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UPDATE

Integrating new sea-level scenarios into coastal risk and adaptation assessments: An ongoing process

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Abstract

The release of new and updated sea-level rise (SLR) information, such as from the Intergovernmental Panel on Climate Change (IPCC) Assessment Reports, needs to be better anticipated in coastal risk and adaptation assessments. This requires risk and adaptation assessments to be regularly reviewed and updated as needed, reflecting the new information but retaining useful information from earlier assessments. In this paper, updated guidance on the types of SLR information available is presented, including for sea-level extremes. An intercomparison of the evolution of the headline projected ranges across all the IPCC reports show an increase from the fourth and fifth assessments to the most recent "*Special Report on the Ocean and Cryosphere in a Changing Climate*" assessment. IPCC reports have begun to highlight the importance of potential high-end sea-level response, mainly reflecting uncertainties in the Greenland/Antarctic ice sheet components, and how this might be considered in scenarios. The methods that are developed here are practical and consider coastal risk assessment, adaptation planning, and long-term decision-making to be an ongoing process and ensure that despite the large uncertainties, pragmatic adaptation decisions can be made. It is concluded that new sea-level information should not be seen as an automatic reason for abandoning existing assessments, but as an opportunity to review (i) the assessment's robustness in the light of new science and (ii) the utility of proactive adaptation and planning strategies, especially over the more uncertain longer term.

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1 | INTRODUCTION

Global mean sea-level change represents one of the most certain consequences of human-induced climate change and is expected to cause impacts on people, natural systems, and infrastructure (Church et al., 2013b; Cubasch et al., 2013; IPCC, 2019; Wong et al., 2014), although the magnitude of future sea-level rise (SLR) remains uncertain. Furthermore, as SLR has a long-term (geological scale) response to warming, 20th and 21st century temperature increases commit the Earth to rising sea levels for many centuries (Clark et al., 2016; Oppenheimer et al., 2019). Hence, information on future sea levels around the world's coasts is required to understand the likely impacts and adaptation[1] needs.

The uncertainties surrounding the magnitude and timing of future change in sea level are deep, which means that they are generally represented through scenarios rather than a probability distribution and any risk[2] and adaptation assessments have to be generated based on a suitable set of scenarios (Hinkel et al., 2019). Scenarios are plausible, alternative visions of the future developments of complex systems that are either inherently unpredictable, for example, future emissions and mitigation, or have high epistemic uncertainties, for example, the lack of knowledge about the future ice sheet contribution to SLR. They can be applied locally, nationally, regionally, and globally (Field et al., 2014; Minano et al., 2018), but the reliability of, or difficulties associated with, developing and using scenarios continue to be seen as a constraint to risk and adaptation assessment and application in coastal areas (Hayes et al., 2018; Ramm et al., 2017). To fully serve all of the adaptation needs, the set of scenarios used in an assessment needs to sample the "full" space of uncertainties, otherwise there is the risk of maladaptation.

Since the Intergovernmental Panel on Climate Change (IPCC) fourth assessment report (AR4), a new set of climate forcing scenarios, known as the representative concentration pathways (or RCPs), have been developed (Moss et al., 2010). These were used in the fifth assessment (AR5) and have been combined with the new shared socioeconomic pathways (SSPs; O'Neill et al., 2014) for the next IPCC assessment (AR6, due in 2021). The RCPs were used to drive a new set of climate and cryosphere models in the AR5 to produce new SLR estimates. Importantly, the AR5 closed the sea-level budget over the instrumental record period, showing a good match between measurements of sea level and the sum of estimates of the SLR components. From a user perspective, this increases the level of confidence in both understanding and the ability to simulate SLR. The recently published *Special Report on the Ocean and Cryosphere in a Changing Climate* (SROCC; IPCC, 2019) builds on the AR5 providing new insights on the contribution from the cryosphere to sea level and consideration of post-2100 SLR.

Making real-world decisions that depend on SLR and variability requires appreciating and having an approach for dealing with the deep uncertainties in SLR (van der Pol & Hinkel, 2019). For a planner interested in the coastal zone, the uncertainty on what will be a level of extreme water can be considered having three main components. First, there is the uncertainty in the pathway of future greenhouse gases (GHGs) driving a change in climate. Despite recent discussions (Hausfather & Peters, 2020), the convention within the climate change community is not to attribute probabilities to different emissions futures because it is difficult to do this in a robust way (Hinkel et al., 2019). Hence, any longer-term SLR information is scenario-dependent. The second uncertainty component concerns current understanding of how the climate system works and being able to model what this might mean, for example, for future SLR the understanding of the magnitude of the contribution from the Antarctic ice sheet remains uncertain (Edwards et al., 2019). In theory, this class of uncertainty is reduced as knowledge increases, but the timescale of this process is uncertain. The third type of uncertainty is associated with natural variations in the climate system, for instance, the randomness associated with particular types of weather events driving storm surges. Planners are typically used to this latter uncertainty in the present day and represent it with a return period curve, although this curve might change in the future. For time-mean[3] SLR, the first two uncertainties typically dominate.

When considering improving guidance on SLR scenarios, this paper argues that the publication of new results (including IPCC data) does not automatically invalidate earlier assessments of coastal risks or adaptation needs. Rather, risk assessments should consider a range of SLR scenarios with existing assessments being reinterpreted in the light of new SLR scenarios instead of being discarded. Nicholls et al. (2014) provided guidance on the development and use of SLR scenarios drawing upon the AR4. This paper updates this and provides guidance on developing SLR scenarios across all the relevant components of SLR, including how to incorporate this new information within risk and adaptation assessments. Unlike the earlier guidance, there is an explicit recognition that SLR scenarios will continue to evolve. The main literature cited is post-2013, with a few key exceptions, and readers are advised to read the earlier paper for older references. Throughout, the nomenclature follows Gregory et al. (2019).

2 | SCENARIO REQUIREMENTS FOR SEA-LEVEL RISK ASSESSMENT AND ADAPTATION PLANNING

The "standard" risk assessment approach for changing sea levels has been often described as top–down. In other words, global SLR scenarios are downscaled from global climate models to the regional and then local scale with a sequence of analytical steps that begin with the climate system and move through biophysical and then socioeconomic risk assessment and, ultimately, to adaptation strategies (Carter et al., 1994; Freire et al., 2016).

In recent years, there has been a move toward adaptation decision support and action, rather than simply assessing potential impacts and risks (Dittrich et al., 2016). This creates a wider range of requirements for SLR scenarios (Hallegatte et al., 2012; Hinkel et al., 2019; Stammer et al., 2019). Increasing numbers of coastal adaptation decisions are being informed by scenario-based analysis including higher elevations for coastal land reclamation and harbor works, higher crest heights for coastal defenses, and wider building setbacks on undefended coasts. A wide array of decision support tools are now applied to assess coastal adaptation, which come with specific requirements for SLR scenarios (Hinkel et al., 2019).

In addition, a mechanism is needed by which risk and adaptation assessments can draw in new sea-level knowledge as it emerges. Digesting and interpreting new IPCC results for application is a process that in itself can take several years, and several national scenario programs have recently completed updating their national SLR scenarios based on the AR5 results, as shown by Dutch, US, and UK examples (KNMI, 2014; Sweet et al., 2017; UKCP18, 2019). At the same time, research is always progressing and, since 2013, new publications have contributed to knowledge and ongoing scientific debates. This evolving nature of sea-level information can be addressed in two complementary ways. First, when assessments of risks and adaptation plans are made, users should consider how much SLR scenarios would need to change in order to invalidate the adaptation plan. Only when new scientific or scenario information would indicate a major change should plans need to be reassessed. Second, regular monitoring of new SLR scenarios and science is needed as they affect in situ and planned adaptations; this is similar to the ex-post monitoring of climate signals applied in dynamic adaptive decision-making (Haasnoot, Brown, et al., 2019; Haasnoot, Warren, & Kwakkel, 2019).

Typically, adaptive decision-making approaches do not define precise long-term adaptation actions but rather outline a range of adaptation options to keep open over a range of future time horizons, given that the sea level is rising. The focus is then on nearer-term plans based on current best estimates of change. Such approaches build in monitoring of the climate system for the identification of thresholds beyond which additional action is required. When coastal stakeholders are strongly risk-averse, such as planning long-lived infrastructure, the high-end tail may be more important for risk assessments and adaptation planning (Ranger et al., 2013; Stammer et al., 2019; Wahl et al., 2018); robust decision-making approaches are increasingly applied to coastal adaptation, given the deep uncertainty about future SLR (Hallegatte et al., 2012; Lempert et al., 2013; Wong & Keller, 2017) to support adaptive adaptation approaches (Bloemen et al., 2018; Brown et al., 2017; Haasnoot, Brown, et al., 2019; Otto et al., 2015).

Although it may be desirable to fully quantify the distribution of future SLR from extreme high to extreme low estimates, this is not considered practical by many researchers as is discussed later in the paper. In the absence of a full uncertainty distribution, based on needs discussed above, the following requirements are key:

1. **best estimate or most likely sea-level scenarios** from the central part of the sea-level distribution—each IPCC report has reported a range of possible estimates of rise suitable for this need,
2. **high-end and low-end[4] sea-level scenarios**, which consider the tails of the distribution but to which robust probabilities cannot be assigned, and
3. **monitoring** to understand when and how the real world deviates from simulated sea-level change (Ranger et al., 2013).

In addition, sea-level scenarios may need to include sea-level extreme events (tides, surges, and waves), which contribute to total water level. This is becoming increasingly feasible at local to global scales (UKCP18, 2019). To date, most risk assessments have concentrated on the consequences of a change in "mean" sea levels as this is where the science is more certain. However, it is also important to define realistic sea-level extremes for today and consider how they might change. It is now recognized that at some locations, changes in tide can be sizable, given sea-level change and storm surge height might change with climate change (Howard et al., 2019). Waves are important from the perspective of coastal flooding and infrastructure damage. This more comprehensive thinking can be seen in recent risk assessments, which have stressed factors such as changing wave run-up and storms combined with SLR in coastal areas (Storlazzi et al., 2018; Vousdoukas et al., 2017; Vousdoukas et al., 2018).

3 | THE COMPONENTS OF A SEA-LEVEL SCENARIO

Future sea-level change at any location comprises global mean SLR components, combined with regional and local SLR contributions. In addition, extreme sea-level (ESL) components (tides, storm surges, and waves) have to be considered to capture the full range of possibilities for risk and adaptation studies. Treatment of uncertainty is important, with regional-scale estimates typically being more uncertain than global mean averages. Furthermore, some components are less understood than others. For example, the role of the dynamic wave contribution (an important factor along many open coastlines) is often ignored or greatly simplified due to limited observational data and models being computationally too expensive to apply for present or future conditions.

3.1 | Time-mean sea-level change

To estimate time-mean relative sea-level (RSL) change for specific locations, the contributions from components at global, regional, and local scales need to be considered. For any given site, these can be integrated using Equation (1):

$$\Delta \mathrm{RSL} = \Delta \mathrm{SL}_{\mathrm{GMSL}} + \Delta \mathrm{SL}_{\mathrm{OD}} + \Delta \mathrm{SL}_{\mathrm{GRD}} + \Delta \mathrm{SL}_{\mathrm{VLM}}, \tag{1}$$

where

$\Delta \mathrm{RSL}$ is the local change in time-mean relative sea level (the change between the ocean surface and the land /ocean floor)

$\Delta \mathrm{SL}_{\mathrm{GMSL}}$ is the change in global mean sea level

$\Delta \mathrm{SL}_{\mathrm{OD}}$ is the regional variation in time-mean sea level due to ocean dynamics (including the mean effect of atmospheric pressure changes)

$\Delta \mathrm{SL}_{\mathrm{GRD}}$ is the regional variation in time-mean sea level resulting from the redistribution of mass between land and ocean, which leads to variations in gravitational, rotational, and deformational (GRD) effects

$\Delta \mathrm{SL}_{\mathrm{VLM}}$ is the local/regional change in sea level due to vertical land movement (VLM)

Global mean sea-level change ($\Delta \mathrm{SL}_{\mathrm{GMSL}}$) is a result of the change in the global volume of the ocean. In the 20th/21st century, this is expected to be primarily due to (i) thermal expansion of the ocean as it warms and (ii) barystatic sea-level change, which includes mass loss of glaciers and ice caps, and the Greenland and Antarctic ice sheets (IPCC, 2013). Other processes such as human modifications to the hydrological cycle are typically smaller when considering contributions to future change, although this should be reviewed as knowledge develops (Wada et al., 2017).

Ocean dynamic factors ($\Delta \mathrm{SL}_{\mathrm{OD}}$) include differences in the rates of oceanic thermal expansion, changes in long-term wind and atmospheric pressure, and changes in ocean circulation (Bouttes et al., 2012; Han et al., 2010; Yin et al., 2010). These cause large regional departures of up to 50%–100% from the global average change for the thermal expansion component of sea-level change. Distinct regional features in the Southern Ocean and in the North Atlantic are associated with increasing GHG emissions through changes in wind stress and surface heat flux (Bilbao et al., 2015; Bouttes & Gregory, 2014; Slangen et al., 2015).

Gravitational, rotational, and deformational changes ($\Delta \mathrm{SL}_{\mathrm{GRD}}$) are driven by the redistribution of mass between the ocean and Greenland, Antarctica, glaciers, or land water reservoirs (the barystatic change). This results in a distinct regional signature with a sea-level fall close to the source of mass loss and an above-average SLR (up to 120%–130%) in the far field (Slangen et al., 2014; Spada et al., 2012). These gravitational "fingerprints" have been used to produce regional sea-level change scenarios as in the AR5 (Church et al., 2013b), other regional scenarios, and subsequent national assessments (Carson et al., 2016; de Vries et al., 2014; Goodwin et al., 2017; Grinsted et al., 2015; Kopp et al., 2014; McInnes et al., 2015; Slangen, van de Wal, et al., 2017).

Vertical land movement (uplift and subsidence) (ΔSL_{VLM}) is caused by various natural and human-induced geological processes (Peltier et al., 2014; Pfeffer & Allemand, 2016; Woppelmann & Marcos, 2016). Natural causes include (i) neotectonics, (ii) glacial isostatic adjustment (GIA), (iii) tectonics, and (iv) sediment compaction/consolidation. In addition, human activities can influence rates of subsidence in coastal lowlands and deltas by land reclamation and by fluid extraction such as lowering water tables through groundwater extraction, increased drainage, or oil and gas extraction. These human-enhanced processes are generally localized to Holocene- and Pleistocene-age deposits and can locally exceed the magnitude of RSL changes expected due to climate change through the 21st century (Allison et al., 2016; Erkens et al., 2015; Minderhoud et al., 2017; Nicholls, 2018).

3.2 | Extreme sea levels

Many risks on the coast and inshore marine environments result from ESL events due to high tides, storm surges, and/or extreme wave conditions (IPCC, 2012). In the future, relative mean sea level is expected to be the main driver for changes in total sea level (TSL) (Marcos & Woodworth, 2017; Menéndez & Woodworth, 2010; Wahl & Chambers, 2015) but may also be influenced in some locations and some model simulations by changes in atmospheric winds and pressure. In other words, it is the rise in mean sea level that makes the current extreme water levels occur more frequently (Oppenheimer et al., 2019; Vitousek et al., 2017; Wahl et al., 2017) and the magnitude of this change depends on the slope of the exceedance curve, where the return period or probability is plotted (typically in log–log plots) against the associated water-level height (see Figure S1 for examples of exceedance curves from selected locations); the lower the slope, the greater the effect of any given mean sea-level change in terms of amplifying the frequency with which certain thresholds are exceeded in the future. The results from such an analysis also depend on the extreme value distribution model that is applied to describe the ESLs (see Figure S1 and Wahl et al., 2017).

The effect of changing RSL on TSL can also be estimated with a so-called SLR allowance. This allowance is the height a coastal structure needs to be elevated to maintain the same frequency and likelihood of ESL events under future RSL rise (Hunter, 2010; Slangen, van de Wal, et al., 2017). The allowance depends on mean RSL and the RSL uncertainties, in addition to the variability of ESL at a certain location. The allowances are largest in regions with a large RSL rise and/or RSL uncertainty, in combination with a small variability in ESL, which typically occurs around the equator (Figure 1).

In addition to changes in ESL due to changes in RSL, the characteristics of ESL can change as follows and contribute to additional changes in TSL:

$$\Delta \mathrm{ESL} = \Delta\eta_A + \Delta\eta_{NTR} + \Delta\eta_W, \tag{2}$$

$$\Delta \mathrm{TSL} = \Delta \mathrm{RSL} + \Delta \mathrm{ESL}, \tag{3}$$

where

ΔESL is the total change in regional extreme sea-level components (excluding RSL)

$\Delta\eta_A$ is the change in tides

$\Delta\eta_{NTR}$ is the change in storm surges (or non-tidal residuals)

$\Delta\eta_W$ is the change in the wave contribution, usually expressed as wave setup or wave run-up

ΔTSL is the change in total sea level as the sum of changes in the time-mean sea level and ESL components

Changes in tides ($\Delta\eta_A$): with rising mean sea level and increased water depth, tidal wave propagation is modulated. Tidal range can therefore increase or decrease, affecting extreme value statistics (Arns et al., 2015). Changes are in the order of few centimeters for 0.5-m RSL rise (Pickering et al., 2017; Schindelegger et al., 2018) and as such negligible compared to other drivers of changes in TSL (Vousdoukas et al., 2017). However, tide changes would become more relevant (in the order of decimeters locally) under high-end SLR scenarios of 2 m or more (Pickering et al., 2017; Schindelegger et al., 2018). In many urbanized estuaries, more pronounced changes have been observed in the past

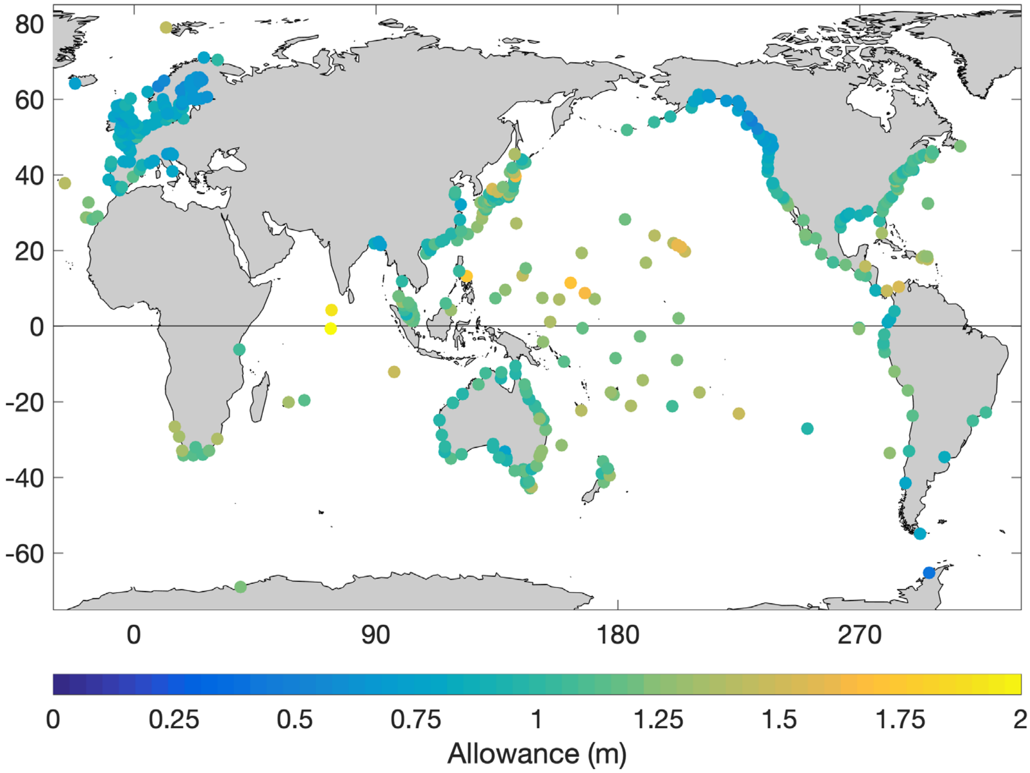


FIGURE 1 Sea-level rise allowances (m) for 2010–2100 sea-level change scenarios from AR5, RCP8.5. (Reproduced under CC BY 4.0 from Slangen, van de Wal, et al., 2017)

(and will likely continue into the future) due to land claim, dredging, and channel deepening (Haigh et al., 2020; Ralston et al., 2019; Talke et al., 2014; Talke & Jay, 2019).

Changes in storm surges ($\Delta\eta_{NTR}$): changes in the storm surge climate can result from changes in frequency, intensity, and/or tracks of extra-tropical and tropical storms. Such changes are less understood and were often ignored in earlier assessments or were assessed through sensitivity analysis, for example, by increasing return water levels by 10%–20% reflecting uncertainties in climate change effects on storminess (DEFRA, 2006; Wolf et al., 2015). More recently, the advent of process-based global storm surge models (Muis et al., 2016; Muis et al., 2020) allows a better understanding of the possible effects of a warming world on the global storm surge climate (Muis et al., 2020; Vousdoukas et al., 2018).

Changes in waves ($\Delta\eta_{W}$): changes in the offshore wave contribution are driven by changes in the wind climate. Model studies suggest coherent regional patterns with some regions likely to experience decreases in significant wave height and vice versa (Hemer et al., 2013). Similar results were reported for extreme wave conditions, with increasing trends in many southern hemisphere regions and decrease for many northern hemisphere regions. RSL also has a direct effect on the nearshore wave climate as it relaxes the breaker criterion, allowing larger waves to propagate to shore (Arns et al., 2017). Whether or not this effect is relevant depends on the geographic setting, bathymetry, and the type of shoreline (hardened or soft with the possibility to adjust [by erosion] to a new equilibrium).

Although all these components are not formally additive due to nonlinear feedback and effects of SLR (Arns et al., 2015; Arns et al., 2017), Equations (2) and (3) are a first approximation in most circumstances.

The uncertainty range in total projected SLR will depend on the assumed correlation between the different components. For instance, there is a correlation between thermal expansion and surface warming, which will clearly influence ice melt contributions, but it is often assumed that there is little correlation between ice melt model parameters and surface warming. (Church et al. 2013a, 2013b) describe the details of the calculations for combining uncertainties used in the AR5. The recent SROCC made similar assumptions for combining uncertainties (Oppenheimer et al., 2019). For future ESL, an ideal situation would be to combine all uncertainties. However, in many situations including all uncertainties is practically difficult (see section A15 in Palmer et al., 2018). However, the authors recommend that the component with the greatest uncertainty be considered in any application.

Overall, changes in the ESL components are less well understood than changes in RSL components, globally, regionally, and locally. This applies to historic, present, and future events, especially those with long return periods.

4 | METHODS FOR SEA-LEVEL SCENARIO DEVELOPMENT

4.1 | Overview

Risk assessments and adaptation planning can be conducted to different levels of detail from exploratory analyses to highly detailed approaches. Using observed and extrapolated trends is one approach, while Table 1 summarizes

TABLE 1 Summary of sea-level components versus levels of assessment (see in particular Sections 4.3–4.5), including socioeconomic scenarios as a vital component to these assessments (see Section 4.7)

		Level of assessment		
Sea-level component		Detailed	Intermediate	Exploratory
Global sea-level change (including ice melt)	ΔSL_{GMSL}	For instance, AR5, SROCC, or similar source. Update with new IPCC reports when available. Include high-end scenarios (above IPCC range)		
Regional sea-level change	ΔSL_{OD}	Ocean dynamics (including mean effect of atmospheric pressure changes) driven deviations from individual models	Scale local deviations or similar, via pattern scaling	±50% sensitivity analysis (Hulme et al., 2002)
	ΔSL_{GRD}	Model correction for GRD effects (IPCC)	Scale fingerprints with the projected time series	Assume no change
Vertical land movement	ΔSL_{VLM} due to natural causes	Intermediate level plus local observations; e.g., GPS, long-term tide gauge observations, or detailed geological analysis	Regional patterns of land motions from geological synthesis or GIA model estimates	Assume no change, except in river deltas where 1 or 2 mm/year subsidence is expected (Meckel et al., 2007; Vafeidis et al., 2008)
	ΔSL_{VLM} due to human-induced causes	Intermediate level plus analysis of subsidence potential, including driver prognosis (e.g., ground water extraction)	Synthesize changes based on geological setting, especially deltas (Tessler et al., 2018) and subsiding coastal cities (Nicholls, 2018)	Assume no additional change to above, except in major cities located on river deltas and apply appropriate indicative subsidence values (e.g., 10 mm/year (Wang et al., 1995) as a sensitivity analysis)
Changes in wave, surge and/or tidal component to extreme sea level	ΔESL	Modeling using local/regional models or statistical downscaling driven by climate models	Sensitivity study; e.g., no change and arbitrary increase (e.g., 10% increase of 100-year event)	Assume no change
Linkage to socioeconomic scenarios		Downscaled global scenarios (e.g., SSP) or other relevant local data	Simple consideration of how scenarios (e.g., SSPs) might influence regional or local socioeconomic development (make assumptions explicit)	

Abbreviations: GIA, glacial isostatic adjustment; GRD, gravitational, rotational, and deformational; IPCC, Intergovernmental Panel on Climate Change; SSP, socioeconomic pathway.

how SLR scenarios might be developed with different levels of data availability and assessment. Based on experience, SLR scenarios are likely to evolve from a first scoping assessment of the problem and its issues toward an increasingly detailed understanding of the risks and ultimately to design and implementation of appropriate adaptation measures.

4.2 | Observed and extrapolated trends

Extrapolations of sea-level trends from observed data are a simple method for directly creating local relative SLR scenarios where such observations are available (Weisse et al., 2014). They are particularly useful where the planning or scenario timescale is short, especially when compared to the dominant periods of natural variability affecting a given region (Nicholls et al., 2011). Extrapolation of historic trends may provide a lower bound SLR estimate, assuming no further climate change. For typical observed rates of SLR, extrapolation ideally requires 50+ years of data (Douglas, 1991). This can be reduced to 30–35 years if sea-level index methods can be applied (Woodworth et al., 2009); for instance, sea-level indices were created for the English Channel using results from six locations with some degree of coherence (Haigh et al., 2009) and in areas of faster change (e.g., those experiencing rapid subsidence) (Kolker et al., 2011). Utilization of local extrapolated historical trends should be cautious in light of future climate change and also consider multidecadal variability caused by modes such as the North Atlantic Oscillation (Knudsen et al., 2011) or the Pacific Decadal Oscillation (Hamlington et al., 2013; Newman et al., 2016). For longer timescales, detrended estimates of sea-level variability can be combined with other methods, such as physical modeling, to consider longer-term trends (Weisse et al., 2014), although there is a danger that some of the longer period variability will be removed.

There are significant paper-based records of sea-level change, which can be retrieved by data archeology, enhancing historic understanding (Bradshaw et al., 2015; Woodworth et al., 2017). This can improve adaptation planning, and efforts in this regard are often triggered by extreme events such as the response to Superstorm Sandy (Talke et al., 2014). As well as instrumental records, links to geological records of sea-level change can also be made and may provide useful context (Long et al., 2014; Woodworth et al., 2011). Ocean reanalysis provides another source of data that complement these observations and can be useful for historic sea-level analysis (Carton et al., 2018; Zuo et al., 2018).

4.3 | Modeled sea-level change projections

Frequently sea-level projections are generated using physically based models such as those reported in Church et al. (2013b) and Oppenheimer et al. (2019). To estimate the magnitude and rate of sea-level change resulting from climate change, global climate models are forced with estimates of future GHG emissions or atmospheric concentrations. Some components of SLR, such as thermal expansion, are produced directly by the models, whereas others, typically ice melt contributions, are calculated offline with driving data coming from the global climate model. Comprehensive reviews can be found in Church et al. (2013b) and SROCC (Oppenheimer et al., 2019). In the future, with the introduction of more comprehensive earth system components within climate models, some of these offline components might be calculated directly from the model.

The evolution of the range of SLR estimates through the various IPCC assessment reports up to the recent SROCC is summarized in Figure 2, with more details on the approaches in supporting information. The global mean SLR estimated in the AR5 (Church et al., 2013b) differs from earlier IPCC reports due to both the different climate forcing (resulting from different emission scenarios) and improvements to the techniques for calculating SLR components. This is a consequence of a new generation of general circulation models with updated atmospheric and ocean warming levels leading to new ice melt estimates and heat uptake for thermal expansion estimates. Models of glaciers and ice sheets have also improved. In addition, Church et al. (2013b) included terrestrial water storage and a different approach to combining uncertainties from the component terms into total SLR (Church et al. 2013a, 2013b). This will be improved further in the next IPCC assessment, including the use of forcing data that have been updated to account for new scenarios of GHG emissions in combination with societal scenarios (O'Neill et al., 2016; Tebaldi et al., 2020).

SLR projected in the AR5 (Church et al., 2013b) for the RCP emissions scenarios is shown alongside estimates using the AR5 modeling approach, but with the older Special Report on Emissions Scenarios (SRES) A1B forcing scenario as a comparator in Table S1. The global average SLR rate is expected to exceed the observed 1.7 mm/year between 1901 and 2010 (Church et al., 2013b), although not all RCPs sustain a rise above the 3 mm/year observed rate over the last couple of decades (Nerem et al., 2018). This latter point represents an important decision for SLR scenario construction, whether the recent observed rate is a long-term trend or part of a cycle of longer-period variability. A recent work (Slater & Shepherd, 2018) highlights that the Antarctic contribution has been tracking the trajectory of the larger SLR scenarios. As there is not a definitive answer to this question at present, the choice might largely depend on the level of risk aversion of the scenario user or the approach to decision-making in the planning process.

Many early national and subnational risk assessments focused on SLR with a "plausible range" derived from expert judgment for sensitivity analysis (Cooper & Lemckert, 2012; Ghoussein et al., 2018; Satta et al., 2016). As with all assessments, these results remain useful in terms of potential risks and adaptation strategies and should not simply be discarded because new SLR scenarios have emerged. Rather, they form a foundation for future assessments, with the adaptation measures being re-evaluated against more contemporary SLR estimates.

Semi-empirical approaches, based on the assumption that a quantitative relationship can be developed between the past global sea-level and temperature change, allow the calculation of future SLR directly from (reduced complexity) climate model predictions of future global warming. The results of the semi-empirical approaches can be used as a type of SLR scenario. There has been widespread debate about the validity of these approaches (Bittermann et al., 2013; Lowe & Gregory, 2010; Rahmstorf et al., 2012; von Storch et al., 2008). Typical semi-empirical approaches assume that the relationship between SL and other variables holds into the future, but as ice sheet dynamics, or other processes indirectly linked to climate change, become more important this may not be valid. The most recent approaches have improved the methodology and consider, for instance, differences in the response time of different SLR components (Jevrejeva et al., 2016).

4.4 | High-end scenarios of sea-level change

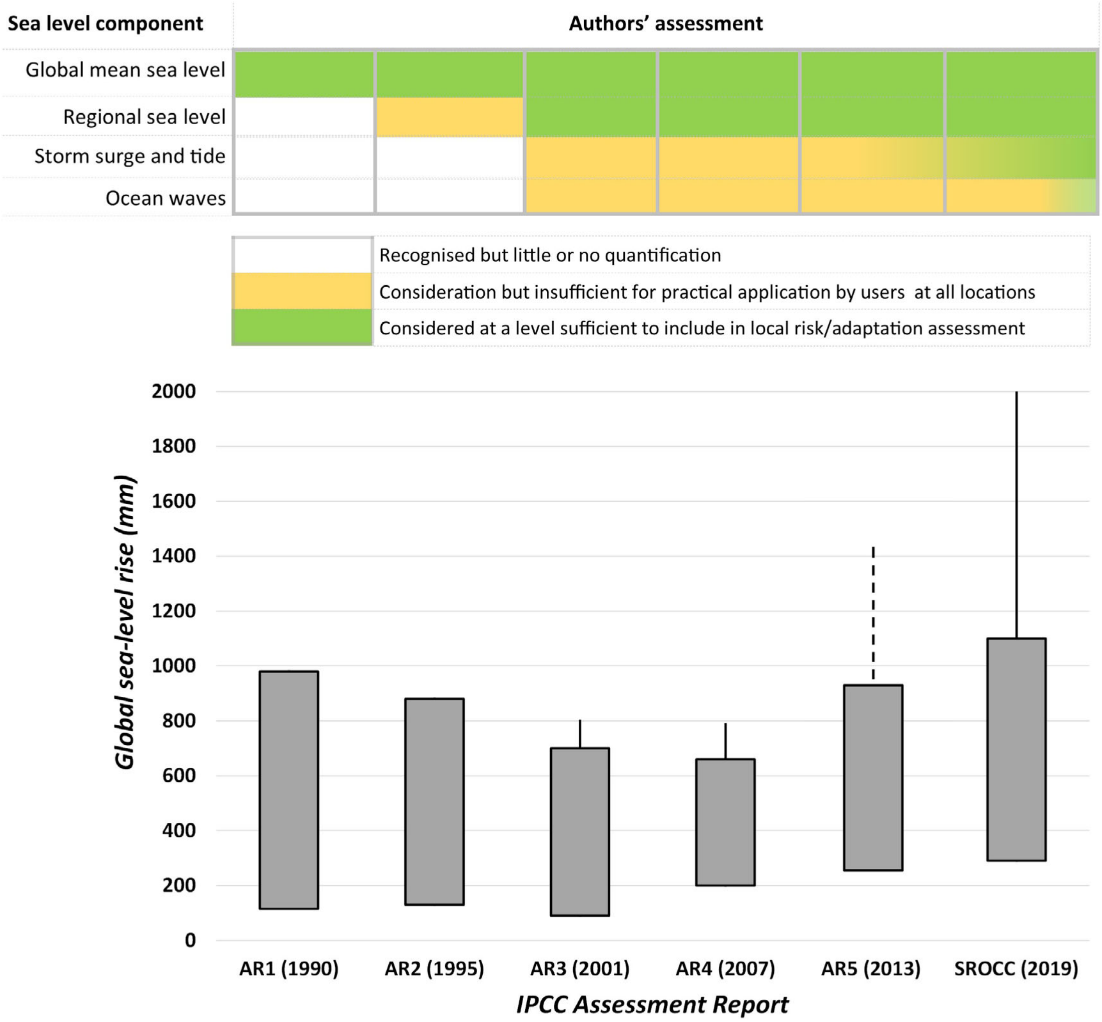
The current generation of models outlined in Section 4.2 does not include all the processes that govern future SLR, including climate–carbon cycle feedback or the full effects of changes in ice sheet flow (IPCC, 2013). Lowe et al. (2009) highlighted the need for a high-end (or H++ in their terminology) scenario that considers evidence describing the low probability tail for the SLR distribution. In the AR5, Church et al. (2013b) concluded there is scope for a further several tens of cm beyond the likely range, mostly from the Antarctic contribution (Figure 2). Although risk assessments and especially adaptation plans may focus on the AR5 likely ranging as discussed below, this may not be sufficient for risk-averse users (Hinkel et al., 2015).

High-end SLR scenarios can be constructed by considering multiple lines of evidence, including observations, palaeo records, model sensitivity studies, modeled SLR scenarios studies (Nicholls et al., 2014), and expert judgment (Bamber et al., 2019). For instance, there is a considerable body of literature suggesting that rapid deglaciation in Greenland or Antarctica could lead to global SLR during the next few centuries in the order of several meters (Church et al., 2013b), but with considerable uncertainty. While of great concern, collapse of the West Antarctic Ice Sheet is thought to have a low likelihood of occurrence during the 21st century. However, this does not mean that the probability of this happening is zero and hence should be considered by risk-averse users. Furthermore, this likelihood increases substantially in subsequent centuries (Levermann et al., 2013).

More recent estimates attempt to use a range of evidence and methods to estimate the potential 21st century contribution from ice sheets to SLR. Although the evidence presented up to the AR5 considered the potential for an Antarctic marine ice sheet instability, the current debate focuses on the potential for marine ice cliff instability (MICI). MICI has been observed in Greenland, but if it were to happen around the Antarctic ice sheet, it could provide a large additional contribution to SLR estimates. DeConto and Pollard (2016) provided an initial estimate of this term, which has been factored into some SLR scenarios (Gornitz et al., 2019; Kopp et al., 2017; Le Bars et al., 2017). However, there is still considerable debate as to whether the MICI mechanism could occur on the timescale and over the spatial extent required to reach these SLR estimates (Edwards et al., 2019; Pattyn, 2018). Thus, although current understanding is that rapid ice melt has a low and unquantified probability during the 21st century, exclusion based on current observations and computer models is not yet possible. Until these rates can be either ruled out or their probability estimated, it is prudent to consider the potential risks and adaptation options on coastal assets with a high value in the event of such large rises (Keller et al., 2008; Stammer et al., 2019).

The treatment of ice sheet contributions represents a fast-moving area of science that has been considered in the SROCC (Oppenheimer et al., 2019) and will be considered again in the AR6 (due 2021). Thus, placing too much focus on the details of current probability density functions (PDFs) for the full range of SLR, in particular their upper tail, is not recommended. Rather, this is an important knowledge area to monitor. However, this and other uncertainties in the estimation of future SLR, across the full range of sea levels, should not be taken as an excuse for inaction (Paulik et al., 2020).

Although Nicholls et al. (2014) included a range for H++, the interest from many coastal planners focuses on the high end of this range (Le Cozannet, Nicholls, et al., 2017; Stammer et al., 2019). The earlier upper bound for this global H++ range follows the reasoning of Rohling et al. (2007) and considers the dynamic effects of the ice sheets as advocated by Pfeffer



Sea level component	Authors' assessment					
Global mean sea level	🟩	🟩	🟩	🟩	🟩	🟩
Regional sea level	⬜	🟨	🟩	🟩	🟩	🟩
Storm surge and tide	⬜	⬜	🟨	🟨	🟨/🟩	🟨/🟩
Ocean waves	⬜	⬜	🟨	🟨	🟨	🟨/🟩

⬜	Recognised but little or no quantification
🟨	Consideration but insufficient for practical application by users at all locations
🟩	Considered at a level sufficient to include in local risk/adaptation assessment

FIGURE 2 Evolving sophistication of the treatment of sea-level projections (upper) and (lower) range of global mean sea-level scenarios from 2010 to 2100 in the Intergovernmental Panel on Climate Change (IPCC) reports (with adjustments and extensions as needed). The solid bar represents the 5th–95th percentile of the model outputs, which is often interpreted in the most recent IPCC assessment as the "likely" range and vertical lines represent a wider range including additional uncertainties (see supporting information for details)

et al. (2008). However, the upper limit of the H++ scenario is difficult if not impossible to precisely estimate or define. Individual studies show that values vary according to local knowledge and understanding (Gornitz et al., 2019; Horton et al., 2015; Lowe et al., 2009; Vellinga et al., 2009), and Bamber et al. (2019) argue climate-induced SLR between 0.5 and 2 m by 2100 is not implausible. In considering the upper end of H++, the "several tens of cm" above the likely range reported by Church et al. (2013b) (i.e., up to about 1.5-m rise) or the expert-elicited 2-m rise by 2100 recognized in the recent SROCC could be utilized (Oppenheimer et al., 2019). The much larger estimates of DeConto and Pollard (2016) could also be considered. However, this needs to be balanced with the ongoing debate and other views suggesting lower rises such as Levermann et al. (2014), Golledge et al. (2015), Ritz et al. (2015), and Edwards et al. (2019), as well as the forthcoming AR6 assessment. Although these updates are expected, the guidance in Table S1 retains the original H++ estimates, but these should be reviewed after the AR6. Local SLR scenarios for the H++ scenario also need to consider gravitational effects; this will require judgment on where the land ice mass loss occurs.

4.5 | Regional sea-level rise scenarios

SLR scenarios vary with location, and there is now greater understanding than that in the study by Nicholls et al. (2014) of the regional drivers, including consideration of gravitational fingerprints and GIA terms (Section 3.1).

Where regional information is available, it should be used in scenario construction. Users of SLR scenarios might also want to consider local factors, which include storm surges, tides, and waves (Section 3.2) and make use of more localized VLM, although in the latter case, caution is required to avoid double counting with the regional component.

4.5.1 | Ocean dynamic factors (ΔSL_{OD})

Ocean dynamic changes can be estimated with atmosphere–ocean general circulation models (AOGCMs), which simulate the geographic distribution of sea-level change caused by ocean processes (Gregory et al., 2001; Yin, 2012) using single model or ensemble model outputs. Individual models calculate that some regions show a rise substantially more than the global average rise (up to twice the global average), but others a sea-level fall (Church et al., 2001). However, the continuing lack of similarity in spatial patterns between the models means that confidence in regional dynamic sea-level scenario projections is currently low. The AR5 combined (or ensemble) model results (Church et al., 2013b) are shown in Figure 3. This shows a smaller-than-average SLR in the Southern Ocean and larger-than-average in the Arctic. This variation can be attributed to enhanced freshwater input from precipitation and continental runoff, steric changes, wind stress change, or thermal expansion (Bouttes et al., 2012; Yin, 2012), and further improvements in understanding are expected (Gregory et al., 2016; Hamlington et al., 2018).

Although it is preferable to have direct access to AOGCM ensembles to create SLR scenarios, the regional pattern of thermal expansion under SRES and RCP forcing can be approximated using a pattern-scaling method following the classic paper of Santer et al. (1990) and more recent coastal examples (Perrette et al., 2013; Thomas & Lin, 2018; Yin et al., 2010). In applying the pattern-scaling method to sea level, "standardized" (or "normalized") patterns of regional thermal expansion change, as produced by coupled AOGCMs (which include changes in wind stress, ocean circulation, and other factors), are derived by dividing the average spatial pattern of change for a future period (e.g., 2071–2100) by the corresponding global mean value of thermal expansion for the same period. The resulting standardized sea-level pattern is thereby expressed per unit of global mean thermal expansion and can be incorporated into tools for SLR scenario generation (Warrick, 2009).

4.5.2 | Mass-induced changes in the gravity field of the Earth (ΔSL_{GRD})

Prior to the AR5, GRD factors had not been widely considered in SLR scenarios. However, it is significant for scenarios with a large ice melt component (e.g., Figure 4). The regional change in response to mass redistribution is typically

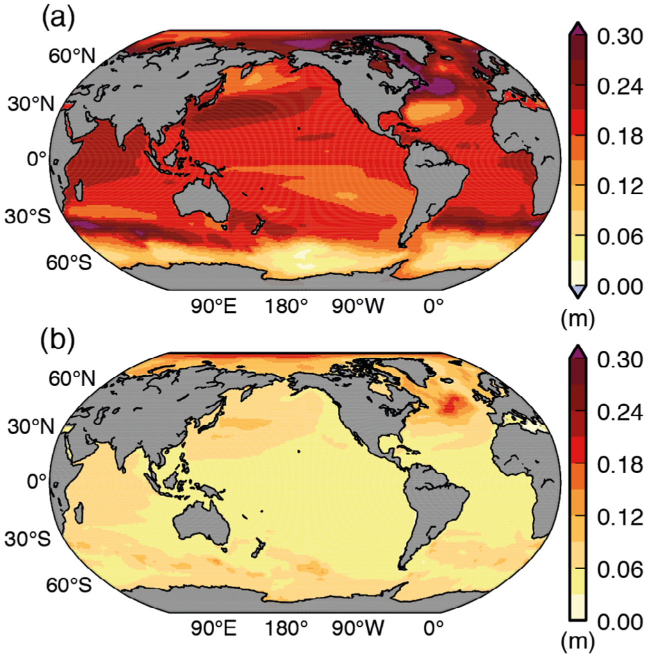


FIGURE 3 (a) Ensemble mean projection of the time-averaged dynamic and steric sea-level changes for the period 2081–2100 relative to the reference period 1986–2005, computed from 21 CMIP5 climate models (in meters), using the RCP4.5 scenario. The figure includes the globally averaged increase in steric sea level of 0.18 ± 0.05 m. (b) Root-mean square (RMS) spread (deviation) of the individual model result around the ensemble mean (meters) (reproduced from figures 13 to 16 in Church et al., 2013b). Note that the global mean differs from table 13.5 in Church et al. (2013b) by less than 0.01 m, as a slightly different set of CMIP5 models was used

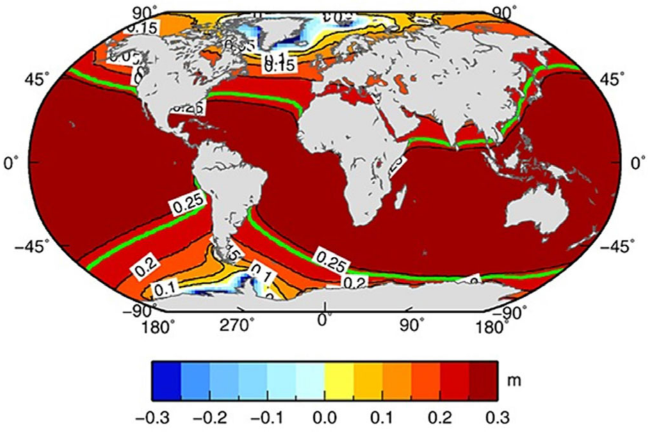


FIGURE 4 Sea-level change (m) for the year 2100 (relative to year 1992) associated with combined Greenland and Antarctic ice sheet melt under a mid-range (A1B) scenario. The green contour shows the global mean change (taken from figure 1 in Spada et al., 2013)

referred to as a "fingerprint" and can be computed using a numerical model that solves the sea-level equation; Slangen, Adloff, et al. (2017) provides a comprehensive review. Uncertainties in this contribution arise mainly due to uncertainties in the estimated magnitude and locations of the cryosphere and terrestrial mass changes.

4.5.3 | Vertical land movement (uplift and subsidence) (ΔSL_{VLM})

VLM is expected to be less than the rise resulting from oceanographic changes in most locations over the 21st century as, in most parts of the world, VLM rates are typically only 1–2 mm/year. However, large subsiding river deltas and especially some large cities on deltas and alluvial plains are important exceptions (Erkens et al., 2015; Tessler et al., 2018). Correcting SLR scenarios for VLM matters as, depending on their sign, they may amplify or reduce the effects of future SLR. In rapidly subsiding areas, they may dominate SLR scenarios. Although some regional-scale measurements and modeling may be available (e.g., at city [Miller et al., 2013], delta [Brown & Nicholls, 2015; Becker et al., 2020], or regional scales [Love et al., 2016; National Research Council, 2012]), obtaining rates of VLMs can be problematic as long data sets are required (Whitehouse, 2018; Woppelmann & Marcos, 2016) and human-induced subsidence may vary with time (Kaneko & Toyota, 2011).

To estimate the contribution of local land movement to RSL change in the future, the climate change related portion of SLR needs to be subtracted from the observed local trend (see Section 4.2). Various methods have been advanced to quantify and correct for this local trend (Miller et al., 2013; Woppelmann & Marcos, 2016), including using long-term geological data, tide gauge, or GPS measurements (Gehrels & Woodworth, 2013; Montillet et al., 2018; Pfeffer et al., 2017).

GIA is a component of ΔSL_{VLM}, which includes the ongoing response to the last deglaciation, which can be globally modeled albeit with significant uncertainties (Spada, 2017), and is widely included in SLR scenarios (e.g., Church et al., 2013b). In some regions of the world that were near previously glaciated areas, such as around Northern European coastlines, it can have an important effect (Palmer et al., 2018). GIA corrections are often applied to regional or local geological and/or geodetic observational data sets (Khan et al., 2017; Roy & Peltier, 2015; Shennan et al., 2018) and used in regional SLR scenarios (Johansson et al., 2014).

Historical experience is unlikely to be a good guide to future changes in tectonically active areas, as most vertical land changes may occur during infrequent earthquake events, which are not predictable and can even be in an opposite sense to the trends occurring between earthquakes (Garrett et al., 2016; Hayward et al., 2016; Long & Shennan, 1998). Similarly, deltas can display complex spatial and temporal changes in land motions caused by a combination of natural and human-related processes that may result in high subsidence rates (Ericson et al., 2006; Syvitski, 2008; Tessler et al., 2018), as illustrated in detail for the Mississippi delta (Hak et al., 2016; Jankowski et al., 2017; Kuchar et al., 2017).

Human-induced subsidence that accompanies land reclamation, changes in sediment supply, and associated solid-earth loading due to dam construction and groundwater extraction (Hung et al., 2018) can also be important and need to be considered in detailed SLR risk and adaptation assessments where locally relevant. The coast of south, southeast, and east Asia is a hotspot for these issues due to the large population and extensive sedimentary coastal flood plains

(Besset et al., 2016; Erkens et al., 2015; Hutabarat & Ilyas, 2017). Forecasting future human-induced subsidence is difficult (Erkens & Sutanudjaja, 2015), and the best available approach is a guided sensitivity analysis drawing on local measurements and experience or analogs from similar settings if this is not possible.

4.6 | The use of probabilistic sea-level scenarios

Ideally, planners would like a precise and unique prediction of future sea level over coming decades, but this is beyond scientific capability. As noted in the introduction, the convention within the climate change community is not to attribute probabilities to different emission futures. In the absence of a single unique prediction of the future and a single unique PDF ***across*** GHG scenarios, it is tempting to aim for a single PDF to represent all the uncertainties ***within*** a given GHG scenario (called probabilistic sea-level scenarios). Although there has been an increasing trend in the last few years of providing such probabilistic SLR scenarios from physical, semi-empirical, and reduced complexity models to support risk and adaptation assessment strategies (Goodwin et al., 2017; Horton et al., 2020; Jevrejeva et al., 2016; Kopp et al., 2014; Kopp et al., 2017; Le Bars et al., 2017), it is the authors' assertion that it is certainly not yet possible to capture all of the uncertainties in a single PDF. It is even not possible to produce a PDF conditioned on a particular climate emission scenario that is accepted as being robust and can be agreed upon by the SLR science community. However, studies that produce PDFs can provide a useful contribution, including, in particular, helping inform likely ranges in expert assessments of the literature, such as in recent IPCC reports. These difficulties of quantifying the uncertainties are acknowledged by some authors (Kopp et al., 2017), but this is not readily appreciated by stakeholders who have a preference for quantitative information which PDFs often appear to provide. Therefore, from the pragmatic perspective for most users, caution should be attached to the use of individual PDFs within climate scenario development, except for perhaps in the next 30 years when emissions uncertainty is small (Hinkel et al., 2019).

As it is not yet possible to define a single agreed probabilistic scenario (i.e., a set of single PDFs within each emission scenario), there is value in considering sets of PDFs from multiple studies, as well as other lines of evidence as described in the previous sections (Stammer et al., 2019). For example, multiple PDFs and other lines of evidence can be combined into imprecise probability functions or possibility functions as demonstrated by Hinkel et al. (2018), van der Pol and Hinkel (2019), and Le Cozannet, Manceau, and Rohmer (2017), and this is a useful route to meaningful dialog between sea-level scientists and users to coproduce appropriate SLR scenarios. One possibility, as yet unexplored, would be to combine PDFs from multiple studies and assess them in the context of storylines or narrative approaches (Katsman et al., 2008).

4.7 | Linking sea-level change to wider scenario aspects

SLR risks and adaptation needs depend on more than just the amount of SLR at a given location. Coastal areas are changing dramatically due to socioeconomic drivers and this will continue (Wong et al., 2014). For example, coastal populations are expected to grow substantially, and economic growth can be very large when compounded over multiple decades (Merkens et al., 2016; Merkens & Vafeidis, 2018; Neumann et al., 2015). Thus, there is a change in not only the hazards from SLR but also to the vulnerability and exposure from SLR, including the capacity for deployment of adaptation measures. In some settings such as deltas, higher population densities may also indirectly enhance human-induced subsidence, and this may need to be considered.

In the Coupled Model Intercomparison Project (CMIP) 6, the four RCP scenarios are complemented by five SSP scenarios (Riahi et al., 2017). Unlike in the earlier SRES global scenarios, there is no one-to-one correspondence between climate and socioeconomic scenarios, leading to many more possible combinations. However, it was recognized that some combinations are considered unlikely to occur or would require potentially infeasible mitigation actions to be achieved. In addition, there is the constraint of available computing power, and therefore, only a few RCP/SSP combinations are focused upon in the majority of the CMIP process (O'Neill et al., 2016; Tebaldi et al., 2020).

The SSP scenarios can also be downscaled to national/subnational coastal regions (O'Neill et al., 2017), and for detailed analysis, this is advised (Frame et al., 2018; Kebede et al., 2018; Merkens & Vafeidis, 2018). It is also worth noting that socioeconomic scenarios other than the SSPs can also be used in assessments where this is appropriate. For example, socioeconomic scenarios could be derived from local or national development plans. Some analyses use a two-

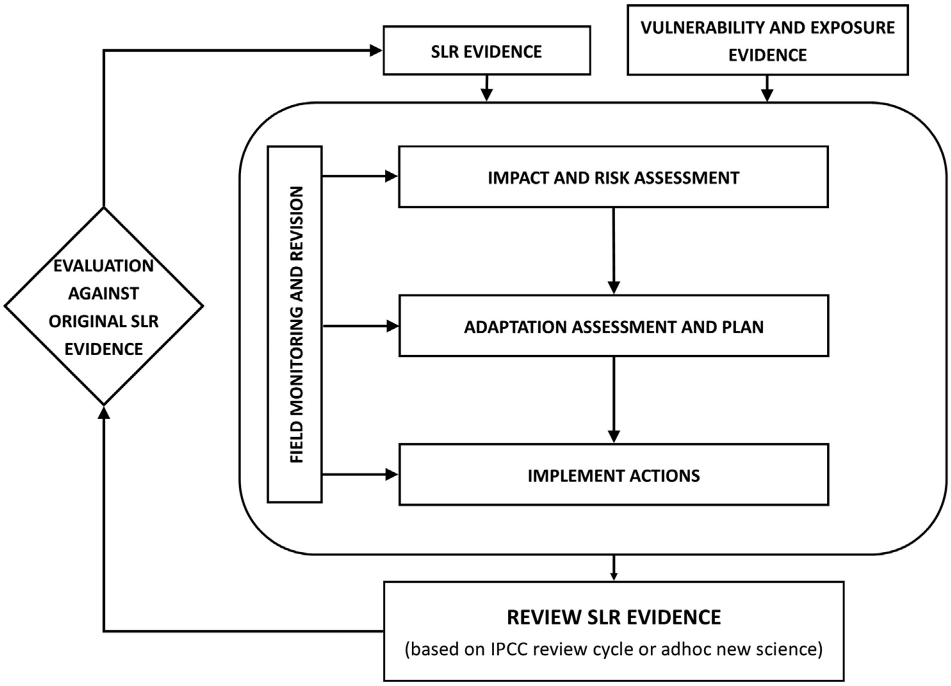


FIGURE 5 Process for the revision/updating of sea-level rise (SLR) evidence within risk and adaptation assessments and planning

by-two matrix of climate versus socioeconomic change (Deltacommissie, 2008). There is also scope to address local stakeholder needs, including participatory approaches (Allan et al., 2018).

5 | REVISION/UPDATING PROCESS OF SEA-LEVEL SCENARIOS FOR RISK AND ADAPTATION ASSESSMENTS

Building on Nicholls et al. (2014), this section considers the important issue of how to address updated scenario information, which should be expected and planned for in risk and adaptation assessment.

Over time, the scenarios and information used to inform and refine risk and adaptation assessments will be improved or updated. A critical question is whether the new SLR (and other) information is sufficient to change the approach or decisions concerning risk and adaptation assessments and resulting adaptation plans. Importantly, new information should not be seen as an automatic reason for abandoning existing adaptation plans (Dewulf & Biesbroek, 2018), but as an opportunity to assess (i) the plan's robustness in the light of new science and (ii) the utility of proactive planning strategies, especially in the longer term. Adaptation planning draws on two distinct and independent strands of information: (i) changes in the magnitude of SLR and the associated risks and (ii) the effectiveness of adaptation, which also depends on vulnerability and exposure. Hence, although both types of information will evolve, change in one type of information does not necessitate change in the other. In the case of new SLR projections, there is a need to re-interpret vulnerability and adaptation responses such as design thresholds for engineered systems (Ramm et al., 2018; Spirandelli et al., 2016) in addition to the ongoing observational monitoring of sea level in the real world. As experience grows, so appropriate guidance across all the adaptation approaches outlined by Oppenheimer et al (2019) can be developed.

An implication of the above is that there should be an evaluation process for assessing when and how to update an adaptation plan. This should be built directly into any plan and be designed to consider regular updates to SLR (and changes to vulnerability and exposure) information, as well as understanding of the effectiveness of adaptation. Figure 5 illustrates the dual aspects (hazard and exposure/vulnerability), which, when evaluated, may initiate a revision or update of an existing adaptation plan. For the hazard (i.e., SLR), new adaptation plans are often developed in response to new scenarios. Here, the counter view is advocated that, because of the high scientific uncertainty, there is value in considering old and new SLR scenarios together, although this is rarely done in practice. Where there is overlap with earlier SLR scenarios, this can lead to greater confidence in aspects of the climate or SLR modeling and new adaptation plans may not be necessary. Where new information either widens or narrows the spread of potential SLR, including its rate, there is value in understanding if this is because of additional evidence or because some of the older evidence is no longer valid. This understanding will again indicate whether or not a new plan is advisable and hence underpin informed decision-making. Updated information on aspects of exposure and vulnerability will also occur and may be more influential in terms of any adaptation plan revision than changes to SLR. These could be related to change in objectives or acceptable risk levels (EA, 2016; Phillips et al., 2018); the occurrence of an extreme event (Hill, 2012; Lumbroso et al., 2017); identification of new factors and drivers (e.g., changing development, demographic or economic trends or insights [Hardy & Hauer, 2018; Arto et al., 2019; Sayers et al., 2018; Jiménez et al., 2012]); changes in responsibilities (e.g., legal, administrative [Pitt, 2008]); and adoption of new/improved approaches (e.g., pathways approach [Haasnoot, Warren, & Kwakkel, 2019]).

For all types of new information, the level/type of change that would trigger a revision of the adaptation plan needs to be considered. This is particularly important for engineered adaptation responses as, if selected, the legacy of such structures often constrains future plans. No action is a valid decision, but this should arise from analysis rather than ignorance and inertia. The no action option is available in all types of adaptation decision framing, although its treatment will be different in methodologies that explicitly consider the value of delaying decisions such as real option approaches (Woodward et al., 2014; Wreford et al., 2020).

Evaluation of SLR scenarios can be either on a periodic or on a responsive basis. Re-evaluation of SLR scenarios against adaptation or vulnerability thresholds could therefore follow the regular updating of IPCC reports, which provide standard, reliable new SLR scenarios and update the science, or it might follow national guidance updates periodically updated linked to the IPCC cycle (every 6–7 years) as discussed in Section 2. For very risk-averse applications or where there is a particularly high rate of local observed or projected SLR, for instance, where this includes a large contribution due to local subsidence, then a shorter review period might be appropriate. Furthermore, it is not possible to anticipate how future SLR scenarios will evolve. Taking specific infrastructure as an example, the Thames Estuary Plan for London's tidal flood defenses includes a 5-year review period, which last took place in 2016, with a more comprehensive 10-year review for 2020. Another, more hypothetical, example is the construction of new nuclear power stations, which takes 10–20 years of design and construction followed by many decades of operation (Vidal, 2018). Just the design and construction period will experience multiple IPCC and new SLR information cycles. Considering a start in 2007 with the publication of the AR4 scenarios, two IPCC revisions with increasing projections would have been experienced to date (Figure 2), possibly triggering the need for a redesign. This shows the benefits of considering the H++ scenario range, which is particularly relevant to this problem (Wilby et al., 2011). In general, the design of SLR scenario evaluation within adaptation processes should consider the diverse user scenario requirements (Hinkel et al., 2019) to maximize relevance and effectiveness, such as major engineering projects as above versus poorer rural communities where retreat might be expected (Lincke & Hinkel, 2018).

6 | DISCUSSION

Since the first review guidance of Nicholls et al. (2014), there have been important developments in the science and practice concerning sea-level change, which influence but do not fundamentally change thinking about SLR scenarios. There have been improvements in the understanding of SLR, and there is more confidence in the understanding of key processes. At the same time, the paper of DeConto and Pollard (2016) has emphasized the deep uncertainty of some parts of the problem and stimulated much further discussion. It is important to remember that this paper is a single study in a large body of knowledge and ask how much does it change understanding of future scenarios? Much discussion of this paper treats it like a game changer that invalidates all previous SLR scenarios. Here, the authors argue that this is the wrong conclusion and it merely informs the science debate and practitioners should consider the full range of evidence. However, a growing body of evidence has followed DeConto and Pollard (2016) adding further information on physical processes and their likelihood (Bamber et al., 2019; Edwards et al., 2019), highlighting the importance of not ruling out the larger amounts of SLR in the H++ scenarios as presented in Nicholls et al. (2014). Overall, it is important to create a robust scenario framework that is designed to evolve with the collective understanding—including high-end SLR scenarios as well as changing understanding of exposure/vulnerability. This provides a flexible process that acknowledges that the deep uncertainty about future sea levels is likely to persist for the next few decades and risk and adaptation assessment and planning must operate under this constraint. The focus is on understanding the full range of possible changes, including the low probability but high consequence parts of the distribution. This is where sea-level science is most uncertain, but it is rightly focused upon under a risk management approach as this is extremely relevant for risk evaluation and adaptation decisions (Hinkel et al., 2019).

A single robust PDF for SLR capturing all sources of uncertainty is considered desirable to create certainty in decision-making by many users, but this cannot be provided due to irreducible uncertainty in future emissions. Also within a given emission scenario, it is argued here, the science is not yet at a point where this can be done robustly across the full range of outcomes. One approach to illustrating the different estimates of future SLR from alternative PDFs plus alternative estimates of the highest possible amounts of SLR is to draw on possibility theory (Le Cozannet, Manceau, & Rohmer, 2017). Although this still requires subjective choices to be placed on some of the information strands, it provides a tool to engage with potential users. In the absence of a single robust PDF that extends to the highest values, the H++ scenario approaches provide a pragmatic high-end range, which can evolve with our understanding (Stammer et al., 2019). The goal should be to engage decision-makers to think across the full range of possibility while also considering their level of risk aversion (Hinkel et al., 2019). However, planners should not focus solely on high-end scenarios; rather, these should be considered part of stress tests or surveys of what future adaptation options need to be kept open. An approach that is gaining attention is the use of storylines or plausible narratives to navigate and communicate the deep uncertainty in future climate response (Katsman et al., 2008; Shepherd et al., 2018), although it has yet to be extensively applied to SLR.

SLR during the 21st century has been the focus here, but it must be kept in mind that SLR is almost certain to continue long after 2100, even if atmospheric GHG concentrations are stabilized in this century. Further research and practice should also consider beyond the 2100 time horizon. This needs to include changes under the low emissions consistent with the Paris Agreement when SLR will still occur and require adaptation, albeit at a much slower and hence more manageable rate (Nicholls et al., 2018). The recent SROCC (IPCC, 2019) highlights the importance of these post-2100 SLR scenarios. However, caution should be used as the confidence beyond 2100 is likely to be lower than SLR scenarios for an earlier period (Palmer et al., 2018).

The science of sea-level change and the science of SLR risks and adaptation decision making are not considered together enough (Hinkel et al., 2019). However, adaptation approaches that address SLR uncertainty are coming to the fore (Haasnoot et al., 2013; Lawrence et al., 2018; Ranger et al., 2013). Adaptation can be addressed in a progressive and stepwise manner where SLR is planned for using current SLR scenarios, but the plan needs to be flexible enough to respond to monitoring and the increasing understanding of sea-level change over the coming decades, as addressed by the adaptation pathways approach (Haasnoot, Brown, et al., 2019). Although this approach is already widely applied, future work should also build on decision-making under deep uncertainty and promote flexible adaptation such as learning scenarios, real options analysis, and decision tree analysis (Marchau et al., 2019). This means that despite the large uncertainties, adaptation plans that minimize under- or overadapting (Hinkel et al., 2019; Wreford et al., 2020) such as building too high or too low, over- or underrelocating or over- or underreliance on nature-based adaptation can be formulated. Given that the uncertainties of SLR are universal, these approaches will probably be widely applicable around the world's coasts, especially in coastal cities with high values and growing flood risk (Hallegatte et al., 2013; Nicholls et al., 2015).

However, analysis often needs to begin with human decisions rather than SLR, which is the most insightful way to consider SLR adaptation. Some decisions are short-term, and hence, SLR is considered irrelevant. Other decisions are easily reversible and adjustable, and there is little need to anticipate future sea-level changes. However, long-term infrastructure such as flood defense systems or nuclear power stations and, more widely, coastal cities and settlements will often need to anticipate SLR beyond 2100. Land use and planning, including widespread land reclamation (Bisaro et al., 2019; Martín-Antón et al., 2016) and island creation/expansion (Brown et al., 2020; Watkin et al., 2019), also requires information on long-term SLR. The gap between science and practice provides an opportunity to develop coastal climate services to support these decisions (Le Cozannet, Nicholls, et al., 2017).

The analysis here has emphasized that, in addition to SLR, exposure and vulnerability need to be considered. In addition, adaptation to SLR is rapidly developing, especially the recognition of adaptation as an ongoing multistep process that needs to be linked to wider coastal development. To date, there has been a strong focus on engineered systems and accommodation, protection, and advance where quantitative estimates of SLR are needed for design (e.g., a dike height). SLR scenarios are also needed for retreat and nature-based approaches, and there is less application experience in this area, despite analyses such as Lincke and Hinkel (2018) suggesting that globally retreat (managed or otherwise) will be the dominate response (measured by coastal length). National analyses also suggest increased utilization of retreat and the need for transitions from "hold the line" to more dynamic coasts (CCC, 2018).

In selecting an adaptation, the social and political economy dimensions of SLR risk and adaptation also need to be acknowledged. The coastal zone supports diverse livelihoods, economic activities, and cultural identities, giving rise to social conflicts among actors with diverging interests in coastal zone development and adaptation (Graham et al., 2013; Hinkel et al., 2018; Oppenheimer et al., 2019; Ramm et al., 2018). As a result, it is generally contested what constitutes "good" adaptation, and hence, any approach to adaptation should consider the diversity of values and interests of stakeholders affected by SLR and adaptation (Gorddard et al., 2016; Sovacool et al., 2015; Wise et al., 2014). Improved understanding across these diverse situations will develop in practice, and it is important that the learning concerning SLR scenarios is captured and synthesized for wider application.

7 | CONCLUSION

SLR scenarios have been applied to risk and adaptation assessment and planning for more than 30 years. Over time, these scenarios have become more sophisticated as scientific knowledge increased and the components of sea-level change were better defined. Hence, today, a much more sophisticated set of sea-level scenarios is possible, including extremes, and significant developments can be expected in the coming few years. Nonetheless, deep uncertainty still remains a concerning key factor, especially the potential ice sheet contribution to mean sea level (IPCC, 2019), and this is unlikely to be resolved in the near future.

To undertake risk and adaptation assessment in this situation of high uncertainty requires a pragmatic approach that recognizes both end-user needs and what sea-level science can provide. Sea-level scenarios have evolved with appreciation of these issues, and this evolution should be expected to continue with regular updates from the IPCC and sporadic inputs when new journal papers with different projections or views appear (e.g. DeConto & Pollard, 2016), triggering debate. It is argued here that as new knowledge on SLR emerges it should be analyzed and incorporated alongside earlier work as part of the overall body of knowledge, rather than being seen to automatically supersede it. Scenario development should be designed to reflect this process and be evolutionary and flexible to changing understanding, while building on earlier work. Periodic review and learning are relevant regardless of which particular adaptation decision-making approach is used. As such, scenario development should be seen as an ongoing process that is complementary to risk and adaptation assessment and planning and is relevant to the multiple types and approaches to adaptation.

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CONFLICT OF INTEREST

The authors have declared no conflicts of interest for this article.

AUTHOR CONTRIBUTIONS

Robert Nicholls: Conceptualization; writing-original draft; writing-review & editing. **Susan Hanson:** Conceptualization; writing-original draft; writing-review & editing. **Jason Lowe:** Conceptualization; writing-original draft; writing-

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DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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ENDNOTES

[1] The IPCC definition of adaptation is used here "The process of adjustment to actual or expected climate and its effects. In human systems, adaptation seeks to moderate or avoid harm or exploit beneficial opportunities." The following adaptation options are identified for relative sea-level rise: advance, protect, accommodate, retreat, and ecosystem-based adaptation (Oppenheimer et al., 2019).

[2] The term risk assessment is used throughout this paper in preference to impact assessment as it incorporates both impact and probability and follows general usage in climate change assessment.

[3] The time-mean sea-level change component includes some sources of variability such as those due to thermal expansion, ice melt, or terrestrial water storage, but excludes storm surges, tides, and waves.

[4] Low-end SLR is less relevant than high-end SLR estimates, but has applications for example in areas with high rates of land uplift (e.g., northern Baltic) where relative sea-level could start to rise or maybe continue to fall (Shennan et al., 2018). However, this paper does not include low-end scenarios due to insufficient information being available.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of this article.

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