Toward a unified approach to quantify uncertainties in sea-level projections

Classification: Physical sciences – Sustainability science

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Abstract

Coastal impacts of climate change and the related mitigation and adaptation needs requires assessments of future sea-level changes. Following a common practice in coastal engineering, probabilistic sea-level projections have been proposed for at least 20 years. This requires a probability model to represent the uncertainties of future sea-level rise, which is not achievable because potential ice sheets mass losses remain poorly understood given the knowledge available today. Here, we apply the principles of extra-probabilistic theories of uncertainties to generate global and regional sea-level projections based on uncertain components. This approach assigns an imprecision to a probabilistic measure, in order to quantify lack of knowledge pertaining to probabilistic projections. This can serve to understand, analyze and communicate uncertainties due to the coexistence of different processes contributing to future sea-level rise, including ice-sheets. We show that the knowledge gained since the 5th Assessment report of the IPCC allows better quantification of how global and regional sea-level rise uncertainties can be reduced with lower greenhouse gas emissions. Furthermore, Europe and Northern America are among those profiting most from a policy limiting climate change to RCP 2.6 versus RCP 4.5 in terms of reducing uncertainties of sea-level rise.

1. Introduction

Sea level will continue to rise for years to centuries due to climate warming caused by anthropogenic greenhouse gas emissions (**1-4**). Global sea-level rise results from: (1) the thermal expansion of the oceans; (2) the increase of ocean mass due to the melting of mountain glaciers, and (3) mass loss from Antarctic and Greenland ice sheets, as well as (4) contributions from land or ground water (**1,2,5-8**). In addition, there are regional sea-level rise components due to the effects of ocean circulation and the redistribution of mass, heat and salt within the ocean, atmospheric pressure (hereafter termed ocean component), as well as solid earth deformation in response to past and present mass redistributions (e.g. deglaciations) (**9**).

So far, sea-level projections have been used for a range of purposes from quantifying adaptation needs to understanding the benefits of mitigation of climate change (**10-12**). However, the sea-level projections available today are not well aligned with the needs of coastal adaptation practitioners (**13-14**). In fact, coastal adaptation practitioners and the scientific community producing sea-level information have different objectives: science aims at gaining knowledge on the physical processes causing sea-level rise, while adaptation is concerned with the resilience of society to sea-level rise and related changes. This sometimes requires consideration of the full range of sea-level rise uncertainty, including the uncertainties arising from lack of knowledge and consensus amongst experts, and this results in a wide range of projections due to the different interpretations (**15-20**).

Despite being a powerful tool for uncertainty treatment, probability remains a poor descriptor of situations characteristic by such lack of knowledge. As acknowledged by the sea-level science community itself, no single probability model can yet be recommended (**7,21,22**). Extra-probabilistic theories of uncertainty are well suited to quantify uncertainties in sea-level projections because they recognize that several probability functions are consistent with the knowledge available (**23-26**) (see methods). As a general principle, extra-probabilistic theories of uncertainties consider that probabilistic measures are themselves uncertain and assign an imprecision to this measure (**24,27,28**). This allows consideration of the uncertainties pertaining to the probabilistic projections (**29,30**).

In this paper, we apply the principles of extra-probabilistic theories of uncertainties across the different steps allowing the generation of global and regional sea-level projections based on uncertain components (See methods and section 2). We use a procedure for jointly propagating uncertain components represented by probabilistic and extra-probabilistic distributions and for addressing the issue of dependencies between components (see methods). We apply the approach to the AR5 likely components, but we also examine post-AR5 studies on ice sheet melting (**31-33**). Our aim is to provide a complementary approach to deal with uncertainties in sea-level projections, especially with regard to the needs of the most risk-averse stakeholders (**11-14**). Many issues discussed in this paper have been already identified in previous studies (**7,18-22,29,30**). Here, the novelty of our approach consists of applying a mathematical framework that provides quantitative insight into concepts expressed in fuzzy terms so far, such as ambiguity, high-end scenarios and deep uncertainties.

This paper proceeds as follows: in section 2, we model the uncertainties of sea-level components in an extra-probabilistic framework, focusing in particular on ice-sheets melting. In section 3, we provide extra-probabilistic sea-level projections and examine how they can be used to deliver quantitative measures for uncertainties in a consistent manner across regions, time horizons and climate scenarios. Finally, section 4 examines the global and regional dependency of extraprobabilististic sea-level projections on greenhouse gas emissions.

2. Modelling uncertainties in sea-level components

2.1 Sources of ambiguity in sea-level projections

After Kopp et al. (2017) (**7**), and the earlier study of Ellsberg, 1961 (**34**), the term 'ambiguity' is defined as the uncertainty due to the coexistence of several equally credible probability functions to describe a variable, such as future global sea-level rise. The dynamic mass discharge of the Antarctic ice sheet is the most obvious, but not the only, source of ambiguity in sea-level projections (Supplementary

Figure 1). In fact, two distinct processes causing dynamic mass loss of the ice sheet are currently considered: (1) marine ice sheet instability (MISI), which possibly explains observations in West-Antarctica (**35,36**) and could contribute to global sea-level rise of up to 0.3m by 2100 (**3,32**), and (2) the marine ice cliffs instabilities (MICI), which involves a rapid retreat of ice shelves in response to a combined effect of hydro-fracturing and dislocation of ice cliffs formed at the ice sheet margins (**33**). This latter process is observed in very limited regions of Greenland and Antarctica, and it requires substantial ice melt at the surface, which may not happen in Antarctica over the 21st century (**37**). Furthermore, the process itself is poorly understood from a physical point of view and is therefore heavily parametrized in models. However, MICI is associated with large ice loss in Antarctica and it could cause 1 m of global sea-level rise by 2100 (**33**) (Supplementary Figure 1). Today, the probability of MICI is unknown, but as it is considered possible, sea-level projections assuming MICI provide relevant information for risk-averse coastal adaptation practitioners. Hence, two families of probabilistic projections coexist today for the Antarctic dynamic contribution to sea-level rise: those compliant with the 5th assessment report (AR5) of the IPCC, whether involving MISI or not, and those also involving MICI (**38**) (Supplementary Figure 1).

Coupled ice-sheet projections combining the rapid dynamics and surface mass balance (difference between snow accumulation and the melt and sublimation of snow and ice) of the Greenland ice sheet (GIS) are provided in a probabilistic form based on a suite of climate models (**31**). Over the last two decades, global climate models underestimate the contribution of the Greenland ice sheet surface mass balance to global sea-level rise by a factor of two (**39-41**). Future observations and research should establish whether this discrepancy is due to multi-decadal modes of Greenland climate variability, or if higher resolution climate model capture atmospheric changes sufficiently well to reconcile observed or modelled Greenland ice sheet surface mass balance. Until this is resolved, sea-level projections should consider the possibility that this bias remains in the future, leading to Greenland ice sheet contributions to sea-level rise equal to twice the probabilistic assessment of Fürst et al. (2015) (**31**) (Supplementary Figure 2).

Other sources of ambiguity include Antarctic surface mass balance (**42-44**), glacier melting (**45-49**), and groundwater extraction (Supplementary Figure 3; Supplementary Table 1). Here, we rely on the AR5 statement (**1**), which provides likely ranges for all these components without delivering upper and lower bounds. Hence, following the approach of Le Cozannet et al. (2017) (**30**), we complete possibility distributions fitted to the AR5 likely ranges with upper and lower bounds available in the literature (see Supplementary Table 1).

We assume that the ocean component can be described by a Gaussian distribution across the 21 CMIP5 models (16 for RCP 2.6) used in sea-level projections after Slangen et al. (2014) (**6**) and Carson et al. (2016) (**8**). This Gaussian assumption has been evaluated by Jackson and Jevrejeva (2016) (**50**) using a larger model ensemble. They concluded that the distribution of the ocean component across models was Gaussian (if some outliers were removed, especially in the tropics and the Mediterranean). However, this Gaussian assumption could be questioned in future studies, considering dependences between CMIP5 models, the limitations due to the small number of CMIP5 models (16 to 21), and, ultimately, the processes included in each models, which may perform differently depending on the region considered (**51,52**). The same caveat applies to the effects of the global isostatic adjustment (GIA), which can display large uncertainties locally (**53**). However, there is currently little basis to bound vertical ground motions due to the GIA, so that we follow here the AR5 approach (**1**), which arguably interpret the difference between two GIA models as the standard deviation of a Gaussian distribution (**1,54,55**). While it is too early to model the ocean and GIA contributions through appropriate extra-probabilistic distribution, our assumptions can be justified because ice mass losses are the dominant source of ambiguity in sea-level projections and most important to consider.

2.2 Experimental design

The extra-probabilistic sea-level projections presented in Figure 1 (and in all other figures of this paper) are computed by a Monte-Carlo procedure jointly propagating uncertain components represented by probabilistic and extra-probabilistic distributions (Supplementary Figure 3) (**24**) (see methods). To evaluate the knowledge gained since the AR5, we consider the two following groups of extra-probabilistic projections:

- Alter-AR5 global mean sea-level projections, which sum the Gaussian ocean sea-level component with extra-probabilistic ice and land water components adjusted to the AR5 likely ranges (**1**), while remaining bounded by minimum and maximum possible contributions (**50,56-58**) (Supplementary Table 1). We call them Alter-AR5 because they are computed based on an extra-probabilistic approach to the AR5 likely ranges of sea-level components (Methods).
- Post-AR5 projections, which consider the recent advances regarding the simulation of Antarctic dynamics and Greenland ice sheet melting (**31-33**).

In a probabilistic framework, assumptions regarding the dependencies of components of sea-level rise have large impacts on the final distribution (**59**). Here, our reference set of simulations assumes full dependency between the ocean, glacier, Greenland, and Antarctic surface mass balance components through their relation to global mean surface temperature. We assume that the Antarctic surface mass balance is anticorrelated with the other components, because it is expected that more precipitation will accumulate on the margins of Antarctica in a warmer climate, thus reducing global sea-level rise. Other dependence schemes are tested (Supplementary Table 1) and presented in the Supplementary Figures.

3. Results: extra probabilistic sea-level projections and quantitative metrics of uncertainty

Figure 1 displays extra-probabilistic global sea-level projections by 2100 under RCP 8.5 in a cumulative distribution diagram. These sea-level rise projections are bounded by two functions, the upper and lower cumulative probability bounds, hence defining a probability-box (p-box), which includes all probabilistic projection compliant with our assumptions. The “ill-known” sea-level rise cumulative distribution function by 2100 under RCP 8.5 is located in between these two bounds, which are computed according to the joint probabilistic-extra-probabilistic procedure described in the methods section. The ambiguity in global sea-level projection can therefore be appraised by comparing these upper and lower bounds, but it may also be quantified simply by computing the area comprised between these two functions. This region is called the “Ambiguity area criterion” (AAC) in the remainder of this paper.

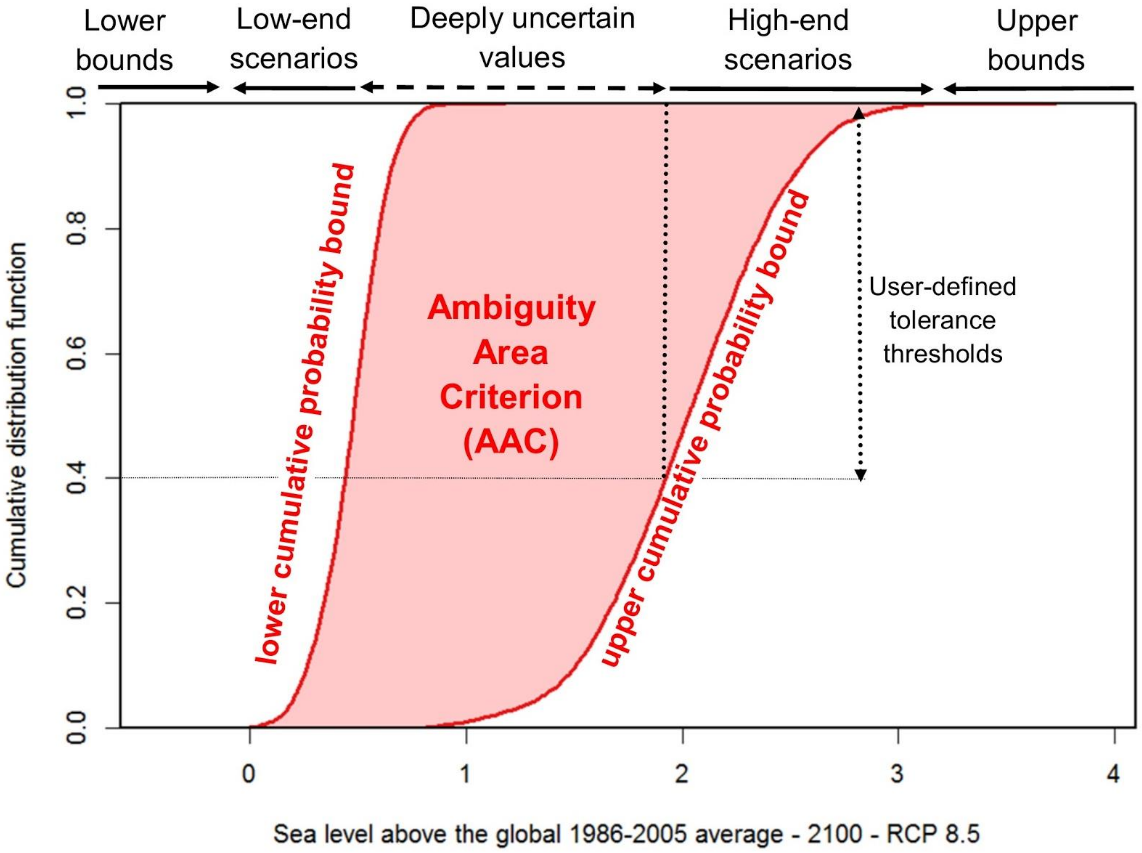


Figure 1: Global extra-probabilistic sea-level projection for 2100 (RCP 8.5) presented in a cumulative distribution diagram, and proposing unified criteria to identify deeply uncertain sea-level values or low-end and high-end scenarios. The projection presented here corresponds to post-AR5 simulations.

Coastal adaptation practitioners can refer to cumulative distribution diagrams such as Figure 1 in order to appraise the safety margin provided by the sea-level scenarios they are using and define:

- deeply uncertain sea-level scenarios, corresponding to sea-level rise values, whose probability can not be quantified precisely enough to inform adaptation, due to high disagreements between possible probabilistic models. For example, in Figure 1, values are considered deeply uncertain if the uncertainty of their probability exceeds 60%.

- high-end and low-end scenarios, whose probabilities can be bounded. For example, Figure 1 defines high-end (respectively low-end) scenarios as sea-level rise values, whose probabilities is lower than a user-defined risk tolerance threshold, set at 60% in Figure 1. Hence, in Figure 1, low-end scenarios correspond to future sea levels whose probabilities to be exceeded can not exceed 60%.
- lower and upper bounds, corresponding to sea-level scenarios, whose probability is extremely low whatever the probabilistic frameworks considered. In the example of Figure 1, this corresponds to sea-level rise values lower than 0m and higher than 3m, whose probabilities are always lower than 1%. While there is no physical basis to support sea-level scenarios in this range today, users with high risk-aversion, such as those planning the maintenance and decommissioning of nuclear power plants, may still consider such lower and upper bound in their adaptation strategy, for example to align their sea-level scenarios with the safety margins applicable in their working processes, or at least have a strategy in place if these scenarios are praised.

Depending on their risk-aversion, users can define risk tolerance thresholds to distinguish high-end and low-end scenarios from deeply uncertain sea-level rise values (**11-14**). This threshold can be associated to an uncertainty on the cumulative probability function. In the remainder of this paper, thresholds ranging from 1% to 10% are presented.

AR5 authors did not provide any very likely range of future sea level (90-100% probability), because of the lack of literature and understanding on the very unlikely high-end values of projected temperatures and sea-level components. Here, Figure 1 proposes a framework applicable at any location and allowing coastal adaptation practitioners to define the most appropriate sea-level scenario given their decision context (**11-14**). Furthermore, the terminology proposed here has the advantage of defining precisely concepts, which have previously been loosely defined so far, such as ambiguity, deep uncertainties, high-end scenarios and upper bounds.

4. Discussion: dependency of extra-probabilistic sea-level projections on greenhouse gas emissions

4.1 Changes in global sea-level projections since the AR5

In this subsection, we examine how the knowledge gained since AR5 has modified global sea-level projections that can be obtained through an extra-probabilistic approach. The gray and red polygons in Figure 2 present the upper and lower cumulative distribution functions for Alter-AR5 and Post-AR5 simulations for RCP 8.5 in 2100 (Supplementary Table 1). Note that the shape of the Alter-AR5 upper distribution can be explained by the high uncertainty of the upper bound of the contribution of Antarctic ice sheet and by the dependence scheme used here (see section 2 and Supplementary Figure 3). In fact, considering different dependence schemes leads to qualitatively similar results, although Alter-AR5 simulations are more sensitive to assumptions regarding dependencies. This can be explained by the long fat tails of probability boxes associated with the likely ranges (**30**), which remain more apparent in global projections when stronger dependencies between components are assumed. However, in the case of Post-AR5 simulations, these choices have only a minor impact on the uncertainties of extra-probabilistic sea-level projections (Supplementary Figure 4).

Different perspectives can be taken to compare uncertainties in sea-level projections. For example, the AR5 statement implies that the probability that sea-level rise exceeds 1.5m by 2100 is lower than 33%, but Figure 2 shows that it is lower than 55% according to the Alt-AR5 simulations, and lower than 90% according to the post-AR5 simulations. This illustrates that the uncertainties in sea-level projections depend heavily on the uncertainty model chosen for each sea-level component, as well as on the method chosen to aggregate uncertainties of individual sea-level components. Overall, if sea-level rise values higher than 2m are left aside, post-AR5 simulations are shifted to the right in a CDF diagram compared to previous estimates, implying larger deeply uncertain and greater high-end sea-level scenarios.

The ambiguity criterion of global sea-level projections, as defined in Figure 1, is 8% larger in post-AR5 projections than for alter-AR5 projections for RCP8.5. However, it is reduced by 40% and 60% for RCP 4.5 and 2.6 respectively (Supplementary Figure 5). These examples show in a quantitative manner that the ambiguity of sea-level projections by 2100 is much smaller for lower RCP scenarios in post-AR5 simulations (as expressed by Horton et al., 2018 (**22**)). Furthermore, it shows that for RCP 8.5, the knowledge gained since AR5 has neither resulted in a reduction of ambiguity of sea-level projections, nor in allowing coastal adaptation planners to reduce the range of plausible sea-level scenarios. Hence, when designing sea-level scenarios, coastal adaptation practitioners should not necessarily expect a reduction of uncertainties with the acquisition of new knowledge. Instead, they may anticipate that upper and lower cumulative bounds will continue to evolve in the future.

The results presented in Figure 2 are sensitive to outliers and extreme modeling results. For example, Post-AR5 sea-level projections strongly rely on a single study implementing the Marine Ice Cliff Instability (**33**), and, to a smaller extent, to current capabilities of Greenland ice-sheet melting models (see section 2). Nevertheless, Alter-AR5 simulations shown in Figure 2 remind that sea-level projections displayed ambiguity before this particular study. Whatever the limitations of each single study considered here, the uncertainty propagation procedure (Methods) guarantees that no line of evidence in the published literature supports any probabilistic sea-level projection outside the colored area in Figure 2.

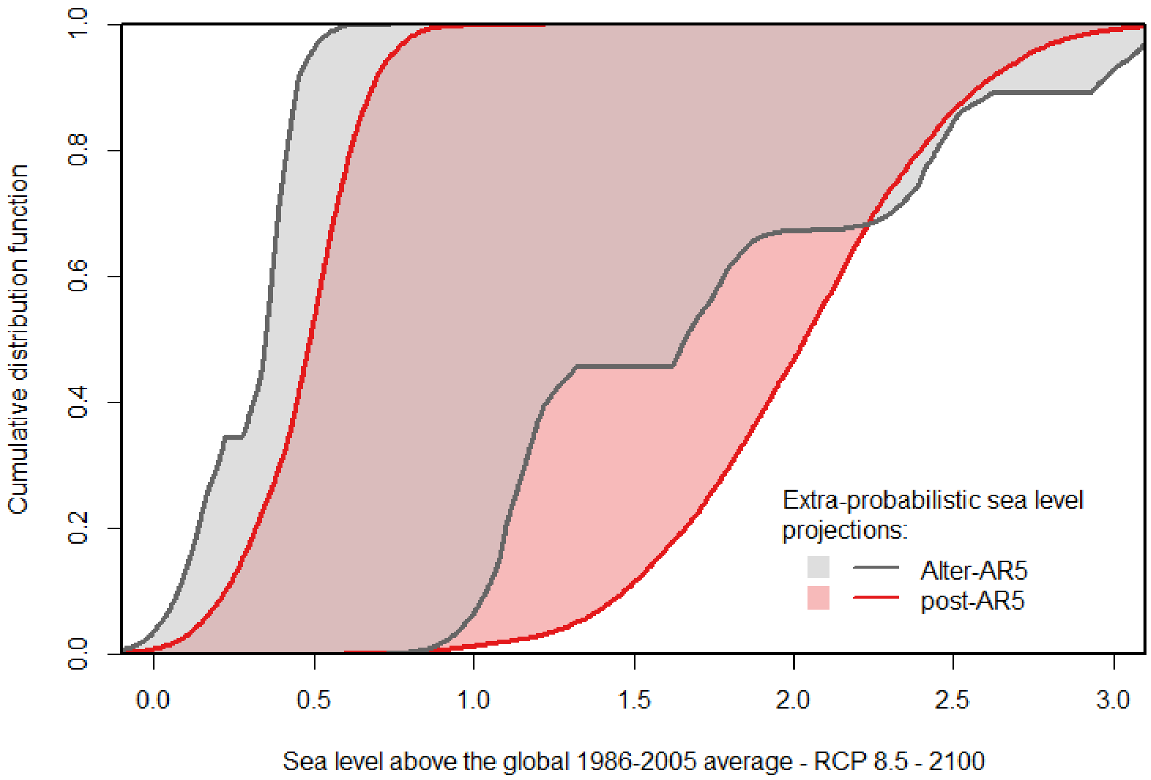


Figure 2: Extra-probabilistic sea-level projections based on Alter-AR5 and Post-AR5 simulations. Supplementary Figure 5 provides the same results for RCP 4.5 and RCP 2.6 by 2100, and Supplementary Figure 6 for all RCP by 2055.

4.2 Regional implications

The ambiguity of sea-level rise displays regional variability due to the non-uniform response of the solid Earth to the melting of ice (Figure 3) (**2,6,7**). This reflects that ambiguity is mostly due to dynamic mass loss from the Antarctic and Greenland ice sheets. Contrary to the global mean (Figures 1 and 2), the sea-level projections presented in Figure 3 and Supplementary Figure 7 are applicable at regional scales and can be combined with information on local vertical ground motions, sea-level variability and extreme water levels in order to create local relative sea-level rise scenarios suitable to inform adaptation. They provide a baseline for coastal adaptation practitioners to design locally applicable extra-probabilistic projections as well as high-end and low-end scenarios as in Figure 1.

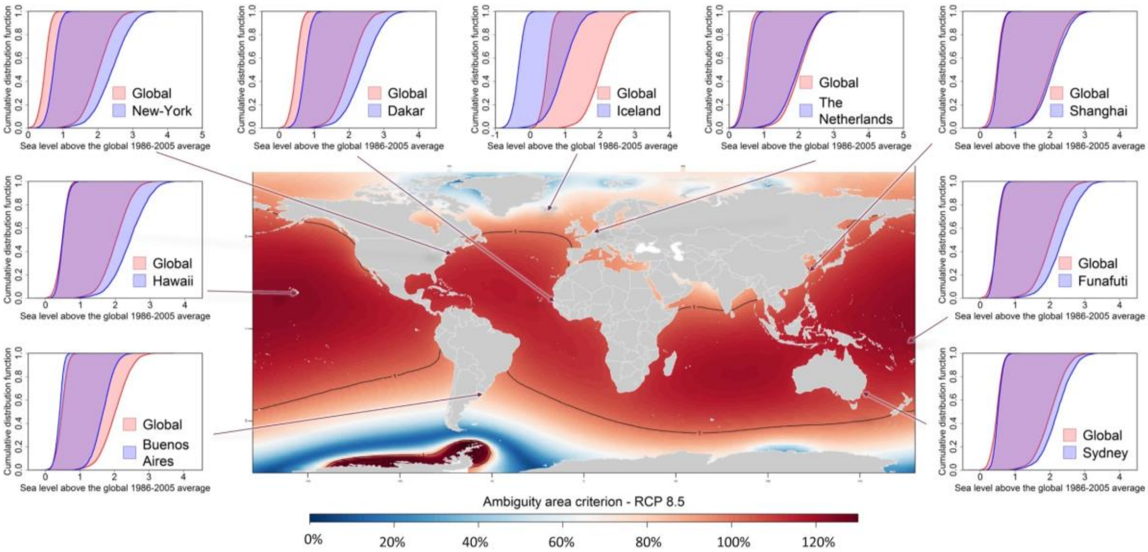
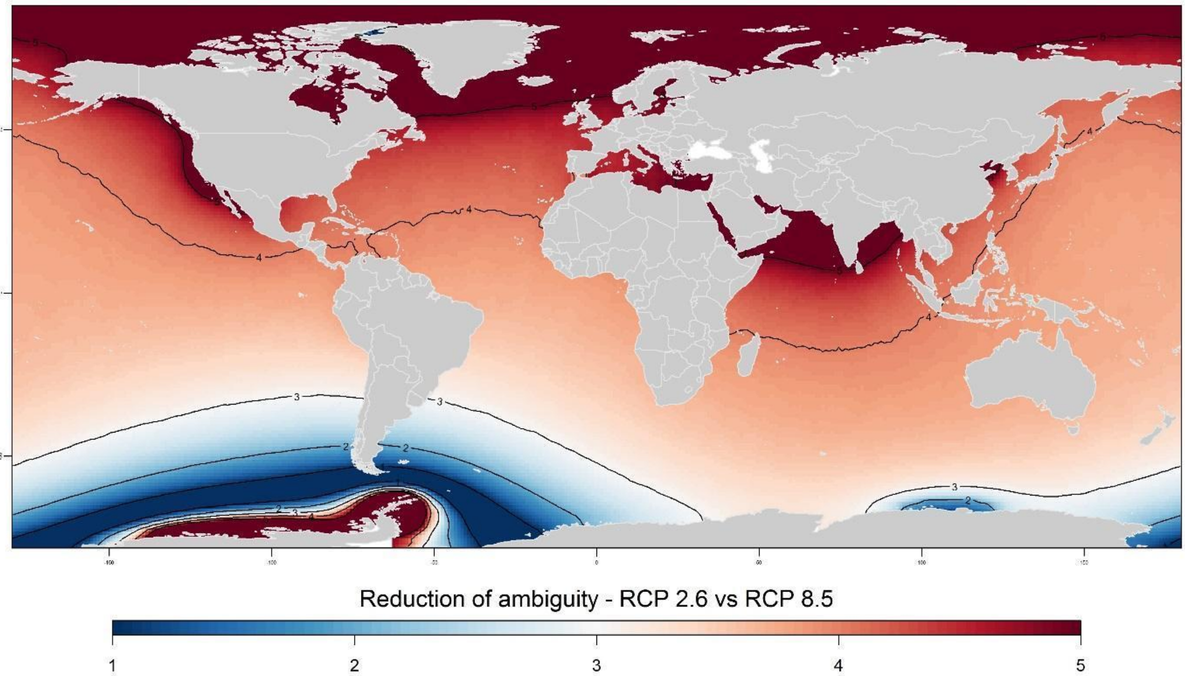


Figure 3: Regional variability of AAC (ambiguity area criterion) in the case of post-AR5 simulations. The AAC is expressed as a percentage of the global mean. Projections provided are for 2100 with respect to a 1986-2005 mean.

Figure 4 displays the benefits, in terms of ambiguity reduction, of achieving RCP 2.6 and RCP 4.5 compared to a RCP 8.5 baseline, which is assumed to represent business-as-usual greenhouse gas emissions. Figure 4 shows that mitigating climate change reduces the ambiguity in sea-level projections in almost all inhabited regions. However, while climate change mitigation reduces sea-level projection ambiguity almost uniformly along inhabited coastlines of the world if RCP 4.5 is achieved, reaching the more ambitious RCP2.6 benefits the countries of the Indian subcontinent, the Middle East and eastern Mediterranean, northern Europe, the west coast of North America, around the Yellow Sea, and the Arctic the most. More generally, Europe and all of North America see higher benefits. This is due to the fact that RCP4.5 strongly reduces the risk of a large contribution from the Greenland ice sheet (Supplementary Figure 2) (**31**), whereas the projections of dynamics ice sheets melting in Antarctica are significantly lower for RCP 2.6 compared to RCP 4.5 (Supplementary Figure 1). This reduction of ambiguity has obvious implications for adaptation in these areas, as the lower ambiguity simplifies the process of selecting appropriate sea-level scenarios for planning and design: e.g., design height standards or setback lines for coastal infrastructures. For mitigation policies, this implies that western countries are among those who benefit the most from reducing climate change well below current Intended Nationally Determined Contributions (INDCs). As these countries have established a global economy based on the combustion of fossil fuels and remain massive contributors to today's greenhouse gas emissions, the result of Figure 4 can be seen as an additional incentive for finding mitigation solutions allowing to reach the 2°C target.

The contribution of the different sea-level components to the ambiguity of regional and global sea-level projections is closely related to the diversity in and the amount of studies on these components. Since AR5, a lot of effort has been dedicated to studies on the contribution of Antarctica to global sea-level rise (**7,50,58,60,61**). This has led to estimates based on a diverse range of methods from process-based statistical estimates (**32**) to numerical simulations with recently developed parametrizations (**33**). In contrast, the contribution of thermal expansion is directly derived from the CMIP5 simulations, which are all coupled Atmosphere-Ocean Global Circulation Models (AOGCMs). There are no new estimates of thermal expansion based on global warming including plausible feedback processes, which are not represented in AOGCMs. In addition, there are no post-AR5 estimates of thermal expansion. Altogether, the diversity of approaches to estimate the contributions of different components to sea-level rise may exacerbate the large dependency of ambiguity to specific components such as Antarctica.



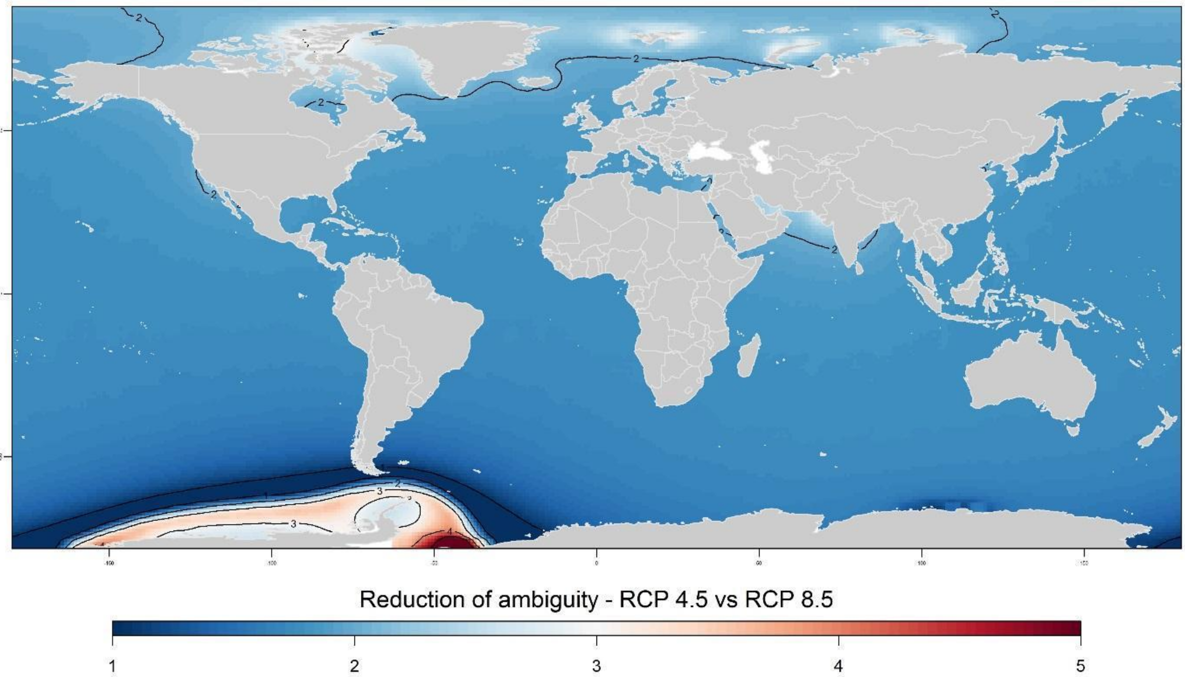


Figure 4: regional reduction of ambiguity in sea-level projections by 2100 induced by climate change mitigation policies according to the ambiguity area criterion: above RCP 2.6 versus RCP8.5; below: RCP 4.5 versus RCP 8.5 (note difference in scales in the two figures). These figures read as follows: the ambiguity in sea-level projections are reduced by a factor 4 (respectively 2) along the coasts of Africa if RCP 2.6 (respectively: RCP 4.5) is preferred to the business-as-usual scenario (RCP 8.5).

5. Conclusions

This study applies the principle of extra-probabilistic theories of uncertainties across the different steps leading to global and regional sea-level projections based on their components. From a methodological point of view, we provide a consistent and unified framework to quantify ambiguity, deep uncertainties and define high-end and low-end scenarios across many coastal locations, thus providing directly applicable projections to inform coastal adaptation planners.

The analysis shows a strong relationship between quantitative measures of ambiguity and RCP scenarios. This emphasizes the strong dependency of sea-level projections on greenhouse gas emissions, which is less apparent if only one probabilistic sea-level projection is considered. Furthermore, this enables the benefit, in terms of ambiguity reduction, of achieving RCP2.6 or RCP4.5 versus RCP8.5 to be quantified. We find that developed countries are among those who benefit the most, in terms of such uncertainty reduction. This is one benefit of climate mitigation that is rarely considered.

Our conclusions rely on the current state of understanding of each component of sea-level rise. This state of understanding is evolving over time. For example, future studies may conclude that the Marine Ice Cliff Instability is unlikely to occur during the 21st century. Overall, and notwithstanding limitations of our ability to define uncertain components of future sea-level rise, the extra-probabilistic approach can be seen as an attempt to address the needs of users considering likely estimates and low-probability high-impact scenarios within a unified framework.

6. Methods

6.1 Sources of ambiguity in sea-level projections

We apply the principles of extra-probabilistic theories of uncertainties, which use imprecise probability functions to extract quantitative metrics of ambiguity. Depending on the source of information describing uncertainties for each component, we apply the most appropriate mode of representation:

possibility distributions (**62**) or probability boxes (**63**) constructed based on the maximum and minimum CDF available in the literature, or probability functions.

The AR5 provides likely intervals, within which the considered variable is expected to lie with a probability higher than 2/3 (table 1 of Mastrandrea et al., 2010 (**64**), see Supplementary Text). Given a likely range, the probability of exceeding a particular threshold is bounded by two step functions, which delineate all plausible probability functions compliant with this likely range (**30**). We complement the likely range with supplementary information that allows bounds to the maximum contribution of each component of sea-level rise to be estimated, mostly from Jackson and Jevrejeva (2016) (**50**). For example, the sea-level rise contribution from Greenland cannot exceed 5m, which corresponds to the total amount of sea-level equivalent in this ice sheet. By 2100, these values are further limited by the kinematics of ice melting processes (**56**). Supplementary Table 1 indicates which assumptions have been made for each component of future sea-level rise.

6.2 Joint probabilistic-extra-probabilistic propagation of uncertainties

Uncertainty propagation consists of evaluating the impacts of the uncertainties associated with the inputs of a model on the outputs of interest. Here, the model of interest computes global and regional sea-level projections. It is simply the sum of the uncertainty components of future sea-level rise, considering the dependencies between these components. We apply a Monte-Carlo-like approach, namely the independent random set approach (**65**), to jointly propagate uncertainties of probabilistic and extra-probabilistic input parameters across the model. This method extends the classic probabilistic Monte-Carlo approach by selecting an interval for each probability of exceedance level instead of a single value. The method accounts for stochastic dependencies and anti-dependencies among input parameters: during each step of the propagation procedure, we select the same levels of probability of exceedance for two fully dependent variables, or the complement of this probability of exceedance for an anti-dependent variable (in the case of Antarctic surface mass balance).

6.3 Regional projections

The regional projections are computed following Slangen et al. (2014) (**6**): for each 1°x1° cell in the ocean: we apply the same Joint probabilistic-extra-probabilistic propagation of uncertainties, considering the regional variability of the ocean component as well as the fingerprints of mass contributions to sea-level rise. Finally, the contribution of the global isostatic adjustment is added as a Gaussian contribution, as in the AR5. Other vertical ground motions caused by anthropogenic or natural processes (tectonics, volcanism, variations in the water content in recent sedimentary layers, groundwater or hydrocarbure extractions, etc.) (**11, 66**) are not considered, and, where relevant, should be added as an additional source of uncertainty for local application.

6.4 Implementation

We use the R-package Hyrisk (Hybrid Methods for Addressing Uncertainty in RISK Assessments) (**67**), supplemented with additional functions allowing the inclusion of p-boxes as uncertainty input parameters. We obtain the regional extra-probabilistic projections by performing 250 simulations in the Monte-Carlo procedure. We forced the input random variable to follow a Sobol' sequence of quasi-random numbers (**68**) in order to accelerate the convergence of the computation of the extra-probabilistic projections.

Data availability statement: results from Figure 3 and Supplementary Figure 7 will be provided as a supplementary dataset.

Authors contributions

GLC Designed research; all authors performed research; JCM, JR Contributed new analytic tools; MC, AS, DS provided data; All analyzed results, wrote and revised the paper.

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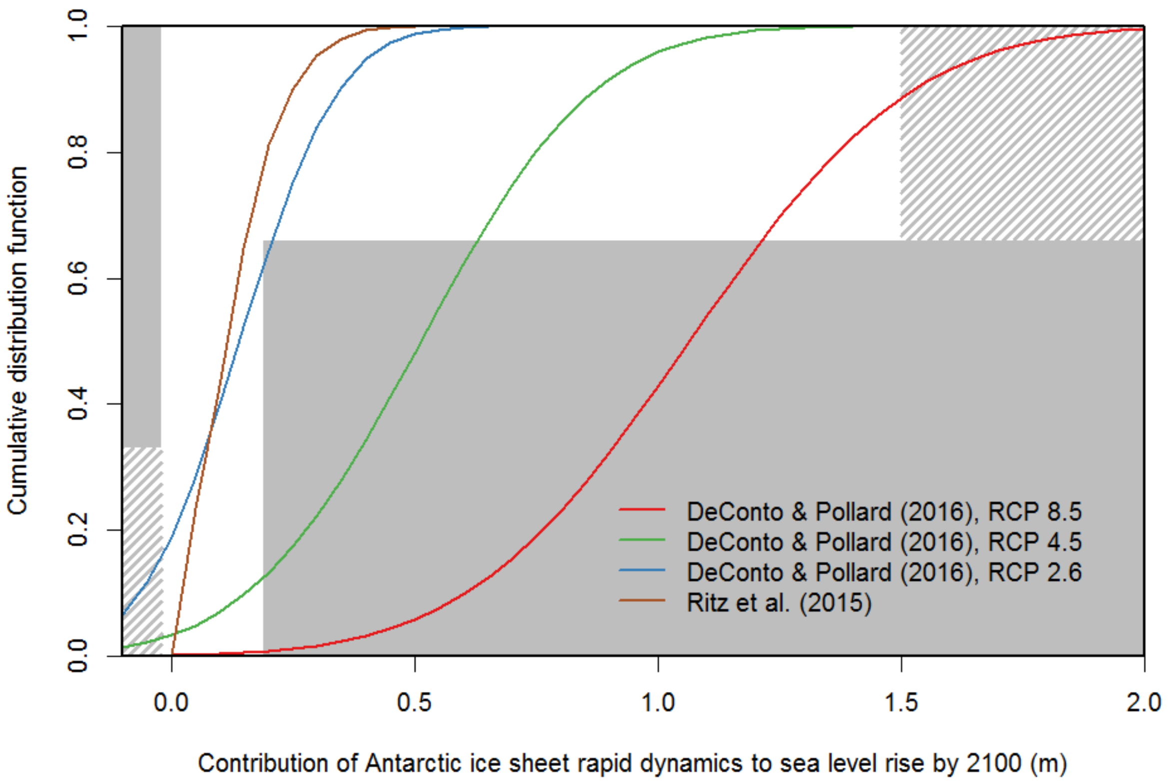
Supplementary material

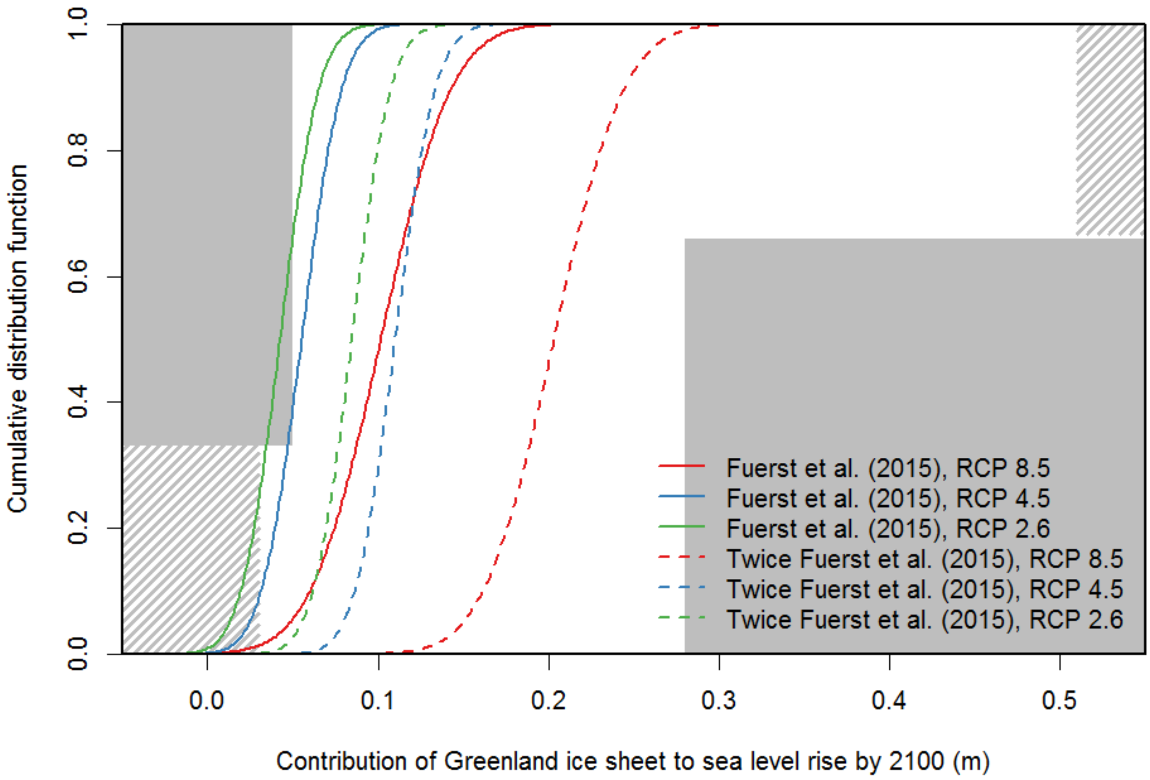
Supplementary Table 1: summary of Alter-AR5 and Post-AR5 simulations presented in this study. We use the posterior simulations of Ritz et al. (2015) (**32**). We use the worst-case simulations in DeConto and Pollard (2016) (**33**).

<table>
<tr><th></th><th>Alter-AR5 – 2055</th><th>Alter-AR5 - 2100</th><th>Post AR5 - 2100</th></tr>
<tr><td>Thermal expansion</td><td colspan="3">Gaussian distribution</td></tr>
<tr><td>Greenland ice sheet</td><td colspan="2">AR5 likely range, bounded by the maximum and minimum values provided by Jackson and Jevrejeva (2016) (50)</td><td>See Supp. Fig 2</td></tr>
<tr><td>Glaciers</td><td colspan="3" rowspan="2">AR5 likely range, bounded by the maximum and minimum values provided by Jackson and Jevrejeva (2016) (50)</td></tr>
<tr><td>Antarctic surface mass balance</td></tr>
<tr><td>Antarctic dynamics</td><td colspan="2">AR5 likely range, bounded by the maximum and minimum values provided by Jackson and Jevrejeva (2016) (50)</td><td>See Supp Fig 1.
Lower CDF: Ritz et al. (2015) (32)
Upper CDF: RCP 8.5 and 4.5: DeConto and Pollard (2016) (33); RCP 2.6: Ritz et al., (2015) (32)</td></tr>
<tr><td>Groundwater</td><td colspan="3">AR5 likely range, bounded by the maximum and minimum values provided by Jackson and Jevrejeva (2016) (50)</td></tr>
<tr><td>Global isostatic adjustment (regional simulations only)</td><td colspan="3">Gaussian distribution with mean and standard deviations equal to the mean and difference of the Lambeck and Peltier global GIA models, as in the AR5 regional simulations (1)</td></tr>
<tr><td>Reference dependence scheme</td><td colspan="3">Ocean, glaciers and ice sheets surface mass balance, considering accumulation of snow over Antarctica in a warmer climate.</td></tr>
<tr><td>Other dependence scheme tested</td><td>No dependencies</td><td colspan="2">Fully independent</td></tr>
</table>

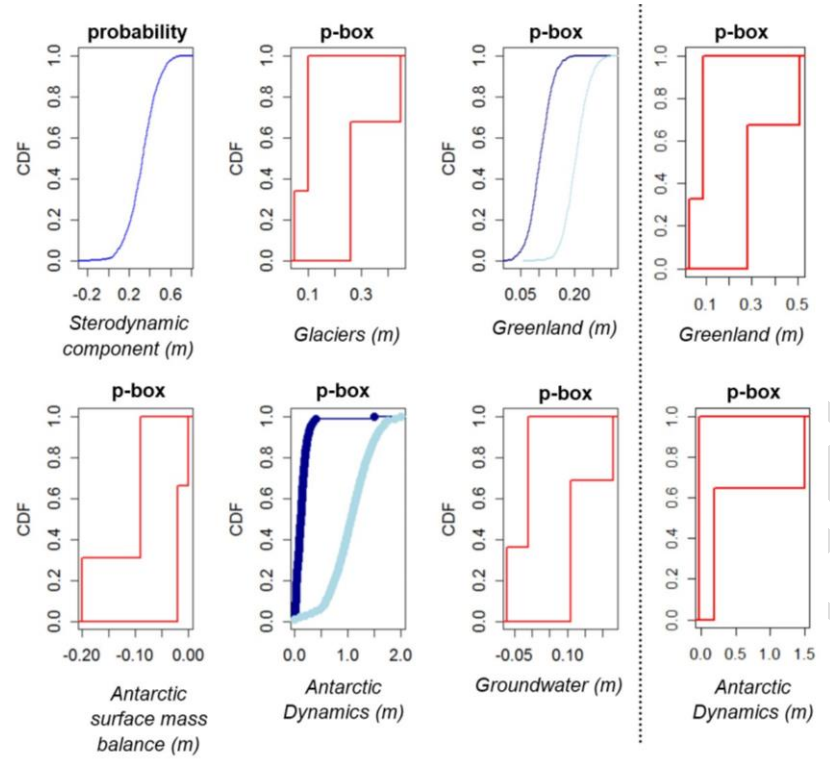
Supplementary Figures



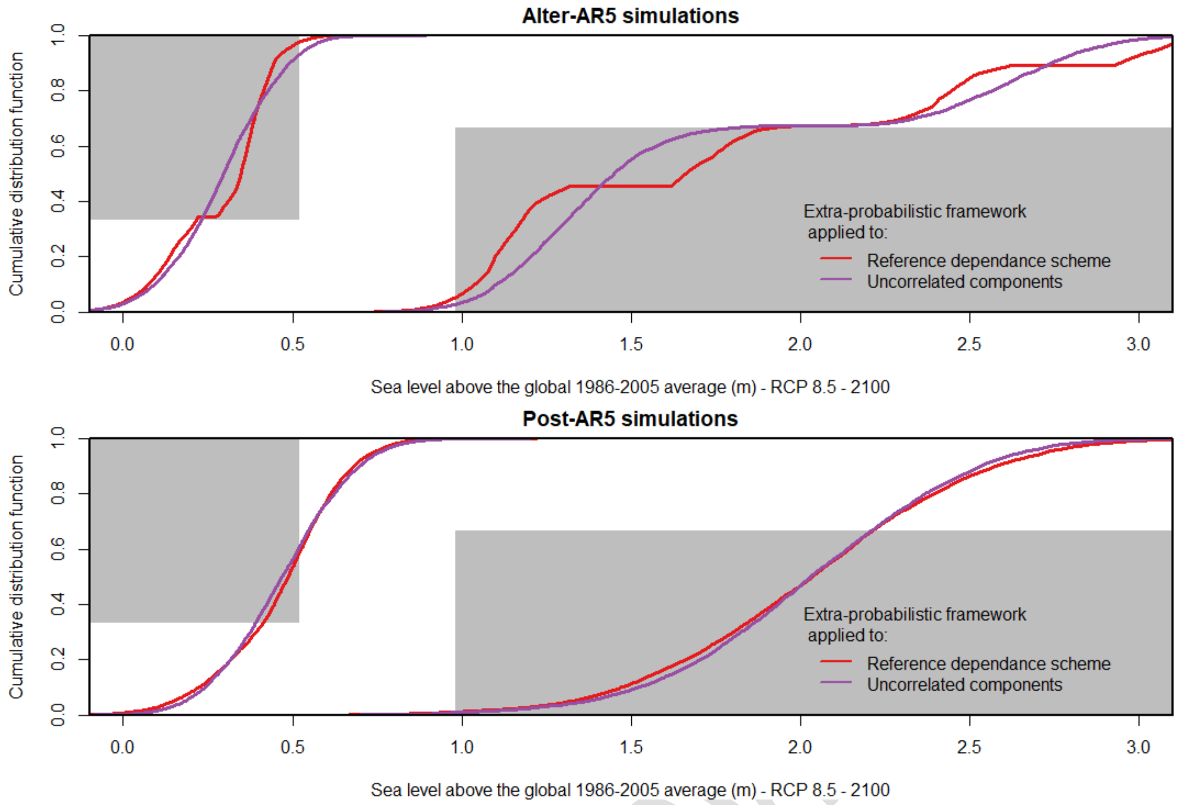
Supplementary Figure 1. Cumulative distribution functions (CDF) representing the contribution of Antarctic dynamics, according to Ritz et al. (2015) (**32**) and DeConto and Pollard (2016) (**33**). Note that the latter CDF are conditional to greenhouse gas emissions (RCP scenarios), whereas only the initiation of the melting in each sector depends on greenhouse gas emissions in Ritz et al. (2015) (**32**). Hence, this probabilistic statement is largely independent of any climate change scenario. Note that the probabilistic projection of Ritz et al. (2015) (**32**) displayed here considers observations. The CDF provided by DeConto and Pollard (2016) (**33**) include both Antarctic dynamics and surface mass balance. The latter contribution is removed here (-0.019m, -0.047m and -0.075m for RCP 2.6, 4.5 and 8.5, respectively). The white area represent the p-box considered here in the Alter-AR5 simulations (**30**). It is based on: (1) the likely range of the IPCC (white and dashed gray areas), which is the same for all RCP scenarios; (2) information on the maximum and minimum possible contributions of Antarctica according to Jackson and Jevrejeva (2016) (dashed gray areas). For the translation of a likely range in a CDF diagram, see Le Cozannet et al. (2017) (**30**).



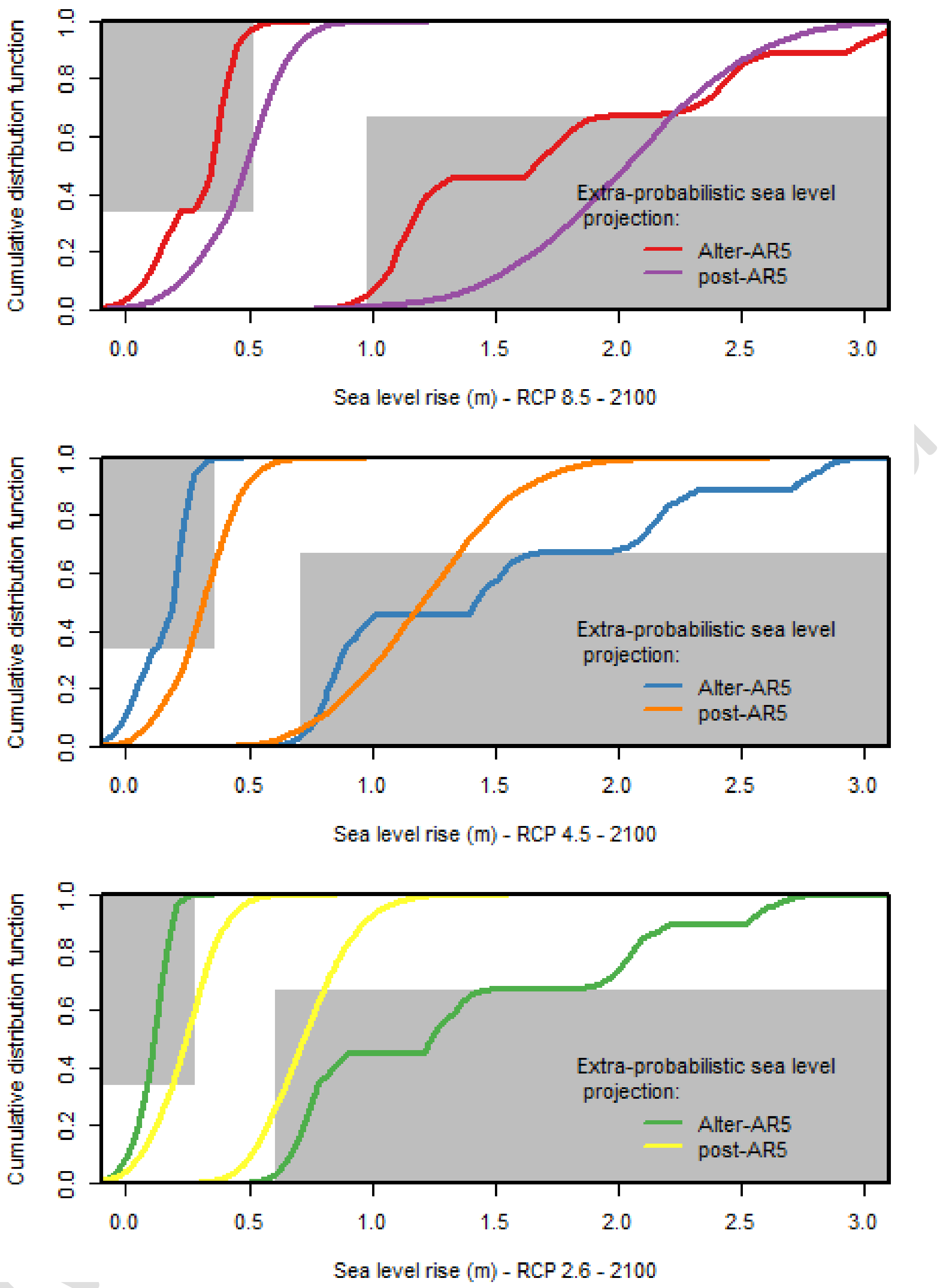
Supplementary Figure 2. Cumulative distribution functions (CDF) representing the contribution of Greenland, according to Fürst et al. (2015) (**31**), and considering a scenario where the contribution of Greenland is twice that of Fürst et al 2015 (**31**). The white area represents the p-box considered in the Alter-AR5 simulations (see legend of Supplementary Figure 1). It is based on the fusion of likely ranges in the IPCC AR5 for all RCP scenarios (white and dashed gray areas). The dashed gray areas are excluded based on Jackson and Jevrejeva (2016) (**50**).



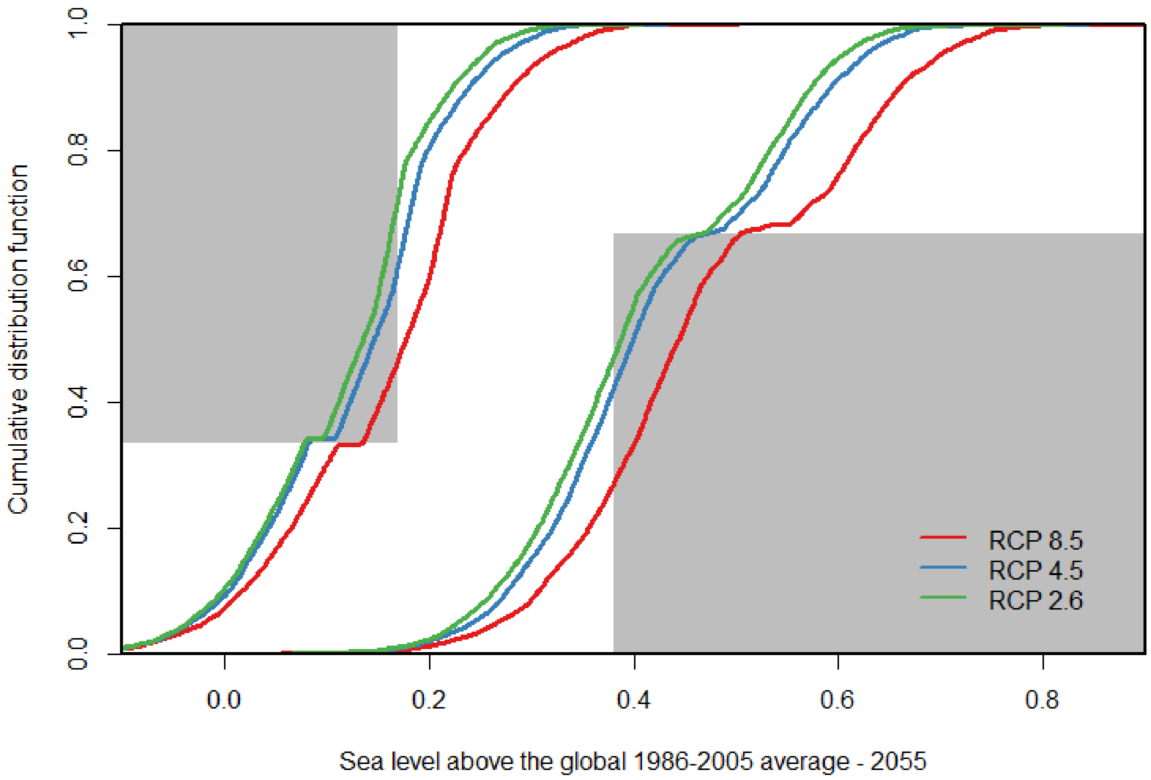
Supplementary Figure 3: mixed probabilistic / extra-probabilistic input parameters used here to compute global and regional sea-level changes in the case of the RCP 8.5 Alter-AR5 (top) and Post-AR5 (bottom) simulations by 2100. All parameters are shown in a CDF diagram (cumulative density function or p-boxes).



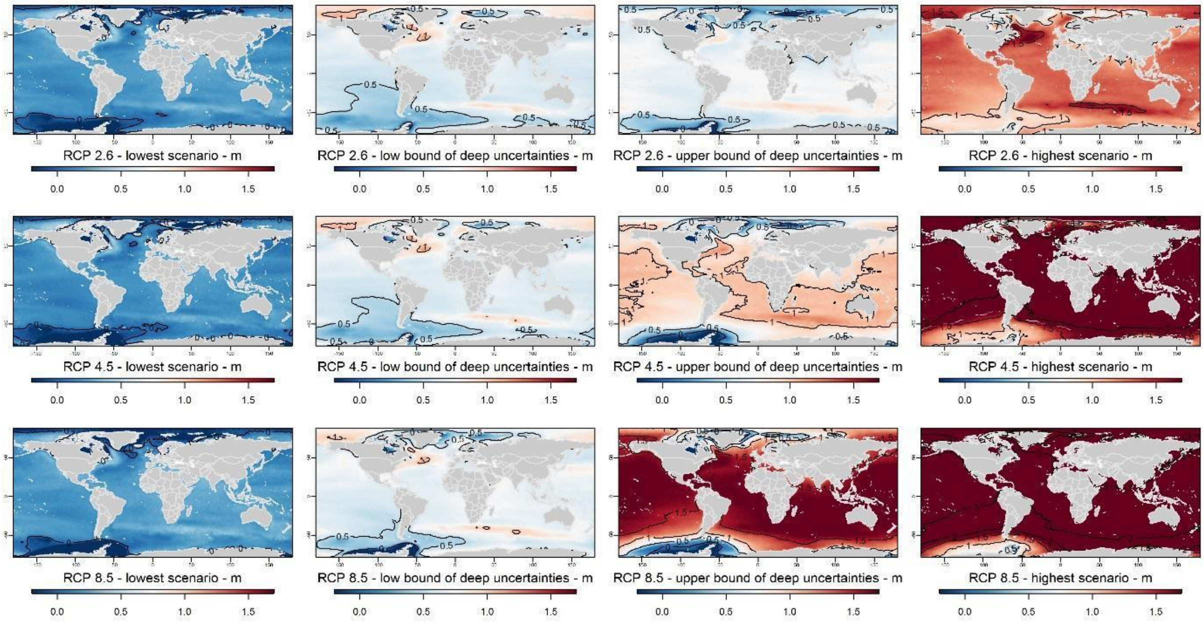
Supplementary Figure 4: impact of other dependence schemes. The white area represents the p-box implied by the AR5 likely range (**30**). This figure illustrates that for Post-AR5 simulations and, to a lesser extent, for Alter-AR5 simulation, considering different dependence schemes has only a small effect on the upper and lower cumulative probability bounds, and is a negligible source of uncertainties given the large ambiguity in sea-level projections. Hence, with the current ambiguity in sea-level projections, considering different dependence schemes is not necessary.



Supplementary Figure 5: global extra-probabilistic sea-level projections obtained for each climate change scenario (RCP 2.6, 4.5 and 8.5) based on the IPCC statement on components, for both Alter-AR5 and Post-AR5 simulations. The white area represents the p-box implied by the AR5 likely ranges (**30**).



Supplementary figure 6: global extra-probabilistic projections by 2055. The white area is the fusion of the likely ranges of all three scenarios RCP 2.6, 4.5 and 8.5. This figure shows that there is consistency in the mixed probabilistic/extra-probabilistic frameworks proposed here and those applied in the IPCC AR5 by 2055, translating the fact that the ocean component of sea-level rise (considered Gaussian in both cases) is a major contribution to uncertainties by this time horizon.



Supplementary figure 7: regional extra-probabilistic projections displaying regional lowest and highest scenarios (1% tolerance threshold) as well as lower and upper bounds of deep uncertainties (10% tolerance threshold). There is no physical basis to support sea-level scenarios outside the minimum and maximum values, but users may select scenarios outside this range if this is aligned with the security margins applicable in their sectors (see definitions in Figure 1 ; maps are smoothed with a 5°x5° mean filter).

Supplementary text: uncertainty frameworks applicable to sea-level projections

S.1 Probabilistic sea-level projections

In the area of coastal engineering, probabilities are the most widely used tool to describe uncertainties. For example, in France, coastal risk prevention plans prepare for flooding events with probabilities of exceedance of 1/100 per year, whereas the newly proposed highest protection standards in the Netherlands consider dike failure probabilities ranging from 1/10,000 to 1/100,000 in coastal areas (**i**). Probabilistic sea-level projections provide a probability function representing the uncertainties of future sea levels at particular time horizons (e.g., 2050, 2100). They are commonly (but not always) produced by propagating uncertainties of each component of sea-level rise by means of a Monte Carlo approaches (2,10,50,60,ii).

S.2 Reasons for considering other frameworks to represent uncertainties

While probabilities are very widely used to represent sea-level uncertainty, it is questionable if these are the right tool for supporting coastal practitioners, because sea-level rise projections are ambiguous: several probabilistic sea-level projections exist, reflecting different assumptions on the causes of future sea-level rise, and, as acknowledged by the sea-level science community itself (**7,21,22**), no single probability model can be recommended yet to support coastal adaptation practitioners. The coexistence of different but equally credible probabilistic statements in future sea-level changes defines the concept of “ambiguity of sea-level projections” (**7**), following the original work of Ellsberg (1961) (**34**) on risk and decision making).

S.3 extra-probabilistic theories of uncertainties and their application to sea-level projections

Extra-probabilistic theories of uncertainties are well suited to analyze ambiguity in sea-level projections because they recognize that several probability functions are compliant with the knowledge available (**23-26**) (see methods). As a general principle, extra-probabilistic theories of uncertainties consider that probabilistic measures are themselves uncertain, and assign an imprecision to this measure (**24,27,28**).

In the area of sea-level rise, at least two extra-probabilistic theories of uncertainties, the theory of evidence (**iii**) and the possibility theory (**62**), have been used by coastal engineers and scientists. The purpose of these studies was to represent the ambiguity due to conflicting expert elicitations of sea-level rise (**29,30**), to propagate uncertainties through coastal impact models, or to perform a sensitivity analysis.

S.4 Use of extra-probabilistic theories of uncertainties in the IPCC reports

The IPCC recommended using fuzzy boundaries to define likelihood statements (**64**), where the current state of knowledge prevents reliance on a single probability function (**64**). For example, in the 5th Assessment report (AR5) of the IPCC, uncertainties in sea-level projections are provided in the form of a likely range (**1**). According to the definition, the probability that future sea-level rise falls within the *likely* range is between 66% and 100% (**64**), so that the probability of exceeding the upper limit of the likely range (e.g., 0.98m by 2100 in the RCP 8.5 scenario) could be 0 to 33% (**20,30**). As per its definition (Mastrandrea et al., 2010), a *likely* range can be immediately interpreted within an extra-probabilistic framework, such as probability bound analysis (**63**), within which any cumulative distribution consistent with the knowledge available are bounded by an upper and lower probability distribution.

In AR5, however, the extra-probabilistic approach was not applied across all steps of producing global and regional sea-level projections. The likely ranges of independent contributions of components of future sea-level rise were summed quadratically, reflecting a slightly different definition of the likely range (“approximately 66%”, as in Church et al., 2013 (**iv**)), and a probabilistic propagation of uncertainties assuming Gaussian distributions. Consequently, the spread of the likely range of global sea-level rise was set to 0.52-0.98m by 2100 in the AR5, to be compared with a likely range of 0.3-1.3m that would result if no assumption is made regarding the shape of the distributions and their interdependence, and likely intervals are therefore simply added. This approach separates the (probabilistic) propagation of uncertainties from the final assessment, provided in extra-probabilistic terms (**v**), but the issue remains that the choice of a particular uncertainty framework has large impacts on the final uncertainty range conveyed to coastal stakeholders.

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