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The achievability of low-emission IPCC sea-level rise scenarios

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The Intergovernmental Panel on Climate Change (IPCC) AR6 report (2021) provides a range of projections on greenhouse gas emissions and global warming, and the consequential impact on global sea level through thermal expansion of sea water and by glacier and ice-sheet mass loss. This paper assesses the likelihood of lower IPCC sea-level rise scenarios (SSP1–1.9 and SSP1–2.6) in light of current ice-sheet observations and model limitations, alongside today's emissions trends and current shortfall of climate commitments. We conclude that 'low-end' projections may underestimate the true pace and magnitude of future sea-level rise and, if we continue on today's mid-higher emissions pathway (SSP3–7.0), sea-level outcomes of more than 1 m by 2100 should be planned for. The worst can still be avoided through rapid deep emissions reductions, but it is essential that the IPCC continues to reflect these true risks for decision-makers, with rises of more than 2 m this century and several metres thereafter a real possibility.

This article is part of the Theo Murphy meeting issue 'Next generation ice-sheet bed measurements'.

1. Introduction

Ice loss from glaciers and ice sheets is making the largest contribution to sea-level rise, with the contribution from ice sheets now surpassing that of glaciers

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[1–4]. This paper focuses on the contribution from ice sheets as they are not only the largest potential contributor to sea-level rise but also the source of the greatest uncertainty, particularly the Antarctic ice sheets.

The Intergovernmental Panel on Climate Change (IPCC)'s Sixth Assessment Report (AR6) [3] projects a damaging, yet relatively modest median range for global mean sea-level rise by 2100 of 0.38 m under SSP1–1.9 to 0.77 m under SSP5–8.5, while warning that substantially higher rises cannot be ruled out owing to uncertainties in ice-sheet dynamics not captured fully by current models. The report emphasises that large uncertainties persist regarding both the rate and the magnitude of sea-level rise, particularly beyond the twenty-first century. Its projected 17th–83rd percentile range for global sea-level rise by 2300 lies between 0.3 and 6.8 m, and up to 16 m under a high-impact, low-likelihood storyline [3]. Van de Wal *et al.* [5] provide 'high-end' sea-level rise estimates of 0.9–1.6 m by 2100 and 1.6–10.4 m by 2300, depending on emissions scenario, all of which fit within the IPCC's scenarios. Under further warming, ice sheets look set to make a contribution to global sea level at a level not seen since the last deglaciation.

Since the release of AR6, studies have largely supported sea-level rise estimates towards the mid- and upper-end of those likely ranges, whereas sea-level rise below the likely IPCC range is only statistically feasible if warming is limited to 1.5°C [6]. Observational data suggest that the pace of sea-level rise and ice mass loss is accelerating [4], with glaciers retreating faster than projected in some areas [7]. Hamlington *et al.* [8] report that rates of sea-level rise have more than doubled over the satellite era, from approximately 2.1 mm yr^{-1} in 1993 to approximately 4.5 mm yr^{-1} in 2023. They note that if this trend continues over the coming three decades, global sea levels could rise by 169 mm, consistent with mid-range IPCC projections. This is supported by Wang *et al.* [9], who find that extrapolating current observations continues to align with mid-range projections to 2050. In addition, Fricker *et al*. [2] demonstrated that extrapolating observed trends forward to 2100 leads to sea-level outcomes that exceed all medium-confidence projections. After 2100, Seroussi *et al*. [10] found that Antarctic mass loss could accelerate considerably, with model simulations indicating a potential sea-level equivalent (SLE) contribution of up to 6.9 m by the year 2300. Recent studies highlight how current ice-sheet models underestimate mass loss, suggesting that future sea-level rise could be greater than projected under 'likely' scenarios [7,11–14].

Given these risks, it is increasingly important to reassess the plausibility of low-emission sea-level rise scenarios. With current emissions trajectories placing us on course for approximately 3°C of warming [15], well beyond the SSP1–1.9 pathway, the lowest emissions scenarios may no longer represent realistic outcomes. In this paper, we evaluate recent evidence for sea-level rise projections at or above the high-end IPCC scenarios for 2100 and beyond, to ascertain whether we are heading into a second major phase of deglaciation, dominated by ice-sheet responses to greenhouse gas emissions.

We note that our criticism of the large knowledge gaps on this important topic is not criticism of the community that generated that knowledge, but of support levels that are not commensurate with the value of knowledge returned by additional research.

2. Committed sea-level rise

Ice-sheet dynamics and delayed responses to current warming mean that substantial sea-level increases are already committed over millennial time scales, irrespective of emissions scenarios [16]. For example, Box *et al.* [17] estimate that approximately 30 cm of additional sea-level rise is already committed from the Greenland Ice Sheet. In Antarctica, which has the capacity to drive much larger increases, Reese *et al.* [18] found mass loss from the West Antarctic Ice Sheet (WAIS) under present-day climate conditions ranges from 2.7 to 3.5 m SLE over multi-millennial time scales owing to ongoing ice-sheet destabilization processes that are difficult to observe and cannot be reversed once triggered. Such outcomes, irrespective of emissions, will mean substantial alterations to coastlines and coastal infrastructure, not to mention the lives and livelihoods that would be affected. When future emissions are factored in, even under low emissions scenarios, sea levels are projected to rise even further beyond what is already committed. For example, Klose *et al.* [19] project up to 6 m of sea-level rise from Antarctica under the low emissions scenario (SSP1–2.6) over multi-millennial time scales.

3. Past climate and sea-level change

Glaciological and geological records from past warm periods demonstrate that a relatively rapid, multi-metre sea-level rise is possible. For example, during the Last Interglacial (125 000–116 000 years ago), when global average temperatures were approximately 1°C warmer than pre-industrial levels (i.e. approx. 0.4°C cooler than now), sea levels may have reached 6–9 m higher than now [20], and evidence shows loss of ice from Antarctica probably exceeded the approximately 3 m SLE of ice contained in West Antarctica [21,22]. Further results indicate early extensive loss of ice from Antarctica, probably including all of West Antarctica and some East Antarctic ice, followed by partial regrowth as major ice loss shifted to Greenland [23,24]. Interpretation is complicated both by the asynchrony in the timing of peak ice loss between Antarctica and Greenland [25] and by evidence that the Ronne Ice Shelf, including the Skytrain Ice Rise, remained largely intact during this period [26]. Resolving paleo-sea levels during previous interglacials is clearly an imperative.

Meltwater pulses demonstrate the potential for abrupt sea-level rise. These events, triggered by the rapid decay of ice-age ice sheets [27], issued large volumes of freshwater to nearby oceans and led to ocean circulation change and knock-on consequences for regional climate. The last deglaciation led to approximately 130 m of sea-level rise over approximately 10 000 years between 20 and 10 ka. Sea-level rise was far from constant during this period, however. At approximately 14 650 years ago, the sea level is thought to have risen by almost 20 m within 500 years [28], triggered by ice loss, especially from the Laurentide Ice Sheet in North America, and with evidence of near-instantaneous ice-sheet ungrounding and rapid grounding line retreat of the Scandinavian Ice Sheet of 55–610 m per day [29]. Within the past 200 years, the Thwaites Glacier, which is considered vulnerable to rapid collapse and could destabilize much of the WAIS, has experienced retreat rates of more than 2.1 km per year [30]. Furthermore, a comparison of geological evidence and model simulations of changes in the Amundsen Sea sector of West Antarctica produced a 5000 year mismatch, with the model thinning earlier than suggested by the geological record and the record suggesting more rapid thinning of the ice sheet [31]. As Scambos & Abdalati [32] note, such past events 'raise the spectre of unseen surprises' in our future.

Although much current Antarctic research focuses on the vulnerable WAIS, the marine basins of East Antarctica have also experienced significant mass loss during past warm periods [33,34]. These basins, notably the Wilkes and Aurora subglacial basins, may hold the potential for significant contributions to sea-level rise beyond 2100, particularly if global temperature limits outlined in the Paris Agreement are exceeded [35].

When considered within the broader context in which ice-sheet models have often struggled to reproduce the full magnitude of sea-level rise inferred from proxy reconstructions, particularly when processes such as ice-shelf hydrofracture or Marine Ice-Cliff Instability (MICI) [36] are not included, these past analogues suggest that future projections solely from numerical ice-sheet models may underestimate the potential for nonlinear and rapid responses in ice dynamics. Moreover, because the current rate of global warming is much higher than for previous events in the geological record [37], ice sheets may be pushed past critical thresholds faster than at any time in geological history, suggesting that comparisons with the past may further underestimate the scale and speed of future ice loss and global sea-level rise.

4. Sources of future sea-level rise uncertainty

Projections of future sea-level rise are deeply uncertain, due in large part to limitations in observational data, incomplete understanding of important physical processes and discrepancies among modelling approaches. Worryingly, these uncertainties largely point to sea-level rise projections higher than current median estimates. They span several areas, including ice-sheet dynamics, ocean–ice interactions, emissions trajectories and the complex feedback driving polar climate variability. We must also remember that polar ice sheets remain in many parts unexplored, and in areas where reconnaissance geophysical data exist, the resolution of boundary conditions such as bed topography masks real glacial geomorphology and, because of this, key processes by which ice flows [38,39].

Siegert *et al*. [1] identified six ways in which ice-sheet modelling and sea-level rise projections could be improved: Mapping of subglacial topography and ice-covered bathymetry; collection of ocean data at ice-sheet margins; geophysical measurements of subglacial conditions and processes; improved coupling between ice, ocean and atmospheric models; laboratory, field and modelling investigations of ice fracturing; and resolving past changes to ascertain key glaciological driving processes. Some progress has been made, but there is still much work to do, with both Pattyn *et al*. [40] and Fricker *et al.* [2] reiterating the need for advancing knowledge in these areas.

(a) Emissions scenarios and temperature thresholds

The extent of future sea-level rise is heavily dependent on the trajectory of greenhouse gas emissions over the coming decades. DeConto *et al.* [41] found that limiting global warming to 2°C results in Antarctic ice mass loss rates similar to those observed today through to 2100. However, under a high-emissions scenario consistent with approximately 3°C of warming, the rate of Antarctic mass loss between 2060 and 2100 increases by an order of magnitude, aligning with rates seen during the last deglaciation. The full response of the Antarctic ice sheet under such a scenario is not expected to manifest until after 2100 [42], emphasizing the need to look beyond this date. When the IPCC published its First Assessment Report, the year 2100 was 110 years away; for the upcoming Seventh Assessment, it will be barely more than 70 years in the future.

In Greenland, the critical threshold for triggering abrupt and substantial ice-sheet loss is estimated to lie between 1.7 and 2.3°C of warming [43]. Under current emissions pathways, this threshold could be surpassed within the next few decades, making significant mass loss from the Greenland Ice Sheet increasingly likely over the coming centuries and millennia. Furthermore, a recent synthesis has concluded that sustained global temperatures exceeding 1°C above pre-industrial levels are sufficient to commit the planet to several metres of sea-level rise, indicating that the widely adopted 1.5°C limit may be inadequate to prevent long-term ice-sheet collapse [22].

Once net zero is reached, continued ocean heat uptake could continue to destabilize ice sheets, especially if warming thresholds have already been surpassed [16]. Some modelling studies, although not all, suggest that the WAIS may have passed a point of no return [44,45], and one study has shown little difference in Antarctic ocean warming between the most ambitious targets and mid-range emissions scenarios to 2100 [46]. Given that ice mass loss in Antarctica is strongly driven by ocean warming, this suggests that mid-range scenarios cannot be avoided, and emissions mitigation can only reduce the risk of the worst-case sea-level rise scenario for the twenty-first century. On a longer time scale, however, twenty-first-century emissions have a much greater influence on Antarctica's contribution to sea-level rise, with multi-metre differences between emissions scenarios in subsequent centuries [42].

If temperature thresholds are passed in the immediate future, more areas of the Greenland and Antarctic ice sheets become vulnerable to retreat and potential collapse over the following centuries and millennia. If the world moves beyond 2°C, there is a risk of cascading processes (sometimes referred to as tipping points), amplifying risks and increasing the rate of mass loss [47]. Even small differences in peak warming may have long-lasting effects on ice-sheet stability and global sea level.

(b) Model resolution and calibration

Seroussi *et al*. [10] highlight that the choice of ice-sheet model is the single largest contributor to uncertainty in long-term sea-level forecasts. Despite significant improvements in recent years [48], no ice-sheet model has prognostically reproduced the acceleration of mass imbalance of the Greenland and Antarctic ice sheets observed over the past 30 years [1]. This failure reflects both incomplete understanding and the difficulty of representing critical physical processes in numerical simulations, and limitations to major datasets and boundary conditions (such as bed topography) that are input to models.

One example of oversimplified parameterization within ice-sheet models lies in the Glen–Nye flow law, where the exponent n is usually set to a uniform value of 3. However, recent work suggests that n may vary significantly in space and time, particularly in rapidly evolving regions where $n = 4$ may be more appropriate [49]. Assuming a fixed value of 3, as has been the tradition in glaciology for many decades, can lead to systematic underestimations of ice flow in sectors undergoing dynamic thinning, thereby underplaying the potential for rapid retreat [11].

Another important oversimplification involves the basal lubrication of fast-flowing ice. In the Seroussi *et al.* [10] study, and many others, much of the difference between models arises from the specification of the exponent m in the sliding- or till-deformation law. Models generally specify a uniform value for their entire domain; however, data indicate strong spatial variations, suggesting that a single value is inappropriate [50].

Model resolution also presents a major limitation to successful outcomes. Ocean models typically resolve spatial scales on the order of 100 km, which fails to capture mesoscale phenomena such as eddies, sub-ice-shelf circulation and warm water intrusions [1]. Ice-sheet models similarly lack the spatial granularity required to accurately represent complex bed topography, which plays a critical role in modulating basal sliding and grounding-line migration. Such resolution limitations can obscure stabilizing features or fail to resolve pathways of rapid ice flow [51].

Model calibration plays a critical role in shaping sea-level rise projections, but it remains a significant source of uncertainty. Calibration involves adjusting model parameters to align with observational and/or geological data, yet the choice of observational constraints can significantly affect results, particularly over time scales beyond a century [52]. Felikson *et al.* [53] show that estimates of mass change can vary by as much as 119% depending on which datasets are used, highlighting the sensitivity of model outcomes to calibration design.

Emerging approaches aim to enhance calibration using machine learning (ML). ML techniques have the potential to refine parameter estimates, improve emulation of unresolved sub-grid processes and dynamically adjust model behaviour in data-rich regions. However, these methods require high-resolution, high-quality training data, which is something that remains scarce in many glaciological settings [51]. Without such data, the use of ML-enhanced calibration remains limited.

(c) Regional climate simulations, extreme weather and feedback

Accurately modelling regional climate change in polar regions remains a significant challenge, and general circulation models tend to underestimate the rate of warming at the poles [54]. Recent studies have highlighted the main drivers of uncertainty, including increased interannual climate variability, extreme weather events, and poorly resolved feedback mechanisms [55].

Extreme weather is an important driver of mass balance variations for both Greenland and Antarctica [56]. Since 2012, Greenland has experienced a sequence of extreme high and low melt anomalies, including periods in high summer (e.g. July 2012) when high temperatures led to the whole ice sheet experiencing surface melting, highlighting the increasing influence of interannual climate variability on glaciological extremes. These fluctuations have significant implications for surface melt, ice-flow dynamics and calving processes. Projections that fail to incorporate such variability risk substantial underestimation of long-term mass loss [55]. Beckmann & Winkelmann [57] project that under RCP8.5, Greenland's sea-level contribution could increase by an additional 2–45 cm by 2300 if the frequency of extreme events rises, with the ice sheet potentially losing an extra 6000–26 000 km^2 of area relative to projections without extremes.

Atmospheric rivers (ARs) further complicate regional climate dynamics. While ARs can temporarily increase surface mass balance through enhanced snowfall, particularly in East Antarctica, their net effect over longer time scales is concerning. These events can significantly amplify surface melting, especially along the coastal margins, contributing to the weakening and disintegration of ice shelves. Wille *et al*. [58] found that ARs are responsible for approximately 40% of total summer meltwater production across the Ross Ice Shelf and nearly 100% of meltwater in higher-elevation regions of Marie Byrd Land. During winter, ARs generate between 40 and 80% of meltwater on ice shelves such as Wilkins, Bach, George VI and Larsen B and C. Furthermore, ARs were linked to 60% of all calving events on the Antarctic Peninsula between 2000 and 2020 [59], highlighting their critical role in ice-shelf destabilization. Davison *et al*. [60] show that extreme variability in snowfall can have a significant short-term impact on West Antarctica's contribution to sea-level rise. This underscores the importance of accurately simulating both precipitation extremes and mean trends in regional climate models.

Observations from a 2021 AR event over Greenland show that it caused extensive surface ablation (removal of ice through melting or sublimation) and bare ice exposure, with the snowline climbing to 788 ± 90 m. Despite rainfall contributing only a minor portion of surface energy, the associated snow darkening had a strong amplifying effect on melt, increasing ablation by 28% at 1840 m elevation and by 51% at 1270 m [17]. This albedo-melt feedback is poorly constrained in models and leads to a highly nonlinear response to warming [61]. Zeitz *et al*. [62] found that the melt-albedo feedback alone can lead to an additional 12 cm of SLE of projected mass loss by 2300 under RCP2.6 and an additional 70 cm under RCP8.5. These results underscore the importance of surface feedback for future ice-sheet stability and highlight the urgent need to improve their representation within models.

(d) Topographic mapping, basal conditions and isostatic adjustment

Accurate representation of subglacial and basal conditions is critical for constraining future sea-level rise. Inaccuracies in subglacial data can significantly affect the reliability of model projections. One major limitation has been the incomplete mapping of coastal bathymetry in both Greenland and Antarctica [1]. Deep troughs, which often provide critical pathways for warm ocean water to access ice-sheet margins, are frequently smoothed out by interpolation methods, leading to an underestimation of vulnerability in ice-sheet models.

Progress has been made with the development of BedMachine Antarctica [38,63] and Bedmap3 [39], which have improved spatial resolution and data assimilation methods. However, uncertainties remain, particularly regarding bed roughness and its measurement biases. For example, radar flight orientation can influence the detection of bed features, potentially misrepresenting subglacial details that affect ice-flow dynamics. The roughness of the bed can make a significant difference to sea-level rise projections [38]. Rough beds can slow glacier retreat, but interpolation tends to smooth the bed, and the use of these parameters may overestimate mass loss. Swath radar and other focused techniques can greatly improve knowledge of the bed [64], but remain difficult and highly limited.

Till rheology (flow and deformation) is poorly constrained, and the mechanical behaviour of subglacial sediments varies significantly between hard and soft beds, affecting sliding velocity. Recent efforts have focused on developing new parameterizations for spatially heterogeneous basal materials [65]. Aitken *et al*. [66] used a suite of geophysical techniques to understand the location and distribution of sedimentary basins in Antarctica, to understand their potential influence on ice flow (including through groundwater [67]). Such information has yet to be adopted in most ice-sheet modelling, however.

Another uncertainty arises from glacial isostatic adjustment (GIA). GIA can have a stabilizing effect by uplifting bedrock and reducing grounding line retreat on decadal to centennial time scales [68]. However, the magnitude and spatial distribution of this response depend critically on the rheology of the underlying mantle. In many ice-sheet models, GIA is simplified using spatially uniform Earth models, which can misrepresent stabilizing feedback. Coulon *et al*. [69] found that using uniform Earth models may overestimate GIA's stabilizing effect, potentially underestimating continent-wide mass loss.

Uncertainties in geothermal heat flux (GHF) have been identified as a significant factor compounding the overall uncertainty in projections of sea-level rise [70]. However, it remains one of the least constrained inputs in ice-sheet modelling. For large sectors of both Greenland and Antarctica, GHF estimates rely on sparse proxy data and coarse geophysical models. In addition, ice-sheet models struggle to incorporate deformational heating processes. Recent work [71] shows that many models fail to replicate observed borehole temperature profiles, underscoring the gap between theoretical representations and real-world thermomechanical behaviour.

It is unknown whether approximately one third of the Greenland Ice Sheet ice-bed interface is frozen or thawed [72]. This ambiguity in the basal state contributes to substantial variability in modelled ice discharge, particularly from fast-flowing regions such as the Northeast Greenland Ice Stream, where GHF-related uncertainty alone has been linked to an estimated 2.10 Gt yr^{-1} of uncertainty in mass loss [73]. Accurately measuring and modelling these basal conditions requires resolving subglacial topography at sub-kilometre scales [74].

(e) Subglacial hydrology

Simulating the evolution of subglacial hydrology is essential for projecting ice-sheet sensitivity to climate and for associated contributions to sea-level change [75]. However, current numerical subglacial hydrology models are computationally expensive, limiting their application in large-scale or long-term ice-sheet simulations. As a result, the dynamic evolution of subglacial drainage is often neglected or highly simplified in continental-scale models, introducing a key source of uncertainty in projections.

Recent research highlights the significant implications of these omissions. Zhao *et al*. [14] found that incorporating dynamic subglacial hydrology can increase projected ice discharge from the Antarctic ice sheet by up to a factor of three compared to standard models, potentially contributing an additional 2.2 m to global sea-level rise by 2300.

Groundwater remains another area of potential significance to the flow of ice in both Greenland and Antarctica that is both poorly constrained and understood, and thus presently lacking in ice-sheet models [67].

Gourmelen *et al*. [76] show that increased subglacial flooding events could either stabilize or destabilize West Antarctic ice loss. On one hand, episodic water drainage might reduce ice–ocean interaction by flushing warm water away from grounding lines. On the other hand, it could trigger abrupt changes in ice flow by altering basal stress and grounding zone position. These competing influences highlight the complexity of subglacial processes and the need for more nuanced representation in predictive models.

To address these issues, researchers are exploring novel methods to accelerate simulations. For example, Verjans & Robel [77] demonstrate the potential of ML to emulate the results of physically based subglacial hydrology models with significantly reduced computational demand. These surrogate models can capture behaviours of water flow and storage while enabling longer and larger-scale simulations that were previously not feasible.

(f) Ice shelves, grounding lines and ice–ocean interaction

Observational data on ocean conditions along the coastlines of Antarctica and Greenland remain sparse and are often limited to short time series. This lack of *in situ* measurements hampers the ability to accurately constrain basal melt rates, sub-shelf ocean circulation and the thermal forcing that governs ice-shelf thinning and grounding line retreat. Consequently, thermal ocean forcing is often poorly represented in ice-sheet models [1], leading to underestimation of retreat rates [78–80].

Milillo *et al*. [7] found that in certain regions of Antarctica, grounding line retreat is progressing more rapidly than simulated by existing models on annual time scales. They attribute this discrepancy to inadequately resolved ice–ocean interactions.

Increased sub-shelf melting is a primary driver of mass loss from the Amundsen Sea sector of Antarctica, and the potential for ice-shelf disintegration remains a major source of uncertainty in projections of Antarctic contributions to future sea-level rise [5]. A transition to a warmer ocean regime within sub-ice-shelf cavities has the potential to initiate irreversible retreat of the grounding line, particularly in vulnerable regions such as the Ronne–Filchner and Ross ice shelves [48]. Should such a transition occur, ice loss from these currently more stable sectors could accelerate dramatically, mirroring the rapid changes already underway in the Amundsen sector. Changes in sub-shelf cavity geometry have been shown to substantially influence basal melt rates, with variations near the grounding line ranging from a 75% reduction to a 75% increase [81]. This is particularly important because sub-shelf cavity geometry is often poorly constrained.

While grounding line representation in ice-sheet models has improved in recent years, significant physical processes remain under-represented. One such process is seawater intrusion beneath grounded ice, which has been proposed as a critical mechanism that could accelerate mass loss from the WAIS [13]. Observational evidence suggests that pressurized seawater can intrude several kilometres inland beneath grounded ice, exacerbating the ice-sheet's vulnerability to oceanic warming. Rignot *et al.* [13] argue that this mechanism may help to explain the discrepancy between the rapid ice loss observed in recent decades and the slower retreat predicted by current ice-sheet models. Furthermore, seawater intrusion could act as a tipping-point process, potentially triggering runaway retreat and a greater-than-anticipated contribution to global sea-level rise [78].

(g) Calving and marine ice cliff instability

Despite its central role in glacier dynamics and sea-level rise, no universally accepted robust iceberg calving law currently exists, which continues to constrain the ability of numerical models to simulate calving events. Calving rates have been prescribed using simplistic assumptions, such as setting them equal to ice velocity at the terminus. Greene *et al*. [12] report that simplified or poorly resolved calving schemes may have led to an underestimation of mass loss from Greenland by as much as 20%.

Recent studies have begun to address these limitations through the use of continuum damage mechanics. This framework models the initiation and evolution of microfractures within the ice as crevasses, which form due to tensile stresses and propagate vertically through the ice column. These crevasses weaken the ice structure by reducing its effective viscosity and can be advected downstream with the ice flow, eventually contributing to large-scale calving events [40]. Such improvements in crevasse modelling offer promise for better representing the transition from surface damage to full-thickness failure, but observational constraints and parameter uncertainty remain significant challenges.

Beyond a critical threshold in ice-shelf stability, which is influenced by factors such as crevasse characteristics, side shear, nature and abundance of pinning points, and meltwater wedging, ice shelves break off entirely. To date, no persistent regrowth of an ice shelf has been observed, indicating a pronounced hysteresis in which the system does not readily return to its previous state even if external conditions are reversed [82]. Breakoff exposes an ice cliff to damage in many ways, including undercutting by melting and opening of crevasses behind the unsupported cliff, and introduces additional stresses related to the cliff, all of which tend to increase the rate of thinning, leading to the retreat of grounded ice. Such processes are not generally included in large models.

One of the central processes accounted for under the IPCC's high-impact, low-likelihood scenario is MICI [83]. It suggests that once an ice cliff exceeds a critical height (approx. 100 m), it will become structurally compromised and collapse under its own weight, potentially triggering a feedback loop of retreat and accelerating sea-level rise. However, this process remains a subject of ongoing debate, with proponents as well as critics noting large uncertainties.

No ice cliffs of the necessary height currently exist to directly observe MICI processes. Edwards *et al.* [84] caution that projections incorporating MICI may have overestimated its role in twenty-first-century sea-level rise, partly due to limited observational validation. They argue that increased confidence in MICI-based projections will require a broader ensemble of models with improved physical representation of ice-shelf collapse and stress thresholds. Although our knowledge of the processes involved in MICI remains limited, ice cliffs that exceed a certain height are likely to fail, reinforcing the potential for instability [85]. Given the potentially dramatic impact of MICI on ice-sheet loss and sea-level rise, it cannot be discounted or ignored in discussions on future sea-level rise.

5. Likelihood of achieving low emissions targets

Recent assessments show that the feasibility of achieving the IPCC's SSP1–1.9 pathway, which aligns with the Paris Agreement's 1.5°C goal, is increasingly in doubt [15]. Achieving this target would require not only deep and immediate emissions cuts but also the large-scale deployment of carbon dioxide removal technologies. These nascent technologies cannot be relied upon, with uncertain scalability, high costs, and significant energy demands [16,86].

Recent observations further erode confidence in the achievability of the multi-year average 1.5°C threshold. According to the Copernicus Climate Change Service [87], the year 2024 was the first full calendar year to exceed 1.5°C above pre-industrial levels. Bevacqua *et al.* [88] state that the 1.5°C threshold will be permanently exceeded by the early 2030s in the absence of immediate and stringent mitigation efforts. However, owing to the way the threshold is calculated, we shall only be able to confirm the breach of 1.5°C a decade after the event. Therefore, it serves as a delayed and impractical benchmark for informing urgent policy decisions.

Current nationally determined contributions remain insufficient to keep warming below 1.5°C, and many countries are falling short of forming and enacting policies in support of their own pledges. The United Nations Emissions Gap Report [15] estimates that, without enhanced ambition and immediate policy implementation, global temperatures are likely to rise by 2.6–3.1°C by the end of the century.

Surpassing the 1.5°C threshold significantly increases the likelihood of triggering self-reinforcing climate feedbacks that could lead to irreversible global environmental change [89,90]. This could release additional greenhouse gases and further accelerate warming and ice-sheet melt [91].

While speculative geoengineering strategies such as solar radiation management have been proposed to counteract warming, research shows that these interventions are not viable substitutes for emissions reductions. In polar regions, in particular, geoengineering is not a workable approach to prevent the destabilization of ice sheets or avoid sea-level rise [92]. Moreover, such approaches carry substantial geopolitical, ethical, financial and environmental risks.

6. Policy implications

Rapid and decisive action to reduce greenhouse gas emissions remains the only reliable way to minimize the risk of worst-case sea-level rise scenarios. Delays in mitigation come with escalating costs yet, despite decades of scientific warnings and international climate negotiations, meaningful global reductions in emissions have yet to materialize. Far from being an excuse not to act, uncertainties in sea-level rise projections mean that delaying action raises the spectre of unpleasant surprises.

These delays mean that, in addition to mitigation, adaptation planning is now essential. Rising sea levels are inevitable, even with low emissions, and governments must invest in ice-sheet research at a scale that reflects the magnitude of the threat if they want to make appropriate decisions [93]. Without such efforts, decision-makers risk underestimating the long-term consequences of inaction, leaving coastal communities unprepared for the changes ahead. Long lead times for action, such as those needed for relocation of major settlements, mean that plans should include a contingency for high-impact scenarios [5].

Every fraction of a degree in avoided warming now translates to reduced long-term sea-level rise and a more manageable adaptation burden in the decades and centuries ahead. Today's policy-makers face a critical ethical and practical question: How much of future generations' settlements, land and infrastructure is today's society prepared to sacrifice to the sea?

7. Future research directions

The upcoming Fifth International Polar Year (IPY) in 2032–2033 presents a critical opportunity for the scientific community to undertake a globally coordinated effort to study polar climate processes and effects. Building on past international collaborations, this initiative can serve as a catalyst to address key uncertainties in projections of sea-level rise and broader Earth system responses.

Several research priorities have emerged that will help to improve the predictive capacity of ice-sheet modelling and thus reduce uncertainties in sea-level rise projections:

(a) Improved mapping of seafloor bathymetry and subglacial topography

High spatial and temporal resolution mapping of the ocean floor and subglacial bed is critical to constraining sea-level rise projections. Swath multibeam surveys can be used to generate realistic maps of sub-ice geomorphology, enabling more accurate estimates of bed roughness. Automation of data processing would speed up the pathway from collection to use. In addition, re-processing existing datasets could yield more accurate and useful products.

(b) Renewed focus on glacial geomorphology

Geomorphological evidence of past glaciation provides crucial insights into ice dynamics, retreat mechanisms and stability thresholds. As mapping of the basal topography improves, this knowledge will allow us to integrate geomorphological data into probabilistic sea-level rise projections.

(c) Better-constrained geothermal heat flux

GHF exerts a critical control on basal ice-sheet conditions, influencing melt rates and ice-flow behaviour. However, current estimates remain poorly constrained, especially across East Antarctica, where direct observations are sparse. Reducing this uncertainty will require expanded borehole drilling, alongside enhanced use of indirect geophysical methods and modelling.

(d) Enhanced monitoring across temporal and spatial scales

Sustained, high-resolution monitoring of ice–ocean–atmosphere interactions is essential for detecting early signs of instability and validating model predictions.

Large-scale international collaborations will be increasingly critical for data collection. The upcoming Antarctica InSync project exemplifies this approach, bringing together diverse stakeholders from academia, government, industry and philanthropic organizations to advance cross-disciplinary research.

Remote sensing capabilities optimized for polar regions will continue to play an important role. Notable missions include the European Space Agency's CRISTAL (Copernicus Polar Ice and Snow Topography Altimeter) mission and NASA's NISAR (NASA-ISRO Synthetic Aperture Radar), successfully launched on 25 July 2025, both of which are designed to provide critical insights into ice-sheet dynamics and cryospheric change.

In areas where satellite coverage is limited or unavailable, the expanding use of unmanned aerial vehicles (UAV) and autonomous underwater vehicles (AUV) is opening new opportunities for fine-scale, high-frequency observations in otherwise inaccessible environments.

(e) Expanded geophysical field campaigns in vulnerable sectors including in East Antarctica

While the WAIS has received considerable attention owing to its marine-based configuration and current retreat, much of its bed remains unmeasured. New bed measurements, collected in ways most useful to models, are clearly needed. Furthermore, large regions of the East Antarctic bed remain under-sampled and poorly resolved. Recent studies indicate that ice-sheet sectors such as Wilkes Land and the Aurora and Recovery subglacial basins could be highly vulnerable to oceanic warming and ice-shelf weakening, underlining the urgency for targeted geophysical measurements [35,94].

(f) Extreme weather and Antarctic ice-shelf vulnerability

Antarctica is increasingly experiencing extreme events, such as ARs and marine heatwaves, that pose significant risks to ice-shelf integrity [56]. These events are often poorly represented in models but may play a decisive role in triggering ice-shelf collapse and accelerating upstream ice flow. Better modelling of extreme weather events in polar regions, alongside improving understanding of the physical mechanisms underlying ice-shelf weakening and collapse, is a priority. Integration of these processes into coupled Earth system and ice-sheet models is essential for reducing uncertainty in future sea-level rise projections.

(g) More sophisticated modelling

The development of next-generation ice-sheet models is essential for accurately quantifying future sea-level rise risks [2]. These models must be capable of incorporating high-resolution (less than 1 km) topographic and geophysical data. They should also capture complex Earth system feedback through full coupling. This includes tipping points, such as Atlantic meridional overturning circulation shutdown, and other nonlinear climate responses, as well as processes that are currently unknown or poorly constrained. A central priority is the quantification of structural and parametric uncertainties, which will enable more robust probabilistic projections that encompass the full spectrum of plausible future scenarios, thereby improving risk assessment and decision-making.

8. Ways forward for the IPCC

The IPCC's low-impact scenarios warrant reassessment. If governments have not put forward policies to achieve these scenarios and their feasibility relies on the large-scale deployment of carbon dioxide removal technologies, they will not be achievable. Given current emissions trends and geopolitical instability, it may be necessary to reconsider which pathways are realistically within reach.

Observations suggest we are currently tracking sea-level rise pathways consistent with intermediate- to high-emission scenarios [2]. These trajectories are already producing rapid increases in the rate of sea-level rise [8], with some regions, such as the Western Pacific, already experiencing greater increases than the global average [3]. Future sea-level rise is projected to be amplified in the tropics, the Northwest Atlantic and the Austral Ocean [95]. Ice-sheet models are unable to adequately resolve some processes [1,2]; consequently, projections may underestimate the true pace and magnitude of future sea-level rise.

It is essential that the IPCC continues to reflect the true risks of future sea-level rise, especially within its summary for policy-makers. Higher-end sea-level outcomes cannot be ruled out and, indeed, if we continue on the mid-higher emissions pathway, they should be expected. Such an outcome would profoundly change our future world in ways not experienced since the last deglaciation and could severely test international governance arrangements and treaties, which were not set up to deal with such events. The worst can still be avoided, however, through rapid, deep emissions reductions. The window to secure the low-emissions outcome is closing, however, which means that decision-makers must begin to fully appreciate that sea-level rises of more than 1 m and even over 2 m within this century, and of several metres thereafter are a real possibility [96; 3].

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