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Rising Sea Levels: Helping Decision-Makers Confront the Inevitable

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ABSTRACT

Sea-level rise (SLR) is not just a future trend; it is occurring now in most coastal regions across the globe. It thus impacts not only long-range planning in coastal environments, but also emergency preparedness. Its inevitability and irreversibility on long time scales, in addition to its spatial non-uniformity, uncertain magnitude and timing, and capacity to drive non-stationarity in coastal flooding on planning and engineering timescales, create unique challenges for coastal risk-management decision processes. This review assesses past United States federal efforts to synthesize evolving SLR science in support of coastal risk management. In particular, it outlines the: (1) evolution in global SLR scenarios to those using a risk-based perspective that also considers low-probability but high-consequence outcomes, (2) regionalization of the global scenarios, and (3) use of probabilistic approaches. It also describes efforts to further contextualize regional scenarios by combining local mean sea-level changes with extreme water level projections. Finally, it offers perspectives on key issues relevant to the future uptake, interpretation, and application of sea-

KEYWORDS

coastal risk management; extreme water levels; managing uncertainty; regional/local sea-level rise scenarios; risk-based approach

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level change scenarios in decision-making. These perspectives have utility for efforts to craft standards and guidance for preparedness and resilience measures to reduce the risk of coastal flooding and other impacts related to SLR.

Introduction

For nearly four decades it has been clear that global sea-level rise (SLR) and its local manifestations present a hazard for which preparation is critical to help minimize public health and safety risks, costly economic damages, and security threats. Because SLR is not just a future trend but is occurring today in most coastal regions of the world, it has implications not only for long-range planning but also for emergency preparedness and other short-term considerations. Global SLR is not only inevitable (i.e., a directional global trend well into the next century; Church et al. 2013a; Meehl et al. 2012; Mengel et al. 2018) and likely irreversible on millennial timescales (Clark et al. 2016; Levermann et al. 2013; Solomon et al. 2009), but also on many planning and engineering timescales drives non-stationarity in coastal flooding (Obeysekera and Salas 2016; Sweet et al. 2014). Past and variable future emissions, and earth system responses to these emissions, will lead to divergent outcomes in SLR. These preceding characteristics lead to deep uncertainty in projecting future SLR (Kopp et al. 2017; Lempert et al. 2004). As a result, global SLR poses unique challenges for decision processes associated with planning and preparedness in the coastal environment and argues for a risk-based approach to preparing for future SLR. United States (US) federal agency efforts summarized in this article have been motivated, in large part, by the need to aggregate, integrate, and synthesize evolving SLR science into actionable information for decision-makers to best support risk management in the coastal environment.

Our author team includes US government scientists and engineers with responsibilities to advance scientific understanding and also to further agencies' abilities to make informed and scientifically defensible decisions that meet both mission and public interests. This article reflects perspectives gleaned through work at the interface between science and decision-making in the context of individual agency needs (Hall et al. 2016; TMAC 2015; USACE 2013, 2014), national assessments (Parris et al. 2012; Sweet et al. 2017), or national policy support (FEMA 2015). Although most of the work described has been US-focused, some efforts have been global in scope (e.g., US military sites worldwide; Hall et al. 2016).

This article has three main objectives. First, we discuss how the development of global SLR scenarios has evolved, progressing from the scenario approaches of the National Research Council (NRC 1987), to projections of future global SLR derived from climate models, and broader scenarios that leverage additional lines of scientific evidence to more comprehensively bracket the full range of risks that decision-makers need to consider. This includes, for example, information about low-probability but high-consequence outcomes at the tail end of the distribution of future global SLR (e.g., Hinkel et al. 2015). Risk in this context is framed explicitly by the decision under consideration: the type of decision, its expected performance integrated over a desired lifetime, and its association with the decision-maker's tolerance for and capacity to address the adverse consequences of a "wrong" decision (Hall et al. 2016). As a shorthand expression, we use "risk-based" herein when referring to a decision-maker's consideration of a broader range of potential risks posed by SLR, versus the use of a single or "most likely" future (see Water Resources Council 1983; for an example of this latter use).

Second, we provide an overview of the various approaches to regionalizing global SLR information and summarize associated advances used to develop regional SLR scenarios. As part of this discussion, we highlight the shift in risk management currently taking place, from a focus solely on changes in future mean sea level to the assessment of potential changes in extreme *still* water levels (ESWL; e.g., inclusive of storm surge and tides but not waves) and ultimately inclusive of extreme total water levels (ETWL; i.e., inclusive of waves) and confounding factors, such as inland precipitation that leads to concurrent fluvial flooding (Moftakhari et al. 2017b). This evolution also shifts the conversation from something difficult to link to personal experience (X amount of future SLR) to something more obviously impactful (noticeable increases in the frequency of flood events that people remember), including flooding associated with tidal events (e.g., king tides) exacerbated by SLR.

Third, we offer perspectives and paths forward on key issues relevant to the future uptake, interpretation, and application of sea-level change scenarios in decision-making. These include: (1) using multiple SLR scenarios to bound risk that also account for extreme water levels, (2) incorporating high-end projections in future SLR scenarios (Hinkel et al. 2015) and for which the science on relevant processes—e.g., ice-sheet dynamics—is evolving most rapidly (e.g., DeConto and Pollard 2016), (3) acknowledging the increased prevalence of probabilistic approaches (e.g., Kopp et al. 2014) in scenario development and highlighting the corresponding implications for the interpretive guidance that should be provided to end users, and (4) increasing the role of coproduction between scientists and decision-makers in developing SLR scenarios.

In the remainder of the article, we accomplish the first two objectives by first providing background information on the role of science and the scientific community in assisting decision-makers to confront global SLR and key scientific and risk management issues involved in developing and applying SLR and ESWL/ETWL scenarios for local decision-making purposes. We then highlight US federal agency, interagency, and subnational efforts to develop sea-level change information within an "actionable science" context (Beier et al. 2015; FEMA 2015; Hall et al. 2016). The seven case studies we present demonstrate ongoing linkages between federal scenario development efforts and those of US regions, states, and cities. Finally, we address objective three by synthesizing key insights from this collective body of work to advance the future development and use of SLR and ESWL/ETWL scenarios for decision-making.

Background

Effective preparedness in a given decision context requires assessing the risk posed to plans and valued assets. As a forward-looking exercise, coastal planning must consider potential future changes. As such, coastal managers have long considered changes in sea level and their relationship to coastal flooding and land erosion (e.g., Bruun 1954, 1962). In a 1987 review of the engineering implications of SLR, the NRC recommended that SLR scenarios would be useful for developing and analyzing alternative decision paths, fostering flexible engineering design, and avoiding precluding future options (NRC 1987). A scientifically supported range of SLR scenarios enables decision-makers to understand how risk may change in terms of magnitude and timing at specific locations and supports developing and evaluating alternative measures to manage the risk.

In the near term (i.e., out to about 20 years) prudent planning may involve considering relative SLR based on the observed record, its potential future trends, and historical natural variability to project local recurrent flood risk. In the long term, which is often relevant to infrastructure investments, more comprehensive methods and uncertainty assumptions are required. Here, as context for the subsequent case studies, we briefly illustrate the evolution of and challenges involved with the development in the US of (1) credible and useful global mean SLR scenarios, (2) regionalization of those scenarios, and (3) their linkage to recurrent flood risk.

Uncertainty in future SLR arises only in part from underlying physical uncertainty. Complex societal issues, such as policy decisions regarding emissions, contribute significantly to uncertainty to future SLR estimates, especially past mid-century when SLR scenarios diverge significantly from one another (Bindoff et al. 2007; Church et al. 2013a; Kopp et al. 2014, 2017). Determining how best to respond can be informed by science, but is generally grounded in decision-making processes inherent to project planning and goals, cost-benefit analyses, engineering design practices, and legal considerations, all of which are heavily impacted by the degree of risk aversion of the decision-makers (e.g., see USACE 2014) and their associated capacity to manage risk. Although recognition of the importance of translating science into actionable information is growing, the expertise needed remains relatively underappreciated and under-incentivized in academic and government science circles (Dilling and Lemos 2011). Coproduction of actionable information is a promising avenue to increase this translation (e.g., Vogel, McNie, and Behar 2016).

The physical basis for sea-level change and its future global, regional, and local trends has been heavily studied since at least the 1970s (e.g., Clark and Lingle 1977; Gornitz, Lebedeff, and Hansen 1982); however, until more recently, less attention has been paid to translating this understanding into science usable in decision-making. Scientists may be hesitant to work across the science-policy boundary, in part due to a lack of understanding of decision-makers' needs and the processes by which decisions are implemented. They also may fail to appreciate that integrating the complex decision factors involved in coastal zone management into the development of sea-level change information is an area of novel discovery in its own right, every bit as complex as the study of fundamental earth system processes. Engaging in such boundary-spanning endeavors is critical, as it is one of the most effective ways for researchers to assist decision- and policy-makers in the appropriate use of science to inform complex decisions, through engagement and coproduction of knowledge (Lemos and Morehouse 2005; Meadow et al. 2015; Vogel, McNie, and Behar 2016).

Global mean SLR will continue into the future. The full extent of SLR will depend on future greenhouse gas (GHG) emissions, the sensitivity of the climate system to those emissions, and the dynamic response of large, land-based ice sheets in a warming climate. Society therefore faces a long-term commitment to managing SLR, while at the same time facing substantial uncertainty about its magnitude, timing, and local manifestations. These characteristics create distinctive challenges for decision processes associated with coastal planning and preparedness and, in turn, create the conditions in which the needs of a given decision (or class of decisions) determine those aspects of the science that are most relevant and should be emphasized (Hall et al. 2016; Weaver et al. 2013). Coastal decision-making in diverse decision contexts requires a clear set of principles or guidelines that can help ascertain which SLR scenario or set of scenarios is appropriate, defensible, and actionable.

One important consideration is the significant regional variation in how SLR will be realized at any given point along the coast, which underscores the importance of developing more locally and regionally relevant SLR information. Other technical considerations create the need for additional guidelines, such as (1) use of different temporal baselines for calculating SLR scenario projections (e.g., 1992 vs. 2000) and whether these time periods serve as mid-points of a tidal epoch (such as 1992) that practitioners can relate to local water level information, (2) choice of datasets and time periods (i.e., geologic, tide gauge, and satellite observations and their associated lengths of record) to establish a historical, observation-based SLR trajectory, and (3) availability of visualization tools that accurately portray risks. These all present pragmatic challenges for development and application of spatially relevant and usable SLR scenarios, and they have been instrumental in driving the US federal agency efforts described in this article. These efforts represent a concerted, ongoing process of self-learning within federal agencies to develop such information, informed by the evolving science of SLR at each iteration.

A key aspect of this learning process has been the realization that existing climate science assessment processes, though providing a robust foundation of scientific understanding and identifying critical knowledge gaps, were not necessarily supplying all the most decision-relevant SLR information needed to support preparedness planning and adaptation decision-making in the coastal zone. Hinkel et al. (2015) describe how the purposes of major scientific assessments, like those of the Intergovernmental Panel on Climate Change (IPCC; e.g., Church et al. 2013a), as compared with assessments of risk intended to more directly support decision-making, have led to an under-emphasis on certain decision-relevant aspects of the science. These include high-end estimates of future global mean SLR that emerge, not exclusively from the process-based models that the IPCC emphasizes, but also from multiple additional lines of scientific evidence, such as estimates of the maximum physical plausible rates of ice-sheet changes (e.g., Pfeffer, Harper, and O'Neel 2008), rapidly evolving process-level understanding of the complex behavior of the Greenland and Antarctic ice sheets under global warming (e.g., DeConto and Pollard 2016), and structured expert judgment (e.g., Bamber and Aspinall 2013). Although the IPCC acknowledged the potential for larger increases in global mean sea level (e.g., Church et al. 2013b), their primary focus on central tendencies and "likely" futures is not as useful for decision-makers who wish to test plans and policies against a broader range of scientifically plausible future SLR (see also NRC 2012). This is important, because many impacts in the coastal environment, such as frequency of coastal flooding and flooding pathways, are highly nonlinear with SLR (Gutierrez, Williams, and Thieler 2009). Such approaches are consistent with best practice in a diverse range of risk-centric fields in which public safety or financial losses are at stake (Kunreuther et al. 2013; Oppenheimer, Little, and Cooke 2016; Thistlethwaite et al. 2018). Indeed, interest is growing in leveraging these best practices to retool climate assessments generally to produce the kind of knowledge and information most useful in such risk-based decision frameworks (Weaver et al. 2017).

In addition, a major focus of US federal efforts has been to produce regional SLR scenarios consistent with the global scenarios and add the effects of extreme water levels to make them more relevant for decision-making at the local scale (e.g., Hall et al. 2016; Sweet et al. 2017). Doing this, as described in the subsequent case studies, has involved new science and the practical and innovative use of existing datasets.

Because the enterprise of US federal SLR information and product development has been relatively well-coordinated (e.g., among departments and agencies and as part of periodic National Climate Assessments) over the past decade, efforts have been able to build on each other in a systematic way. Advances have included:

- Bounding a fuller range of scientifically plausible future global mean SLR over the 21st Century (and beyond), including physically plausible high-end scenarios (Hall et al. 2016; Parris et al. 2012; Sweet et al. 2017; USACE 2013)
- Developing local and regional SLR information that is consistent with global mean sea- level (GMSL) projections and scenarios and incorporates the effects of ocean dynamics, gravitational and rotational changes arising from mass redistribution, vertical land movement (VLM), and other processes (Hall et al. 2016; Sweet et al. 2017)
- Improving understanding of the likelihood of different future SLR outcomes under a range of GHG emissions pathways and developing contingent probability distributions that capture these dependencies and integrate multiple lines of scientific evidence, including observations, models, and expert elicitation (Sweet et al. 2017).

In addressing these issues, one productive tension that has emerged is between efforts to provide discrete, non-probabilistic scenarios (e.g., quasi-bounding cases) of future SLR, to inform scenario planning-type applications, and efforts to construct probabilistic projections. These latter efforts integrate different sources of information to construct plausible distributions of probability in a Bayesian sense, in which probability provides a quantitative (but non-unique) measure of the strength of evidence for different futures. Probabilistic projections estimate central and tail projections in a consistent manner, endogenously incorporating factors that are outside human control (e.g., ocean and ice-sheet responses to forcing) and conditioning on factors largely under human control (i.e., forcing). We conclude that these approaches are complementary, and, taken together, can better support both scientific assessment and decision-making by providing a more unified look across the needs and practices of both.

Finally, although increasing relative sea level (RSL; sea-level relative to land at a particular location) is the primary driver of increased permanent inundation along affected coastlines, increased frequency of periodic coastal flooding is an early indicator of rising seas. Due to RSL rise, the entire spectrum of ocean-flood height probabilities relative to

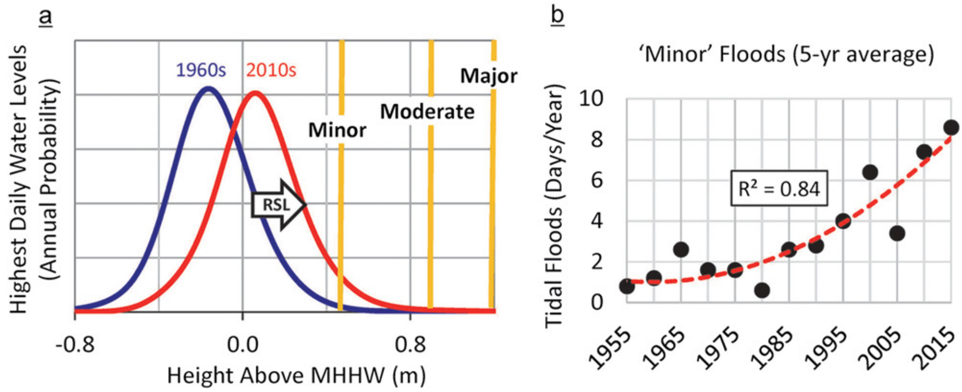

Figure 1. (a) Multi-year empirical (smoothed) distributions for daily highest water levels in Norfolk, Virginia, USA for the 1960s and 2010s, showing extent that local relative sea level (RSL) rise has increased the flood probability relative to impact thresholds defined locally by NOAA's National Weather Service (http://water.weather.gov/ahps) for minor (~0.5 m: *nuisance* level), moderate (~0.9 m) and major (~1.2 m: local level of Hurricane Sandy in 2012) impacts, relative to mean higher high water (MHHW) tidal datum of the National Tidal Datum Epoch (1983–2001) and due to RSL rise. (b) Annual flood frequencies (based upon 5-year averages) in Norfolk for recurrent tidal floods with minor impacts are accelerating, as shown by the quadratic trend fit (goodness of fit [R^2] = 0.84). From Sweet et al. (2017).

a fixed location (i.e., annual exceedance probabilities [AEP] expressed as the percent chance of being equaled or exceeded in any given year: e.g., an 0.2 AEP flood has a 20 percent chance of occurrence in any given year) are increasing, but the consequences are most readily observed in a change in frequency of the higher probability AEP events (i.e., those that correspond to minor flooding). As a result, coastal floods exceeding the US National Oceanographic and Atmospheric Administration's (NOAA) elevation threshold for local "minor" (or nuisance level) impacts today generally occur more than once per year (Sweet et al. 2017) and their frequency or occurrence is rapidly increasing and accelerating in dozens of coastal towns (Ezer and Atkinson 2014; Sweet and Park 2014; Sweet et al. 2014), as shown in Figure 1(a). Such flooding during high-tide can occur during relatively calm conditions with no local storm effects present. Minor tidal flooding adversely affects ground-level and subsurface infrastructure in many US coastal communities (e.g., roadways, storm/waste/fresh-water systems, and private/commercial property) that are not designed for repetitive salt-water exposure or inundation (Figure 1(b)). Recognition is growing that such lower-magnitude, higher-probability tidal flooding will pose a substantial challenge to coastal communities due to the sheer frequency of events expected in the coming future decades (Dahl et al. 2017; Moftakhari et al. 2015, 2017a; Sweet and Park 2014). With increasing sea levels occasional minor flooding will evolve into chronic flooding (Sweet et al. 2018), leading the public to increasingly demand solutions from decision-makers.

Case studies: US federal agency and subnational efforts to develop risk-based SLR scenarios

This section uses seven different case studies to highlight efforts of individual US federal agency, coordinated interagency, and nonfederal subnational efforts to develop useful and actionable sea-level change information. The first six case studies are loosely arranged in chronological order of activities, though some efforts, such as by the US Army Corps of Engineers (USACE), are ongoing and have a long history. Interagency efforts, such as those in support of the Third and Fourth US National Climate Assessments (NCA3 and NCA4) and the development of a US federal flood risk management standard that for the first time considered the impacts of climate change on sea-level change, are interspersed with the individual agency efforts. The final case study provides an overview of parallel efforts by US regions, states, and cities—many intersecting with the efforts of the federal agencies that created mutual learning and leveraging—to develop SLR scenarios useful for decision-making. When applicable to a case study, additional details are provided in Supplemental Materials.

US Army Corps of Engineers

The USACE has a long history of addressing and providing guidance related to changes in sea level (see Supplemental Materials for a brief chronology). The first specific guidance was issued in the form of a 1986 guidance letter (USACE 1986), based on an NRC committee report (NRC 1987), that required changing sea levels be considered in the planning and design of coastal flood control and erosion protection projects. The current guidance (USACE 2013) requires consideration of three scenarios, while also allowing consideration of a maximum plausible upper bound of global mean sea-level change (such as the 2.0 m global scenario of Parris et al. [2012]) if justified by project conditions.

The USACE also has provided technical guidance for application of future sea-level scenarios depending on the various USACE mission areas and project types (USACE 2014). Examples of how to incorporate the effects of sea-level change on coastal processes, project performance, and project response within a tiered, risk-based planning framework are included. Moreover, web-based tools have been developed to automate the computation of the scenarios, making results more accessible, consistent, and repeatable. Specific tools are described in Supplemental Materials.

Third US National Climate Assessment (NCA3)

Sea-level change scenarios had not been included in the US national climate assessment process prior to NCA3 (Kunkel, Moss, and Parris 2016). An important facet of the NCA3 effort was an element of balancing the supply and demand side of information related to coastal vulnerability to SLR. Specifically, the NCA3 scenarios were developed through an elicitation process that included a diverse group of experts from five different US federal agencies, eight different academic institutions, and a regional government agency (Kunkel, Moss, and Parris 2016). This group included not just physical scientists, but also social scientists with experience in risk communication and decision-making under uncertainty. Based on the guidance of the US federal advisory committee governing NCA3, the goal was to synthesize the scientific literature on global SLR to provide (1) scenarios that would bound global conditions to 2100 (using 1992 as a starting point) and (2) descriptions of the factors that cause regional variations (Parris et al.

2012). The primary audience of the scenarios report was intended to be intermediate users, specifically the scientists and experts drafting the sectoral and regional chapters of the NCA, but the authors also intended that regional and local experts could use the information to conduct more specific analyses to meet their own needs.

Through the integration of the science of risk communication and robust decision-making, the authors decided to focus on a broad range of scenarios and multiple lines of evidence to support preparedness for a range of possible future conditions. The high-end scenario of global SLR by 2100 of 2.0 m (6.6. ft) was based on Pfeffer, Harper, and O'Neel (2008) and the low-end scenario of 0.2 m (0.7 ft) was based on extrapolated tide gauge observations. Two intermediate scenarios (1.2 m or 3.9 ft or and 0.5 m or 1.6 ft) were designed to be logically connected to the A2 or B1 (moderate) emission scenarios, respectively. Individual scenarios were not assigned a likelihood or confidence statement. The overall range, though broad, was estimated based on expert judgment with very high confidence (greater than nine in 10 chance) to capture future SLR. Although model projections at the time suggested that intermediate levels of SLR (0.3 to 1.2 m or 1 to 4 ft) might be considered more likely, the literature summarized in the report revealed notable, peer-reviewed evidence that higher amounts of SLR were possible by the end of the century (Kunkel, Moss, and Parris 2016; Parris et al. 2012 and references therein). At the time, emissions-based, process-model projections included only limited terms for contributions from ice sheets, which conflicted with the group's priority to inform preparedness for a wide range of plausible futures. As discussed below, this limitation has been addressed subsequently in US federal analyses by leveraging approaches developed by Kopp et al. (2014) and Horton et al. (2015).

US Federal Emergency Management Agency

The US Federal Emergency Management Agency (FEMA) administers the National Flood Insurance Program (NFIP). The NFIP insures against the one-percent annual chance flood (sometimes referred to as the "hundred-year flood"). NFIP insurance policies are in effect only for one-year terms and are renewed annually; consequently, insurance rates are based on an understanding of the present, or "current conditions," flood risk. Importantly, flood insurance rate maps do not show future flood hazards based on projected "future conditions" in physical processes such as long-term erosion and SLR, consistent with the 1968 National Flood Insurance Act that created the NFIP.

Subsequent NFIP reform legislation and responses to congressional mandates began to recognize possible impacts from sea-level change, though no policy changes resulted. In the aftermath of Hurricane Katrina in 2005, however, the US Government Accountability Office (GAO 2007) recommended that FEMA investigate the impact of climate change on the NFIP. More recently, in 2012, the US Congress recognized the need to reform certain aspects of the NFIP and enacted the Biggert-Waters Flood Insurance Reform Act (BW-12). The GAO report and BW-12 compelled studies and reports (e.g., by the TMAC 2015) that provided recommendations to FEMA on how to incorporate the best available climate science, SLR, and future development in assessing future flood risk. For example, TMAC (2015, 11) recommended that FEMA "work with [other federal agencies] to provide a set of regional sea-level rise scenarios, based on

Parris et al. (2012) for coastal regions of the U.S. out to the year 2100, that can be used by FEMA for future coastal flood hazard estimation." Supplemental Materials provides additional details on FEMA's history in addressing coastal flooding, erosion, and SLR.

US Federal Flood Risk Management Standard

In 2013 the Hurricane Sandy Rebuilding Strategy (HSRTF 2013) adopted a higher flood standard for the Sandy-affected region to ensure that US federally funded buildings, roads, and other projects were rebuilt stronger to withstand future storms. The strengthened standard was similar to existing flood-risk standards in place in the States of New York and New Jersey. The Sandy Task Force also recommended that the federal government create a national flood-risk standard for federally funded projects beyond the Sandy-affected region. The US *Climate Action Plan* (EOP 2013) directed federal agencies to update their flood-risk reduction standard to ensure that federally funded projects across the country last as long as they are intended. Federal agencies, via the Mitigation Framework Leadership Group (MitFLG), collaborated on this update in 2014.

The resultant Federal Flood Risk Management Standard (FFRMS; FEMA 2015), issued in January of 2015 as part of Executive Order 13690 (EO 2015; since revoked by EO 13807, Section 6, in August 2017), gave federal agencies the flexibility to select one of three approaches for establishing the flood elevation and associated hazard area they use in siting, design, and construction to deliver the level of resilience needed:

1. The Climate-Informed Science Approach—Use data and methods informed by best-available, actionable climate science;
2. The Freeboard Value Approach—Use 2 ft (0.6 m) above the 1% annual chance (0.01 AEP) event (also referred to as the base flood) elevation for standard projects and 3 ft (0.9 m) above the 1% annual chance event elevation for critical buildings, such as hospitals and evacuation centers; or
3. The 0.2% Annual Chance Flood Approach—Use the 0.2% annual chance (0.002 AEP) event floodplain and elevation.

The FFRMS, as envisioned, was focused on all US federal actions involving new construction or substantially improved construction and did not impact operation of the NFIP. If structures, however, were built with increased flood resilience, a positive effect on insurance rates could have resulted for those structures covered by NFIP policies. Increased resilience also could improve a community's score in FEMA's Community Rating System (see Supplemental Materials) when the community accepted building standards more stringent than the NFIP minimum requirements.

Guidance to implement the climate-informed science approach was provided in the agency implementation guidelines (FEMA 2015: Appendix H). The guidelines specified that each federal agency should factor potential relative sea-level change into federal investment decisions located as far inland as the extent of estimated tidal influence, now and into the future, using the most appropriate methods for the scale and consequences of the decision. When using global mean SLR scenarios, the agency implementation guidelines recommended agencies account for, at minimum, local VLM adjustments to the global scenarios if such data are available. Specifically, the implementation guidelines recommended using the interagency (Parris et al. 2012; developed in support of the US's NCA3 [Melillo, Richmond, and Yohe 2014]) or similar global-mean SLR scenarios, adjusted to reflect local conditions. In addition, RSL conditions would be combined with surge, tide, and wave data using methods appropriate to policies, practices, criticality, and consequences. As of the revocation of the FFRMS, US federal agencies such as FEMA, USACE, and Housing and Urban Development were in the process of developing and receiving public comment on proposed rules and implementation plans.

Regional sea-level scenarios for US Department of Defense sites worldwide

The US Department of Defense (DoD) has the responsibility for the continuity of the US military mission at military installations and other sites worldwide. Over 1800 US domestic and international military installations and individual smaller sites are situated in coastal or tidally influenced regions. In recognition of the risk to operational readiness and national security from rising sea levels, the US DoD chartered an interagency working group to develop a risk-based, decision-making methodology applicable to individual DoD sites worldwide that acknowledges the deep uncertainty and spatial- and temporal-specific differences associated with future SLR and associated extreme water levels, with a focus on enhancing and facilitating screening-level vulnerability and impact assessments for DoD sites (Hall et al. 2016).

The approach first built off of and refined the global SLR scenarios developed by Parris et al. (2012), regionalized the scenarios over three time horizons (i.e., 2035, 2065, and 2100), and finally, for most sites, added ESWL scenarios (i.e., not including waves) for four different event probabilities (i.e., 1, 2, 5, and 20% annual chance [or 0.01, 0.02, 0.05, and 0.2 AEP] events). Initial global SLR scenarios encompassed 0.2 to 2.0 m as the bounding scenarios similar to Parris et al. (2012) but used 0.5 m increments for three additional intermediate scenarios (0.5, 1.0, and 1.5 m, respectively). Regionalization applied local adjustments associated with VLM, gravitational and other changes due to ice melt, and dynamic adjustments associated with changes in ocean circulation. Extreme water levels due to tides and storms were accounted for using a variety of methods dependent on tide gauge data availability and quality. Additional details about the methodologies used and technical challenges encountered and their resolution are provided in summary fashion in the Supplemental Materials, with example data outputs provided by Supplemental Material Table S1 and Supplemental Material Figures S1–S4, and comprehensively in Hall et al. (2016).

Hall et al. (2016) included information on the scientific basis and other underlying context for their choice of global scenarios to regionalize and methods for their regionalization, uncertainty estimations, considerations not addressed (e.g., future non-stationarity of extreme events), data limitations at the site level and in some cases possible compensations, and, finally, illustrative examples to demonstrate applications of the scenario information and other considerations (for example, illustrating the benefits of regional frequency analysis and fine-resolution topographic data to determine storm flood levels). The scenario information was not meant to provide "the" answer; rather,

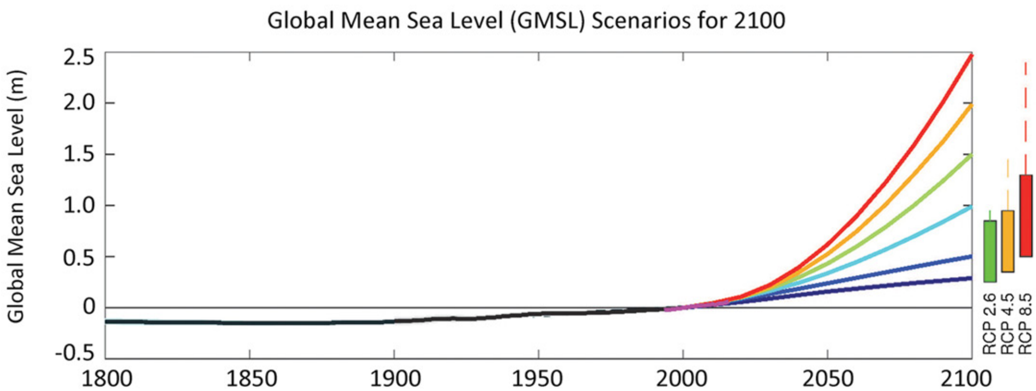

Figure 2. Six representative GMSL rise scenarios from Sweet et al. (2017) for 2100 (6 colored lines) relative to historical geological, tide gauge, and satellite altimeter GMSL reconstructions from 1800 to 2015 (black and magenta lines) and central 90% conditional probability ranges (colored boxes) of RCP-based GMSL projections of recent studies (Church et al.2013a; Grinsted et al.2015; Kopp et al.2014, 2016; Mengel et al.2016; Slangen et al.2014). These central 90% probability ranges are augmented (dashed lines) by the difference between the median Antarctic contribution of Kopp et al. (2014) probabilistic GMSL/RSL study and the median Antarctic projections of DeConto and Pollard (2016), which have not yet been incorporated into a probabilistic assessment of future GMSL. The Sweet et al. (2017) scenarios differ from the other federal-sponsored studies cited herein (Hall et al.2016; Parris et al.2012; USACE2013) in anchor point (2000 vs. 1992), low-end scenario (0.3 m vs. 0.2 m), and high-end scenario (2.5 m vs. 2.0 m).

it was intended to assist DoD decision-makers and others in making robust choices to manage their risks in the context of plausible future sea and extreme water levels. Two specific scenario applications are highlighted in the Supplemental Materials: (1) use of scenarios within an adaptive risk management context and (2) scenario application in the zero to 20-year timeframe (Supplemental Material Figure S5).

All data are housed in a database that is access-restricted given sensitivities to potential future vulnerabilities of government sites; however, the methodologies described in Hall et al. (2016) are generally applicable to any location globally. The database includes SLR and ESWL scenario information by site (for some sites ESWLs could not be determined) that can be accessed through a graphical-user interface.

Nationalizing the use of regional SLR scenarios in the US

Just as the DoD needs the best assessment and supporting datasets about their sites and installations for their decision-making, so do other agencies, and coastal communities in general. Building from the Hall et al. (2016) effort, the US Federal Interagency Sea Level Rise and Coastal Flood Hazard Scenarios and Tools Task Force convened to develop future SLR scenarios for the entire US as a resource for all users (Sweet et al. 2017; Figure 2). The Task Force assembled an interagency and academic group of scientists to assess the most up-to-date scientific literature on global and regional sea-level projections. One of their aims was to update the global SLR scenario work of Parris et al. (2012), with the goal of informing NCA4 (see Volume I [Wuebbles et al. 2017]).

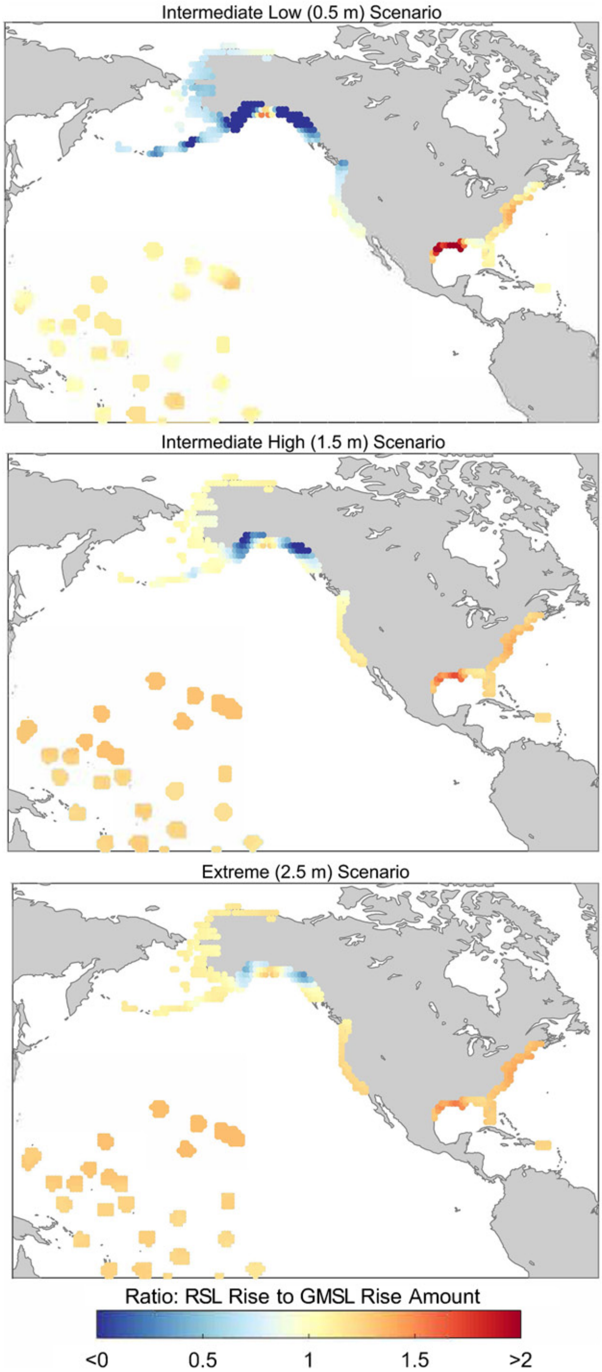

Figure 3. Ratio of the 21st century RSL rise amount at each 1-degree grid to the global mean SLR value for the Intermediate Low, Intermediate High, and Extreme scenarios. A value of 1 indicates the same amount of RSL rise as the global mean SLR amount. From Sweet et al. (2017).

Sweet et al. (2017) first reevaluated the lowest and highest scenarios of Parris et al. (2012) and Hall et al. (2016). Based on the approximately 3 mm/yr GMSL trend since the early 1990s (e.g., Hay et al. 2015), they elevated the Low scenario to 0.3 m of 21st century global-mean SLR. Based on several assessments indicating that 2.0 m did not constitute a maximum of physically plausible 21st century global mean SLR (e.g., Horton et al. 2015; Kopp et al. 2014; Miller et al. 2013; Sriver et al. 2012), recent observational literature indicating ongoing Antarctic ice-sheet instability (e.g., Rignot et al. 2014), and modeling results indicating the potential for new modes of instability (e.g., DeConto and Pollard 2016), they raised the highest global-mean SLR scenario to 2.5 m by 2100.

Similar to Hall et al. (2016), Sweet et al. (2017) discretized the global-mean SLR range into 0.5-m increments leading to six scenarios (Low, Intermediate-Low, Intermediate, Intermediate-High, High, and Extreme) corresponding to 21st century global-mean SLR of 0.3, 0.5, 1.0, 1.5, 2.0, and 2.5 m. Sweet et al. (2017). They also extended the scenarios out to 2200, and, for consistency with a significant portion of the SLR projections literature, they used an anchor point of 2000 rather than 1992, the midpoint of the last tidal datum epoch used by practitioners.

Sweet et al. (2017) then leveraged the projections framework of Kopp et al. (2014) to both characterize the time series of GMSL change consistent with the end-of-century levels and to characterize consistent regional mean sea-level changes around these six discrete GMSL rise scenarios. The Kopp et al. (2014) framework draws upon (1) structured expert judgment and the expert assessment of the IPCC Fifth Assessment Report (AR5) for ice-sheet changes, (2) global climate model-driven projections for thermal expansion, dynamic sea level, and glacier changes, and (3) historical relationships between population, dam construction, and groundwater withdrawal for global mean sea-level change. Sweet et al. (2017) applied the Kopp et al. (2014) outcomes at both tide-gauge sites and on a 1° grid covering the US coastline. They provided these projections both with and without VLM included to facilitate use of alternative or user-defined sources of VLM information, such as Global Positioning System stations. The ratio of local RSL relative to the GMSL is shown for year 2100 in Figure 3 under the Intermediate-Low, Intermediate-High, and Extreme scenarios (medium sub-scenario). These ratios illuminate a number of key insights, including how along almost all US coasts outside Alaska RSL is projected to be higher than the global average under all three of these scenarios, with particularly large ratios for the Northeast Atlantic and Western Gulf of Mexico coastlines.

Relative SLR is not just a long-term issue, but has near-term consequences for coastal communities as evidenced by an increased frequency of "minor" tidal flooding already apparent from decades worth of RSL rise (e.g., Sweet et al. 2014). Sweet et al. (2017) built on this concept to frame the effects of future RSL in terms of how the frequency of more disruptive/damaging "moderate" coastal flooding events (e.g., for which NOAA Weather Forecasting Offices would issue warnings) may change in the future under the new set of SLR scenarios. The elevation for moderate flooding differs along the US coastline, but in general the median value is about 0.8 m (2.6 feet) above the highest average tide, and locally it is about a 0.2 AEP flood event. Applying this flood-frequency definition broadly around the US, Sweet et al. (2017) found that annual flood-frequencies will likely increase 25-fold at most of the 90 cities along the US coastline (outside of Alaska) by about (±5 years) 2080, 2060, 2040, and 2030 under the Low, Intermediate-Low, Intermediate, and Intermediate-High scenarios, respectively. The time horizon for this transition can be thought of in terms of an amount of remaining "freeboard," which is typically only about 0.35 m (median value) at tide gauge locations examined.

US subnational efforts to develop and apply SLR scenarios

Parallel to US federal efforts, US regional, state, and city efforts have evolved over time in addressing the challenges of SLR and recurrent flooding. As these efforts have evolved, they have informed federal advances and vice versa. Refinements, generally with addition of complexity, can be grouped into "waves." Each wave is described briefly below, with specific examples of implementation provided in Supplemental Materials and Table S2 therein.

Wave I

A variety of subnational assessments adopted approaches similar to that of early efforts by the US Army Corps of Engineers (USACE 2009) and later Parris et al. (2012). In addition, some states relied heavily on global SLR projections prepared under the auspices of the IPCC. Wave I can be characterized by (1) a small number of discrete scenarios, with no probabilities assigned, and (2) incorporation of the differences between global and regional sea-level change due to VLM, often as estimated from tide gauges, but not due to other sources.

Wave II

A second wave of subnational SLR projections employed a more careful consideration of different component processes contributing to SLR and their associated geographic patterns. In these studies the results of analyses generally were simplified to a small number of scenarios, in which the uncertainties in the different contributing processes were a combination of uncertainties within and across emissions scenarios.

Wave III

A third wave of projections extended the component-based approach, introducing probabilistic assessments of the different contributing factors that were summed to yield probabilities of local sea-level changes conditional on emissions scenarios. In particular, the New York City (NYC) Panel on Climate Change (NPCC 2013) pioneered the probabilistic method, which was later extended by the work of Kopp et al. (2014).

Wave IV

A fourth wave further considered the implications of uncertainty, in particular the deep uncertainty associated with high-end projections. Much of the work to date has focused on Antarctica's potential contribution to such scenarios and projections. Looking forward, the possibility cannot be ruled out that additional potential drivers of extreme SLR (e.g., Greenland, additional processes in Antarctica) will garner further scientific attention, likely through a blend of models, process-based analyses, paleo-information, and expert judgment.

Synthesis of our current understanding and next steps

The recent federal efforts to develop future SLR information summarized in this article have been motivated by a desire to more effectively support emergency preparedness, long-range coastal planning, and risk management processes in general. Because the federal SLR information enterprise has been relatively well-coordinated over the past decade, successive efforts have been able to build on each other in a systematic attempt to address important scientific and technical issues. This has allowed the federal agencies to provide progressively richer and more comprehensive SLR information over time, informed by the evolving science at each iteration.

Much of this article has been retrospective, intended to summarize and review the progress that has been made to date. This progress also enables us to identify key insights that have emerged from this work that can inform efforts to improve the use-value of SLR information products going forward. In this context, two key insights from the experiences documented in this article are: (1) the need to plan for future SLR, as well as associated changes in extreme water levels, within a risk management framework and (2) the desirability of greatly increasing the commitment to coproduction, between scientists and decision-makers, of scientific information products intended to inform decision-making.

In risk management, information about future SLR is important for analyzing the performance of alternative decision paths, as well as for developing new response options. Understanding SLR, however, is only one aspect of building an overall risk profile. The total risk to be managed also encompasses other physical dimensions, such as site elevation and characteristics of the coastline, the presence of people and things of value (such as sensitive infrastructure and ecosystems), project design life and cost, flood map and elevation data availability and accuracy, capacity for evacuation during extreme events, and a variety of institutional, regulatory, and political constraints. Collectively, these factors establish the overall decision context and tolerance for risk over the planning horizon. Within a risk management framework, a key simplifying step often will be to shift the core question being asked: from how much SLR is expected in the future to how much SLR would have to occur, and by when, to trigger important risks, and their required responses, within the given decision context.

In recent years, scenario planning approaches have been leveraged—as evidenced by the various efforts described herein—to help understand how risk may change across a range of scientifically supported SLR scenarios (globally, or at specific locations). In the presence of deep uncertainty about long-term future SLR, stress-testing plans and policies against representative scenarios can reveal potential vulnerabilities and clarify the risks that need to be managed over time. Identifying or providing the most relevant scenarios is therefore a critically important task within a risk-based decision framework, for which formal guidance (e.g., FEMA 2015; USACE 2014) or a clear set of guiding principles can aid in the appropriate and defensible use of SLR information in decision-making.

One basic good practice of scenario planning is to choose scenarios that clearly distinguish between futures in which a given set of plans or policies fail and those in which they succeed (Lempert 2013). With SLR, planners may need to select scenarios appropriate for long-term, systemic risk management, near-term emergency preparedness planning, or both. For the nearer term (e.g., the next 20–30 years), prudent planning might focus on incorporating the implications of relative SLR based on the observed record, its potential future trends, and historical natural variability in mean sea level attributable in part to coupled decadal atmospheric-oceanic processes to local recurrent flood risk (e.g., see Hall et al. 2016 and Supplemental Material).

For long-term planning, by contrast, a disproportionate fraction of total risk may be associated with low-probability but high-consequence futures, both because many impacts in the coastal zone are nonlinear with respect to the amount of SLR, and because low-probability SLR futures are themselves highly nonlinear over time. Whenever substantial investments are involved, exposure of life and property is high, or options and flexibility to adjust and adapt over the presumed long lifetime of a project are limited, physically plausible high-end SLR scenarios can be extremely useful in defining overall risk and suggesting the kinds of adaptation options that might need to remain available over the long term. Bounding one's risk management problem in this way is at minimum an important thought exercise, as part of planning due diligence, and also a way to challenge ingrained assumptions. It also may spark thinking about adaptation pathways that previously have not been considered, as occurred with the Thames Estuary 2100 project (Hinkel et al. 2015; Ranger, Harvey, and Garbett-Shiels 2013). As a result, continued scientific progress in understanding climate sensitivity and ice-sheet behavior under warming—leading to a more robust definition of the upper end of the distribution of possible future SLR over the coming decades and centuries—will have direct relevance for coastal planning and decision-making. Because the science is advancing rapidly in this area, this is one place where explicit coproduction processes involving both scientists and decision-makers can really help maximize the decision relevance of scientific information products for coastal risk management (Lemos and Morehouse 2005; Meadow et al. 2015, Vogel, McNie, and Behar 2016).

In addition to scenario development for high-end SLR, another area of recent scientific and technical advances for which an increased commitment to coproduction is likely to be beneficial is the recent emergence of efforts to construct more fully probabilistic descriptions of potential future SLR (as per Kopp et al. 2014, and referenced heavily in this article). These approaches are proving valuable in a number of ways, first and foremost by increasing the scientific transparency and reproducibility of efforts to develop future SLR information, particularly in an environment in which the science is evolving rapidly. This is because a Bayesian probabilistic framework provides a way of systematically integrating diverse lines of evidence and enables clear and quantitative demonstrations of the sensitivity of the results to alternative assumptions: for example, the impact of replacing the estimates of Bamber and Aspinall (2013) with those of DeConto and Pollard (2016) (Kopp et al. 2017). In addition, because probabilistic projections tend to be developed individually for alternative GHG emissions pathways, they can help distinguish between scenario-dependent time periods in which SLR is already locked in by inertia and time periods in which emissions reductions can significantly slow the rate of SLR. Finally, they are flexible enough to potentially serve as the underlying dataset supporting a diversity of analytic and decision-making frameworks, from traditional scenario planning approaches to expected utility calculations.

Despite these benefits, however, the direct and sole use of Bayesian probabilities in decision support is subject to inherent limitations, as well as pitfalls arising from a lack of complete understanding of these limitations and the appropriate application of this kind of probabilistic SLR information in practice (Behar et al. 2017; Horton et al. 2018). For example, because current probabilistic projections are generally constructed so as to be conditional on inherently unpredictable aspects of the problem, such as the future GHG emissions pathway, it is not possible to identify a single probability distribution for future SLR, especially over post-2050 timeframes when significant differences emerge between SLR associated with alternative emissions pathways. Furthermore, because of uncertainties in SLR science, particularly with respect to catastrophic ice-sheet mass loss scenarios over longer time horizons, multiple scientifically justifiable probability distributions can be constructed for future SLR, even for a single emissions pathway. The non-uniqueness of the probability distribution reflects the deep uncertainty or ambiguity in the underlying science (Heal and Millner 2014; Kasperson 2008). Although a range of decision-analytic approaches can represent deep uncertainty by using multiple probability distributions, excessive weight on any one may lead to too much or too little emphasis being placed on the most deeply uncertain outcomes (e.g., the upper end of potential future SLR). Finally, combining Bayesian probabilities with extreme water level frequencies based on observation is not straightforward, though many users are not aware of this, and hence combine the two without taking the precautions that the non-uniqueness of the Bayesian probabilities warrant.

Because of these limitations and complexities, a productive tension has emerged between efforts to develop discrete, non-probabilistic scenarios of future SLR (in some cases themselves informed by the probabilistic approaches) and these more recent efforts to construct conditional, Bayesian probability distributions of future SLR. The potential richness of the additional information provided by probabilistic approaches is accompanied by a correspondingly enhanced complexity and potential for misunderstanding and misuse. For example, whereas decision-makers presented with a probability distribution may find the concrete nature of the numbers attractive and user-friendly, failure to appreciate the nature of the underlying uncertainties may lead them to be overconfident about their knowledge of the future, thereby failing to appropriately consider possible high-end futures in planning. In addition, cognitive benefits may accrue for those decision-makers that are forced to grapple with discrete, non-probabilistic scenarios, as they interrogate their own risk preferences and challenge long-held assumptions. Taken together, then, the judicious use of both approaches can jointly better support both scientific assessment and decision-making.

To reap the full benefits of integrating these approaches, however, will again likely require a significant scaling up of coproduction processes between scientists and decision-makers. For example, decision-makers may require additional guidance on how to combine Bayesian and frequentist probabilities appropriately in a given analysis (e.g., when trying to understand how a historical flood frequency might transform across a distribution of possible future sea levels). In addition, coproduction may assist in determining how far the tails of the distribution should extend for risk management purposes. Scientists cannot unilaterally determine this, as this choice touches on questions of risk tolerance and which futures to consider in a risk assessment. Scientists, however, can assist decision-makers in understanding the consequences of their choices and provide guidance on how scenario information might be applied.

Finally, to our knowledge, this article is one of the first attempts to document how federal and subnational efforts are increasingly emphasizing the importance of considering extreme water levels layered atop SLR and the challenges involved. It is now clear that SLR matters in the short-term for increases in high-frequency, low amplitude flood events. Additional complexities due to SLR interactions with storm surge, waves, erosion, shoreline configuration changes, and data accuracy questions remain to be addressed (e.g., Little et al. 2015). Moreover, coastal flooding, as exacerbated by SLR and extreme water levels, mostly is considered independently of heavy precipitation that frequently occurs simultaneously, along with concomitant river flooding (Moftakhari et al. 2017b; Wahl et al. 2015). Recent events, such as Hurricane Harvey that impacted US states along the Gulf of Mexico in 2017, suggest that we will need to account for both to capture the full range of risk.

Given the uncertainties involved, the plausible range of future global mean SLR will likely remain broad for decades. As a result, decision-makers should not look for quick fixes or shortcuts. For example, central tendencies or means, given they are estimated based on probability distributions that are themselves tied to a set of representative, but not all possible, emissions pathways, should be applied with caution, as they often will fail to capture the full range of risk that must be considered. This reality has at times caused consternation among end users, and therefore has led to alternate approaches, such as allowing assigning arbitrary default values for projected increases in future SLR applied generically (e.g., FEMA 2015). Such approaches are a response to the complexity and uncertainties associated with applying current SLR information but can lead to over-investment in adaptive responses in some applications, under-investment in others, and potentially overall maladaptation to future SLR—the risk of a one-size-fits-all response.

More effective alternative approaches are emerging rapidly, such as dynamic adaptive approaches for applying SLR scenarios in decision-making (e.g., Haasnoot et al. 2013; Hall et al. 2016; USACE 2014). Adaptive management of coastal risk in the context of future SLR also underscores the need for an ongoing commitment to monitoring and periodic reassessment of previous decisions and potential options in the face of new information and emerging trends. This can be aided by the continued development of coastal climate services (Le Cozannet et al. 2017) and further research into constraining the uncertainty of those factors—social and physical—that complicate the development and application of scenario information in the coastal environment. US federal scientists and engineers, working closely with nonfederal partners, have played a pivotal role to date in developing the science-based understanding and implementation tools associated with such information. They have done so, and will continue to do so, to assist their agencies in making informed and scientifically defensible decisions to achieve their missions and serve the public interest.

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