




Rising Sea Levels: Helping Decision-Makers Confront the Inevitable

John A. Hall, Christopher P. Weaver, Jayantha Obeysekera, Mark Crowell, Radley M. Horton, Robert E. Kopp, John Marburger, Douglas C. Marcy, Adam Parris, William V. Sweet, William C. Veatch & Kathleen D. White


To cite this article: John A. Hall, Christopher P. Weaver, Jayantha Obeysekera, Mark Crowell, Radley M. Horton, Robert E. Kopp, John Marburger, Douglas C. Marcy, Adam Parris, William V. Sweet, William C. Veatch & Kathleen D. White (2019) Rising Sea Levels: Helping Decision-Makers Confront the Inevitable, *Coastal Management*, 47:2, 127-150, DOI: [10.1080/08920753.2019.1551012](https://doi.org/10.1080/08920753.2019.1551012)

To link to this article: <https://doi.org/10.1080/08920753.2019.1551012>

 View supplementary material 

 Published online: 24 Jan 2019.

 Submit your article to this journal 

 Article views: 130

 View Crossmark data 



Rising Sea Levels: Helping Decision-Makers Confront the Inevitable

John A. Hall^{a*}, Christopher P. Weaver^b, Jayantha Obeysekera^{ct}, Mark Crowell^d, Radley M. Horton^e, Robert E. Kopp^f, John Marburger^{g‡}, Douglas C. Marcy^h, Adam Parrisⁱ, William V. Sweet^j, William C. Veatch^k, and Kathleen D. White^l

^aDepartment of Defense, Strategic Environmental Research and Development Program and Environmental Security Technology Certification Program, Alexandria, Virginia, USA; ^bEnvironmental Protection Agency, National Center for Environmental Assessment, Research Triangle Park, North Carolina, USA; ^cSouth Florida Water Management District, Adaptation to Sea Level Rise Project, West Palm Beach, Florida, USA; ^dFederal Emergency Management Agency, Federal Insurance and Mitigation Administration, Risk Management Directorate, Washington, DC, USA; ^eLamont Doherty Earth Observatory, Columbia University, Palisades, New York, USA; ^fDepartment of Earth & Planetary Sciences and Institute of Earth, Ocean, and Atmospheric Sciences, Rutgers University, New Brunswick, New Jersey, USA; ^gOffice of the Oceanographer of the Navy, Washington, DC, USA; ^hNational Oceanic and Atmospheric Administration, Office for Coastal Management, Charleston, South Carolina, USA; ⁱScience and Resilience Institute at Jamaica Bay, City University of New York—Brooklyn College, Brooklyn, New York, USA; ^jNational Oceanic and Atmospheric Administration, Center for Operational Oceanographic Products and Services, Silver Spring, Maryland, USA; ^kUS Army Corps of Engineers, New Orleans District, New Orleans, Louisiana, USA; ^lUS Army Corps of Engineers, Headquarters, Engineering and Construction Directorate, Washington, DC, USA

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

CONTACT John A. Hall ✉ j2hall@blm.gov 📠 National Interagency Fire Center, 3833 S. Development Avenue, Boise, ID 83705-5354, USA.

This article has been republished with minor changes. These changes do not impact the academic content of the article.

*Present address: US Department of the Interior, Bureau of Land Management, Joint Fire Science Program, Boise, ID, USA

†Present address: Sea Level Solutions Center, Florida International University, Miami, FL, USA

‡Present address: Jupiter Intelligence, San Mateo, CA, USA

Color versions of one or more of the figures in the article can be found online at www.tandfonline.com/ucmg.

📎 Supplemental Materials for this article can be accessed at <https://doi.org/10.1080/08920753.2019.1551012>

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

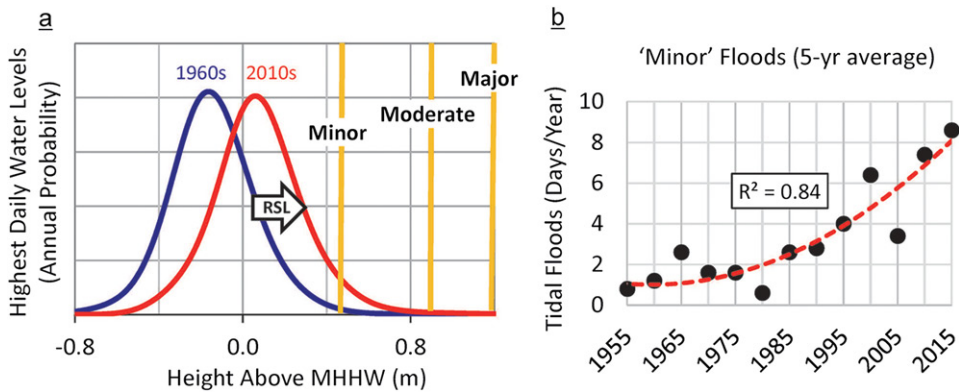


Figure 1. (a) Multi-year empirical (smoothed) distributions for daily highest water levels in Norfolk, Virginia, USA for the 1960s and 2010s, showing extent that local relative sea level (RSL) rise has increased the flood probability relative to impact thresholds defined locally by NOAA’s National Weather 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,

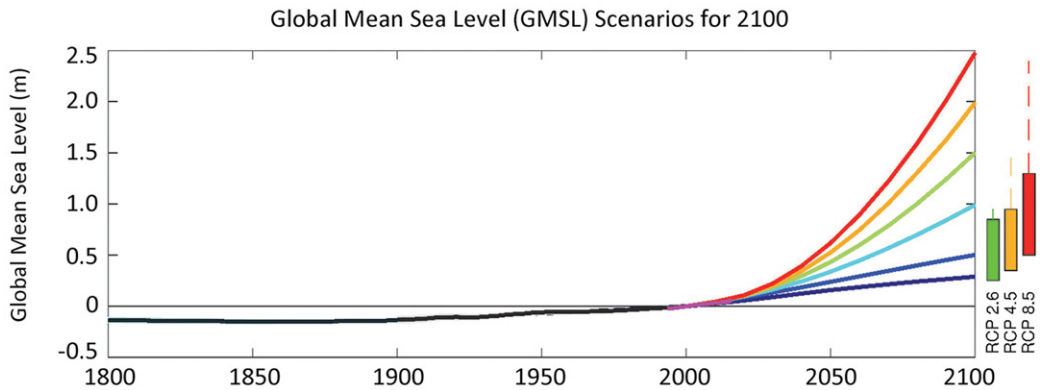


Figure 2. Six representative GMSL rise scenarios from Sweet et al. (2017) for 2100 (6 colored lines) relative to historical geological, tide gauge, and satellite altimeter GMSL reconstructions from 1800 to 2015 (black and magenta lines) and central 90% conditional probability ranges (colored boxes) of 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]).

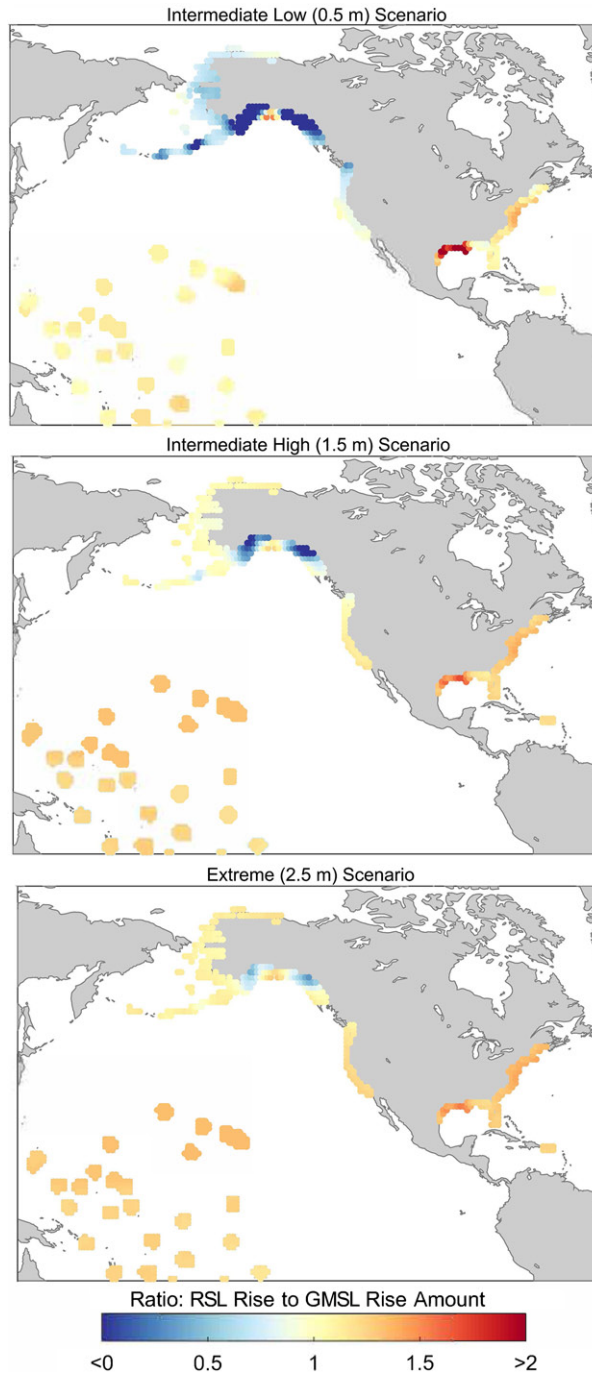


Figure 3. Ratio of the 21st century RSL rise amount at each 1-degree grid to the global mean SLR value for the Intermediate Low, Intermediate High, and Extreme scenarios. A value of 1 indicates the same amount of RSL rise as the global mean SLR amount. From Sweet et al. (2017).

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.

Acknowledgments

The views expressed are those of the authors and do not represent the policies or opinions of any US government or state agency. The authors thank Kimberly Gotwals and Erik Tucker for their assistance with figure preparation. The manuscript was improved by the comments of Andy Miller, Marissa Liang, and an anonymous reviewer. The authors dedicate this article to the memory and career of Margaret A. Davidson: colleague, friend, and champion of enduring coastal management.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

R.E.K. was supported in part by a grant from the Rhodium Group (for whom he has previously worked as a consultant), as part of the Climate Impact Lab consortium, as well as by grants from the National Science Foundation (ICER-1663807) and National Aeronautics and Space Administration (80NSSC17K0698).

References

- Bamber, J. L., and W. P. Aspinall. 2013. An expert judgment assessment of future sea level rise from ice sheets. *Nature Climate Change* 3 (4):424–7. doi:10.1038/nclimate1778
- Behar, D., R. Kopp, R. DeConto, C. Weaver, K. White, K. May, and R. Bindenschadler. 2017. Planning for sea-level rise. An American Geophysical Union talk in the form of a coproduction experiment exploring recent science. <https://www.wucaonline.org/assets/pdf/pubs-agu-consensus-statement.pdf> (accessed November 28, 2018).
- Beier, P., D. Behar, L. Hansen, L. Helbrecht, J. Arnold, C. Duke, M. Farooque et al. 2015. *Guiding principles and recommended practices for co-producing actionable science: A how-to guide for DOI Climate Science Centers and the National Climate Change and Wildlife Science Center. Report to the Secretary of the Interior*. Washington, DC: Actionable Science Workgroup of the Advisory Committee on Climate Change and Natural Resource Science.
- Bindoff, N. L., J. Willebrand, V. Artale, A. Cazenave, J. Gregory, S. Gulev, K. Hanawa et al. 2007. Observations: Oceanic climate change and sea level. In *Climate change 2007: The physical science basis. Contribution of working group I to the fourth assessment report of the intergovernmental panel on climate change*, eds. S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor, and H. L. Miller, 385–432. Cambridge, United Kingdom and New York, New York: Cambridge University Press.
- Bruun, P. 1954. Coastal erosion and development of beach profiles. *Beach Erosion Board, Technical memorandum no. 44*. Washington, DC: USACE.
- Bruun, P. 1962. Sea level rise as a cause of erosion. *Journal of the Waterways and Harbors Division, American Society of Civil Engineers* 88:117–32.
- Church, J. A., P. U. Clark, A. Cazenave, J. M. Gregory, S. Jevrejeva, A. Levermann, M. A. Merrifield et al. 2013a. Sea level change. In *Climate change 2013: The physical basis. Contribution of working group I to the fifth assessment report of the intergovernmental panel on climate change*, eds. T. F. Stocker, D. Qin, G. -K. Plattner, M. Tignor, S. K. Allen, J. Boschung,

- A. Nauels, Y. Xia, V. Bex, and P. M. Midgley, 1137–216. Cambridge, UK: Cambridge University Press.
- Church, J. A., P. U. Clark, A. Cazenave, J. M. Gregory, S. Jevrejeva, A. Levermann, M. A. Merrifield et al. 2013b. Sea-level rise by 2100. *Science (New York, N.Y.)* 342 (6165):1445.
- Clark, J. A., and C. S. Lingle. 1977. Future sea-level changes due to West Antarctic ice sheet fluctuations. *Nature* 269 (5625):206–9. doi:10.1038/269206a0.
- Clark, P. U., J. D. Shakun, S. A. Marcott, A. C. Mix, M. Eby, S. Kulp, A. Levermann et al. 2016. Consequences of twenty-first-century policy for multi-millennial climate and sea-level change. *Nature Climate Change* 6 (4):360–9. doi:10.1038/nclimate2923.
- Dahl, K. A., E. Spanger-Siegfried, A. Caldas, and S. Udvardy. 2017. Effective inundation of continental United States communities with 21st century sea level rise. *Elementa: Science of the Anthropocene* 5:37. doi:10.1525/elementa.234.
- DeConto, R. M., and D. Pollard. 2016. Contribution of Antarctica to past and future sea-level rise. *Nature* 531 (7596):591–7.
- Dilling, L., and M. C. Lemos. 2011. Creating usable science: Opportunities and constraints for climate knowledge use and their implications for science policy. *Global Environmental Change* 21 (2):680–9. doi:10.1016/j.gloenvcha.2010.11.006.
- EO. 2015. Executive Order 13690—Establishing a federal flood risk management standard and a process for further soliciting and considering stakeholder input. 80 Federal Register (FR), 6425–8.
- EO. 2017. Executive Order 13807—Establishing discipline and accountability in the environmental review and permitting process for infrastructure projects. 82 FR, 40463–9.
- EOP. 2013. The President’s climate action plan. Washington, DC: Executive Office of the President.
- Ezer, T., and L. P. Atkinson. 2014. Accelerated flooding along the U.S. East Coast: On the impact of sea-level rise, tides, storms, the Gulf Stream, and the North Atlantic Oscillations. *Earth’s Future* 2 (8):362–82. doi:10.1002/2014EF000252.
- FEMA. 2015. *Guidelines for implementing executive order 11988, Floodplain management, and executive order 13690, Establishing a federal flood risk management standard and a process for further soliciting and considering stakeholder input.* Washington, DC: FEMA.
- GAO. 2007. *Climate change: Financial risks to federal and private insurers in coming decades are potentially significant.* GAO 07-285. Washington, DC: GAO.
- Gornitz, V., S. Lebedeff, and J. Hansen. 1982. Global sea level trend in the past century. *Science (New York, N.Y.)* 215 (4540):1611–4.
- Grinsted, A., S. Jevrejeva, R. E. M. Riva, and D. Dahl-Jensen. 2015. Sea level rise projections for Northern Europe under RCP 8.5. *Climate Research* 64 (1):15–23. doi:10.3354/cr01309.
- Gutierrez, B. T., S. J. Williams, and E. R. Thieler. 2009. Ocean coasts. In *Coastal sensitivity to sea-level rise: A focus on the mid-Atlantic region.* A report by the US Climate Change Science Program and the Subcommittee on Global Change Research, coordinating lead author J.G. Titus and lead authors K. E. Anderson, D. R. Cahoon, D. B. Gesch, S. K. Gill, B. T. Gutierrez, E. R. Thieler, and S. J. Williams, 43–56. Washington, DC: US Environmental Protection Agency.
- Haasnoot, M., J. H. Kwakkel, W. E. Walker, and J. ter Maat. 2013. Dynamic adaptive pathways: A method for crafting robust decisions for a deeply uncertain world. *Global Environmental Change* 23 (2):485–98. doi:10.1016/j.gloenvcha.2012.12.006.
- Hall, J. A., S. Gill, J. Obeysekera, W. Sweet, K. Knuuti, and J. Marburger. 2016. *Regional sea level scenarios for coastal risk management: Managing the uncertainty of future sea level change and extreme water levels for Department of Defense coastal sites worldwide.* Alexandria, Virginia: Department of Defense, Strategic Environmental Research and Development Program.
- Hay, C. C., E. Morrow, R. E. Kopp, and J. X. Mitrovica. 2015. Probabilistic reanalysis of twentieth-century sea-level rise. *Nature* 517 (7535):481–4.
- Heal, G., and A. Millner. 2014. Reflections on uncertainty and decision making in climate change economics. *Review of Environmental Economics and Policy* 8 (1):120–37. doi:10.1093/reep/ret023.

- Hinkel, J., C. Jaeger, R. J. Nicholls, J. Lowe, O. Renn, and S. Peijun. 2015. Sea-level rise scenarios and coastal risk management. *Nature Climate Change* 5 (3):188–90. doi:10.1038/nclimate2505.
- Horton, B. P., R. E. Kopp, A. J. Garner, C. C. Hay, N. S. Khan, K. Roy, and T. A. Shaw. 2018. Mapping sea-level change in time, space and probability. *Annual Reviews of Environment and Resources* 43:481–521.
- Horton, R. M., C. Little, V. Gornitz, D. Bader, and M. Oppenheimer. 2015. New York City Panel on Climate Change 2015 Report. Chapter 2: Sea level rise and coastal storms. *Annals of the New York Academy of Sciences* 1336:36–44.
- HSRTF. 2013. Hurricane Sandy rebuilding strategy: Stronger communities, a resilient region. Report to the President of the US from the Hurricane Sandy Rebuilding Task Force.
- Kasperson, R. E. 2008. Coping with uncertainty: Challenges for environmental assessment and decision making. In *Uncertainty and risk: Multidisciplinary perspectives*, eds. G. Bammer and M. Smithson, 337–47. London, United Kingdom: Earthscan.
- Kopp, R. E., R. M. DeConto, D. A. Bader, C. C. Hay, R. M. Horton, S. Kulp, M. Oppenheimer, D. Pollard, and B. H. Strauss. 2017. Evolving understanding of Antarctic ice-sheet physics and ambiguity in probabilistic sea-level projections. *Earth's Future* 5 (12):1217–33. doi:10.1002/2017EF000663.
- Kopp, R. E., R. M. Horton, C. M. Little, J. X. Mitrovica, M. Oppenheimer, D. J. Rasmussen, B. H. Strauss, and C. Tebaldi. 2014. Probabilistic 21st and 22nd century sea-level projections at a global network of tide-gauge sites. *Earth's Future* 2:1–24.
- Kopp, R. E., A. C. Kemp, K. Bittermann, B. P. Horton, J. P. Donnelly, W. R. Gehrels, C. C. Hay, J. X. Mitrovica, E. D. Morrow, and S. Rahmstorf. 2016. Temperature-driven global sea-level variability in the common era. *Proceedings of the National Academy of Sciences* 113 (11): E1434–41. doi:10.1073/pnas.1517056113.
- Kunkel, K. E., R. Moss, and A. Parris. 2016. Innovations in science and scenarios for assessment. *Climatic Change* 135:55–68.
- Kunreuther, H., G. Heal, M. Allen, D. Edenhofer, C. B. Field, and G. Yohe. 2013. Risk management and climate change. *Nature Climate Change* 3 (5):447–50. doi:10.1038/nclimate1740.
- Le Cozannet, G., R. Nicholls, J. Hinkel, W. Sweet, K. McInnes, R. Van de Wal, A. Slangen, J. Lowe, and K. White. 2017. Sea level change and coastal climate services: The way forward. *Journal of Marine Science and Engineering* 5 (4):49. doi:10.3390/jmse5040049.
- Lemos, M. C., and B. Morehouse. 2005. The co-production of science and policy in integrated climate assessments. *Global Environmental Change* 15 (1):57–68. doi:10.1016/j.gloenvcha.2004.09.004.
- Lempert, R. 2013. Scenarios that illuminate vulnerabilities and robust responses. *Climatic Change* 117 (4):627–46. doi:10.1007/s10584-012-0574-6.
- Lempert, R., N. Nakicenovic, D. Sarewitz, and M. Schlesinger. 2004. Characterizing climate-change uncertainties for decision-makers. *Climatic Change* 65 (1/2):1–9. doi:10.1023/B:CLIM.0000037561.75281.b3.
- Levermann, A., P. U. Clark, B. Marzeion, G. A. Milne, D. Pollard, V. Radic, and A. Robinson. 2013. The multimillennial sea-level commitment of global warming. *Proceedings of the National Academy of Sciences* 110 (34):13745–50. doi:10.1073/pnas.1219414110.
- Little, C. M., R. M. Horton, R. E. Kopp, M. Oppenheimer, G. A. Vecchi, and G. Villarini. 2015. Joint projections of US East Coast sea level and storm surge. *Nature Climate Change* 5 (12): 1114–20. doi:10.1038/nclimate2801.
- Meadow, A. M., D. B. Ferguson, Z. Guido, A. Horangic, and G. Owen. 2015. Moving toward the deliberate coproduction of climate science knowledge. *American Meteorology Society* 7:179–91.
- Meehl, G. A., Hu, A. C. Tebaldi, J. M. Arblaster, W. M. Washington, H. Teng, B. M. Sanderson, T. Ault, W. G. Strand, and J. B. White III. 2012. Relative outcomes of climate change mitigation related to global temperatures versus sea-level rise. *Nature Climate Change* 2 (8):576–80. doi:10.1038/nclimate1529.
- Melillo, J. M., T. C. Richmond, and G. W. Yohe, eds. 2014. *Climate change impacts in the United States: The Third National Climate Assessment*. Washington, DC: US Global Change Research Program, US Government Printing Office.

- Mengel, M., A. Levermann, K. Frieler, A. Robinson, B. Marzeion, and R. Winkelmann. 2016. Future sea level rise constrained by observations and long-term commitment. *Proceedings of the National Academy of Sciences* 113 (10):2597–602.
- Mengel, M., A. Nauels, J. Rogelj, and C.-F. Schleussner. 2018. Committed sea-level rise under the Paris Agreement and the legacy of delayed mitigation action. *Nature Communications*. 9, 601.
- Miller, K. G., R. E. Kopp, B. P. Horton, J. V. Browning, and A. C. Kemp. 2013. A geologic perspective on sea-level rise and its impacts along the U.S. mid-Atlantic coast. *Earth's Future* 1 (1):3–18. doi:10.1002/2013EF000135.
- Moftakhari, H. R., A. AghaKouchak, B. F. Sanders, D. L. Feldman, W. Sweet, R. A. Matthew, and A. Luke. 2015. Increased nuisance flooding along the coasts of the United States due to sea level rise: Past and future. *Geophysical Research Letters* 42 (22):9846–52. doi:10.1002/2015GL066072.
- Moftakhari, H. R., A. AghaKouchak, B. F. Sanders, and R. A. Matthew. 2017a. Cumulative hazard: The case of nuisance flooding. *Earth's Future* 5 (2):214–23. doi:10.1002/2016EF000494.
- Moftakhari, H. R., G. Salvadori, A. AghaKouchak, B. F. Sanders, and R. A. Matthew. 2017b. Compounding effects of sea level rise and fluvial flooding. *Proceedings of the National Academy of Sciences* 114 (37):9785–90. doi:10.1073/pnas.1620325114.
- NRC. 1987. *Responding to changes in sea level, engineering implications*. Committee on Engineering Implications of Changes in Relative Mean Sea Level, Marine Board, Commission on Engineering and Technical Systems, National Research Council of the National Academies. Washington, DC: The National Academy Press.
- NRC. 2012. *Sea-level rise for the coasts of California, Oregon, and Washington: Past, present, and future*. Committee on Sea Level Rise in California, Oregon, Washington; Board on Earth Sciences and Resources and Ocean Studies Board; Division on Earth and Life Studies. National Research Council of the National Academies. Washington, DC: The National Academies Press.
- NPCC. 2013. *Climate risk information 2013: Observations, climate change projections, and maps*, eds. Rosenzweig, C., and W. Solecki. Prepared for use by the City of New York Special Initiative on Rebuilding and Resiliency. New York, New York: NPCC.
- Obeysekera, J., and J. D. Salas. 2016. Frequency of recurrent extremes under nonstationarity. *Journal of Hydrologic Engineering* 21:1339.
- Oppenheimer, M., Little, C. M., and R. M. Cooke. 2016. Expert judgement and uncertainty quantification for climate change. *Nature Climate Change* 6 (5):445–51. doi:10.1038/nclimate2959.
- Parris, A. P., P. Bromirski, V. Burkett, D. Cayan, M. Culver, J. Hall, R. Horton et al. 2012. *Global sea level rise scenarios for the United States National Climate Assessment*. National Oceanic and Atmospheric Administration (NOAA) Technical Report OAR CPO-1. Silver Spring, MD: US Department of Commerce, NOAA, Office of Atmospheric Research.
- Pfeffer, W. T., J. T. Harper, and S. O'Neel. 2008. Kinematic constraints on glacier contributions to 21st-century sea-level rise. *Science (New York, N.Y.)* 321 (5894):1340–3.
- Ranger, N., A. Harvey, and S.-L. Garbett-Shiels. 2013. *Safeguarding development aid against climate change: Evaluating progress and identifying best practice*. London, United Kingdom: Centre for Climate Change Economics and Policy (Working Paper No. 157) and Grantham Research Institute on Climate Change and Environment (Working Paper No. 140).
- Rignot, E., J. Mouginot, M. Morlighem, H. Seroussi, and B. Scheuchl. 2014. Widespread, rapid grounding line retreat of Pine Island, Thwaites, Smith, and Kohler glaciers, West Antarctica, from 1992 to 2011. *Geophysical Research Letters* 41 (10):3502–9. doi:10.1002/2014GL060140.
- Slangen, A. B. A., M. Carson, C. A. Katsman, R. S. W. van de Wal, A. Köhl, L. L. A. Vermeersen, and D. Stammer. 2014. Projecting twenty-first century regional sea-level changes. *Climatic Change* 124 (1-2):317–32. doi:10.1007/s10584-014-1080-9.
- Solomon, S., G. K. Plattner, R. Knutti, and P. Friedlingstein. 2009. Irreversible climate change due to carbon dioxide emissions. *Proceedings of the National Academy of Sciences* 106 (6): 1704–9. doi:10.1073/pnas.0812721106.
- Srifer, R. L., N. M. Urban, R. Olson, and K. Keller. 2012. Toward a physically plausible upper bound of sea-level rise projections. *Climate Change* 115 (3-4):893–902. doi:10.1007/s10584-012-0610-6.

- Sweet, W. V., G. Dusek, J. Obeysekera, and J. J. Marra. 2018. Patterns and projections of high tide flooding along the U.S. coastline using a common impact threshold. NOAA Technical Report NOS CO-OPS 086. Silver Spring, MD: US Department of Commerce, NOAA, National Ocean Service, Center for Operational Oceanographic Products and Services.
- Sweet, W. V., R. E. Kopp, C. P. Weaver, J. Obeysekera, R. M. Horton, E. R. Thieler, and C. Zervas. 2017. Global and regional sea level rise scenarios for the United States. NOAA Technical Report NOS CO-OPS 083. Silver Spring, MD: US Department of Commerce, NOAA, National Ocean Service, Center for Operational Oceanographic Products and Services.
- Sweet, W. V., and J. Park. 2014. From the extreme and the mean: Acceleration and tipping point of coastal inundation from sea level rise. *Earth Futures* 2 (12):579–600.
- Sweet, W. V., J. Park, J. J. Marra, C. Zervas, and S. Gill. 2014. Sea level rise and nuisance flood frequency changes around the United States. NOAA Technical Report NOS CO-OPS 73. Silver Spring, MD: US Department of Commerce, NOAA, National Ocean Service, Center for Operational Oceanographic Products and Services.
- TMAC. 2015. *Future conditions risk assessment and modeling report*. Washington, DC: TMAC.
- Thistlethwaite, J., A. Minano, J. A. Blake, D. Henstra, and D. Scott. 2018. Application of re/insurance models to estimate increases in flood risk due to climate change. *Geoenvironmental Disasters* 5(8):9.
- USACE. 1986. *Letter on relative sea level change dated 21 March 1986*. USACE Directorate of Civil Works. Washington, DC: USACE.
- USACE. 2009. *Water resources policies and authorities incorporating sea-level change considerations in Civil Works programs*. EC 1165-2-211. Washington, DC: USACE.
- USACE. 2013. *Incorporating sea level change in Civil Works programs*. ER 1100-2-8162. Washington, DC: USACE.
- USACE. 2014. *Procedures to evaluate sea level change: Impacts, responses, and adaptation*. Engineer Technical Letter 1100-2-1. Washington, DC: USACE.
- Vogel, J., E. McNie, and D. Behar. 2016. Co-producing actionable science for water utilities. *Climate Services* 2-3:30–40.
- Wahl, T., S. Jain, J. Bender, S. D. Meyers, and M. E. Luther. 2015. Increasing risk of compound flooding from storm surge and rainfall for major US cities. *Nature Climate Change* 5 (12): 1093–7.
- Water Resources Council. 1983. *Economic and environmental principles and guidelines for water and related land resources implementation studies*. Washington, DC: USWRC.
- Weaver, C. P., R. J. Lempert, C. Brown, J. A. Hall, D. Revell, and D. Sarewitz. 2013. Improving the contribution of climate model information to decision making: The value and demands of robust decision frameworks. *Wiley Interdisciplinary Reviews: Climate Change* 4 (1):39–60.
- Weaver, C. P., R. H. Moss, K. L. Ebi, P. H. Gleick, P. C. Stern, C. Tebaldi, R. S. Wilson, and J. L. Arvai. 2017. Reframing climate change assessments around risk: Recommendations for the U.S. National Climate Assessment. *Environmental Research Letters* 12 (8):080201. doi:10.1088/1748-9326/aa7494.
- Wuebbles, D. J., D. W. Fahey, K. A. Hibbard, D. J. Dokken, B. C. Stewart, and T. K. Maycock, eds. 2017. *Climate science special report: Fourth National Climate Assessment*. Volume I. Washington, DC: US Global Change Research Program.

Hall et al.: Rising Sea Levels: Helping Decision-Makers Confront the Inevitable

Supplemental Material

Text

1. Additional details regarding the United States Army Corps of Engineers

Sea levels have been an important factor for the United States (US) Army Corps of Engineers (USACE) since its formation in 1802, beginning with its predecessors' earliest involvement in coastal engineering in the late 1700s building and rehabilitating coastal fortifications for national defense. Since the 19th century, coastal engineers inside and outside the USACE collected measurements of mean sea level, tides, surge, and other coastal water levels and considered the effects of changing sea levels on coastal erosion (Bruun 1962; Schwartz 1965). These concerns spurred the USACE (1971) National Shoreline Study, which raised awareness inside the USACE about the potential threats changing sea level posed to missions and operations.

By the mid-1980s, growing realization of the potential effects of sea-level change on coastal shorelines, including adverse impacts to infrastructure, public health, and safety, as well as increased economic damages led to an interdisciplinary expert study by a National Research Council (NRC) committee. The committee's report (NRC 1987) discussed the growing concern of global sea-level rise (SLR) associated with the increasing percentage of the nation's populations, businesses, and industry moving, living, and building near the Pacific, Atlantic, and Gulf coasts. These coastal and geological engineering experts concluded with remarkable foresight that "the most appropriate present engineering strategy is not to adopt one particular sea level rise scenario, but instead to be aware of the probability of increasing sea level and to keep all response options open" (NRC 1987, 4).

Information developed during the preparation of the 1987 NRC report formed the basis of a 1986 USACE guidance letter (USACE 1986) that required changing sea levels be considered in the planning and design of coastal flood control and erosion protection projects. Subsequent planning guidance (USACE 1989) required that project plans be formulated based on the observed local relative rate of change (historical rate), but also consider the consequences to the project of the full range of NRC scenarios. An update (USACE 2000) addressed sensitivity to the historical and NRC high rate (equivalent to 1.5 m at 2100) of sea-level change. More detailed planning and engineering policy (USACE 2009, 2011) was followed by the release of the current guidance (USACE 2013) that requires consideration of three scenarios. The three required scenarios are adjusted to a start date of 1992 (midpoint of the 1983–2001 National Tidal Datum Epoch) and assume a current global SLR of 1.7 mm/yr based on Bindoff et al. (2007) for the low-rate or historical scenario. USACE coastal practitioners, however, also are allowed to consider a higher rate of sea-level change (for example, the 2.0 m at 2100 global scenario of Parris et al. [2012]) as a maximum plausible upper bound of global mean sea-level change if justified by project conditions (USACE 2013). In addition, the flexibility to use even higher scenarios, when justified, can account for changes in statistically significant trends and new knowledge about changing sea levels. USACE projects—similar to large infrastructure projects in general—often take years to plan, fund, design, and construct, so this flexibility reflects a

practical approach, given that frequent adjustments open the possibility for unintended risk transfer across closely related projects and unequal economic comparisons between projects when assessing project justification.

In addition to defining the three scenarios that USACE practitioners must consider when planning and designing coastal projects, USACE also has provided specific technical guidance to assist application in a context-dependent manner (USACE 2014). For example, a sea-level calculator has been developed to generate a number of authoritative scenarios (e.g., as provided by Parris et al. 2012, Sweet et al. 2017; USACE 2013) for any National Oceanic and Atmospheric Administration (NOAA) tide gauge that is part of the National Water Level Observation Network. An extension supports estimates of relative SLR at USACE tide gauges in the high-subsidence environment of coastal Louisiana based on long-term USACE tide gauge data (Veatch 2017). In Louisiana, Alaska, and other areas of high local land movement, computed estimates of mean sea level may not align with the 1983–2001 National Tidal Datum Epoch (NTDE) but instead may center on a different time period such as the modified five-year NTDE (Gill et al. 2014). Applying sea-level change scenarios to associated local tide gauges may require shifting the tidal datum in time to align the scenario start date with the observed sea level (USACE 2014). The same procedure may apply when using scenarios with start or anchor dates other than 1992. This shift typically is performed using the observed historical rate of sea-level change at the tide gauge in question. A sea-level tracker tool is under development to enable decision-makers to visualize such discontinuities and trends in long-term tide gauge data, including inter- and intra-annual tidal water level variability, change in mean sea level over time relative to scenarios, and superimposition of tidal datums and extreme *still* water levels (ESWL) on scenarios. These tools help advance the application of sea-level guidance in a consistent and repeatable manner, facilitating its broad adoption and helping assure its appropriate implementation.

2. Additional details regarding the United States Federal Emergency Management Agency

The National Flood Insurance Program (NFIP), administered by the US Federal Emergency Management Agency (FEMA), is an insurance, mapping, and land-use management program that makes federally backed flood insurance available to home and business owners in communities that participate in the program and insures against the one-percent annual chance flood. Areas subject to the one-percent annual chance flood (sometimes referred to as the “hundred-year flood”) are termed Special Flood Hazard Areas (SFHAs), with corresponding water surface elevations identified as Base Flood Elevations (BFEs). This information is displayed on Flood Insurance Rate Maps (FIRMs) (Crowell, Hirsch, and Hayes 2007; Divoky, Eberbach, and Crowell 2012; Pasterick 1998). Rates are based on what is considered the current flood risk and do not account for long-term erosion and SLR. Reform legislation in 1973 (Flood Disaster Protection Act) did address erosion, but only to the extent that it made damages caused by individual storm- or event-driven erosion eligible for coverage under the NFIP.

FEMA completed a congressionally mandated report in 1991 on the effect of SLR on the NFIP (FEMA 1991; TMAC 2015), about the same time as the release of the International Panel on Climate Change’s (IPCC) First Assessment Report (AR1; Houghton, Jenkins, and Ephraums 1990). No significant policy changes resulted; however, recognition of the possibility of

significant future SLR impacts on the NFIP prompted FEMA to provide SLR-related incentives in the voluntary Community Rating System (CRS) program. The CRS encourages communities to implement floodplain management measures that exceed minimum NFIP standards (TMAC 2015).

A renewed interest in how climate change might impact the NFIP occurred in the aftermath of Hurricane Katrina in 2005. Findings from an ensuing study recommended by the US Government Accountability Office (GAO 2007) indicated that by 2100 changing climate (i.e., changes in precipitation patterns, sea levels, long-term erosion, frequency and intensity of coastal storms) and population growth could result in a median increase in the size of coastal and riverine SFHAs anywhere from 40 to 45 percent (AECOM 2013). The study also noted that as a result of this size increase, the total number of NFIP insurance policies could grow by 80 to 100 percent.

In 2012 the Biggert-Waters Flood Insurance Reform Act (BW-12) mandated the creation of a Technical Mapping Advisory Council (TMAC), whose purpose was to recommend to FEMA, in a series of annual reports, ways to improve FEMA flood maps and the flood mapping process. The TMAC also was required to prepare a one-time Future Conditions Risk Assessment and Modeling Report (Future Conditions Report [TMAC 2015]). One of the report's recommendations was specific to coastal and Great Lakes areas, and it specifies that the products and information "include the future effects of long-term erosion and sea/lake level rise" (TMAC 2015, 10). Sub-recommendations further advise FEMA on specific aspects of incorporating SLR and long-term erosion within the framework of the NFIP, including providing a set of regional SLR scenarios based on Parris et al. (2012) for coastal regions of the US (TMAC 2015, 11).

A special case that arose in the aftermath of Hurricane Sandy in 2012 demonstrates the viability and value of such recommendations. In the days following Sandy's landfall, FEMA rushed to prepare Advisory Base Flood Elevation (ABFE) maps for New York and New Jersey. The ABFEs were intended to be used by state and local officials to guide rebuilding and recovery decisions until official, regulatory FIRMs and BFEs could be prepared. Various federal, state, and local officials raised concerns, however, regarding the lack of consideration of future SLR in the preparation of the ABFEs. As a result, an interagency federal team was created for the purpose of developing non-regulatory SLR tools that could be used in conjunction with ABFEs and BFEs. The team included representatives from the U.S. Global Change Research Program, NOAA, USACE, and FEMA. The SLR tools were developed over a period of three months and included interactive maps and calculators that projected future BFEs and SFHA boundaries out to 2100. Decision-makers in New York and New Jersey used the tools successfully for rebuilding purposes (e.g., see Parris 2014).

3. Additional details regarding Hall et al. (2016) methodologies for United States

Department of Defense sites worldwide

Systemic Adjustments: Technical Challenges Addressed and Key Innovations

Systemic trends are those components of regional sea-level change that are anticipated to exhibit a persistent directional trend in their behavior over the period 2015 to 2100 (Hall et al. 2016). Three components are considered to contribute to regional- or local-scale adjustment to the global SLR scenarios. These are vertical land movement (VLM), dynamic sea-level (DSL) change (ocean dynamics such as changes in circulation patterns), and gravitational, rotational, and deformational adjustments associated with the redistribution of mass from glaciers, ice caps, and land-based ice sheets (see Kopp et al. 2015 for a review of the factors driving geographic variability in sea-level change). Because Department of Defense (DoD) sites are located worldwide, it was a significant challenge to develop a reasonable, consistent approach that enables the estimation of these components across a wide range of global scenarios when considering the range and quality of data available to estimate VLM and the quite different regional responses to ice mass loss and DSL.

Vertical Land Movement Adjustment. VLM is an important factor when considering future vulnerability to inundation from SLR and coastal storms. VLM can be due to a variety of factors, including response of the earth's surface to changes in land-ice cover over the past ~20 thousand years (modeled, along with accompanying changes to the Earth's gravitational field and rotation, by Glacial Isostatic Adjustment [GIA] models), post-earthquake deformations, and slow tectonic movement. Locally, land subsidence also can contribute, due to withdrawal of hydrocarbons (oil and gas) and groundwater and local sediment compaction. Rates of local subsidence can change over relatively short time periods (e.g., a decade) if a local pumping withdrawal activity stops or mitigation by fluid replacement occurs; however, a simplifying assumption was made that VLM has a constant linear trend through 2100 for any given site.

Depending on the cause, VLM can be positive (uplift) or negative (subsidence). Because site-specific information regarding VLM was not readily available for the DoD sites considered, Hall et al. (2016) used three primary data sources: (a) long-term tide gauge records (Zervas et al. 2013), (b) direct measurements from continuously operating global positioning system (GPS) stations (JPL 2013; Snay et al. 2007; C. Demts, personal communication 2015), and (c) GIA model output (Peltier 1998; 2004). Because of differing degrees of accuracy (often determined by length of record of the measurements) and spatial proximity of the VLM data's collection point relative to site location, Hall et al. (2016) used a prioritization scheme, based on accuracy and proximity, for determining which VLM data source to use for each site. For sites for which both a tide-gauge and a GPS station were not available, GIA model estimates were used as the last resort. Measurement (or model) points within 3 km of a site were considered a direct measurement, whereas those outside 3 km were considered extrapolated as a means to express the degree of confidence in the measurements. Table S1 illustrates the breakdown in the VLM data source used across all of the DoD sites and whether the measurement was considered direct, extrapolated, or modeled. Rates unsurprisingly ranged broadly as depicted in Figure S1 given the global coverage of DoD sites.

Table S1. Distribution of the number of times a particular type of vertical land movement source was used (from Hall et al. 2016)

VLM Source	# of Sites Using Source Type	Site 3 km or less away	Site more than 3 km away
Global Isostatic Adjustment Model Direct (GIAD)	17	✓	
Global Isostatic Adjustment Extrapolated (GIAE)	69		✓
Continuous GPS System Direct (GPSD)	128	✓	
Continuous GPS System Extrapolated (GPSE)	919		✓
Tide Gauge Direct (TGD)	94	✓	
Tide Gauge Extrapolated (TGE)	546		✓

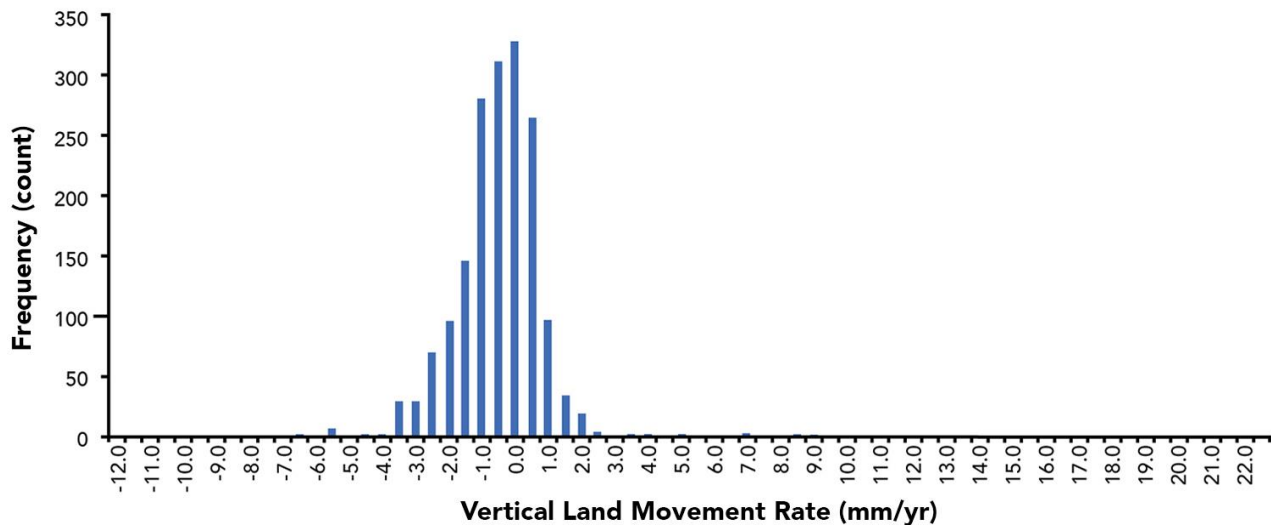


Figure S1. Histogram for rates of vertical land movement at 1,744 Department of Defense sites worldwide (from Hall et al. 2016).

Dynamic Sea-Level Adjustment. Regional sea levels may differ substantially from a global average due to a variety of factors that may be associated with persistent and natural modes of the climate system, such as the El Niño Southern Oscillation (ENSO), Atlantic Multidecadal Oscillation (AMO), and Pacific Decadal Oscillation (PDO), and other factors affecting atmosphere/ocean dynamics. The dynamic redistribution of ocean water masses is caused by both episodic and long-term changes in winds, air pressure, air-sea heat and freshwater fluxes, and ocean currents. Persistent patterns of sea-level variations, which are of interest for longer-term projections, may result from long-term changes in the current and wind fields, changes in the regional and global ocean heat and freshwater content, and the associated redistribution of ocean properties such as heat content and salinity (Church et al. 2013a; Yin, Griffies, and

Stouffer 2010). Global climate model projections provide a source of projections for DSL change under future climate change emission scenarios.

To incorporate DSL in the DoD study, the “pattern scaling” approach used in Perrette et al. (2013) and the underlying data were used. Perrette et al. (2013) used 22 simulations from General Circulation Models (GCM) participating in the Coupled Model Intercomparison Project Phase 5 (CMIP5) that were available at the time of their study. In support of the DoD study, M. Perrette (personal communication 2014) made specific runs for the years 2035, 2065, and 2100 and provided global means and gridded data on a 1° global mesh of relevant components contributing to regional sea-level change. The corresponding methods are documented in Perrette et al. (2013). The phrase “pattern-scaling” used here is defined as the deviation of dynamic sea level from the mean steric SLR (mean thermal expansion) scaled by the global mean surface temperature. Perrette et al. (2013) developed pattern-scaling factors using the results of a subset of 20 GCMs and a regression approach to normalize the dynamic sea-level changes as a function of temperature. An example of the scaling pattern computed for the Representative Concentration Pathway (RCP) 8.5 scenario and year 2100 is shown in Figure S2.

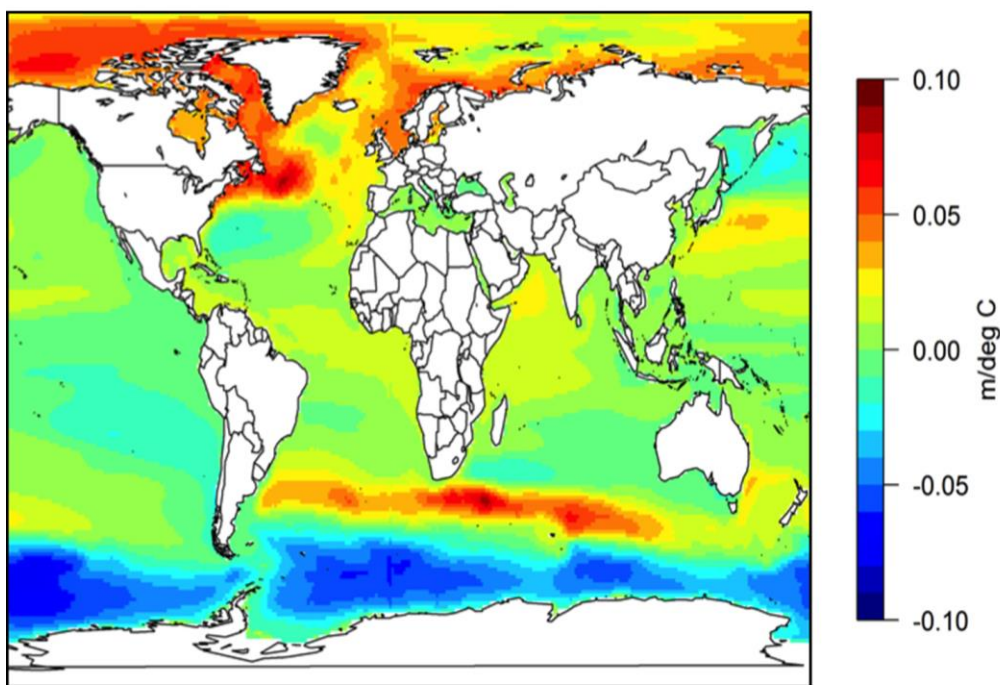


Figure S2. Example of pattern-scaling described in the text corresponding to RCP 8.5 scenario for year 2100 (from Hall et al. 2016 based on data provided by M. Perrette, personal communication 2014).

Regional Sea-Level Adjustments Associated with Ice Mass Loss. When land-based ice (i.e., glaciers, ice caps, and ice sheets) melts due to warming, the corresponding effect on regional sea level due to mass redistribution is far from uniform, and the spatial signature of the melt water is quite variable in space (Church et al. 2013a; Grinsted et al. 2015). This non-uniform pattern

arises from multiple causes that manifest themselves in an interacting manner. When land ice melts, the mass that was concentrated in the ice disperses into the ocean; as a consequence, the gravitational attraction of that mass becomes less concentrated in the area undergoing mass loss. In the vicinity of the shrunken ice—up to a distance of about 2000 km—regional sea level therefore falls (Clark and Lingle 1977; Mitrovica et al. 2011; Slangen et al. 2012). Far from the shrunken ice, conservation of mass implies a SLR in excess of the global mean level (Clark and Lingle 1977; Mitrovica et al. 2011). The redistribution of mass also alters the rate and orientation of Earth’s rotation, further redistributing water. Finally, the change in the surface loading (both by the ice and by the ocean) also deforms the Earth’s surface, causing uplift underneath the shrunken ice and subsidence underneath the more loaded ocean (Clark and Lingle, 1977; Mitrovica et al. 2011; Slangen et al. 2012). In many studies (e.g., Grinsted et al. 2015; Tamisea et al. 2010) the Earth’s response to the change in surface loading is assumed to be instantaneous (i.e., elastic). Over many centuries to millennia, the Earth’s mantle re-equilibrates to the change in loading, giving rise to isostatic adjustment. Finally, shoreline change due to melt water and shrinking marine-based ice also affect the regional sea-level pattern (Mitrovica et al. 2011; Tamisea et al. 2010).

Mass change in each ice sheet (i.e., those associated with Greenland or Antarctica) or a continental glacier produces a distinct spatial signature of relative sea-level change, often known as a sea level “fingerprint” (Mitrovica et al. 2011; Spada, Bamber, and Hurkmans 2013). The fingerprint is typically expressed as a ratio between regional relative sea-level change and global mean sea-level change. Hall et al. (2016) employed the model of Bamber and Riva (2010) as used by Perrette et al. (2013) to generate fingerprints.

The components associated with the fingerprints are ice melts from glaciers and ice caps (GIC; see Perrette et al. [2013] for data sources and assumptions), Greenland ice sheet (GrIS), and Antarctica ice sheet (AIS). Once the global mass addition from a particular source is known, the adjustments for any location can be computed using the appropriate fingerprint. Figure S3 shows the fingerprints corresponding to each of the ice mass sources. The approach used for the DoD study required regional adjustments for all three components (GIS, GrIS, and AIS), each global mean SLR scenario (0.2 m, 0.5 m, 1.0 m, 1.5 m, and 2.0 m), and a given time epoch (2035, 2065, and 2100). The probability distributions available from Kopp et al. (2014) were used for estimating the contribution of each ice-melt source subject to a global mean SLR scenario. See Hall et al. (2016) for additional details of the methodology.

Extreme Water Levels: Technical Challenges Addressed and Key Innovations

Coastal flooding, erosion, and damages from extreme water events threaten coastal installations and sites and their assets. Knowledge of their event probabilities today and first-order estimates of how their flooding magnitude, frequency, and extent might change in response to scenarios of local SLR is an important contribution of the Hall et al. (2016) effort. Such information is key to maintaining critical infrastructure, public works, and functionality of sector-specific systems.

Impacts during events occur over a range of hydraulic conditions, from those associated with calm-weather tidal (bathtub-like) flooding to those with severe coastal storms with large waves

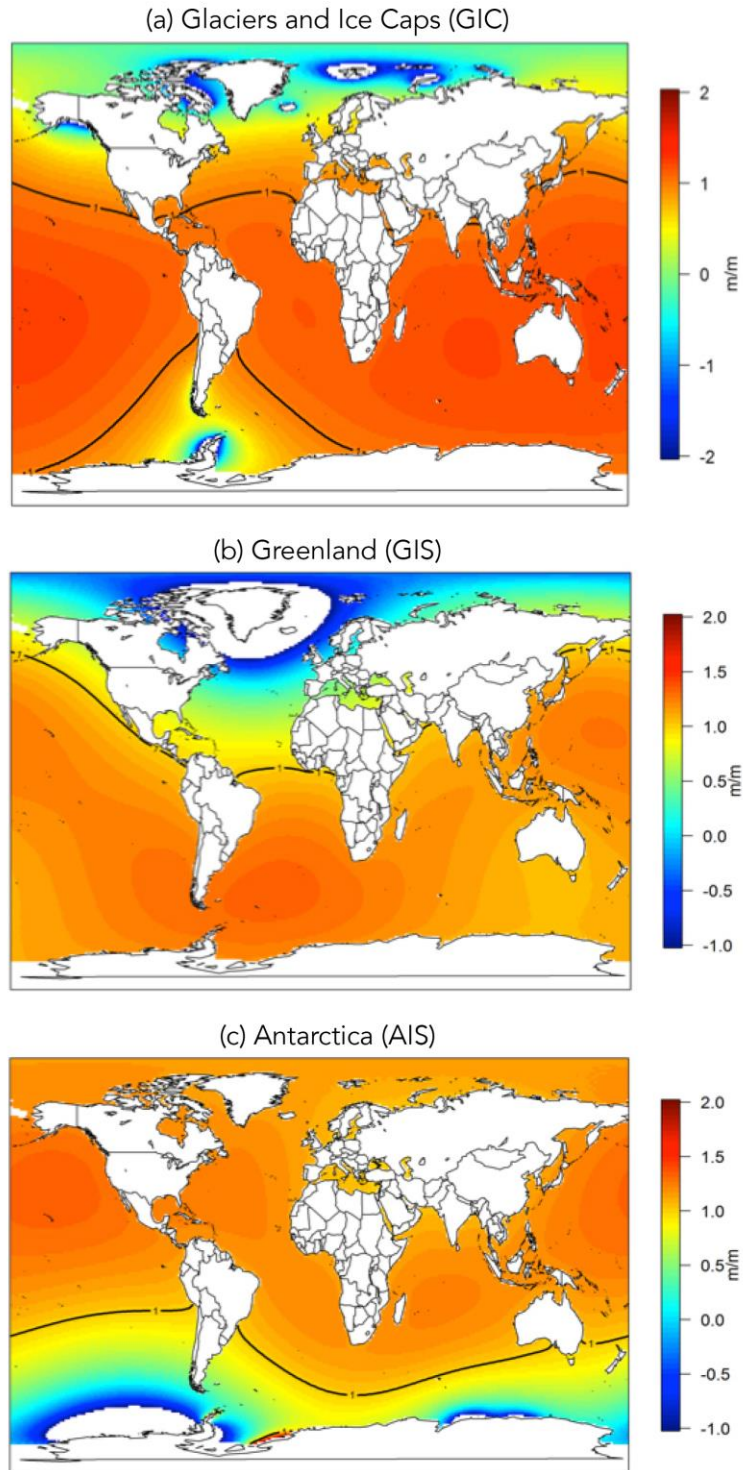


Figure S3. Fingerprints of (a) Glaciers and Ice Caps; (b) Greenland Ice Sheet, and (c) Antarctica Ice Sheet (from Hall et al. 2016). The scale bar represents the ratio of SLR at a particular location to the melt volume (in meters) associated with each of the source components. The solid contour line (ratio equals 1) represents locations where the sea-level increase associated with ice melt from a particular component is equivalent to the global mean value of sea-level increase due to the associated increased mass addition from ice melt from that component.

and their pounding effects. Due to limitations in obtaining localized wave effect information such as runup (setup or swash) during events and dynamical simulations to estimate rarely observed event probabilities from a particular location (landfalling tropical storm) for over 1800 sites worldwide, Hall et al. (2016) focused on event probabilities statistically derived from tide gauge measurements corresponding to ESWLs. To overcome the latter limitation (spatial constraints to sampling the rare event), the authors used a regional frequency analysis (RFA; Hosking and Wallis 1997) based approach of tide gauge data to estimate local extreme-event probabilities for DoD coastal sites. The RFA method uses summary statistics of historical water level events at a particular location to delineate a region across which a shared ESWL probability density up to a localized scaling factor. Data from historical annual water level maxima within such a “homogeneous” region were then normalized, combined, and fit using a Generalized Extreme Value (GEV) distribution. The RFA approach used: (1) increased the population sampling of low probability events (e.g., 1 percent annual chance of occurrence or the 0.01 Annual Exceedance Probability [AEP] flood event) by pulling observations from multiple observations platforms within a sufficiently large region but whose extreme response share common statistical properties, (2) minimized record-length statistical biases that can affect direct statistical estimates, and (3) permitted estimates for locations not co-located with a tide gauge. Indeed, this enabled ESWL estimates to be provided for about a third of the sites that otherwise lacked a representative local tide gauge (Hall et al. 2016).

To use more of the tide gauge record, the nontidal residual component (NTR: difference between observed and predicted based upon astronomical tide theory) of the water level was analyzed. For instance, often times a storm surge during an event of highest magnitude may have occurred during a low tide (such as during Hurricane Sandy along portions of the mid-Atlantic; e.g., see Sweet et al. 2013). By analyzing all such extreme NTR values independent of the tidal cycle, the probability distribution of event magnitudes and their frequencies is expanded to include more information deemed possible but not directly observed. To estimate flood levels for future 1, 2, 5, and 20 percent annual chance [or 0.01, 0.02, 0.05, and 0.2 AEP] events, the assumption was explicit that such “unobserved” dynamical response could occur at any tidal cycle and that future “observed” probabilities could be approximated as the NTR extreme probability distribution on top of the local mean higher high water (MHHW) tidal datum that is shifted according to the magnitude of the local SLR scenario. The authors recognized that the probability of a particular water level event is actually a joint probability between the astronomic tide and NTR component possible for a location, but were unable to provide such a solution as astronomic tide predictions were not available for many of the DoD sites. As a result, within regions where ESWLs are dominated largely by time-dependent changes in tide range (e.g., king tides) and NTR (storm surge) is relatively small such as within Pacific island locations (Merrifield et al. 2013; Sweet et al. 2014), assuming use of MHHW as the basis for an event would tend to under-estimate contemporary probabilities based on observations (tide + NTR). In addition, although other factors likely will affect future ESWLs (e.g., changing tide range and storm surge characteristics associated with high sea levels), the assumptions used by Hall et al (2016) followed procedures often used for screening level estimate purposes (e.g., Tebaldi, Strauss, and Zervas 2012).

Figure S4 shows water levels for NTR 0.01 AEP flood events based on an RFA of annual maxima values fit by GEV distributions (Coles 2001). Levels are highest where tropical storms (e.g., U.S. Southeast and Gulf Coasts) and strong extratropical storms (e.g., US Northeast Coast,

southern Alaska) occur and especially so when such events make landfall with a wide adjacent continental shelf. On the other hand, relatively low NTR return levels occur along the US Southwest Pacific mainland coasts and ocean islands due to bathymetric constraints on storm surge magnitudes occurring over narrow continental shelves found in these regions. In these regions wave effects during extreme events can be as large as or larger than the NTR as measured at tide gauges (Sweet et al. 2015). The results in Figure S4 are similar to ESWL patterns based upon direct statistical estimates using a singular tide gauge (NOAA [Zervas 2013] and Climate Central [Tebaldi, Strauss, and Zervas 2012]), as well as based on synthetic storm surge information generated by dynamical simulations conducted by the USACE (Nadal-Caraballo et al. 2015). For instance, comparison of “observed” water levels by Hall et al. (2016) methods with 100-year recurrence levels along US East Coast locations, the linear regression goodness of fit measures (R^2) are 0.89, 0.94 and 0.68 compared with the results of NOAA, Climate Central, and USACE, respectively. Comparison with 20-year event probabilities with the NOAA and Climate Central estimates are closer ($R^2 = 0.95$ and 0.94) revealing that method differences are most apparent within the lower probability results, which is to be expected.

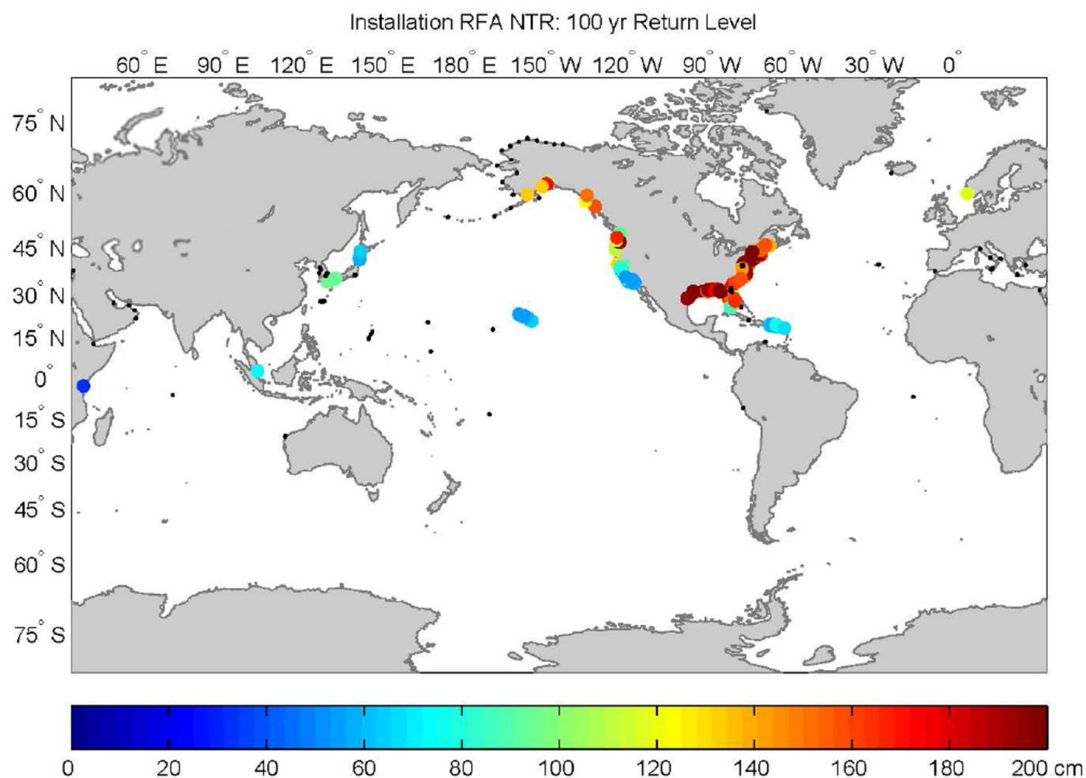


Figure S4. 0.01 Annual Exceedance Probability flood levels (cm) for non-tidal residual levels at selected United States Department of Defense sites worldwide (from Hall et al. 2016).

4. Case study examples from Hall et al. (2016)

Two specific scenario applications are highlighted here: (1) use of scenarios within an adaptive risk management context and (2) scenario application in the zero to 20-year timeframe.

Adaptive risk management

A consideration of the decision type, desired decision longevity, and risk tolerance in combination can go a long way towards simplifying scenario choice. When decisions are sensitive, however, to the degree of resource commitment, an adaptive risk management approach may be preferable. The situations necessitating an adaptive approach are potentially the most frequent given generally the limited resources that may be available for response actions and the uncertainties involved in future SLR, ESWLs, and other factors. As a result, it is best when decisions made within this framework are to some degree reversible or lend themselves to a phasing of needed response actions over time while retaining cost effectiveness and robust asset protection throughout. Hall et al. (2016) identified three basic elements of an adaptive approach to coastal risk management from a military infrastructure perspective: (1) apply scenarios to bound risk and invest in measures to maintain infrastructure and mission functions from less than 20 years to perhaps mid-century, (2) monitor trends in sea level and ESWLs over time, and (3) periodically update the assessment of the upper bound scenarios for longer timeframes and implement new measures accordingly. In general outline, these elements are consistent with those recommended by Hinkel et al. (2015) and USACE (2014), Hallegatte et al.'s (2012) notion of a reversible and flexible response strategy, and Lowe et al.'s (2009) application for the Thames River Barrier. Hall et al. (2016) provide a conceptual example (their Figure 5.12) to illustrate the approach. Decision-makers must recognize this approach requires iterative decision-making in which assumptions and decisions are revisited over time. Each decision point, and thus the choice of bounding scenarios, should be robust for the desired timeframe, not preclude future response options, and facilitate the appropriate timing of the next decision.

Scenario usage within the next 20 years

Although military and national security planners are familiar with scenario usage, other than perhaps weapons system development future planning time horizons tend to be less than 10 years and no more than 20 years. Given that the effects of SLR is already causing amplified and more frequent flooding, those concerned with military infrastructure vulnerability/resiliency and issues of geopolitical stability need information that addresses the near and moderate timeframes (i.e., out to 20 years from present). SLR scenarios based on RCPs generally show little divergence in their median values and distributions through mid-century (Kopp et al. 2014). Moreover, over the next 20 years or so, regional deviations from global mean sea-level change attributable to long-term, persistent, DSL and ice-melt processes will be negligible (< 0.1 m; Hall et al. 2016). The preceding conditions enable a simplification of bounding scenario choices over a 20-year time horizon. VLM trends, however, still may be important to consider. So too is interannual variability (IAV) in DSL attributable to cycles such as ENSO, AMO, and PDO that affect mean sea-level estimates. Although their effects are assumed to average out over longer timeframes, they are important to consider within a 20-year timeframe (Hall et al. 2016).

Figure S5 shows the approach conceptually using assumptions from Hall et al. (2016) of a lower (0.2 m) and upper (2.0 m) global mean SLR scenarios anchored at the 1992 tidal epoch, a beginning point of 2015 (not shown in the figure), and the availability of local VLM data and tide gauge information to calculate IAV. Scenario information can be discretized in five-year time steps (with the recognition that these represent average anticipated conditions and not predictions per se). Two standard deviations of the residuals in detrended local mean sea level at a representative tide gauge of at least 30 years record are computed to arrive at values for IAV. Another simplifying assumption is that IAV does not change over the 20-year time horizon. Depending on the desires of the user, annual chance event probability information can be added as well (see Hall et al. 2016 for details).

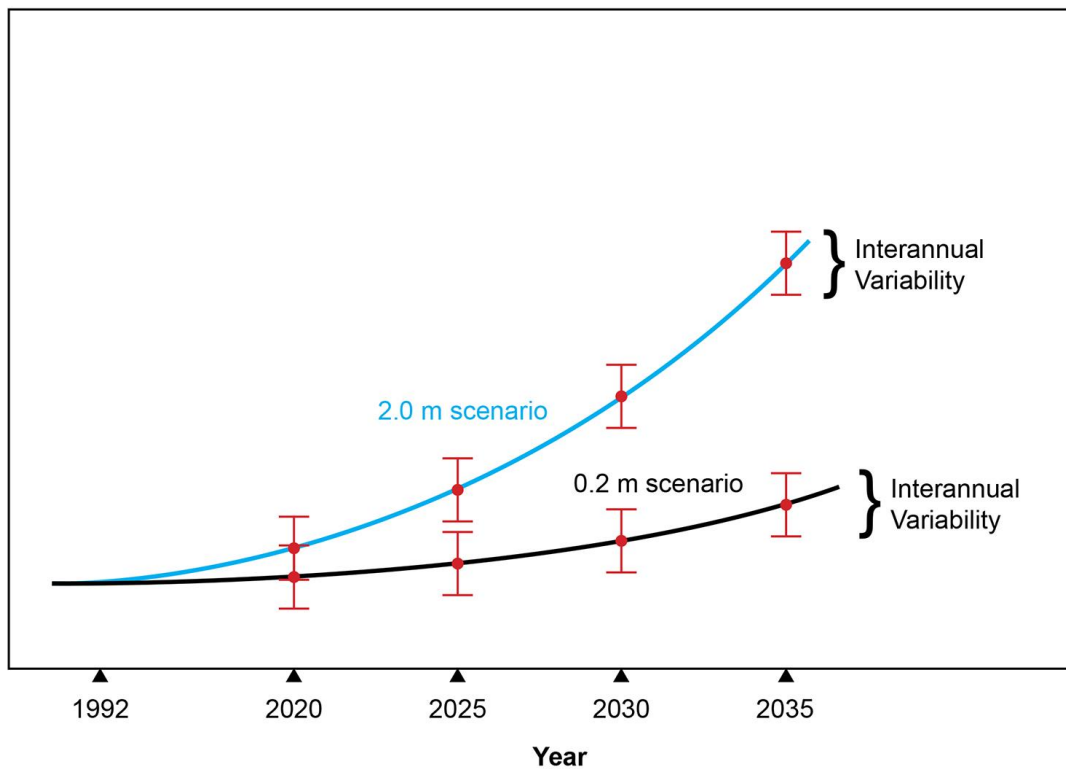


Figure S5. Conceptual diagram to illustrate application of SLR scenarios in the zero to 20-year timeframe (from Hall et al. 2016). The depiction of interannual variability is illustrative and not to scale with the rest of the figure.

5. Additional details regarding US Subnational Efforts to Develop and Apply SLR Scenarios

The main text briefly described the more or less sequential “waves” of efforts in the US to address the challenges of SLR and recurrent flooding that occurred at regional, state, and city level and that paralleled federal efforts. In the text below and in Table S2 specific examples are provided of these various efforts.

Wave I. As part of this wave regions and states used a small number of discrete scenarios, with no probabilities assigned, and did not account for the differences between global and regional sea-level change, other than the contribution of VLM. For example, the Southeast Florida Regional Climate Change Compact (Southeast Florida Regional Climate Change Compact Technical Ad Hoc Work Group 2011) relied on the range of global mean SLR scenarios from USACE (2009), as did Louisiana (Coastal Protection and Restoration Authority of Louisiana 2012). The New Hampshire Coastal Resources Commission (Kirshen et al. 2014) selected an unmodified subset of the Parris et al. (2012) projections, whereas the Massachusetts Office of Coastal Zone Management (MOCZM 2013) adopted the Parris et al. (2012) scenarios, adjusted for subsidence. Connecticut Public Act 13–179 (State of Connecticut 2013) adopted the Parris et al. (2012) scenarios into statute. Based on a literature review, the Delaware Department of Natural Resources and Environmental Control (DDNREC 2009) developed a range of discrete scenarios from 0.5 to 1.5 m, whereas the North Carolina Coastal Resource Commission (2010) developed three scenarios, spanning a range of 0.38 to 1.4 m of global mean SLR by 2100.

Taking a different approach, the 2008 California Climate Assessment (Cayan et al. 2008) used the semi-empirical model of Rahmstorf (2007) and projections of global mean surface temperature change from six GCMs under three different emissions scenarios to generate SLR scenarios. Other states relied heavily on the IPCC. The Maryland Climate Change Commission (2008) developed a pair of global mean SLR scenarios based on the projections of Meehl et al. (2007; IPCC Fourth Assessment Report [AR4]), with adjustments for accelerated ice melting. The North Carolina Coastal Resource Commission (2015) relied on the projections of Church et al. (2013a; AR5), augmented by estimates of VLM, with no effort made to incorporate other factors that cause divergence between regional and global mean SLR. The Southeast Florida Regional Climate Change Compact (Southeast Florida Regional Climate Change Compact Sea Level Rise Work Group 2015) expanded their earlier Wave I type work to use projections of both USACE and the IPCC to recommend a mid-range and high-risk scenario for future planning.

Wave II. In Wave II different contributing factors and their associated uncertainties and geographic patterns became a focus. Two initial efforts led the way. For the state of Washington, Mote et al. (2008) regionalized sea-level projections including steric ocean effects and VLM, though not the gravitational, rotational, and deformational effects of mass redistribution. The first New York City Panel on Climate Change (Horton et al. 2010; 2011b) and New York State ClimAID assessments (Horton et al. 2011a) regionalized SLR in a similar fashion and included a “rapid ice melt scenario” informed by the first application of semi-empirical methods to AR4 GCMs (Horton et al. 2008).

Table S2. Waves of refinement in development of SLR scenarios by United States cities, states, and regions

City, State, or Region	Wave I <ul style="list-style-type: none"> • Discrete scenarios with no likelihoods assigned • Vertical land motion the only regional/local adjustment to global scenarios 	Wave II <ul style="list-style-type: none"> • Contributing factors considered, as well as their uncertainties and geographic patterns 	Wave III <ul style="list-style-type: none"> • Extended component-based approach • Introduced probabilistic assessments of contributing factors conditioned on emissions scenarios 	Wave IV <ul style="list-style-type: none"> • Addressed deep uncertainty associated with high-end scenarios and projections
Boston				Douglas et al. 2016
New York City		Horton et al. 2010; 2011b	NPCC 2013 (see also Horton et al. 2014; 2015), though not explicitly conditional	
California	Cayan et al. 2008			Cayan et al. 2016; Griggs et al. 2017
Connecticut	State of Connecticut 2013			
Delaware	DDNREC 2009			
Florida	Southeast Florida Regional Climate Change Compact Technical [Ad Hoc] Work Group 2011; 2015			

City, State, or Region	Wave I	Wave II	Wave III	Wave IV
Louisiana	Coastal Protection and Restoration Authority of Louisiana 2012	Coastal Protection and Restoration Authority of Louisiana 2017		
Maryland	Maryland Climate Change Commission 2008	Boesch et al. 2013		
Massachusetts	MOCZM 2013			
New Jersey		Miller et al. 2013 (not officially adopted by the state)	Kopp et al. 2016 (stakeholder, non-governmental effort)	
New York		Horton et al. 2011a	Horton et al. 2014	
New Hampshire	Kirshen et al. 2014			
North Carolina	NCCRC 2010		NCCRC 2015	
Oregon			Dalton et al. 2017	
Washington		Mote et al. 2008	Miller et al. 2016; Petersen et al. 2015	
Pacific Coast		NRC 2012		

Later, the National Research Council (2012) analysis of SLR off the coast of California, Oregon, and Washington played a seminal role in introducing methodologies associated with Wave II to U.S. subnational projections (but focused on a mid-range emissions projection; see Hall et al. 2016, page 2–17 for a critique). The Maryland Climate Change Commission (Boesch et al. 2013) adapted this methodology, as did (in a non-governmental institutional setting) Miller et al. (2013) for New Jersey. The 2017 Louisiana Coastal Zone Management Plan (Coastal Protection and Restoration Authority of Louisiana 2017) adapted the NRC (2012) approach, and it also considered projections from Church et al. 2013a) and a semi-empirical model (Jevrejeva, Moore, and Grinsted 2012) to derive a range of estimates for Gulf Coastal regional sea-level change that are assigned uniform probability (i.e., each estimate has an equal likelihood of occurrence).

Wave III. Probabilistic approaches appeared during this wave, as well as advancing considerations of how different individual components contributed to SLR. The New York City (NYC) Panel on Climate Change (NPCC 2013; see also Horton et al. 2010; 2011b; 2014; 2015) was at the forefront of these efforts. It pioneered the probabilistic method, though it did not separate out different emissions scenarios. The panel also fattened its distribution by assuming perfect correlation among different components: e.g., its 90th percentile projection sums the 90th percentile projection for each of the individual components. The former decision reflected NYC stakeholder emphasis on integrated risk rather than projections dependent on a specific RCP. The latter decision reflected a desire to broaden the range of outcomes, given an implicit assumption that the individual components, as understood at the time, were more likely to undersample than oversample the full range of possible outcomes. NPCC methods and projections were applied in a range of decision-contexts, including Master Planning at National Aeronautics and Space Administration Centers (Rosenzweig et al. 2014), and as New York City and state laws and statutes. Building on NPCC (2013), and as later described in Horton et al. (2015), Kopp et al. (2014) developed probabilistic projections, conditional upon RCPs, at a global set of tide-gauge sites originally to support the US economic climate risk analysis of the Risky Business Project (Bloomberg, Paulson, and Steyer 2014) and American Climate Prospectus (Houser et al. 2014; 2015). These projections also were adopted directly for an economic risk analysis by the Congressional Budget Office (Dinan 2017), employed in the Third Oregon Climate Assessment (Dalton et al. 2017) and New Jersey Climate Adaptation Alliance (Kopp et al. 2016) to support a statewide stakeholder network, and adapted by Washington Sea Grant for county-level analyses in the North Olympic Peninsula (Petersen et al. 2015) and Island County (Miller et al. 2016).

Wave IV. Uncertainty, in particular the deep uncertainty associated with high-end scenarios and projections, became a primary focus during Wave IV. Kopp et al. (2014) reacted to the uncertainty inherent in global SLR projections by emphasizing the high-end tail of their projections, in particular noting the similarity between the 99.9th percentile of their RCP 8.5 projections and other estimates of the maximum physically plausible level of 21st century global mean SLR (e.g., Miller et al. 2013). Buchanan et al. (2016) noted the need for special attention to these high-end projections in decision frameworks in light of this deep uncertainty. Economic analyses using the Kopp et al. (2014) projections (e.g., Diaz 2016; Dinan 2017; Houser et al. 2015) have generally not emphasized the high-end tail, but some subnational assessments do employ them (e.g., Kopp et al. 2016). Recent ice-sheet modeling studies incorporating ice-shelf hydrofracturing and ice-cliff collapse mechanisms (DeConto and Pollard 2016; Kopp et al. 2017; Pollard, DeConto, and Alley 2015) have identified specific physical pathways leading to > 1 m of global mean SLR contribution from Antarctica alone in the 21st century, further emphasizing the importance of considering high-end tail projections.

Subsequent subnational assessments considered the implications of these preceding studies in several different manners. The Boston Research Advisory Group (Douglas et al. 2016) and the Fourth California Climate Assessment (Cayan et al. 2016) replaced the Antarctic projections of Kopp et al. (2014) with results based on a 29-member ensemble of Antarctic ice-sheet projections from DeConto and Pollard (2016) (see also Kopp et al. 2017). The California Ocean Science Trust (Griggs et al. 2017) took a different approach: they retained the RCP-conditional probabilistic projections of Kopp et al. (2014), while adding a separate scenario (labeled “H++”)

leading to 2.5 m of global mean SLR in the 21st century. Their H⁺⁺ scenario was drawn from the Extreme scenario of Sweet et al. (2017) and justified both by DeConto and Pollard (2016)'s new ice-sheet modeling results and other assessments of the maximum physically plausible 21st century SLR (e.g., Miller et al. 2013).

References

- AECOM. 2013 The impact of climate change and population growth on the National Flood Insurance Program through 2100. Report prepared for the Federal Emergency Management Agency by AECOM in association with Michael Baker Jr., Inc. and Deloitte Consulting, LLP. New York, NY and Los Angeles, CA: AECOM.
- Bamber, J. L., and R. Riva. 2010. The sea level fingerprint of recent ice mass fluxes. *The Cryosphere* 4:621–627.
- Bindoff, N. L., J. Willebrand, V. Artale, A. Cazenave, J. Gregory, S. Gulev, K. Hanawa, et al. 2007. Observations: Oceanic climate change and sea level. In *Climate change 2007: The physical science basis*. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, eds. S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor, and H. L. Miller, 385–432. Cambridge, United Kingdom and New York, New York: Cambridge University Press.
- Bloomberg, M. R., H. M. Paulson, and T. F. Steyer. 2014. *Risky business: the economic risks of climate change in the United States*. New York, New York: Risky Business Project.
- Boesch, D. F., L. P. Atkinson, W. C. Boicourt, J. D. Boon, D. R. Cahoon, R. A. Dalrymple, T. Ezer, et al. 2013. Updating Maryland's sea-level rise projections. Special Report of the Scientific and Technical Working Group to the Maryland Climate Change Commission. Cambridge, Maryland: University of Maryland Center for Environmental Science.
- Bruun, P. 1962. Sea level rise as a cause of erosion. *Journal of the Waterways and Harbors Division, American Society of Civil Engineers* 88:117–132.
- Buchanan, M. K., R. E. Kopp, M. Oppenheimer, and C. Tebaldi. 2016. Allowances for evolving coastal flood risk under uncertain local sea-level rise. *Climatic Change* 137:347–362.
- Cayan, D. R., P. D. Bromirski, K. Hayhoe, M. Tyree, M. D. Dettinger, and R. E. Flick. 2008. Climate change projections of sea level extremes along the California coast. *Climatic Change* 87:57–73.
- Cayan, D. R., J. Kalansky, S. Iacobellis, and D. Pierce. 2016. Creating probabilistic sea level rise projections. Technical Report TN 211806. Sacramento, CA: California Energy Commission.
- Church, J. A., P. U. Clark, A. Cazenave, J. M. Gregory, S. Jevrejeva, A. Levermann, M. A. Merrifield, et al. 2013a. Sea level change. In *Climate change 2013: The physical basis*. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, eds. T. F. Stocker, D. Qin, G. -K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P. M. Midgley, 1137–1216. Cambridge, United Kingdom: Cambridge University Press.
- Clark, J. A., and C. S. Lingle. 1977. Future sea-level changes due to West Antarctic ice sheet fluctuations. *Nature* 269:206–209.
- Coastal Protection and Restoration Authority of Louisiana. 2012. Louisiana's comprehensive master plan for a sustainable coast. Baton Rouge, LA: Coastal Protection and Restoration Authority of Louisiana.

- Coastal Protection and Restoration Authority of Louisiana. 2017. Louisiana's comprehensive master plan for a sustainable coast. Baton Rouge, LA: Coastal Protection and Restoration Authority of Louisiana.
- Coles, S. 2001. *An introduction to statistical modeling of extreme values*. London, United Kingdom: Springer-Verlag.
- Crowell, M., E. Hirsch, and T. L. Hayes. 2007. Improving FEMA's coastal risk assessment through the National Flood Insurance Program: An historical overview. *Marine Technology Society Journal* 41:5–13.
- Dalton, M. M., K. D. Dello, L. Hawkins, P. W. Mote, and D. E. Rupp. 2017. The Third Oregon Climate Assessment report. Corvallis, Oregon: Oregon Climate Change Research Institute, College of Earth, Ocean, and Atmospheric Sciences, Oregon State University.
- DeConto, R. M., and D. Pollard. 2016. Contribution of Antarctica to past and future sea-level rise. *Nature* 531:591–597.
- Delaware Department of Natural Resources and Environmental Control (DDNREC). 2009. Recommended sea level rise scenarios for Delaware. Report prepared by the DDNREC Sea Level Rise Technical Workgroup. Dover, DE: DDNREC.
- Diaz, D. B. 2016. Estimating global damages from sea level rise with the Coastal Impact and Adaptation Model (CIAM). *Climatic Change* 137:143–156.
- Dinan, T. 2017. Projected increases in hurricane damage in the United States: The role of climate change and coastal development. *Ecological Economics* 138:186–198.
- Divoky, D., D. Eberbach, and M. Crowell. 2012. The impact of climate change on the National Flood Insurance Program. In *Sea level rise and coastal infrastructure: prediction, risks and solutions*, eds. B. Ayyub and M.S. Kearney, 59–77. Reston, Virginia: American Society of Civil Engineers (ASCE), CAB International.
- Douglas, E., P. Kirshen, R. Hannigan, R. Herst, A. Palardy, R. DeConto, D. FitzGerald, et al. 2016. Climate change and sea level rise projections for Boston: the Boston Research Advisory Group Report. Boston, Massachusetts: Climate Ready Boston.
- Federal Emergency Management Agency (FEMA). 1991. Projected impact of relative sea level rise on the National Flood Insurance Program. Washington, DC: FEMA.
- Government Accountability Office (GAO). 2007. Climate change: Financial risks to federal and private insurers in coming decades are potentially significant. GAO-07–285. Washington, DC: GAO.
- Gill, S., G. Hovis, K. A. Kriner, and M. F. Michalski. 2014. Implementation of procedures for computation of tidal datums in areas with anomalous trends in relative mean sea level. NOAA Technical Report NOS CO-OPS 68. Silver Spring, Maryland: US Department of Commerce, NOAA, National Ocean Service, Center for Operational Oceanographic Products and Services.
- Griggs, G., J. Árvai, D. Cayan, R. DeConto, J. Fox, H. A. Fricker, R. E. Kopp, C. Tebaldi, and E. A. Whiteman. 2017. Rising seas in California: An update on sea-level rise science. Oakland, CA: California Ocean Science Trust.
- Grinsted, A., S. Jevrejeva, R. E. M. Riva, and D. Dahl-Jensen. 2015. Sea level rise projections for Northern Europe under RCP 8.5. *Climate Research* 64:15–23.
- Hall, J. A., S. Gill, J. Obeysekera, W. Sweet, K. Knuuti, and J. Marburger. 2016. Regional sea level scenarios for coastal risk management: Managing the uncertainty of future sea level change and extreme water levels for Department of Defense coastal sites worldwide.

- Alexandria, Virginia: Department of Defense, Strategic Environmental Research and Development Program.
- Hallegatte, S., A. Shah, R. Lempert, C. Brown, and S. Gill. 2012. Investment decision making under deep uncertainty—Application to climate change. Policy Research Working Paper 6193. Washington, DC: The World Bank, Sustainable Development Network, Office of the Chief Economist.
- Hinkel, J., C. Jaeger, R. J. Nicholls, J. Lowe, O. Renn, and S. Peijun. 2015. Sea-level rise scenarios and coastal risk management. *Nature Climate Change* 5:188–190.
- Horton, R. M., D. A. Bader, C. Rosenzweig, A. T. DeGaetano, and W. Solecki. 2014. Climate change in New York State: Updating the 2011 ClimAID climate risk information supplement to NYSERDA report 11–18 (Responding to climate change in New York State). Final report 14–26 prepared for the NYSERDA. Albany, New York: New York State Energy Research and Development Authority.
- Horton, R., D. Bader, L. Tryhorn, A. DeGaetano, and C. Rosenzweig. 2011a. Climate risks. In *Responding to climate change in New York State: The ClimAID integrated assessment for effective climate change adaptation*. Technical report, eds. C. Rosenzweig, W. Solecki, A. DeGaetano, M. O’Grady, S. Hassol, and P. Grabhorn, 15–48. Albany, New York: New York State Energy Research and Development Authority.
- Horton, R. M., V. Gornitz, D. A. Bader, A. C. Ruane, R. Goldberg, and C. Rosenzweig. 2011b. Climate hazard assessment for stakeholder adaptation planning in New York City. *Journal of Applied Meteorology and Climatology* 50:2247–2266.
- Horton, R. M., V. Gornitz, M. Bowman, and R. Blake. 2010. Chapter 3. Climate observations and projections. In *Climate change adaptation in NYC: Building a risk management response*, eds. C. Rosenzweig and W. Solecki. *Annals of the New York Academy of Sciences* 1196:41–62.
- Horton, R., C. Herweijer, C. Rosenzweig, J. Liu, V. Gornitz, and A. C. Ruane. 2008. Sea level rise projections for current generation CGCMs based on the semi-empirical method. *Geophysical Research Letters* 35, L02715, doi:10.129/2007GL032486.
- Horton, R. M., C. Little, V. Gornitz, D. Bader, and M. Oppenheimer. 2015. New York City Panel on Climate Change 2015 Report. Chapter 2: Sea level rise and coastal storms. *Annals of the New York Academy of Sciences* 1336:36–44.
- Houghton, J. T., G. J. Jenkins, and J. J. Ephraums, eds. 1990. Climate change: The IPCC Scientific Assessment. Report prepared for the Intergovernmental Panel on Climate Change by Working Group I. Cambridge, Great Britain, New York, NY, and Melbourne, Australia: Cambridge University Press.
- Houser, T., R. Kopp, S. Hsiang, R. Mui-Wood, K. Larsen, M. Delgado, A. Jina, et al. 2014. American climate prospectus: Economic risks in the United States. New York, New York: Rhodium Group.
- Houser, T., S. Hsiang, R. Kopp, K. Larsen, M. Delgado, A. Jina, M. Mastrandrea, et al. 2015. *Economic risks of climate change: an American prospectus*. New York, New York: Columbia Press.
- Hosking, J. R. M., and J. R. Wallis. 1997. *Regional frequency analysis—An approach based on L-moments*. Cambridge, United Kingdom and New York: Cambridge University Press.
- Jet Propulsion Laboratory (JPL) of the California Institute of Technology. 2013. Introduction to JPL’s GPS time series. Pasadena, California: National Aeronautics and Space

- Administration. Accessed October 2015:
http://sideshow.jpl.nasa.gov/post/tables/GPS_Time_Series.pdf.
- Jevrejeva, S., J. C. Moore, and A. Grinsted. 2012. Sea level projections to AD2500 with a new generation of climate change scenarios. *Global and Planetary Change* 80–81:14–20.
- Kirshen, P., C. Wake, M. Huber, K. Knuuti, and M. Stampone. 2014. Sea-level rise, storm surges, and extreme precipitation in coastal New Hampshire: Analysis of past and projected future trends. Portsmouth, New Hampshire: Sustainability Institute at the University of New Hampshire.
- Kopp, R., A. Broccoli, B. Horton, D. Kreeger, R. Leichenko, J. A. Miller, P. Orton, et al. 2016. Assessing New Jersey's exposure to sea-level rise and coastal storms: Report of the New Jersey Climate Adaptation Alliance Science and Technical Advisory Panel. New Brunswick, New Jersey: Rutgers University. doi:10.7282/T3ZP48CF.
- Kopp, R. E., R. M. DeConto, D. A. Bader, C. C. Hay, R. M. Horton, S. Kulp, M. Oppenheimer, D. Pollard, and B. H. Strauss. 2017. Evolving understanding of Antarctic ice-sheet physics and ambiguity in probabilistic sea-level projections. *Earth's Future* 5:1217–1233.
- Kopp, E. T., C. C. Hay, C. M. Little, and J. X. Mitrovica. 2015. Geographic variability of sea-level change. *Current Climate Change Reports* 1:192–204.
- Kopp, R. E., R. M. Horton, C. M. Little, J. X. Mitrovica, M. Oppenheimer, D. J. Rasmussen, B. H. Strauss, and C. Tebaldi. 2014. Probabilistic 21st and 22nd century sea-level projections at a global network of tide-gauge sites. *Earth's Future* 2:1–24.
- Lowe, J.A., C.P. Howard, A. Pardaens, J. Tinker, J. Holt, S. Wakelin, G. Milne, et al. 2009. UK climate projections science report: Marine and coastal projections. Exeter, United Kingdom: Met Office Hadley Centre.
- Maryland Climate Change Commission. 2008. Maryland Climate Action Plan. Baltimore, Maryland: Department of the Environment.
- Massachusetts Office of Coastal Zone Management (MOCZM). 2013. Sea level rise: Understanding and applying trends and future scenarios for analysis and planning. Boston, Massachusetts: Massachusetts Office of Coastal Zone Management.
- Meehl, G. A., T. F. Stocker, W. D. Collins, P. Friedlingstein, A. T. Gaye, J. M. Gregory, A. Kitoh, et al. 2007. Global climate projections. In *Climate change 2007: The physical science basis*. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, eds. S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor, and H. L. Miller, 748–846. Cambridge, United Kingdom and New York, New York: Cambridge University Press.
- Merrifield, M. A., A. S. Genz, C. P. Kontoes, and J. J. Marra. 2013. Annual maximum water levels from tide gauges: Contributing factors and geographic patterns. *Journal of Geophysical Research: Oceans* 118:2535–2546.
- Miller, I. M., S. Petersen, M. Fougerat, D. Pucci, L. Clark, and B. Wood. 2016. Sea level rise and coastal flood risk assessment: Island County, Washington. Austin, Texas: Adaptation International.
- Miller, K. G., R. E. Kopp, B. P. Horton, J. V. Browning, and A. C. Kemp. 2013. A geologic perspective on sea-level rise and its impacts along the U.S. mid-Atlantic coast. *Earth's Future* 1:3–18.
- Mitrovica, J. X., N. Gomez, E. Morrow, C. Hay, K. Laychev, and M. E. Tamisea. 2011. On the robustness of predictions of sea level fingerprints. *Geophysical Journal International* 187:729–742.

- Mote, P., A. Petersen, S. Reeder, H. Shipman, and W. Binder. 2008. Sea level rise in the coastal waters of Washington State. University of Washington Climate Impacts Group and the Washington Department of Ecology.
- Nadal-Carballo, N. C., J. A. Melby, V. M. Gonzalez, and A. T. Cox. 2015. North Atlantic Coast comprehensive study: coastal storm hazards from Virginia to Maine. Report ERDC/CHL TR-15-5. Vicksburg, Mississippi: USCAE, Engineer Research and Development Center.
- National Research Council (NRC). 1987. Responding to changes in sea level, engineering implications. Committee on Engineering Implications of Changes in Relative Mean Sea Level, Marine Board, Commission on Engineering and Technical Systems, National Research Council of the National Academies. Washington, DC: The National Academy Press.
- NRC. 2012. Sea-level rise for the coasts of California, Oregon, and Washington: Past, present, and future. Committee on Sea Level Rise in California, Oregon, Washington; Board on Earth Sciences and Resources and Ocean Studies Board; Division on Earth and Life Studies. National Research Council of the National Academies. Washington, DC: The National Academies Press.
- New York City Panel on Climate Change (NPCC). 2013. Climate risk information 2013: Observations, climate change projections, and maps, eds. C. Rosenzweig and W. Solecki. Prepared for use by the City of New York Special Initiative on Rebuilding and Resiliency. New York, New York: NPCC.
- North Carolina Coastal Resources Commission (NCCRC). 2010. North Carolina sea level rise assessment report. Prepared by the North Carolina Coastal Resources Commission Science Panel. Raleigh, NC: NCCRC.
- NCCRC. 2015. North Carolina sea level rise assessment report: 2015 update to the 2010 report and 2012 addendum. Prepared by the North Carolina Coastal Resources Commission Science Panel. Raleigh, NC: NCCRC.
- Parris, A. 2014. How Hurricane Sandy tamed the bureaucracy. *Science and Technology* 30:83–90.
- Parris, A. P., P. Bromirski, V. Burkett, D. Cayan, M. Culver, J. Hall, R. Horton, et al. 2012. Global sea level rise scenarios for the United States National Climate Assessment. National Oceanic and Atmospheric Administration (NOAA) Technical Report OAR CPO-1. Silver Spring, Maryland: US Department of Commerce, NOAA, Office of Atmospheric Research.
- Pasterick, E. T. 1998. The National Flood Insurance Program. In *Paying the price: the status and role of insurance against natural disasters in the United States*, eds. H. Kunreuther and R. J. Roth, Sr., 125–154. Washington DC: Joseph Henry Press.
- Peltier, W. R. 1998. Postglacial variations in the level of the sea: Implications for climate dynamics and solid-earth geophysics. *Review of Geophysics* 36:603–689.
- Peltier, W. R. 2004. Global glacial isostasy and the surface of the ice-age Earth: The ICE-5G (VM2) model and GRACE. *Annual Review of Earth and Planetary Sciences* 32:111–149.
- Perrette, M., F. Landerer, R. Riva, K. Frieler, and M. Meinshausen. 2013. A scaling approach to project regional sea level rise and its uncertainties. *Earth System Dynamics* 4:11–29.
- Petersen, S., J. Bell, I. Miller, C. Jayne, K. Dean, and M. Fougerat. 2015. Climate change preparedness plan for the North Olympic Peninsula. A Project of the North Olympic Peninsula Resource Conservation & Development Council (NOP RC&D) and Washington Department of Commerce, with funding from the Environmental Protection Agency. Port Townsend, WA: NOP RC&D.

- Pollard, D., R. M. DeConto, and R. B. Alley. 2015. Potential Antarctic ice sheet retreat driven by hydrofracturing and ice cliff failure. *Earth and Planetary Science Letters* 412:112–121.
- Rahmstorf, S. 2007. A semi-empirical approach to projections future sea level rise. *Science* 315:368–370.
- Rosenzweig, C., R. M. Horton, D. A. Bader, M. E. Brown, R. DeYoung, O. Dominguez, and K. Toufexis. 2014. Enhancing climate resilience at NASA centers: A collaboration between science and stewardship. *Bulletin of the American Meteorological Society* 95:1351–1363.
- Schwartz, M. L. 1965. Laboratory study of sea level rise as a cause of shore erosion. *Journal of Geology* 73:528–534.
- Slangen, A. B. A., C. A. Katsman, R. S. W. van der Wal, L. L. A. Vermeersen, and R. E. M. Riva. 2012. Towards regional projections of twenty-first century sea-level change based on IPCC scenarios. *Climate Dynamics* 38:1191–1209.
- Snay, R., M. Cline, W. Dillinger, R. Foote, S. Hilla, W. Kass, J. Ray, J. Rohde, G. Sella, and T. Soler. 2007. Using Global Positioning System-derived crustal velocities to estimate rates of absolute sea level change from North American tide gauge records. *Journal of Geophysical Research* 112:B04409, doi:10.1029/2006JB004606.
- Southeast Florida Regional Climate Change Compact Technical Ad Hoc Work Group. 2011. A unified sea level rise projection for Southeast Florida. A document prepared for the Southeast Florida Regional Climate Change Compact Steering Committee.
- Southeast Florida Regional Climate Change Compact Sea Level Rise Work Group. 2015. Unified sea level rise projection for Southeast Florida. A document prepared for the Southeast Florida Regional Climate Change Compact Steering Committee.
- Spada, G., J. L. Bamber, and R. T. W. L. Hurkmans. 2013. The gravitationally consistent sea-level fingerprint of future terrestrial ice loss. *Geophysical Research Letters* 40:482–486.
- State of Connecticut. 2013. An act concerning the permitting of certain coastal structures by the Department of Energy and Environmental Protection. Public Act No. 13–179.
- Sweet, W. V., R. E. Kopp, C. P. Weaver, J. Obeysekera, R. M. Horton, E. R. Thieler, and C. Zervas. 2017. Global and regional sea level rise scenarios for the United States. NOAA Technical Report NOS CO-OPS 083. Silver Spring, Maryland: US Department of Commerce, NOAA, National Ocean Service, Center for Operational Oceanographic Products and Services.
- Sweet, W. V., J. Park, S. Gill, and J. Marra. 2015. New ways to measure waves and their effects at NOAA tide gauges: A Hawaiian-network perspective. *Geophysical Research Letters* 42:9355–9361.
- Sweet, W. V., J. Park, J. J. Marra, C. Zervas, and S. Gill. 2014. Sea level rise and nuisance flood frequency changes around the United States. NOAA Technical Report NOS CO-OPS 73. Silver Spring, Maryland: US Department of Commerce, NOAA, National Ocean Service, Center for Operational Oceanographic Products and Services.
- Sweet, W. V., C. Zervas, S. Gill, and J. Park. 2013. Hurricane Sandy inundation probabilities today and tomorrow (In *Explaining extreme events of 2012 from a climatic perspective*). *Bulletin American Meteorological Society* 94:S17–S20.
- Tamisiea, M. E., E. M. Hill, R. M. Ponte, J. L. Davis, I. Velicogna, and N. T. Vinogradova. 2010. Impact of self-attraction and loading on the annual cycle in sea level. *Journal of Geophysical Research: Oceans* 115: C07004, doi:10.1029/2009JC005687.
- Tebaldi, C. B. H. Strauss, and C. E. Zervas. 2012. Modeling sea level rise impacts on storm surges along U.S. coasts. *Environmental Research Letters* 7:1–11.

- Technical Mapping Advisory Council (TMAC). 2015. Future conditions risk assessment and modeling report. Washington, DC: TMAC.
- US Army Corps of Engineers (USACE). 1971. Report on the National Shoreline Study. Washington, DC: USACE.
- USACE. 1986. Letter on relative sea level change dated 21 March 1986. USACE Directorate of Civil Works. Washington, DC: USACE.
- USACE. 1989. Guidance on the incorporation of sea level rise possibilities in feasibility studies. Engineer Circular (EC) 1105–2–186. Washington, DC: USACE.
- USACE. 2000. Planning Guidance Notebook. Engineer Regulations (ER) 1105–2–100. Washington, DC: USACE.
- USACE. 2009. Water resources policies and authorities incorporating sea-level change considerations in Civil Works programs. EC 1165–2–211. Washington, DC: USACE.
- USACE. 2011. Sea-level change considerations for Civil Works programs. EC 1165–2–212. Washington, DC: USACE.
- USACE. 2013. Incorporating sea level change in Civil Works programs. ER 1100–2–8162. Washington, DC: USACE.
- USACE. 2014. Procedures to evaluate sea level change: Impacts, responses, and adaptation. Engineer Technical Letter 1100–2–1. Washington, DC: USACE.
- Veatch, W. C. 2017. 2015 updated atlas of U.S. Army Corps of Engineers historic daily tide data in coastal Louisiana. Mississippi River Geomorphology and Potamology Report No. 14. Vicksburg, MS: USACE Mississippi Valley Division.
- Yin, J. J., S. M. Griffies, and R. J. Stouffer. 2010. Spatial variability of sea level rise in twenty-first century projections. *Journal of Climate* 23:4585–4607.
- Zervas, C. 2013. Extreme water levels of the United States 1893–2010. NOAA Technical Report NOS CO-OPS 67. Silver Spring, Maryland: US Department of Commerce, NOAA, National Ocean Service, Center for Operational Oceanographic Products and Services.