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		✓

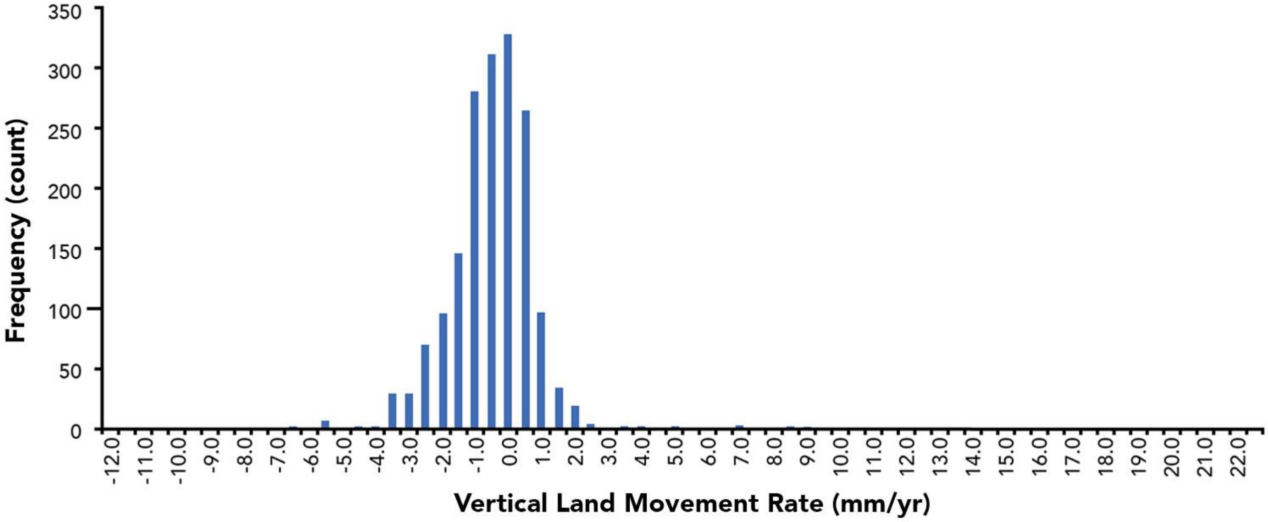


Figure S1. Histogram for rates of vertical land movement at 1,744 Department of Defense sites worldwide (from Hall et al. 2016).

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.

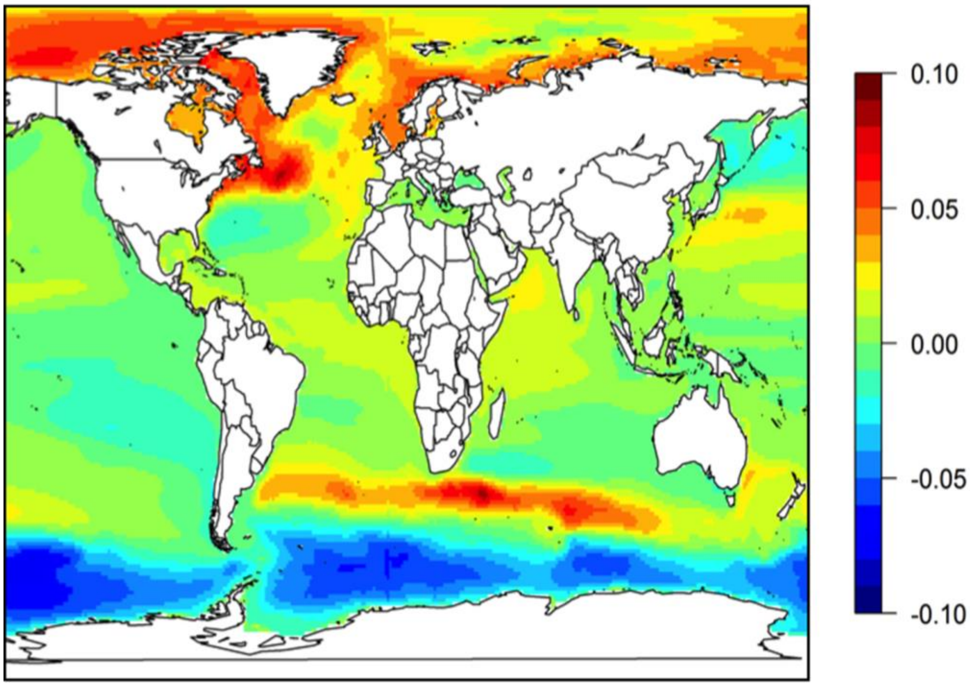


Figure S2. Example of pattern-scaling described in the text corresponding to RCP 8.5 scenario for year 2100 (from Hall et al. 2016 based on data provided by M. Perrette, personal communication 2014).

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.

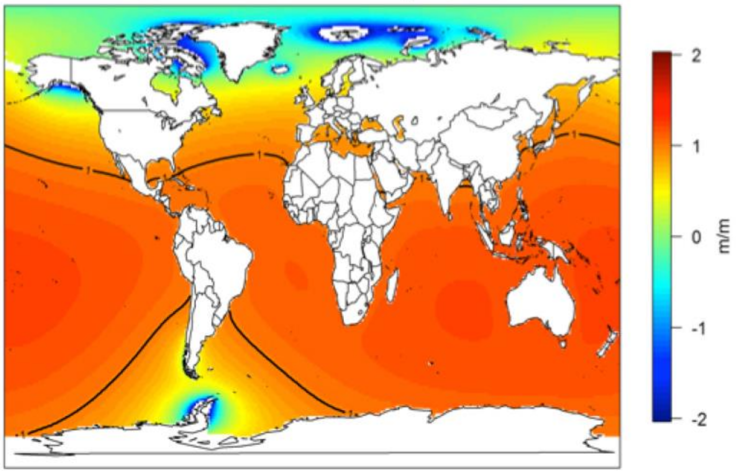
The components associated with the fingerprints are ice melts from glaciers and ice caps (GIC; see Perrette et al. [2013] for data sources and assumptions), Greenland ice sheet (GrIS), and Antarctica ice sheet (AIS). Once the global mass addition from a particular source is known, the adjustments for 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

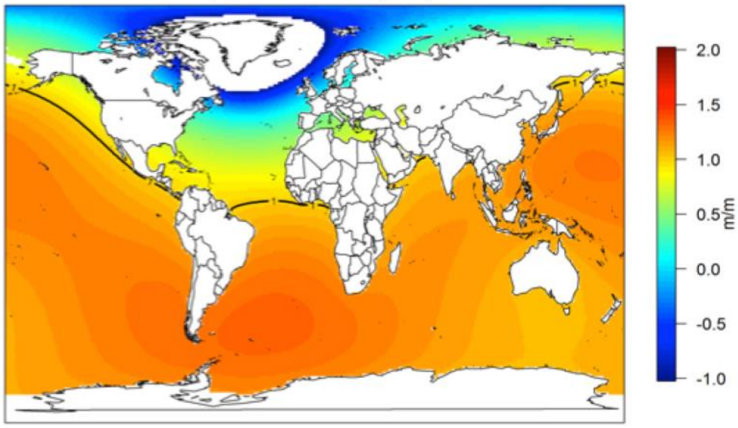
Coastal flooding, erosion, and damages from extreme water events threaten coastal installations and sites and their assets. Knowledge of their event probabilities today and first-order estimates of how their flooding magnitude, frequency, and extent might change in response to scenarios of local SLR 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

(a) Glaciers and Ice Caps (GIC)



(b) Greenland (GIS)



(c) Antarctica (AIS)

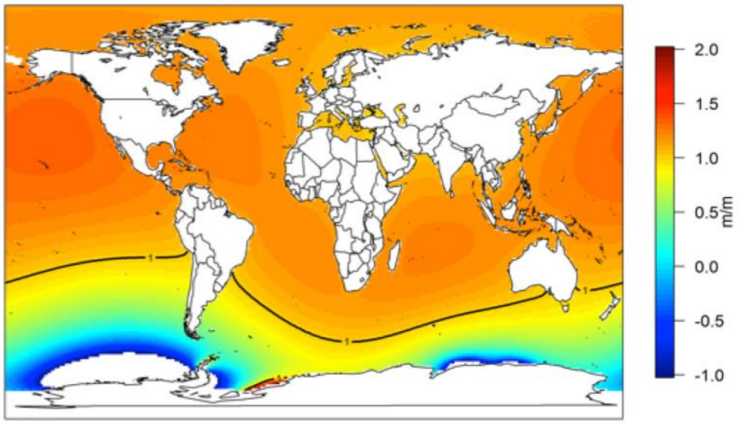


Figure S3. Fingerprints of (a) Glaciers and Ice Caps; (b) Greenland Ice Sheet, and (c) Antarctica Ice Sheet (from Hall et al. 2016). The scale bar represents the ratio of SLR at a particular location to the melt volume (in meters) associated with each of the source components. The solid contour line (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.

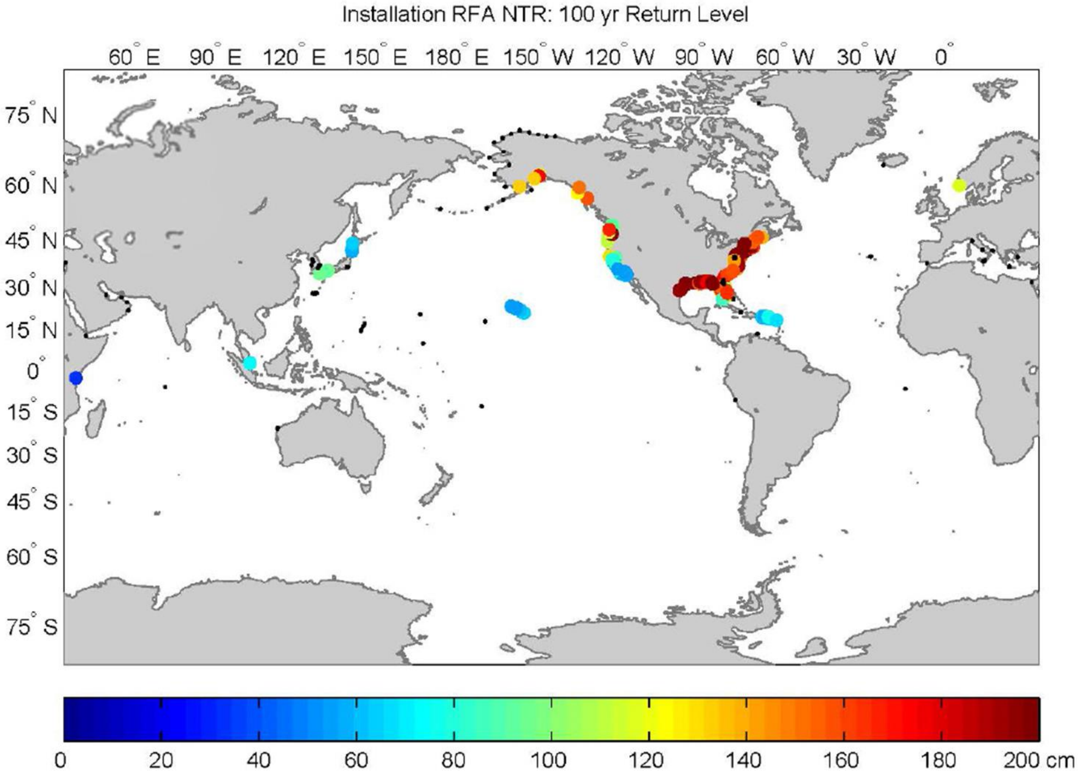


Figure S4. 0.01 Annual Exceedance Probability flood levels (cm) for non-tidal residual levels at selected United States Department of Defense sites worldwide (from Hall et al. 2016).

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).

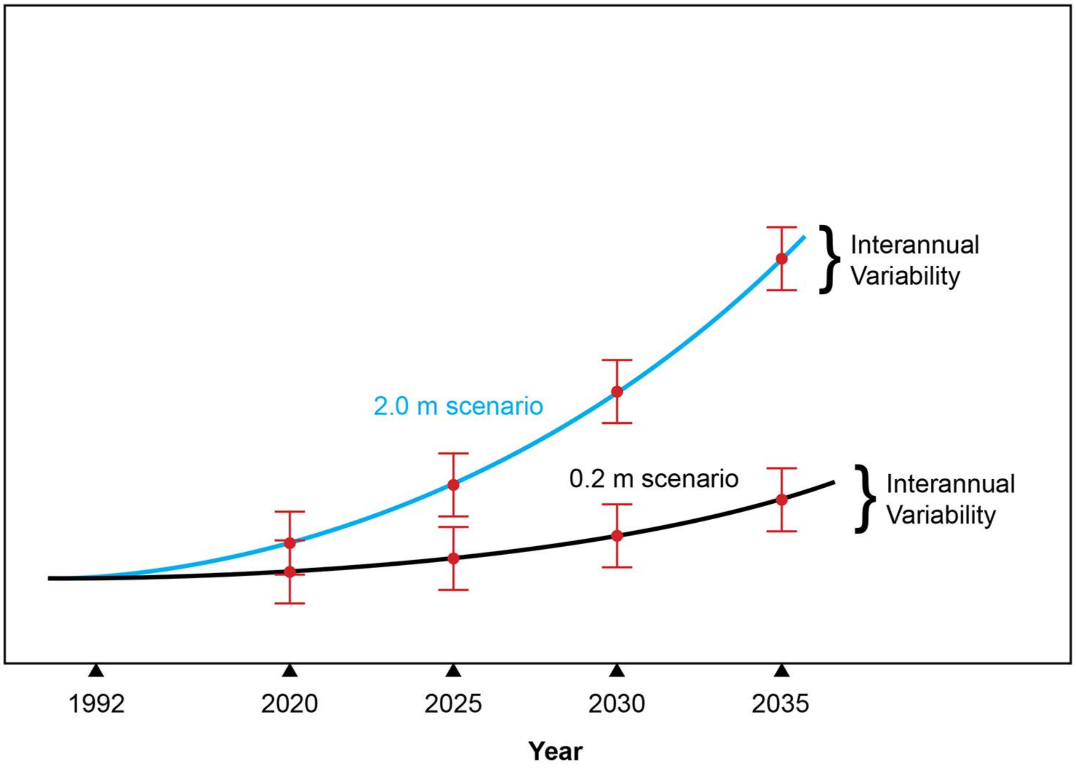


Figure S5. Conceptual diagram to illustrate application of SLR scenarios in the zero to 20-year timeframe (from Hall et al. 2016). The depiction of interannual variability is illustrative and not to scale with the rest of the figure.

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** • Discrete scenarios with no likelihoods assigned • Vertical land motion the only regional/local adjustment to global scenarios	**Wave II** • Contributing factors considered, as well as their uncertainties and geographic patterns	**Wave III** • Extended component-based approach • Introduced probabilistic assessments of contributing factors conditioned on emissions scenarios	**Wave IV** • 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).

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