Advanced Review

Sea-level scenarios for evaluating coastal impacts

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Global-mean sea-level rise will drive impacts and adaptation needs around the world's coasts over the 21st century and beyond. A key element in assessing these issues is the development of scenarios (or plausible futures) of local relative sea-level rise to support impact assessment and adaptation planning. This requires combining a number of different but uncertain components of sea level which can be linked to climatic and non-climatic (i.e., uplift/subsidence of coastal land) factors. A major concern remains about the possibility of significant contributions from the major Greenland and Antarctic ice sheets and this must be factored into the assessments, despite the uncertainty. This paper reviews the different mechanisms which contribute to sea-level change and considers a methodology for combining the available data to create relative (or local) sea-level rise scenarios suitable for impact and adaptation assessments across a range of sophistication of analysis. The methods that are developed are pragmatic and consider the different needs of impact assessment, adaptation planning, and long-term decision making. This includes the requirements of strategic decision makers who rightly focus on low probability but high consequence changes and their consequences. Hence plausible high end sea-level rise scenarios beyond the conventional Intergovernmental Panel on Climate Change (IPCC) range and which take into account evidence beyond that from the current generation of climate models are developed and their application discussed. Continued review and development of sea-level scenarios is recommended, starting with assimilating the insights of the forthcoming IPCC AR5 assessment.

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INTRODUCTION

Global-mean sea-level change is one of the more certain impacts of human-induced climate change, although the magnitude of future change remains uncertain. Furthermore it is likely that sea-level changes will continue for centuries even if greenhouse gas (GHG) emissions concentrations were to be stabilized owing to the time scales associated with climate processes and feedbacks.[1–5] Given the large and growing concentration of population and economic activity in the coastal zone, as well as the importance of coastal ecosystems, the potential impacts of sea-level change have evoked widespread concern for more than two decades.[6–8]

Some potential impacts of a change in sea level have already been assessed locally, nationally, regionally, and globally.[9–11] However, the scope of assessment and the methodologies employed have varied significantly. Most of these studies have been based on scenarios: alternative images

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of the future, which facilitate the assessment of developments in complex systems that are either inherently unpredictable, or have high scientific uncertainties.[12,13] The reliability of, or difficulties associated with, developing and using scenarios has emerged as an important problem and constraint for impact and adaptation studies. Since the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) in 2007, some organizations and countries have invested considerable resources in developing such scenarios,[14–16] and generic sea-level scenario guidance drawing on the AR4 and some post-AR4 insights was produced.[17] Ongoing development of such guidance is essential to assist scientists, engineers, and policy analysts who are assessing impacts and potential responses to sea-level change, across the world's coasts. Decisions about impacts and adaptation cannot be delayed until better sea-level scenarios emerge, and ignoring high end uncertainty can lead to misleading impact assessments and poor decisions.[18,19]

This paper reviews the different mechanisms which contribute to sea-level change. It considers a methodology for combining the available data to create relative (or local) sea-level rise scenarios that is suitable for impact and adaptation assessments across a range of sophistication of analysis. This paper considers these scenario needs and provides generic guidance on their development and appropriate use from the perspective of the end user while drawing on the best sea-level science. It considers the full range of situations from cases of little data and few or no previous studies to those where significant data and experience of earlier studies are available. The timescale is between 30 and 100 years into the future as this corresponds to the most relevant timescales considered for most developments in the coastal zone. Longer timescales may be relevant in some cases,[20] and in the future this is expected to receive more attention.

The starting point is the AR4 and the extensive discussion on sea-level change which it has stimulated. For example, in the AR4, the quantified rise is between 18 and 59 cm by the 2090s, representing the 5th–95th percentile range of sea-level change due to thermal expansion, melting of small glaciers, surface melting of the major ice sheets, and a time invariant dynamic ice sheet term.[21] However, this excludes the larger potential contribution of sea-level rise from the enhanced melting or collapse of the Greenland and Antarctic ice sheets.[4,22] Observational evidence since 2000 has increased concerns that a more rapid contribution to sea-level rise from the Greenland and Antarctic ice sheets might be occurring,[23–26] although there is mixed evidence as whether this represents a long-term trend or decadal or multi-decadal variability.[27,28] Thus, a possible upper limit for 21st century global-mean sea-level rise, although both potentially large and poorly quantified, represents an extension to the 18–59 cm range previously mentioned.[29] The AR4 does provide an illustrative estimate of the additional sea-level change that might result from increased ice discharge during the 21st Century of up to 17 cm, derived by scaling observed ice dynamic contributions linearly with predicted warming. Importantly, higher contributions from this source are not excluded (IPCC, Ref 21, p. 14; Ref 29, p. 45). While such large sea-level rise scenarios ($\geq$1-m rise) are considered unlikely during the 21st century, the potential contribution to risk is of sufficient concern to merit consideration in impact and adaptation studies. In policy terms, low probability but high consequence events rightly attract interest, including questions about what adaptation responses would be available if such a situation was realized. Hence, scenarios that include a full range of estimates of sea-level rise over the next 100 years are considered here, as well as a discussion of their application.

The paper is structured as follows. Section *Sea-Level Rise and Impact and Adaptation Assessment* considers sea-level rise and impact/adaptation assessment. Section *Relative Sea-Level Change Components* discusses relative sea-level change and its components. Section *Methods for Relative Sea-Level Scenario Development* considers methods of sea-level rise scenario development, including high-end scenarios. Section *Scenario Choice and Availability for Impact and Adaptation Assessment* considers the selection of scenarios for application. Section *Discussion* discusses the implications and Section *Conclusion* concludes.

SEA-LEVEL RISE AND IMPACT AND ADAPTATION ASSESSMENT

Sea-level impact and adaptation studies are important as they have significant socioeconomic effects[11] associated with the following physical consequences of any change in coastal water levels:

- Inundation, flood and storm damage;
- Long-term wetland loss (and change);
- Long-term erosion (direct and indirect morphological change);
- Potential saltwater intrusion.

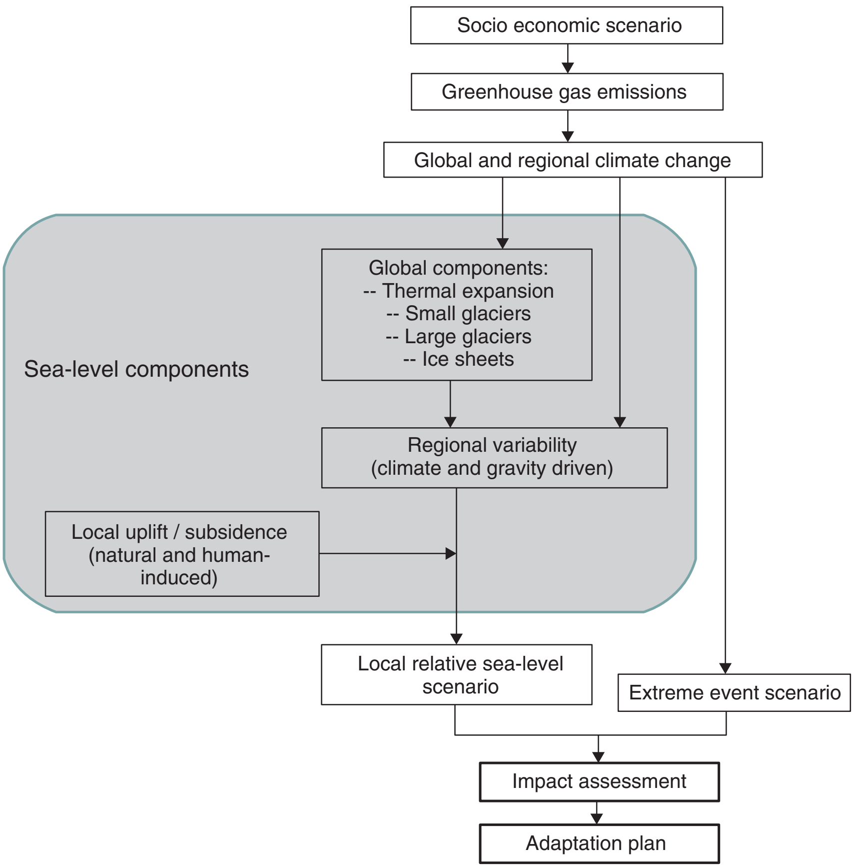

FIGURE 1 | Components for developing sea-level scenarios within impact assessment and adaptation planning. With the Special Report on Emissions Scenarios (SRES) there is a 1:1 relationship between the socioeconomic scenario and resulting climate change; the newer representative concentration pathways (RCPs) are not coupled to single socioeconomic scenarios and the analysis starts with the greenhouse gas trajectory.

The standard impact assessment approach is often described as top-down as it combines scenarios downscaled from global climate models to the local scale with a sequence of analytical steps that begin with the climate system and move through biophysical and then socioeconomic impact assessment and ultimately to adaptation strategies[30,31] (Figure 1). Importantly, sea-level changes are caused by relative (or local) changes, which are composed of the sum of global, regional, and local trends related to changing oceans and land levels which can be significant (see Figure 2), reflecting the different sea-level processes occurring at each location. For instance, Nezugaseki, Japan, exhibits a sudden abrupt sea-level change due to a natural phenomenon (an earthquake) which would cause significant and unavoidable changes; Bangkok, Thailand, shows acceleration in the rate of sea-level rise in the 1960s due to more rapid subsidence from increasing groundwater extraction; relative sea level at Helsinki, Finland, is falling due to the rising of the land surface which may offset the potential impacts of any climate-induced rise in sea level.

It is important to remember that at all stages of an impact and adaptation assessment process, a diverse range of uncertainties are encountered. A large uncertainty surrounds future GHG emissions and the possible evolution of their underlying drivers, as reflected in a wide range of future emissions pathways in the literature.[32,33] This uncertainty is compounded in going from GHG concentrations in the atmosphere to global and regional climate change; from regional change to local change, local change to potential and actual impacts; and finally from these to the formulation of adaptation and mitigation measures and policies. These uncertainties are discussed further in the following sections.

RELATIVE SEA-LEVEL CHANGE COMPONENTS

Relative sea-level change for a specific location needs to consider the contributions from the components at all scales (see Figure 1).[17] It is possible to integrate

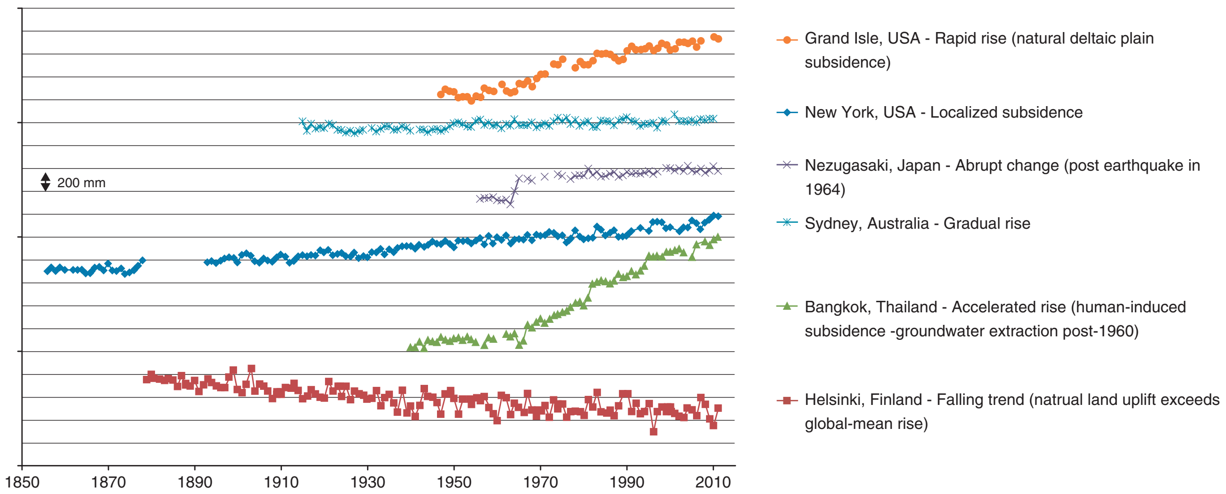

FIGURE 2 | Contrasting relative sea-level observations over the 19th/20th/early 21st centuries. The offsets between records are for display purposes. Data from the permanent service for mean sea level (http://www.pol.ac.uk/psmsl/).

these for a given site using Equation 1:

$$\Delta RSL = \Delta SL_G + \Delta SL_{RM} + \Delta SL_{RG} + \Delta SL_{RLM} \quad (1)$$

where, ΔRSL is the total change in relative sea level, ΔSL_G the change in global mean sea level, ΔSL_{RM} the regional variation in sea level from the global mean due to meteo-oceanographic factors, ΔSL_{RG} the regional variation in sea level due to changes in the earth's gravitational field, and ΔSL_{RLM} the change in sea level due to vertical land movement.

These components are now considered in turn.

1. *Global-mean sea-level change* (SL_G) is a result of the change in the global volume of the ocean. In the 20th/21st century, this is expected to be primarily because of (1) thermal expansion of the ocean as it warms (e.g., Yin et al.[34]), (2) the melting of small glaciers and ice caps due to global warming,[4,35,36] and (3) changes in the mass balance of the Greenland and Antarctic ice sheets which are less certain.[3,28,37–40] Other processes such as human modifications to the hydrological cycle are typically less significant when considering contributions to future change, although this should be reviewed as knowledge develops.[41] Recent progress[42,43] has demonstrated that the measured global sea-level rise during the 20th century can largely be reconciled with the sum of the potential sources when uncertainty is included, with particularly good agreement in recent years (Table 1).

2. *Regional and/or local spatial variations* in sea-level change due to three causes:

a. *meteo-oceanographic factors* (SL_{RM}) such as differences in the rates of oceanic thermal expansion, changes in long-term wind and atmospheric pressure, and changes in ocean circulation.[44–49] These factors could be significant, causing large regional departures of up to 50–100% from the global average value for the thermal expansion component of sea-level change. However, coupled atmosphere–ocean general circulation models (AOGCMs) of these effects under global warming do not agree on the pattern of change.[4,34,50]

b. *Changes in the regional gravity field of the Earth* (SL_{RG}) due to ice melting (caused by redistribution of mass away from Greenland, Antarctica as well as small glaciers). This means that global sea-level change caused by the melting of an ice sheet will not be evenly distributed as a single 'global eustatic' or global-mean value.[51–53]

c. *Vertical land movements (uplift and subsidence)* (SL_{RLM}) due to various natural and human-induced geological processes.[54–57] Natural causes include (1) neotectonics, (2) glacio-isostatic adjustment (GIA), and (3) sediment compaction/consolidation. In addition, human activity has often influenced rates of subsidence in susceptible coastal lowlands such as deltas by land reclamation and by lowering water tables through water extraction and improved drainage.[58,59] These human-enhanced processes are generally localized to Holocene-age deposits and can locally exceed the magnitude of changes expected owing to climate change through the 21st century.[60–64]

TABLE 1 | Contributions to the Sea Level Budget (mm/year) Since 1972 based on Church et al. Ref 43

Component	1972 to 2008	1993 to 2008
Total from tide gauges	1.83 ± 0.18b	2.61 ± 0.55
Total from tide gauges and altimeter	2.10 ± 0.16	3.22 ± 0.41
1. Thermal expansion	0.80 ± 0.15	0.88 ± 0.33
2. Glaciers and ice caps	0.67 ± 0.03	0.99 ± 0.04
3. Greenland ice sheet	0.12 ± 0.17	0.31 ± 0.17
4. Antarctic ice sheet	0.30 ± 0.20	0.43 ± 0.20
5. Terrestrial storage	−0.11 ± 0.19	−0.08 ± 0.19
Sum of components (1+2+3+4+5)	1.78 ± 0.36	2.54 ± 0.46

The regional components of relative sea-level rise are generally less well quantified than the global components at present. Nonetheless, it is important that they are considered in impact and adaptation assessment to make the link between (global) climate change and (regional to local) coastal management strategies.

METHODS FOR RELATIVE SEA-LEVEL SCENARIO DEVELOPMENT

There are several different methods for determining appropriate sea-level scenarios according to the purpose of the assessment and available data.[17,65] These include (1) extrapolating observed data, (2) process-based or statistical models at global and regional scales, and (3) synthetic methods. These are considered in turn.

Observed and Extrapolated Trends

Extrapolations of sea-level trends from the observed data (e.g., tide gauge records, Figure 1) are useful as a direct method for creating local relative sea-level scenarios. They are particularly useful where the planning or projection time-scale is short, especially when compared to the dominant periods of natural variability affecting a given region.[17] Extrapolation ideally requires 50+ years of data,[66] although this can be reduced to 30–35 years if there are sufficient long-term records available to use sea-level index methods.[67,68] In areas of rapid subsidence such as delta plains, or subsiding cities, analysis of shorter records can still provide a constraint on the rate of subsidence (e.g., Bangkok and Grand Isle in Figure 2).

It is also important to remember that impacts are often more related to temporal extremes of sea level, rather than the annual average value. Analysis of records of observed water levels can provide estimates of return periods of extreme levels and their trends at specific locations.[69,70]

Model-Based Global-Mean Sea-Level Change

Climate model simulations are commonly undertaken to estimate the magnitude and rate of sea-level change resulting from global warming-related factors. To address the uncertainty associated with climate system dynamics and future GHG emissions, the IPCC developed a range of ‘alternative’ futures related to how varying socioeconomic and technological factors may influence future emissions and climate change termed the Special Report on Emissions Scenarios (SRES).[71] These SRES scenarios were used in the AR4 and are still used in many studies and assessments, such as the United Kingdom Climate Change Risk Assessment.[72] The IPCC Fifth Assessment Report (AR5) (which will be released in stages during 2013 and 2014) is using a new set of GHG concentration trajectories called the representative concentration pathways (RCPs).[33,73] The RCPs are named according to the radiative forcing at the end of the 21st century, with the lowest trajectory RCP2.6 expected to give an eventual warming around 2°C above preindustrial levels for equilibrium climate sensitivity of around 3°C.[74] The trajectory with the highest concentrations, RCP8.5, is expected to give a warming in excess of 4°C for a transient climate response of around 2°C (which falls within both model and observationally constrained estimates).[75] By design, the lowest RCP gives a warming considerably below that resulting from the lowest SRES scenario for the same climate model parameters.

As our scientific understanding improves, a common objective is to narrow the uncertainty range of likely sea-level rise. However, under our current understanding of possible changes, while 21st century sea-level rise below 1 m is still considered more likely, there remains a low but not negligible risk of much larger rises (>1 m) in sea level, which are of particular relevance to impact and adaptation assessment.[19,76] The precise quantitative properties of this part of the distribution are simply not known at the present time. Consequently, Lowe et al.,[14] Nicholls et al.,[77] and Horton et al.[65] among others consider two ranges of future global-mean sea-level values: (1) the AR4 range, as reported in the IPCC Synthesis report[29] and (2) a more extreme range derived from a range of sources which describes the low probability tail. These are here termed the *AR4 S* and *H++* ranges, respectively. They

TABLE 2 | Estimates of Global-Mean Sea-Level Rise for the 21st Century (Relative to 1980 to 1999) Excluding the Carbon Feed-Back Cycle for the Six SRES Marker Scenarios

				SRES Marker Scenario					
				B1	B2	A1B	A1T	A2	A1FI
2025	*AR4 S*	Range (m)	High	0.12	0.11	0.13	0.14	0.09	0.10
			Low	0.06	0.06	0.07	0.08	0.07	0.07
	H++	Range (m)	High	0.25	0.25	0.25	0.25	0.25	0.25
			Low	0.09	0.10	0.11	0.11	0.11	0.13
2055	*AR4 S*	Range (m)	High	0.23	0.23	0.26	0.27	0.23	0.26
			Low	0.12	0.10	0.12	0.15	0.13	0.15
	H++	Range (m)	High	0.75	0.75	0.75	0.75	0.75	0.75
			Low	0.22	0.25	0.27	0.26	0.29	0.33
2085	*AR4 S*	Range (m)	High	0.34	0.38	0.42	0.40	0.43	0.50
			Low	0.16	0.15	0.17	0.22	0.19	0.23
	H++	Range (m)	High	1.52	1.52	1.52	1.52	1.52	1.52
			Low	0.39	0.45	0.51	0.48	0.53	0.63
2095	*AR4 S*	Range (m)	High	0.38	0.43	0.48	0.45	0.51	0.59
			Low	0.18	0.16	0.19	0.24	0.21	0.26
	H++	Range (m)	High	1.83	1.83	1.83	1.83	1.83	1.83
			Low	0.46	0.53	0.60	0.57	0.63	0.75

AR4 *S* is the range taken from the IPCC AR4 Synthesis Report.[29] H++ is a more extreme range based on various sources (see Section *The H++ Range of Sea-Level Change*). The *H++* low value for each scenario is scaled up ice discharge and the top of the *H++* range comes from assuming 2 m at 2100.[17] All values are period-averaged values for relevant decade containing the year.

should be updated as new data becomes available (e.g., AR5), with the ultimate goal of merging into a single range or distribution as understanding improves. While impact and especially adaptation assessments may focus on the *AR4 S* as discussed below, the inclusion of the *H++* range allows for pragmatic sensitivity and uncertainty testing, reflecting the user's purpose and risk aversion. It also recognizes that the *AR4 S* range, or that from more recent modeling studies, may not be able to represent some key physical behaviors, namely the contribution from ice dynamic processes, that may add significantly to sea-level rise on a century timescale.[39] The AR4 S range is discussed here and the H++ range is discussed further in Section *The H++ Range of Sea-Level Change*.

AR4 provides projections for the quantifiable components of the sea-level budget using a hierarchy of models. These range from coupled AOGCMs through to simple climate models (SCMs) forced by a variety of emissions scenarios to model global sea-level change (a discussion of the different models can be found in Randall et al.[78]). For each SRES marker scenario, change is represented by 5–95% range based on the spread of AOGCM results, not including uncertainty in carbon cycle feedbacks (Table 2). Thermal expansion is the dominant contribution to sea-level change during the 21st century with glaciers and ice caps, and the Greenland Ice Sheet also projected to contribute positively. Further, the average rate of sea-level rise is expected to exceed the 1.8 mm/year rate observed between 1961 and 2003, although not all scenarios sustain a rise above the 3 mm/year observed over the last couple of decades.[23]

The AR4 assessment shows that losses from the ice sheets of Greenland and Antarctica have very likely contributed to sea-level rise over the period 1993–2003.[26] There has been considerable speculation about possible abrupt sea-level changes in future, owing to rapid melting and/or collapse of ice in the Polar Regions,[26,37,79,80] including their secondary effects via changes to ocean circulation.[81] AR4 included a sensitivity calculation in which rapid ice dynamics are scaled with projected change in temperature, but considered it impossible at the time to specify an upper end of a range for sea-level change. More recent simulations, for instance in the ice2sea project,[82] have improved our understanding, for instance, of fast ice streams and outlet glaciers on ice sheets and their interaction with the ocean but considerable uncertainty remains.

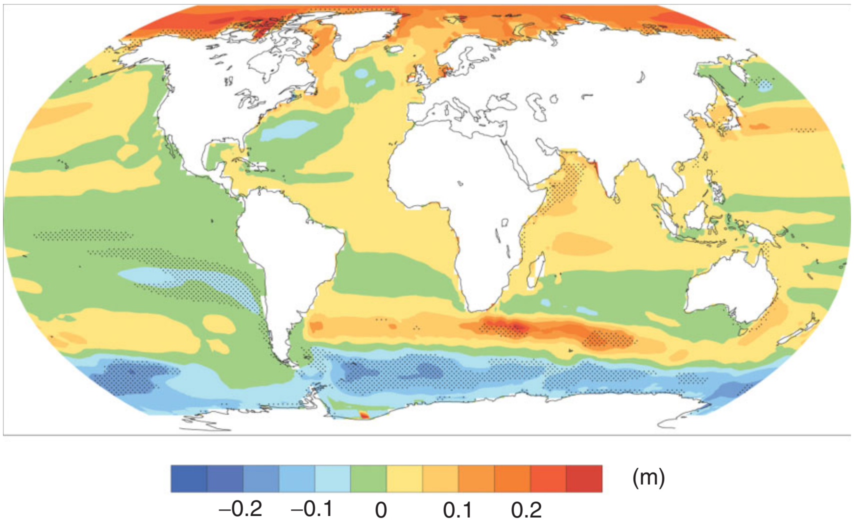

FIGURE 3 | Ensemble mean variations in local sea-level change (m) from the global average (i.e., positive values indicate greater local sea level change than global) during the 21st century with the SRES A1B scenario. Stippling indicates where the variation between the models is less than the ensemble mean. (Source: Figure 10.32 of Ref 4. Many similar features are seen in the more recent analysis of Yin[34]).

Model-Based Regional Sea-Level Change

To date, most coastal impact and adaptation assessments have ignored regional variations in sea-level scenarios, largely because of a lack of technical guidance and access to the necessary data in a usable form. Nevertheless, regional and local assessments would benefit from considering the components of sea-level change on a more individual basis, as the uncertainty for sea-level change during the 21st century at any site is very likely to be larger than the global-mean scenarios alone suggest.

Meteo-Oceanographic Factors (SL_{RM})

Regional variations in atmospheric circulation, ocean circulation and warming rates, spatial variations in mass redistribution, and the interactions between them can lead to significant deviations of regional sea-level change from the globally averaged trend. These can be estimated with AOGCMs, which simulate the geographic distribution of sea-level change caused by ocean processes[34,83] 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.[84] However, the continuing lack of similarity in spatial patterns between the models means that confidence in regional sea-level projections is currently low. The AR4 combined (or ensemble) model results[85] are shown in Figure 3. This shows a smaller than average sea-level rise 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, or wind stress change[86] or thermal expansion.[44] Recent work with post-AR4 models have extended these results.[34,47]

To create scenarios, the regional pattern of thermal expansion under SRES forcing can be approximated using a pattern-scaling method.[49,87] While 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 sea-level scenario generation.[88]

Another approach for constructing local sea-level scenarios based on the SRES-forcing makes qualitative use of available information for a sensitivity analysis. For example, where the local deviations from the global mean from a set of climate models are not available, the range of uncertainty can be captured by applying a ±50% factor of global-mean change.[89]

Changes in the Regional Gravity Field of the Earth (SL_{RG})

This factor has not been widely considered to date. This is particularly important for scenarios with a large ice melt component, but less so for those dominated by thermal expansion. For example, Katsman et al.[15] incorporate the impacts of gravitation changes in their construction of sea-level rise scenarios for the northeast Atlantic by multiplying the eustatic contributions from ice melt with the ratio of the local to global-mean sea-level rise shown in Figure 4. Boesch et al.[90] makes a similar calculation for the US East

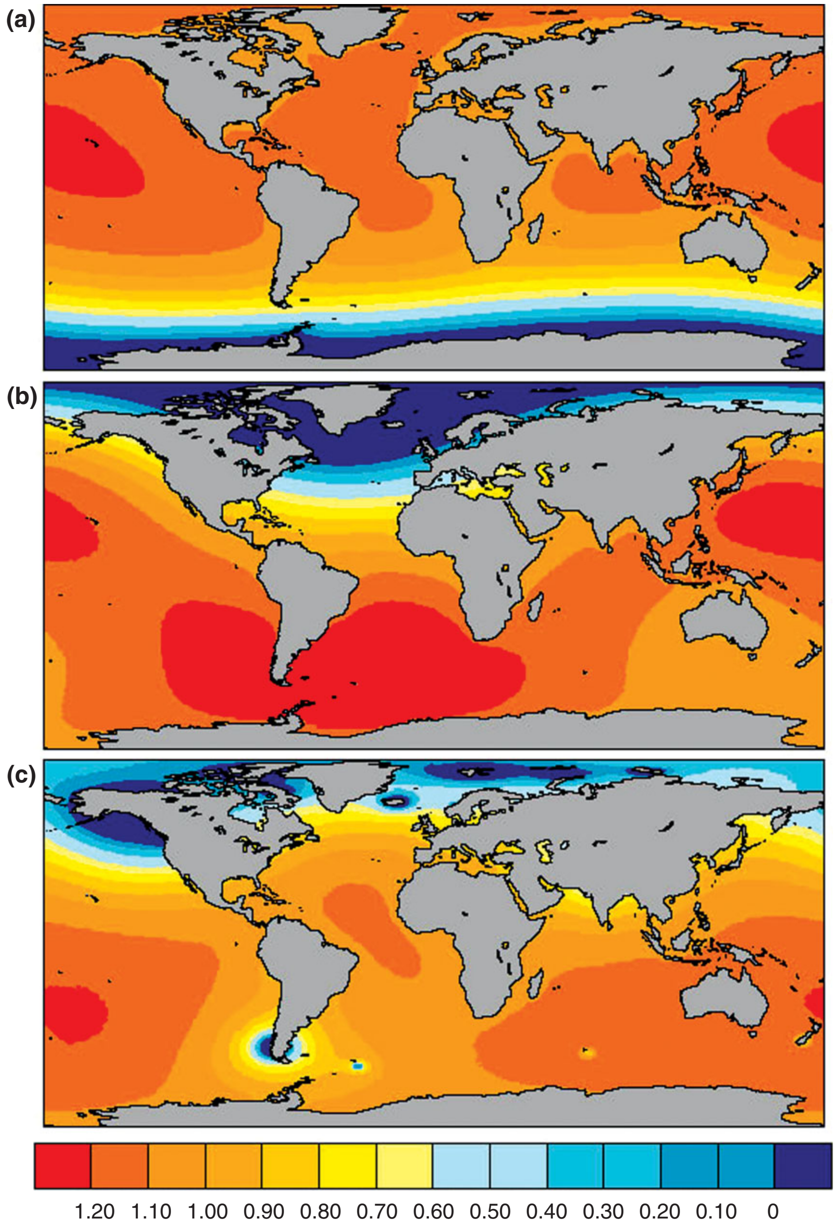

FIGURE 4 | (a) Sea-level rise (in mm) caused by melting of an amount of Antarctic land-ice equivalent to 1 mm of globally average sea-level rise. (b) Analogous calculation, but for Greenland land-ice. (Reprinted with permission from Ref 53. Copyright 2001 Nature Publishing Group)

Coast. More recent estimates of this term have some similar large scale features[51,52,91]

Vertical Land Movements (Uplift and Subsidence) (SL_{RLM})

In general, during the 21st century, vertical land movement is expected to be less than the rise resulting from oceanographic changes in most locations, because in most parts of the world, rates are typically only 1–2 mm/year. However, correcting for vertical land motions matters because depending on their sign they may amplify or reduce the effects of future sea-level rise. While some regional-scale modeling may be available (e.g., city scale), rates of vertical land movements can be problematic as long data sets are required.[92–94]

To estimate the contribution of local land movement to relative sea-level change in the future, the climate change related portion of sea-level rise needs to be subtracted from the observed local trend. Various methods have been advanced to quantify and correct for this local trend,[95,96] including using one or more of long-term geological data, tide gauge, or GPS measurements.[55,97] However, these techniques are only available at specific sites and have a significant uncertainty.[98]

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.[99–101] 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 very significant subsidence rates,[57,102–105] e.g., up to 8 mm/year at Grand Isle within the Mississippi delta (Figure 1).

Where neither modeled nor observed sea-level records are available, either regional[55,106] or global (e.g., Peltier[56]) datasets on the GIA vertical component based on models can be used. Corrections for GIA using the Peltier[56] GIA model are posted on the Permanent Service for Mean Sea-Level (PMSL) web site for individual tide gauges from around the world (http://www.psmsl.org/train_and_info/geo_signals/gia/peltier/). However, note that all the other natural and human-induced geological components of sea level are not included.

Human-induced subsidence can also be important and needs to be captured in sea-level impact and adaptation assessment, where relevant. For instance, the World Bank[107] considers subsidence to be a comparable threat to climate-induced sea-level rise for coastal cities on Asian deltas such as Shanghai and Bangkok. Forecasting future subsidence is difficult and the best approach is a guided sensitivity analysis drawing on local experience, or possibly analogues from similar settings. In some ways significant subsidence is similar to the H++ scenario, a large plausible change with high uncertainty, so there is a need to consider it within assessments, but the judgement of the assessor will also be critical. Hence, the assumptions made for this factor need to be explicit, so they can be discussed and debated.

Synthetic Methods and Sensitivity Studies

Where there is no data available or the alternative ways of generating sea-level scenarios are not considered to be applicable, it is still possible to carry out an impact analysis. This is performed by using a nominal value for the change in sea level (e.g., 0.5, 1, and 1.5 m) with no given time period. This method has been successfully used in a number of studies from country to global scales.[13,108] A range of values can be used to develop an appreciation of the potential impacts or determine thresholds in the magnitude of impacts.

The complexity of the scenarios required depends upon the question being posed from scoping analyses of the magnitude of the problem to more detailed impact assessments, and ultimately analysis of adaptation measures. Many national and subnational impact assessments to date have focused on a uniform 1-m rise in relative sea level, following the recommendations of the IPCC Common Methodology first published in 1991.[109]

The H++ Range of Sea-Level Change

The current generation of models does not include all of the processes that govern future sea-level rise, including climate-carbon cycle feedbacks or the full effects of changes in ice sheet flow.[29] There is a considerable body of literature suggesting that rapid deglaciation in Greenland or Antarctica could lead to global sea-level rise during the next few centuries in the order of several meters,[21] but considerable uncertainty remains.[37] The potential contribution to global sea level from a rapid collapse of the West Antarctic Ice Sheet (WAIS) would raise sea level by up to 3.3 m[22] occurring over a period variously estimated as 5–50 centuries, though possibly faster.[110,111] Such an abrupt disintegration of the WAIS is considered to have a low probability during the 21st century,[112,113] although its likelihood could increase substantially in successive centuries[3] depending on the rate of climate change during this century. More recent estimates (see Table 3) attempt to use a range of evidence and methods to estimate the potential 21st century contribution from ice sheets to sea-level rise.

Semiempirical approaches, based on the assumption that a quantitative relationship can also be developed between past global sea level and temperature change, allow the calculation of future sea-level rise directly from climate model predictions of future global warming. In these studies, uncertainty in projected warming is often included which can provide a probability distribution of sea-level rise. There is debate about the validity of these approaches[124–130] and projections are generally greater than the IPCC models (Table 3A). Approaches based on physical constraints, past analogues, and expert judgement (Table 3B, C) have also generated variable rates of global sea-level rise or estimated contributions from individual components.

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 and, until these rates can be either ruled out or their probability estimated, it is prudent to at least assess the impact on coastal assets with high value in the event of such large rises.[112] A key difficulty is providing a plausible high end (H++) scenario range for sea-level scenarios.

TABLE 3 | Comparison of Sea-Level Change Projections for the 21st Century

Study	21st Century Sea Level Rise (m)	Comment
IPCC		
IPCC AR4[4]	0.18–0.59 m	Without future acceleration of Greenland and Antarctic dynamic term
IPCC AR4[4]	Up to 0.76 m	With future acceleration of Greenland and Antarctic dynamic term
A (Semiempirical Models)		
Rahmstorf[114]	0.5–1.4 m	Semiempirical, derived using observations
Horton et al.[115]	0.54–0.89 m	Semiempirical, derived using simulated past temperature and sea level rise. Excludes high end emission scenarios (A1FI). Not including statistical uncertainty in the fit
Vermeer and Rahmstorf[116]	0.75–1.9 m	Semiempirical, derived using observations
Jevrejeva et al.[117]	0.6–1.6 m	Semiempirical, derived using observations
Grinsted et al.[118]	0.72–1.6 m (based on Moberg temperatures) or 0.96–2.15 m (based on Jones and Mann temperature)	Semiempirical, derived using observations
B (Physical Evidence)		
Pfeffer et al.[39]	2 m possible. 0.8 m more plausible	Based on physical constraints of deglaciation
Rohling et al.[119]	1.6 ± 0.8 m	Based on combining coral data with sea-level reconstruction using stable oxygen isotope records during last interglacial period (a palaeo-climate analogue)
Kopp et al.[120]	0.56–0.92 m	Ice sheet component only based on sea level indicators spanning the last interglacial stage (a palaeo-climate analogue)
New York Panel on Climate Change,[121]	1 m	Ice melt component only based on the average rate of sea-level rise during the last deglaciation
Grant et al.[122]	1.2 m	Sea-level reconstruction using stable oxygen isotope records over the last 150,000 years, including the last interglacial period (a palaeo-climate analogue). Rates are averaged over a millennium, so do not constrain rates over shorter periods
C (Expert Elicitation)		
Bamber and Aspinall[123]	0.84 m (95th percentile)	Ice melt term only, to which other sea-level components need to be added
D (Combined)		
UKCP09[14]	0.12–0.76 m from IPCC range, and up to 2 m (H++)	Based on IPCC and physical reasoning. Numbers are for the UK without land movement
Katsman et al.[15]	0.55–1.15 m (global)	Based on IPCC and physical reasoning

Here, one is developed (see Table 2) based on the AR4 and recent papers (see Table 3); effectively, this is a type of guided sensitivity scenario based on expert judgement of the sea-level science.

Following AR4, the lower bound of the *H++* range is derived by scaling with projected temperature increases, the recent observed contributions from Greenland and the WAIS to sea-level change, and combining them with projected change in sea level from current models. This results in a lower bound of around 75 cm by 2090–2099 relative to 1980–1999 for the A1FI SRES scenario [59 cm (*sea-level rise*) +17 cm (*scaled up ice sheet discharge*) in Table 10.7 of Meehl et al.[4]]. Globally, the upper bound for this global *H++* range follows the reasoning of Rohling et al.[119] and considers the dynamic effects of the ice sheets as advocated by Pfeffer et al.[39] On the basis of an analogue of the last interglacial (about 127,000 to 110,000 years ago) when sea level, climate, and ice masses were broadly similar to today, sea levels are estimated to have risen up to 1.6 ± 0.8 m/century with contributions coming from both the Greenland and Antarctic ice sheets.[119] Using a different methodology, Pfeffer et al.[39] argue that it is physically untenable for the total rise by 2100 to exceed 2.0 m and a scenario that allows for accelerated ice melt due to ice dynamics lies between 0.8 and 2.0 m. As discussed earlier, gravitational effects are also relevant in scenario development for the *H*++ cases; this will require judgement on where the ice melt occurs.[14,131,132]

Clearly, the upper limit of the H++ scenario is difficult to precisely estimate or define, especially at the local scale. Individual studies show that values vary according to local knowledge and understanding,[14,121,133] and values of climate-induced sea-level rise between 0.5 and 2 m by 2100 are not implausible during this century. These values also show that earlier assessments based on similar magnitude synthetic scenarios of sea level remain of value in interpreting the impacts of sea-level rise over the 21st century.[108,134,135] However, it is important to recognize that as the science develops so the H++ range should be reviewed—there is already some emerging evidence that it might be appropriate to lower the upper value and this will be evaluated after the upcoming IPCC Fifth Assessment Report is published.

SCENARIO CHOICE AND AVAILABILITY FOR IMPACT AND ADAPTATION ASSESSMENT

The process of sea-level scenario development already discussed is largely quantitative, but in many cases a high precision may not be required. As an example, when considering flood risk management, extreme water levels are typically required to 0.1 m accuracy.[136] For a local study, if resources are available, the impact assessment could consist of local socioeconomic scenarios and downscaled/processed IPCC sea-level scenarios combined with surge estimates and vertical land movement observations. Moreover, it is also important to remember that as impact assessments are commonly based on elevation data, there is no requirement for a sea-level scenario with 0.01 m accuracy when the topographical data generally has a vertical precision of 0.3 m at best.[137]

On the basis of our review of sea-level rise scenarios and the needs of impact and adaptation and assessment, Table 4 summarizes how sea-level scenarios might be developed with different levels of data availability and assessment. Simple scenarios can allow preliminary impact assessments which can inform broad adaptation requirements. The first assessment is rarely the last, and as more research on sea level is conducted so future scenarios can be improved following Table 4. Hence, the impact assessment need not be delayed until perfect information is available. Rather, sea-level rise scenarios should evolve with the impact and adaptation assessments from a first scoping of the problem and its issues toward a more detailed understanding of impacts and ultimately to adaptation measures. This stresses that adaptation assessment to sea-level change is best considered a process rather than expecting a single assessment to address all issues to conclusion.

Some examples of sea-level rise scenarios developed for impact and adaptation assessment under different levels of data availability are illustrated in Table 5. They illustrate a wide range of assumptions concerning the sea-level components that are considered. Further, the upper range of the scenarios often exceeds a 1-m rise and hence embraces the H++ range.

The choice of sea-level scenarios will also vary with the focus and objectives of the assessment being carried out (see Figure 5). Impact assessments should aim to identify the magnitude of any thresholds for impacts across the full range of projected sea levels (the AR4 S and post-AR4 scenarios, including H++ ranges); the H++ limit selected being based on available knowledge (global and local) with clear reasoning provided. For adaptation assessments the selection of sea-level scenarios may be restricted, for example, owing to consistency in the magnitude of impacts across the scenarios identified in the impact assessment or the probability of the sea-level rise occurrence. In practice, adaptation assessments or strategies may tend to focus on the AR4 S range, although there may be interest in the potential adaptation options under the H++ range, and their consistency with the options for the AR4 S range. For instance, if the preferred option changed from protect to retreat as the rise in sea level increased, this would raise difficult questions concerning the preferred adaptation option across the range of uncertainty. Engineered adaptation responses, if selected within the adaptation assessment, will be limited by technological or budgetary constraints to an ultimate single 'design' scenario. As such adaptation will be a costly exercise, it is assumed that the design scenario will be carefully evaluated and the uncertainty across the scenarios will again be a

TABLE 4 | Summary of Sea-Level Components versus Levels of Assessment. As Socioeconomic Scenarios Are Needed for Impact and Adaptation Assessment These Are Included.

		Level of Assessment		
Sea-Level Component		Detailed	Intermediate	Minimum
Global sea-level change (including ice melt)	SL_G		IPCC AR4 or similar (and H++ range)	
Regional sea-level change	SL_{RM}	Meteo-oceanographic driven deviations from individual models for appropriate scenario	Scaled up local deviations and Figure 3 or similar; use pattern-scaling equation/software	Use ± 50% (based on Hulme et al.[89])
	SL_{RG}	Correction for gravity effects	Scale predictions according to Figure 4	Assume globally uniform uniform eustatic sea-level rise
Natural vertical land movement	LM_N	Local observations, e.g., GPS, long time series local tide gauge or relevant geological data (Ideally, consider a range of values)	Regional patterns of land motions inferred from geological data/GIA model estimates	Assume no change
Human-induced vertical land movement	LM_H	Analysis of subsidence potential, including prognosis (e.g., ground water extraction)	Assume arbitrary changes based on geological setting	Assume no change
Changes in storm surge component to extreme sea level	SS	Local modeling using regional models or statistical downscaling driven by climate models	Sensitivity study with no change, then range of change over 50/100 year period (e.g., 10 to 20% increase)	Assume no change
Socio-economic scenario		Downscaled global scenarios (e.g., SRES) or other relevant local scenario (see http://sres.ciesin.columbia.edu/tgcia/)	Global scenario (e.g., SRES) (if baseline used make explicit)	

key consideration. This may lead to the analysis of different possible sequences of adaptation measures (or adaptation pathways) combined with explicit learning about future sea levels based on monitoring. This approach is being applied to plan the future of London's flood defences.[19,142]

Range of Scenarios

While uncertainties remain large, it is prudent to consider a wide range of scenarios in any assessment so that the full range of uncertainties and risks can be explored, and to avoid estimates of sea-level impacts being rendered invalid every time new sea-level projections become available.[140] It is also advisable to use the most detailed data available and appropriate for the scale of the impact analysis. As a basis for adaptation planning, the minimum requirement is to use the full range reported in the AR4 which represents the best available projections for the currently quantifiable parts of the sea-level budget for the 21st century, and in 2013/2014 this should be updated to use new values from the AR5. The consideration of a range of scenarios, including a high end H++ type scenario, allows uncertainty, sensitivity, risks, and long-term adaptation planning to be included in the analysis, particularly where assets of high economic, social, or environmental value and long lifetimes are concerned, and where near-term adaptation choice could constrain the ability to up-scale adaptation responses at a later stage. However, it is important to note that the literature underpinning expectations about future sea level will continue to evolve beyond the AR5 as scientific understanding develops.

Extreme Events

Many impacts on the coast and inshore marine environments will result from extreme events affecting sea level, such as storm surge.[143] The magnitude of extreme events at any particular time or place is influenced by tidal conditions, storm severity, decadal-scale variability, and regional mean sea level. While

TABLE 5 | Examples of Sea-Level Scenarios Developed for Impact and/or Adaptation Analysis

			Sea-Level Component					
Reference	Context	Level of Assessment	SL_G	SL_{RM}	SL_{RG}	LM_N	LM_H	SS
Dennis et al.[138]	Country level (Senegal)	Minimum—synthetic	✓			✓		
DEFRA[139]	Local-regional (England/Wales)	Intermediate	✓			✓		
Snoussi et al.[108]	Country level (Morocco)	Minimum—synthetic	✓					
Lowe et al.[14] (see also Environment Agency[140])	Up to country level (UK)	Detailed	✓	✓		✓		✓
Rosenzweig and Solecki[132]	New York (USA)	Detailed	✓			✓		✓
USACE[141]	National	Intermediate	✓			✓		
Katsman et al.[15]	The Netherlands	Detailed	✓	✓	✓			
Hanson et al.[13]	Global	Intermediate—synthetic	✓			✓	✓	✓
Parris et al.[16]	Up to country level (USA)	Detailed	✓	✓		✓		✓
Boesch et al.[90]	Maryland (USA)	Detailed	✓	✓	✓	✓		

See Table 4 for Sea-Level Component.

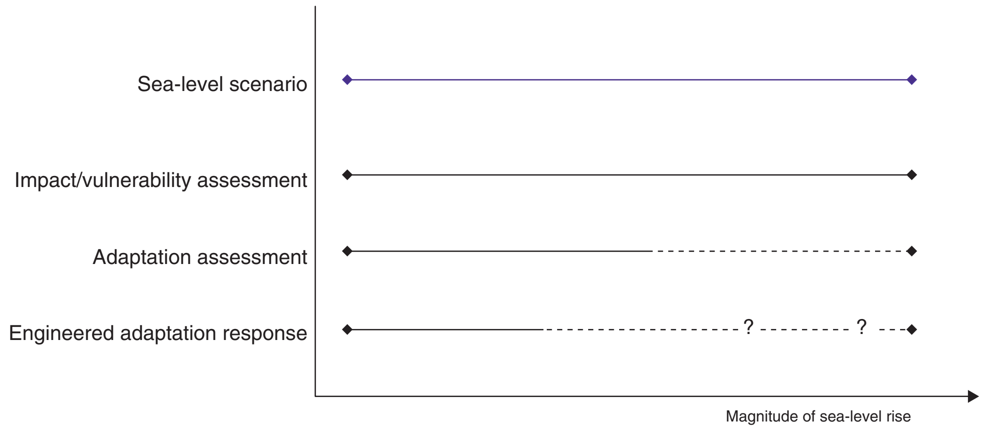

FIGURE 5 | Illustration of the magnitude of sea-level rise which needs to be considered for a range of assessments.

these phenomena are not formally additive, for a first approximation they can be summed as demonstrated by Lowe et al.[144] for the North Sea. Analysis of the high-quality Newlyn tide gauge record in the UK suggests that this was a reasonable assumption for the 20th century.[136,145]

To date, future changes in storm surges due to meteorological change have only been simulated at a small number of locations, with significant differences in the response depending on the region.[146] While it is desirable to include changes in extreme water levels that result from changes in atmospheric storminess, the method of doing so will depend on the scope of the individual impact study. Where time permits, employing both dynamic simulation of storm surges and statistical down-scaling approaches is the most comprehensive approach.[147]

However, it is important to note that flood levels will increase and flood events become more frequent as sea level rises even if storm intensity and behavior remain unchanged. An alternative way to view this is that a rise in sea level makes the same water level occur more frequently and the magnitude of this effect depends on the shape of the exceedance curve; the flatter the shape, the greater the effect of any given sea-level change (see Figure 6).[148,149] The addition of current surge, tide (and wave) levels to projected changes in sea level can provide a first approximation for impact and adaptation assessments. In addition, the impacts of increases of 10–20% across the range of return periods might be considered as a sensitivity analysis,[139,150] reflecting possible climate change effects and the uncertainties of our estimates of return periods.

FIGURE 6 | Estimates of the vertical allowances (m) necessary for sea-level rise from 1990 to 2100 under the A1FI emissions scenario. The allowances are based on a spatially varying rise in mean sea level and the statistics of storm tides observed at each location. The uncertainty in the projections of sea-level rise was fitted to a normal distribution. The size of the allowance is indicated by dot diameter. Yellow triangles indicate allowances <0.4 m. Source: Dr J Hunter[149]

DISCUSSION

The science of sea-level rise and the science of sea-level rise impacts and adaptation are too rarely considered together. In our view, this has hindered the pragmatic development of scenarios that address impact and adaptation assessment needs. This review has attempted to address this deficiency in a manner that recognizes the limits to our understanding of future sea-level rise and selects appropriate methods. The focus is on understanding the full range of possible change, including the low probability but high consequence parts of the distribution. This is the area where sea-level science is most uncertain, but it is rightly focused upon in a risk management approach that covers the low probability but high damage possibilities when considering impacts and adaptation. Hence the H++ scenario is recommended as a high-end scenario. The goal here is not to 'scare people' as some have interpreted, but rather to encourage policy makers to think across the full range of possibility. Large sea-level rise scenarios have been considered in both London and the Netherlands, where protection seemed the best strategy in all cases.[140,151] Further, consistent sets of adaptation measures are apparent that allow incremental improvement and upgrade to the defenses. Hence, the problem can be addressed in a progressive and adaptive manner where sea-level rise is planned for now, and that plan includes monitoring and learning about sea-level change over the coming decades. This means that sea-level rise can be fully prepared for without over-adapting. Given that the uncertainties of sea-level rise are global, this approach will probably be widely applicable around the world's coasts, especially in major coastal cities with high values and growing flood risk.[152]

Importantly the focus of analysis in this paper is on human decisions, rather than starting with sea-level rise. Some decisions are short-term and hence sea-level rise is an irrelevance. Others are easily reversible and adjustable and there is little need to anticipate future sea levels. However, long-term infrastructure such as flood defense systems, or nuclear power stations do need to anticipate future sea-level rise: in the latter case for more than a century.[20] While the focus in this paper has been on top-down approaches to analysis, the methods shown here are also appropriate to more bottom-up decision-centric approaches. In these cases, the sea-level scientist moves from a data provider to a stakeholder in the assessment process. On the basis of the experience discussed in London and elsewhere there is merit in further exploring this approach.

It is also important to remember that sea-level rise associated with global warming is only one aspect of possible changes to coastal climate. Other aspects of coastal climate (e.g., sea surface temperature, wave climate, and run-off) are also likely to change with many adverse and some beneficial effects that will often interact with sea-level rise. To date, most impact assessments of coastal areas have simply considered sea-level rise only and assumed all other climate factors are constant. However, relevant climate scenarios should be considered where appropriate. This approach could be extended to non-climate changes,[12,153] which are often also of significance. This is entirely consistent with supporting coastal management analysis which needs to address all the changing risks, whatever their cause.

CONCLUSION

Future sea-level rise seems inevitable owing to global warming, but the rates and geographical patterns of change remain uncertain. However, as this paper demonstrates, it is possible to develop useful scenarios of sea-level rise at any location, conduct an impact assessment, and start to consider suitable adaptation policies/planning. The robustness of these results will vary according to the data available and/or the assumptions made for each sea-level change component, so these assumptions should always be explicit within the assessment report.

On the basis of this extensive review, it is important to recognize that scenario development is only one step in a process. Hence, the effort made toward scenario development should be proportional to the resources of the overall study and the questions being posed. At any site, the understanding of scenarios is expected to progressively develop as part of an iterative process of impact and adaptation assessment. At the same time, the understanding of sea-level rise will improve and this knowledge should be reviewed and incorporated into the guidance that supports these assessments. The inclusion of the forthcoming AR5 assessment will be an important step in this process.

Lastly, given the large uncertainties in future conditions, there is some risk that sea-level rise assumed for a selected adaptation measures may be exceeded. Hence, in addition to scenario development, ongoing monitoring of actual sea-level rise, and expert interpretation of the observations, is essential so that additional measures can be implemented in a timely manner if required.

Twenty-first century sea-level rise adaptation has been focused on here but it must be kept in mind that sea-level rise is expected to continue long after 2100, even if atmospheric GHG concentrations are stabilized this century. Given the likelihood of many coastal structures being planned today still being in existence in 100 years, further research should also look beyond the 2100 time horizon.

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