if a possible link is found between global warming and the current circulation changes observed in summer over Greenland, this could significantly amplify the melt acceleration projected for the future via a newly recognized positive feedback. Therefore, to achieve this, it will be critical to further understand and improve the representation of changes in atmosphere and ocean global circulation in global and regional climate model simulations.

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Author contributions

F.P. and C.R. coordinated the study, F.P., C.R. and E.H. led the writing, and all authors contributed to the writing and discussion of ideas. J.T.M.L., P.K.M. and L.D.T. contributed the data that led to Figure 1. L.F. designed Figure 3. N.R.G. provided the data that led to Figure 4.

Competing interests

The authors declare no competing interests.

References

1. Enderlin, E. M. *et al.* An improved mass budget for the Greenland ice sheet. *Geophys. Res. Lett.* **41,** 866–872. ISSN: 19448007 (2014).
2. Rignot, E., Jacobs, S, Mouginot, J & Scheuchl, B. Ice-shelf melting around Antarctica. *Science* **341,** 266–70. ISSN: 1095-9203 (2013).
3. Depoorter, M. A. *et al.* Calving fluxes and basal melt rates of Antarctic ice shelves. *Nature* **502,** 89–92. ISSN: 1476-4687 (2013).
4. Hanna, E., Mernild, S. H., Cappelen, J. & Steffen, K. Recent warming in Greenland in a long-term instrumental (1881-2012) climatic context: I. Evaluation of surface air temperature records. *Environmental Research Letters* **7,** 045404 (2012).
5. Hanna, E. *et al.* Ice-sheet mass balance and climate change. *Nature* **498,** 51–59. ISSN: 0028-0836 (2013).

6. Bamber, J. L., Westaway, R. M., Marzeion, B. & Wouters, B. The land ice contribution to sea level during the satellite era. *Environmental Research Letters* **13,** 063008 (2018).

7. Wilton, D. *et al.* High resolution (1 km) positive degree-day modelling of Greenland ice sheet surface mass balance, 1870–2012 using reanalysis data. *Journal of Glaciology* (2016).

8. Fettweis, X. *et al.* Brief communication: Important role of the mid-tropospheric atmospheric circulation in the recent surface melt increase over the Greenland ice sheet. *Cryosphere* **7,** 241–248. ISSN: 19940416 (2013).

9. Hall, R., Erdélyi, R., Hanna, E., Jones, J. M. & Scaife, A. A. Drivers of North Atlantic Polar Front jet stream variability. *International Journal of Climatology* **35,** 1697–1720. ISSN: 1097-0088 (2015).

10. Lim, Y.-K. *et al.* Atmospheric summer teleconnections and Greenland Ice Sheet surface mass variations: insights from MERRA-2 RECEIVED. *Environ. Res. Lett.* **11** (2016).

11. Hanna, E., Cropper, T. E., Hall, R. J. & Cappelen, J. Greenland Blocking Index 1851–2015: a regional climate change signal. *Int. J. Climatol.* **36,** 4847–4861. ISSN: 10970088 (2016).

12. Fettweis, X. *et al.* Estimating the Greenland ice sheet surface mass balance contribution to future sea level rise using the regional atmospheric climate model MAR. *The Cryosphere* **7,** 469–489 (2013).

13. Hofer, S., Tedstone, A. J., Fettweis, X. & Bamber, J. L. Decreasing cloud cover drives the recent mass loss on the Greenland Ice Sheet. *Science Advances* **3,** n/a–n/a (2017).

14. Van den Broeke, M. *et al.* Greenland Ice Sheet Surface Mass Loss: Recent Developments in Observation and Modeling. *Current Climate Change Reports* **3,** 345–356. ISSN: 2198-6061 (2017).

15. Van Tricht, K. *et al.* Clouds enhance Greenland ice sheet meltwater runoff. *Nature Communications* **7.** Article, 10266 EP – (2016).

16. Edwards, T. L. *et al.* Effect of uncertainty in surface mass balance-elevation feedback on projections of the future sea level contribution of the Greenland ice sheet. *Cryosphere* **8,** 195–208. ISSN: 19940416 (2014).

17. Vizcaino, M. *et al.* Coupled simulations of Greenland Ice Sheet and climate change up to A.D. 2300. *Geophys. Res. Lett.* **42** (2015).

18. Goelzer, H., Robinson, A., Seroussi, H. & van de Wal, R. Recent Progress in Greenland Ice Sheet Modelling. *Current Climate Change Reports* **3,** 291–302 (2017).

19. Moon, T., Joughin, I., Smith, B. & Howat, I. 21st-Century Evolution of Greenland Outlet Glacier Velocities. *Science* **336,** 576–578. ISSN: 0036-8075 (2012).

20. Bigg, G. R. *et al.* A century of variation in the dependence of Greenland iceberg calving on ice sheet surface mass balance and regional climate change. *Proceedings of the Royal Society of London A: Mathematical, Physical and Engineering Sciences* **470,** n/a–n/a. ISSN: 1364-5021 (2014).

21. Holland, D. M., Thomas, R., deYoung, B., Ribergaard, M. & Lyberth, B. Acceleration of Jakobshavn Isbrae Triggered by Warm Subsurface Ocean Waters. *Nature Geosci.* **1,** 659–664 (2008).

22. Khan, S. A. *et al.* Sustained mass loss of the northeast Greenland ice sheet triggered by regional warming. *Nature Climate Change* (2014).

23. Nick, F. M. *et al.* Future sea-level rise from Greenland's main outlet glaciers in a warming climate. *Nature* **497,** 235–238. ISSN: 1476-4687 (2013).

24. Zwally, H. J. *et al.* Surface Melt-Induced Acceleration of Greenland Ice-Sheet Flow. *Science* **297,** 218–222. ISSN: 0036-8075 (2002).

25. Sundal, A. *et al.* Melt-induced speed-up of Greenland ice sheet offset by efficient subglacial drainage. *Nature* **469,** 521–524. ISSN: 0028-0836 (Jan. 2011).

26. Shannon, S. R. *et al.* Enhanced basal lubrication and the contribution of the Greenland ice sheet to future sea-level rise. *Proc. Natl. Acad. Sci.* **110,** 14156–14161. ISSN: 0027-8424 (2013).

27. Fürst, J. J., Goelzer, H. & Huybrechts, P. Ice-dynamic projections of the Greenland ice sheet in response to atmospheric and oceanic warming. *The Cryosphere* **9,** 1039–1062 (2015).

28. Goelzer, H. *et al.* Sensitivity of Greenland ice sheet projections to model formulations. *J. Glaciol.* **59,** 733–749. ISSN: 00221430 (2013).

29. Nowicki, S. *et al.* Insights into spatial sensitivities of ice mass response to environmental change from the SeaRISE ice sheet modeling project II: Greenland. *Journal of Geophysical Research: Earth Surface* **118,** 1025–1044. ISSN: 2169-9011 (2013).

30. Morlighem, M. *et al.* Modeling of Store Gletscher's calving dynamics, West Greenland, in response to ocean thermal forcing. *Geophys. Res. Lett.* **43,** 2659–2666. ISSN: 19448007 (2016).

31. Aschwanden, A., Fahnestock, M. A. & Truffer, M. Complex Greenland outlet glacier flow captured. *Nature Communications* **7,** 10524. ISSN: 2041-1723 (2016).

32. Morlighem, M., Rignot, E., Mouginot, J., Seroussi, H. & Larour, E. Deeply incised submarine glacial valleys beneath the Greenland ice sheet. *Nature Geoscience* **7,** 418–422 (June 2014).

33. Benn, D. I., Warren, C. R. & Mottram, R. H. Calving processes and the dynamics of calving glaciers. *Earth-Science Reviews* **82,** 143–179. ISSN: 00128252 (2007).

34. Bondzio, J. H. *et al.* The mechanisms behind Jakobshavn Isbrae's acceleration and mass loss: A 3-D thermomechanical model study. *Geophysical Research Letters* **44.** 2017GL073309, 6252–6260. ISSN: 1944-8007 (2017).

35. Robinson, A. & Goelzer, H. The importance of insolation changes for paleo ice sheet modeling. *The Cryosphere* **8,** 1419–1428 (2014).

36. Tedesco, M. *et al.* The darkening of the Greenland ice sheet: trends, drivers, and projections (1981–2100). *The Cryosphere* **10,** 477–496 (2016).

37. Tedstone, A. J. *et al.* Dark ice dynamics of the south-west Greenland Ice Sheet. *The Cryosphere* **11,** 2491–2506 (2017).

38. Ryan, J. C. *et al.* Dark zone of the Greenland Ice Sheet controlled by distributed biologically-active impurities. *Nature Communications* **9,** 1065. ISSN: 2041-1723 (2018).

39. Ridley, J., Gregory, J. M., Huybrechts, P. & Lowe, J. Thresholds for irreversible decline of the Greenland ice sheet. *Clim. Dyn.* **35,** 1065–1073. ISSN: 09307575 (2010).

40. Robinson, A., Calov, R. & Ganopolski, A. Multistability and critical thresholds of the Greenland ice sheet. *Nat. Clim. Chang.* **2,** 429–432. ISSN: 1758-678X (2012).

41. Levermann, A. *et al.* The multimillennial sea-level commitment of global warming. *Proc. Natl. Acad. Sci.* **110,** 13745–13750. ISSN: 0027-8424 (2013).

42. Shepherd, A. *et al.* Mass balance of the Antarctic Ice Sheet from 1992 to 2017. *Nature* **558,** 219–222. ISSN: 1476-4687 (2018).

43. Smith, A. M., Bentley, C. R., Bingham, R. G. & Jordan, T. A. Rapid subglacial erosion beneath Pine Island Glacier, West Antarctica. *Geophysical Research Letters* **39.** L12501, n/a–n/a. ISSN: 1944-8007 (2012).

44. Lenaerts, J. T. M., Vizcaino, M., Fyke, J., van Kampenhout, L. & van den Broeke, M. R. Present-day and future Antarctic ice sheet climate and surface mass balance in the Community Earth System Model. *Clim. Dyn.* **47,** 1367–1381. ISSN: 14320894 (2016).

45. Thomas, E. R. *et al.* Regional Antarctic snow accumulation over the past 1000 years. *Climate of the Past* **13,** 1491–1513 (2017).

46. Palerme, C. *et al.* Evaluation of current and projected Antarctic precipitation in CMIP5 models. *Clim. Dyn.* **48,** 225–239. ISSN: 14320894 (2017).

47. Kuipers Munneke, P., Picard, G., Van Den Broeke, M. R., Lenaerts, J. T. M. & Van Meijgaard, E. Insignificant change in Antarctic snowmelt volume since 1979. *Geophys. Res. Lett.* **39,** 6–10. ISSN: 00948276 (2012).

48. Trusel, L. D. *et al.* Divergent trajectories of Antarctic surface melt under two twenty-first-century climate scenarios. *Nat. Geosci.* **8,** 927–932. ISSN: 1752-0894 (2015).

49. Kingslake, J., Ely, J. C., Das, I. & Bell, R. E. Widespread movement of meltwater onto and across Antarctic ice shelves. *Nature* **544,** 349 EP – (2017).

50. Bell, R. E. *et al.* Antarctic ice shelf potentially stabilized by export of meltwater in surface river. *Nature* **544.** Letter, 344–348. ISSN: 0028-0836 (2017).

51. Reese, R., Gudmundsson, G. H., Levermann, A. & Winkelmann, R. The far reach of ice-shelf thinning in Antarctica. *Nature Climate Change* **8,** 53–57. ISSN: 1758-6798 (2018).

52. Borstad, C. *et al.* A constitutive framework for predicting weakening and reduced buttressing of ice shelves based on observations of the progressive deterioration of the remnant Larsen B Ice Shelf. *Geophys. Res. Lett.* **43,** 2027–2035. ISSN: 19448007 (2016).

53. Scambos, T. A., Hulbe, C., Fahnestock, M. & Bohlander, J. The link between climate warming and break-up of ice shelves in the Antarctic Peninsula. *J. Glaciol.* **46,** 516–530. ISSN: 00221430 (2000).

54. Munneke, P. K., Ligtenberg, S. R. M., Van Den Broeke, M. R. & Vaughan, D. G. Firn air depletion as a precursor of Antarctic ice-shelf collapse. *J. Glaciol.* **60,** 205–214. ISSN: 00221430 (2014).

55. Banwell, A. F., MacAyeal, D. R. & Sergienko, O. V. Breakup of the Larsen B Ice Shelf triggered by chain reaction drainage of supraglacial lakes. *Geophys. Res. Lett.* **40,** 5872–5876. ISSN: 00948276 (2013).

56. Massom, R. A. *et al.* Antarctic ice shelf disintegration triggered by sea ice loss and ocean swell. *Nature* **558,** 383–389. ISSN: 1476-4687 (2018).

57. Abram, N. J. *et al.* Acceleration of snow melt in an Antarctic Peninsula ice core during the twentieth century. *Nature Geoscience* **6,** 404–411 (2013).

58. DeConto, R. M. & Pollard, D. Contribution of Antarctica to past and future sea-level rise. *Nature* **531,** 591–597. ISSN: 0028-0836 (2016).

59. Jacobs, S. S., Jenkins, A., Giulivi, C. F. & Dutrieux, P. Stronger ocean circulation and increased melting under Pine Island Glacier ice shelf. *Nature Geoscience* **4,** 519 EP – (2011).

60. Pritchard, H. D. *et al.* Antarctic ice-sheet loss driven by basal melting of ice shelves. *Nature* **484,** 502 EP – (2012).

61. Greenbaum, J. S. *et al.* Ocean access to a cavity beneath Totten Glacier in East Antarctica. *Nature Geoscience* **8,** 294–298 (Apr. 2015).

62. Wouters, B. *et al.* Dynamic thinning of glaciers on the Southern Antarctic Peninsula. *Science* **348,** 899–903. ISSN: 0036-8075 (2015).

63. Paolo, F. S. *et al.* Response of Pacific-sector Antarctic ice shelves to the El Niño/Southern Oscillation. *Nature Geoscience,* n/a–n/a. ISSN: 1752-0908 (2018).

64. Little, C. M. & Urban, N. M. CMIP5 temperature biases and 21st century warming around the Antarctic coast. *Ann. Glaciol.* **57,** 69–78. ISSN: 02603055 (2016).

65. Asay-Davis, X. S., Jourdain, N. C. & Nakayama, Y. Developments in Simulating and Parameterizing Interactions Between the Southern Ocean and the Antarctic Ice Sheet. *Current Climate Change Reports* **3,** 316–329 (2017).

66. Dinniman, M. S., Klinck, J. M. & Hofmann, E. E. Sensitivity of circumpolar deep water transport and ice shelf basal melt along the west antarctic peninsula to changes in the winds. *J. Clim.* **25,** 4799–4816. ISSN: 08948755 (2012).

67. Kusahara, K. & Hasumi, H. Pathways of basal meltwater from Antarctic ice shelves: A model study. *Journal of Geophysical Research: Oceans* **119,** 5690–5704. ISSN: 2169-9291 (2014).

68. Hellmer, H. H., Kauker, F., Timmermann, R., Determann, J. & Rae, J. Twenty-first-century warming of a large Antarctic ice-shelf cavity by a redirected coastal current. *Nature* **485,** 225–228. ISSN: 0028-0836 (2012).

69. Timmermann, R. & Hellmer, H. H. Southern Ocean warming and increased ice shelf basal melting in the twenty-first and twenty-second centuries based on coupled ice-ocean finite-element modelling. *Ocean Dyn.* **63,** 1011–1026. ISSN: 16167341 (2013).

70. Schoof, C. Ice sheet grounding line dynamics: Steady states, stability, and hysteresis. *Journal of Geophysical Research: Earth Surface* **112.** F03S28, n/a–n/a. ISSN: 2156-2202 (2007).

71. Pattyn, F. *et al.* Results of the Marine Ice Sheet Model Intercomparison Project, MISMIP. *The Cryosphere* **6,** 573–588 (2012).

72. Favier, L. *et al.* Retreat of Pine Island Glacier controlled by marine ice-sheet instability. *Nat. Clim. Chang.* **4,** 117–121. ISSN: 1758-678X (2014).

73. Joughin, I., Smith, B. E. & Medley, B. Marine Ice Sheet Collapse Potentially Under Way for the Thwaites Glacier Basin, West Antarctica. *Science* **344,** 735–738. ISSN: 0036-8075 (2014).

74. Mouginot, J., Rignot, E. & Scheuchl, B. Sustained increase in ice discharge from the Amundsen Sea Embayment, West Antarctica, from 1973 to 2013. *Geophysical Research Letters* **41,** 1576–1584. ISSN: 1944-8007 (2014).

75. Dutrieux, P. *et al.* Strong Sensitivity of Pine Island Ice-Shelf Melting to Climatic Variability. *Science (80-.).* **343** (2014).

76. Nias, I. J., Cornford, S. L. & Payne, A. J. Contrasting the Modelled sensitivity of the Amundsen Sea Embayment ice streams. *J. Glaciol.* **62,** 552–562. ISSN: 00221430 (2016).

77. Seroussi, H. *et al.* Continued retreat of Thwaites Glacier, West Antarctica, controlled by bed topography and ocean circulation. *Geophys. Res. Lett.* n/a–n/a. ISSN: 00948276 (2017).

78. Bassis, J. N. & Walker, C. C. Upper and lower limits on the stability of calving glaciers from the yield strength envelope of ice. *Proc. R. Soc. A Math. Phys. Eng. Sci.* **468,** 913–931. ISSN: 1364-5021 (2012).

79. Pollard, D., DeConto, R. M. & Alley, R. B. Potential Antarctic Ice Sheet retreat driven by hydrofracturing and ice cliff failure. *Earth and Planetary Science Letters* **412,** 112 –121 (2015).

80. Cornford, S. L. *et al.* Century-scale simulations of the response of the West Antarctic Ice Sheet to a warming climate. *Cryosphere* **9,** 1579–1600. ISSN: 19940424 (2015).

81. Golledge, N. R. *et al.* The multi-millennial Antarctic commitment to future sea-level rise. *Nature* **526,** 421–425. ISSN: 0028-0836 (2015).

82. Gasson, E., DeConto, R. M., Pollard, D. & Levy, R. H. Dynamic Antarctic ice sheet during the early to mid-Miocene. *Proceedings of the National Academy of Sciences* **113,** 3459–3464. ISSN: 0027-8424 (2016).

83. Golledge, N. R., Levy, R. H., McKay, R. M. & Naish, T. R. East Antarctic ice sheet most vulnerable to Weddell Sea warming. *Geophysical Research Letters* **44.** 2016GL072422, 2343–2351. ISSN: 1944-8007 (2017).

84. Mengel, M. *et al.* Future sea level rise constrained by observations and long-term commitment. *Proc. Natl. Acad. Sci.* **113,** 2597–2602. ISSN: 0027-8424 (2016).

85. Arthern, R. J. & Williams, C. R. The sensitivity of West Antarctica to the submarine melting feedback. *Geophys. Res. Lett.* **44,** 2352–2359. ISSN: 19448007 (2017).

86. Waibel, M. S., Hulbe, C. L., Jackson, C. S. & Martin, D. F. Rate of Mass Loss Across the Instability Threshold for Thwaites Glacier Determines Rate of Mass Loss for Entire Basin. *Geophysical Research Letters.* 2017GL076470, n/a–n/a. ISSN: 1944-8007 (2018).

87. Pattyn, F., Favier, L. & Sun, S. Progress in Numerical Modeling of Antarctic Ice-Sheet Dynamics. *Current Climate Change Reports* **3,** 174–184 (2017).

88. Stewart, A. L., Klocker, A. & Menemenlis, D. Circum-Antarctic Shoreward Heat Transport Derived From an Eddy- and Tide-Resolving Simulation. *Geophysical Research Letters* **45.** 2017GL075677, 834–845. ISSN: 1944-8007 (2018).

89. Niwano, M. *et al.* NHM–SMAP: spatially and temporally high-resolution nonhydrostatic atmospheric model coupled with detailed snow process model for Greenland Ice Sheet. *The Cryosphere* **12,** 635–655 (2018).

90. Durand, G. & Pattyn, F. Reducing uncertainties in projections of Antarctic ice mass loss. *The Cryosphere* **9,** 2043–2055 (2015).

91. Cornford, S. L. *et al.* Adaptive mesh, finite volume modeling of marine ice sheets. *J. Comput. Phys.* **232,** 529–549. ISSN: 00219991 (2013).

92. Nowicki, S. M. J. *et al.* Ice Sheet Model Intercomparison Project (ISMIP6) contribution to CMIP6. *Geoscientific Model Development* **9,** 4521–4545 (2016).

93. Vernon, C. L. *et al.* Surface mass balance model intercomparison for the Greenland ice sheet. *The Cryosphere* **7,** 599–614 (2013).

94. Nowicki, S. *et al.* Insights into spatial sensitivities of ice mass response to environmental change from the SeaRISE ice sheet modeling project I: Antarctica. *Journal of Geophysical Research: Earth Surface* **118,** 1025–1044. ISSN: 21699011 (2013).

95. Goelzer, H. *et al.* Design and results of the ice sheet model initialisation experiments initMIP-Greenland: an ISMIP6 intercomparison. *The Cryosphere* **12,** 1433–1460 (2018).

96. Zickfeld, K., Solomon, S. & Gilford, D. M. Centuries of thermal sea-level rise due to anthropogenic emissions of short-lived greenhouse gases. *Proceedings of the National Academy of Sciences* **114,** 657–662 (2017).

97. Clark, P. U. *et al.* Consequences of twenty-first-century policy for multi-millennial climate and sea-level change. *Nat. Clim. Chang.* **6,** 360–369. ISSN: 1758-678X (2016).

98. Thomas, Z. A. Using natural archives to detect climate and environmental tipping points in the Earth System. *Quat. Sci. Rev.* **152,** 60–71. ISSN: 02773791 (2016).

99. Robinson, A., Calov, R. & Ganopolski, A. An efficient regional energy-moisture balance model for simulation of the Greenland Ice Sheet response to climate change. *The Cryosphere* **4,** 129–144 (2010).

100. Ganopolski, A., Winkelmann, R. & Schellnhuber, H. J. Critical insolation-CO2 relation for diagnosing past and future glacial inception. *Nature* **534,** 1–2. ISSN: 0028-0836 (2016).

Highlighted references

Bamber et al.[6] A systematic, detailed and insightful review of Greenland Ice Sheet (and other land ice) mass balance changes between 1992 and 2016, that provides a very useful post-AR5 synthesis.

Hofer et al.[13] This study highlights the importance of Greenland cloud cover changes on surface energy and mass balance.

van den Broeke et al.[14] A state-of-the-science critical review of outstanding research questions in Greenland Ice Sheet surface mass balance work.

Fuerst et al.[27] Authoritative study on Greenland Ice Sheet future change and resulting sea-level rise to 2300, indicating that volume loss is mainly caused by increased surface melting and that the largest modelled uncertainties relate to surface mass balance and the underpinning climate projections rather than ice-sheet dynamics.

Tedesco et al.[36] An excellent and detailed review highlighting the importance of Greenland albedo changes.

Shepherd et al.[42] Most recent and up-to-date mass balance estimate of the Antarctic ice sheet showing significant increased contributions the ice sheet to SLR over the last decade.

DeConto and Pollard[58] High-end projections of Antarctic ice sheet contribution to SLR based on ice shelf hydrofracturing and subsequent ice cliff collapse.

Golledge et al.[81] Long-term (multi-millennial) projections of the Antarctic ice sheets and potential tipping points.

Pattyn et al.[87] Review on recent advances in modelling of the Antarctic ice sheet. Highlights our current understanding of ice-dynamical processes that are key to future predictions.

Nowicki et al.[92] Outline of the new phase of ice-sheet model intercomparisons linked to the Coupled Model Intercomparison Project CMIP6.

Figure 1: Annual mean surface mass fluxes (in Gt a^{-1}) as a function of global mean temperature anomaly with respect to the preindustrial era (1850-1920). (a) GrIS SMB, (b) GrIS runoff, (c) Antarctic SMB, (d) Antarctic surface melt. Red colours indicate model realizations of present-day ice sheets (RACMO2 and MAR forced by ERA reanalysis data). Blue colours indicate model realizations of future ice sheets. In panel (a) and (b), MAR is forced with CESM-CAM5 1.5 and 2.0 future scenarios (+1.5 and 2.0 °C w.r.t. preindustrial). In panel (c), RACMO2 is forced with a HadCM3 A1B scenario. In panel (d), CESM-CAM5 1.5 and 2.0 future scenarios include surface melt parametrized in terms of near-surface temperature[48]. Trend lines are shown for future (blue) model realizations. Boxes delimit two standard deviations in temperature and SMB components over the present-day period (red boxes) and the stationary climate over 2061-2100 in the CESM-CAM5 1.5 (light blue boxes) and 2.0 (dark blue boxes) scenarios. None of these simulations include coupling to an ice-dynamical model.

Figure 2: GrIS stability as a function of the imposed regional summer temperature anomaly (dT) with best-estimate model parameter values. (a) GrIS surface mass balance by sector versus dT, diagnosed from regional climate model simulations with a fixed, present-day ice-sheet topography. (b) Expected SLR contribution of GrIS after 1, 5 and 15 ka (solid, dashed and dotted lines, respectively) versus constant dT. The vertical lines in both panels show the probability of crossing the tipping point for melting the ice sheet (2.5%, 50% and 97.5% credible intervals) to 10% of its current volume or less, as estimated by an ensemble of dynamic quasi-equilibrium simulations of the GrIS under a slowly warming climate.[40].

Figure 3: MISI and MICI as main drivers for potential (partial) collapse of the Antarctic ice sheet. MISI (a) can lead to unstable retreat of grounding lines resting on retrograde bed slopes, a very common situation in Antarctica. MISI stems from a positive feedback loop between the increased (i) flux and (ii) ice thickness at the grounding line after the latter starts to retreat. MICI (b) is the result of collapse of exposed ice cliffs (after the ice shelf collapses due to hydro-fracturing) under their own weight. MISI applies for a retrograde slope bed, while MICI can also apply for prograde slopes. Both MISI and MICI are thus superimposed for retrograde slopes[58,87]. The red colour qualifies the heat forcing exerted by the ocean against the ice shelf basal surface.

Figure 4: AIS stability as a function of the imposed regional annual mean temperature anomaly. Changes in SMB (a) and SLR contribution (b) for AIS relative to 2000 CE as simulated under spatially-uniform temperature increases that follow RCP trajectories to 2300 CE and then stabilize[81]. Colored lines denote different years (CE) data are averages of ‘high’ and ‘low’ scenarios, denoting two different grounding-line parametrisations. Grey shading shows approximate equivalent global mean temperature anomaly for an Antarctic mean temperature anomaly of 1.5-2.0 °C, accounting for polar amplification.

Box 1: Projections of ice sheet mass loss

Projections of ice-sheets contribution to SLR are established using ice flow models that compute the evolution of ice sheets under given climate scenarios. Many of these models were constructed to study the evolution of ice sheets across glacial-interglacial cycles, and are not therefore ideally suited to making projections for this century. Accordingly, the last decade has seen the modelling community repurpose these many models, increasing the confidence in the skill of ice-sheet models (particularly interaction with boundary conditions, such as ice/ocean and ice/bedrock), but they still lag somewhat behind other areas of the climate system.

Atmospheric and oceanic forcings are the primary drivers of ice-sheet change, and knowledge of the evolution of precipitation and surface melt is obtained from regional or global circulation models or parametrizations, while ocean circulation models or parametrizations are used to provide melt at the front of marine-terminating glaciers and the underside of floating ice shelves. Accurate information on the properties of substrate underlying ice sheets (such as bedrock elevation and sediment rheology) are also important in determining reliable estimates of ice sheet evolution.

For low-emission scenarios and in the near term, the **initial state used by ice sheet models is a key control** on the reliability of their projections because the anticipated mass loss is relatively small in comparison to the total mass of the ice sheets. Two main families of initialization strategies are currently employed. The first is **spin-up** of the model over glacial-interglacial periods, which ensures that the internal properties of the ice sheet are consistent with each other but which may have an inaccurate representation of the ice sheets' contemporary geometry and velocity. The alternative is the

assimilation of satellite data, which may lead to inconsistencies in flow properties but has a greatly improved representation of current geometry and surface velocity. These two approaches lead to large differences in the initial conditions from which projections are made and therefore create a significant spread in projected contributions to future SLR, even when forced with similar datasets[29,94]. Disentangling the impacts of natural variability and forced climate change is also more difficult for these low emission scenarios, but new model intercomparisons tend to focus on this aspect[95].

Box 2: Climate commitment and tipping points

For the long-term evolution of the ice sheets, on multi-centennial to multi-millennial time scales, feedbacks with the atmosphere and ocean increase in importance. When subjected to perturbed climatic forcing over this time scale, the ice sheets manifest large changes in their volume and distribution. These changes typically occur with a significant lag in response to the forcing applied, which leads to the concept of climate commitment: changes that will occur in the long-term future, are committed to at a much earlier stage[96]. Because of the long residence time of CO_2 in the atmosphere, climate change in coming decades will most probably last long enough to dictate ice sheet evolution over centuries and millennia[41,58,81,97]. Furthermore, the ice sheets are subject to threshold behaviour in their stability, since a change in boundary conditions like climate forcing can cause the current ice-sheet configuration to be unstable. Crossing this so-called tipping point leads the system to equilibrate to a qualitatively different state[98] (by melting completely, for example). The existence of a tipping point implies that ice-sheet changes are potentially irreversible — returning to a pre-industrial climate may not stabilize the ice sheet once the tipping point has been crossed. A key concept here is the timeframe of reversal, because many ice sheet changes may only be reversible over e.g. a full glacial-interglacial cycle with natural rates of changes in climatic variables. For both Greenland and Antarctica, tipping points are known to exist for warming levels that could be reached before the end of this century[58,81,99]. The unprecedented rate of increase in GHGs over the Anthropocene leaves open the question of irreversible crossing of tipping points. For example, it is possible that the expected future increase in GHGs will prevent or delay the next ice sheet inception[100].