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Illustrative Multi-Centennial Projections of Global Mean Sea-Level Rise and Their Application

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Key Points:

- Projections of global mean sea-level rise to 2500 have [5, 95]% intervals of [0.3, 4.3]m under SSP1-2.6 and [1.0, 7.6]m under SSP2-4.5
- The most uncertain sea-level contributor continues to be the Antarctic ice sheet, with multiple studies considered to build a projection
- Despite the uncertainties, our projections can be used to analyze their societal implications and recognize and potentially avoid lock-ins

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Abstract

We produce projections of global mean sea-level rise to 2500 for low and medium emissions scenarios (Shared Socioeconomic Pathways SSP1-2.6 and SSP2-4.5) relative to 2020, based on extending and combining model ensemble data from current literature. We find that emissions have a large effect on sea-level rise on these long timescales, with [5, 95]% intervals of [0.3, 4.3]m and [1.0, 7.6]m under SSP1-2.6 and SSP2-4.5 respectively, and a difference in the 95% quantile of 1.6 m at 2300 and 3.3 m at 2500 for the two scenarios. The largest and most uncertain component is the Antarctic ice sheet, projected to contribute 5%–95% intervals of [−0.1, 2.3]m by 2500 under SSP1-2.6 and [0.0, 3.8]m under SSP2-4.5. We discuss how the simple statistical extensions used here could be replaced with more physically based methods for more robust predictions. We show that, despite their uncertainties, current multi-centennial projections combined into multi-study projections as presented here can be used to avoid future "lock-ins" in terms of risk and adaptation needs to sea-level rise.

Plain Language Summary

Sea levels are predicted to rise for hundreds to thousands of years, even if emissions are reduced. Decisions about how to adapt to more frequent and severe coastal flooding need predictions showing a range of possible futures. However, few computer modeling studies of the contributing factors to sea level rise extend as far as the year 2300, and few to 2500. We present illustrative predictions of global mean sea level rise for low and medium emissions scenarios to 2500 by combining previous modeling studies and extending them where necessary. We take the widest possible range when combining studies, to show many possible futures. Predictions for global average sea level rise are 0.3–4.3 m at 2500 for the low emissions scenario, where global warming stays below around 2°C. Under medium emissions, where long-term warming is predicted to be around 2–5°C, the predictions are around double this: from 1.0 to 7.6 m. Our aim is to outline possible long-term futures based on physical understanding, so decision-makers can analyze potential implications for society and avoid making decisions that are difficult to change later. We describe some potential applications of our projections, as well as key knowledge gaps and future research directions.

1. Introduction

The Sixth Assessment Report (AR6) of the Intergovernmental Panel on Climate Change (IPCC, 2021a) presented *likely* ranges of global mean sea-level rise to the year 2150, rather than only 2100 as in previous reports, reflecting both the increasing nearness of the end of this century and the rising concern for long-term (100 + year) sea level changes (Clark et al., 2016; Hinkel et al., 2019). However, these projections were only for processes for which there was at least *medium confidence*; projection of total sea level rise under all plausible processes was not possible due to the associated deep uncertainty (Kopp et al., 2023). The AR6 projected a *likely* rise of 0.46–0.99 m by 2150, relative to 1995–2014, under the low greenhouse gas emissions scenario [Shared Socioeconomic Pathway: Meinshausen et al. (2020)] SSP1-2.6, and 0.98–1.88 m under the very high emissions scenario SSP5-8.5, though they could not rule out much higher rises under SSP5-8.5 due to "*deep uncertainty*" in ice sheet processes (IPCC, 2021a). Beyond this date, the AR6 report did not make likelihood statements; instead, projections to 2300 were produced in a similar manner to the 2150 projections, with a fourth estimate made using a separate projection of ice sheet contributions. These were then summarized from the lowest seventeenth and highest 83rd percentile across the four different estimates [a "p-box" approach (Le Cozannet et al., 2017)]: at 2300, the stated 17th–83rd percentile ranges were 0.3–3.1 m under SSP1-2.6 and 1.7–6.8 m under SSP5-8.5. In

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addition, AR6 presented literature estimates with the possibility of a global mean sea-level rise exceeding 15m under SSP5-8.5 arising from ice sheet instabilities (DeConto et al., 2021) which could not be excluded. Despite there being some studies in the literature that gave projections under RCP4.5 to 2300 (Kopp et al., 2014, 2017; Nauels et al., 2017, Palmer et al., 2020); summarized in IPCC (2021a, Table 9. SM.8), the AR6 chose not to present assessed projections under SSP2-4.5 "as simulations that extend beyond 2100 for the other scenarios are too few for robust results." (IPCC, 2021a, SPM Figure 8). Projections beyond 2300 under the SSP extensions were also not provided (Meinshausen et al., 2020).

However, we argue that there is a need for probabilistic projections of multi-century sea-level rise under low and intermediate emissions scenarios, for a number of reasons. Decisions made in the near future that affect emissions over the coming decades will affect sea level for hundreds to thousands of years (e.g., Clark et al., 2016), due to the slow responses of the ocean and ice sheets to cumulative greenhouse gas emissions. Sea level will remain high on these timescales even if atmospheric warming is reversed by removal of carbon dioxide from the atmosphere (DeConto et al., 2021; IPCC, 2021a). Adaptation stakeholders making long-term decisions, such as planning long-life coastal infrastructure and adaptation, also need multi-century projections, particularly up to 100 years, and longer in some cases (Hinkel et al., 2019). R. J. Nicholls, Hanson, et al. (2021) found in a survey of adaptation stakeholders that there is demand for projections up to 2,200, with some interest in timescales of up to 1,000 years (see Discussion). Beyond the 2,200 timeframe, estimates of sea-level rise can inform broad thinking about long-term risks and coastal futures which inform coastal policy (e.g., R. J. Nicholls et al. (2008)). Long-term commitment of the oceans, cryosphere, and sea-level change was part of the AR6 Working Group I chapter outline co-produced at the 46th session of the IPCC with stakeholders (IPCC, 2017), and interest in post-2100 sea-level rise was re-affirmed by several government representatives in the plenary session of the Summary for Policymakers (IPCC, 2021b). Finally, long-term projections under medium scenarios are needed because the slow but sizable progress in mitigation of climate change reported by the AR6 (IPCC, 2022b) suggests that global warming may follow an intermediate pathway. Providing only low and very high emissions scenarios is therefore not sufficient for adaptation planning.

We address these gaps by making probabilistic model-based projections for global mean sea-level rise to 2500 under low and intermediate emissions scenarios (SSP1-2.6 and SSP2-4.5) by extending and combining estimates for each individual contribution: the Antarctic and Greenland ice sheets, glaciers, thermal expansion, and land water storage. The estimates are based on the AR6 (IPCC, 2021a) and other published studies. We extrapolate projections for individual contributions from 2300 to 2500, where necessary, combining multiple model projections for Antarctica and Greenland due to the deep uncertainty arising from ice sheet instabilities. We then combine all contributions to present projections for total global mean sea-level rise. Given the long timescales and inherent uncertainty, these projections should be viewed as illustrative. Our aim is to provide long-term projections based on physically based models, where possible, complemented with simple, transparent extrapolation where needed, to provide an outline of long-term global mean sea-level changes under low and medium emissions scenarios, and show where key knowledge gaps remain. Finally, we discuss how current multi-century projections may be used by stakeholders to avoid adaptation "lock-ins," drawing on user workshops and a literature review (Capar et al., 2020; R. J. Nicholls, Hanson, et al., 2021) carried out for a European Union Horizon 2020 project on sea-level rise (PROTECT: https://protect-slr.eu), and highlight future research directions.

Throughout this work, we follow the sea level terminology outlined in Gregory et al. (2019).

2. Methods

2.1. Selection of Estimates and Scenarios

We use projections from physically based models of the individual contributions (rather than "semi-empirical" or other types of extrapolation) as far as possible, and in particular perturbed parameter ensemble studies (for probability distributions of sea-level contributions). We also only use projections forced by Representative Concentration Pathways (RCPs) or Shared Socioeconomic Pathways (SSPs).

As in the AR6 (IPCC, 2021a), we assume that RCP2.6 and RCP4.5 correspond to the SSPs with similar radiative forcing at 2,100 (SSP1-2.6 and SSP2-4.5), though the SSPs tend to be slightly warmer. SSP1-2.6 and SSP2-4.5 are projected to result in warming of 1.0–2.2°C and 2.3–4.6°C in 2300 (5%–95%), relative to 1850–1900 (IPCC, 2021a, Table 4.9), while RCP2.6 and RCP4.5 result in around 0.6–1.8°C and 2.1–4.1°C for 2281–2300

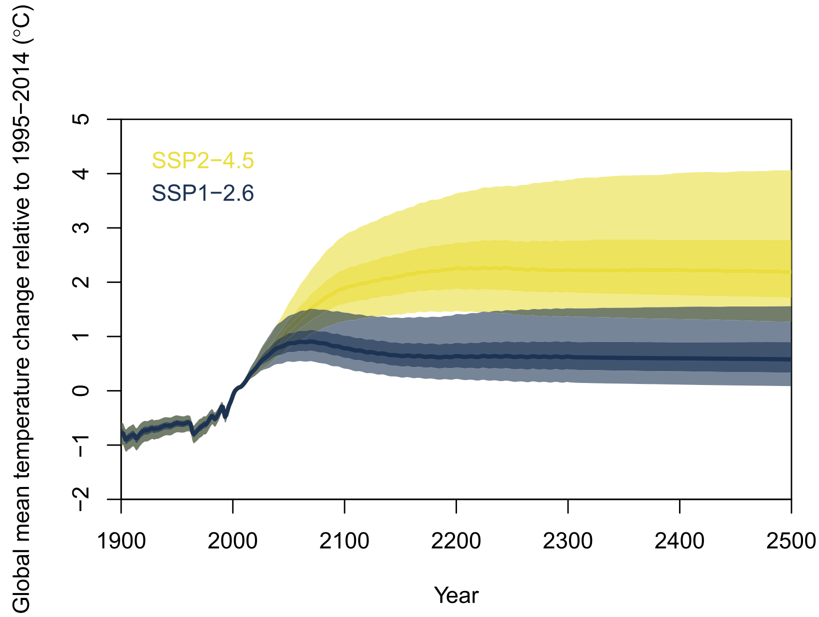

Figure 1. Global mean surface temperature changes for the historical period (1900–2014) and under the emissions scenarios SSP1-2.6 and SSP2-4.5 (2015–2500), simulated by a simple climate model for the AR6 (see text for details).

(IPCC, 2013, Table 12.2). Figure 1 shows the global mean surface temperature projections from AR6 (C. Smith, 2021; see Chapter 7, Appendix 7.A.2) that were used for the AR6 global mean sea level projections (Chapter 9). The SSP extensions to 2500 assume that most greenhouse gas emissions are zero after 2250 or earlier, so concentrations decline from 2250 to 2300. Radiative forcing decreases from around 2050 in SSP1-2.6 and around 2200 in SSP2-4.5.

We do not provide projections for the very high emissions scenario, SSP5-8.5, as current Nationally Determined Contributions under the Paris Agreement fall well below this extreme emissions trajectory (Meinshausen et al., 2022). There is also far greater uncertainty in the long-term ice sheet contributions under this scenario (IPCC, 2021a; Lowry et al., 2021; Stokes et al., 2022). Of the other SSPs, we focus on RCP2.6/SSP1-2.6 and RCP4.5/SSP2-4.5, as these are the scenarios for which model ensemble data are most widely available.

The ice sheet contributions are derived predominantly from physical ice sheet models, extended from 2300 where needed using randomly sampled sub-linear extrapolation; the glacier contribution is from the IPCC AR6 assessment (which uses physical glacier models up to 2100 and statistical models after), extended from 2300 using linear extrapolation; the thermal expansion uses ocean heat content projections from the IPCC AR6 assessment of equilibrium climate sensitivity and transient climate response (which uses a simple climate model) and expansion coefficients derived from physical climate models up to 2100; and the land water storage uses the IPCC AR6 assessment to 2300, assuming no further contribution from this date. All contributions are distributions, rather than single values: ensembles of physical model simulations, statistical Monte Carlo samples, or quantiles describing the full shape of the distribution. All the AR6 projections are made relative to 1995–2014, and other studies are relative to 2000 or similar: the baselines are all standardised here to 2020. A summary of the methods used over different time-horizons is given in Table 1.

All values are in meters sea-level equivalent (m, for brevity).

2.2. Antarctic Ice Sheet

Antarctica is projected to be the largest contributor to multi-century future sea-level rise, particularly under very high emissions (IPCC, 2021a), but the *deep uncertainty* characterized by the IPCC arises from *low confidence* in understanding and modeling processes of ice sheet instability: in particular, Marine Ice Sheet Instability (MISI) (Pattyn & Morlighem, 2020) and the hypothesized Marine Ice Cliff Instability (MICI) (DeConto et al., 2021;

Table 1
Summary of the Methods Used to Build Contributions to Sea Level Rise, Both in the Original Studies and the Methods Used in This Paper

Contribution	Previous studies	This study
Antarctica (Bulthuis et al., 2019)	**2000–3000:** Emulation of fETISh to generate projections under RCPs	–
Antarctica (DeConto et al., 2021)	**2000–2300:** Use the Penn State model, the only ice sheet model to incorporate MICI, to create projections under RCPs	**2300–2500:** Sub-linear extrapolation as described in Section 2.2
Antarctica (Levermann et al., 2020)	**2020–2300:** Linear response theory is applied to 16 ice sheet models to build ice dynamic projections under SSPs; extended from 2100 to 2300 with surface mass estimate for the IPCC AR6	**2300–2500:** Sub-linear extrapolation as described in Section 2.2
Antarctica (Lowry et al., 2021)	**1970–2300:** Emulation of PISM to create extensions of RCPs	**2300–2500:** Sub-linear extrapolation as described in Section 2.2
Greenland (Aschwanden et al., 2019)	**2000–3000:** PISM used to create extensions of RCPS, extrapolating temperature anomalies from 2200 to 2300 to 2500, and keeping monthly values constand afterward	–
Greenland (IPCC, 2021a)	**2020–2100:** Physical models are used to build projections under SSPs. **2100–2300:** Extrapolations created with constant rates of mass loss	**2300–2500:** Sub-linear extrapolation as described in Section 2.2
Glaciers (IPCC, 2021a)	**2020–2100:** Simulations from glacier models used to build projections under SSPs. **2100–2300:** Statistical models fitted to simulations in order to extend them to 2300	**2300–2500:** Linear extrapolation
TE (IPCC, 2021a)	**2020–2100:** AR6 projections of ocean heat content are converted to global mean thermosteric sea-level rise (GMTSLR) by fitting a linear regression	**2100–2500:** Expansion coefficients are derived from these regressions and combined to create a distribution; this was then sampled from to estimate GMTSLR up to 2500
LWS (IPCC, 2021a)	**2020–2300:** A statistical relationship between historical and future populations and dam impoundment and groundwater extraction is used to build projections	**2300–2500:** Extrapolations are made under an assumption of no further contributions

DeConto & Pollard, 2016). We therefore combine four ice sheet model ensemble studies to consider a range of projections: Bulthuis et al. (2019), DeConto et al. (2021), an extension of Levermann et al. (2020) to 2300 generated for the AR6 (IPCC, 2021a), and Lowry et al. (2021). These studies vary in modeling approach and timescale. Bulthuis et al. (2019) use the f.ETISh ice sheet model, and statistical emulation of this, to generate projections under RCPs up to the year 3000. DeConto et al. (2021) generated projections under RCPs up to 2300, using the only ice sheet model to incorporate MICI—a process that, if widespread and unmitigated by local processes, could lead to rapid ice sheet losses. These (along with structured expert judgment: see below) were the basis of the AR6 *low confidence* projections for Antarctica. We chose not to include the 2500 projections from DeConto and Pollard (2016) due to the limitations outlined by their later study. Levermann et al. (2020) apply linear response theory to an ensemble of 16 ice sheet models, using statistical methods analogous to emulation to make projections of the ice dynamic contribution to sea-level under RCPs to 2100. This method was applied in the AR6 to generate extended projections under SSPs—adding an estimate for the surface mass balance component, which was not included in the original study—to inform the assessed range at 2300, along with Bulthuis et al. (2019) and other literature (IPCC, 2021a), and these extensions are used here. Lowry et al. (2021) use the Parallel Ice Sheet Model (PISM) and emulation to produce projections under RCPs to 2300, which are constrained with historical data; these were published after the AR6 deadline, so were not included in their assessment.

We did not use the AR6 assessments for Antarctica, due to our preference for deriving estimates directly from the physically based, perturbed parameter, long-term simulations underlying the assessments (of which some were also published later). The AR6 *medium confidence* projections extend only to 2150, of which the last 50 years are extrapolated using a constant rate of mass loss (see AR6 Section 9.6.3.2.2), and the *low confidence* projections to 2150 and 2300 also include structured expert judgment (J. L. Bamber et al., 2019), which (unavoidably) lacks transparency in the assumptions and processes included (IPCC, 2021a).

Extrapolation from 2300 to 2500 was required for the projections by DeConto et al. (2021), the Levermann et al. (2020) extensions, and Lowry et al. (2021). We first interpolated the decadal data to annual values, and then performed linear regression on each simulation in the ensemble to estimate the rates of sea-level contribution during the final 50 years (2250–2300). A simple linear extrapolation after 2300 was deemed unsuitable, given the declining concentrations and radiative forcings in the SSP extensions (Section 2.1), so we assumed the rate of ice mass loss was generally likely to decrease. We therefore extrapolated linearly using gradients sampled uniformly in the range [10 to 100]% of the rate of sea-level contribution in the previous 50 years to represent the rate of mass loss tending to slow under decreasing climate forcing. This is intended as a simple method of extending the ensembles in a transparent way; alternative statistical approaches and requirements for more physically based projections are described in the Discussion.

We apply the p-box approach to the four sets of projections for the total global mean sea-level (see Results). It should be noted that the use of the p-box method has maximized the range of outcomes across the studies included.

2.3. Greenland Ice Sheet

We use two data sets for the Greenland ice sheet: Aschwanden et al. (2019), which are currently the only multi-century perturbed parameter ensemble model projections (extending to 2500), and one of the IPCC (2021a) sets of projections that extends to 2300.

The SROCC (IPCC, 2019) had noted that the projections by Aschwanden et al. (2019) were much higher than previous studies, especially under RCP8.5 and beyond 2100, and attributed this to the use of spatially uniform warming over the ice sheet leading to an over-estimation of surface melt rates in the ablation zone. However, we include them here because the AR6 assessed this could also reflect deep uncertainty arising from surface processes (IPCC, 2021a), and because projections for low-medium emissions scenarios are more similar to other estimates (e.g., J. L. Bamber et al. (2019), structured expert judgment: 5%–95% interval 0.28–1.28 m at 2300 under 2°C warming).

The IPCC long-term projections fit statistical models to simulations from multiple ice sheet models to 2100, then extrapolate to 2300 using constant rates of mass loss (IPCC, 2021a). Here, we choose to use these AR6 assessments, despite them only using physical models to 2100, because so little other probabilistic evidence from physical models is available. This allows us to compare them with the projections from Aschwanden et al. (2019) and represent some additional uncertainty in physically based projections. We interpolate the AR6 projections from decadal to annual values and extrapolate from 2300 to 2500 using the method described in Section 2.2.

As for Antarctica, we apply the p-box approach to the two sets of projections for the total global mean sea-level (see Results).

2.4. Glaciers

The glacier contributions are based on projections to 2300 from the AR6 (IPCC, 2021a), which fitted statistical models to simulations from multiple glacier models to 2100, then used these to extend to 2300. We use only the AR6 assessments due to a lack of literature: few physically based glacier model simulations exist beyond 2100, and few perturbed parameter ensembles exist at all.

We interpolate the projections from decadal to annual values, and then extrapolate from 2300. We apply a cap of 0.29 m to the total glacier contribution to sea-level change, adjusting the value estimated by Farinotti et al. (2019) to a 2020 baseline. Unlike the ice sheets, here we use the simpler assumption that the rate of mass loss is constant from 2250, that is, that their smaller volumes result in continuing losses as the glaciers equilibrate to past warming. In any case, their small total contribution means they are either lost by 2300, or else the method of extrapolation does not much affect total global mean sea-level beyond this date when combined with the other components.

2.5. Thermal Expansion

The ocean has absorbed approximately 90% of the radiative imbalance associated with greenhouse gas forcing of the climate system. This ocean heat uptake results in global sea level rise through thermal expansion, changing the sea water density and expanding its volume. This thermal expansion, or thermosteric sea-level rise, is currently the dominant contributor to sea-level rise (IPCC, 2021a). To project the contribution of thermal expansion to sea-level rise up to 2500, we use an approach based on the method used in the IPCC AR6 (Chapter 9 Supplementary Material: 9.SM.4.3).

Global mean thermosteric sea-level rise (GMTSLR) is estimated from AR6 projections of Ocean Heat Content (OHC) up to 2500, which were made with a two-layer simple climate model under the extended SSPs (adapted for simple climate models: Nicholls et al., 2020) using the AR6 assessments of equilibrium climate sensitivity and transient climate response (Chapter 7, Appendix 7.A.2). The OHC projections are converted to GMTSLR by multiplication with expansion coefficients, which were derived in the AR6 by fitting, for individual CMIP6 models, a linear regression between GMTSLR from a given model against OHC emulated by the two-layer model tuned with CMIP6 calibration parameters (C. J. Smith et al., 2021). The linear regression was performed with an intercept of zero, for the period 2015–2100, across all SSPs. This resulted in an expansion coefficient for each CMIP6 model considered, which were combined to create a distribution of expansion coefficients. This distribution was clipped based on the Root Mean Square Error (RMSE) between emulated global surface air temperature and the equivalent from individual CMIP6 models, retaining models with RMSE less than or equal to the 85th percentile of the cumulative distribution of RMSE for all models considered. A normal distribution fit to the remaining expansion coefficients had a mean and standard deviation of 0.113 ± 0.013 m/YJ. We randomly draw expansion coefficients from this distribution to estimate GMTSLR from the AR6 OHC projections up to 2500 (rather than only to 2300, as the AR6 did).

Structural uncertainty in thermal expansion (TE) mainly stems from the GCMs used for its calculation and the approach used for its extension. Studies focusing on projecting the TE contribution to sea-level change may choose a different set of GCMs depending on availability of models and the objectives of their study, so the "structural uncertainty" arising from comparing such projections may not only include model biases, but also uncertainty of criteria. Despite those differences, structural uncertainty in TE between different studies/projections is significantly lower than for land-ice components, especially when assessing centennial changes as done in our study. Since the land-ice component is the most important driver of this uncertainty in multi-centennial projections, and TE projections are rather similar between studies using different approaches (Kopp et al., 2014, 2017; Nauels et al., 2017; Palmer et al., 2020), we opted for comparing different projections for land-ice contributions and not TSLR. As structural uncertainty stemming from ice sheet processes is significantly larger on the timescales relevant for our study, we opted to only focus on structural uncertainty for ice-sheet processes.

2.6. Land Water Storage

The anthropogenic land water storage contribution to sea-level is presumed to primarily consist of the contributions of groundwater extraction (Wada et al., 2012) and dam impoundment (Chao et al., 2008). Here we extrapolate the IPCC AR6 projections of land water storage from 2300 to 2500. To account for the effect of societal development, the AR6 projections apply a statistical relationship to link historical and future global population (under SSPs) with dam impoundment and groundwater extraction (Kopp et al., 2014; Rahmstorf, 2012). Given the dependence of those drivers on social development and policies, it becomes increasingly difficult to assume this relationship with population holds over the long-term.

Hence, we simply assume that there is no further net land water storage contribution to sea-level beyond 2300. In other words, we assume that after this time no further dams are built inland, and that groundwater extractions are compensated by recharge of aquifers. In any case, land water storage is the smallest contributor to total global mean sea-level (IPCC, 2021a, Table 9.11); although we are making strong assumptions here, we do not believe providing better estimates would significantly alter our results. Unlike other contributions to sea level rise, our results here are reported to the nearest centimetre, rather than decimeter, due to their smaller magnitude.

2.7. Total Global Mean Sea-Level

We calculate the total global mean sea-level (GMSL) under the assumption that all of these components are fully correlated. This is a simple sum of the quantiles for all components. A more sophisticated approach would be preferred in future, particularly when the studies disagree substantially (see Discussion). Other studies have considered the effect of assuming full correlation or independence of contributions on total sea level projections: for example, van de Wal et al. (2022) found that assuming independence reduced their global mean sea level projections at 2300 by 1.8 m under the very high emissions scenario SSP5-8.5, compared with full correlation, and by 0.3 m under the SSP1-2.6 scenario that we present here.

3. Results

The four sets of Antarctic projections vary widely: some 5%–95% intervals at 2500 do not overlap with each other (Figure 2, Table 2). Contributions to GMSL are lowest for projections from Bulthuis et al. (2019), with 5%–95% interval contributions of [−0.1, 0.5]m and [0.0, 1.3]m under SSP1-2.6 and SSP2-4.5. The highest contributions

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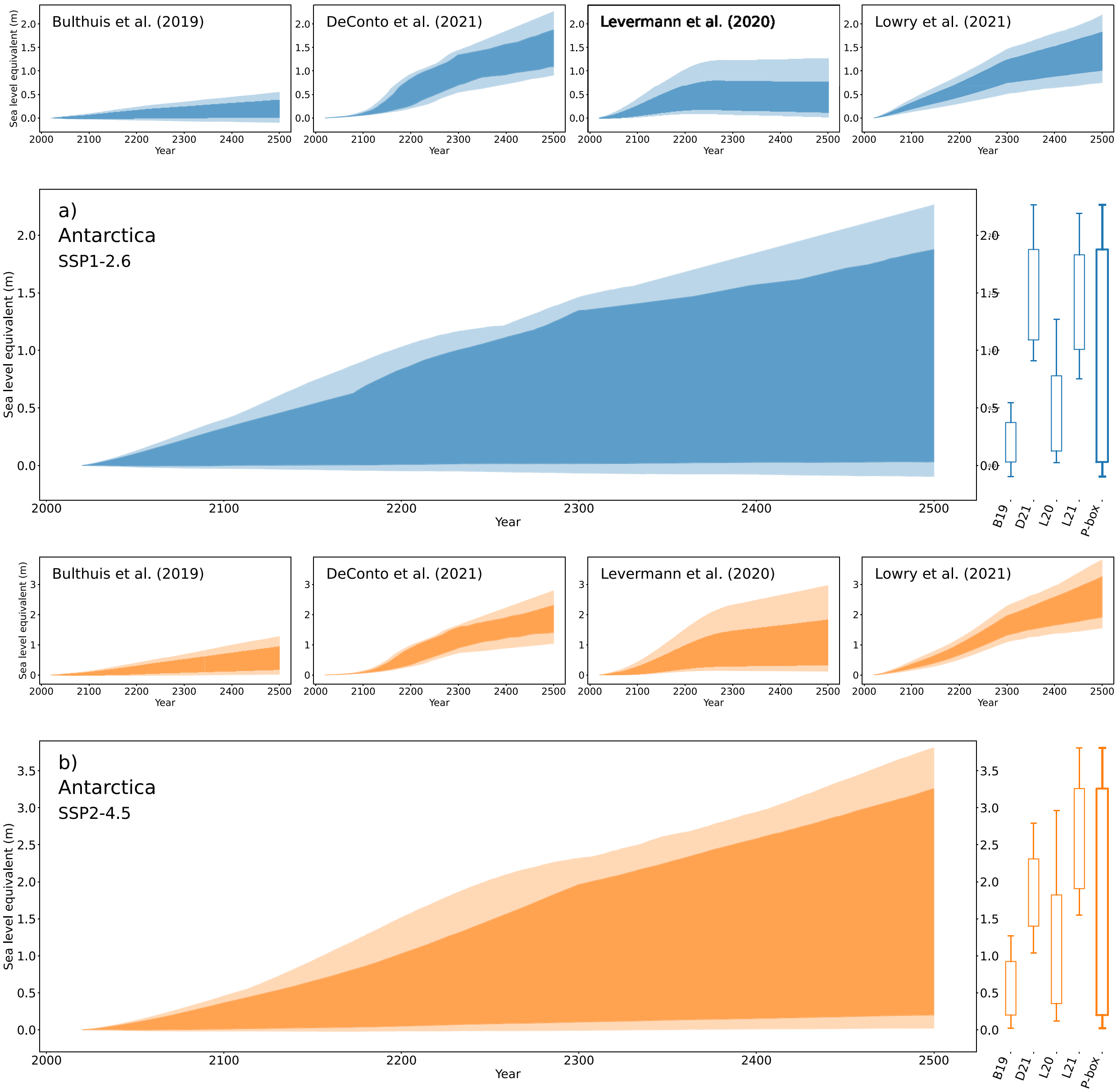

Figure 2. Projections of the Antarctic contribution to sea-level change to 2500 (m). Projections under (a) SSP1-2.6 and (b) SSP2-4.5 from Bulthuis et al. (2019) and from three studies extended from 2300 using randomly sampled sub-linear extrapolation DeConto et al. (2021), Lowry et al. (2021) and the extensions of Levermann et al. (2020) for the AR6 (IPCC, 2021a) are shown in the top panels. The p-box projection is shown in the bottom panel. Darker shaded regions represent the 17%–83% intervals, and lighter shaded regions represent the 5%–95% intervals. Box and whiskers show the 17%–83% and 5%–95% intervals at 2500. All projections are relative to 2020.

are based on extrapolation of Lowry et al. (2021) under SSP2-4.5 ([1.6, 3.8]m). For the lower scenario, SSP1-2.6, the highest projections are those extrapolated from Lowry et al. (2021) and DeConto et al. (2021), at [0.8, 2.2] m and [0.9, 2.3]m, respectively. Projections based on the Levermann et al. (2020) extensions for the AR6 lie in between these other studies.

There is a clear difference between scenarios in the Greenland projections by Aschwanden et al. (2019): the 5%–95% interval contribution at 2500 under SSP1-2.6 is [0.2, 1.1]m, compared with over double this ([0.5, 2.2]m) under SSP2-4.5 (Figure 3, Table 2). The probability density function under SSP2-4.5 is also noticeably broader, reflecting the general tendency toward greater uncertainty under higher emissions. The projections from the AR6 (IPCC, 2021a) do not display such large differences between emissions scenarios; at 2500, the 5%–95% interval projections under SSP2-4.5 are around 20–30 cm larger than under SSP1-2.6 ([0.4,

Table 2
Projected Contributions to Sea-Level Change, Relative to 2020, at 2300, 2400, and 2500 in Quantiles [5, 17, 83, 95] (meters Sea-Level Equivalent)

Shared Socioeconomic Pathway (SSP)	2300	2400	2500
Antarctic ice sheet (Bulthuis et al., 2019)			
SSP1-2.6	[−0.1, 0.0, 0.2, 0.3]	[−0.1, 0.0, 0.3, 0.4]	[−0.1, 0.0, 0.4, 0.5]
SSP2-4.5	[−0.0, 0.1, 0.5, 0.7]	[0.0, 0.2, 0.7, 1.0]	[0.0, 0.2, 0.9, 1.3]
Antarctic ice sheet (DeConto et al., 2021)			
SSP1-2.6	[0.6, 0.7, 1.4, 1.4]	[0.7, 0.9, 1.6, 1.8]	[0.9, 1.1, 1.9, 2.3]
SSP2-4.5	[0.7, 0.9, 1.6, 1.7]	[0.9, 1.2, 1.9, 2.2]	[1.0, 1.4, 2.3, 2.8]
Antarctic ice sheet (Levermann et al., 2020)			
SSP1-2.6	[0.1, 0.2, 0.8, 1.2]	[0.1, 0.1, 0.8, 1.2]	[0.0, 0.1, 0.8, 1.3]
SSP2-4.5	[0.1, 0.3, 1.5, 2.3]	[0.1, 0.3, 1.6, 2.6]	[0.1, 0.4, 1.8, 3.0]
Antarctic ice sheet (Lowry et al., 2021)			
SSP1-2.6	[0.5, 0.8, 1.2, 1.5]	[0.6, 0.9, 1.5, 1.8]	[0.8, 1.0, 1.8, 2.2]
SSP2-4.5	[1.1, 1.3, 2.0, 2.3]	[1.4, 1.6, 2.6, 2.9]	[1.6, 1.9, 3.3, 3.8]
Antarctic ice sheet (p-box)			
SSP1-2.6	[−0.1, 0.0, 1.4, 1.5]	[−0.1, 0.0, 1.6, 1.8]	[−0.1, 0.0, 1.9, 2.3]
SSP2-4.5	[−0.0, 0.1, 2.0, 2.3]	[0.0, 0.2, 2.6, 2.9]	[0.0, 0.2, 3.3, 3.8]
Greenland ice sheet (Aschwanden et al., 2019)			
SSP1-2.6	[0.1, 0.2, 0.5, 0.7]	[0.1, 0.2, 0.7, 0.9]	[0.2, 0.3, 0.9, 1.1]
SSP2-4.5	[0.2, 0.4, 1.0, 1.2]	[0.3, 0.5, 1.4, 1.7]	[0.5, 0.8, 1.8, 2.2]
Greenland ice sheet (IPCC, 2021a)			
SSP1-2.6	[0.2, 0.2, 0.4, 0.5]	[0.2, 0.3, 0.5, 0.6]	[0.2, 0.3, 0.6, 0.7]
SSP2-4.5	[0.3, 0.3, 0.6, 0.6]	[0.3, 0.4, 0.7, 0.8]	[0.4, 0.5, 0.8, 1.0]
Greenland ice sheet (p-box)			
SSP1-2.6	[0.1, 0.2, 0.5, 0.7]	[0.1, 0.2, 0.7, 0.9]	[0.2, 0.3, 0.9, 1.1]
SSP2-4.5	[0.2, 0.3, 1.0, 1.2]	[0.3, 0.4, 1.4, 1.7]	[0.4, 0.5, 1.8, 2.2]
Glaciers			
SSP1-2.6	[0.1, 0.1, 0.3, 0.3]	[0.1, 0.1, 0.3, 0.3]	[0.1, 0.1, 0.3, 0.3]
SSP2-4.5	[0.1, 0.2, 0.3, 0.3]	[0.2, 0.3, 0.3, 0.3]	[0.2, 0.3, 0.3, 0.3]
Thermal expansion			
SSP1-2.6	[0.1, 0.2, 0.3, 0.4]	[0.1, 0.2, 0.4, 0.5]	[0.1, 0.2, 0.4, 0.5]
SSP2-4.5	[0.3, 0.4, 0.6, 0.7]	[0.3, 0.4, 0.8, 0.9]	[0.3, 0.4, 0.9, 1.1]
Land water storage			
SSP1-2.6	[0.03, 0.04, 0.09, 0.11]	[0.03, 0.04, 0.09, 0.11]	[0.03, 0.04, 0.09, 0.11]
SSP2-4.5	[0.04, 0.07, 0.15, 0.18]	[0.04, 0.07, 0.15, 0.18]	[0.04, 0.07, 0.15, 0.18]
Total global mean sea-level change			
SSP1-2.6	[0.2, 0.5, 2.6, 2.9]	[0.3, 0.6, 3.0, 3.6]	[0.3, 0.7, 3.6, 4.3]
SSP2-4.5	[0.7, 1.1, 4.0, 4.7]	[0.9, 1.3, 5.2, 6.0]	[1.0, 1.5, 6.4, 7.6]

1.0] and [0.2, 0.7]m, respectively). The uncertainty is also smaller for both emissions scenarios. This is to be expected, considering the assumption of constant rate of mass loss from 2100 to 2300 in the underlying data set (IPCC, 2021a).

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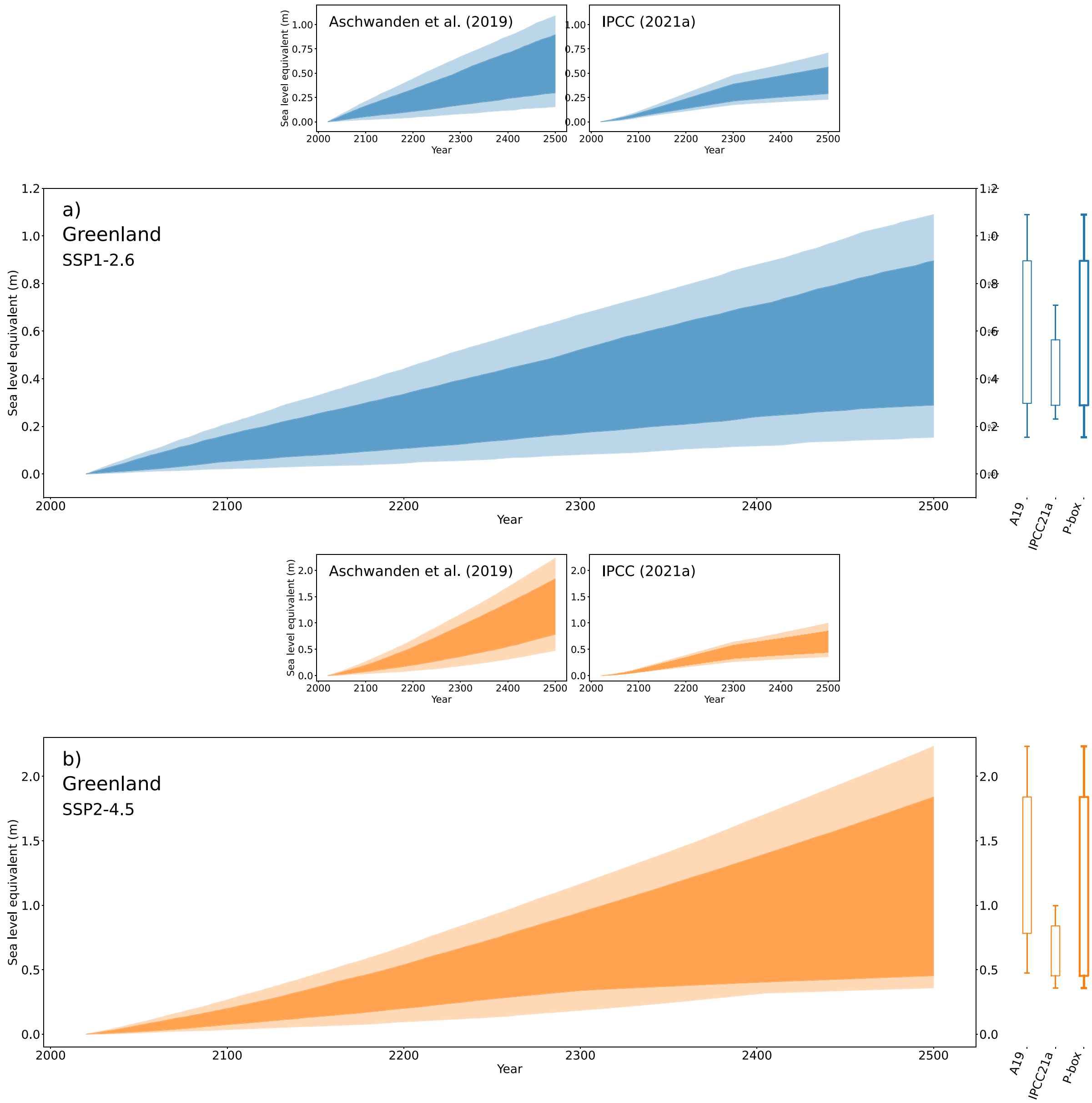

Figure 3. Projections of the Greenland contribution to sea-level change to 2500 (m). Projections under (a) SSP1-2.6 and (b) SSP2-4.5 from Aschwanden et al. (2019) and from the AR6 (IPCC, 2021a) extended from 2300 under randomly sampled sub-linear extrapolation are shown in the top panels. The p-box projection is shown in the bottom panel. Darker shaded regions represent the 17%–83% intervals, and lighter shaded regions represent the 5%–95% intervals. Box and whiskers show the 17%–83% and 5%–95% intervals at 2500. All projections are relative to 2020.

The world's glaciers are projected to almost certainly have completely melted by 2500 under SSP2-4.5 (Figure 4); all glaciers disappear by the year 2260, with a likely [17, 83]% range of [2190, 2439]. Under the lower emissions scenario, there is still some possibility of complete disappearance beyond 2200, but it is much less likely.

The contribution from thermal expansion (Figure 4) does not increase much beyond 2300, and projections tend to reach a steady state by 2500. This can be explained by the declining forcing beyond 2300 (Section 2.1), combined with the (assumed) relatively fast response to forcing, compared with the ice sheets. As for other contributions, projections under SSP2-4.5 are more uncertain than for SSP1-2.6. Under higher emissions and therefore greater warming, the deep ocean may play a more significant role in driving thermal expansion, which may increase the uncertainties further. But processes governing heat transfer between the atmosphere and the ocean are generally expected to be less uncertain than those governing ice sheet instabilities (such as MISI and MICI), particularly

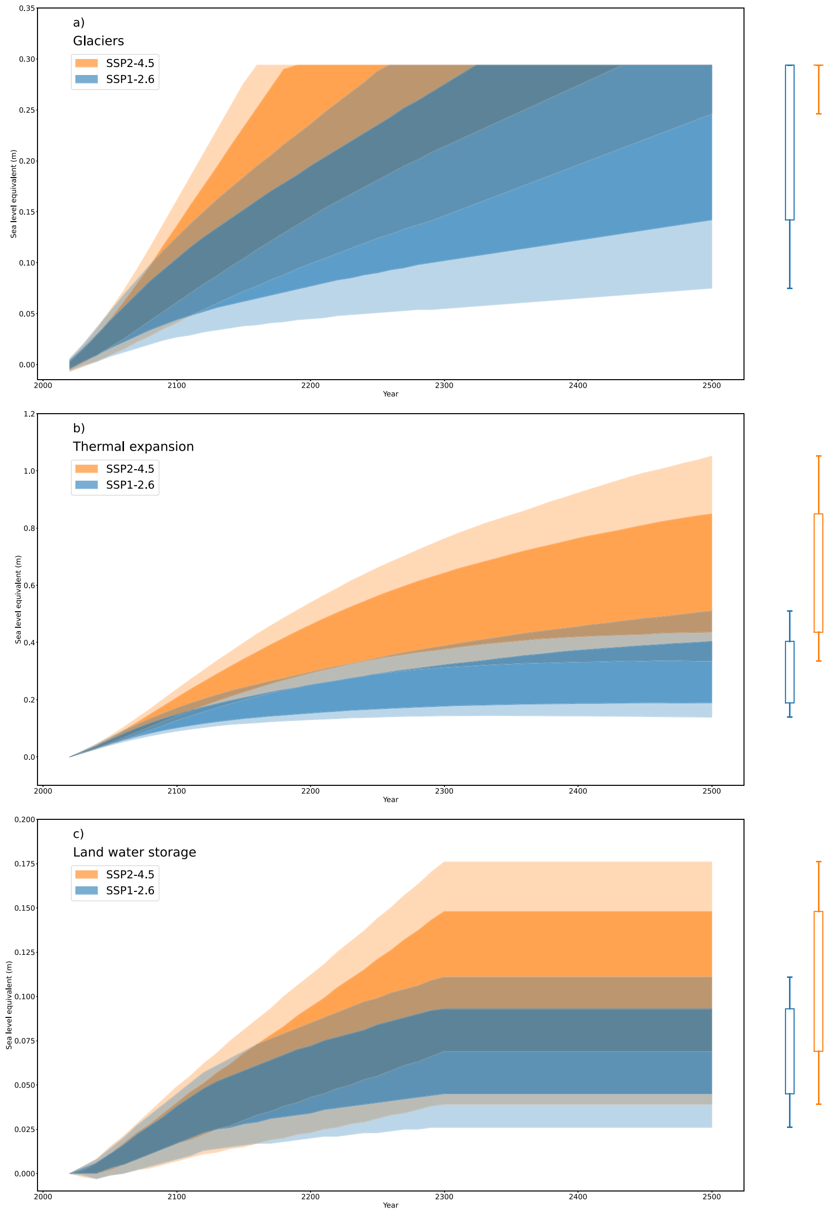

Figure 4. Projections of other contributions to sea-level change to 2500 (m). (a) Projected contributions under SSP1-2.6 and SSP2-4.5 from: (a) glaciers, from the AR6 (IPCC, 2021a) assessment extended from 2300 using linear extrapolation, (b) thermal expansion, using a method similar to that used for the AR6 (IPCC, 2021a) projections to 2300, and (c) land water storage, from the AR6 (IPCC, 2021a) extended from 2300 by assuming no further contribution. Darker shaded regions represent the 17%–83% intervals, and lighter shaded regions represent the 5%–95% intervals. Box and whiskers show the 17%–83% and 5%–95% intervals at 2500. All projections are relative to 2020.

under high emissions. Thermal expansion contributes a similar amount to Greenland under SSP1-2.6 at 2300 and 2500, but around two thirds of the ice sheet's contribution under SSP2-4.5 (Table 2).

Land water storage projections remain below 0.18 m (95%; Figure 4), with 5%–95% ranges of [0.03, 0.11]m under SSP1-2.6 and [0.04, 0.18]m under SSP2-4.5. The projections remain fixed between 2300 and 2500.

Total global mean sea-level rise at 2400 reaches [0.3, 3.6] m and [0.9, 6.0] m, and at 2500 reaches [0.3, 4.3] m and [1.0, 7.6] m, under SSP1-2.6 and SSP2-4.5 respectively (Figure 5 and Table 2).

The low confidence projections to 2300 constructed for the AR6 (IPCC, 2019, Table 9.11) are given in Table 3 for comparison. To reflect the small number of projections available at this time scale, we show the ranges at the

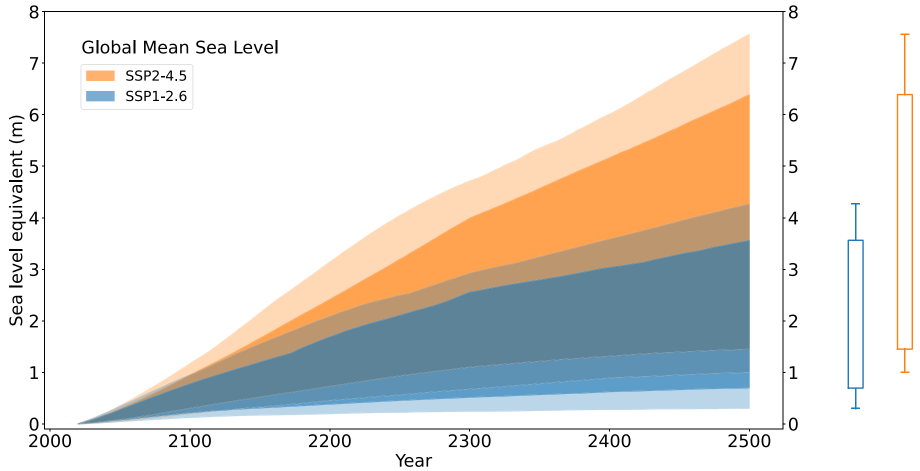

Figure 5. Projections of global mean sea-level rise to 2500 (m). Total global mean sea-level change to 2500 based on the projections in Figures 2–4. Combinations are made assuming full correlation. Darker shaded regions represent the 17%–83% intervals, and lighter shaded regions represent the 5%–95% intervals. Box and whiskers show the 17%–83% and 5%–95% intervals at 2500. All projections are relative to 2020.

workflow level that is, we report the two studies used for SSP1-2.6 and one study used for SSP2-4.5. Our p-box projections for the ice sheets are generally more conservative (i.e., wider intervals) than the AR6; for the most part, the AR6 17% quantiles are higher, and the 83% quantiles are lower. This leads to our total GMSL projections also being more conservative.

4. Discussion

Here, we discuss uncertainties in individual components and their combination in our multi-centennial projections, the potential use of these long-term projections by stakeholders, and recommendations for addressing knowledge gaps.

4.1. Antarctic Projections

We focus here on Antarctica, which has the largest projected contributions to sea-level rise, and the greatest difference between estimates (here as elsewhere). Many choices in ice sheet model structure and setup contribute to these differences, including grid resolution, treatment of the feedbacks between the climate and ice sheet, and interactions between the ice sheet and the bed. We highlight some key differences likely to be most important here.

The largest projections are by DeConto et al. (2021) and Lowry et al. (2021). The first of these is to be expected, as this model includes a representation of Marine Ice Cliff Instability (MICI) (DeConto et al., 2021; DeConto &

Table 3
Median and Likely Ranges of Low Confidence Projections of Sea Level Rise at 2300 From the AR6 (IPCC, 2021a), Relative to 1995–2014 (m)

	SSP1-2.6		SSP2-4.5
	J. L. Bamber et al. (2019)	DeConto et al. (2021)	DeConto et al. (2021)
Antarctic ice sheet	0.09 (−0.01–0.25)	0.08 (0.06–0.12)	0.65 (−0.15–1.59)
Greenland ice sheet	0.13 (0.07–0.30)	0.06 (0.01–0.10)	0.49 (0.27–1.29)
Glaciers	0.09 (0.07–0.11)		0.32 (0.25–0.32)
Thermal expansion	0.14 (0.11–0.18)		0.51 (0.39–0.68)
Land water storage	0.03 (0.01–0.04)		0.11 (0.07–0.15)
Total global mean sea-level change	1.57 (0.78–3.16)		2.10 (1.19–3.55)

Pollard, 2016) and sets a high maximum rate of ice loss in this ensemble that particularly influences the longer-term (IPCC, 2021a). The process of MICI, and how to represent it in models, is contested but not ruled out (e.g., IPCC, 2021a; Stokes et al., 2022). However, the model of Lowry et al. (2021) is not a priori expected to lead to particularly rapid Antarctic losses. This might be explained by the large response simulated by the model under a constant modern climate: the default control simulation contributes 0.71 m from 2025 to 2300. If we were to assume this were entirely model drift, as is often the case in long-term simulations, that is, a cumulative artifact of small errors in the model structure and setup, rather than a realistic multi-century committed response to the modern climate, then subtracting this drift (as in Stokes et al. (2022)) would give 5%–95% intervals of −0.22–0.69 m for SSP1-2.6 and 0.35–1.51 m for SSP-2.45 at 2300, that is, more consistent with the other studies (overlapping all, to some extent). Lowry et al. (2021) do take steps to reduce model errors: for example, requiring their ensemble to match satellite observations of recent sea-level contribution, which excludes the low end of their projection range. But given their rate of sea-level contribution under constant climate (2.6 mm/yr sustained over three centuries) is 7–8 times larger than both the AR6 estimate of committed Antarctic dynamic response during the 21st century (0.33 ± 0.16 mm/yr to 2100, albeit based on limited evidence) and the total response observed from 2006 to 2018 (0.37 mm/yr), and that all of this response is from East Antarctica (103% at 2100% and 94% at 2300), rather than in the West where most losses are expected, we suggest this may be predominantly unphysical drift so adjusted projections might be more robust.

A further consideration is the degree to which Antarctic snow accumulation increases in a warmer climate, offsetting dynamic losses from the ice sheet and reducing the net sea-level contribution. This has been found to vary strongly with climate model (e.g., Edwards et al.. 2021; IPCC, 2021a; Seroussi et al.. 2020). Lowry et al. (2021) predominantly use a global climate model with relatively low snow accumulation, which may contribute to their higher estimates.

A more general challenge in comparing long-term ice sheet projections is that the scenarios often vary, due to the relative lack of global (and, particularly, regional) climate model projections beyond 2100. Projections to 2300 by Bulthuis et al. (2019) and DeConto et al. (2021) use the RCP extensions (Meinshausen et al., 2011), and the Levermann et al. (2020) AR6 projections use the SSP extensions (Meinshausen et al., 2020; Z. R. J. Nicholls et al., 2020). In contrast, Lowry et al. (2021) use the RCPs to 2100 then fix the climate, to allow the use of global climate models that were not run further: this tends to give larger climate changes under low and medium emissions scenarios, because forcing declines during 2100–2300 in the extensions, and therefore might also contribute to their higher projections. After 2300, Bulthuis et al. (2019) fix the climate; this is a similar response to the simple climate model projections generated for the AR6 IPCC, 2021a (not shown) that are used here for thermal expansion to 2500.

4.2. Limitations and Interpretation

4.2.1. Choice of Studies

Sea-level projections are particularly challenging with respect to quantifying uncertainties, because of the causal chain involving multiple climate models, land ice models, and plausible input parameters and initialisations for each, and a given study tends to focus on some at the expense of others. The relative lack of multi-centennial scenario-based projections exploring land ice model uncertainties restricts any study synthesizing them: our prioritization of probabilistic, physically based projections under RCPs or SSPs limited us to a small number of data sets. Projections from other climate and land ice models would differ, particularly for Antarctica for which the sign of the contribution by 2100 (sea-level rise or fall) is not completely certain, and multi-centennial responses diverge substantially (IPCC, 2019, 2021a; Payne et al., 2021; Seroussi et al., 2020). But without full perturbed parameter ensembles, it would be difficult to include other models in this study.

We could have chosen to include studies using predominantly statistical or simple physical modeling, rather than complex physical models (e.g., Nauels et al., 2017; Palmer et al., 2020). These approaches should tend to become less necessary in future, as perturbed parameter ensembles using physical models become increasingly used for long-term projections; ensembles are now also routinely supplemented with statistical emulation to improve estimates of probability distributions, especially for Antarctica (e.g.,: Berdahl et al., 2021; DeConto et al., 2021; Edwards et al., 2019, 2021; Gilford et al., 2020; Hill et al., 2021; Levermann et al., 2020; Wernecke et al., 2020).

4.2.2. Extrapolation Beyond 2300

We used simple extrapolation from 2300 to 2500 for most of the components: sub-linear extrapolation with randomly sampled rates for the ice sheets, linear extrapolation for the glaciers, and a fixed (no further) contribution

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for land water storage. This is similar to other studies where constant rates or other assumptions were used for some or all sea-level components beyond 2100 (e.g., IPCC 2021a; Kopp et al., 2014; Palmer et al., 2020). We could have instead used statistical modeling of these contributions as a function of global mean temperature, as in the AR6 projections for glaciers to 2300, and other studies (e.g., IPCC 2013; Nauels et al., 2017; Palmer et al., 2020).

However, we believe this more complex approach might (therefore) be interpreted with undue confidence. Although for the land ice this would be based on physical relationships between ice loss and warming from simulations to 2300, it would extrapolate far beyond the bounds of these relationships: not so much in global temperature, as these low and medium scenarios do not continue warming beyond 2300, but in time, due to the slow response of most of these components. Arguably, this is already the case for the AR6 glacier projections from 2100 to 2300. In other words, assumptions must be made about the nature of this temperature-dependence that are less transparent than simple extrapolation. This is even more the case for the societal relationships assumed between population and land water storage, which we do not attempt to continue beyond 2300.

For the ice sheets, our use of sub-linear rather than linear extrapolation after 2300 was motivated by the declining greenhouse concentrations in the extended SSPs. This is also broadly supported by multi-millennial simulations by Golledge et al. (2015) in which rates of Antarctic sea-level contribution from 2300 to 2500 are 64%–74% those from 2250 to 2300 under RCP2.6 and RCP4.5 (the range arises mainly from two model versions), and by the individual (i.e., not ensemble) projections to 2500 of DeConto et al. (2021) under 3°C of warming, where the rate of mass loss decreased from 0.60 m/century between 2250 and 2300 to 0.43 m/century between 2300 and 2500, that is, 72% of the earlier rate. In the Bulthuis et al. (2019) Antarctic projections, the ensemble members are most often linear (i.e., the mode of this ratio is 100%) for both scenarios, but many decelerate (sub-linear) or accelerate. The acceleration might be influenced by the projections being relatively low, if some changes (e.g., retreat of the East Antarctic Wilkes basin, which occurs under higher warming and some parameter values; Bulthuis et al., 2019) are triggered later than in other models. Rates for Greenland sea-level contribution in the Aschwanden et al. (2019) ensembles are most often sub-linear under low emissions (mode = 87%) and linear under medium emissions (99%), but this study uses a larger climate forcing than the others: beyond 2300, the warming from 2200 to 2300 trend is extrapolated to 2500, rather than using constant climate as in Bulthuis et al. (2019) (Section 4.1). When combined with the spatial-averaging of Greenland climate (Section 2.3), and a high maximum value in the ensemble for the positive degree day factor (with higher values enhancing surface melt sensitivity to warming), this suggests the projections show much greater mass loss than other models would show under the extended SSPs (IPCC, 2019, 2021a), so we judge it reasonable to use a lower range of post-2300 rates here. Based on these comparisons, our chosen bounds (10%–100% of the earlier rate of mass loss) could therefore have been chosen differently, but any acceleration or deceleration strongly depends on the ice sheet topography at 2300, which depends on model structure and setup. Perturbed parameter ensembles from a range of ice sheet models, driven with a range of climate models, under standardised emissions scenarios, would be needed to estimate the distribution of rate changes with confidence: in which case, the extrapolation would no longer be needed.

We performed a sensitivity test on the effect changes in gradient bounds has on our projections. We tried bounds of [-10, 80]% and [30, 120]% to extrapolate the projections from DeConto et al. (2021); results can be seen in Figure 6. We chose to extrapolate DeConto et al. (2021), as this study gave some of the highest projections, and thus was influential on the Antarctic p-box, and total GMSL projections. The change in sea level contribution at 2500 for SSP1-2.6 is approximately 20 cm for both extrapolations; the [5, 95]% intervals for the low and high extrapolations are [0.8, 2.0]m and [1.1, 2.5]m respectively compared to [0.9, 2.3]m for the original. This would affect the AIS p-box at the higher end of projections, but not lower, as the projections from Bulthuis et al. (2019) had the lowest quantiles below the median. For SSP2-4.5, the differences are slightly larger, with the low and high extrapolations giving [5, 95]% intervals of [0.9, 2.5]m and [1.2, 3.1]m compared to [1.0, 2.8]m for the original. However, this would not have an effect on the AIS p-box as the projections extrapolated from Lowry et al. (2021) dominated the higher quantiles for this scenario.

If a stakeholder preferred to use projections without these simple extrapolations, we note that the underlying data sets all extend to 2300 (albeit using some simple extrapolations and fits in the AR6 components). So the projections at 2300 presented here use the p-box approach to combine the ice sheet studies, and combine contributions under full correlations and standardised baselines. These still represent a new multi-study estimate, based mostly

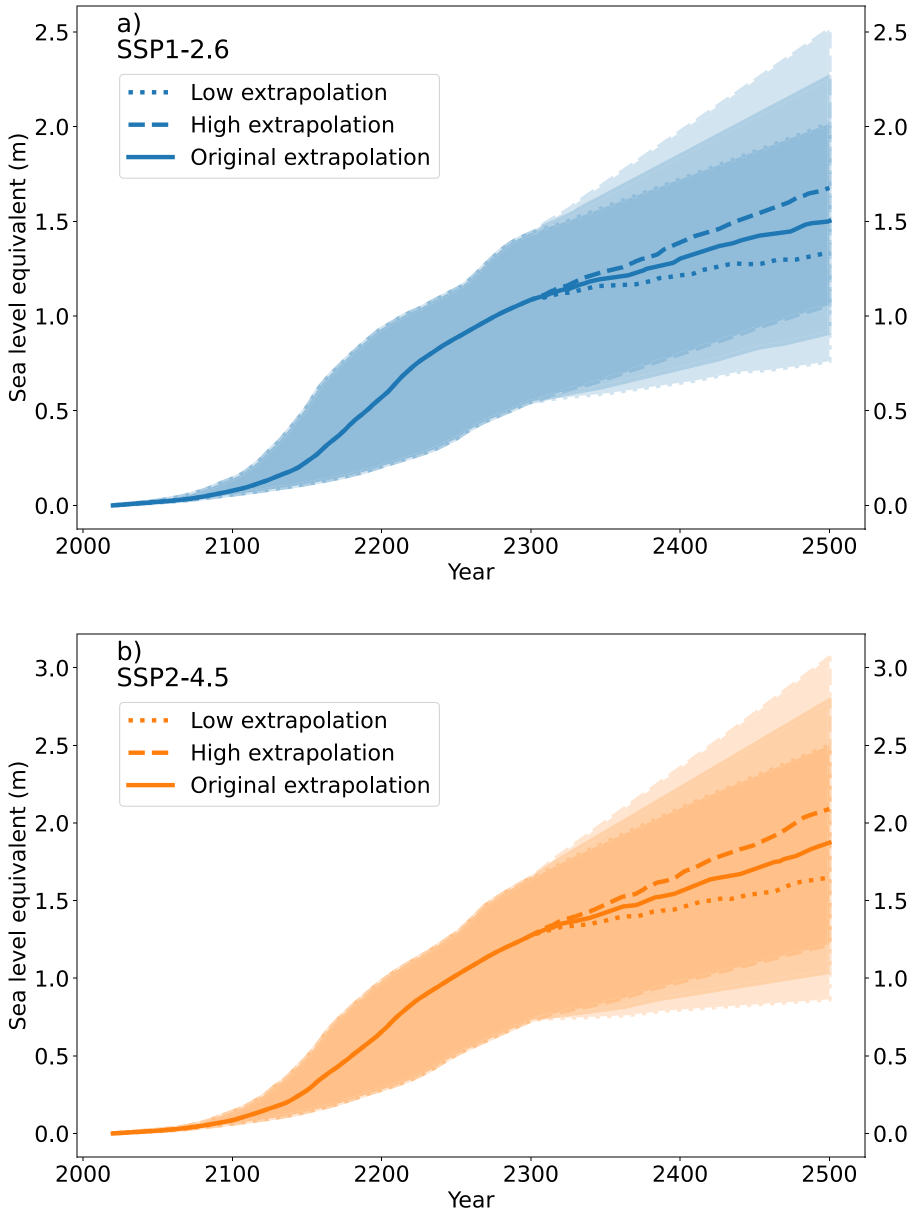

Figure 6. Effect of using different gradient ranges in extrapolating projections from DeConto et al. (2021). The solid lines show the original extrapolation, using a [10, 100]% range for the gradients. The dotted lines show the [5, 50, 95]% quantiles using a [−10, 80]% range for the gradients, and the dashed lines show a [30, 120]% range. The effect is small, leading to a difference at 2500 of approximately 20 cm in sea level contribution for SSP1-2.6, and 30 cm for SSP2-4.5.

on physical modeling, of the probabilities of different global mean sea-level changes at 2300 under low and medium emissions scenarios.

4.2.3. Combining Studies and Sea-Level Contributions

We chose a more conservative approach to combining ice sheet studies: the "p-box"-based approach used in the AR6 (IPCC, 2021a), taking the minimum of quantiles below the median, the maximum of quantiles above the median, and averaging the medians.

When combining individual sea-level contributions, we assumed all were fully correlated, calculating a linear sum of quantiles to estimate total global mean sea-level rise. This equates to an assumption that the climate change under a given scenario—and other uncertain factors driving the sensitivity of each part of the earth system to that change—affect each sea-level contribution in a similar way. However, if climate changes affect some contributions differently (e.g., land water storage is not directly related to warming, Section 2.6; Antarctic accumulation is anticorrelated, Section 4.1), or if other uncertainties are uncorrelated (e.g., if reality follows the high-end projections for glaciers but the low-end for thermal expansion), which is likely, then the probability distributions would be narrower. Alternative approaches are described in Section 4.4. Working on multi-centennial timescales, it is plausible to assume the uncertainty in ocean thermal expansion is correlated with surface warming rather than anti-correlated. When building shorter-term (century-scale) projections, this assumption is more uncertain: sea level rise from thermal expansion may be anti-correlated with sea level rise from land ice, as surface warming for a given radiative forcing is reduced by increased ocean heat uptake, or this may be compensated by amplifying climate feedbacks. Similar arguments apply for higher emissions scenarios where radiative forcing is still rising, such as SSP5-8.5.

We also do not attempt to constrain the individual contributions or total projections with the degree of model agreement with observations (or indeed palaeoclimate reconstructions), beyond what is already done in some individual studies (e.g., DeConto et al., 2021; Lowry et al., 2021), instead focusing on providing a broad range of projections. An alternative choice would be to calibrate the projections, where simulations of past change are available, using a ruling out (history matching) or weighting (Bayesian) approach. Such a calibration could also be used in weighting individual studies, rather than calculating p-boxes.

4.3. Potential Application of Multi-Centennial Projections

Table 4 presents long-term management and policy issues that require information on sea-level scenarios well beyond 2100, based on literature reviews and stakeholder workshops with sea-level science users on their needs (Capar et al., 2020; R. J. Nicholls, Hanson, et al., 2021) carried out for the EU project PROTECT (https://protect-slr.eu). These decisions represent a minority of current coastal adaptation decision, but they can be highly significant and bring multiple co-benefits if addressed in the near-term. For example, the Alliance of Small Islands States have already been successful in advocating for stronger climate action in international negotiations (de Águeda Corneloup & Mol, 2014; Ourbak & Magnan, 2018) based at least in part on expected sea-level rise under low and medium emissions post-2100. Any further success in this area will come with multiple co-benefits such as better health and wellbeing, food production, water and climate risk management, and may help with curbing biodiversity losses (IPCC, 2022a).

In spite of their limitations, our results already provide projections that can inform these decisions. Relevant for international climate negotiations (first row of Table 4), we provide global projections consistent with both mitigation policies implemented prior to COP26 (SSP2-4.5) and with the Paris Agreement goal of limiting warming to well below 2°C (SSP1-2.6) (Figure 5). If we consider our projections, the exceedance of 2m of global mean sea-level rise would be delayed by over 250 years by following the lower of the two scenarios (median estimate of 2249 for SSP2-4.5, beyond 2500 for SSP1-2.6), that is, keeping to the upper limit of the Paris Agreement, as can be seen in Figure 7. Although this may not prevent erosion or submergence of small atoll islands, this would grant more time for adaptation efforts such as relocation of communities or artificial island-raising (Amores et al., 2022; Brown et al., 2023; van der Pol et al., 2023). Besides this mitigation challenge, adaptation requires a range of projections that depends on stakeholders' time horizons and risk aversions (Hinkel et al., 2019). In this area of climate negotiations, future studies may address the need for even lower global warming levels, corresponding to the 1.5° target (SSP1-1.9), in particular to inform vulnerable coastal and island nations.

A first subset of adaptation problems aims at understanding and ideally avoiding lock-ins in the long term (next section of Table 3) (IPCC, 2022a, Cross-Chapter Box SLR). A "lock-in" is defined in the AR6 IPCC (2021a) as "*a situation in which the future development of a system, including infrastructure, technologies, investments, institutions and behavioral norms, is determined or constrained ("locked in") by historical developments.*" Lock-in is especially important in the coastal context as sea level rises for multiple centuries even if global temperature is stabilized. Relevant decisions and policies that could be informed regarding lock-in include land use planning at a broad scale for existing and new critical infrastructure management and development. These require information assessing the impacts of sea-level rise by 2150 to inform infrastructure design, management and planning, and well beyond 2150 for strategic planning in large coastal plains and estuaries with high population densities. This might inform the development of long-term adaptive pathways (Haasnoot et al., 2021; Ranger et al., 2013). Projections under SSP1-2.6 and SSP2-4.5 could be sufficient for a first assessment in these case studies, because SSP1-2.6 corresponds to the upper target of the Paris Agreement and SSP2-4.5 is often used for

Table 4
Long-Term Management and Policy Issues Which Are Informed by Centennial to Multi-Centennial Sea-Level Information and the Extent to Which This Research Can Inform Them

Management problem		Users	Illustrative application and time scales	Extent to which this work may respond to the need
Climate negotiations to improve NDCs[a]		Highly vulnerable nations	Small island nations (IPCC, 2022a, Chapter 15) on timescales of centuries, and arguably all nations with significant populated coastal lowlands on similar timescales, such as the major deltas where long-term threats are similar to the islands (Nienhuis et al., 2023)	Key point in future climate negotiations will be to increase NDC ambition and reduce the gap between NDCs and implemented policies: our centennial and multi-centennial scenarios respond to this need. SSP1-1.9 projections would be required to inform highly vulnerable coastal and island nations
Avoiding lock-ins in the long term	Land use planning at the scale of flood plains	Countries and regions with large low-lying areas as found in deltas (e.g., Netherlands, Egypt, China)	Plan defense systems, for example, in the Nile Delta in Egypt (IPCC, 2022a, Cross-Chapter Paper 4). Timescale: decades to centuries	Our scenarios provide information allowing to assess committed adaptation needs. However, they do not allow stress-testing of critical infrastructures due to the absence of a high-end scenario
	Adaptation of existing long-living infrastructure	Private and public operators and safety authorities of critical infrastructure (e.g., government environment agencies, utility companies, etc.)	Estuarine Barriers: for example, in London and the Netherlands. Existing coastal nuclear plans. Plan and sustain ports and associated industrial activities in the long term. Timescale: decades to centuries (IPCC, 2022a, Cross Chapter Box: Sea-level Rise)	
	New infrastructure development	New large nuclear reactors (OECD Nuclear Energy Agency, 2006)	Timescales: at least 60 years, without considering lead times and decommissioning	
Conservation or management of natural, cultural and industrial heritage	Conservation of cultural heritage	Cultural heritage authorities	Centuries or more (Contestabile, 2014; Marzeion & Levermann, 2014)	Our scenarios address committed adaptation needs. However, they do not guarantee that assets at risk will remain unexposed as no upper bound for sea-level rise can be provided yet
	Management of degraded environments	Environmental authorities and agencies	Landfills (R. J. Nicholls, Beaven et al., 2021). Nuclear waste management.	
	Conservation of coastal ecosystems, natural habitats and coastal landscape.	Conservation agencies, natural reserves	Strategic planning and land acquisition for conservation agencies and NGOs (e.g., Conservatoire du Littoral, France or National Trust, UK)	

[a]Nationally Determined Contributions.

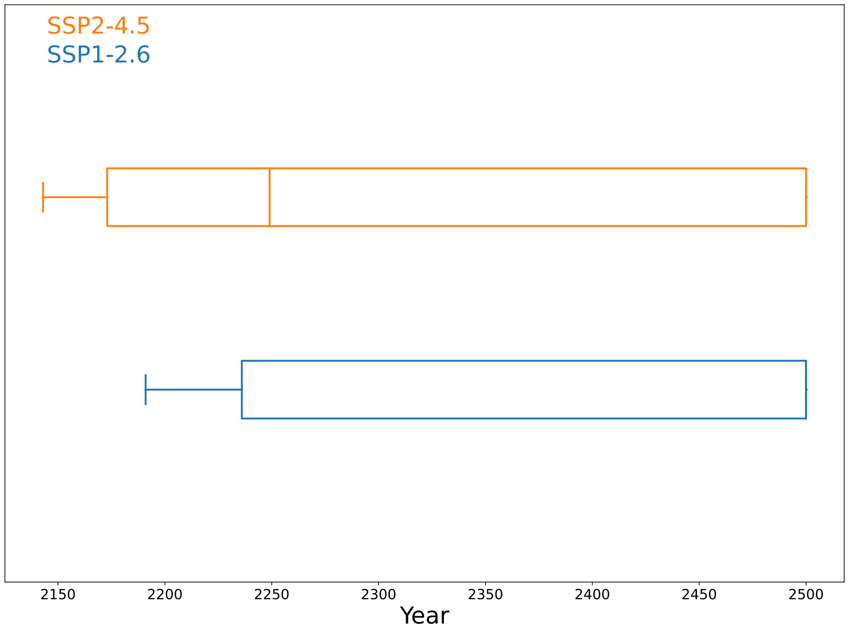

Figure 7. Timing of when GMSL exceeds a threshold of 2 m under our projections.

coastal adaptation, as shown in Europe by McEvoy et al. (2021). A scenario is also needed for stress testing of critical infrastructure, but this may be already covered to a large extent by the low-likelihood, high-impact (i.e., high-end) projections to 2150 provided by the AR6 (IPCC, 2021a, 2021b) and others (van de Wal et al., 2022).

A second subset of adaptation problems (final section of Table 4) relates to the conservation of cultural and environmental heritage, and the management of our past industrial activities (Marzeion & Levermann, 2014; R. J. Nicholls, Beaven, et al., 2021). Our results provide information for a baseline, "no regret" scenario. If the system at risk is perceived as having a very high value (e.g., an ancient city, such as Venice in Italy or Ste Marie de la Mer in France), or if the damages resulting from flooding or erosion (e.g., of landfills or polluted soils) are considered unacceptable, then again a high-end scenario could also be useful, to ensure that adaptation measures are robust against unlikely large changes.

Projections for stress-testing or pessimistic adaptation planning, that is, under higher emissions scenarios than SSP2-4.5, would require further model ensemble simulations to be run: either for scenarios still judged plausible (e.g., SSP3-7.0, or a fixed warming level of 3°C), or else for very high emissions (SSP5-8.5) to interpolate projections for intermediate scenarios as in Edwards et al. (2021). Importantly, very high emissions scenarios such as SSP5-8.5 are already used for coastal planning in Europe (McEvoy et al., 2021). However, as emissions and warming levels increase, the uncertainties—particularly for Antarctica—increase rapidly. One approach for users to interpret the *deep uncertainty* for a given scenario would be to choose sets of projections according to their risk tolerance. Projections using only Bulthuis et al. (2019) for the Antarctic contribution, for example, would be straightforward to recalculate (using Table 2 and the Supp. Info) for low-end, minimum adaptation projections as in Le Cozannet et al. (2019), and equivalently using only DeConto et al. (2021) or Lowry et al. (2021) for high-end, "pessimistic" projections (e.g.,: Edwards et al., 2021; van de Wal et al., 2022).

Further research is needed to identify current decisions that require centennial to multi-centennial projections. However, Table 4 already provides evidence that our current level of understanding in sea-level projections to 2500 is already sufficient to respond to a number of stakeholder needs.

4.4. Further Research Needs

There are several research gaps that require further attention for long-term projections exploring model uncertainties.

4.4.1. Long-Term Ensemble Projections

The AR6 (IPCC, 2021a) drew on large international multi-model intercomparison projections for the ice sheets and glaciers, but these were necessarily limited in timescale (to 2100) and the exploration of plausible parameter values and initializations. More long-term ensemble model projections are needed: for example, only one perturbed parameter ensemble study for Greenland extended beyond 2100, and none for the global glaciers.

However, long-term ensemble projections for contributions to sea level rise are partly limited by the relative lack of long-term global climate model simulations, both in terms of scenarios (see Section 4.4.2) and exploration of climate model uncertainties. Using simple climate models to drive projections, as in the AR6 and the thermal expansion projections here, allows greater exploration of climate uncertainty for a given scenario than a single complex global climate model (or even multi-model ensemble), though this does require the use of further simple physical models or emulators to characterize the temperature- (or climate-) dependence of the sea-level components. But each study can only partially sample climate model uncertainty, even if using a simple climate model or several CMIP models. All projections of climate change are incomplete samples of our uncertainty about the future, and projections of climate impacts are inevitably even more limited because multiple layers of modeling are involved. To fully explore both scenarios (Section 4.4.2) and model uncertainties would require the CMIP community to routinely provide many more global climate model simulations to 2300 and beyond. Users of climate impact information should therefore always be aware that there is a possibility of impacts lying outside the projected ranges.

There was very wide variation across the four studies for Antarctica; this is in part due to the inclusion of MICI by DeConto et al. (2021), although Lowry et al. (2021) had similarly high projections. Differences arise from scenario definition, climate model and ice sheet model structure, the extent to which parameter and initialization uncertainties are explored, and whether there is any adjustment for model drift or agreement with past observations. The reliability of different model structures and parameterizations should be explored in more detail, using observations and ideally also palaeoclimate changes.

4.4.2. Scenarios, Including High Ends

As discussed in Section 4.3, projections for higher emissions scenarios than SSP2-4.5 are needed for stress-testing the resilience of existing or future critical coastal infrastructure under extreme sea-level projections (Table 4). Many projections for sea-level components, perhaps even most, do exist for very high emissions (RCP8.5/SSP5-8.5), but we did not include these here. This was for two reasons: current climate policies and nationally determined contributions suggest emissions are extremely unlikely to evolve along (or close to) those trajectories for multiple centuries, and there is very large disagreement between ice sheet studies, which makes extending and interpreting the projections challenging. For example, extending the DeConto et al. (2021) projections under SSP5-8.5 using the methods here gave a maximum Antarctic sea-level contribution of over 25m. Such extreme predictions would require far more physical justification than a simple extrapolation can provide, and could be actively unhelpful given that multi-century high emissions might reasonably be considered impossible, given current knowledge and technologies (J. Bamber et al., 2022; Piecuch & Das, 2022; van de Wal et al., 2022).

However, there are other, medium-high, emissions scenarios that are more plausible, such as SSP3-7.0, fixed levels of warming such as 2.5, three or 3.5°C, or scenarios of carbon dioxide removal, and these are much more rarely used. Greater adoption of these for model simulations would bring two advantages: first, it would enable robust assessment of non-linearities in the response to emissions, such as critical thresholds of ice sheet instability and irreversibility as highlighted by DeConto et al. (2021), who find a threshold for triggering widespread MICI between 2 and 3°C warming. These nonlinearities become particularly important over multi-century timescales, as differences between scenarios accumulate. Second, it would enable assessment of global mean sea-level rise, and therefore coastal impacts, for scenarios that relate more closely to current and potential future policies and pledges (Hausfather & Peters, 2020). Users are interested in intermediate scenarios to assess adaptation needs under plausible trajectories of sea-level rise, and to understand avoided risks when increasing the ambition of pledges and policies. This latter point also highlights the need for very low emissions scenarios (SSP1-1.9 and/or 1.5°C warming), to assess the impacts and benefits of strong mitigation.

However, extensions of emissions scenarios beyond 2100 should be consistent. Using the same scenarios across all sea-level components is essential for comparing and combining multiple studies and building more robust projections. The extended SSPs to 2500 are the obvious current choice for storyline-based scenarios; climate forcing may be easier to obtain for fixed global warming levels, approximated by repeating model simulation years, to relate to Paris Agreement temperature targets, such as is done in DeConto et al. (2021). Although this is not the ideal solution to the lack of long-term simulations, it is a pragmatic option for creating meaningful projections.

Clearly there is a trade-off, given finite computational resources, between running models for more scenarios and exploring other uncertainties (previous section). The answer to "Which to choose?" is "both," but relative computing budget for each scenario will depend on the model: a model that is very sensitive to uncertain parameters, and for which information about the best parameter values is limited, might need to focus more on perturbing these than another which is more tightly constrained. Sensitivity tests, particularly in conjunction with emulation for more detailed understanding, are the standard way to evaluate priorities for ensemble design.

4.4.3. Correlations Between Components

Finally, our assumption of fully correlated contributions from land ice, thermal expansion and land water storage may over-estimate the uncertainties, though assuming full independence would under-estimate them. One alternative is to induce known climate correlations by using the same global mean temperature forcing to drive each individual contribution, while allowing other uncertainties to be independent (e.g., Edwards et al., 2021; IPCC, 2021a, 2013; Palmer et al., 2020); the other is to estimate other correlations, through systematic exploration of common uncertainties in model ensembles [see, e.g., comparisons of independent and correlated basal melt sensitivities across the three regions of Antarctica in Edwards et al. (2021)], or to assert them with expert judgment (e.g.,: J. L. Bamber et al., 2019; Kopp et al., 2014). Large multi-model projects (such as PROTECT: Section 4.3) are increasingly able to explore these relationships in detail.

5. Conclusion

Here we have presented a set of indicative projections of global mean sea-level rise to 2500 for the extended low (SSP1-2.6) and medium (SSP2-4.5) emissions scenarios. By extrapolating (where needed) and combining a set of ensemble projections for each individual component from the literature, we have created time series of the probabilities of different contributions to sea-level from the Antarctic and Greenland ice sheets, the glaciers, thermal expansion and land water storage, based on physical model simulations (as far as possible) and transparent methods of extension of these. As the Antarctic ice sheet is the largest source of uncertainty in future sea-level rise, we considered four different studies in making our projections, as well as two for the Greenland ice sheet. There are differences of over 1m at 2500 in total global mean sea-level rise between the two emissions scenarios, most of which occurs by 2300.

We have also examined points that need to be considered to use, and improve upon, these projections. There is a lack of multi-century perturbed parameter ensemble projections for the individual sea-level components, especially under intermediate storyline (RCP or SSP) scenarios, and especially for Greenland and the global glaciers. New projections must consider the definition of multi-century scenarios, so estimates can be compared and combined, as well as exploring the impact of uncertain processes and model inputs. We discuss how, despite their limitations, our sea-level scenarios can inform climate negotiations and long-term adaptation decisions.

Data Availability Statement

Projections are available in an online repository at Turner (2023) (quantiles for all components and the total), along with links to original sea level contribution data where these are available online (as listed below). Figures were made with Matplotlib version 3.2.1 (Caswell et al., 2020; Hunter, 2007) and R version 4.2.2.

Original sea level contribution projections:

IPCC (2021a), DeConto et al. (2021), and Levermann et al. (2020): Files were downloaded from Garner et al. (2021) for the IPCC projections (used for all sea level components here except Antarctica), and also the IPCC estimates for Antarctica from DeConto et al. (2021) and Levermann et al. (2020) (e.g., standardised baseline period; extension of Levermann et al. (2020) to 2300 with surface mass balance estimate). The IPCC projections for Greenland and glaciers are also available in the open access data folder of Turner (2023).

Lowry et al. (2021): Files were downloaded via the Data Availability section of the original study and are also available in the open access data folder of Turner (2023).

Bulthuis et al. (2019): Results were obtained by request from Kevin Bulthuis, as described in the Data Availability section in the original study.

Aschwanden et al. (2019): Results were obtained by request from Andy Aschwanden.

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