COMMENTARY:

Sea-level rise scenarios and coastal risk management

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The IPCC's global mean sea-level rise scenarios do not necessarily provide the right information for coastal decision-making and risk management.

Global mean sea-level (GMSL) rise is a major concern for coastal managers and society at large. Since 1988, the IPCC has engaged in a strenuous effort to tackle this kind of challenge at the interface of science and practical decision-making. In this role, the IPCC has recently updated its scenarios of GMSL rise with the release of its Fifth Assessment Report (AR5). For coastal managers, these scenarios are the most authoritative source of information about future global sea levels, and the coastal chapter of the second Working Group of AR5 (WGII) shows that these scenarios are indeed used widely around the world to assess coastal risk and adaptation[1]. But for the management of high-risk coastal areas, these scenarios are not the right tools to use, at least not when used exclusively. This should not come as a surprise because the IPCC scenarios are designed from the perspective of the first Working Group of the IPCC (WGI), which aims to understand and reduce uncertainty, a viewpoint that is quite different from the one of coastal management, which aims to reduce risks. Unfortunately, this is not spelled out clearly both within and beyond the IPCC reports.

A WGI perspective

The sea-level research contributing to the IPCC scenarios is an essential step towards understanding the Earth system. From this perspective, the scenarios of AR5 estimate that GMSL is likely to rise by 0.26–0.55 m from 1986–2005 to 2081–2100 under the lowest greenhouse-gas concentration scenario (RCP2.6) and by 0.45–0.82 m under the highest greenhouse-gas concentration scenario considered (RCP8.5)[2]. Prominent misinterpretations of the IPCC GMSL scenarios have occurred and been discussed both after AR4[3] and AR5[4]. To understand the meaning of these statements, it is useful to unpack them in three successive steps.

First, these statements are not just the results of models, but are expert judgements on the results of models. Such expert judgement is an attempt to come to terms with the fact that the reliability of model results is hard to assess. The word "likely" in the above statements is part of an agreed vocabulary called calibrated uncertainty language and expresses the consensus among the Lead Authors of an IPCC chapter on the probability of a statement being true. "Likely", for example, is used for a probability of 66–100% and "very likely" for a probability of 90–100%.

Second, these statements are based on one type of approach for producing information on future GMSL: process-based models. These are models incorporating the laws of physics, combined with parameterizations of processes that cannot be captured in sufficient detail to apply those laws. The sea-level rise chapter of AR5 also assesses other approaches, such as semi-empirical models, physical constraints on ice-sheet dynamics and palaeo-records of sea-level change. GMSL ranges attained through those other approaches lie consistently above those of process-based models. These results are, however, not synthesized into the IPCC scenarios, because the AR5 WGI authors state that they have less confidence in the approaches[2].

Third, the ranges produced for each emission scenario — for example, the range of 0.45–0.82 m of sea-level rise by 2081–2100 mentioned above — are derived by using ensembles of process-based models and treating the spread of projections from different models as normal distributions representing imperfections of the different models and/or stochastic properties of the underlying reality[2]. For the thermal expansion component of GMSL, for example, the IPCC authors used projections of 21 atmosphere–ocean general circulation models. The 5th and 95th percentiles of the Gaussian frequency distribution so constructed were taken as upper and lower boundaries for the ranges.

A coastal risk management perspective

From a coastal risk management viewpoint, there are two main concerns about using these IPCC scenarios. The first concern is that the IPCC scenarios focus on the central distribution rather than the high-risk tail of GMSL change. Inhabitants of densely populated coastal zones, however, share a strong aversion to major floods, and the IPCC scenarios have not been designed for this kind of situation. The likely range of the IPCC scenarios means that there is a 0–33% probability of GMSL rise lying outside this range[5], which is not tolerable from a risk-averse perspective. For those situations, the upper tail end of the distributions is also a relevant piece of information.

Although less visible, the only piece of information given in the Summary for Policy Makers of the WGI report of AR5 on the higher end of the distribution is a footnote to Table SPM.2 stating that there is medium confidence that GMSL rise will not exceed the likely range by "several tenths of a meter of sea level rise during the 21st century"[6]. This piece of information is helpful, but remains of limited use to coastal risk management. For one, it is difficult to interpret and apply in an assessment. Furthermore, medium confidence in GMSL not exceeding a given value is not a sufficient reason to rule out higher GMSL for a highly risk-averse coastal manager.

A second and related concern about using the IPCC scenarios is that risk management requires an analysis of decisions against all available knowledge including all uncertainties and also ambiguities among expert opinions and their distinct approaches[7]. The IPCC scenarios, however, do not synthesize the evidence beyond the particular set of 21 process-based models. Other methods should not be disregarded in constructing sea-level scenarios for coastal risk management even if confidence in them is lower, because lower-confidence information is still relevant for risk-averse decision-making. We note that informed coastal managers often seek their own interpretation of these diverse sources of information in the absence of an IPCC perspective.

It is also important to acknowledge that information on global sea-level rise needs to be downscaled to the local risk-management situation, taking into account regional and local spatial variations in sea-levels due to meteo-oceanographic factors, gravitational effects related to ice melting, and local uplift or subsidence processes, which add further uncertainties in risk assessment[8].

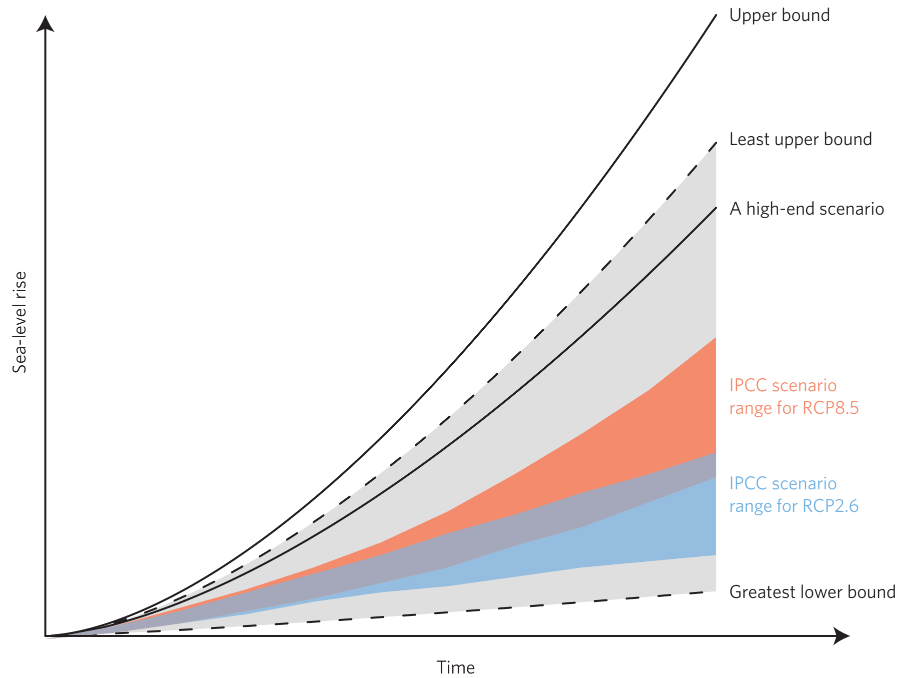

Figure 1 | Illustration of scenarios for GMSL rise discussed in this paper. The area shaded in grey illustrates the space of possible scenarios and the areas shaded in blue and red the process-model-based ranges of the IPCC scenarios for RCP2.6 and RCP8.5, respectively.

Ways forward

Improving the current approach applied by IPCC WGI to generate scenarios based on model ensembles in order to come up with probability ranges that would satisfy high-risk coastal management decisions (say 99% or 99.9%) does not seem to be a feasible way forward in the near future. As the IPCC authors acknowledge, there is no agreed or formal way of attaining quantified uncertainty ranges from model ensembles, because any distribution thus attained is biased towards a number of process-based models, which are not independent of each other and "do not represent a systematically sampled family of models but rely on self-selection by the modelling groups"[9]. In fact, it is not even clear what a 'systematic sample' would be in this context, nor is it clear what the sample space would be.

Accepting that probabilities cannot be established, the subsequent question from the perspective of high-risk decision-making is whether the problem can be bounded. One route would be to come up with a least upper bound in the sense of worst-case scenario (Fig. 1). The AR5 authors have concluded that the current state-of-knowledge does not allow this[2], and it is also questionable whether this would ever be possible, as such an approach would need to include the full range of results attained across all approaches to estimating GMSL. Note that the AR5 authors use "upper bound" in the sense of least upper bound.

Accepting that a worst-case scenario in the sense of a least upper bound cannot be established, risk management would proceed to attempt to bound the problem from either above or below. Bounding the problem from above would mean coming up with an upper bound that lies above the worst-case scenario, in the sense of an impossible scenario (Fig. 1). For GMSL rise, such an upper bound would be much easier to construct than a worst-case scenario or probabilistic range. One could, for example, take the maximum GMSL of all plausible model runs and other approaches such as, for example, physical constraints on ice-sheet dynamics and add a safety margin on top of this. Bounding the problem from below would mean combining available high GMSL estimates into a plausible but very unlikely high-end scenario without, however, attempting to quantify its probability (Fig. 1).

This type of thinking — using an upper bound or high-end scenario — has already been applied in coastal risk-management practice, prominently in the Thames Estuary 2100 (TE2100) Project for London. The motivation for the TE2100 Project was concern that accelerating sea-level rise would not allow sufficient time to upgrade or replace the Thames Estuary Barrier, because such large engineering tasks require 25–30 years for planning and implementation[1]. This project considered initially a local twenty-first century sea-level rise of up to about 4 m as an upper bound for decision-making attained through expert judgement based on linearly combining current high-end estimates of the components of twenty-first century sea level[10,11]. Later, this upper bound was replaced with a high-end scenario of 2.7 m (which also includes allowance for larger surges during extreme events), attained through a pragmatic combination of insights from observations of average rates of sea-level rise during the last interglacial period taken from Rohling *et al.*[12], physical arguments presented in Pfeffer *et al.*[13], and uncertainties in downscaling and regional and local factors. This high-end scenario was used alongside the likely range of sea-level rise, with the likely range initially setting the plans for adaptation over the next few decades, but the high-end scenarios informing what additional adaptation options need to be kept open, as well as providing a driver for continued monitoring. The project found that there is an adaptation pathway (that is, a sequence of measures) that can be realized even in the worst case, but that there are alternative adaptation pathways should sea-level rise be lower[14].

The TE2100 project also illustrates another point important for sea-level adaptation: there is no need to have the full information about twenty-first century GMSL today. Although building defences and establishing other adaptation measures does take time, this can be done much faster than GMSL rises. As a result, a sound strategy can be as follows: (1) invest in measures that keep an area safe in the near term (say to 2050) and keep longer-term options open; (2) monitor GMSL over time; and based on this, (3) update the assessment of the longer-term upper bound and implement new measures, as appropriate.

A management strategy based on a sequence of upper bounds can be framed in terms of resilience, robust decision-making, adaptive management and other conceptual schemes relevant for decision-making under uncertainty. This also includes cost–benefit analysis, which is important to note as cost–benefit analysis is prescribed by law for measures such as dam-building in some major countries. It then corresponds to assessing the costs and benefits of a policy rule rather than of a rigid plan. If a decision can be broken down into steps such that additional information may become available between them without excessive learning costs, policy rules are superior to rigid plans.

Directions for future research

Although upper-bounds and high-end scenarios have entered the world of coastal risk-management practice, this topic has not received sufficient attention from sea-level sciences. New research is needed to complement ongoing work on projecting the central range of GMSL with the development of high-end scenarios and robust upper bounds for different time horizons corresponding to different decisions, and to improve those specifications as new — comforting or threatening — evidence becomes available. Methods are required that integrate across all available knowledge on GMSL, including those approaches for which confidence is lower. This should also include science for better downscaling of global estimates to the local decision-making context, as well as the engagement of the relevant coastal risk-management institutions. The integrative nature of this research programme requires an authoritative assessment of all available knowledge, and this should be an explicit focus for any future IPCC assessment of sea-level rise. In particular, the subdivision of the IPCC assessment into working groups by disciplines, with sea-level science sitting in WG1 and coastal risk management in WG2, hinders a strong focus on better understanding the high-end tail of sea-level rise in support of risk management. Given that the mandate of the IPCC is to be policy-relevant, a more effective organization of its assessment would be by policy questions. One of these questions should link sea-level rise information to the needs of coastal risk management. ❐

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