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LETTER

Bounding probabilistic sea-level projections within the framework of the possibility theory

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Abstract

Despite progresses in climate change science, projections of future sea-level rise remain highly uncertain, especially due to large unknowns in the melting processes affecting the ice-sheets in Greenland and Antarctica. Based on climate-models outcomes and the expertise of scientists concerned with these issues, the IPCC provided constraints to the quantiles of sea-level projections. Moreover, additional physical limits to future sea-level rise have been established, although approximately. However, many probability functions can comply with this imprecise knowledge. In this contribution, we provide a framework based on extra-probabilistic theories (namely the possibility theory) to model the uncertainties in sea-level rise projections by 2100 under the RCP 8.5 scenario. The results provide a concise representation of uncertainties in future sea-level rise and of their intrinsically imprecise nature, including a maximum bound of the total uncertainty. Today, coastal impact studies are increasingly moving away from deterministic sea-level projections, which underestimate the expectancy of damages and adaptation needs compared to probabilistic laws. However, we show that the probability functions used so-far have only explored a rather conservative subset of sea-level projections compliant with the IPCC. As a consequence, coastal impact studies relying on these probabilistic sea-level projections are expected to underestimate the possibility of large damages and adaptation needs.

1. Introduction

While sea-level rise is one of the most unavoidable consequences of climate change, its evolution over the 21st century remains uncertain (IPCC 2013a, Kopp *et al* 2014). Coastal impact studies need to consider these uncertainties for two reasons: first, neglecting them would result in underestimations in future average impacts or adaptation needs (Purvis *et al* 2008, Hunter 2012, Hunter *et al* 2013, McInnes *et al* 2015); secondly, addressing the challenge of sea-level rise requires to test different coastal management strategies against the full range of projections (Hinkel *et al* 2015). Hence, defining mathematical tools able to represent sea-level rise projections with their uncertainties is not only a theoretical exercise, but it has practical applications for coastal adaptation.

Most studies published so far have represented the uncertainties of future sea-level rise using either ensemble sea-level projections (e.g. Mc Innes *et al* 2014), or probability density functions (Purvis *et al* 2008, Hunter 2012, Hunter *et al* 2013, Kopp *et al* 2014, Anderson *et al* 2015, Buchanan *et al* 2015, Le Cozannet *et al* 2015, 2016). Ensemble predictions rely on climate models outcomes, which do not capture all uncertainties, mainly because the physical processes involved in polar ice-sheets melting is still incompletely understood. To overcome this limitation, probabilistic sea-level projections have combined modeling outcomes with expert knowledge (Oppenheimer *et al* 2016). For example, the sea-level projections presented in the 5th Assessment report (AR5) of the Intergovernmental Panel on Climate Change (IPCC) are based on a consensus among the authors of the report on sea-level rise. Similarly, the more recent projections of Kopp *et al* (2014) use the results from the survey conducted by Bamber and Aspinall (2013).

The theory of probabilities appears too constraining to combine and represent such uncertainties. First, it mixes the different sources of uncertainties in a single format, which can give a false appearance of a precise knowledge (Klir 1989). Second, the probability setting is too rich to be entirely supplied by individuals (Dubois and Prade 1994): the identification of the probability distribution requires more information than what experts are able to provide, which is often restricted to a limited number of quantiles, such as the median and the likely range (IPCC 2013a). Given these pieces of information, many mathematical probabilistic laws may exist (Dubois and Prade 1994). This prevents from trusting that a single probability density function can represent the uncertainty of future sea-level rise (De Vries and van de Wal 2015).

Extra-probabilistic methods have been designed to address this type of issues (see a review by e.g. Dubois 2007). The general principle of these methods can be viewed as assigning imprecision to probabilistic measures (i.e. upper and lower probability bounds, cf. Baudrit *et al* 2007). By applying such extra-probabilistic methods, we can expect to represent the scarce, imprecise and incomplete knowledge involved in sea-level projections, which is part of the information relevant for coastal managers (De Vries and van de Wal 2015). The use of extra-probabilistic methods is already well established in the field of climate change impact assessments (Kriegler and Held 2005, Hall *et al* 2007, Ghosh and Mujumdar 2009). However, to our knowledge, only one study applied these principles to the issue of sea-level rise (Ben Abdallah *et al* 2014), in an attempt to reconcile the projections of the 4th Assessment Report (AR4) with those obtained by semi-empirical projections (Rahmstorf 2007). Our approach differs from this previous work as it attempts to identify all probability density functions compatible with the AR5. Indeed, for many users of sea-level rise projections, the IPCC provides the reference information, upon which any coastal impact assessment study will be based.

We focus here on the specific case of future sea-level rise by 2100 for the RCP 8.5 scenario, which relates to high (but not necessarily maximum) greenhouse gas emissions over the 21st century. Our analysis combines the constraints provided by the AR5 (IPCC 2013a) with more recent knowledge on the ice-sheets melting. By integrating these different pieces within extra-probabilistic theory, we raise the question of a potential bias in coastal impact studies, which may (or may not) have considered only a subset of possible probability density functions, given the available knowledge on future sea-level rise.

This contribution proceeds as follows: first, we review the available knowledge regarding future sea-level rise published since the AR5 (section 2). Then, we interpret it within the framework of the possibility theory (section 3). In section 4, we present the possibility distribution resulting from the AR5 constraints and other results. Finally, in section 5, we examine how previous probabilistic assessments of future sea-level rise compare with the envelope of distributions that can be inferred from the interpretation, and we discuss the potential and limits of using the possibility theory to represent sea-level rise projections.

2. Available data and information on future sea-level rise

The AR5 provides sea-level projections, whose uncertainties are described using the terms defined by Mastrandrea *et al* (2010) (left side of figure 1). To provide an extra-probabilistic interpretation of sea-level rise projection compliant with the IPCC, this section translates the AR5 results into the language of uncertainties shown in the right side of figure 1.

IPCC sea-level rise projections are obtained by summing different contributions to future sea-level rise, as obtained from process based models (IPCC 2013a). This includes: (1) the thermal expansion of water due to ocean warming; (2) the melting of mountain glaciers and of the Greenland and Antarctic ice-sheets; (3) the contributions of groundwater extractions and continental surface waters. All these terms are uncertain, resulting in an uncertain sea-level projection, whereby global sea-level rise is '*likely (medium confidence) to reach the 5%–95% range of projections from process-based models*' (IPCC 2013b, section 13.SM.1.2 and IPCC 2013c, section 12.4.1.2). In the case of the RCP 8.5 scenario, this implies a rise of sea-level of 0.52 m to 0.98 m by 2100 with respect to a 1985–2006 average. The term of 'medium confidence' refers to process-based sea-level projections upon which these figures are based.

For physical reasons, there exists an upper limit to sea-level rise by 2100 (Jevrejeva *et al* 2014). However, no value was provided by the IPCC, considering that the scientific basis was still insufficient to define it precisely (Church *et al* 2013). Nevertheless, recent global sea-level rise projections can be used to evaluate this limit (table 1). While the values provided in table 1 vary from 1.5 m to several meters, the related studies collectively suggest that there is a low level of consensus for global sea-level rise projections exceeding 1.5 m to 2 m by 2100. Furthermore, the IPCC states sea-level can exceed +1 m by 2100 only if the Antarctica ice sheets melts quicker than estimated. Hence, recent results regarding the future melting of Antarctica can be used to define an envelope of the upper tails of global sea-level rise distributions compliant with the IPCC. Studies anticipating contributions from the Antarctic ice-sheet in the order of a few 10 cm imply that the sum of all components of global sea-level rise will not exceed 1.5 m by 2100. However, two recent studies in table 2 suggest that higher values are possible (Hansen *et al* 2016, De Conto and Polar 2016).

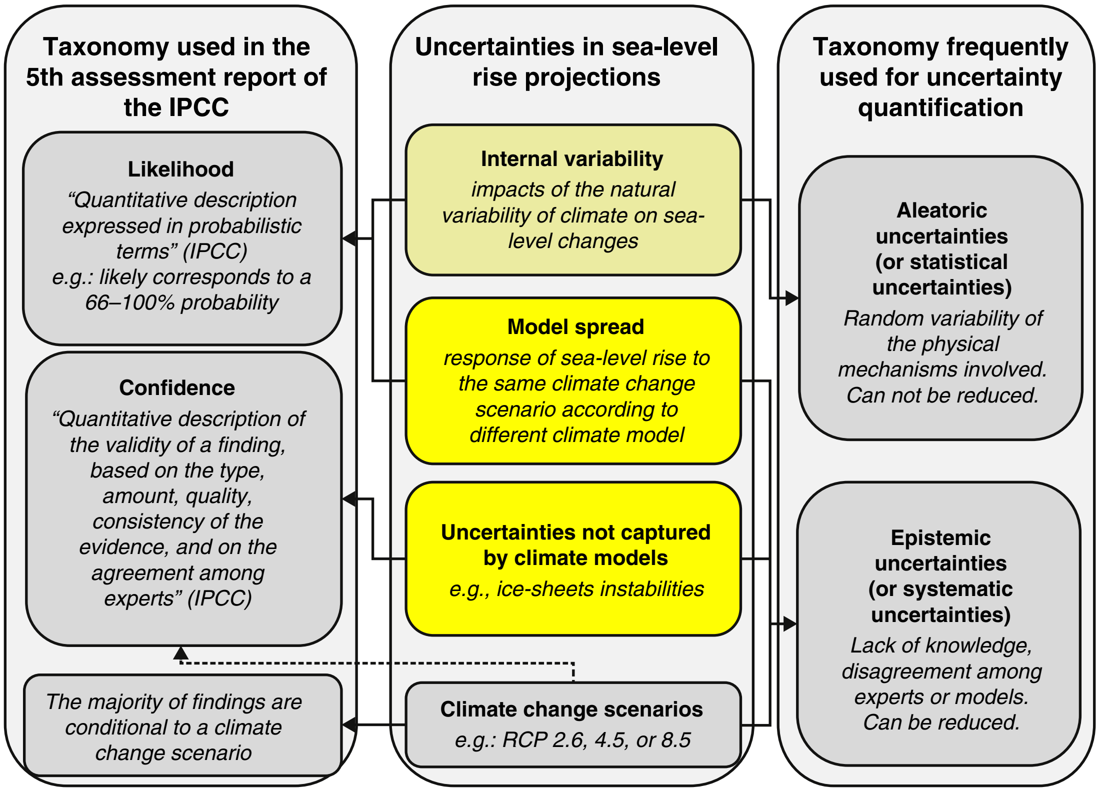

Figure 1. Description of uncertainties affecting sea-level rise projections according to two taxonomies frequently used in the climate and extra-probabilistic science communities (after: Mastrandrea *et al* 2010, Van Asselt and Rotmans 2002, De Vries *et al* 2014). This contribution focuses on the case of sea-level rise by 2100, and is therefore mostly concerned with epistemic uncertainties shown in the yellow boxes. Note that by 2100, the internal variability is supposed to have less impacts to uncertainties in sea-level projections (De Vries *et al* 2014).

Table 1. Published upper limits for global sea-level rise by 2100 with respect to a 1986–2005 average. Note that a correction of 1.4 mm must be applied to the data of Kopp *et al* (2014) as they are provided with respect to 2000. Note that for three studies below, ice-sheets melting projections are based on the same expert elicitation exercise of Bamber and Aspinall (2013).

Source	Upper limit for sea-level rise by 2100 for the RCP 8.5 scenario	Approach
IPCC 2013	A few 10 cm above 1 m (medium confidence). No precise value is provided (Church *et al* 2013).	Process-based models and full assessment of the scientific literature
Kopp *et al* 2014	1.77 m (99.5% quantile); 2.46 m (99.9% quantile)	Statistical combination of model outcomes with the expert judgment of Bamber and Aspinall (2013)
Horton *et al* 2014	Values provided for the 95th percentile: 1.5 m (median); 1 m to 2 m (50% of respondent); 5 individual responses exceed 3 m.	Survey of 90 experts in sea-level science
Jevrejeva *et al* 2014	1.8 m (95% quantile)	Statistical combination of model outcomes and the expert judgment of Bamber and Aspinall (2013)
Jackson and Jevrejeva 2016	1.67 m (95% quantile); 2.22 m (99% quantile)	Statistical combination of model outcomes and the expert judgment of Bamber and Aspinall (2013)

We use this existing piece of literature as follows: in accordance with the IPCC calibrated language, we consider the 'likely range' (i.e. 0.52 m to 0.98 m by 2100) as a confidence interval with a 66% degree of confidence, so that the probability of falling within this interval ranges from 0.66 to 1 (table 1 in Mastrandrea *et al* 2010). The complementary studies in tables 1 and 2 allow inferring a plausible support (minimum and maximum values) for sea-level rise by 2100 under the RCP 8.5 scenario. For such high greenhouse gas emission scenarios, a slowdown of sea-level rise rates is unconceivable, so that the minimum value of future sea-level projections can be derived from linear extrapolations of the current rates of 3.4 mm yr^{-1} (Cazenave *et al* 2014). Conversely, tables 1 and 2 show that there is a high level of disagreement among studies and experts regarding the physical upper limit to sea-level rise. The review above shows that 3 different maximum values can be considered (1.5 m, 2 m or 5 m). However, these maximum values cannot be considered equally. Referring to the IPCC terminology, we note that a 'medium degree of agreement' exists for maximum values of 1.5 m or 2 m, whereas a maximum value of 5 m is characterized by a 'low

Table 2. Contribution of Antarctica to future sea-level by 2100 under the RCP 8.5 climate change scenario, according to studies published since 2013.

Source	Antarctic ice-sheet contribution by 2100 for the RCP 8.5 scenario, unless otherwise specified	Approach
Ritz *et al* 2015	30 cm (95% quantile), maximum possible value: 50 cm	Statistical physical approach
Bamber and Aspinall 2013	84 cm (Greenland and Antarctic ice sheets) Based on a best estimate of global temperature rise of 3.5 °C to 3.7 °C in average	Experts jugement
Hansen *et al* 2016	Multi-meter sea-level rise within the coming 50–150 years	Exponential response of ice-sheets melting to regional warming
Golledge *et al* 2015	0.39 m for simulations incorporating grounding-line retreat	Physical approach
Little *et al* 2013	13 cm (95th percentile)	Bayesian approach combining modeling results, expert judgment, and observations.
Levermann *et al* 2014	Dynamic Antarctic discharge estimated at 0.21 m (95% quantile)	Linear response of ice-sheets melting to regional warming
DeConto and Pollard 2016	1 m or more	Physical approach, with additional dynamic processes included

degree of agreement'. Still, this latter value must be integrated in our analysis, because rejecting it would imply that we consider some of the studies and results above as invalid, including the questions raised by Hansen *et al* (2016) regarding the (non)-linearity assumed for the response of ice-sheets melting to regional warming.

3. Method: choice of the possibility theory and basic notions

The introductory section has mentioned several frameworks developed to explicitly account for imprecise and/or incomplete information. Among all these frameworks, the possibility theory (Dubois and Prade 1988) has the advantage of being able to integrate information provided in the form of (probabilistic) confidence intervals (Baudrit and Dubois 2006). The possibility theory has been applied in several domains, including seismic risks (Rohmer and Baudrit 2011), risk related to CO_2 geological storage (Loschetter *et al* 2016), environmental risk (Baudrit *et al* 2007), nuclear safety (Destercke and Chojnacki 2008), food engineering (Baudrit *et al* 2009), and metrology (Mauris 2013). Since information provided by the IPCC likely sea-level projections take the form of confidence intervals, the possibility theory appears particularly suited in the context of our contribution.

Within the possibility theory, the state of knowledge is represented through a so-called possibility distribution π ($\mathbb{R} \rightarrow \}[0, 1]$), which returns for each value x of a given variable X, the degree of possibility that X is equal to x. When $\pi(x) = 1$, the value x is considered as totally possible, when $\pi(x) = 0$ the value x is considered as impossible. Therefore, if experts can guarantee that X is comprised with certainty in a given interval $[a, b]$, the resulting possibility distribution will be equal to 1 on $[a, b]$ and to 0 elsewhere. However, more knowledge may indicate that X is not only included in $[a, b]$ with certainty, but also comprised in a nested interval $[c, d]$ with a degree of confidence λ. As a consequence, the probability that X falls within $[c, d]$ respects the inequality $\lambda \leq P(X\in[c, d]) \leq 1$ (table 1 in Mastrandrea *et al* 2010). Therefore, the following possibility distribution will be used to represent this imprecise information:

$$\pi(x) = \begin{cases} 0 \text{ if} x \notin [a, b] \\ 1 \text{ if} x \in [c, d] \\ 1 - \lambda \text{ if} x \in [a, c] \cup [d, b] \end{cases}$$

This simple example for one nested confidence interval is displayed on figure 2(*a*). The same process can be followed for more nested intervals associated to decreasing levels of confidence.

From such a distribution, two different measures can be derived for a given interval A: (1) the possibility of A $\Pi(A) = \sup_{x\in A}\pi(x)$ and (2) the necessity of A, $N(A) = 1 - \Pi(A^C)$, where A^C is the complement of A. These two measures are the bounds of the ill-known probability measure of A and reflect the uncertainty regarding this probability measure (Dubois and Prade 1992). Coming back to the simple example above, we can verify that $\Pi([c, d]) = 1$ and $N([c, d]) = \lambda$, and that the probability measure that $X \in [c, d]$ falls in between. Consequently, $\Pi(] - \infty, x])$ and $N(] - \infty, x])$, with $x \in \mathbb{R}$, can be respectively seen as upper and lower cumulative distribution functions (CDF) and form a probability box (referred to as 'p-box' in the following) that contains the ill-known CDF. This representation though less precise than the possibility distribution itself (the probability family induced by the possibility distribution is included in that induced by the p-box, see Baudrit and Dubois 2006) is a useful representation tool notably when dealing with risk evaluation issues (e.g. threshold violation checking or probability of exceedance). The p-box induced by the

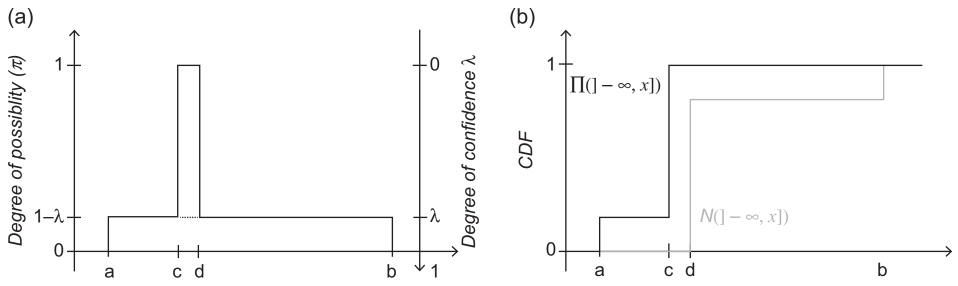

Figure 2. Example showing a possibilistic representation of confidence intervals information (*a*), and the probability box induced by this possibility distribution (*b*).

possibility distribution displayed on figure 2(*a*) is shown on figure 2(*b*).

Section 2 shows that different values have been published regarding the physical upper limit to the sea level rise by 2100. Nevertheless, they must be aggregated within the possibilistic framework, in order to get a synthetic picture of the uncertainty associated to conflicting projections. Here, a fusion rule adapted to redundant information is required, because the only disagreement relates to the three different maximum values for sea-level rise projections (1.5 m, 2 m and 5 m), while the minimum value and likely range value remain always the same. As other extra-probabilistic theories, the possibility theory is flexible regarding conflicting information fusion (Destercke *et al* 2009) and many aggregation operators have consequently been proposed in the literature (see e.g. Dubois *et al* 1999). In this study we use the weighted arithmetic mean operator, which is adapted when the sources of information are partially in conflict (Destercke 2008), and inputs are potentially correlated (Chebbah 2014). The weighted arithmetic rule of N different sources with associated weight w_i can be expressed as follows:

$$\pi_{\mathrm{wmean}}(x) = \frac{1}{\sum_{i=1..N} w_i} \sum_{i=1..N} w_i \pi_i(x)$$

In our study, we assign the following weights to each maximum value of sea-level rise by 2100: $w_{1.5\mathrm{m}} = 0.5$, $w_{2\mathrm{m}} = 0.4$, $w_{5\mathrm{m}} = 0.1$. By doing so, we define a ponderation, which reflects a lack of consensus in the scientific community regarding the maximum possible contribution of ice-sheets over the coming century. This assumption is further discussed in section 5.4.

4. Results: a possibilistic representation of sea-level rise by 2100 under the RCP 8.5 scenario

The two previous sections have shown how we use the principles of the theory of possibilities to provide a synthetic picture of the information provided in the AR5 and of the complementary scientific literature available (tables 1 and 2). Figure 3 displays the resulting possibilistic representation of sea-level rise by 2100 under the RCP 8.5 climate change scenario. Figure 3(*a*) shows the three possibility distributions $\pi_{1.5\mathrm{m}}$, $\pi_{2\mathrm{m}}$ and $\pi_{5\mathrm{m}}$, corresponding to the three different maximum values for sea-level rise by 2100. It also displays the π_{wmean} possibility distribution, which results from the fusion of those three distributions. If no physical limit to future sea-level rise was considered, the possibility distribution would extend to the infinite on the right hand side of figure 3(*a*). Importantly, figure 3(*a*) makes no assumption regarding the actual shape of probability density functions representing future sea-level rise, thus overcoming two important limitations of probabilistic frameworks, which either require to select a particular distribution (e.g. Gaussian or raised-cosine as in Hunter *et al* (2013); or Beta as in Le Cozannet *et al* 2015), or obtain a non-parametric probability function by summing specific probability functions representing each component of future sea-level rise (Kopp *et al* 2014).

Figure 3(*b*) presents the p-box induced by π_{wmean}, which contains the ill-known cumulative distribution functions representing future sea-level rise and consistent with the information reviewed in section 2. This p-box can be superimposed with probabilistic cumulative distribution functions used in previous studies to represent sea-level rise projections. The figure distinguishes four groups of probabilistic sea-level projections: (1) pre-AR5 sea-level projections (dashed lines), which were elaborated before the publication of the studies reviewed in section 2; (2) post AR4 assessments, based on semi-empirical models (Rahmstorf 2007, dotted purple line) (3) sea-level projections based on the AR5 (solid lines); (4) one post-AR5 assessment (dotted red line). To enable comparisons (see next section), all these projections have been referenced with respect to the average sea-level over the period 1986–2005, as in the AR5.

Coastal managers responsible for adapting to the adverse effects of sea-level rise will require possibilistic projections applicable locally. However, the local p-boxes can be substantially different from the global p-box presented in figure 3(*b*) (Slangen *et al* 2014, Kopp *et al* 2014, McInnes *et al* 2015). To design possibilitic sea-level projections applicable at local

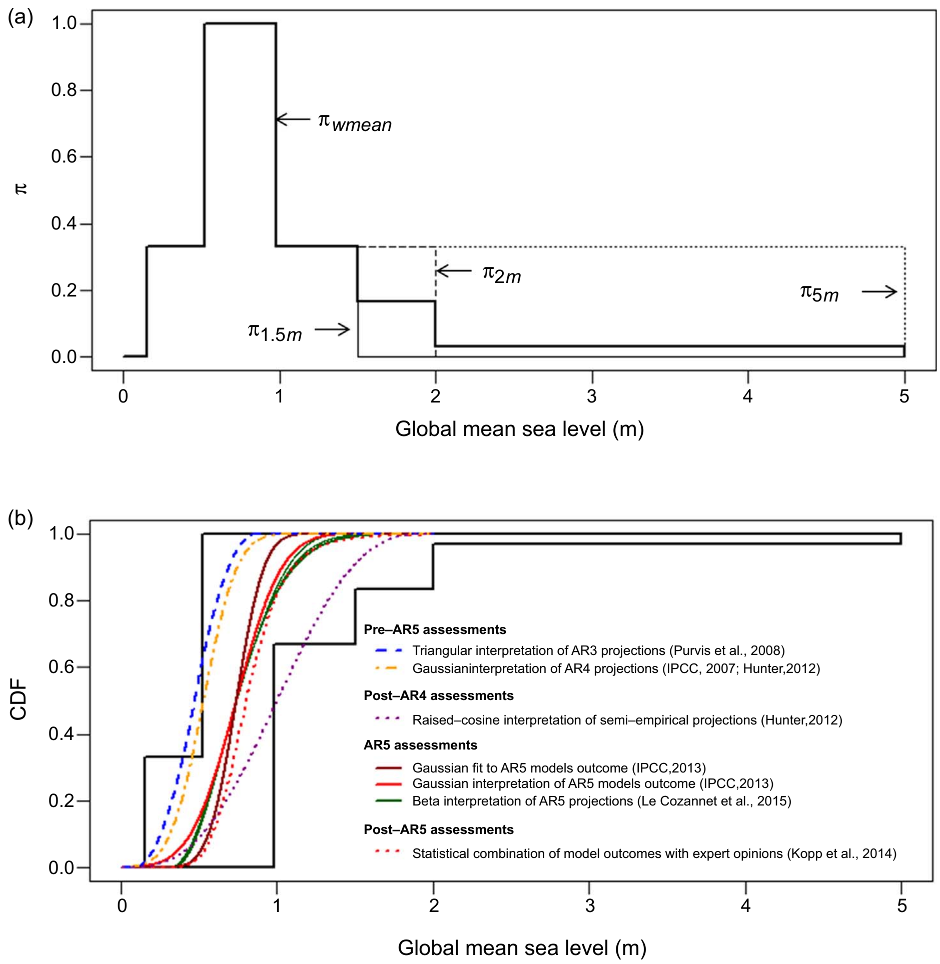

Figure 3. Possibilistic interpretation of sea-level rise projections by 2100 for the climate change scenario RCP 8.5. (*a*) Possibility distributions corresponding to the three assumptions regarding the maximum sea-level rise by 2100 (1.5 m, 2 m and 5 m; fine black lines respectively solid, dashed and dotted) and aggregated possibility distribution (dark black line). (*b*) Probability box (dark lines) induced by the aggregated possibility distribution compared with published probability functions used for coastal impact assessments (dashed lines: pre-AR5 assessments; solid lines: based on AR5; dotted lines: post AR4 and post AR5 assessments). All projections are provided with respect to 1986–2005, as in the IPCC AR5 report.

scales, coastal managers can combine local information on vertical ground motions (e.g. Santamaría-Gómez *et al* 2012, Wahl *et al* 2013, Raucoules *et al* 2013, Wöppelmann and Marcos 2015) with the regional likely range and upper bound of sea-level projections, published, for example, by IPCC (2013a) and Jackson and Jevrejeva (2016). Alternatively, they may apply the approach of section 3 to each component of sea-level rise, possibly taking advantage of an expert elicitation approach (see section 5.4). This will allow them to combine aleatoric and epistemic uncertainties of sea-level projections with those of coastal processes (e.g. frequency of storms, sedimentary processes, etc.), and, ultimately, to integrate them in their decision-making workflow (Haasnoot *et al* 2013, Ranger *et al* 2013).

5. Comparison with previously published probabilistic sea-level projections

In this section, we compare the p-box representation of sea-level rise presented in figure 3(*b*) with probabilistic sea-level rise projections used in previous coastal impact studies.

5.1 Probabilistic projections based on pre-AR5 assessments

Pre-AR5 assessments shown in figure 3(*b*) correspond to two important studies in the field of coastal impact of sea-level rise: Purvis *et al* (2008) showed that considering only mean or median sea-level rise projections leads to underestimating the mathematical expectation of damages. Similarly, Hunter (2012) showed that the mathematical expectation of the sea-level allowances (i.e. level by which coastal defenses must be raised to keep the same flooding probability) is underestimated if the uncertainties on sea-level rise is neglected. Figure 3(*b*) shows that these cumulative distribution functions are close to the possibility function Π (i.e. the upper bound of the probability box induced by the possibilistic representation of the AR5 data) but relatively distant from the necessity function N (i.e. the lower bound of the p-box). This can be attributed to differences in estimations of the ice sheet contributions to future

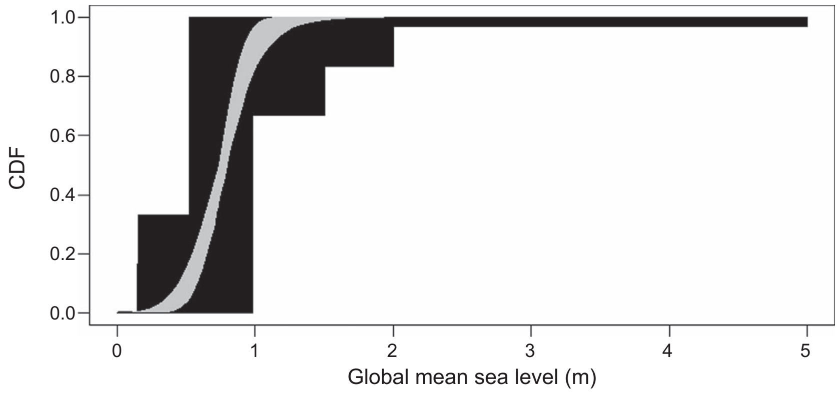

Figure 4. Area of possible values taken by cumulative probability density functions bounded by (1; gray area) three probabilistic projections compliant with the AR5 (Hunter *et al* 2013, Kopp *et al* 2014, Le Cozannet *et al* 2015); (2; dark and gray areas) the p-box obtained in this study (see figure 3).

Table 3. Possible values for the probabilities of exceeding global sea-level rise value thresholds allowed by: (1) the set of probabilistic projections bounded by AR5 compliant studies (Hunter *et al* 2013, Kopp *et al* 2014, Le Cozannet *et al* 2015); (2) the possibility distribution obtained in this study (see figure 3); (3) a similar possibility distribution obtained using a different set of weights ($w_{1.5m} = 0.8$, $w_{2m} = 0.19$, $w_{5m} = 0.01$; see section 5.4). Values below 10^{-6} are rounded to zero.

Global sea-level rise value threshold	0.5 m	1 m	1.5 m	2 m	3 m
Interval obtained from previous AR5 studies	[0.85; 0.97]	[0.031; 0.18]	[0; 0.013]	[0; 0.0026]	[0; 0.00033]
Interval obtained from the possibility distribution provided in this study	[0.67; 1.00]	[0; 0.33]	[0; 0.17]	[0; 0.033]	[0, 0.033]
Interval obtained from the possibility distribution provided in this study with an alternative set of weights	[0.67; 1.00]	[0; 0.33]	[0; 0.066]	[0; 0.0033]	[0.00, 0.0033]

sea-level rise, or in the interpretation of the spread of process-based models outcomes. In addition, these two cumulative distribution functions are based on greenhouse gas emissions underpinned by the scenario RCP 8.5 (Meinhausen *et al* 2011), which are not strictly comparable to the projections in the AR5 report.

5.2 Probabilistic projections based on semi-empirical models

Semi-empirical sea-level projections use macro-scale relationships between sea-level rise (or its components) and global mean surface temperature rise (Rahmstorf 2007, Vermeer and Rahmstorf 2009, Grinsted *et al* 2010, Rahmstorf *et al* 2012, Jevrejeva *et al* 2012, Perrette *et al* 2013, Hu *et al* 2013, Mengel *et al* 2016). Once fitted on historical data, semi-empirical models generally lead to sea-level projections slightly higher than the estimates from process-based models. Based on the synthesis of Nicholls *et al* (2011), Hunter (2012) represented uncertainties in semi-empirical projections available at that time using a raised-cosine distribution (purple dotted curve in figure 3(*b*)). Figure 3(*b*) shows that this distribution falls outside the boxes over a limited interval only, corresponding to sea-level rise values of 1 m to 1.2 m. Hence, considering the range of uncertainties allowed by the IPCC and other studies reviewed in section 2 finally leads to reducing the disagreement between IPCC results and semi-empirical models (as represented in Hunter 2012) to a small interval of 20 cm only.

5.3 AR5 and post-AR5 probabilistic projections

Figure 3(*b*) also displays distributions based on the IPCC AR5 report (IPCC 2013), as well as one post-AR5 curve (Kopp *et al* 2014), which is mostly based on similar assumptions: as a main difference, the tail of the distribution of ice-sheets melting used by Kopp *et al* (2014) is based on the expert survey published by Bamber and Aspinall (2013). All distributions based on AR5 and post AR5 assessment are fully integrated in the p-boxes shown in figure 3(*b*). Their likely range lies in the middle of the boxes, denoting a full consistence with our possibilistic interpretation of the IPCC projections.

Figure 4 identifies two representations of the imprecision in probabilistic sea-level rise projections by 2100 for the RCP 8.5 scenario: (1) the p-box induced by the possibility distribution obtained in section 4, which are based on the constraints provided by the IPCC and the studies reviewed in section 2; (2) the area of possible values covered by the set of probability distributions compliant with the AR5 used in previous coastal impact studies (gray area in figure 4): Hunter *et al* (2013), Kopp *et al* (2014) and Le Cozannet *et al* (2015). Figure 4 highlights the large domain, which has not yet been explored by coastal impact studies based on probabilistic sea-level projections. Table 3 provides more quantitative insights: for example, probabilistic sea-level projections compliant with the AR5 collectively indicate that one possible probabilistic interpretation provides an exceedance probability up to 0.26% for the 2 m sea-level rise value. Here, the possibility distribution highlights the doubt in this low value of 0.26%, and it underlines that the probability could actually vary between 0 and 3%. As previously outlined by De Vries and van de Wal (2015), such a gap appears more realistic than the precise value of 0.26%, because it directly depends on the knowledge underlying the construction of the uncertainty representations, and not on subjective choices such as a parametric probability density function (e.g. Beta or Gaussian). From these results and discussion, we suggest that possibility distributions are more realistic representation of the imprecise knowledge that characterizes uncertainties in sea-level rise projections.

5.4 Robustness of the outcomes

In this contribution, the final possibility distribution is obtained through an aggregation process using weights based on the representativeness of different sea-level projections available in the scientific literature (tables 1 and 2). These weights subjectively reflect a lack of consensus regarding the upper bound of sea-level rise by 2100, but we acknowledge that they are themselves uncertain. Other weighting schemes may consider a stronger consensus in favor of smaller upper bounds. However, even if w_{5m} is reduced to 1% and $w_{1.5m}$ is raised to 80%, the uncertainty interval obtained from the p-box remains larger than the uncertainty interval of previous AR5-compliant studies (table 3, last row). New expert elicitation could be conducted to update these weights. To this aim, two rigorous and robust approaches can be used:

- behavioral approaches, consisting of facilitating exchanges among experts to reach a single consensus (e.g. the Delphi method, Linstone and Turoff 1975), but are potentially subject to group biases (McBride *et al* 2012).
- mathematical approaches (e.g. Destercke and Chojnacki 2008), which remain sensitive to individual experts biases during elicitation (McBride *et al* 2012) and methodological choices during the aggregation process, so that a trade-off must finally be found between the consistency (i.e. the agreement with each experts' opinion) and the informativeness (i.e. the precision) of the outcome.

As long as our knowledge regarding ice-sheets melting remains incomplete, sea-level projections will require methods and research to combine expert opinions with modeling results (Bamber and Aspinall 2013, De Vries and van de Wal 2015, 2016, Bamber *et al* 2016, Oppenheimer *et al* 2016). In this context, our possibility-based approach can be considered an additional tool to trigger and structure the discussion among expert groups concerned with producing sea-level projections with their uncertainties.

Finally, once compared to the p-boxes shown in figure 3, the probabilistic sea-level projections used so-far appear either very cautious (case of projections based on the AR3, AR4 and AR5), or display small deviations only. However, our results are fully compliant with the sea-level projections provided by the IPCC for the RCP 8.5 scenario, and with the complementary studies listed in tables 1 and 2. As the latter complementary studies are used to further constrain the tail of the possibility distribution, the conclusion would be the same if they had not been considered.

This result has important implications for coastal impact studies using probabilistic sea-level projections: by disregarding probabilistic sea-level projections close to the necessity function N, high-impact scenarios are left aside. However, they are recognized important to consider in coastal management (Nicholls *et al* 2014, Hinkel *et al* 2015). Future work could assess to which extent neglecting the imprecision in probabilistic sea-level projections may increase the risk of maladaptation traps (Magnan *et al* 2016) in different types of coastal areas.

6. Conclusion

Recognizing that no single probability density function can represent the whole range of uncertainty sources related to future sea-level rise, this contribution provides a possibilistic interpretation of future global sea-level rise, which is compliant with the AR5 and more recent works concerned with the maximum contribution of ice-sheets melting. The results are presented in the form of an envelope of cumulative distributions functions, also called probability boxes (p-boxes). While the uncertainties of AR5 sea-level projections are provided in a format, which is essentially designed to communicate uncertainties efficiently, the probability box shown in figure 3(*b*) bounds all probability density functions compliant with the information available. The method presented here can be useful for communicating the epistemic uncertainties to users of probabilistic sea-level projections, such as coastal engineers, scientists and managers in charge of planning adaptation. It could also help structuring the debate among scientists involved in evaluating sea-level projections, especially when consensus and disagreements must be evaluated. Future work could focus on applying similar principles to regional components of sea-level changes.

These results illustrate that a single probability density function fails to represent the lack of knowledge on future sea-level rise. Instead, we show that many different probability density functions are consistent with the IPCC and the existing complementary information on ice-sheets melting. Hence, our results highlight that in the field of sea-level rise projections, overconfidence in a single probability density function leads to ignoring much of the epistemic uncertainties, which, however, are an essential part of the information that needs to be conveyed.

Previous studies have questioned the IPCC sea-level projections, suggesting they are underestimating future change (e.g. Rahmstorf 2007, Horton *et al* 2014, Hansen *et al* 2016). While our interpretation of future sea-level rise complies with the likely range of the IPCC, we find that probability density functions currently used for coastal impacts lie in the lower range of our possibilistic interpretation of the IPCC projections, or even below. This is suggestive of successive self-censorship of scientists concerned with future sea-level rise and their coastal impacts. We suggest that this has led to overoptimistic assessments of sea-level rise impacts in the published scientific literature.

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