Framework for high-end estimates of sea-level rise for stakeholder applications

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Abstract:

An approach to analyze high-end sea-level rise is presented to provide a conceptual framework for high-end estimates as a function of time scale, thereby linking robust sea-level science with stakeholder needs. Instead of developing and agreeing on a set of high-end sea-level rise numbers, or using an expert consultation, our effort is focused on the essential task of providing a generic conceptual framework for such discussions, and demonstrating its feasibility to address this problem. In contrast, information about high-end sea level rise projections was derived previously either from a likely range emerging from the highest view of emissions in the IPCC assessment (currently the RCP 8.5 scenario) or from independent ad-hoc studies and expert solicitations. Ideally users need high-end sea level information representing the upper tail of a single joint sea level frequency distribution, that considers all plausible yet unknown emission scenarios as well as involved physical mechanisms and natural variability of sea level, but this is not possible. In the absence of such information we propose a framework that would infer the required information from explicit conditional statements (lines of evidence) in combination with upper (plausible) physical bounds. This approach acknowledges the growing uncertainty in respective estimates with increasing time scale. It also allows consideration of the various levels of risk aversion of the diverse stakeholders who make coastal policy and adaptation decisions, whilst maintaining scientific rigor.

1 Introduction

Observed and expected sea-level rise is a prominent result of climate change with profound consequences for coastal societies, especially those on low-lying lands and islands (IPCC 2018). A dominant cause of future long-term sea-level rise is anthropogenic CO_2 emissions (Church et al. 2013), and the response of individual climate system components to the associated temperature increase, notably the thermal expansion of ocean water and mass loss from glaciers, and ice sheets, which add mass and volume to the ocean. Based on the output from climate models, sea-level rise scenarios have been produced with increasing sophistication since the 1980s. Recently, the fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC) provided a likely range of future sea level rise under various climate change scenarios (Church et al., 2013, Slangen et al. 2014), thereby accounting for expert judgment on the interpretation of the range of simulated model outputs. An overview of sea-level projection available during for 21st century is presented by Garner et al. (2018).

For a low-forcing scenario (RCP2.6), AR5 assessed that sea-level rise by 2100 relative to the period 1986–2005 will likely be in the range of 0.28 to 0.61 m. For a high emission RCP8.5 type forcing, the rise will *likely* be in the range 0.52 to 0.98 m. Within the IPCC nomenclature *likely* refers to a probability exceeding 66% (Mastrandrea et al. 2010); at the same time the *likely range* is also used for the interval 17%-83% of a not necessarily symmetric probability density function (pdf). Therefore the *likely range* does not explicitly consider the tails of the distribution or describes any asymmetry in these tails, information that is essential for risk adverse stakeholders interested in the high-end tails of the distribution. Hence, information about the *likely* range of global mean sea level (GMSL) is insufficient to plan the full range of coastal adaptation responses (Hinkel et al., 2019).

The only guidance that the AR5 gave for high-end scenarios at the end of the 21st century was that there was medium confidence that any additional contribution, beyond the likely range, would not exceed several tenths of a meter during the 21st century, leaving room for user interpretation. This was based on the understanding that only the collapse of marine-based sectors of the Antarctic ice sheet, if initiated, could cause global mean sea level to rise substantially above the *likely* range during the 21st century. In this context marine ice sheet instability was considered to be the key process; however, there was insufficient knowledge to be more specific and to explicitly and reliably estimate possible magnitudes, because data records were scarce and too short and the physical understanding of grounding line retreat was incomplete.

At the time of writing the AR5, it was concluded that there was insufficient evidence in the published literature to describe the shape of the tail of the probability distribution. This reflects the high uncertainty in all sea-level components and future emissions, and thus the magnitude of sea level rise through the 21st century, both globally and regionally. The lack of detailed knowledge about future emissions and our limited understanding of physical processes controlling Antarctic ice sheet dynamics are the biggest uncertainties, particular for long-term projections of sea-level rise. Hence, estimates of high-end sea-level rise become increasingly uncertain further into the future.

Despite the difficulties to specify high-end sea level rise from a physical modeling perspective, stakeholders have a strong desire for information about the high-end sea level rise tails of the distribution outside the specified likely IPCC range (Hinkel et al., 2015; Cozannet et al., 2017b; Hinkel et al., 2019). In addition, many stakeholders and decision makers have a strong need for regional to local relative sea-level (RSL) information, including vertical land movement. This information allows analysis of the consequences across the range of sea-level rise and responses, including issues of timing (Haasnoot et al. 2019b). Along most coastlines, local sea-level changes can differ significantly by up to 20% or more from the global mean change, and, together with long-period tidal effects, this can greatly increase the frequency of a given extreme water level event by a factor of 100 or more with 50 cm of sea-level rise (Church et al., 2013).

Where sufficient data is available, best estimates of *likely* ranges of regional to local sea level information can be provided (Carson et al., 2016). However, in most instances, information on more severe – high-end – sea level scenarios is important to planners as it frames the greatest risk, largest damages and highest prospective costs in planning adaptation. Hence, there is a significant demand for a curated “worst-case” scenario of sea-level rise for planning purposes and investment decisions, even if such a requirement is difficult to define from a rigorous scientific perspective in terms of amplitudes and probabilities.

Since the AR5 was published new information emerged from evolving science about high-end sea-level rise. However, at the same time new questions arose about whether and how decision makers and engineers might incorporate new, but controversial, science results into their adaptation planning which generally rely on actionable science representing a broad consensus and not simply the latest science (Vogel et al., 2016). Anthropogenic subsidence constitutes another source to RSL with major potential impacts. For sedimentary lowlands such as deltas, this can sometimes be larger than the climate driven RSL rise (Tessler et al., 2018), and in some coastal cities practicing groundwater withdrawal such as Jakarta, local subsidence rates can be more than 10 times current climate-induced RSL (Nicholls, 2018).

Transparency is critical in communicating information about high-end estimates to a wider audience, suggesting the need for a framework providing a rationale for linking high-end estimates of sea-level rise to various types of stakeholder decisions and applications. However, a solid conceptual framework that links sea-level science with stakeholder needs and which is an essential step to provide guidance for stakeholders is lacking. As the meaning of high-end scenarios depend on the risk aversion of stakeholders, an ongoing dialogue between stakeholders and the scientific community is critical to define the needs and develop together appropriate solutions that are scientifically rigorous: i.e. co-production is critical (Vogel et al., 2016; Hall et al., 2019).

Building on multiple existing and sometimes controversial concepts of high-end sea-level changes, definitions and terminology, including probabilistic approaches and upper bound concepts (Table 1), the goal of this paper is to develop a framework and a common language for future high-end estimates of sea-level rise that is useful for stakeholder application. Instead of developing and agreeing on a set of high-end sea-level rise numbers, or using an expert consultation, our effort is focused on providing a generic conceptual framework for such discussions, and demonstrating its feasibility to address this problem. We also consider the implications of high-end estimates on a variety of time scales, from a few decades to the end of the century and beyond. We hope that results framed in such a way will constructively contribute to the debate on high-end sea-level rise by leading to less ambiguous and more robust messages for the science and stakeholder communities alike.

2 User needs for high-end sea level information?

A range of user needs for sea-level rise information can be defined, including high-end scenarios for robust decision-making (Hinkel et al., 2019). For example, long-term planning of flood defenses for London and the Netherlands triggered early work on this question (Lowe et al., 2009; Katsman et al., 2011), while more recently the implications of uncertainty in high-end scenarios of sea-level rise for adaptation in the Port of Los Angeles were considered by Sriver et al. (2018). More generally, there are other possible high-end needs such as: (1) urban planners considering zoning, urban capital improvement plans, and their tax base; (2) city engineers considering the performance and reliability of water supply, wastewater, and storm water management systems, shoreline erosion protection, and flood risk reduction measures; (3) the private sector considering the viability of facilities and supply chains in the near, mid-term, and far future in order to plan capital investments; and (4) changing ecosystems and ecosystem goods and services. All of these users are interested in diverse ranges of impacts and varying adaptation measures, and as a result will have diverse requirements in terms of sea-level rise information.

The constituency of those concerned with coastal adaptation has broadened with time as societal awareness of the threat grew. Today, there is a large set of potential adaptation users with diverse needs (Le Cozannet et al. 2017a; Hinkel et al. 2019). Some adaptation planners consider timescales far into the future due to asset life cycles of 100 years or more (e.g., water and wastewater systems) and for high impact events (e.g., London's and the Netherlands' flood defenses or for coastal nuclear power stations where safety is paramount ;Wilby et al., 2011; Ranger et al., 2013).

Beyond impacting individual infrastructure life-times, these decisions have important implications far beyond the current century in terms of patterns of land use and settlement. However, there are many other adaptation decisions that are shorter term and more easily adjusted over time, such as immediate sand nourishment requirements (Hanson et al., 2002), which are updated on a 10/20-year cycle and hence might use sea-level and erosion observations rather than projections.

The longer the time span, the greater the need for an understanding of the range of possible sea-level rise, and its implications for impacts and adaptation decision making. The emissions scenario is another key variable and to date higher emission scenarios have generally been considered, taking a precautionary route, especially for longer-term decisions. Whilst these are designed using integrated assessment models and projections of future population and GDP up to 2100, beyond 2100 emissions scenarios are typically idealized, for instance continuing 2100 emission levels further into the future or reducing emission levels over an arbitrary time frame (O'Neill et al., 2016).

Further requirements for high-end sea-level rise information comes from those concerned with mitigation. Decisions addressing the ultimate objective of the United Nations Framework Convention on Climate Change (UNFCC), to "prevent dangerous anthropogenic interference with the climate system" (Article 2), require global scale information as well as local or regional scale information, as in adaptation. For mitigation, contrasting different emission pathways is at the core of the analysis. However, for all scenarios, even if we meet the objective of the Paris Agreement to stabilize emissions to meet a climate warming level that is "well below 2°C above pre-industrial levels" (Article 2), there is need for knowledge of the upper end sea-level rise under these conditions as impacts, while reduced, are still expected to require adaptation under all current scenarios. Further sea-level rise is expected to continue beyond 2100 for centuries threatening growing impacts and adaptation needs (Nicholls and Lowe, 2004).

Whilst the literature is beginning to systematically report about the sea-level information needs of some users and the challenges in satisfying them (Le Cozannet et al., 2017a;

Hinkel et al., 2019), this should not be considered a full catalogue. Instead, many needs arise in the practitioner community, often on a local scale, and may not be reported or assessed in the scientific literature. Thus, our assessment of needs in this paper considers both the literature and the wider practical experience of the author team, who has worked on a wide variety of coastal adaptation projects at all scales. Increasingly adaptation planners are also asked to go beyond local considerations or standard cost-benefit analysis and also consider regional to national preferences or other approaches to investment decisions, including recognition of deep uncertainty (e.g., Hallegatte et al., 2012; Aerts et al., 2014, Haasnoot et al., 2019b). Furthermore, information is also needed at the global scale from the mitigation standpoint to understand potential benefits of emission reduction policies in the context of reduced sea-level rise and associated impacts and adaptation needs.

Thus, we recognize that the users of sea-level rise projection information include a wide range of global to local stakeholders concerned with social, economic, environmental and risk prevention policies applicable in coastal areas. Among these users, those requiring high-end scenarios are primarily those recognizing that their management decisions may lead to maladaptation traps (Magnan et al., 2017) above a certain amount of sea-level rise or sea-level rise rates. For example there is a need to move beyond present approaches, such as those used in a disaster risk management approach, which typically assume stationary hazard statistics, towards methods that take account of a changing climate. This includes the iterative approach to risk management promoted by the IPCC (Jones et al., 2014) that acknowledges the climate is changing and we need to consider not just changing hazard but also changing exposure and vulnerability through a risk management lens (Figure 1). Without adaptation, sea-level rise increases flood frequency and reduces time for recovery, challenging to local capacities to maintain acceptable safety standards and appropriate expectations of economic damages. Here, high-end scenarios can be useful to estimate if and when the resilience capacity of each community could be exceeded and what choices this raises in terms of adaptation (advance, protect, accommodate, retreat) (Nicholls, 2018, Haasnoot et al., 2019a).

The most obvious needs for high end scenarios emerge from stakeholders with high risk aversion (Nicholls et al., 2014; Hinkel et al., 2015; Hinkel et al., 2019), that is, from managers of critical infrastructures such as ports, chemical industries or nuclear plants (Wilby et al., 2011) or highly exposed and/or vulnerable settlements such as urbanized estuaries and coasts or low-lying atolls (Ranger et al., 2013, Nurse et al., 2013). The number of potential users of high-end scenarios is probably much larger than previously thought for the following reasons:

1. Adaptation decisions are not independent and raise questions about the needs, adaptive capacity, and degree of risk aversion of neighbors (cf. Nicholls et al., 2013).
2. There is a lack of empirical literature that has elicited and documented risk preferences of coastal users in different social, economic, cultural and ethical contexts (Hinkel et al., 2019), as has been done in some other fields, such as occupational health and safety (e.g., Tchiehe and Gauthier, 2005),
3. Many users do not initially formulate their requirements in a precise way: their need for high-end scenarios only becomes apparent in the process of adaptation as they question storylines involving sea level changes above the likely range and those which exceed their adaptive capacity.

As a consequence, there are many potential users of high-end sea level rise scenarios with a diverse set of needs and concerns. Further empirical research is needed to map them and, ultimately, involve them in the design of appropriate sea-level high-end products. Ongoing developments on climate services for adaptation may support this process (Hewitt et al., 2012; Brasseur and Gallardo, 2016; Le Cozannet et al., 2017a; Vogel et al., 2016).

3 Why is consensus on high-end scenarios difficult to achieve?

Despite the need for high-end scenarios and various attempts at producing these, there is no consensus in the current sea-level literature on high-end sea-level rise scenarios and the methods to be applied to produce them. To understand why there is a lack of consensus, we must first recognize that there are several sources of information about potential high-end scenarios, together with different approaches to aggregating, integrating, and translating this information into actionable science.

As one possible source of information on high-end sea-level rise, we can use evidence from past interglacial periods in the geologic record that experienced warmer polar temperatures and higher global mean sea-level (GMSL) than present today (Dutton et al., 2015). Specifically, the Mid-Pliocene Warm Period (MPWP; ~3.2 to 3.0 million years ago) and the Marine isotope stage 5e (MIS 5e; 129,000-116,000 years ago; the Eemian) both offer useful analogues to the future: sea level was much higher during these warmer periods than today, whereas global mean temperatures where not very different from present-day.

Although the MPWP had radiation conditions more comparable to present-day than MIS 5e conditions, reconstructions from sea-level proxies remain highly challenging (Raymo et al., 2011). In contrast, the MIS 5e peak sea level appears better constrained in the range of 6-9 m above present levels (Kopp et al. 2009). However, the accuracy of the associated polar and local temperature change during that period remains problematic (Otto-Bliesner et al., 2013, Dahl-Jensen et al., 2013, Landais et al. (2016). Also, the associated uncertainty in the mass balance formulation (Helsen et al. 2013) and the role of basal melting in Antarctica, possibly implies that ice sheets are more vulnerable for modest changes, though the physics are poorly understood. It is therefore unclear whether results are applicable for present-day and near future conditions (Horton et al., 2019). So, despite the importance of continued studies on past sea level variations, we can conclude that at present these data alone do not provide enough constraints on high-end centennial sea-level rise for CO_2-driven changes in future.

Another aspect of the problem of estimating high-end sea level projections arises from our limited physical understanding. Several physical processes have been suggested to play a role in the rapid decay of ice sheets in a warmer climate. If the ice is in contact with the ocean, basal melt rates are controlled by water temperature, salinity and flow. Measurements of basal melt rates are logistically challenging and only limited data exists, so even the geometrical conditions of the cavities around the ice sheet are poorly known. Nevertheless, observations suggest that retreat rates are highest in areas where the ice is in contact with the ocean (Rignot et al. 2013, Joughin et al. 2014).

Whether these enhanced melt rates are driven by variability in the ocean temperature or long-term trends cannot yet be deciphered given the limited data and length of the observational record with respect to the time scales of ocean variability and ice sheet response, (Jenkins et al. 2018). Moreover, it is unclear how the ice dynamics respond to a changing basal melt rate. If the ice is resting on a reversed bedrock, enhanced basal melt rates may trigger an instability mechanism, known as the “Marine Ice Sheet Instability” (MISI) (Weertman 1974).

Since the ice flow in these regions depends on the ice thickness (Schoof, 2007), a retreating ice sheet will increase the ice flux to the ocean via a positive feedback. The rate of retreat and the possibility of halting the process depends on local conditions. Pinning-points and shear stress along the margins (Gudmundsson et al., 2012) may counterbalance the increased mass flux and stabilize the ice sheet. At the same time, recent observations in West Antarctica suggest that MISI retreat is already occurring in major outlet systems like Pine Island and Thwaites glacier (e.g. Mouginot et al. 2014). A complete retreat of these basins could result in several meters of sea-level rise due to their large ice volumes. Hence, they are critical for assessing high-end sea level projections.

The rate of retreat of the grounding line and the details of modeling MISI are still debated (Pattyn et al., 2012, 2018). This leads to a wide range of estimates of the ice sheet contribution to sea level, where a modest grounding line retreat formulation yields 0.1 m in

2100 under RCP8.5 (i.e., low SLR contribution), whereas a more aggressive formulation with melt beyond the grounding line yields 0.39 m in 2100 (Golledge et al., 2015) (i.e., high SLR contribution). Levermann et al. (2014) estimates for the same scenario 0.09 m based on a linear response theory including a time delay between oceanic subsurface temperatures and atmosphere temperatures and 0.15 m assuming no time delay. Alternative guidance can be derived from the current observations in those basins as explored by an ice dynamical study by Ritz et al. (2015) for the A1B scenario.

Beside basal melt rates, ice shelves can be destabilized by a combination of increased surface melt initiated by warmer surface temperatures in combination with hydrofracturing whereby the water penetrates into the shelves and leads to a rapid disintegration. Examples of this combined processes have been observed at Larsen A, B, and C which disintegrated in the late 20^{th}/early 21^{st} century (e.g. Rott et al. 1996, Rack et al. 2004). Once the shelves are removed, MISI can occur in some regions, leading to rapid retreat and ice loss. Whether and when hydrofracturing becomes important is strongly dependent on the surface conditions. Trusel et al. (2015) suggested that, for the majority of ice shelves, melt rates are too small to generate enough surface melt before the end of the century under RCP4.5 conditions, but that for RCP8.5 conditions a few ice shelves approach or exceed the necessary threshold. However, over longer time scales and higher temperatures, large scale hydrofracturing might be initiated. Once ice shelves disappear, ice cliffs may form at some locations. These cliffs have a narrow range for which they are stable (Bassis et al. 2012) and might lead to a large ice dynamical contribution from Antarctica (Deconto and Pollard 2016).

Application of DeConto and Pollard (2016), in combination with other processes that contribute to sea level rise, provides the basis of many recent probabilistic sea-level rise estimates with high values for the upper end of the probability distribution function (e.g. LeBars et al. 2017, Kopp et al. 2017). The estimates of DeConto and Pollard (2016), based on unusually high surface melt rates combined with hydrofracturing and ice cliff instability, lead to a sea-level rise which is considerably higher than all other ice sheet models and this is currently heavily disputed (Edwards et al. 2019). Including ice cliff failure in models is currently problematic as there are hardly any observational constraints and as a consequence retreat rates of cliffs are highly uncertain. Geological data provide limited support (Wise et al. 2017) and retreat rates of ice cliffs in narrow fjords in Greenland may not be representative for the wide basins in the Antarctic like the Thwaites glacier.

Nevertheless, the study by DeConto and Pollard pointed to a potential mechanism of significant and rapid retreat of Antarctic ice masses. Its validity is currently debated in the community and statistical emulators question the need of the use of ice cliff instability to explain the observational constraints (Edwards et al. 2019). Hence, sea-level projections outside the IPCC AR5 *likely* range derived from a mechanistic process-based approach remain impossible before a better understanding is developed of the key processes controlling the large uncertainties in ice sheet loss, these being (1) basal melt related to warming and/or changes in ocean circulation, (2) hydrofracturing related to warming surface conditions on Antarctic ice shelves, and (3) ice cliff instability. We also note that for time scales longer than a century, uncertainties in our process understanding increases significantly, further complicating the production of high-end sea-level scenarios.

In the absence of this detailed knowledge of the physical processes, quantified probabilistic approaches are being produced and are widely influencing decision-oriented documents today, including expert elicitation approaches (e.g., Bamber et al., 2013; 2019, Horton et al., 2014). This knowledge is being influential in coastal management in the USA and elsewhere (Hall et al., 2019; State of California 2018). However over confidence in expert elicitations, can imply greater precision in our understanding than is merited and require extensive interpretive guidance that can be missing (Behar et al 2017). In particular, issues associated with both identification of upper end tails for SLR and probabilistic characterization of those tails are currently playing out widely in the United States and elsewhere. As an example, projections relying substantially both on Kopp et al (2014) and DeConto and Pollard (2016) have multiplied in recent years. Many of these have been provided to local and state governments to guide vulnerability assessments and adaptation plans within insufficient guidance and dialogue about their meaning and possible interpretation (Hinkel et al., 2015; Zheng et al 2017).

Below we propose a more robust framework to analyze these problems and develop useful high-end sea-level scenarios that embraces user risk aversion and encourages debate and understanding by the users about uncertainties and level of confidence across all the available information on future sea levels.

4 Framework for high-end sea level scenarios

To improve how high-end sea level information is developed and communicated in support of decision-making, what is needed is an agreed conceptual framework, encompassing several alternative approaches of how information about the upper tail can be produced, analyzed, and integrated with observations and interpreted for the decision-making context. In this context we need to distinguish between five distinct components contributing to the generation of sea level information suitable for decision making: (1) future CO_2 emissions and other climatically active forcing, (2) the regional atmospheric and ocean temperature (and other climate parameters) response to those CO_2 emissions, (3) the sea level response to those CO_2 emissions and temperature changes, (4) the physics of the ice sheet contribution (in particular Antarctica), and (5) understanding stakeholders risk-averseness to sea-level rise for different purposes, ideally using a co-production approach where user can consider both the impacts and available adaptation options. These components combine natural and social science inputs to provide appropriate information for policy and decision analysis.

We illustrate this schematically in Fig. 2, which shows several alternative approaches to generating high-end sea-level rise information based on diverse conceptualizations of high-end sea level. Table 1 provides further information on each of the approaches following Walker et al. (2003), who describe a continuum of projected futures ranging from very well characterized to total ignorance. Until now these distinct conceptualizations of high-end sea level have not been significantly recognized in the scientific literature and in the media (van der Pol and Hinkel, 2019). However, they differ fundamentally in their meaning and implications and should not be confused with each other. Results from one certainly cannot be compared quantitatively to that from another, or combined. Below we discuss different ways of using this knowledge and propose a pragmatic approach, which makes the most of the available physical understanding.

A first possible approach is given by schematic sea-level rise frequency distributions representing CMIP5 RCP scenarios obtained from an ensemble of physics-based coupled climate models amended by off-line information about contributions from the cryosphere and the solid Earth. These are shown as black bell-shape-like curves. Typically, these distribution functions are truncated in their tails due to limited ensemble sizes or, related to the high-end tail, limited representation of physical processes involved, such as ice sheet dynamics. Nevertheless, they are being used to provide estimates of *likely* sea level ranges and the median values for various RCP scenarios.

A second possible approach is given by the blue envelope, which, contrary to the first approach combines the sea level results emerging from all possible, yet unknown emission scenarios (e.g. the CMIP5 RCP scenarios or a wider range of emission) into one single frequency distribution, but also to account for natural variability of sea level usually estimated by an ensemble of model solutions for each of those forcing functions (e.g., Deser et al., 2014, Hu and Deser, 2013). This approach requires providing probabilities for each of these individual CO_2 emission pathways to occur, a recently emerging field (e.g., Webster et al., 2002; Budescu et al., 2009). The utility of this approach has been debated in the climate change scientific community and is largely rejected as the blue curve would be highly sensitive to the likelihoods attached to individual emission scenarios (Lempert &

Schlesinger, 2001; Stirling, 2010). Nevertheless, coastal adaptation decision-making can proceed, and does so in practice, without having a single pdf available (Van der Pol and Hinkel, 2019). However, we note that the pdf will change shape over time, not just as we learn more about the physical system, but also as the options and preferences for future CO_2 emission pathways change.

Circumventing the present difficulty of constructing the blue curve, the most commonly used approach towards providing information on high-end sea-level rise is to provide a conditional statement about sea-level rise under a defined emission scenario. But even with the full probabilistic information for a specific emission scenario, model projections still omit the high-end tail of the projected distribution functions (green vertical line), reflecting our limited physical understanding, e.g., due to our lack of understanding of ice sheet dynamics, though the additional bands including the ice dynamics could be made dependent on the RCP scenario and time scale.

An alternative pragmatic approach, which we advocate, is to develop expert judgment views about the upper tail. This approach separates the range of possible sea-level outcomes exceeding the *likely* range into a series of sea-level rise intervals a few tens of cm wide (called 'bands' hereafter), building on the confidence definitions and lines of evidence adopted in the AR5 and more recent literature. Each band can be assessed for the lines of evidence that support a possible sea-level rise of the band's magnitude together with the respective confidence in this information. Such lines of evidence include physics-based models, palaeo-climate evidence, physical constraints, model sensitivity studies, and expert judgement interpretation of existing projections. Moving to increasingly higher bands, the evidence and agreement among experts for such a rise tends to decline, leading to a decline the confidence represented by the grey bands.

This approach recognizes that we might not have enough information to actually quantify the probability of the upper values. Instead we make more use of confidence. The band with the highest sea-level rise but lowest confidence could then serve as an upper bound estimate for specific practical planning purposes. However, users who are less risk-averse or have adaptive management flexibility that allows adaptation approaches to be revised over time may choose a lower band, or even stay within the RCP range noting the confidence in the highest values tends to be lower. This latter approach represents and builds on the evidence-base available to users. It helps users consider the evidence versus their risk aversion and hence where they might draw the high-end bound for their specific decision. This recognizes that different users have different risk tolerance and therefore different needs (Hinkel et al., 2019) and that the user appropriate high end estimates will differ between users.

Alternatively, one could start from a very high, but physically implausible number (right red band, mainly determined by the loss of all land-ice on Earth), and work downwards toward the smallest possible physically plausible range by examining tighter constraints, e.g., physical limiting arguments on the energy input of the system and/or on rates of change. While the former evidence-based approach is expected to be based on projection information, the latter approach is based on physical constraints on the system – such as the total amount of ice available or possibly the paleo evidence.

Either way, one ultimately would end with an estimate of a high-end range illustrated by the hatched gray area in Fig. 2. We also note that only some lines of evidence have likelihood statements. More often, however, this will not be the case because it is an extrapolation of a distribution trained on lower values. The gray and red ranges therefore will usually come only with confidence statements.

5 A practical path to consensus on a framework on high-end estimates

Despite all the existing scientific and practical difficulties in defining or estimating the high-end sea-level rise, stakeholders have a strong need for information on high-end or upper bound sea-level scenarios in support of coastal planning and adaptation, including the degree of consensus about this information. In the absence of any solid information, the void will be filled with extrapolations, assumptions or guesses, regardless of whether this is scientifically sensible or not. In addition, we have noticed a tendency for the highest of high-end projections to receive disproportionate coverage in print, television, and digital media, the most common source of information for decision makers. This information is often unaccompanied by presentation of the broader research context, key temporal considerations for adaptation planners, or explanation of caveats and limitations. In this context, a careful treatment of high-end sea-level rise, featuring clear criteria of value for adaptation planners, is needed.

Several recently published papers raised awareness on the possible processes contributing substantially to sea-level rise. These papers have raised much attention in the media where they are often treated as facts, whereas in reality they are only contributing single arguments or lines of evidence to an ongoing chain of a scientific debate, which is far from being resolved. All these studies are scenario independent and are unspecific on emissions. Moreover, relevant processes are highly uncertain, featuring limited observational support. Finally, being part of a scientific discourse, the papers usually are not intended and should not, on their own, be used to guide planning and certainly not adaptation investment. As such, they do not alone represent actionable science for decision makers, though as knowledge and observations evolve, they can first inform lines of evidence or physical limits in Figure 2, and as understanding grows more probabilistic approaches.

Because of the existing confusion about multiple perspectives on high-end scenarios (Fig. 2, and Table 1), there needs to be a reconciliation of which approach or combination of approaches is most relevant for what purpose and which provides the best scientific support to governments, coastal decision-makers, and the public. This requires reconciling the multiple perspectives by integrating the best scientific information and guidance to provide a consensus on actionable science that can be used by governments and coastal decision-makers depending on their needs. Such considerations and reconciliations need to consider the time-evolution of the system: a 10-50 year prediction (that also has to account for natural variability) is different from a 100 year projection (Hinkel et al. 2019) and quite different from a multi-century projection (Fig. 3). Within this framework, stakeholder's understanding of high-end scenarios and their relevance to different decisions can improve and become more sophisticated, including explicit identification of variable risk tolerance.

As an example, in the UK an H++ scenario range was used to assist in the analysis of the future of flood risk management for London for the next 100+ years (Lowe et al., 2009; Nicholls et al., 2014). Importantly, H++ was not linked to any probability but rather was considered more pragmatically as a plausible range of policy relevance by risk averse decision makers in the context of flexible adaptation and the mean sea-level component extended to about 2-m rise by 2100. It has been used in sensitivity testing of flood management options and has given confidence in the Thames Estuary 2100 project plans for London (Ranger et al., 2013). Further, H++ was applied to nuclear power station design on coasts (Wilby et al., 2011). Importantly, the H++ scenario regional upper bound, and the high-end probabilistic scenarios extend well beyond the global likely range reported in the IPCC AR5 report, since, as explained above, the likely range does not specify an upper bound. As an example, the most recent thinking on updating H++ in the UK has been informed by user interaction through a process of co-development and acknowledges that a single H++ range based on current scientific knowledge might not represent the needs of multiple users. Instead, it may be more appropriate for users to follow the approach we described in section 4 of this paper and consider the confidence in the evidence for different levels of sea-level rise in the upper tail of plausible sea-level rise, relating it to their particular level of risk aversion. Users with different levels of risk aversion may choose alternative H++ upper bounds depending on their particular application, which is typically influenced by national standards and national regulators. Thus, the upper bound of sea-level rise considered for a user planning the development of a nuclear power station and a user proposing a farming development near the coast is almost certain to be quite different.

Katsman et al. (2011) produced a plausible high-end scenario for the Dutch Delta Commission for their adaptation program in 2100 and 2200. However, their method was very different to H++ as they summed the uncertainties in the components quadratically, producing a smaller rise (Le Bars, 2018), but moreover used current observed rates of dynamical ice mass loss as their starting point, essentially ruling out the possibility that new emerging dynamical processes like Marine Ice Cliff Instability will dominate the Antarctic contribution to 2100. The strength was the constraint posed by the observations of ice mass loss. The Katsman et al. (2011) approach provided a high-end estimate of about 1 m for 2100 and 3.5-m for 2200, emphasizing the major challenges low-lying coasts will face beyond 2100 without climate mitigation. This in itself points to the fact that high end projections cannot be viewed without a specification of the time scale. However, it needs to be recognized by (almost) all users that whatever the considered time frame, sea level will continue to rise well beyond the end of this time frame (Clark et al., 2016; Nicholls et al., 2018). This implies we could, instead, present results in such a way that uncertainties are being specified in terms of the time a specific rise in sea level occurs, be it 1m, 1.5m or 2m or any other user-relevant threshold. The implication for users of sea-level rise information is that we can express uncertainty as either a range of sea-level rise at a given year or we can present a sea-level threshold and represent uncertainty in the year at which that level might be reached. For some users who have an awareness of a vulnerability at a particular threshold of sea-level rise this approach would allow them to move beyond the issue of whether they will be affected, to one in which they can consider the time-scale over which they need to act. We recall that under present climate change conditions eventually sea level will rise many meters if no further mitigation actions come into effect. The only remaining open question then would be: when?

Rather than extrapolating observations or using highly parameterized physical processes it might be more helpful to characterize the tails of the sea-level projections either with explicit conditional statements (lines of evidence) together with upper (plausible) physical bounds, thereby acknowledging the increasing uncertainty with increasing range prohibiting a likelihood statement as discussed above in the context of Fig. 2. Such a consideration needs to be made as a function of time scale considered. In this context we need to consider that, regardless of the time scale considered, the largest source of uncertainty currently reside in the ice sheet contribution to sea level rise. Our building blocks for the bands of upper physical bounds are therefore different ice sheet related processes. According to their timescale they can migrate from being excluded to being included in the high-end estimate as lines of evidence multiply/are further developed.

Turning this into a practical recipe for future high-end sea level estimates, we show in Fig. 3, three time frames, each of which will have considerably different considerations for sea-level rise. Fig. 3a represents the near-term 10 – 50 year time frame over which the impact of different emission scenarios is small (see also Hu and Bates, 2018), resulting in fairly similar likely ranges from low and high-end emission scenarios. On 10-50 year time scale the Greenland and Antarctic ice sheet contribution maybe larger than estimated (gray-blocks), but a collapse of the West-Antarctic ice sheet is not foreseen (red-block)

Turning to a 100-year time frame (Fig. 3b), these lines of evidence for higher numbers would involve (with increasing uncertainty) West-Antarctic ice mass loss, and an East-Antarctic collapse. In the opposite direction invoking physical plausibility, significant East-Antarctic ice loss would be the least likely contribution, while hydro-fracturing and instability would be the physically more plausible upper constraint.

Going beyond the centennial time-frame to 200 years or more, an RCP 2.6 type emission pathway would likely lead to a reduced rate of sea level rise, while a business as usual RCP 8.5 pathway would result in an increasing rate of rise to above and beyond levels reported for the end of the 21st century and would reach several meters of height over coming centuries. Lines of evidence for upper bounds would then involve hydro-fracturing and ice cliff instability and significant East Antarctic ice loss. Regarding plausibility limits, one would need paleo-evidence, most plausible would be orbit parameters that eventually can lead to glacial cycles.

In practice, considering all scenarios in a decision process is not always needed or required, implying that building a high-end scenario is combining a climate driven probability distribution of sea-level rise, conditional on a given high-end emission scenario (e.g. RCP 8.5 or higher), combined with one or more building blocks. Above all these simplifications, it still would be desirable to better know the shape of a sea level pdf given a specific emission scenario. Very likely it will be skewed positively towards large numbers for global averages (regionally this can be the opposite, especially along some coastal regions; see, e.g., Carson et al., 2015). There is no evidence, however, that the shape of the pdf will remain the same for all time scales. Instead it is anticipated that on the decadal time scale a more symmetric Gaussian-type distribution is plausible, given that much of the spread is caused by natural variability. With increasing time scale, however, more and more feedback processes would come into action, eventually possibly leading to significant asymmetries with very high upper tails, making use of this information for planning purposes increasingly more difficult. Most individual infrastructure decisions are 100 years or less in timescale, with notable exceptions such as nuclear power stations. However, there are longer-term implications of individual decisions on say the development of a city or protection of a delta, and resulting lock-in for adaptation decisions (e.g., Seijger et al., 2018). These are issues that need to be explored with the relevant stakeholders.

6 Implications and Concluding Remarks.

Building a shared framework about robust and scientifically sound high-end sea-level rise information is extremely important to better support coastal decision makers and stakeholders. This is especially true for risk-averse stakeholders who need this information to plan long-term coastal adaptation responses. Such information also bears important implications for mitigation targets as recognized in the recent IPCC special report on a 1.5°C global warming (Hoegh-Guldberg et al. 2018) quantifying the reduced risk in terms of sea-level rise for a 1.5°C warming as compared to a 2°C warming. Clearly this does not address the high-end sea-level rise projections which are associated more with RCP8.5 rather than the RCP2.6 scenario type of studies in SR1.5 (Hoegh-Guldberg et al. 2018).

To provide a robust consensus about high-end sea-level rise information, a solid and agreed conceptual framework is essential to provide a scientifically rigorous presentation of the information, which also allows the risk aversion of diverse users to be considered. Such a framework cannot be based simply on expert elicitation or on the latest studies. Instead it needs to be timeframe- and emission-scenario- specific, and it also needs to go beyond previous IPCC considerations on the likely range for sea-level rise projections and consider the nature of developing lines of evidence. It can be established by moving toward information about the upper tail of the underlying sea-level rise distribution function, considering all relevant physical mechanisms including natural climate variability, and also all possible emission scenarios. In addition, this framework should distinguish between widely accepted high end projections and those still considered experimental, and therefore not yet actionable, science. Finally, this framework needs to consider time scale.

As a step in this direction we proposed here to use available information about the upper tail of the sea-level rise through the combined use of explicit conditional statements (lines of evidence) with upper (plausible) physical bounds, thereby acknowledging the increasing uncertainty with increasing time scale. The limited knowledge implies that a likelihood statement is not possible.

Pursuing such an approach could link previous IPCC-based information with Coastal Climate Services by informing users as to how to translate IPCC global and regional information into local user requirements. To provide such sea-level related climate services and to help stakeholders using new emerging sea-level science results to maximum effectiveness calls for greater international co-operation and co-production (i.e., integrating science with user needs) to develop sea-level change climate services. Such an approach will help users to apply information about sea-level rise in practice, and will better inform the science community about these needs. The important role of social science research to better frame decision needs is also apparent and this effort must be truly interdisciplinary to succeed.

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Level of uncertainty considered (after Walker et al. 2003)	**Examples in the area of sea-level rise**	**Related approaches to select high-end sea-level scenario** (see section 3)	**Comment on existing high-end scenarios** (see section 3)
Determinism (assuming no uncertainties)	Single fixed sea level allowance, for use in design guidance and codes (e.g., French regulatory 60cm sea-level rise scenario for 2100 (MEDDTL, 2011), and port design guidance (Thoresen, 2014).	Not applicable: this approach neglects uncertainties in sea-level projections and therefore does not consider high-end change.	
Statistical uncertainties (can be adequately described in statistical terms)	Probabilistic sea-level predictions, independent from external assumptions such as RCP scenarios (see Figure 2). (note that there are no known example of such predictions in the current published literature (Hinkel et al., 2018)).	High-end scenarios based on the selection of thresholds in the upper tail of probabilistic sea-level prediction (e.g., 0.1%, 1%, 5%.) (e.g., see method in Jevrejeva et al., 2014).	The upper tail of the distributions are currently considered too poorly constrained to define precise high-end scenarios (Horton et al., 2018; Le Cozannet et al., 2017b). Existing probabilistic projections do not yet combine all RCP scenarios (see Figure 2).
Scenario uncertainties (depend on fundamental uncertainties external to the system considered, such as human policies and environmental changes)	Alternative futures described by probabilistic projection and conditioned to RCP scenarios (e.g., Kopp et al., 2014; Jackson and Jevrejeva, 2016; De Winter et al., 2017; Kopp et al., 2017; Garner et al., 2018).	High-end scenarios provided in a probabilistic form, and assuming high greenhouse gas emissions and ice contributions (Jackson and Jevrejeva, 2016; Le Bars et al., 2017) High-end scenarios based on the selection of thresholds in the upper tail of a probability distribution conditioned to RCP8.5 (e.g.,: Jevrejeva et al., 2014)	See above: probabilistic projections provide some basis to estimate the most likely scenarios but there is limited confidence in higher quantiles (Horton et al., 2018; Le Cozannet et al., 2017a). It is unsure that RCP8.5 is the most appropriate assumption for defining high-end scenarios applicable for coastal adaptation (e.g., Hinkel et al., 2018).
	Sea-level change scenarios exploring a limited number of greenhouse gas emissions and land ice contributions.	High-end scenarios provided as single values or intervals, based on the sum of the various sea-level contributions (NRC, 1987; Katsman et al., 2011).	Need for research in the area of ice-sheet melting modeling to better evaluate the *plausibility* of different ice-sheet melting mechanisms at various time horizons (see section 3).
Recognized ignorance (known unknowns)	Sea-level scenarios considering quantifications of lower and upper limits for future sea-level changes. Extra-probabilistic sea-level projections (e.g., likely range of Church et al., 2013) based on several different system models.	Scenarios beyond the likely range, but remaining within physical constraints (e.g., limits to land ice melting kinematics (Pfeffer et al., 2008) and/or assuming sustained or acceleration of ground subsidence (Wang et al., 1995). Scenarios considering diverse lines of evidences, eventually exceeding current estimates of physical constraints (e.g., H++ scenarios, Wilby et al., 2011; Ranger et al., 2013; Nicholls et al., 2014)	Need for research in the area of ice-sheet melting modeling to better evaluate the *maximum contributions* of ice-sheets mechanisms at various time horizons (see section 3).
Total ignorance (unknown unknowns)	Sea-level scenarios not considered possible today, but which could be considered possible in the future if new physical processes are discovered (e.g., 5-6m sea-level rise scenarios by 2100 considered in Keller et al. (2008) “in an adaptation “thought” experiment. Lack strong basis to explore this level of uncertainty in a systematic way (Walker et al., 2003)		

Table 1: Approaches to select high-end sea-level scenarios as a function of the level of uncertainty considered following the approach of Walker et al. (2013).

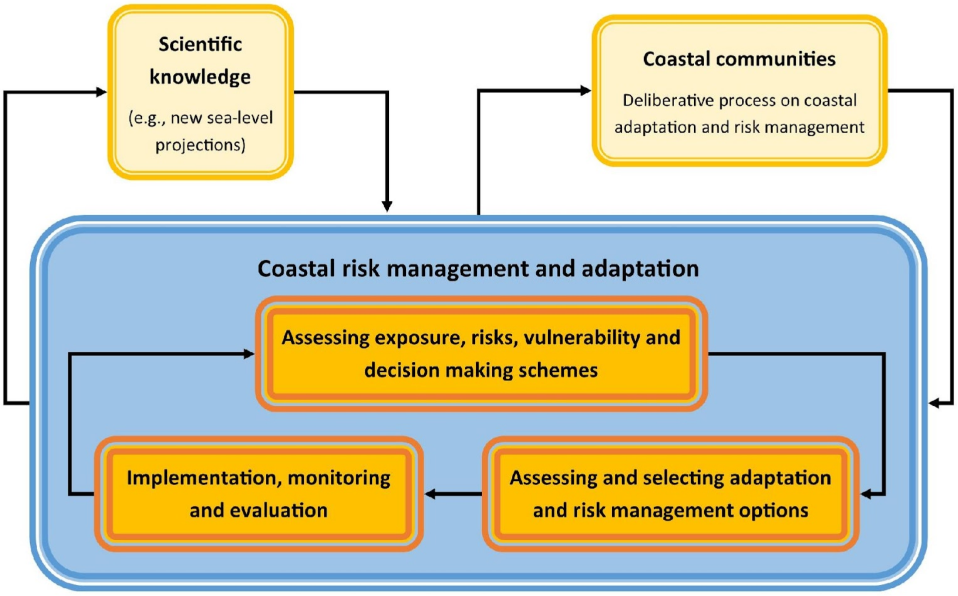


Figure 1: Schematic of an iterative coastal adaptation approach (Adapted from IPCC, 2013, Jones et al., 2014) which is an iterative process, which updates adaptation measures and strategies over time (see AR5 WG2 Ch2 https://www.ipcc.ch/site/assets/uploads/2018/02/WGIIAR5-Chap2_FINAL.pdf)

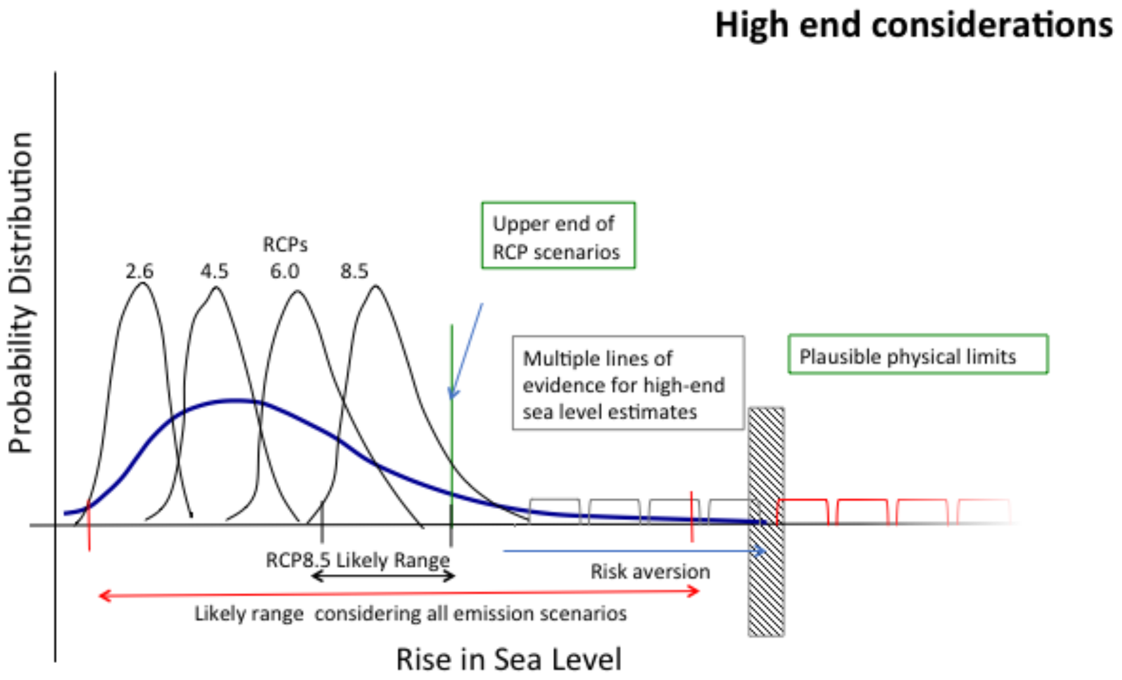
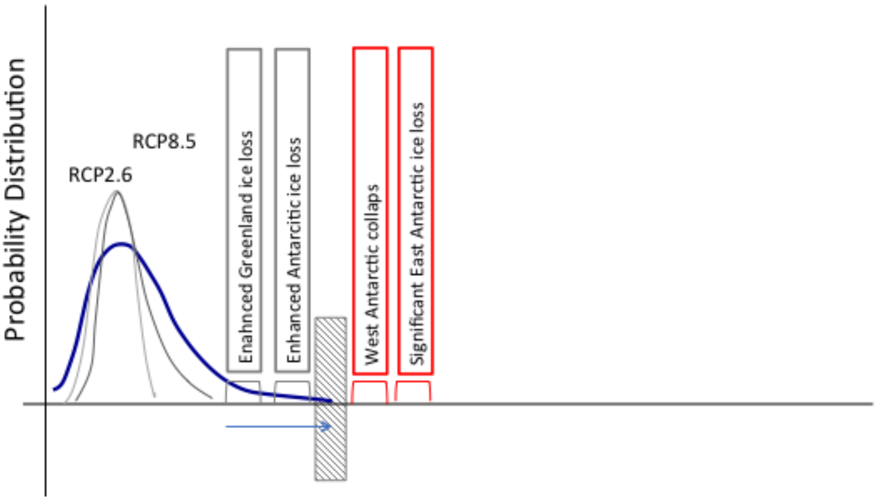


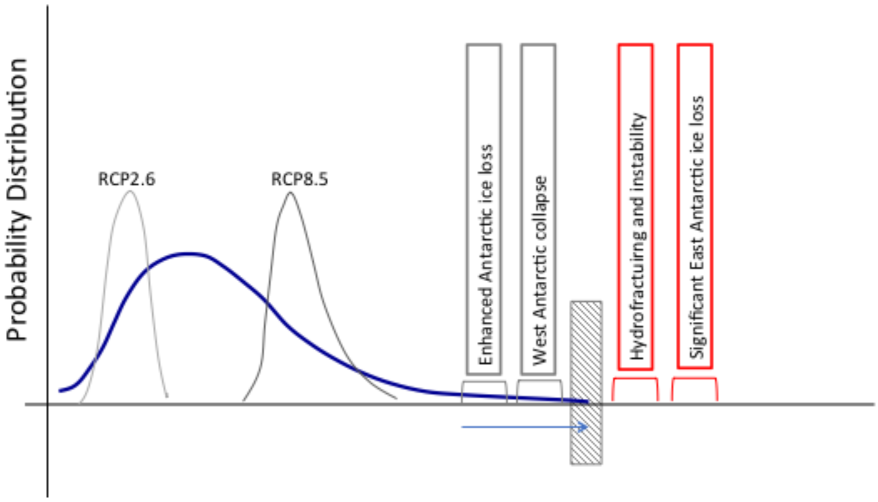
Figure 2: Multiple concepts of high-end sea-level. The x-axis is the amount of sea-level rise for a given time-interval. In the vertical the figure displays the probability density. The blue curve represents a combined pdf for all possible emission scenarios. The grey and red building blocks have to be added to the RCP curves depending on the risk aversion of the users. The hatched vertical bar represents the range in which the high-end is being expected to reside for a particular stakeholder. The distinction between gray and red building blocks is lines of evidence vs physical implausibility.

Time scale 10-50 yrs



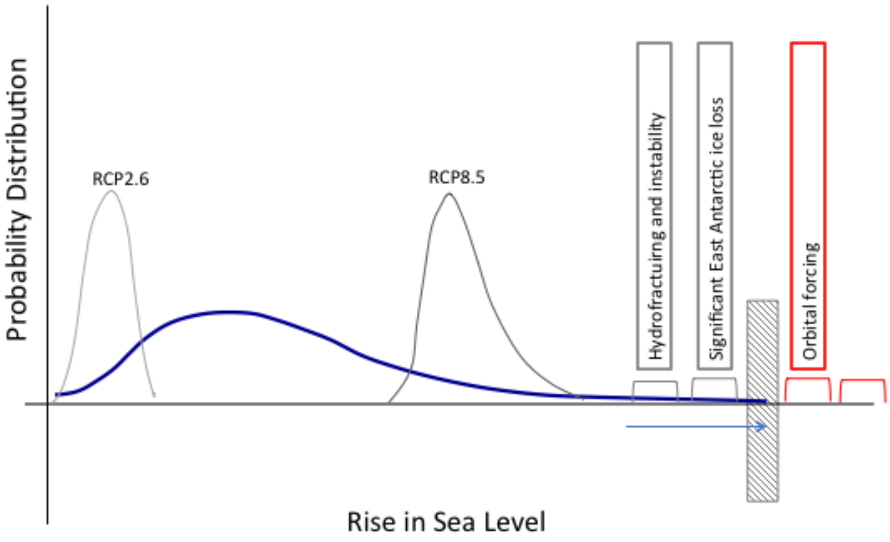
a

Time scale 100 yrs



b

Time scale >100 yrs



c

Fig. 3: Concepts of sea-level rise as a function of time scale. (a) Decadal to multi-decadal time scale for which natural variability is a significant factor. (b) 100-year time scale equivalent to the 100-yr projection discussed in AR5 (Church et al, 2013). (c) 200+ year time scale. The building blocks might shift from red to gray if the time scale of interest gets longer. The distinction between gray and red building blocks is lines of evidence vs physical implausibility as a function of time scale.