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Communicating future sea-level rise uncertainty and ambiguity to assessment users

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Future sea-level change is characterized by both quantifiable and unquantifiable uncertainties. Effective communication of both types of uncertainties is a key challenge for translating sea-level science to inform long-term coastal planning. Scientific assessments play a key role in the translation process and have taken diverse approaches to communicating sea-level projection uncertainty. Here, we review how past Intergovernmental Panel on Climate Change (IPCC) and regional assessments have presented sea-level projection uncertainty, how IPCC presentations have been interpreted by regional assessments, and how regional assessments and policy guidance simplify projections for practical use. This information influenced the IPCC Sixth Assessment Report (AR6) presentation of quantifiable and unquantifiable uncertainty with the goal of preserving both elements as projections are adapted for regional application.

Future sea-level change is characterized by two qualitatively different types of uncertainty: quantifiable uncertainty, which can be represented by single, well-defined probability distributions, and ambiguity, a form of deep uncertainty that cannot be so represented (for further explanation, see Box 1) [1]. Ambiguity arises when analysts do not know or cannot agree upon key structural relationships within a system and/or the probability distributions describing key parameters [1–3]. It emerges in situations in which reasonable analysts can interpret a common set of facts in highly divergent ways (or cannot interpret them at all) and results in disagreement among probability distributions for key outcomes estimated using alternative approaches [3]. For example, quantifiable uncertainty is reflected in individual probability distributions of projected 21st century sea level change, while ambiguity is reflected in the divergence among alternative distributions (Fig. 1a, b).

The sources of ambiguity in sea-level projections include process-level structural uncertainty and other difficult to quantify aspects, particularly involving ice sheets and their interactions with other components of the climate system. Socioeconomic factors, particularly those controlling emissions, are also a source of ambiguity, and have long been addressed by making projections conditional upon emissions scenarios; this approach does not differ in treatment between sea level and other climate projections [4,5]. Sea-level projections extending only a few decades into the future and under lower emissions scenarios exhibit less ambiguity than do projections in the longer term and under higher emissions scenarios [6,7]. Ambiguity poses a challenge for decision frameworks, such as benefit-cost analysis, that presume the existence of well-defined distributions. For risk- and ambiguity-averse decision makers with substantial value at stake, ambiguity may require the application of robust decision-making approaches, such as the development of 'adaptation pathways' that begin with low-regret options and identify contingencies to be followed adaptively as various socioenvironmental thresholds are neared [8–12].

A comprehensive scientific characterization of uncertainty and ambiguity is information rich and too complicated for many applications. As a result, coastal adaptation policies – such as conservation and development regulations, building codes, and land use and infrastructure plans – often simplify the scientific sea-level projections to a small set of sea-level scenarios of future change [13–16]. Here, we define scientific 'sea-level projections' as quantitative estimates of the likelihood of different amounts of sea level rise over time, typically conditional upon assumptions about emissions (e.g., the Representative Concentration Pathway or Shared Socioeconomic Pathway climate scenarios) and other relevant processes. We define decision-oriented ‘sea-level scenarios’ as quantitative values or trajectories of sea level intended as reference points for decision-making [17]. Projections describe the future, while scenarios guide decision making about the future. This distinction based on purpose and practice differs modestly from more theoretical definitions that consider emissions-conditional probabilistic projections a form of scenario [18].

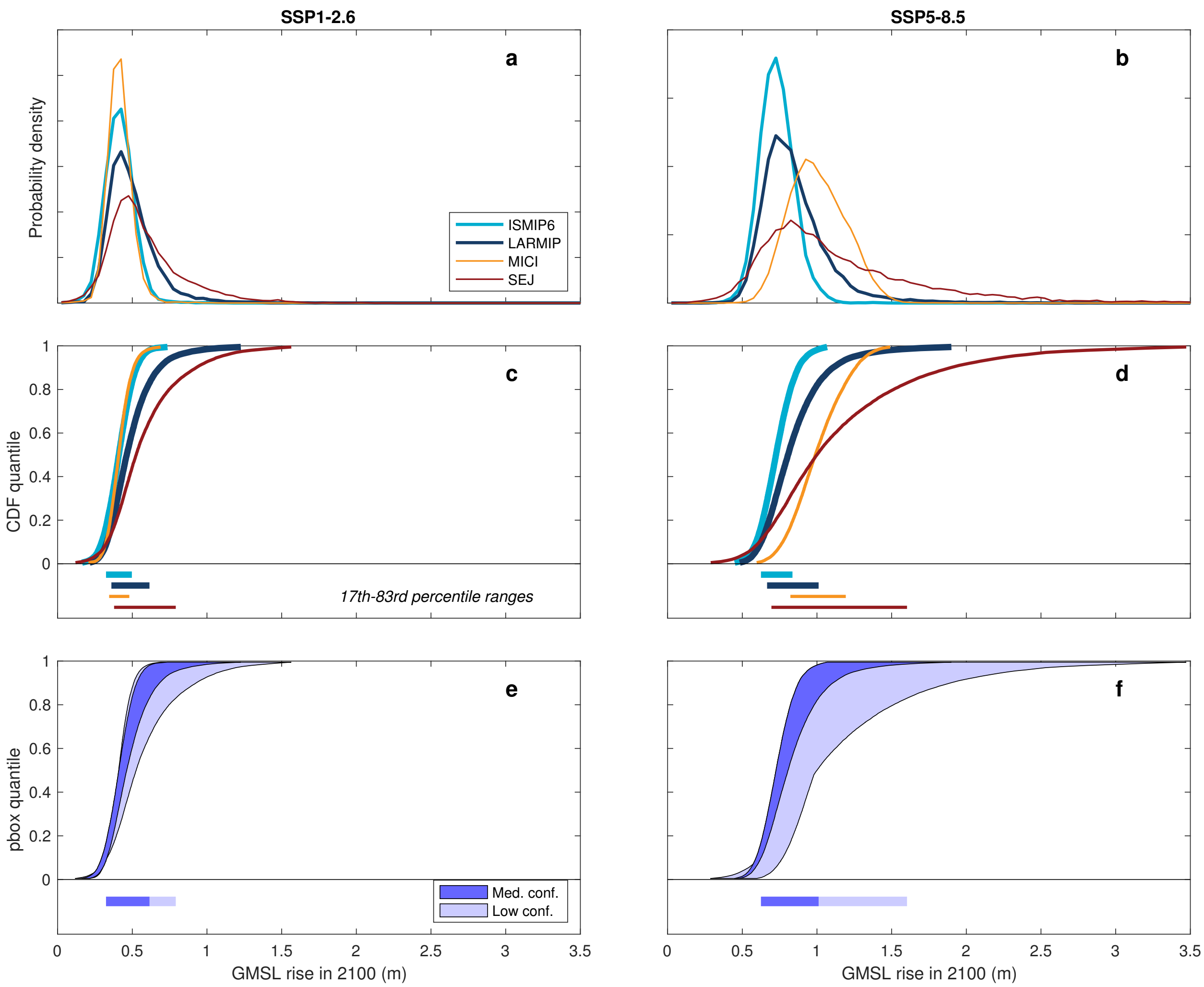


Fig. 1. Generation of 2100 global mean sea level (GMSL) projection p-boxes in AR6. Distributions are shown for the low emissions SSP1-2.6 scenario (a, c, e) and the very high emissions SSP5-8.5 scenario (b, d, f). (a-b) Four alternative probability distributions, incorporating Ice Sheet Model Intercomparison Project for CMIP6 (ISMIP6, light blue), Linear Antarctic Response Model Intercomparison Project (LARMIP, dark blue), Antarctic Marine Ice Cliff Instability-permitting (MICI, orange), and structured expert judgement-based (SEJ, red) ice-sheet projections. (c-d) Cumulative distribution functions corresponding to the probability distributions in a-b. (e-f) *Medium confidence* (dark blue) and *low confidence* (light blue) p-boxes. The width of the p-box provides a metric of ambiguity. Bars at bottom of panels c-f show the lower 17th-upper 83rd percentile range for each distribution/p-box. AR6 interpreted the lower 17th-upper 83rd percentile range of the *medium confidence* p-box as representing the *likely* contribution of included processes to GMSL rise. Likelihood labels were not ascribed to other ranges.

Sea-level scenarios are derived from scientific sea-level projections through the work of 'boundary chains' [19,20], which are sets of boundary organizations [21] that together link primary research to policy and practice (Fig. 2). Scientific assessment panels play key roles in these boundary chains, providing a point at which information is collected, judged, synthesized, and approved by a group of experts (and in some cases, also approved by government representatives or other decision makers) [22]. The IPCC Working Group 1 (WG1, physical science) integrates many years of scientific literature into projections of global – and, in the most recent assessments, regional – sea-level change under different emissions scenarios. These projections are often key inputs into national or subnational sea-level assessments (hereafter, 'regional assessments'); in some cases, the IPCC's numerical values and its framing of uncertainty are adopted with little modification by regional assessments, and in almost all cases, they serve as an important point of comparison. Regional assessments (and, in some cases, the IPCC assessment directly) in turn inform policy documents that guide adaptation practice and may have the force of law. Along the boundary chain, information is targeted and simplified: from an ensemble of different projections in the primary literature, to a systematized, synthesized set of projections in the IPCC assessment, and ultimately to a single or small number of scenarios guiding practice [14,23].

Foundational to the concept of boundary chains is Gieryn's concept of 'boundary objects' and the work necessary to create and maintain these objects [24]. Boundary objects are knowledge products that help translate between scales of governance, serve as adaptable items between different audiences, and articulate boundaries between epistemic domains and types of expertise [24–26]. In this Review, we focus upon key sea-level rise figures and tables that serve as boundary objects that are communicated, repackaged, and reframed along the sea-level boundary chain and as 'anchoring devices' that focus epistemic attention and criticism [27,28]. Boundary objects have been deployed from assessment to applied contexts to help "bridge conflicting logics" and assist in decision making [29]. As architectural elements, figures and tables stand out from assessment report text and receive more attention during drafting, review, approval, and post-publication presentation; how to represent uncertainty and ambiguity in these elements is thus a critical choice faced by assessment authors. Different ways of communicating quantifiable uncertainty and ambiguity in assessment reports, and particularly in these boundary objects, can lead to different interpretations in subsequent links on the boundary chain and thus, potentially, to different policy outcomes.

Scientific assessment reports often have important audiences outside the sea-level boundary chain: for the IPCC, for example, the primary audiences include the governments participating in the United Nations Framework Convention on Climate Change and the general public. Other work has examined the efficacy of IPCC choices regarding uncertainty communication in the broad context of public communication about climate [29–40]. This substantial literature has been instrumental in the maturation of uncertainty guidance and usage within the IPCC reports and in international decision making. However, while the iterative pipeline of uncertainty guidance and implementation within the IPCC is generally robust, the same cannot be said of the translation of IPCC ambiguity into other assessment and decision-making contexts.

Because the pathway from assessed scientific projections to adaptation policy guidance is particularly direct in the context of sea-level rise [7], this Review focuses specifically on communication of future sea level information along the major connections of the research-to-policy boundary chain. It examines the history of uncertainty and ambiguity communication in sea-level projections, with a primary focus on scientific assessment reports, and places the approach adopted by the IPCC's Sixth Assessment Report (AR6) in historical context. In addition to contributing to the scholarship on sea level assessment, we seek to highlight key choices about uncertainty and ambiguity communication for assessment authors and to help users along the boundary chain understand the conceptual framings that underlie these choices. We argue that the AR6 approach, which explicitly communicates both types of uncertainty using key boundary objects, will ease the task of policy makers who must balance the two types of uncertainty based on risk context at the regional level.

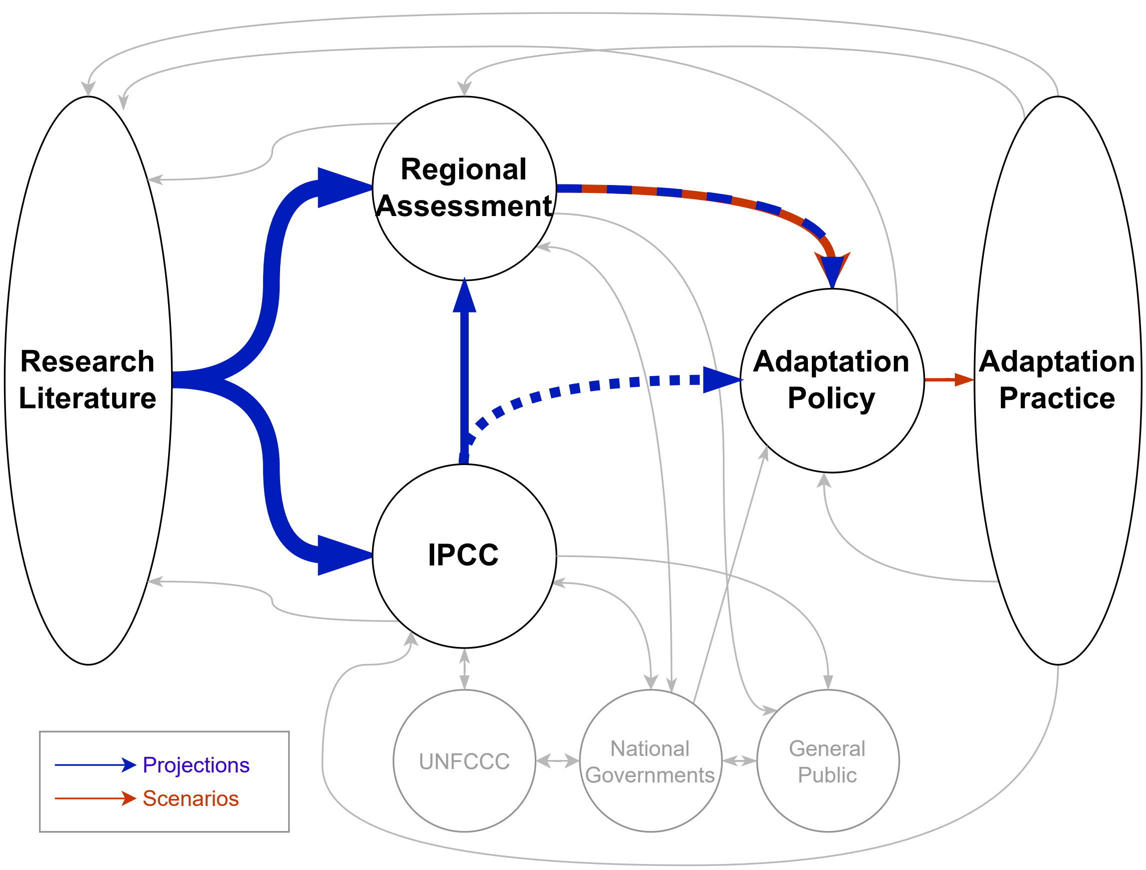


Fig. 2. The boundary chain linking the research literature about future sea-level change, via the IPCC and regional assessments, to adaptation policy and practice. Arrows reflect the flow of information. Projections, as produced in the scientific literature and synthesized by the IPCC, express the likelihood of different amounts of sea-level change over time, under different emissions scenarios and other varying assumptions. Scenarios, as recommended by policy guidance and in some cases produced by regional assessments, simplify this scientific information into a small number of sea levels or time-series of sea levels to guide practice. Declining widths of colored arrows represent the simplification of information along the boundary chain. Feedbacks along the entire chain, reflected in the grey arrows, can inform the questions researchers and assessment panels ask and how they communicate their results. This right hand side of this diagram is highly simplified; adaptation policy, for example, may pass through multiple levels of governance before influencing specific practical decisions.

Box 1 | Uncertainty and ambiguity

The distinction between quantifiable uncertainty and ambiguity has a long history in risk analysis. Frank Knight [94] distinguished between "measurable uncertainty," which he also dubbed "Risk," and "unmeasurable uncertainty," for which he reserved the term "Uncertainty" and which is sometimes referred to in subsequent literature as "Knightian uncertainty." Knightian risks are characterized by quantifiable probability distributions, and therefore can be the subject of confident investments by risk-taking businesses; Knightian uncertainties cannot be.

The term 'ambiguity', introduced by Daniel Ellsberg [2] as a metric of Knightian uncertainty, is an inverse measure of "the amount, type, reliability, and unanimity of information." Greater ambiguity is associated with lower confidence in an assessment of probabilities, and vice versa. In situations of ambiguity, people may exhibit preferences among different possible actions that are not consistent with describing states of nature by a single, self-consistent probability distribution. Ambiguity arises when multiple reasonable probability distributions over states of nature exist and analysts are not confident assigning weights to them or cannot agree on how to do so.

The concept of ambiguity is closely related to the concept of 'deep uncertainty', defined by Lempert et al. [3] as referring to states when "analysts do not know, or the parties to a decision cannot agree on, (1) the appropriate models to describe the interactions among a system's variables, (2) the probability distributions to represent uncertainty about key variables and parameters in the models, and/or (3) how to value the desirability of alternative outcomes." The first two elements of the definition of deep uncertainty are associated with high ambiguity, low confidence, and the absence of unanimity, though the 'deep uncertainty' framing suggests a more dichotomous criterion than that of ambiguity.

The IPCC began to formalize uncertainty guidance with the Third Assessment Report and, over time, its approach has matured to reflect epistemic diversity in the concept, in understanding and usage. Though the IPCC did not use the term 'ambiguity' or acknowledge its Ellsbergian heritage, since the Fifth Assessment Report it has formally distinguished between two axes of uncertainty: likelihood and confidence [89,95]. Likelihood corresponds to quantifiable uncertainty, although in IPCC usage the probabilities reflected with likelihood terms are usually imprecise probability terms (e.g., '*likely*' means '66-100% probability' and '*very likely*' means '90-100% probability'). Confidence is a measure of the "type, amount, quantity and consistency of evidence" and the "degree of agreement" – with increasing confidence closely paralleling decreases in Ellsbergian ambiguity. (In AR4 and subsequent IPCC reports, formally defined likelihood and confidence terms are italicized.) Building on the IPCC typology, ref. 18 suggested presenting sea-level projection uncertainty using tiered imprecise probability distributions of different levels of confidence, a concept developed independently by the AR6 author team and closely related to Ellsberg's original conception of the relationship between ambiguity and probability distributions.

Probability boxes, or p-boxes, provide a convenient way to visualize the distinction between quantifiable uncertainty and ambiguity (Fig. 1c-f) [96,97]. Where multiple probability distributions (e.g., Fig. 1c-d) can describe a quantity, the p-box (e.g., shaded areas in Fig. 1e-f) delimits the probability bounds that contain all their cumulative distribution functions. For example, the 83rd percentile of the p-box covers the values from the lowest 83rd percentile to the highest 83rd percentile of all distributions considered. All probability distributions will agree that there is at least a 66% likelihood (i.e., in IPCC terminology, that it is *likely*) that the true value of a quantity lies between the lower 17th percentile and upper 83rd percentile of the p-box (e.g., compare shaded areas and bars in Fig. 1e-f). The width of the p-box is a metric of ambiguity: where there is a high degree of unanimity in the estimate of a given percentile, the p-box will be narrow, while where there is a high degree of ambiguity, the p-box will be wide.

The presence of ambiguity in sea-level and climate projections has implications for decision-making paradigms [7,10–12]. Benefit-cost analysis (BCA), for example, derives from a subjective expected utility maximization approach, which requires both well-defined probability distributions and preferences that are reducible to a unidimensional utility function [10]. Ambiguous inputs to a decision analysis violate the first requirement and are also often associated with more complex preference structures. Thus, problems in which decisions are sensitive to ambiguous inputs pose fundamental challenges to BCA, and are often best addressed with alternative, multi-objective robust decision-making approaches [12]. Where it is significant, clearly communicating ambiguity thus can be of crucial importance for decision making.

Characterizing uncertainty and ambiguity in the IPCC

Global mean sea level rise is driven by processes including global mean thermal expansion (~38% of the total rise from 1900-2018), glacier mass loss (~41%), polar ice sheet mass loss (~29%), and changes in water stored on land (~-8%) [6]. All these terms contribute to sea-level rise projection uncertainty (e.g., Fig. 3a), and since sea-level rise projections first appeared in the modern scientific literature in the 1970s, ice sheet processes have been recognized as an especially important driver of ambiguity.

The literature particularly emphasizes ambiguity associated with the potential behavior of the West Antarctic Ice Sheet (WAIS). With the bulk of the ice sheet grounded below sea level, WAIS exhibits dynamics that are challenging to understand, model, and project. As John Mercer [41] noted in 1978, WAIS "can exist only so long as its grounded portion is buttressed by fringing ice shelves, …. [which] are vulnerable to both oceanic and atmospheric warming." Drawing on geological precedents, Mercer warned of a "threat of disaster" from WAIS and highlighted the ambiguity of the hazard, noting that there was "at present, no way of knowing whether the models err on the optimistic or pessimistic side."

In 1982, Vivien Gornitz and colleagues [42] focused on quantifiable uncertainties, using a statistical model to estimate an 18-year lagged sea-level response to warming of about 16 cm/K. However, they also cautioned about ambiguity not reflected in this scaling relationship, noting that it was "not inconceivable that … continued warming and rise of sea level could cause rapid, highly nonlinear disintegration" of WAIS.

Despite these cautionary notes in the early literature, the first three IPCC assessment reports left rapid ice sheet dynamics out of sea-level rise projection tables. The reports viewed such dynamics as low probability rather than ambiguous; they considered a large contribution to sea-level rise from Antarctic mass loss on a century scale to be "unlikely" [43], "low" likelihood [44], or "*very unlikely*" [45] (Table 1, Table

S1). (See Box 1 for an explanation of formal likelihood and confidence language used by the IPCC and increasingly formalized started with the Third Assessment Report; in this Review, we denote formalized language with an asterisk.)

Table 1. Representative IPCC chapter quotes describing assessment of ambiguity in the ice sheet contributions to sea level.

Report	**Chapter Text**
First Assessment Report (1990)[43]	"A rapid disintegration of the West Antarctic Ice Sheet due to global warming is unlikely within the next century."
Second Assessment Report (1995)[44]	"Concern has been expressed that the West Antarctic Ice Sheet might 'surge', causing a rapid rise in sea level. The current lack of knowledge regarding the specific circumstances under which this might occur, either in total or in part, limits the ability to quantify the risk. Nonetheless, the likelihood of a major sea level rise by the year 2100 due to the collapse of the West Antarctic Ice Sheet is considered low."
Third Assessment Report (2001)[45]	"The range of projections given above makes no allowance for ice-dynamic instability of the WAIS. It is now widely agreed that major loss of grounded ice and accelerated sea level rise are very unlikely during the 21st century."
Fourth Assessment Report (2007)[50]	"It must be emphasized that we cannot assess the likelihood of any of these three alternatives [(steady, reduced, or scale up ice discharge)], which are presented as illustrative. The state of understanding prevents a best estimate from being made."
Fifth Assessment Report (2013)[56]	"Based on current understanding, only the collapse of marine-based sectors of the Antarctic ice sheet, if initiated, could cause global mean sea level to rise substantially above the *likely* range during the 21st century. This potential additional contribution cannot be precisely quantified but there is *medium confidence* that it would not exceed several tenths of a meter of sea level rise during the 21st century."
Special Report on the Ocean and Cryosphere in a Changing Climate (2019)[73]	"Processes controlling the timing of future ice-shelf loss and the extent of ice sheet instabilities could increase Antarctica's contribution to sea level rise to values higher than the *likely* range on century and longer time-scales (*low confidence*). Evolution of the Antarctic Ice Sheet beyond the end of the 21st century is characterized by deep uncertainty, as ice sheet models lack realistic representations of some of the underlying physical processes... There is *low confidence* in threshold temperatures for ice sheet instabilities and the rates of GMSL rise they can produce."
Sixth Assessment Report (2021)[6]	"Higher amounts of GMSL rise before 2100 could be caused by earlier-than-projected disintegration of marine ice shelves, the abrupt, widespread onset of marine ice sheet instability and marine ice cliff instability around Antarctica, and faster-than-projected changes in the surface mass balance and discharge from Greenland. These processes are characterized by deep uncertainty arising from limited process understanding, limited availability of evaluation data, uncertainties in their external forcing and high sensitivity to uncertain boundary conditions and parameters. In a low-likelihood, high-impact storyline, under high emissions such processes could in combination contribute more than one additional metre of sea level rise by 2100."

Table S1 provides a comparison of chapter and Summary for Policymakers text.

However, the presumed stability of WAIS changed in the IPCC Fourth Assessment Report (AR4) [27]. A slew of surprising observations had appeared in the literature [46], for which existing ice sheet models could not account [47], and new methods of sea-level projection were emerging that contrasted with the consensus storyline (e.g., ref. [48]). There also was increasingly intense public scrutiny over the work of the IPCC itself, along a continuum of interests from climate contrarians to climate activists, as well as a growing number of institutions trying to incorporate climate projections into their planning [e.g., 49].

AR4 cautiously concluded that the likelihood of future changes in ice-sheet discharge – whether steady, reduced, or accelerated – could not be assessed, and therefore offered neither a best estimate nor a *likely* range of future sea-level change [50] (Table 1, Table S1, Fig. S1). Instead, 5th-95th percentile ranges were presented to "[characterize] the spread of model results" but not interpreted in terms of likelihood.

Within the AR4 projection chapter, the summary table (table 10.7 in ref. [50]) and figure (fig. 10.33 in ref. [50]) include estimated ranges of potential contributions from "scaled-up ice sheet discharge" (up to 0.17 m between 1980-1999 and 2080-2099 under the highest emissions scenario) but did not add these estimates into total sea-level rise projections. The figure caption reiterated the caution that "we cannot assess the likelihood of any of [current, reduced, or scaled-up ice sheet discharge], which are presented as illustrative" (fig 10.33 in ref. [50]). The Summary for Policymakers (SPM) table (table SPM.3 in ref. [51]) reduces this caution to a column header noting that it is presenting a "model-based range excluding future rapid dynamical changes in ice flows", but also includes in the associated text a caution that "larger values cannot be excluded, but understanding of these effects is too limited to assess their likelihood or provide a best estimate or upper bound for sea-level rise" [51].

The issue of how AR4 represented uncertainty around sea level rise, especially ambiguity arising from changes in ice dynamics, was contested at the time [22,27,48,52,53]. Some argued that bucking user expectations by refusing to provide *likely* ranges when the science could not support it was 'courageous'; others, that excluding some but not all ice sheet processes in presented ranges would lead to confusion about what was represented [27]. By not articulating a formal conceptual framework for projection ambiguity and not communicating ambiguity in report figures and tables, AR4 may have caused some users to plan based exclusively on the partial information captured by quantifiable uncertainty. On the other hand, some sophisticated regional assessments did build on AR4's flagging of the potential contribution of accelerated ice sheet discharge, taking AR4 projections plus scaled-up discharge estimates as a point of comparison for independently developed high-end projections [54,55]. For example, the United Kingdom's 2009 assessment [55] explained the value of such high-end scenarios, noting the potential to use physically plausible high-end scenarios for contingency planning and developing monitoring strategies.

In contrast to AR4, the IPCC Fifth Assessment Report (AR5) did assess *likely* ranges of future sea-level change [56] (Fig. S2, S3). The AR5 sea-level projections were generated through a probabilistic approach that involved sampling uncertainties, with the results presented as median and *likely* ranges and the shape of the distribution left unstated. While '*likely*' in the IPCC's post-TAR formal terminology refers to a probability of between 66 and 100%, the authors of the AR5 sea level chapter used a slightly different interpretation. As they clarified in a short letter to *Science* [57], they interpreted that there was "roughly a one-third probability that sea-level rise by 2100 may lie outside the *likely* range" – i.e., the *likely* range as meaning 'about 66%' rather than 'at least 66%.'

Notably, the reported *likely* ranges included an adjustment for structural uncertainty based upon the report authors' informal expert judgement. Because the 5th-95th percentile range of transient climate response (TCR) in the Coupled Model Intercomparison Project Phase 5 (CMIP5) ensemble aligned with the AR5 assessed TCR *likely* range (based on several lines of evidence), the *likely* ranges of all long-term projections derived from the CMIP5 ensemble – including the sea-level projections – were taken from the 5th-95th percentile of the ensemble range [58]. In the context of sea-level projections, this fact, mentioned in a footnote on the SPM table (table SPM.2 in ref. [59]) appears to have led to considerable confusion [60]. (The practice is still used in the AR6 for some climate indicators, though not global mean surface air temperature change or sea level change [61].)

AR5 also included a semi-quantitative discussion of ambiguity in global mean sea level (GMSL) projections, in the form of a caveat repeated in the text, the chapter table (table 13.5 in ref. [56]) and the SPM table: "Based on current understanding, only the collapse of marine-based sectors of the Antarctic ice sheet, if initiated, could cause global mean sea level to rise substantially above the *likely* range during the 21st century. There is *medium confidence* that this additional contribution would not exceed several tenths of a meter of sea-level rise during the 21st century" [56,59].

Multiple examples from regional assessments that built upon numerical AR5 projections indicate that both of these nuances – the interpretation of the *likely* range derived from the 5th-95th percentile range of model output as "roughly a one-third probability" and the potential for several tenths of a meter additional sea-level rise from marine-based sectors – were not always understood. Of five regional assessments relying quantitatively on AR5 and not having the interpretive guidance of an IPCC author participating as a co-author, four interpreted the *likely* range as having a 90% probability, one interpreted the *likely* range consistent with the canonical IPCC interpretation (66-100%), and none used the interpretation intended by the IPCC authors (about 66%) (see overview in Table S2). Of these five, four made some attempts to consider the contribution of marine-based Antarctic ice sheet sectors to sea level rise above the IPCC *likely* range, but only one motivated this attempt by reference to the IPCC caveat. Our interpretation is that most experts working on the post-AR5 assessments recognized the importance of considering ambiguity in high-end sea-level rise, but often not because of AR5's cautionary statement. Such comparisons along the boundary chain helped motivate innovations adopted by AR6: particularly attention to careful description of *likely* range interpretation and to embedding ambiguity in key boundary objects.

Alternate boundary objects in regional assessments

In the period between AR5 and AR6, US subnational assessments experimented with a variety of ways of communicating sea level uncertainty and ambiguity. (See ref. [62] for an overview of subnational US assessments.) In general, the quantitative bases of these assessments rested upon probabilistic relative sea-level projections. Many employed projections produced by Kopp et al. [63,64], which were developed to provide more comprehensive probability distributions of sea-level change, including greater information about the distributional tails, than was reported by AR5, as well as to make localized information more readily accessible. The communication challenges, however, were similar to those posed by AR5.

Some subnational assessments communicated uncertainty through presenting a broader set of quantiles than the AR5 *likely* ranges and communicated ambiguity through the inclusion of a non-probabilistic, high-end sea-level rise scenario. The 2017 California assessment [65], for example, presented median and likely ranges (in a break from AR5, defined precisely as 17th-83rd percentile), as well as 95th and 99.5th percentiles, and a high-end scenario (labeled H++ (high-plus-plus) following the UK's approach [55]) (Fig. S4). The New York City Panel on Climate Change [66] took a similar approach in 2018, showing four quantiles of projections (10th, 17th, 83rd, and 90th) and a high-end "Antarctic Rapid Ice Melt" scenario (Fig. S6). In both cases, the high-end scenarios were based upon the US government [67] scenario representing an estimated maximum plausible GMSL rise of 2.5 m by 2100 (Box 2).

Other subnational assessments presented multiple alternative probability distributions with different levels of confidence. The State of Maryland [68] emphasized the relatively conservative probabilistic projections of ref. [63] in their primary table (Fig. S7), though highlighted the higher end of the projections by including 95th and 99th percentile projections along with 17th, 50th, and 83rd percentiles. In addition, the primary table appears immediately above text that presents the 17th-83rd percentile range of higher projections that, as opposed to those in the table, incorporate an ice sheet model capable of representing Marine Ice Cliff Instability [69]. The decision to emphasize the higher confidence processes in the table while consigning lower confidence processes to text was a deliberate choice; in an early draft, both results were presented in tables, leading to concerns among the authors that the difference in confidence would not be accurately conveyed.

A third approach was adopted by the 2019 New Jersey Science and Technical Advisory Panel [70] (Fig. S8). Rather than presenting probability distributions, the New Jersey assessment used (but did not illustrate) p-boxes summarizing multiple alternative probability distributions. (P-boxes, discussed in greater detail in Box 1 and illustrated in Fig. 1e–f, describe the bounds of probability across multiple distributions.) The New Jersey report included in these p-boxes both projections relatively consistent with AR5 [63,71] and projections based on a structured expert judgment (SEJ) study of ice sheets that incorporated a broader set of processes [72]. The central table conveys the idea of a p-box by quoting imprecise probabilities; the likely range, for example, is bounded at the low end by numbers that have ">83% chance" of exceedance and at the high end by numbers that have "<17% chance" of exceedance. In practice, this means that the lower end of the reported values are defined by the AR5-aligned projections, and the higher end is defined by the SEJ.

Box 2 | Reduction of scientific assessments of sea level to scenarios for use

The IPCC and regional assessment examples discussed in this paper are focused on characterizing scientific sea level projections. Prior to the 2019 Special Report on Ocean and Cryosphere in a Changing Climate, IPCC provided no guidance on how to simplify this information into decision-oriented sea-level scenarios. In some cases, this simplification happens explicitly (as in the case of the US government's 2017 and 2022 sea level scenarios; ref. [67,98]); in others, it happens implicitly, by focusing on a small number of quantiles, years, and emissions scenarios.

The explicit approach adopted by the U.S. Sea Level Rise and Coastal Flood Hazard Scenarios and Tools Interagency Task Force[67,98] uses several lines of evidence to demarcate a range of potential levels of 21st century GMSL rise, spanning from a linear continuation of the late 20th century trend at the low end to a high-end scenario requiring strong warming and rapid ice-sheet loss (Fig. S9). In ref. [67], the range of scenarios spanned from 0.3 to 2.5 m of GMSL rise over the 21st century, which, based upon the AR6 assessment, was reduced to 0.3 to 2.0 m in ref. [98]. These end-of-century GMSL targets were turned into time-varying scenarios of GMSL and local relative sea level (RSL) change by filtering suites of probabilistic projections for samples consistent with the targets. Probabilities (derived from the 2100 GMSL projections of ref. [63] in ref. [67] and of AR6 in ref. [98]) are associated with the different sea-level scenarios only contextually. (For example, ref. [98] notes that, based on AR6, the 0.5 m scenario has about a 50% chance of being exceeded in 2100 in a 2°C world.) While the reports discuss how the relative likelihood of different sea-level scenarios varies under different emissions scenarios, there is no direct mapping between individual emissions scenarios and individual sea-level scenarios. The broad range of the sea-level scenarios is intended to support their use in adaptive decision making across the range of possible futures, for example by comparing the performance of different management strategies over time under different scenarios [99].

The implicit reduction approach is exhibited most clearly by the State of California's 2018 Sea Level Guidance [13], which took the projections of the 2017 California sea level assessment and simply drew boxes around particular columns (Fig. S5). For decision problems with low risk aversion, for example, the guidance recommended using the 83rd percentile projections; for decision problems with extremely high risk aversion, it recommended using the H++ scenario. Comparison of the presentation of the projections in the California assessment (Fig. S4) and guidance (Fig. S5) highlights the role of key tables as boundary objects — in this case, at the boundary of the state assessment panel and the regulatory body. Similar approaches have been taken by other US states, though with different normative choices (e.g., New Jersey [15] recommends focusing on central, <17% chance and <5% chance projections, depending on risk tolerance).

Uncertainty and ambiguity in AR6

The IPCC Special Report on Oceans and Cryosphere in a Changing Climate (SROCC) represented an intermediary step between the AR5 and AR6, and it also served to integrate across IPCC Working Group 1 and Working Group 2 (impacts, adaptation, and vulnerability). As such, SROCC updated the AR5 GMSL projections to reflect new literature regarding Antarctica [73], but did not develop a completely new set of integrated projections, a task awaiting completion of the Coupled Model Intercomparison Project Phase 6 (CMIP6) global climate model simulations [74]. Importantly, the report also adjusted the use of *likely* which had previously caused confusion when applied to a range: SROCC used the terms '*likely* range' or '*very likely* range' to indicate that the assessed likelihood of an outcome lies specifically within the 17–83% or 5–95% probability range [75].

In part because of the intention to defer a full update to AR6, the representation of GMSL projection data in boundary objects was more limited in SROCC than in AR5 or AR6. While the only table with sea-level rise projections focused on the details of updating the GMSL projections (table 4.4 in ref. [73]), key figures did include elements that drew greater attention to ambiguity and multi-century change. In particular, the SPM figure illustrating GMSL projections (fig SPM.1 in ref. [75]) extended to 2300 while using fainter shading to indicate lower confidence after 2100, and also included bars showing results for the year 2300 using one ice-sheet SEJ study (which were not included in the time series projections) [72]. While, like AR5, the figure showed only *likely* ranges, the long timescale emphasized the potential for substantially larger sea-level change past 2100 (Fig. S10). The corresponding chapter figure (fig 4.2 in ref. [73]) likewise extended to 2300 (Fig. S11) and incorporated bars indicating alternative probability distributions for both 2100 and 2300, derived from an Antarctic ice sheet sensitivity study [76] and from the SEJ study.

Leveraging SROCC's status as a cross-working group product, SROCC also for the first time provided advice on how to simplify the diversity of projections available into sea-level scenarios [75]:

> The sea level rise range that needs to be considered for planning and implementing coastal responses depends on the risk tolerance of stakeholders. Stakeholders with higher risk tolerance (e.g., those planning for investments that can be very easily adapted to unforeseen conditions) often prefer to use the *likely* range of projections, while stakeholders with a lower risk tolerance (e.g., those deciding on critical infrastructure) also consider global and local mean sea level above the upper end of the *likely* range (globally 1.1 m under RCP8.5 by 2100) and from methods characterized by lower confidence such as from expert elicitation.

AR6 [6] developed a new set of integrated sea-level projections and built upon AR5's and SROCC's approaches in several ways. Rather than producing a single set of probability distributions, it produced multiple distributions of GMSL, using different ways of modelling the behaviour of the Antarctic and Greenland ice sheets (Fig. 1a-d). It combined these distributions in p-boxes to produce the reported projections (Fig. 1e-f). Its *likely* range projections included emulated results from the Ice Sheet Model Intercomparison Project for CMIP6 (ISMIP6) [77–79] and the Linear Antarctic Response Model Intercomparison Project (LARMIP) [80]. As both projects integrated results from suites of ice sheet models, as well as incorporating assessments of uncertainty from model inputs and (for ref. [77] and [80]) emulation, the AR6 sea-level chapter authors judged the resulting p-boxes and associated *likely* ranges to reflect a *medium level of agreement* and thus *medium confidence*. In contrast to AR5, no downgrading of uncertainty (e.g., interpreting the 5th-95th percentile ranges of a single ensemble of projections as a *likely* range with about 66% probability) was employed.

The sea level chapter was cautious in its presentation of these *medium confidence* results, noting that they consider "only processes for which projections can be made with at least *medium confidence*" [6]. The *likely* range projections, for example, do not include more ambiguous processes unrepresented in some (or all) of the ISMIP6 ice sheet models. (See also ref. [81], which highlights the lack of climate and ice sheet model consensus regarding the sign of 21st century Antarctic changes.) To address this limitation, AR6 also generated probability distributions that incorporated a broader set of processes. One of these distributions used a single Antarctic ice-sheet model that represents Marine Ice Cliff Instability (MICI) [82]; another relied upon an ice-sheet SEJ study [72]. Because the authors assessed that there was *limited evidence* regarding and *low agreement* on MICI, as well as potentially on other processes considered by the experts participating in the SEJ study, the broader p-boxes including these studies were judged to have *low confidence*. Due to limitations in the underlying literature, *low confidence* projections were produced only for the low emissions SSP1-2.6 and very high emissions SSP5-8.5 scenarios. Because current mitigation policies lead to emissions significantly above SSP1-2.6 but well below SSP5-8.5 [83], this literature gap is a notable limitation. Adequate literature does not currently exist to assess – even at *low* *confidence* – the emissions levels at which the instabilities that play key roles in the SSP5-8.5 *low confidence* projections might become major factors. However, the *low confidence* SSP1-2.6 projections suggest the potential contributions from these instabilities are relatively small under this low emissions scenario (compare the *likely* range and p-box width of *low confidence* projections in Fig. 1e to Fig. 1f), which is consistent with the 2°C Paris Agreement global-mean warming target.

Beyond 2150, AR6 considered all ice sheet projections to be *low confidence* and so did not present time series from 2150 to 2300; instead, it reports indicative summaries of projections for two emissions scenarios (SSP1-2.6 and SSP5-8.5) at the single time point of 2300 (Fig. 3d). These values were based on a combination of projections that included (1) no-acceleration extrapolation of ice sheet changes after 2100, (2) literature-based assessment of ice-sheet changes in 2300, (3) SEJ projections, and (4) the single Antarctic model that represents MICI. For SSP5-8.5, the MICI-permitting projections yield ranges that do not overlap with the other methods (9.5-16.2 m vs. 1.7-6.3 m). This separation highlights the very strong way in which MICI might affect the results, and the substantial ambiguity arising from lack of agreement in the community on the presence and representation of this process [84–86].

On still longer timescales, these projections were complemented by model- and paleo-based assessments of committed sea-level rise over 2,000 and 10,000 years that is associated with different levels of peak global warming. While AR5 [56] had also discussed millennial-scale sea level change, AR6 drew a more direct connection between century- and millennial-scale changes [6]. The AR5 SPM presents paleo sea level, century-scale sea level change, and millennial-scale ice sheet contributions to sea level in separate sections [59]; by contrast, the AR6 SPM, discusses paleo and millennial-scale change as a function of peak global warming in a paragraph that follows immediately after the paragraph presenting century-scale changes [87]. A Technical Summary figure panel synthesizes sea level change on 100-year, 2,000-year, and 10,000-year timescales as a function of peak global warming level (Box TS.4, fig. 1 in ref. [88]) (Fig. 3b). This panel combines *medium confidence* and *low confidence* model-based century-scale projections and *low confidence* millennial scale model-based projections with *medium confidence* paleo sea level and temperature assessments. It is the first figure panel in an IPCC report to make such a direct comparison between paleo sea levels and very long-term future sea level, and thus to provide a possible boundary object to facilitate discussions of these relationships.

The AR6 chapter reiterated SROCC's guidance about the utility of projections above the *likely* range for "stakeholders with a low risk tolerance… because '*likely*' implies an assessed likelihood of up to 16%" of higher values, while pointing to the limitations of likelihood assessments given projection ambiguity: "Because of our limited understanding of the rate at which some of the governing processes contribute to long-term sea level rise, we cannot currently robustly quantify the likelihood with which they can cause higher sea level rise before 2100" [6].

To help ensure that these *low confidence* – but potentially decision-relevant – projections were not lost on regional assessment panels and practitioners as the AR5 caveat about collapse of marine-based Antarctic ice sheet sectors seemingly often was, the *low confidence* projections for a very high-emissions scenario (SSP5-8.5) were presented in core chapter and Technical Summary figures and tables alongside the *medium confidence* projections for the suite of SSP scenarios (Fig. 3, S12, S13). The AR6 approach represents convergent evolution with the recommendations of ref. 18 that sea-level projections be communicated at different levels of confidence. It also draws inspiration from the California (2017)/New York City (2018) approach of presenting a high-end (*low confidence*) scenario alongside probabilistic projections, and the New Jersey (2019) approach of summarizing multiple probabilistic projections with p-boxes. While the quote emphasizes the year 2100, the sea-level projections in AR6 break from practice in past assessment cycles by providing time series that extend to 2150 and are so represented in key tables (e.g., Fig. 3a), as well as chapter and Technical Summary figures (Fig. S13).

The AR6 SPM illustrates the 21st century *low confidence* projections with a curve representing a "low likelihood, high-impact storyline including ice-sheet instability processes" (Fig. 3d). The curve is taken from the upper 83rd percentile of the *low confidence* p-box for SSP5-8.5 and is dashed to indicate the lower degree of confidence. The description draws upon two new frames introduced across the report in AR6. "Low-likelihood, high-impact (LLHI) outcomes" are defined as outcomes "whose probability of occurrence is low or not well known (as in the context of deep uncertainty) but whose potential impacts on society and ecosystems could be high" [89]. While emissions consistent with SSP5-8.5 do themselves have a low probability of occurrence [83], in the context of ambiguous physical processes, as here, the "not well known" probability part of the definition is key. Physical climate storylines [90] are, essentially, scenarios of physical changes that provide narrative detail used to contextualize projections and allow quantitative uncertainties to be assessed, conditional upon assumptions regarding more ambiguous narrative elements. Consistent with AR6 practice, Stammer et al. [91] recommend accompanying probabilistic projections with high-end storylines tied to specific physical processes. For the *low confidence* sea-level projections, AR6 presents a storyline in Box 9.4, which highlights elements including strong warming, "faster-than-projected disintegration of marine ice shelves and the abrupt, widespread onset of [MICI] and marine ice sheet instability (MISI) in Antarctica (Section 9.4.2.4), and faster-than-projected changes in both the surface mass balance and dynamical ice loss in Greenland" [6]. Though these details are not presented in any boundary object, the use of the storyline label serves as a pointer to this description.

AR6 also introduced an alternative projection framing, based on evidence that for some end-users, uncertainty in timing of reaching different sea-level rise "milestones" (e.g., when a particular elevation associated with an 'adaptation tipping point' is reached; see also ref. [92]) is as useful as uncertainty in level at particular points in time. Thus AR6 introduced chapter and Technical Summary figures showing when, under different emissions scenarios, milestones ranging from 0.5 m to 2.0 m GMSL rise would be exceeded (Fig. 3c). This visualization also incorporated both the *medium confidence* projections for all SSPs and the *low confidence* projections for SSP1-2.6 and SSP5-8.5. The milestone framing, which can be applied either to sea-level projections or sea-level scenarios, naturally supports the development of adaptation pathways in contexts where specific sea-level thresholds have particular practical relevance [8]. For the lower range of future sea-level rise, this framing also highlights that uncertainty primarily exists regarding when, not if, a certain threshold will be exceeded.

Recognizing that most end-user decisions are sensitive to local, relative sea-level (RSL) change rather than GMSL change, the AR6 authors also took efforts to make RSL projections more readily available. The AR5 RSL projections were archived by the Integrated Climate Data Center (https://www.cen.uni-hamburg.de/en/icdc/data/ocean/ar5-slr.html) and the SROCC RSL projections were hosted by IPCC as supplemental data files (https://www.ipcc.ch/report/ar6/sr/srocc/download/), but neither were fully accessible and actively communicated through easy-to-use web tools. AR6 projections, by contrast, are communicated both through the IPCC Interactive Atlas (https://interactive-atlas.ipcc.ch) and the more targeted NASA/IPCC Sea Level Projection Tool (https://sealevel.nasa.gov/ipcc-ar6-sea-level-projection-tool). The NASA/IPCC Sea Level Projection Tool is intended to support both regional assessment processes and policymakers who use IPCC projections directly. It focuses on preserving key design elements of the AR6 boundary objects when presenting RSL projections. It allows versions of the core figures and tables presented in the report for GMSL (e.g., analogs to Fig.s 3a, 3c, and 3d) to be produced for RSL projections both at tide gauges and on a global grid. Like the boundary objects in the report, it strives to convey both uncertainty and ambiguity in future sea level through 2150 by including *low confidence* projections alongside the *medium confidence, likely* ranges, as well as to support adaptation pathways development with the milestone framing. In addition to these tools, the comprehensive global and regional projections, along with the open-source system used to generate them, were archived following open science principles [93].

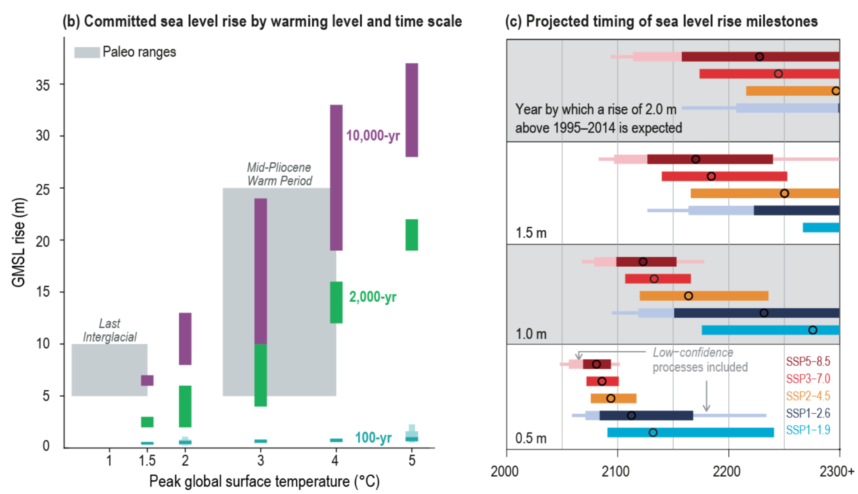
Conclusions

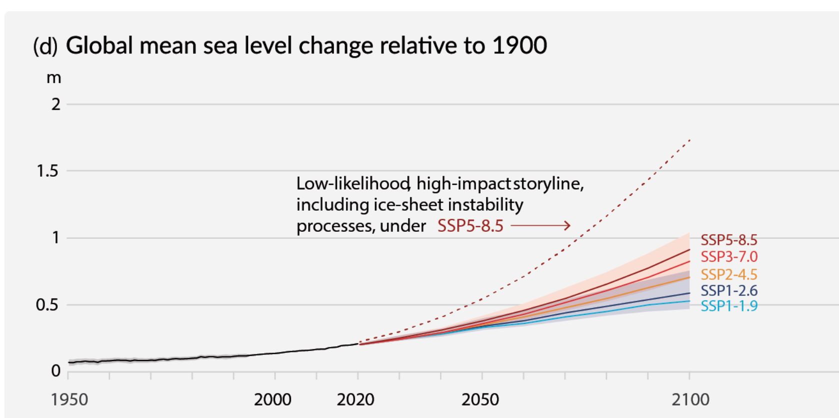
The presence and magnitude of ambiguity in sea-level projections affects the appropriate use of decision frameworks, and thus is important to communicate clearly and efficiently. The AR6 communication approach builds upon experience from AR4, AR5, and SROCC, as well as from regional assessments conducted in the period since AR5. Overall, it attempts to present the ambiguity of sea-level projections (and emphasize the non-comprehensive nature of the *likely* range) without overwhelming the projections of those processes on which there is a reasonable degree of agreement. Both SROCC and AR6 also include some guidance related to how users with different risk tolerances might choose to use the projections. The intent of the AR6 approach is to inform a wide variety of decision-making paradigms, including both risk-neutral approaches that focus on likely outcomes and more risk-averse approaches that rely upon characterization of high-end outcomes.

If the AR6 approach is successful, it will be reflected in future regional assessments that correctly interpret the probabilistic meaning of the *likely* range and consider the possibility of outcomes well above the *likely* range. It may also be reflected in broader use of the milestone framing, in which users consider the uncertainty in when decision-relevant sea level thresholds are exceeded, as well as the more traditional perspective of uncertainty in sea level over time. Whether the AR6 approach is indeed efficacious – and, more broadly, the effects of different communication decisions along the research-to-practice boundary chain on adaptation policy and practice – is an important empirical subject of study. Its investigation requires close collaboration between climate scientists and the social scientists who study scientific practice and communication, as well as with the policymakers who serve as end-users of assessments and the practitioners impacted by policy decisions.

(a) Global mean sea level projections for five Shared Socio-economic Pathway (SSP) scenarios, relative to a baseline of 1995–2014, in metres

	SSP1-1.9	SSP1-2.6	SSP2-4.5	SSP3-7.0	SSP5-8.5	SSP5-8.5 *Low Confidence*
Thermal expansion	0.12 (0.09–0.15)	0.14 (0.11–0.18)	0.20 (0.16–0.24)	0.25 (0.21–0.30)	0.30 (0.24–0.36)	0.30 (0.24–0.36)
Greenland	0.05 (0.00–0.09)	0.06 (0.01–0.10)	0.08 (0.04–0.13)	0.11 (0.07–0.16)	0.13 (0.09–0.18)	0.18 (0.09–0.59)
Antarctica	0.10 (0.03–0.25)	0.11 (0.03–0.27)	0.11 (0.03–0.29)	0.11 (0.03–0.31)	0.12 (0.03–0.34)	0.19 (0.02–0.56)
Glaciers	0.08 (0.06–0.10)	0.09 (0.07–0.11)	0.12 (0.10–0.15)	0.16 (0.13–0.18)	0.18 (0.15–0.21)	0.17 (0.11–0.21)
Land-water Storage	0.03 (0.01–0.04)	0.03 (0.01–0.04)	0.03 (0.01–0.04)	0.03 (0.02–0.04)	0.03 (0.01–0.04)	0.03 (0.01–0.04)
Total (2030)	0.09 (0.08–0.12)	0.09 (0.08–0.12)	0.09 (0.08–0.12)	0.10 (0.08–0.12)	0.10 (0.09–0.12)	0.10 (0.09–0.15)
Total (2050)	0.18 (0.15–0.23)	0.19 (0.16–0.25)	0.20 (0.17–0.26)	0.22 (0.18–0.27)	0.23 (0.20–0.29)	0.24 (0.20–0.40)
Total (2090)	0.35 (0.26–0.49)	0.39 (0.30–0.54)	0.48 (0.38–0.65)	0.56 (0.46–0.74)	0.63 (0.52–0.83)	0.71 (0.52–1.30)
Total (2100)	0.38 (0.28–0.55)	0.44 (0.32–0.62)	0.56 (0.44–0.76)	0.68 (0.55–0.90)	0.77 (0.63–1.01)	0.88 (0.63–1.60)
Total (2150)	0.57 (0.37–0.86)	0.68 (0.46–0.99)	0.92 (0.66–1.33)	1.19 (0.89–1.65)	1.32 (0.98–1.88)	1.98 (0.98–4.82)
Rate (2040–2060)	4.1 (2.8–6.0)	4.8 (3.5–6.8)	5.8 (4.4–8.0)	6.4 (5.0–8.7)	7.2 (5.6–9.7)	7.9 (5.6–16.1)
Rate (2080–2100)	4.2 (2.4–6.6)	5.2 (3.2–8.0)	7.7 (5.2–11.6)	10.4 (7.4–14.8)	12.1 (8.6–17.6)	15.8 (8.6–30.1)





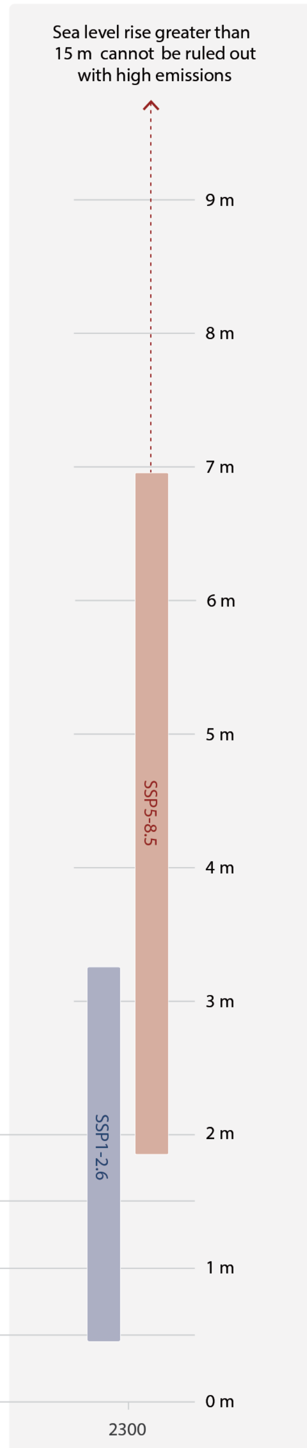


Fig. 3. Different visualizations of global mean sea level (GMSL) projection uncertainty and ambiguity in the IPCC AR6 Working Group 1 report. (a) Tabular presentation of *medium confidence* projections for five SSP scenarios and *low confidence* projections for SSP5-8.5, presented as Table 9.9 [6]. Projections for individual components (first five rows) are for 2100. Values shown are median and *likely* ranges, except for the *low confidence* projections, where presented ranges are 17th-83rd percentile with no formal likelihood assessed. (b) Projected GMSL change on 100- (blue), 2,000- (green), and 10,000 (magneta) time scales as a function of global surface temperature,

relative to 1850-1900, extracted from Box TS.4, Fig. 1b [88]. Dark blue projections are *medium confidence*; others are *low confidence*. Shaded regions show the *medium confidence* assessments of temperature and sea level during the Last Interglacial and Mid-Pliocene Warm Period. (c) Uncertainty in the timing of different GMSL milestones, extracted from Box TS.4, Fig. 1c [88]. *Low confidence* projections are indicated by light shading on the SSP1-2.6 and SSP5-8.5 bars, showing both 17-83rd percentile (thicker line) and 5th-95th percentile (thin line) projections. (d) GMSL as a function of time, extracted from Fig. SPM.8d/e [87]. Ambiguity is represented through the inclusion of a curve representing a "low-likelihood, high-impact" storyline. Other projections through 2100 are *medium confidence, likely* ranges. Projections for 2300 are *low confidence* 17th-83rd percentile ranges. (Note that, in the report Technical Summary and chapter, GMSL projections are shown as continuous time series ending in 2150.) Elements in panels are shown as presented in AR6, with the exception of the addition of the title to panel (a) and the addition of lettering to identify panels.

Supplementary Information contains Table S1, which compares representative quotes from IPCC reports chapters, and Table S2, summarizing regional assessments that interpreted AR5's quantitative sea-level projections, as well as a gallery (Figures S1-S13) of key sea-level projections figures and tables from IPCC and regional assessments.

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Data Availability

The main AR6 sea level projection data are available on Zenodo at https://doi.org/10.5281/zenodo.5914709 [93]. A guide to additional related AR6 sea level data sets is available at https://github.com/Rutgers-ESSP/IPCC-AR6-Sea-Level-Projections.

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Supplementary Information to "Communicating future sea-level rise uncertainty and ambiguity to assessment users"

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This document contains Table S1, comparing representative quotes from IPCC reports chapters and Summaries for Policy Makers, and Table S2, summarizing regional assessments that interpreted AR5's quantitative sea-level projections, as well as a gallery (Figures S1-S13) of key sea-level projections figures and tables from IPCC and regional assessments.

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Table S1. Representative IPCC chapter and Summary for Policymakers (SPM) quotes describing assessment of ambiguity in the ice sheet contributions to sea level.

Report	Chapter Text	Summary for Policymakers Text
First Assessment Report (1990)[1,2]	"A rapid disintegration of the West Antarctic Ice Sheet due to global warming is unlikely within the next century."	"Within the next century it is not likely that there will be a major outflow of ice from West Antarctica due directly to global warming."
Second Assessment Report (1995)[3,4]	"Concern has been expressed that the West Antarctic Ice Sheet might 'surge', causing a rapid rise in sea level. The current lack of knowledge regarding the specific circumstances under which this might occur, either in total or in part, limits the ability to quantify the risk. Nonetheless, the likelihood of a major sea level rise by the year 2100 due to the collapse of the West Antarctic Ice Sheet is considered low."	"In these projections, the combined contributions of the Greenland and Antarctic ice sheets are projected to be relatively minor over the next century. However, the possibility of large changes in the volumes of these ice sheets (and, consequently, in sea level) cannot be ruled out, although the likelihood is considered to be low."
Third Assessment Report (2001)[5,6]	"The range of projections given above makes no allowance for ice-dynamic instability of the WAIS. It is now widely agreed that major loss of grounded ice and accelerated sea level rise are very unlikely during the 21st century."	"Concerns have been expressed about the stability of the West Antarctic ice sheet because it is grounded below sea level. However, loss of grounded ice leading to substantial sea level rise from this source is now widely agreed to be very unlikely during the 21st century, although its dynamics are still inadequately understood, especially for projections on longer time-scales."
Fourth Assessment Report (2007)[7,8]	"It must be emphasized that we cannot assess the likelihood of any of these three alternatives [(steady, reduced, or scale up ice discharge)], which are presented as illustrative. The state of understanding prevents a best estimate from being made."	"For example, if [the ice flow] contribution were to grow linearly with global average temperature change, the upper ranges of sea level rise for SRES scenarios shown in Table SPM.3 would increase by 0.1 to 0.2 m. Larger values cannot be excluded, but understanding of these effects is too limited to assess their likelihood or provide a best estimate or an upper bound for sea level rise."
Fifth Assessment Report (2013)[9,10]	"Based on current understanding, only the collapse of marine-based sectors of the Antarctic ice sheet, if initiated, could cause global mean sea level to rise substantially above the *likely* range during the 21st century. This potential additional contribution cannot be precisely quantified but there is *medium confidence* that it would not exceed several tenths of a meter of sea level rise during the 21st century."	"Based on current understanding, only the collapse of marine-based sectors of the Antarctic ice sheet, if initiated, could cause global mean sea level to rise substantially above the *likely* range during the 21st century. There is *medium confidence* that this additional contribution would not exceed several tenths of a meter of sea level rise during the 21st century."

Continued on next page…

Table S1 (continued). Representative IPCC chapter and Summary for Policymakers quotes describing assessment of ambiguity in the ice sheet contributions to sea level.

Report	Chapter Text	Summary for Policymakers Text
Special Report on the Ocean and Cryosphere in a Changing Climate (2019)[11,12]	"Processes controlling the timing of future ice-shelf loss and the extent of ice sheet instabilities could increase Antarctica's contribution to sea level rise to values higher than the *likely* range on century and longer time-scales (*low confidence*). Evolution of the Antarctic Ice Sheet beyond the end of the 21st century is characterized by deep uncertainty, as ice sheet models lack realistic representations of some of the underlying physical processes... There is *low confidence* in threshold temperatures for ice sheet instabilities and the rates of GMSL rise they can produce."	"Processes controlling the timing of future ice-shelf loss and the extent of ice sheet instabilities could increase Antarctica's contribution to sea level rise to values substantially higher than the *likely* range on century and longer time-scales (*low confidence*). Considering the consequences of sea level rise that a collapse of parts of the Antarctic Ice Sheet entails, this high impact risk merits attention."
Sixth Assessment Report (2021)[13,14]	"Higher amounts of GMSL rise before 2100 could be caused by earlier-than-projected disintegration of marine ice shelves, the abrupt, widespread onset of marine ice sheet instability and marine ice cliff instability around Antarctica, and faster-than-projected changes in the surface mass balance and discharge from Greenland. These processes are characterized by deep uncertainty arising from limited process understanding, limited availability of evaluation data, uncertainties in their external forcing and high sensitivity to uncertain boundary conditions and parameters. In a low-likelihood, high-impact storyline, under high emissions such processes could in combination contribute more than one additional metre of sea level rise by 2100."	"Global mean sea level rise above the *likely* range – approaching 2 m by 2100 and 5 m by 2150 under a very high GHG emissions scenario (SSP5-8.5) (*low confidence*) – cannot be ruled out due to deep uncertainty in ice-sheet processes."

Chapter text is written by the report author teams and incorporates feedback from expert and government review. Summary for Policymakers text is drafted by report author teams, incorporates feedback from expert and government review, and adopted by governments in IPCC plenary session.

Table S2. National and subnational assessments building upon AR5 sea level projections.

Assessment	**Includes an AR4 or AR5 author as co-author**	**Interpretation of AR5 *likely* range**	**Consideration of marine-based sector collapse?**
Canada 2014[15]	No	90%	Yes, acknowledges AR5 caveat and includes high-end scenario to represent
Connecticut 2019 [16]	No	90%	Yes, using sources other than AR5 [17,18]
Louisiana 2017 [19]	No	66-100%	Yes, using sources other than AR5 [20,21]
Netherlands 2014 [22]	Yes	90%	Yes, using sources other than AR5 [23]
North Carolina 2015 [24]	No	90%	No
Norway 2015 [25]	Yes	66-100%	Yes, acknowledges AR5 caveat and uses probabilistic approach to assess high-end outcomes
Singapore 2015 [26,27]	Yes	66-100%	Yes, acknowledges AR5 caveat and includes high-end scenario
United Kingdom 2018 [28]	Yes	66%	Yes, acknowledges AR5 caveat and uses post-AR5 literature [29,30] to illustrate in appendix

This table summarizes the interpretation of AR5 sea-level projections in several national and subnational assessments that were developed in the aftermath of AR5 and that use AR5 as a quantitative point of reference. The AR5 *likely* ranges were intended by the AR5 author team as having roughly a 66% probability, but were derived from the central 90% of model simulations. The canonical IPCC definition of *likely* is 66-100% probability.

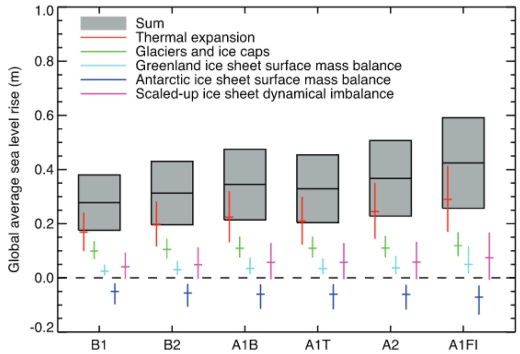

Figure 10.33. *Projections and uncertainties (5 to 95% ranges) of global average sea level rise and its components in 2090 to 2099 (relative to 1980 to 1999) for the six SRES marker scenarios. The projected sea level rise assumes that the part of the present-day ice sheet mass imbalance that is due to recent ice flow acceleration will persist unchanged. It does not include the contribution shown from scaled-up ice sheet discharge, which is an alternative possibility. It is also possible that the present imbalance might be transient, in which case the projected sea level rise is reduced by 0.02 m. It must be emphasized that we cannot assess the likelihood of any of these three alternatives, which are presented as illustrative. The state of understanding prevents a best estimate from being made.*

Table 10.7. *Projected global average sea level rise during the 21st century and its components under SRES marker scenarios. The upper row in each pair gives the 5 to 95% range (m) of the rise in sea level between 1980 to 1999 and 2090 to 2099. The lower row in each pair gives the range of the rate of sea level rise (mm yr^{-1}) during 2090 to 2099. The land ice sum comprises G&IC and ice sheets, including dynamics, but excludes the scaled-up ice sheet discharge (see text). The sea level rise comprises thermal expansion and the land ice sum. Note that for each scenario the lower/upper bound for sea level rise is larger/smaller than the total of the lower/upper bounds of the contributions, since the uncertainties of the contributions are largely independent. See Appendix 10.A for methods.*

		B1		B2		A1B		A1T		A2		A1FI	
Thermal expansion	m	0.10	0.24	0.12	0.28	0.13	0.32	0.12	0.30	0.14	0.35	0.17	0.41
	mm yr^{-1}	1.1	2.6	1.6	4.0	1.7	4.2	1.3	3.2	2.6	6.3	2.8	6.8
G&IC	m	0.07	0.14	0.07	0.15	0.08	0.15	0.08	0.15	0.08	0.16	0.08	0.17
	mm yr^{-1}	0.5	1.3	0.5	1.5	0.6	1.6	0.5	1.4	0.6	1.9	0.7	2.0
Greenland Ice Sheet SMB	m	0.01	0.05	0.01	0.06	0.01	0.08	0.01	0.07	0.01	0.08	0.02	0.12
	mm yr^{-1}	0.2	1.0	0.2	1.5	0.3	1.9	0.2	1.5	0.3	2.8	0.4	3.9
Antarctic Ice Sheet SMB	m	-0.10	-0.02	-0.11	-0.02	-0.12	-0.02	-0.12	-0.02	-0.12	-0.03	-0.14	-0.03
	mm yr^{-1}	-1.4	-0.3	-1.7	-0.3	-1.9	-0.4	-1.7	-0.3	-2.3	-0.4	-2.7	-0.5
Land ice sum	m	0.04	0.18	0.04	0.19	0.04	0.20	0.04	0.20	0.04	0.20	0.04	0.23
	mm yr^{-1}	0.0	1.8	-0.1	2.2	-0.2	2.5	-0.1	2.1	-0.4	3.2	-0.8	4.0
Sea level rise	m	0.18	0.38	0.20	0.43	0.21	0.48	0.20	0.45	0.23	0.51	0.26	0.59
	mm yr^{-1}	1.5	3.9	2.1	5.6	2.1	6.0	1.7	4.7	3.0	8.5	3.0	9.7
Scaled-up ice sheet discharge	m	0.00	0.09	0.00	0.11	-0.01	0.13	-0.01	0.13	-0.01	0.13	-0.01	0.17
	mm yr^{-1}	0.0	1.7	0.0	2.3	0.0	2.6	0.0	2.3	-0.1	3.2	-0.1	3.9

Table SPM.3. *Projected global average surface warming and sea level rise at the end of the 21st century. {10.5, 10.6, Table 10.7}*

Case	Temperature Change (°C at 2090-2099 relative to 1980-1999)[a] Best estimate	Temperature Change (°C at 2090-2099 relative to 1980-1999)[a] *Likely* range	Sea Level Rise (m at 2090-2099 relative to 1980-1999) Model-based range excluding future rapid dynamical changes in ice flow
Constant Year 2000 concentrations[b]	0.6	0.3 – 0.9	NA
B1 scenario	1.8	1.1 – 2.9	0.18 – 0.38
A1T scenario	2.4	1.4 – 3.8	0.20 – 0.45
B2 scenario	2.4	1.4 – 3.8	0.20 – 0.43
A1B scenario	2.8	1.7 – 4.4	0.21 – 0.48
A2 scenario	3.4	2.0 – 5.4	0.23 – 0.51
A1FI scenario	4.0	2.4 – 6.4	0.26 – 0.59

Table notes:
[a] These estimates are assessed from a hierarchy of models that encompass a simple climate model, several Earth System Models of Intermediate Complexity and a large number of Atmosphere-Ocean General Circulation Models (AOGCMs).
[b] Year 2000 constant composition is derived from AOGCMs only.

Figure S1. Tables and figures summarizing GMSL projections from the IPCC Fourth Assessment Report [7,8].

Table 13.5 | Median values and *likely* ranges for projections of global mean sea level (GMSL) rise and its contributions in metres in 2081–2100 relative to 1986–2005 for the four RCP scenarios and SRES A1B, GMSL rise in 2046–2065 and 2100, and rates of GMSL rise in mm yr^{-1} in 2081–2100. See Section 13.5.1 concerning how the *likely* range is defined. Because some of the uncertainties in modelling the contributions are treated as uncorrelated, the sum of the lower bound of contributions does not equal the lower bound of the sum, and similarly for the upper bound (see Supplementary Material). Because of imprecision from rounding, the sum of the medians of contributions may not exactly equal the median of the sum. The net contribution (surface mass balance (SMB) + dynamics) for each ice sheet, and the contribution from rapid dynamical change in both ice sheets together, are shown as additional lines below the sum; they are not contributions in addition to those given above the sum. The contributions from ice-sheet rapid dynamical change and anthropogenic land water storage are treated as having uniform probability distributions, uncorrelated with the magnitude of global climate change (except for the interaction between Antarctic ice sheet SMB and outflow), and as independent of scenario (except that a higher rate of change is used for Greenland ice sheet outflow under RCP8.5). This treatment does not imply that the contributions concerned will not depend on the scenario followed, only that the current state of knowledge does not permit a quantitative assessment of the dependence. Regional sea level change is expected in general to differ from the global mean (see Section 13.6).

	SRES A1B	RCP2.6	RCP4.5	RCP6.0	RCP8.5
Thermal expansion	0.21 [0.16 to 0.26]	0.14 [0.10 to 0.18]	0.19 [0.14 to 0.23]	0.19 [0.15 to 0.24]	0.27 [0.21 to 0.33]
Glaciers[a]	0.14 [0.08 to 0.21]	0.10 [0.04 to 0.16]	0.12 [0.06 to 0.19]	0.12 [0.06 to 0.19]	0.16 [0.09 to 0.23]
Greenland ice-sheet SMB[b]	0.05 [0.02 to 0.12]	0.03 [0.01 to 0.07]	0.04 [0.01 to 0.09]	0.04 [0.01 to 0.09]	0.07 [0.03 to 0.16]
Antarctic ice-sheet SMB[c]	–0.03 [–0.06 to –0.01]	–0.02 [–0.04 to –0.00]	–0.02 [–0.05 to –0.01]	–0.02 [–0.05 to –0.01]	–0.04 [–0.07 to –0.01]
Greenland ice-sheet rapid dynamics	0.04 [0.01 to 0.06]	0.04 [0.01 to 0.06]	0.04 [0.01 to 0.06]	0.04 [0.01 to 0.06]	0.05 [0.02 to 0.07]
Antarctic ice-sheet rapid dynamics	0.07 [–0.01 to 0.16]	0.07 [–0.01 to 0.16]	0.07 [–0.01 to 0.16]	0.07 [–0.01 to 0.16]	0.07 [–0.01 to 0.16]
Land water storage	0.04 [–0.01 to 0.09]	0.04 [–0.01 to 0.09]	0.04 [–0.01 to 0.09]	0.04 [–0.01 to 0.09]	0.04 [–0.01 to 0.09]
Global mean sea level rise in 2081–2100	0.52 [0.37 to 0.69]	0.40 [0.26 to 0.55]	0.47 [0.32 to 0.63]	0.48 [0.33 to 0.63]	0.63 [0.45 to 0.82]
Greenland ice sheet	0.09 [0.05 to 0.15]	0.06 [0.04 to 0.10]	0.08 [0.04 to 0.13]	0.08 [0.04 to 0.13]	0.12 [0.07 to 0.21]
Antarctic ice sheet	0.04 [–0.05 to 0.13]	0.05 [–0.03 to 0.14]	0.05 [–0.04 to 0.13]	0.05 [–0.04 to 0.13]	0.04 [–0.06 to 0.12]
Ice-sheet rapid dynamics	0.10 [0.03 to 0.19]	0.10 [0.03 to 0.19]	0.10 [0.03 to 0.19]	0.10 [0.03 to 0.19]	0.12 [0.03 to 0.20]
Rate of global mean sea level rise	8.1 [5.1 to 11.4]	4.4 [2.0 to 6.8]	6.1 [3.5 to 8.8]	7.4 [4.7 to 10.3]	11.2 [7.5 to 15.7]
Global mean sea level rise in 2046–2065	0.27 [0.19 to 0.34]	0.24 [0.17 to 0.32]	0.26 [0.19 to 0.33]	0.25 [0.18 to 0.32]	0.30 [0.22 to 0.38]
Global mean sea level rise in 2100	0.60 [0.42 to 0.80]	0.44 [0.28 to 0.61]	0.53 [0.36 to 0.71]	0.55 [0.38 to 0.73]	0.74 [0.52 to 0.98]
Only the collapse of the marine-based sectors of the Antarctic ice sheet, if initiated, could cause GMSL to rise substantially above the *likely* range during the 21st century. This potential additional contribution cannot be precisely quantified but there is *medium confidence* that it would not exceed several tenths of a meter of sea level rise.					

Notes:

[a] Excluding glaciers on Antarctica but including glaciers peripheral to the Greenland ice sheet.

[b] Including the height–SMB feedback.

[c] Including the interaction between SMB change and outflow.

Figure S2. Chapter table summarizing GMSL projections from the IPCC Fifth Assessment Report [9]

Table SPM.2 | Projected change in global mean surface air temperature and global mean sea level rise for the mid- and late 21st century relative to the reference period of 1986–2005. {12.4; Table 12.2, Table 13.5}

		2046–2065		2081–2100	
	Scenario	**Mean**	***Likely* range**[c]	**Mean**	***Likely* range**[c]
Global Mean Surface Temperature Change (°C)[a]	RCP2.6	1.0	0.4 to 1.6	1.0	0.3 to 1.7
	RCP4.5	1.4	0.9 to 2.0	1.8	1.1 to 2.6
	RCP6.0	1.3	0.8 to 1.8	2.2	1.4 to 3.1
	RCP8.5	2.0	1.4 to 2.6	3.7	2.6 to 4.8
	Scenario	**Mean**	***Likely* range**[d]	**Mean**	***Likely* range**[d]
Global Mean Sea Level Rise (m)[b]	RCP2.6	0.24	0.17 to 0.32	0.40	0.26 to 0.55
	RCP4.5	0.26	0.19 to 0.33	0.47	0.32 to 0.63
	RCP6.0	0.25	0.18 to 0.32	0.48	0.33 to 0.63
	RCP8.5	0.30	0.22 to 0.38	0.63	0.45 to 0.82

Notes:

[a] Based on the CMIP5 ensemble; anomalies calculated with respect to 1986–2005. Using HadCRUT4 and its uncertainty estimate (5–95% confidence interval), the observed warming to the reference period 1986–2005 is 0.61 [0.55 to 0.67] °C from 1850–1900, and 0.11 [0.09 to 0.13] °C from 1980–1999, the reference period for projections used in AR4. *Likely* ranges have not been assessed here with respect to earlier reference periods because methods are not generally available in the literature for combining the uncertainties in models and observations. Adding projected and observed changes does not account for potential effects of model biases compared to observations, and for natural internal variability during the observational reference period {2.4; 11.2; Tables 12.2 and 12.3}

[b] Based on 21 CMIP5 models; anomalies calculated with respect to 1986–2005. Where CMIP5 results were not available for a particular AOGCM and scenario, they were estimated as explained in Chapter 13, Table 13.5. The contributions from ice sheet rapid dynamical change and anthropogenic land water storage are treated as having uniform probability distributions, and as largely independent of scenario. This treatment does not imply that the contributions concerned will not depend on the scenario followed, only that the current state of knowledge does not permit a quantitative assessment of the dependence. Based on current understanding, only the collapse of marine-based sectors of the Antarctic ice sheet, if initiated, could cause global mean sea level to rise substantially above the *likely* range during the 21st century. There is *medium confidence* that this additional contribution would not exceed several tenths of a meter of sea level rise during the 21st century.

[c] Calculated from projections as 5–95% model ranges. These ranges are then assessed to be *likely* ranges after accounting for additional uncertainties or different levels of confidence in models. For projections of global mean surface temperature change in 2046–2065 *confidence* is *medium*, because the relative importance of natural internal variability, and uncertainty in non-greenhouse gas forcing and response, are larger than for 2081–2100. The *likely* ranges for 2046–2065 do not take into account the possible influence of factors that lead to the assessed range for near-term (2016–2035) global mean surface temperature change that is lower than the 5–95% model range, because the influence of these factors on longer term projections has not been quantified due to insufficient scientific understanding. {11.3}

[d] Calculated from projections as 5–95% model ranges. These ranges are then assessed to be *likely* ranges after accounting for additional uncertainties or different levels of confidence in models. For projections of global mean sea level rise *confidence* is *medium* for both time horizons.

Figure S3. SPM table summarizing GMSL projections from the IPCC Fifth Assessment Report [10].

Feet above 1991-2009 mean	MEDIAN	LIKELY RANGE	1-IN-20 CHANCE	1-IN-200 CHANCE
Year / Percentile	*50% probability SLR meets or exceeds…*	*67% probability SLR is between…*	*5% probability SLR meets or exceeds…*	*0.5% probability SLR meets or exceeds…*
2030	0.4	0.3 — 0.5	0.6	0.8
2050	0.9	0.6 — 1.1	1.4	1.9
2100 (RCP 2.6)	1.6	1.0 — 2.4	3.2	5.7
2100 (RCP 4.5)	1.9	1.2 — 2.7	3.5	5.9
2100 (RCP 8.5)	2.5	1.6 — 3.4	4.4	6.9
2100 (H++)	10			
2150 (RCP 2.6)	2.4	1.3 — 3.8	5.5	11.0
2150 (RCP 4.5)	3.0	1.7 — 4.6	6.4	11.7
2150 (RCP 8.5)	4.1	2.8 — 5.8	7.7	13.0
2150 (H++)	22			

Figure S4. Table summarizing RSL projections for San Francisco, CA, from the 2017 California sea level assessment [31].

TABLE 1: Projected Sea-Level Rise (in feet) for San Francisco

Probabilistic projections for the height of sea-level rise shown below, along with the H++ scenario (depicted in blue in the far right column), as seen in the Rising Seas Report. The H++ projection is a single scenario and does not have an associated likelihood of occurrence as do the probabilistic projections. Probabilistic projections are with respect to a baseline of the year 2000, or more specifically the average relative sea level over 1991 - 2009. High emissions represents RCP 8.5; low emissions represents RCP 2.6. ***Recommended projections for use in low, medium-high and extreme risk aversion decisions are outlined in blue boxes below.***

		Probabilistic Projections (in feet) (based on Kopp et al. 2014)					H++ scenario (Sweet et al. 2017) *Single scenario
		MEDIAN	LIKELY RANGE		1-IN-20 CHANCE	1-IN-200 CHANCE	
		50% probability sea-level rise meets or exceeds...	66% probability sea-level rise is between...		5% probability sea-level rise meets or exceeds...	0.5% probability sea-level rise meets or exceeds...	
				Low Risk Aversion		Medium - High Risk Aversion	Extreme Risk Aversion
High emissions	2030	0.4	0.3 -	0.5	0.6	0.8	1.0
	2040	0.6	0.5 -	0.8	1.0	1.3	1.8
	2050	0.9	0.6 -	1.1	1.4	1.9	2.7
Low emissions	2060	1.0	0.6 -	1.3	1.6	2.4	
High emissions	2060	1.1	0.8 -	1.5	1.8	2.6	3.9
Low emissions	2070	1.1	0.8 -	1.5	1.9	3.1	
High emissions	2070	1.4	1.0 -	1.9	2.4	3.5	5.2
Low emissions	2080	1.3	0.9 -	1.8	2.3	3.9	
High emissions	2080	1.7	1.2 -	2.4	3.0	4.5	6.6
Low emissions	2090	1.4	1.0 -	2.1	2.8	4.7	
High emissions	2090	2.1	1.4 -	2.9	3.6	5.6	8.3
Low emissions	2100	1.6	1.0 -	2.4	3.2	5.7	
High emissions	2100	2.5	1.6 -	3.4	4.4	6.9	10.2
Low emissions	2110*	1.7	1.2 -	2.5	3.4	6.3	
High emissions	2110*	2.6	1.9 -	3.5	4.5	7.3	11.9
Low emissions	2120	1.9	1.2 -	2.8	3.9	7.4	
High emissions	2120	3	2.2 -	4.1	5.2	8.6	14.2
Low emissions	2130	2.1	1.3 -	3.1	4.4	8.5	
High emissions	2130	3.3	2.4 -	4.6	6.0	10.0	16.6
Low emissions	2140	2.2	1.3 -	3.4	4.9	9.7	
High emissions	2140	3.7	2.6 -	5.2	6.8	11.4	19.1
Low emissions	2150	2.4	1.3 -	3.8	5.5	11.0	
High emissions	2150	4.1	2.8 -	5.8	5.7	13.0	21.9

**Most of the available climate model experiments do not extend beyond 2100. The resulting reduction in model availability causes a small dip in projections between 2100 and 2110, as well as a shift in uncertainty estimates (see Kopp et al. 2014). Use of 2110 projections should be done with caution and with acknowledgement of increased uncertainty around these projections.*

Figure S5. Table summarizing RSL projections for San Francisco, CA, from the 2018 California sea level rise guidance, highlighting the selection of specific trajectories for different levels of risk aversion [32].

Table 3.2. **New York City sea level rise projections, including the new Antarctic Rapid Ice Melt (ARIM) scenario, relative to 2000–2004 (in feet)**

Baseline (2000–2004) 0"	NPCC2 2015 sea level rise projections[a] Projections of record for planning: Low estimate (10th percentile)	Middle range (25–75th percentile)	High estimate (90th percentile)	NPCC3 ARIM scenario[b] Growing awareness of long-term risk: ARIM scenario[a]
2020s	0.17 ft	0.33–0.67 ft	0.83 ft	–
2050s	0.67 ft	0.92–1.75 ft	2.5 ft	–
2080s	1.08 ft	1.50–3.25 ft	4.83 ft	6.75 ft
2100	1.25 ft	1.83–4.17 ft	6.25 ft	9.5 ft

[a]The 10th, 25th–75th, and 90th percentile projections are taken from NPCC2 (2015); the six sea level rise components upon which they are based include global and local factors (see Section 3.4.2 and NPCC (2015)). Use of NPCC2 sea level rise projections is confirmed for decision making at this time. The ARIM scenario is based on DeConto and Pollard (2016), Kopp *et al.* (2014; 2017) and informed expert judgments with regard to maximum plausible ice loss rates from Antarctica (see above and Sweet *et al.*, 2017). See this section and Appendix 3.B for full ARIM scenario and explanation.
[b]ARIM represents a new, physically plausible upper-end, low probability (significantly less than 10% likelihood of occurring) scenario for the late 21st century, derived from recent modeling of ice sheet–ocean behavior to supplement the current (NPCC, 2015) sea level rise projections. In the 2020s and 2050s, the ARIM scenario does not lie outside the pre-existing NPCC 2015 range and therefore NPCC 2015 results apply to these two earlier time slices. The ARIM scenario contains uncertainties stemming from incomplete knowledge of ice-sheet processes and atmosphere, ocean, and ice–sheet interactions.

Figure S6. Table summarizing RSL projections for New York, NY, from the 2019 New York City Panel on Climate Change report [33].

Table 2. Projected sea-level rise estimates above 2000 levels for Maryland based on the Baltimore tide-gauge station. Columns correspond to different projection probabilities and rows represent to time horizons and emissions pathways. See caveat in the text concerning potentially greater sea-level rise late this century under higher emissions pathways.

Year	Emissions Pathway	Central Estimate 50% probability SLR meets or exceeds:	Likely Range 67% probability SLR is between:	1 in 20 Chance 5% probability SLR meets or exceeds:	1 in 100 Chance 1% probability SLR meets or exceeds:
2030		0.6 ft	0.4 – 0.9 ft	1.1 ft	1.3 ft
2050		1.2 ft	0.8 – 1.6 ft	2.0 ft	2.3 ft
2080	Growing	**2.3 ft**	1.6 – 3.1 ft	3.7 ft	4.7 ft
	Stabilized	1.9 ft	1.3 – 2.6 ft	3.2 ft	4.1 ft
	Paris Agreement	1.7 ft	1.1 – 2.4 ft	3.0 ft	3.2 ft
2100	Growing	3.0 ft	2.0 – 4.2 ft	5.2 ft	6.9 ft
	Stabilized	2.4 ft	1.6 – 3.4 ft	4.2 ft	5.6 ft
	Paris Agreement	2.0 ft	1.2 – 3.0 ft	3.7 ft	5.4 ft
2150	Growing	4.8 ft	3.4 – 6.6 ft	8.5 ft	12.4 ft
	Stabilized	3.5 ft	2.1 – 5.3 ft	7.1 ft	10.6 ft
	Paris Agreement	2.9 ft	1.8 – 4.2 ft	5.9 ft	9.4 ft

An important caveat using these projections: In not accounting for the prospect of greater polar ice sheet loss, the K14 projections probably underestimate sea-level rise beyond 2050 under higher emissions pathways. While the DP16 projections might be over-estimates, they can serve to inform decisions for which risk aversion is relatively high. Under the Growing Emissions pathway the median (and Likely) sea-level rise projections are 3.6 feet (2.7-4.9 feet) for 2080 and 5.7 feet (4.2-7.9 feet) by 2100. Under the Stabilized Emissions pathway, DP16 projections begin to significantly diverge from K14 after 2080, with median (and Likely) sea-level rise of 3.7 feet (2.6-5.0 feet) for 2100.

Figure S7. Table and text summarizing RSL projections for Baltimore, MD, from the 2018 Maryland sea level rise assessment [34].

Table ES-1: New Jersey Sea-Level Rise above the year 2000 (1991-2009 average) baseline (ft)*

		2030	2050	2070			2100			2150		
				Emissions								
	Chance SLR Exceeds			Low	Mod.	High	Low	Mod.	High	Low	Mod.	High
Low End	> 95% chance	0.3	0.7	0.9	1	1.1	1.0	1.3	1.5	1.3	2.1	2.9
Likely Range	> 83% chance	0.5	0.9	1.3	1.4	1.5	1.7	2.0	2.3	2.4	3.1	3.8
	~50 % chance	0.8	1.4	1.9	2.2	2.4	2.8	3.3	3.9	4.2	5.2	6.2
	<17% chance	1.1	2.1	2.7	3.1	3.5	3.9	5.1	6.3	6.3	8.3	10.3
High End	< 5% chance	1.3	2.6	3.2	3.8	4.4	5.0	6.9	8.8	8.0	13.8	19.6

**2010 (2001-2019 average) Observed = 0.2 ft*

Notes: All values are 19-year means of sea-level measured with respect to a 1991-2009 baseline centered on the year indicated in the top row of the table. Projections are based on Kopp et al. (2014), Rasmussen et al. (2018), and Bamber et al. (2019). Near-term projections (through 2050) exhibit only minor sensitivity to different emissions scenarios (<0.1 feet). Low and high emissions scenarios correspond to global-mean warming by 2100 of 2°C and 5°C above early Industrial (1850-1900) levels, respectively, or equivalently, about 1°C and 4°C above the current global-mean temperature. Moderate (Mod.) emissions are interpolated as the midpoint between the high- and low-emissions scenarios and approximately correspond to the warming expected under current global policies. Rows correspond to different projection probabilities. There is at least a 95% chance of SLR exceeding the values in the 'Low End' row, while there is less than a 5% chance of exceeding the values in the 'High End' row. There is at least a 66% chance that SLR will fall within the values in the 'Likely Range'. Note that alternative methods may yield higher or lower estimates of the chance of low-end and high-end outcomes.

Figure S8. Table summarizing RSL projections for New Jersey from the 2019 New Jersey Science and Technical Advisory Panel Report [35].

Table 2.3: Global mean sea level and contiguous United States scenarios, in meters, relative to a 2000 baseline.

Global Mean Sea Level				Contiguous United States			
	2050	**2100**	**2150**		**2050**	**2100**	**2150**
Low	0.15	0.3	0.4	Low	0.31	0.6	0.8
Intermediate-Low	0.20	0.5	0.8	Intermediate-Low	0.36	0.7	1.2
Intermediate	0.28	1.0	1.9	Intermediate	0.40	1.2	2.2
Intermediate-High	0.37	1.5	2.7	Intermediate-High	0.46	1.7	2.8
High	0.43	2.0	3.7	High	0.52	2.2	3.9

Table 2.4: IPCC warming level–based global mean sea level projections. Global mean surface air temperature anomalies are projected for years 2081–2100 relative to the 1850–1900 climatology. Sea level anomalies are relative to a 2005 baseline (adapted from Fox-Kemper et al., 2021). The probabilities are *imprecise probabilities*, representing a consensus among all projection methods applied. For imprecise probabilities >50%, all methods agree that the probability of the outcome stated is at least that value; for imprecise probabilities <50%, all methods agree that the probability of the outcome stated is *less than or equal to* the value stated.

Global Mean Surface Air Temperature 2081–2100	1.5°C	2.0°C	3.0°C	4.0°C	5.0°C	Unknown Likelihood, High Impact – Low Emissions	Unknown Likelihood, High Impact – Very High Emissions
Closest Emissions Scenario–Based GMSL Projection	Low (SSP1-2.6)	Low (SSP1-2.6) to Intermediate (SSP2-4.5)	Intermediate (SSP2-4.5) to High (SSP3-7.0)	High (SSP3-7.0)	Very High (SSP5-8.5)	Low (SSP1-2.6), *Low Confidence* processes	Very High (SSP5-8.5), *Low Confidence* processes
Total (2050)	0.18 (0.16–0.24)	0.20 (0.17–0.26)	0.21 (0.18–0.27)	0.22 (0.19–0.28)	0.25 (0.22–0.31)	0.20 (0.16–0.31)	0.24 (0.20–0.40)
Total (2100)	0.44 (0.34–0.59)	0.51 (0.40–0.69)	0.61 (0.50–0.81)	0.70 (0.58–0.92)	0.81 (0.69–1.05)	0.45 (0.32–0.79)	0.88 (0.63–1.60)
Bounding Median Scenarios in 2100	Low to Intermediate-Low	Intermediate-Low to Intermediate	Intermediate-Low to Intermediate	Intermediate-Low to Intermediate	Intermediate-Low to Intermediate	Low to Intermediate-Low	Intermediate-Low to Intermediate
Probability > Low (0.3 m) in 2100	92%	98%	>99%	>99%	>99%	89%	>99%
Probability > Int.-Low (0.5 m) in 2100	37%	50%	82%	97%	>99%	49%	96%
Probability > Int. (1.0 m) in 2100	<1%	2%	5%	10%	23%	7%	49%
Probability > Int.-High (1.5 m) in 2100	<1%	<1%	<1%	1%	2%	1%	20%
Probability > High (2.0 m) in 2100	<1%	<1%	<1%	<1%	< %	<1%	8%

Figure S9. Tables summarizing GMSL and contiguous US-average RSL scenarios from the 2022 US Interagency Sea Level Scenarios report (Table 2.3) and linking the 2022 US Interagency Sea Level Scenarios to the IPCC Sixth Assessment Report projections (Table 2.4) [36].

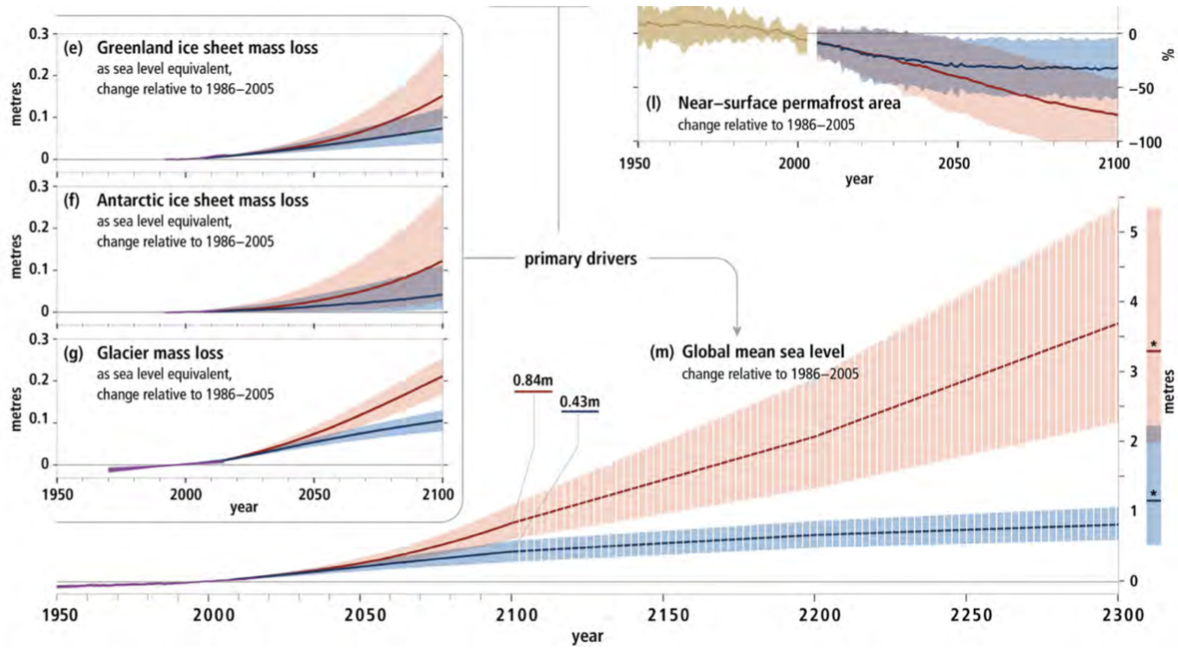

Figure S10. SPM figure from the IPCC SROCC, Figure SPM.1 [12].

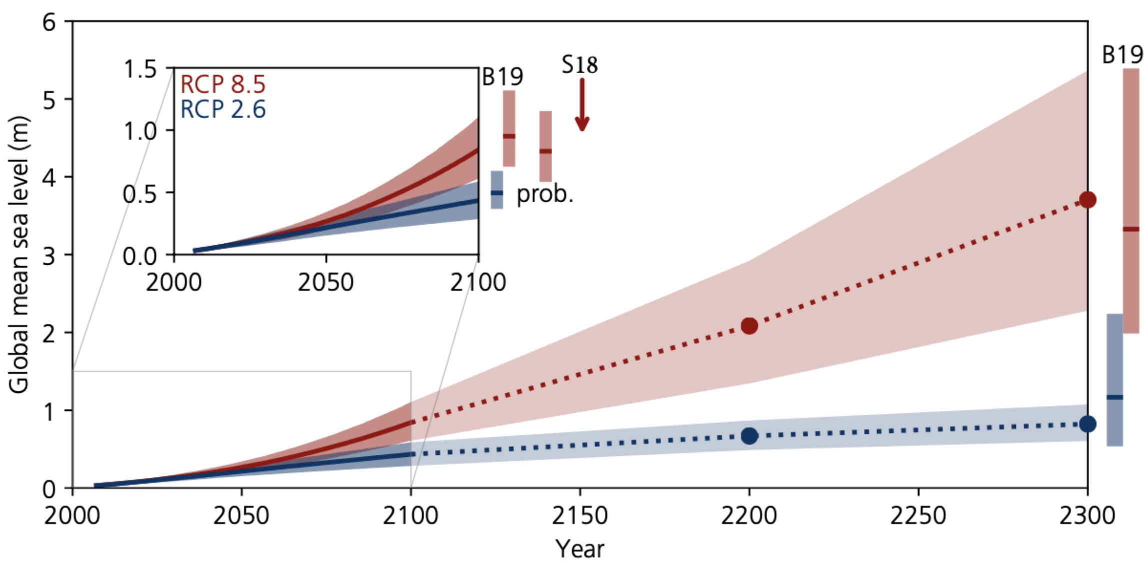

Figure 4.2: Projected sea-level rise until 2300. The inset shows an assessment of the *likely* range of the projections for RCP2.6 and RCP8.5 up to 2100 (*medium confidence*). Projections for longer time scales are highly uncertain but a range is provided (4.2.3.6). For context, results are shown from other estimation approaches in 2100. The two sets of two bars labelled B19 are from an expert elicitation for the Antarctic component (Bamber et al., 2019), and reflect the *likely* range for a 2 and 5°C temperature warming (*low confidence*; details section 4.2.3.3.1). The bar labelled "prob". indicates the *likely* range of a set of probabilistic projections (4.2.3.2). The arrow indicated by S19 shows the result of an extensive sensitivity experiment with a numerical model for the Antarctic ice sheet combined, like the results from B19 and "prob.", with results from Church et al. (2013) for the other components of sea level rise. S19 bars also show the *likely* range.

Figure S11. Chapter figure from the IPCC SROCC [11].

Table 9.9 | Global mean sea level projections for five Shared Socio-economic Pathway (SSP) scenarios, relative to a baseline of 1995–2014, in metres. Individual contributions are shown for the year 2100. Median values (*likely* ranges) are shown. Average rates for total sea level change are shown in mm yr^{-1}. Unshaded cells represent processes in whose projections there is *medium confidence*. Shaded cells incorporate a representation of processes in which there is *low confidence*; in particular, the SSP5-8.5 *low confidence* column shows the 17th–83rd percentile range from a p-box including SEJ- and MICI-based projections rather than an assessed *likely* range. Methods are described in 9.6.3.2.

	SSP1-1.9	SSP1-2.6	SSP2-4.5	SSP3-7.0	SSP5-8.5	SSP5-8.5 *Low Confidence*
Thermal expansion	0.12 (0.09–0.15)	0.14 (0.11–0.18)	0.20 (0.16–0.24)	0.25 (0.21–0.30)	0.30 (0.24–0.36)	0.30 (0.24–0.36)
Greenland	0.05 (0.00–0.09)	0.06 (0.01–0.10)	0.08 (0.04–0.13)	0.11 (0.07–0.16)	0.13 (0.09–0.18)	0.18 (0.09–0.59)
Antarctica	0.10 (0.03–0.25)	0.11 (0.03–0.27)	0.11 (0.03–0.29)	0.11 (0.03–0.31)	0.12 (0.03–0.34)	0.19 (0.02–0.56)
Glaciers	0.08 (0.06–0.10)	0.09 (0.07–0.11)	0.12 (0.10–0.15)	0.16 (0.13–0.18)	0.18 (0.15–0.21)	0.17 (0.11–0.21)
Land-water Storage	0.03 (0.01–0.04)	0.03 (0.01–0.04)	0.03 (0.01–0.04)	0.03 (0.02–0.04)	0.03 (0.01–0.04)	0.03 (0.01–0.04)
Total (2030)	0.09 (0.08–0.12)	0.09 (0.08–0.12)	0.09 (0.08–0.12)	0.10 (0.08–0.12)	0.10 (0.09–0.12)	0.10 (0.09–0.15)
Total (2050)	0.18 (0.15–0.23)	0.19 (0.16–0.25)	0.20 (0.17–0.26)	0.22 (0.18–0.27)	0.23 (0.20–0.29)	0.24 (0.20–0.40)
Total (2090)	0.35 (0.26–0.49)	0.39 (0.30–0.54)	0.48 (0.38–0.65)	0.56 (0.46–0.74)	0.63 (0.52–0.83)	0.71 (0.52–1.30)
Total (2100)	**0.38 (0.28–0.55)**	**0.44 (0.32–0.62)**	**0.56 (0.44–0.76)**	**0.68 (0.55–0.90)**	**0.77 (0.63–1.01)**	**0.88 (0.63–1.60)**
Total (2150)	0.57 (0.37–0.86)	0.68 (0.46–0.99)	0.92 (0.66–1.33)	1.19 (0.89–1.65)	1.32 (0.98–1.88)	1.98 (0.98–4.82)
Rate (2040–2060)	4.1 (2.8–6.0)	4.8 (3.5–6.8)	5.8 (4.4–8.0)	6.4 (5.0–8.7)	7.2 (5.6–9.7)	7.9 (5.6–16.1)
Rate (2080–2100)	4.2 (2.4–6.6)	5.2 (3.2–8.0)	7.7 (5.2–11.6)	10.4 (7.4–14.8)	12.1 (8.6–17.6)	15.8 (8.6–30.1)

Table 9.10 | Global mean sea level (GMSL) projections and commitments for exceedance of five global warming levels, defined by sorting GSAT change in 2081–2100 with respect to 1850–1900. Median values and (*likely*) ranges are in metres relative to a 1995–2014 baseline. Rates are in mm yr^{-1}. Unshaded cells represent processes in whose projections there is *medium confidence*. Shaded cells incorporate a representation of processes in which there is *low confidence*; in particular, the SSP5-8.5 *low confidence* column shows the 17th–83rd percentile range from a p-box, including projections based on structured expert judgement (SEJ) and marine ice cliff instability (MICI) rather than an assessed *likely* range. Methods are described in 9.6.3.2.

	1.5°C	2.0°C	3.0°C	4.0°C	5.0°C	SSP5-8.5 *Low Confidence*
Closest SSPs	SSP1-2.6	SSP1-2.6/SSP2-4.5	SSP2-4.5/SSP3-7.0	SSP3-7.0	SSP5-8.5	
Total (2050)	0.18 (0.16–0.24) m	0.20 (0.17–0.26) m	0.21 (0.18–0.27) m	0.22 (0.19–0.28) m	0.25 (0.22–0.31) m	0.24 (0.20–0.40) m
Total (2100)	**0.44 (0.34–0.59) m**	**0.51 (0.40–0.69) m**	**0.61 (0.50–0.81) m**	**0.70 (0.58–0.92) m**	**0.81 (0.69–1.05) m**	**0.88 (0.63–1.60) m**
Rate (2040–2060)	4.1 (2.9–5.7) mm yr^{-1}	5.0 (3.7–7.0) mm yr^{-1}	6.0 (4.6–8.1) mm yr^{-1}	6.4 (5.0–8.6) mm yr^{-1}	7.2 (5.7–9.8) mm yr^{-1}	7.9 (5.6–16.1) mm yr^{-1}
Rate (2080–2100)	4.3 (2.6–6.4) mm yr^{-1}	5.5 (3.4–8.4) mm yr^{-1}	7.8 (5.3–11.6) mm yr^{-1}	9.9 (7.1–14.3) mm yr^{-1}	11.7 (8.5–17.0) mm yr^{-1}	15.8 (8.6–30.1) mm yr^{-1}
2000-yr commitment	2 to 3 m	2 to 6 m	4 to 10 m	12 to 16 m	19 to 22 m	
10,000-yr commitment	6 to 7 m	8 to 13 m	10 to 24 m	19 to 33 m	28 to 37 m	

Figure S12. Chapter tables from the IPCC AR6 [13].

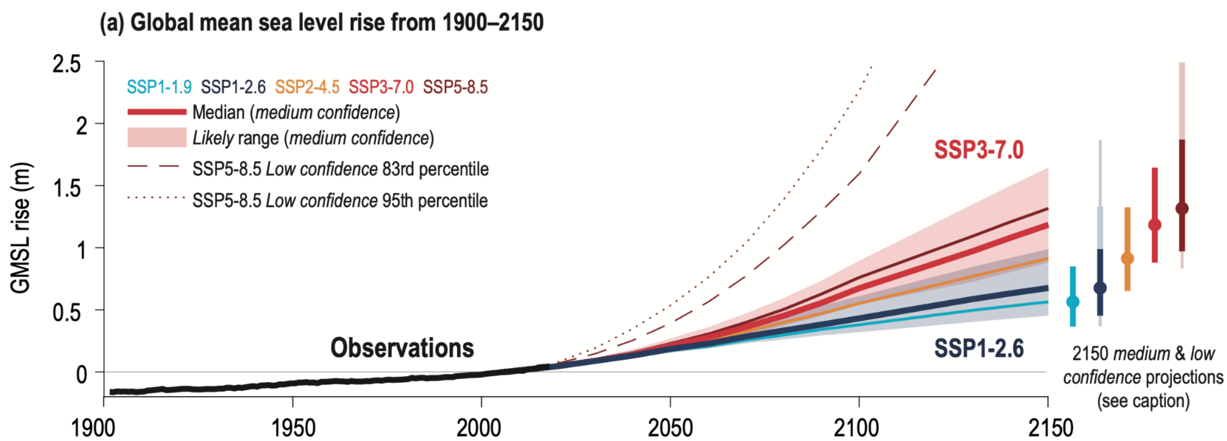

Figure S13. Technical Summary figure (Box TS.4, Fig. 1a) from the IPCC AR6 presenting GMSL time series [37]. Solid lines show median projections. Shaded regions show *medium confidence, likely* ranges from SSP1-2.6 and SSP3-7.0. Dark bars at right show 2150 *likely* ranges for all scenarios. Thick/thin lightly shaded bars show 17th-83rd/5th-95th percentile of *low confidence* projections for SSP1-2.6 and SSP5-8.5 (extending to 4.8/5.4 m for SSP5-8.5).

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